SC/67A/NH/09

Whales from space: spectral and visual description of four mysticete species using VHR satellite imagery

Hannah C. Cubaynes, Peter T. Fretwell, Jennifer A. Jackson

INTERNATIONAL WHALING COMMISSION

Whales from space: spectral and visual description of four mysticete species using VHR satellite imagery

Hannah C. Cubaynes[1, 2], Peter T. Fretwell[1], Jennifer A. Jackson[1]

1 British Antarctic Survey, Cambridge, United Kingdom

2 Scott Polar Research Institute, Department of Geography, University of Cambridge, United Kingdom

ABSTRACT

A new, innovative method is emerging in the field of wildlife monitoring: the use of very high resolution satellite imagery. With a sub-metre resolution, large-sized animals such as baleen whales can now be detected. This is the first study on baleen whale using the WorldView-3 satellite, which has a maximum spatial resolution of 31cm and is the highest resolution satellite presently in orbit. In order to investigate the possibility of identifying, counting and differentiating between mysticete species we acquired satellite images from four different locations to target the breeding or feeding grounds of four candidate species: fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*), southern right (*Eubalaena australis*) and gray whales (*Eschrichtius robustus*). Visual and spectral analysis of each species and their surrounding environment were conducted. All species were successfully manually detected, this includes the first observations from satellite for fin and gray whales. The visual analysis highlighted morphological differences between some of the targeted species with some species more discernible than others, such as the gray and fin whales which were more confidently identified due to their calm behaviour and light body colouration. The white head callosities, typical of southern right whales, were observed on some individuals. The spectral analysis showed no major differences between the species or with their surrounding waters suggesting that object-based rather than spectral analysis may be the most useful approach for auto-detecting whales in future. These results confirm the potential of using satellite imagery to study baleen whales.

INTRODUCTION

Surveys to monitor whale abundance are a crucial means of assessing numbers, densities, trends, distribution and population status, particularly for populations which are still recovering from whaling (Reeves and Smith, 2003; Roman and Palumbi, 2003) and for those which suffer anthropogenic impacts such as ship strikes and entanglement in fishing gear (Mazzuca *et al.*, 1998; Laist *et al.*, 2001; Mayol *et al.*, 2008; IWC, 2011; Vaes and Druon, 2013; IWC, 2015). Currently, nine out of fourteen of the baleen whale species are recorded on the IUCN Red List either as one of the threatened categories (*i.e.* critically endangered, endangered and vulnerable) or as data deficient (IUCN, 2016). Therefore for the majority of baleen whale species, there is a strong conservation based rationale for monitoring abundance and distribution range (Reilly *et al.*, 2008; Reilly *et al.*, 2013).

Presently, whale population sizes and distributions are assessed via boat, land or aerial surveys (e.g. Forcada *et al.*, 1995; Panigada *et al.*, 2011; De Jesús *et al.*, 2014). In this study they are regarded as traditional methods, all of which present definite advantages (*e.g.* species differentiation, individual identification). However, none of them enable the simultaneous monitoring of large geographical ranges, and, or locations less accessible by boat and plane (Fretwell *et al.*, 2014; McMahon *et al.*, 2014; LaRue *et al.*, 2016). Since most baleen whales are highly migratory (Rugh *et al.*, 2001; Mate and Urbán-Ramirez, 2003; Rasmussen *et al.*, 2007; Jefferson *et al.*, 2015), there is a need to survey vast areas for good understanding of migratory routes and of whale distribution and habitat use in each key seasonal habitat. Furthermore some mysticete species, are thought to occur in remote areas and could be present in other similarly inaccessible locations, such as Omura's whales (*B. omurai*) north of Madagascar and sei whales (*B. borealis*) off the southern Chilean coast (Nieukirk *et al.*, 2004; Mellinger *et al.*, 2007; Cerchio *et al.*, 2015; Häussermann *et al*., 2017). The challenges of studying large and remote areas could potentially be assisted by utilising the presence of very high resolution (VHR) satellites orbiting the Earth (Abileah, 2002; Fretwell *et al.*, 2014; LaRue *et al.*, 2016).

VHR satellites provide images with a spatial resolution below the metre, which means features the size of baleen whales (*i.e.* 10-33m) could hypothetically be observed using them. In 2002, Abileah tested this idea with IKONOS (spatial resolution: 82cm panchromatic and 3.2m multispectral) to census marine mammals (Abileah, 2002). On one of the examined images, he identified features as probable marine mammals and specifically humpback whales due to their size and the location and time of the image. However, none of the detections could be confirmed. He also made the first attempt at calculating and comparing the spectral reflectivity of marine mammals with different body colouration. Overall, his findings led him to conclude that VHR satellites might in the near future allow a census of marine mammals, arguing for the necessity of ground-truthing to validate the results, and the need for satellites with higher spatial resolution tend to provide more detailed images, and raise the confidence in detection. A decade later, the WorldView-2 was launched and offered a higher spatial resolution (*i.e.*50cm panchromatic and 1.84m multispectral) than IKONOS. Fretwell *et al.* (2014) analysed images captured by the WorldView-2 satellite, of Península Valdés in Argentina during the breeding season for southern right whales. They successfully detected southern right whales, both manually and automatically, and highlighted the importance of having an automated system to efficiently and rapidly detect whales, compared to traditional methods.

Differentiation among whale species is one of the first challenges for developing an automated VHR whale detection system for measuring species density and distribution. Since species differentiation remains untested for satellite images, we make the first attempt to distinguish baleen whale species from one another on satellite images, using images taken by the WorldView-3 satellite which was launched in 2014 and providing the highest spatial resolution available to date (*i.e.* 31cm panchromatic and 1.2m multispectral). This increased spatial resolution could raise the confidence in whale detection from satellites, and baleen whale species could hypothetically be differentiated in satellite images. Four species known to be highly distinguishable from one another when observed, from a boat, plane or land, were targeted for this study (Jefferson *et al.*, 2015; Perrin *et al.*, 2009). Each of them has also been well studied in their respective feeding and/or breeding grounds (Rowntree *et al.*, 2001; Urbán *et al.*, 2003; Herman *et al.*, 2011; Panigada *et al.*, 2011; Ponce *et al.*, 2012) where they occur in high enough abundance to make a study of each species using VHR satellite technology feasible. The chosen candidates are the fin whale in the Pelagos Sanctuary (France, Monaco and Italy), the humpback whale off Maui Nui, Hawaii (USA), the southern right whale off Península Valdés (Argentina) and the gray whale in Laguna San Ignacio (Mexico). Initially, all the individuals of each species were manually counted and only the “definite” whales were retained, to describe the species in terms of morphology (*e.g.* body shape, measurements and colour), behaviour (*e.g.* surface water disturbances) and spectral signature. Each species was subsequently compared with each other in order ascertain species-specific differences using WorldView-3 images. Next, each of the four target species were compared to their respective surroundings and other non-whale features (*e.g.* plane and boat) if any were present in the imagery. Our ultimate aim with this project is to assess the feasibility of building an automated detection system that will be able to distinguish whale species and count them from space.

METHOD

Four images representing different locations (Fig. 1) were acquired from the WordView-3 satellite operated by DigitalGlobe.

