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SHORT NOTE

Detection, differentiation, and abundance estimation of penguin species by high-resolution satellite imagery

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Abstract Due to its high spatial resolution, broad spatial coverage, and cost-effectiveness, commercial satellite imagery is rapidly becoming a key component of biological monitoring in the Antarctic. While considerable success in surveying emperor penguins (*Aptenodytes forsteri*) has been facilitated by their large size and the visual simplicity of their habitat, there has been considerably less progress in mapping colonies on the Antarctic Peninsula and associated sub-Antarctic islands where smaller penguin species breed on topographically complex terrain composed of mixed substrates. Here, we demonstrate that Adélie penguin (*Pygoscelis adeliae*), chinstrap penguin (*P. antarcticus*), gentoo penguin (*P. papua*), and macaroni penguin (*Eudyptes chrysolophus*) colonies can be detected by high-resolution (2-m multispectral, 40–50-cm panchromatic) satellite imagery and that under ideal conditions, such imagery is capable of distinguishing among groups of species where they breed contiguously. To demonstrate the potential for satellite imagery to estimate penguin population abundance, we use satellite imagery of Paulet Island (63°35′S, 55°47′W) to estimate a site-wide population of 115,673 (99,222–127,203) breeding pairs of Adélie penguins.

Keywords Remote sensing · Adélie penguin · Gentoo penguin · Chinstrap penguin · Macaroni penguin · Zavodovski Island

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Introduction

Seabird population estimation by satellite imagery has been considered a viable alternative to traditional census methods ever since such data became available (e.g., Schwaller et al. 1984, 1989; Guinet et al. 1995; Woehler and Riddle 1998). Recent efforts to survey emperor penguin (*Aptenodytes forsteri*) populations using satellite imagery have convincingly demonstrated the utility of this approach for regional or even continental-scale surveys (Barber-Meyer et al. 2007; Fretwell and Trathan 2009). Previous efforts have concentrated on Adélie (*Pygoscelis adeliae*) and emperor penguins in eastern/continental Antarctica where the relatively homogeneous habitat aids the identification of target species. We are aware of no previous use of satellite imagery to survey chinstrap (*P. antarcticus*), gentoo (*P. papua*) or macaroni penguins (*Eudyptes chrysolophus*), or the use of image analysis to differentiate among multiple target species. Such advances are now possible due to commercial, sub-meter resolution, satellite imagery. We demonstrate that satellite imagery is capable of (1) detecting colonies of *Pygoscelis* and macaroni penguins, (2) differentiating among target species under certain conditions and (3) providing reasonable estimates of population abundance under ideal conditions. Although individual penguins can be detected under certain conditions, our image interpretation approach focuses on the synoptic structure of the colony, which includes reflectance, size, shape, and visual texture characteristic of active colonies as opposed to other landscape features. It is important to note that while automated classification of colonies would be ideal, penguin colonies on the Antarctic Peninsula are embedded in a complex visual environment; as a result, interpretation currently depends heavily on interpreter experience, requiring a detailed appreciation of context for which current automated methods are insufficient. Here, we discuss the progress on manual image interpretation and address some of the challenges that must be overcome for more automated approaches to be developed.

Methods

The satellite images used for this analysis were licensed from DigitalGlobe, Inc. and GeoEye, Inc. through the National Geospatial-Intelligence Agency (NGA) Commercial Imagery Program and are summarized in Table 1. Field data concerning colony locations (including field notes, sketch maps, GPS data, and extensive photodocumentation) were obtained by the Antarctic Site Inventory in advance of satellite image interpretation and are described elsewhere (Lynch et al. 2008; Naveen and Lynch 2011). Data from the South Sandwich Islands (SSI) were obtained by an expedition to the region in January 2011