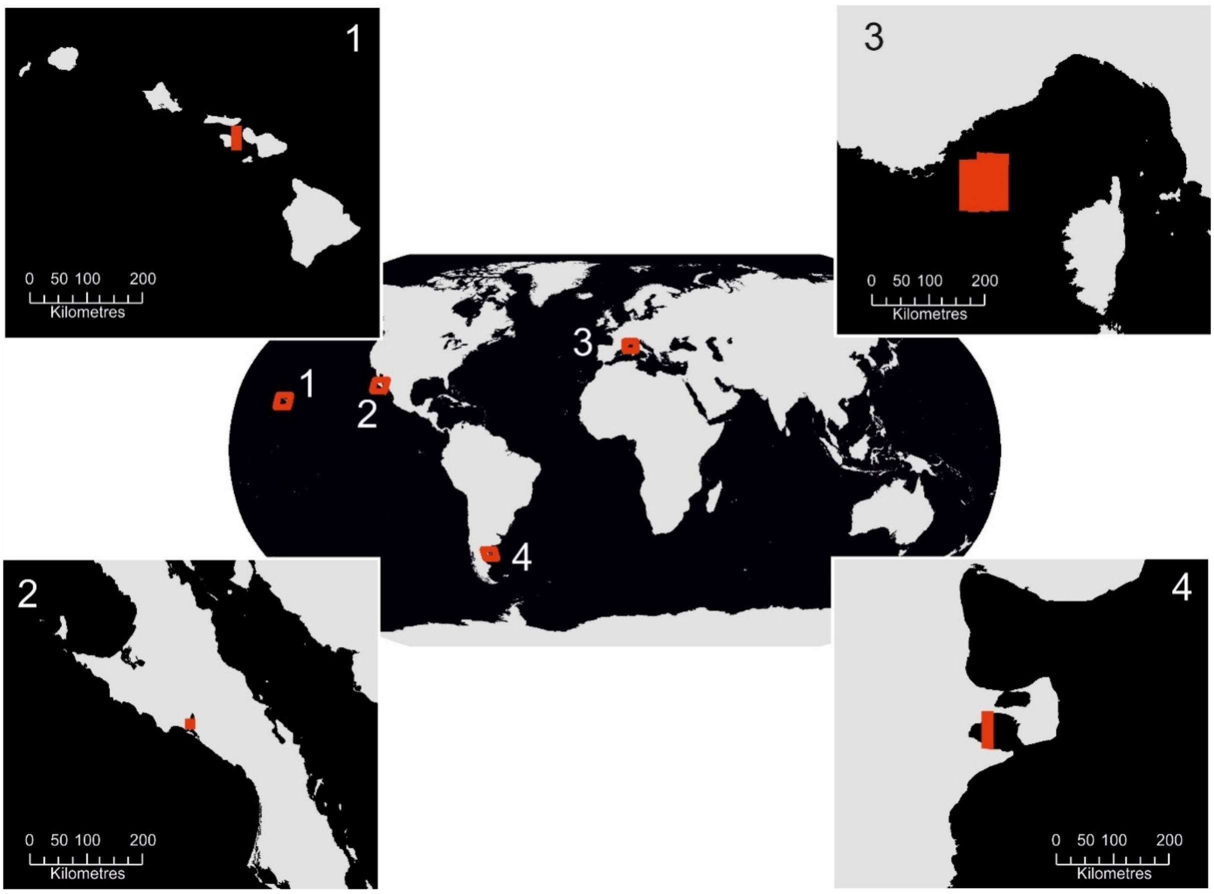


Fig.1 - Locations of study areas: Maui Nui (1), Laguna San Ignacio (2), Pelagos Sanctuary (3) and Península Valdés (4). Red boxes in the four subareas represent the extent of the satellite imagery acquired and used in this study.

Image selection: species and location

The use of satellite imagery to study baleen whales is at an early development stage. To increase the likelihood of whales being present on the images, and to start species identification with relatively simple comparisons, we followed four prime criteria:

- morphological differences: the candidate species display substantial morphological differences from each other);
- whale abundance: in order to achieve good likelihood of having whales present at the sea surface in the images, the time of peak abundance was selected;
- weather conditions: ideally calm waters, *i.e.* few or no white caps and low swell such as in enclosed areas; as Fretwell *et al.* (2014) and Abileah (2002) mentioned a rough sea state can reduce the ability to manually detect whales;
- other megafauna: for each location it was verified that no other large marine animals of similar size to the studied whales were present at the time the images were taken.

Four images were acquired at times and locations where specific baleen whale species were known to exist in reasonable relative density with no other confounding species of large whale thought to be present.

Image 1 was taken on 16 October 2014 of Golfo Nuevo in Península Valdés, Argentina, during the calving season of the southern right whales. Their population has been monitored for the past four decades; hence, it is known that southern right whales inhabit this area between May and December with peak abundance from mid-August until early October (Payne 1986; Cooke *et al.*, 2013; IWC, 2013; Crespo *et al.*, 2014). Although killer whales (*Orcinus orca*) are the only other large marine mammal known to enter this bay, they are much smaller than southern right whales, and arrive later, around December (Iñiguez, 2001). Consequently, the risk of mistaking southern right whales for killer whales was deemed low. Regarding the sea conditions, Golfo Nuevo being a bay, it is considered to be sheltered and relatively calm weather was expected compared to the open ocean.

Image 2 is of the Au'au Chanel in Maui Nui, United States of America taken on 9 January 2015. It is a well-known breeding ground for humpback whales from December to April with peak abundance between February and March (Herman *et al.*, 2011; Baird *et al.*, 2015). In this region, no other marine mammals similar in size to humpback whales have been reported to occur in high numbers during winter. Rarely, blue (*B. musculus*), fin, minke (*B. acutorostrata*), sei and Bryde's whales (*B. edeni*) have been sighted in the deep offshore waters north of the main Hawaiian islands, *i.e.* outside and north of the Au'au Channel. Although sperm whales have been recorded in the region, they tend to stay in deep waters away from the main Hawaiian islands (Mobley *et al.*, 2001; Barlow, 2006; Smultea *et al.*, 2010). The probability of observing one of these species on the tasked satellite image was considered low which reduced the risk of mistaking humpback whales with one of the species mentioned above. The channel being partly enclosed by four islands (*i.e.* Maui in the east, Kaho'olawe in the south, Lana'i in the west and Moloka'i in the north) was judged to be a place with relatively calm waters (*i.e.* low swell).

Image 3 is composed of three images acquired on 19 June 2016 and one on 26 June 2016 of a region of the Pelagos Sanctuary in the Mediterranean, spanning French, Monégasque and Italian waters. In the summer fin whales are known to be present in the deep western offshore waters of this sanctuary (Forcada *et al.*, 1995; Notarbartolo *et al.*, 2003; Panigada *et al.*, 2011). The choice of location for the images was based on the findings of Paniguada *et al.* (2008) who used habitat models to identify an area where the abundance was likely to be the highest. In the Pelagos Sanctuary no other large marine animals, similar in size to the Mediterranean fin whale subpopulation (*i.e.* maximum body length of 24m), have been observed with any regularity or in high numbers. Sperm whales (*i.e.* maximum body length of 18m) are usually found next to steep slope features such as canyons, none of which were located in the studied images (Moulins *et al.*, 2008; Jefferson *et al.*, 2015). There have been exceptionally rare sightings of humpback whales, solitary or in pairs (Frantzis *et al.*, 2004; Dhermain *et al.*, 2015); these can reach a maximum length of 18m (Jefferson *et al.*, 2015). Summer sea conditions in the northern Mediterranean are characterised by flat calm weather and, due to the size and enclosed nature of the Mediterranean basin, the swell was expected to have a short period compared to the open ocean.

Image 4 was taken in Laguna San Ignacio, Baja California, in México on 20 February 2017. It coincides with the calving season for gray whales which occurs from December to March with peak abundance in mid-February (Jones and Swartz, 1984; Urbán *et al.*, 2003). Although humpback whales winter in Baja California they do not aggregate in Laguna San Ignacio (Urbán and Aguayo, 1987; Steiger *et al.*, 1991; Calambokidis and Barlow, 2004). While blue whales are also encountered off the coast of Baja California during winter, there are no reports of sightings within Laguna San Ignacio (Mate *et al.*, 1999; Calambokidis and Barlow, 2004; Bailey *et al.*, 2009). Laguna San Ignacio being a small enclosed area, the swell was expected to be low.

For all images the spatial resolution was 31cm for the panchromatic band, 1.2m for the multispectral bands. All eight multispectral bands were acquired for the images 1, 2 and 3:

- coastal: 400-452nm;
- blue: 448-510nm;
- green: 518-586nm;
- yellow: 590-630nm;
- red: 632-692nm;
- red-edge (Red-E): 706-746nm;
- NIR1 (Near Infra-Red 1): 772-890nm;
- NIR2 (Near Infra-Red 2): 866-954nm.

Concerning image 4, only four out of the eight multispectral bands were acquired (*i.e.* blue, green, red and NIR1), due to resource limitations.

Image analyses: visual

Prior to describing each species on their respective satellite images, they were manually counted. To improve the ability to detect whales, the multispectral images (*i.e.* composed of the eight or four colour bands) were pan-sharpened in *ArcGIS 10.4 ESRI 2017* with their respective panchromatic images, which have a higher spatial resolution. Using a grid system, the full extent of each pan-sharpened image was manually scanned thoroughly at a scale of about 1:1,500. To decide whether a feature was a whale, various criteria listed in Table 1 were used. In addition to account for the confidence of the observer in the identification of whales, each individual was categorised as “definite”, “probable” or “possible”. The classification relied on the value and combination of the

Table 1 criteria as explained in Table 2. Additionally, the proportion of “definite” whales among all counted whales (*i.e.* including “probable” and “possible” individuals) was calculated for each candidate species.

Once all the whales were counted, the “definite” whales were used to morphologically describe how each species looks like from space. The following body parts, if visible, were measured in *ArcGIS 10.4 ESRI 2017*:

- body length (A);
- body width (B);
- flipper length (right flipper: C1; left flipper C2);
- fluke width (D).

For each body parts, the mean and standard deviation were calculated. In addition, the type of whale-sign (*e.g.* surface water disturbances) associated with each species was recorded (Appendix A). While scanning the image, non-whale features such as boats and planes were also logged.

Table 1 - List of criteria to inform whether a feature is a whale and the confidence level of the identification

Criteria	**Yes (2 pts)**	**Maybe (1 pt)**	**No (0)**
Body length range	2	1	0
Body width range	2	1	0
Body shape	2	1	0
Body colour	2	1	0
Associated with surface water disturbance	2	1	0
Fluke	2	1	0
Flipper	2	1	0
Movements*	2	1	0
Head callosities (only right whale)	2	1	0

*for Pelagos satellite images only, if a whale was seen on two images at a different position

Table 2 - Confidence in whale identification: separated into three categories (definite, probable and possible) each based on a combination of criteria listed in Table 1

Certainty	**Range value**	**Description**
Definite whale	6 to 18 pts	At least (3 x yes) or (2 x yes and 2 x maybe)
Probable whale	3 to 5 pts	At least (3 x maybe) or (1 x yes and 1 x maybe), Maximum (2 x yes and 1 x maybe)
Possible whale	1 to 2 (3*) pts	(1 x yes) or (2 x maybe) or (1 x maybe) or *(1 x yes and 1 x maybe if yes correspond to criteria “associated with surface water disturbance” of Table 1)

Image analyses: spectral

For the spectral analysis of whales, "end-members" were designated from each candidate species. These were chosen from among the "definite" individuals. The whales showing most of their body length were selected. In order to obtain the pixel value or radiance (*i.e.* one value per multispectral band), the multispectral image of each location was corrected for the top of atmosphere using *ENVI* software (Harris Geospatial). Then, every pixel constituting the "end-members" was described with one or a combination of the characteristics listed in Appendix B. Only the purest "whale pixels" (*i.e.* the pixels entirely filled with whales) were retained, in order to remove the bias of including water or white water in the radiance value. Indeed, some pixels were made of both water and whale (*i.e.* mixed-pixels), for instance. Concerning the waters and other features, 100 pixels were respectively and randomly chosen for each location and each type of non-whale features.

The values of all pixels were extracted using *ArcGIS 10.4 ESRI 2017*. They were separately averaged for each whale species, and for each feature and waters per location. To allow quantitative comparisons to be made between species, the standard error of the mean was also calculated.

RESULTS

Image analyses: visual

Whale morphology and behaviour

Manual scanning found individuals of each of the four species within their respective satellite images (Fig. 2). Most of the individuals identified were adults with the exception of gray whales calves (*i.e.* one "definite", two "probable" and five "possible") and one "possible" southern right whale calf. In terms of confidence in identification, fin whales had the highest proportion of "definite" individuals, whereas humpback and southern right whales had the lowest. The confidence in gray whale identification was two times higher than for the southern right whales (Table 3).

The total number of whale-like objects (*i.e.* "definite", "probable" and "possible" whales) for fin whales includes three individuals that were likely observed twice (Table 3), as three of the four satellite images acquired for the Pelagos Sanctuary were taken on the same day with intervals of <30 seconds. These three whales were observed in the overlap region of these images, and appeared to have moved. No humpback, southern right, or gray whales were observed twice, as only one satellite image was used for each of these species. Concerning humpback whales, the total number of whale-like objects includes seven "possible" whales based on whale signs, and not associated with any other whales recorded in the image.

The length and width measurements of the body were acquired for all the surveyed species. However, other body measurements such as flipper or fluke lengths could not be measured for all the studied species. Indeed, no flukes were distinctly observed on any of the humpback whales, nor for flippers for southern right whales (Table 3).

Some distinct body characteristics known to be unique features for the respective species were observed on some individuals, such as long flippers for the humpback whales, which were observed on two of the counted individuals. White head callosities, a characteristic specific to right whales, were positively identified on two of the recorded “definite” southern right whales (Table 3).

Along with body features, signs indicating the presence of whales were observed. Some are related to surface water disturbance: after-breach, footprint, wake and contour. There were also other signs not linked to surface water disturbance: blow, defecation. Footprints and contours were observed for each surveyed species. Wake and blow were seen for three out of the four candidate species. After-breach was only witnessed for the humpback whale, likewise with defecation for the southern right whale (Appendix A).

Fig. 2 - Pan-sharpened WorldView-3 satellite images of four gray whales in Laguna San Ignacio (top left), a fin whale in the Pelagos Sanctuary (top right), two humpback whales in Maui Nui (bottom left), and a southern right whale in Península Valdés (bottom right)

Non-whale features

On the satellite images, non-whale features were clearly discernible. Various types of boats were observed in the Pelagos Sanctuary, Laguna San Ignacio and Maui Nui such as ferries, fishing boats, cargo and sail boats. Planes, (*i.e.* passengers and smaller aircrafts) were seen in the Pelagos Sanctuary and Maui Nui (Fig. 3). No boats, or aircrafts or any other non-whale features were observed off Península Valdés (*i.e.* image 1).

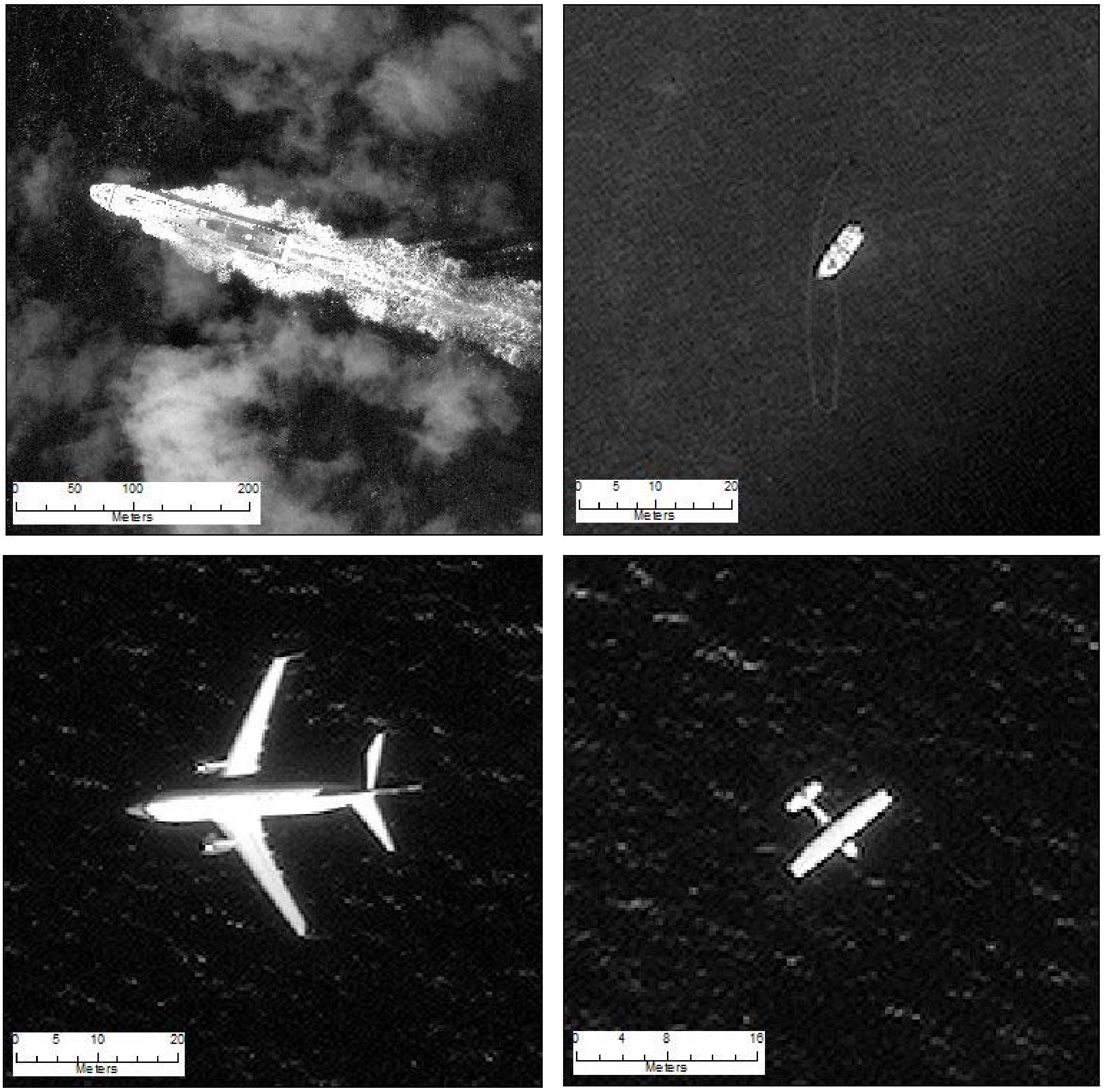


Fig. 3 - Panchromatic WorldView-3 satellite images of non-whale features: a ferry in the Pelagos Sanctuary (top left), a fishing boat in Laguna San Ignacio (top right), a passenger plane in Maui Nui (bottom left), and a small aircraft in Maui Nui (bottom right)

Table 3 - Summary of morphological characteristics and associated whale signs per surveyed species

Species	Location	Date	Area (km^2)	Number of definite whales	Number of probable whales	Number of possible whales	Total number of whales	Proportion of definite whale (%)	Average body measurements (m)	N	Standard Deviation	Whale signs[1] observed in the studied satellite images	Distinctive characteristics
Fin whale ***Balaenoptera physalus***	Pelagos Sanctuary (France, Monaco, Italy)	26/06/2016 19/06/2016	4234	21 (+1)[2]	2 (+2)[2]	5	28 (+3)[2]	75.00 (70.97)[2]	A: 13.49 B: 2.56 C: 1.94 D: 3.68	9 9 6 1	2.92 0.47 0.23 NA	**Surface water disturbances**: Contour, footprint, wake	Streamlined body
Southern right whale ***Eubalaena australis***	Golfo Nuevo, Península Valdés (Argentina)	16/10/2014	560	12	14	33 (1)[3]	59	20.34	A: 10.47 B: 3.08 C: NA D: 4.45	6 6 0 1	2.69 0.39 NA NA	**Surface water disturbances:** Blow, contour , footprint, wake, **Other:** defecation	White callosities on the head
Humpback whale ***Megaptera novaeangliae***	Au'au Channel, Maui Island (USA)	09/01/2015	570	9	18	29	56	16.07	A: 10.62 B: 2.94 C: 2.39 D: NA	5 4 4 0	1.36 0.43 0.53 NA	**Surface water disturbances:** After-breach, blow, contour , footprint, wake	Long flippers
Gray whale ***Eschrichtius robustus***	Laguna San Ignacio, Baja California (Mexico)	20/02/2017	80	25 (1)[3]	15 (2)[3]	22 (5)[3]	62	40.32	A: 12.58 B: 2.90 C: 1.90 D: 3.06	10 9 3 8	0.95 0.44 0.27 0.26	**Surface water disturbances:** Blow, contour , footprint	Pale, whitish body colouration

[1]Cf. Appendix A

[2]Additional individual thought to be observed twice

[3]Number of calves

Image analyses: spectral

As illustrated in Fig. 4, the main results for the spectral analysis are as follows:

- gray whales are the lightest, followed closely by fin whales, then southern right and humpback whales which are much darker;
- gray and fin whales are much brighter than the water, but southern right and humpback whales have very similar spectra to the surrounding water.
- the shape of the spectral profiles are similar and none differ greatly from their environment.
- near infra-red value of all whales and water is at or close to zero.

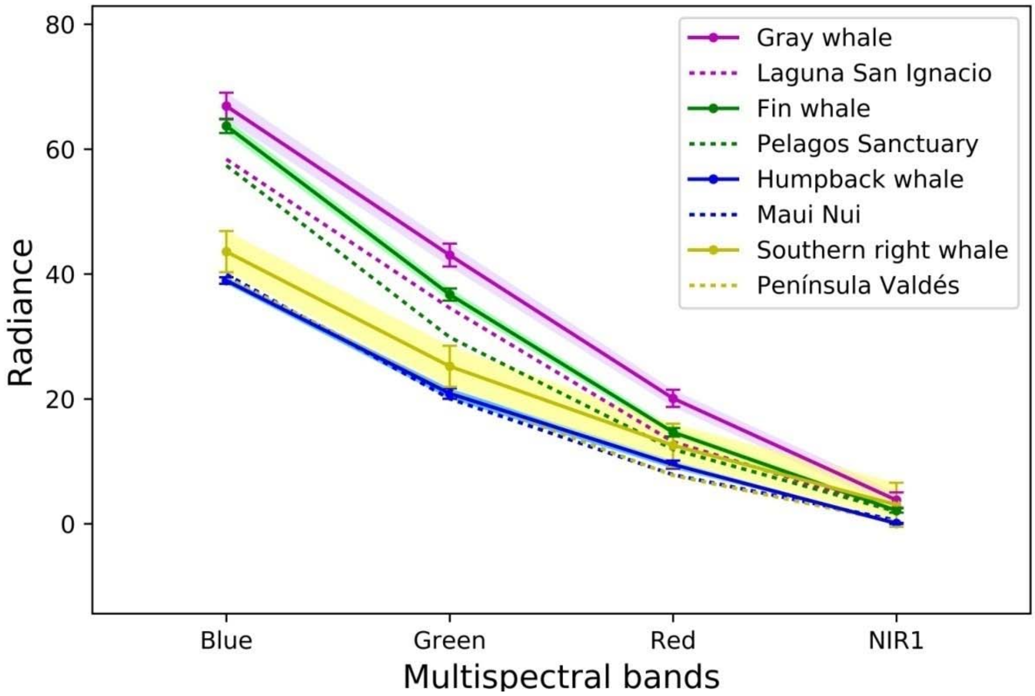


Fig. 4 - Radiance of the four studied species and of the water in each surveyed locations for four multispectral bands

DISCUSSION

Each of the four studied species could clearly be identified on WorldView-3 satellite images. However, some species were harder to detect compared to others. Fin and gray whales were easier to recognise than humpback and southern right whales, which had lower proportions of “definite” individuals. This low proportion among the humpback whales could potentially be due to their well-documented acrobatic nature (Helweg and Herman, 1994; Frankel *et al.*, 1995; Clapham and Mead, 1999), which hindered identification on the satellite image as whale characteristics such as body shape, flippers or fluke could not confidently be recognised. In contrast the confidence in fin whale identification was likely higher as most of the whales were mostly seen travelling, which allowed us to clearly identify whale characteristics. Concerning southern right whales, the low proportion of “definite” whales could be linked to their dark body colouration not easily distinguishable in deep waters, which is where all the southern right whales in this study were observed. In comparison gray whales, which have a lighter body colouration (Jefferson *et al.*, 2015), were twice as frequently identified.

As with Fretwell *et al.* (2014), we successfully detected southern right whales. In the present study they were exclusively seen in the deeper waters of the images, even though the surveyed image contained coastal areas. Payne (1986) noted their preference for waters ~5m in depth. This preference for shallow waters has since been well documented particularly for mother and calf pairs (Rowntree *et al.*, 2001; Crespo *et al.*, 2014). However Crespo *et al.* (2014) reported a shift towards deeper waters, which is consistent with what was seen on the imagery. Among the “definite” southern right whales, one appeared to have a lighter colouration which could be a heavily mottled individual; Jefferson *et al.* (2015) mentions this as being common among southern right whales.

Laguna San Ignacio is a well-known breeding ground for gray whales where calves have been recorded (Jones and Swartz, 1984; Urbán *et al.*, 2003). On the satellite image of this lagoon taken during calving season, some gray whale calves were observed, however only one was identified as “definite”. This low certainty in calf identification might be related to their small size which makes it difficult to see clear whale-like features with the spatial resolution offered by current satellites. This could also explain the absence in our counts of southern right whale calf identifications in the image of Península Valdés, except for one “possible”.

Concerning the measurement of the adult body length on the satellite images, gray whales were the only species which were to be found within their known size range. Adult southern right and humpback whales were close to the lower limit of their size range. In comparison, fin whale body length was below its documented size range (Shirihai and Jarrett, 2006; Jefferson *et al.*, 2015). This discrepancy in body length compared to the known size range could be due to the fact that whales are often positioned diagonally to the sea surface; for instance when a whale is about to surface following a dive, or whilst diving.

The spectral analysis showed that the spectral profiles were fairly identical between the four candidate species. Our results show a similar ranking to Abileah’s hypothetical (2002) spectral reflectivity value between the gray and humpback whale radiance values for the blue, green and red bands. However we found different spectral profiles to Abileah (2002) for these two species. Indeed, in this study the radiance is lower for the red band compared to the green band.

The WorldView-3 satellite allowed us to review more morphological details and whale signs compared to the WorldView-2 satellite (Fretwell *et al.*, 2014) and the IKONOS (Abileah, 2002), which will be useful for automating the detection of mysticetes. For future application of this method to provide measurement of density and even abundance, we will need to better understand how deep below the surface whales can be detected, and to have region-specific information on surface availability to apply appropriate correction factors.

For future baleen whale studies using VHR satellite, we recommend the following criteria to be considered based on the findings of the present study (see Appendix C for a species by species recommendation):

- species general behaviour: *e.g.* travelling or resting which means the animal full body length will likely be parallel to the surface;
- distinct colouration compared to its surrounding waters, *e.g.* if observing whale in deep waters paler colours should be more easily discernible;
- large size animal: animal above 10m in length;
- availability at the surface, *e.g.* long-dive species such as sperm whales might be trickier to observe on satellite images;
- calm waters, *e.g.* species found in coastal waters compared to open-ocean might be easier to detect due to a potentially lower swell;
- co-occurrence of other similar species, *e.g*. potential challenge for mis-identification of species and potential for a positive bias in species-specific counts.

CONCLUSION

This survey is the first to look at whales with the WorldView-3 satellite. It shows that large baleen whales can be seen on VHR satellite imagery. However, some species such as humpback and southern right whales, easily identifiable from boat or aerial survey, might be more difficult to detect on satellite images, owing to a dark body colouration and, or acrobatic behaviour. The reverse is true for species with a calmer behaviour or lighter body colouration, such as fin and gray whales, which seem more easily discernible on satellite images. VHR satellite could therefore be of great potential for monitoring similarly coloured species. Due the vastness of oceans and baleen whale distribution range, manual detection would however be too time consuming to conduct a broad-scale survey. Therefore, a future task will be to automate or semi-automate the detection of each species following Fretwell *et al.* (2014). As concluded from this survey, the spectral profile is similar between the four surveyed species and the shape of the profile is similar to the surrounding environment; however they present morphological differences. Hence, an object –based analysis seem more appropriate than a purely pixel based method. This survey adds to Abileah (2002) and Fretwell *et al.* (2014) findings, with the aim to inform on the feasibility of the use of VHR satellite images to conduct marine mammal research and promote their conservation.

ACKNOWLEDGEMENTS

This research was possible thanks to the MAVA Foundation for their financial support of the “Whales from Space” project. We are also thankful to the DigitalGlobe Foundation for providing us with satellite imagery.

REFERENCES

Abileah, R. 2002. Marine mammal census using space satellite imagery. *U.S. Navy Journal of Underwater Acoustics*, 52(3): 709–724.

Bailey, H., Mate, B.R., Palacios, D.M., Irvine, L., Bograd, S.J. and Costa, D.P. 2009. Behavioural estimation of blue whale movements in the Northeast Pacific from state-space model analysis of satellite tracks. *Endangered Species Research*, 10: 93–106.

Baird, R.W., Cholewiak, D., Webster, D.L., Schorr, G.S., Mahaffy, S.D., Curtice, C., Harrison, J. and Van Parijs, S.M. 2015. 5. Biologically important areas for cetaceans within U.S. waters – Hawaiʻi region. *Aquatic Mammals*, 41(1): 54–64.

Barlow, J. 2006. Cetacean abundance in Hawaiian waters estimated from a summer/fall survey in 2002. *Marine Mammal Science*, 22(2): 446–464.

Calambokidis, J. and Barlow, J. 2004. Abundance of blue and humpback whales in the Eastern North Pacific estimated by capture-recapture and line-transect methods. *Marine Mammal Science*, 20(1): 63–85.

Cerchio, S., Andrianantenaina, B., Lindsay, A., Rekdahl, M., Andrianarivelo, N. and Rasoloarijao, T. 2015. Omura's whales (Balaenoptera omurai) off northwest Madagascar: ecology, behaviour and conservation needs. *Royal Society Open Science*, 2(10): 150301.

Clapham, P.J. and Mead, J.G. 1999. Megaptera novaeangliae. *Mammalian Species*, 604: 1–9.

Cooke, J., Rowntree, V. and Sironi, M. 2013. Southwest Atlantic right whales: interim updated population assessment from photo-id collected at Península Valdéz, Argentina. Paper SC/66a/BRG/23 presented at to the IWC Scientific Committee, May 2015 (unpublished). 10pp. [Available from the office of this journal]

Crespo, E.A., Pedraza, S.N., Dans, S.L., Coscarella, M.A., Svendsen, GM. and Degrati, M. 2014. Number of southern right whales, *Eubalaena australis*, and population trend in the neighbourhood of Peninsula Valdes during the period 1999-2013 by means of aerial and boat surveys. Paper SC/65b/BRG07 presented to the IWC Scientific Committee, May 2014 (unpublished). pp17. [Available from the Office of this Journal]

De Jesús, M., Heckel, G., Breiwick, J.M. and Reilly, S.B. 2014. Migration timing and distance from shore of southbound eastern Pacific gray whales (*Eschrichtius robustus*) off Ensenada, Baja California, Mexico. *Marine Mammal Science*, 30(2): 674–690.

Dhermain, F., Astruc, G., Cesarini, C., Dupont, L., Dupraz, F., Godenir, J., Keck, N., Labach, H. and Wafo, E. 2015. Recensement des échouages de cétacés sur les côtes françaises de Méditerranée, entre 2010 et 2012. *Scientifique Report of Port-Cros national Park*, 29: 103–126.

Forcada, J., Notarbartolo Di Sciara, G. and Fabbri, F. 1995. Abundance of fin whales and striped dolphins summering in the Corso-Ligurian Basin. *Mammalia*, 59(1): 127–140.

Frankel, A.S., Clark, C.W., Herman, L.M. and Gabriele, C.M. 1995. Spatial distribution, habitat utilization, and social interactions of humpback whales, *Megaptera novaeangliae*, off Hawai'i, determined using acoustic and visual techniques. *Canadian Journal of Zoology*, 73(6): 1134–1146.

Frantzis, A., Nikolaou, O., Bompar, J. and Cammedda, A. 2004. Humpback whale (*Megaptera novaeangliae*) occurrence in the Mediterranean Sea. *Journal of Cetacean Research and Management*, 6(1): 25–28.

Fretwell, P.T., Staniland, I.J. and Forcada, J. 2014. Whales from space: Counting southern right whales by satellite. *PLoS ONE*, 9(2): e88655.

Häussermann, V., Gutstein, C.S., Beddington, M., Cassis, D., Olavarria, C., Dale, A.C., Valenzuela-Toro, A.M., Perez-Alvarez, M.J., Sepúlveda, H.H., Mcconnell, K.M., Horwitz, F.E. and Försterra, G. 2017. Largest baleen whale mass mortality during strong El Niño event is likely related to harmful toxic algal bloom. *PeerJPreprints*.

Helweg, D.A. and Herman, L.M. 1994. Diurnal patterns of behaviour and group membership of humpback whales (*Megaptera novaeangliae*) wintering in Hawaiian waters. *Ethology*, 98(3–4): 298–311.

Herman, L.M., Pack, A.A., Rose, K., Craig, A., Herman, E.Y.K., Hakala, S. and Milette, A. 2011. Resightings of humpback whales in Hawaiian waters over spans of 10-32 years: Site fidelity, sex ratios, calving rates, female demographics, and the dynamics of social and behavioral roles of individuals. *Marine Mammal Science*, 27(4): 736–768.

Iñiguez, M.A. 2001. Seasonal distribution of killer whales (*Orcinus orca*) in Northern Patagonia, Argentina. *Aquatic Mammals*, 27(2): 154–161.

IUCN 2016. *The IUCN Red List of Threatened Species. Version 2016-3*. <http://www.iucnredlist.org>. Downloaded on 07 December 2016.

IWC. 2011. Report of the joint IWC-ACCOBAMS workshop on reducing risk of collisions between vessels and cetaceans. Report IWC/63/CC 8 presented to the IWC Conservation Committee, May 2011 (unpublished). 42pp. [Available from the Office of this journal]

IWC. 2013. Report of the IWC workshop on the assessment of southern right whales. *Journal of Cetacean Research and Management*, 14(supplement): 439-462.

IWC. 2015. Report of the third workshop on large whale entanglement issues. Report IWC/66/WK-WI-Rep01 presented to the IWC Workshop on Large Whale Entanglement Issues, April 2015 (unpublished). 40pp. [Available from the Office of this journal]

Jefferson, T.A., Webber, M.A., Pitman, R.L. and Gorter, U. 2015. *Marine mammals of the world : a comprehensive guide to their identification*. Second edition, Academic Press, London, San Diego, Waltham, Oxford. 608pp.

Jones, M.L. and Swartz, S.L. 1984. Demography and Phenology of Gray Whales and Evaluation of Human Activities in Laguna San Ignacio, Baja California Sur, Mexico. *In: The Gray Whale, Eschrichtius robustus*. Jones, M.L., Swartz, S.L. and Leatherwood S. (eds.) pp. 309-374. Academic Press. Orlando.

Laist, D.W., Knowlton, A.R., Mead, J.G., Collet, A.S. and Podestà, M. 2001. Collisions between ships and whales. *Marine Mammal Science*, 17(1): 35–75.

LaRue, M.A., Stapleton, S. and Anderson, M. 2016. Feasibility of using high-resolution satellite imagery to assess vertebrate wildlife populations. *Conservation Biology*, 0(0): 1–8.

Mate, B., Lagerquist, B.A. and Calambodikis, J. 1999. Movements of North Pacific blue whales during the feeding season off southern California and their southern fall migration. *Marine Mammal Science*, 15(4): 1246–1257.

Mate, B.R. and Urbán -Ramirez, J. 2003. A note on the route and speed of a gray whale on its northern migration from Mexico to central California, tracked by satellite-monitored radio tag. *Journal of Cetacean Research and Management*, 5(2): 155–157.

Mazzuca, L., Atkinson, S. and Nitta, E. 1998. Death and entanglements of humpback whales, *Megaptera novaeangliae*, in the main Hawaiian islands, 1972-1996. *Pacific Science*, 52(1): 1–13.

McMahon, C.R., Howe, H., Van Den Hoff, J., Alderman, R., Brolsma, H. and Hindell, M.A. 2014. Satellites, the all-seeing eyes in the sky: Counting elephant seals from space. *PLoS ONE*, 9(3): e92613.

Mellinger, D.K., Stafford, K.M., Moore, S.E., Dziak, R.P. and Matsumoto, H. 2007. An overview of fixed passive acoustic observation methods for cetaceans. *Oceanography*, 20(4): 36–45.

Mobley, J., Spitz, S. and Grotefendt, R. 2001. Abundance of humpback whales in Hawaiian waters: results of 1993-2000 aerial surveys. Report prepared for the Hawaiian Islands Humpback Whale National Marine Sanctuary,Office of National Marine Sanctuaries, National Oceanic and Atmospheric Administration, U.S. Department of Commerce and the Department of Land and Natural Resources, State of Hawaii, September 2001 (unpublished). 17pp. [Available from the Office of this journal]

Moulins, A., Rosso, M., Ballardini, M. and Wurtz, M. 2008. Partitioning of the Pelagos Sanctuary (north-western Mediterranean Sea) into hotspots and coldspots of cetacean distributions. *Journal of the Marine Biological Association of the United Kingdom*, 88(Special Issue 06): 1273–1281.

Nieukirk, S.L., Stafford, K.M., Mellinger, D.K., Dziak, R.P. and Fox, C.G. 2004. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. *Journal of the Acoustical Society of America*, 115(4): 1832–1843.

Notarbartolo-di-Sciara, G., Zanardelli, M., Jahoda, M., Panigada, S. and Airoldi, S. 2003. The fin whale *Balaenoptera physalus* (L. 1758) in the Mediterranean Sea. *Mammal Review*, 33(2): 105–150.

Panigada, S., Lauriano, G., Burt, L., Pierantonio, N. and Donovan, G. 2011. Monitoring winter and summer abundance of cetaceans in the Pelagos Sanctuary (Northwestern Mediterranean sea) through aerial surveys. *PLoS ONE*, 6(7): e22878.

Panigada, S., Zanardelli, M., MacKenzie, M., Donovan, C., Mélin, F. and Hammond, P.S. 2008. Modelling habitat preferences for fin whales and striped dolphins in the Pelagos Sanctuary (Western Mediterranean Sea) with physiographic and remote sensing variables. *Remote Sensing of Environment*, 112(8): 3400–3412.

Payne, R. 1986. Long term behavioural studies of the southern right whale (*Eubalaena australis*). *Report of the International Whaling Commission, Special Issue*, 10: 161–167.

Perrin, W.F., Würsig, B.G. and Thewissen, J.G.M. 2009. *Encyclopedia of marine mammals*. Second edition, Academic, London. 1352pp.

Ponce, D., Thode, A.M., Guerra, M., Urbán R, J. & Swartz, S. 2012. Relationship between visual counts and call detection rates of gray whales (*Eschrichtius robustus*) in Laguna San Ignacio, Mexico. *Journal of the Acoustical Society of America*, 131(4): 2700.

Rasmussen, K., Palacios, D.M., Calambokidis, J., Saborío, M.T., Dalla Rosa, L., Secchi, E.R., Steiger, G.H., Allen, J.M. and Stone, G.S. 2007. Southern Hemisphere humpback whales wintering off Central America: insights from water temperature into the longest mammalian migration. *Biology letters*, 3: 302–305.

Reeves, R.R. and Smith, T.D. 2003. A taxonomy of world whaling: Operations, eras, and data sources. *Northeast Fisheries Science Centre Reference Documents*: 28pp. Available from: National Marine Fisheries Service, 166 Water St., Woods Hole, MA 02543-1026.

Reilly, S.B., Bannister, J.L., Best, P.B., Brown, M., Brownell Jr., R.L., Butterworth, D.S., Clapham, P.J., Cooke, J., Donovan, G.P., Urbán, J. and Zerbini, A.N. 2008. *Balaenoptera omurai*. The IUCN Red List of Threatened Species 2008: e.T136623A4319390. http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T136623A4319390.en. Downloaded on 01 May 2017.

Reilly, S.B., Bannister, J.L., Best, P.B., Brown, M., Brownell Jr., R.L., Butterworth, D.S., Clapham, P.J., Cooke, J., Donovan, G.P., Urbán, J. and Zerbini, A.N. 2013. *Balaenoptera physalus*. The IUCN Red List of Threatened Species 2013: e.T2478A44210520. http://dx.doi.org/10.2305/IUCN.UK.2013-1.RLTS.T2478A44210520.en. Downloaded on 01 May 2017.

Roman, J. and Palumbi, S.R. 2003. Whales before whaling in the North Atlantic. *Science*, 301: 508–510.

Rowntree, V.J., Payne, R.S. and Schell, D.M. 2001. Changing patterns of habitat use by southern right whales (Eubalaena australis) on their nursery ground at Peninsula Valdes, Argentina, and in their long-range movements. *Journal of Cetacean Research and Management Special Issue*, 2: 133–143.

Rugh, D.J., Shelden, K.E.W. and Schulman-Janiger, A. 2001. Timing of the gray whale southbound migration. (*Eschrichtius robustus*). *Journal of Cetacean Research and Management*, 3(1): 31–39.

Shirihai, H. and Jarrett, B. 2006. Whales, dolphins and seals: a field guide to the marine mammals of the world. A&C Black, London. pp384.

Smultea, M. a., Jefferson, T. a. and Zoidis, A.M. 2010. Rare sightings of a Bryde’s whale (*Balaenoptera edeni*) and sei whales (*B. borealis*) (Cetacea: Balaenopteridae) Northeast of O’ahu, Hawai’i. *Pacific Science*, 64: 449–457.

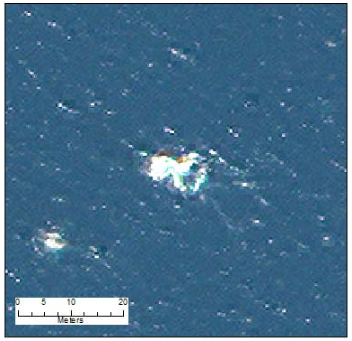
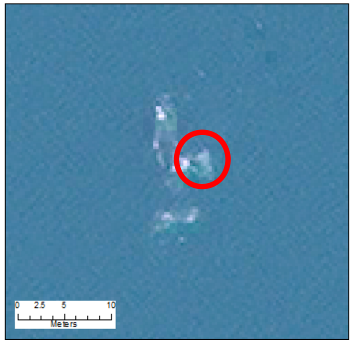
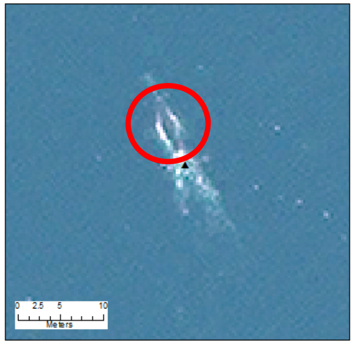
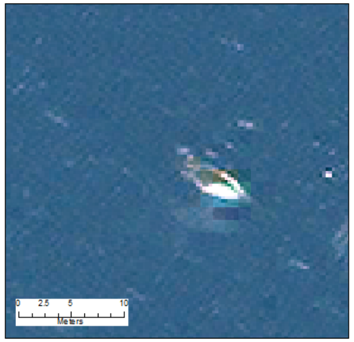
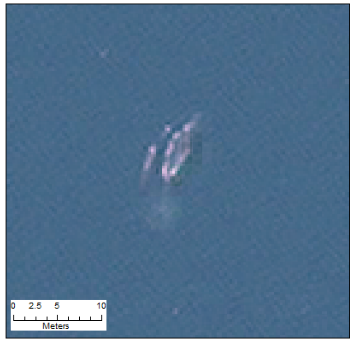
Steiger, G.H., Calambokidis, J., Sears, R., Balcomb, K.C. and Cubbage, J.C. 1991. Movement of humpback whales between California and Costa Rica. *Marine Mammal Science*, 7(3): 306–310.

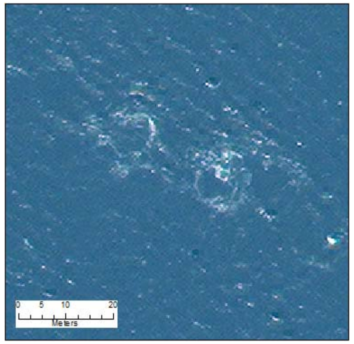
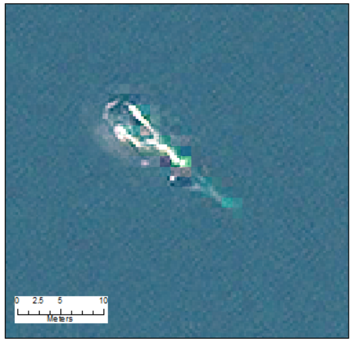
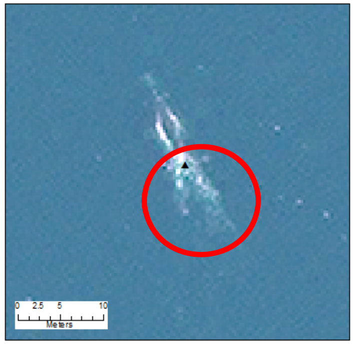
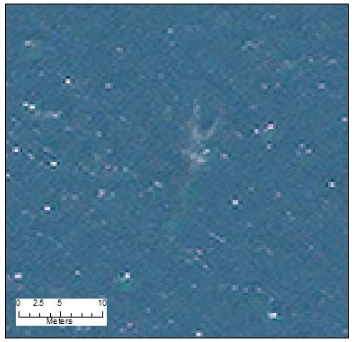
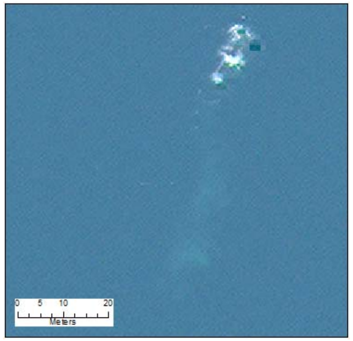
Urbán, J. and Aguayo, A. 1987. Spatial and seasonal distribution of the humpback whale, *Megaptera novaeangliae*, in the Mexican Pacific. *Marine Mammal Science*, 3(4): 333–344.

Urbán R., J., Rojas-Bracho, L., Pérez-Cortés, H., Gómez-Gallardo U, A., Swartz, S.L., Ludwig, S. and Brownell Jr, R.L. 2003. A review of gray whales (Eschrichtius robustus) on their wintering grounds in Mexican waters. *Journal of Cetacean Research and Management*, 5(3): 281–295.

Vaes, T. and Druon, J-N. 2013. Mapping of potential risk of ship strike with fin whales in the Western Mediterranean Sea: A scientific and technical review using the potential habitat of fin whales and the effective vessel density. Report EUR 25847EN prepared for the Joint Research Centre of the European Commission (Available at http://europa.eu/)

Appendix A - Catalogue of the different surface water disturbances and near the surface disturbances associated with whales

Sign	Description	Fin whale	Southern right whale	Humpback whale	Gray whale
After-breach	Large white area left after a whale breached, or lobtailed, flipper-slapped	Not observed on the studied satellite images	Not observed on the studied satellite images		Not observed on the studied satellite images
Blow	Vaporous whitish patch next to a whale, similar looking to fog	Not observed on the studied satellite images			
Contour	White line around part of the whale that is above the surface when the whale is rolling its back or surfacing to breathe				

Sign	Description	Fin whale	Southern right whale	Humpback whale	Gray whale
Footprint	White circle left after whale dived. Observed on satellite images for humpback, fin, southern right whale				
Wake	v-shaped white trail behind the animal				Not observed on the studied satellite images
Defecation	Trail of coloured clouds behind animal	Not observed on the studied satellite images		Not observed on the studied satellite images	Not observed on the studied satellite images

Appendix B - List of pixel descriptions for whales

Pixel_Description	**Comments**
Water	No whale even below the surface
White water	Surf zone, similar to white caps created by the whale, *e.g.* when it surfaces or travel
Whale below the surface	
Whale above the surface	
Possible white flipper	For humpback whale only
Definite white flipper	For humpback whale only
Possible dark flipper	For humpback whale only
Definite dark flipper	For humpback whale only
Possible flipper	For fin, southern right and gray whales
Definite flipper	For fin, southern right and gray whales
Possible white head callosities	For southern right whale only
Definite white head callosities	For southern right whale only
Possible fluke	
Definite fluke	
Blow	
Other definite whale	
Other probable whale	
Other possible whale	
Uncertain	

Appendix C - Recommendation matrix concerning which baleen whale species might be ideal candidates for VHR satellite surveys based on species information from Shirihai and Jarrett (2006), and Jefferson *et al.* (2015). Note that this matrix does not consider the possibility of co-occurrence with similar species, as this aspect varies between localities for each species.

Criteria	Bowhead	North Atlantic right whale	North Pacific right whale	Southern right whale	Pygmy right whale	Grey whales	Humpback whales	Blue whale	Fin whale	Sei whale	Bryde's whale	Omura's whale	Minke whale	Sperm whale
Maximum adult size (m)	20	18.5	19	17	6.5	15	18	33	27	20	16.5	12	11	19
Body shape	Rotund	Rotund	Rotund	Rotund	Slender, streamlined	Robust	Robust	Streamlined	Streamlined	Streamlined	Streamlined	Streamlined	Streamlined	Robust, log-like
Colour (dorsally)	Black (with some white on lower jaw)	Black	Black	Black (with white to light grey blazes)	Dark grey	Brownish grey to ligth grey	Black or dark grey	Blueish grey	Black or dark brownish-grey	Dark grey or brown	Dark grey	Dark grey	Dark grey	Black to brownish grey
Dive length	Long dive	Commonly short dive but up to 50 min sometimes	Commonly short dive but up to 50 min sometimes	Commonly short dive but up to 50 min sometimes	Short dive	Short dive	Commonly short dive but up to 40 min sometimes	Commonly short dive but up to 30 min sometimes	Commonly short dive but up to 30 min sometimes	5 to 20 min	2 to 20 min	Unknown	3 to 20 min	Long dive
Common behaviour(s)	Calm, sometimes accrobatic	Calm, sometimes accrobatic	Calm, sometimes accrobatic	Calm, sometimes accrobatic	Slow and fast swimming	Calm, sometimes accrobatic	Accrobatic	Slow and fast swimming	Slow and fast swimming	Slow and fast swimming	Slow and fast swimming	Unknown	Swimming and sometimes acrobatic	Logging and sometimes acrobatic
Other characteristic(s) helping detection		Whitish head callosities	Whitish head callosities	Whitish head callosities			Long flippers (sometimes white dorsally)							
Recommendation level	2.25	2.60	2.60	2.60	2.75	3.50	2.60	3.50	3.25	3.00	3.00	2.00	2.50	2.50

Key:

For all criteria except "Recommendation level"

- Ideal (4 points)
- Good (3 points)
- Moderate (2 points)
- Problematic (1 point)

For "Recommendation level" criteria only (i.e. average of all other criteria)

- 3.50-4.00
- 3.00-3.49
- 2.50-2.99
- 2.00-2.49
- 1.50-1.99
- 1.00-1.49
- 0.50-0.99
- 0.00-0.49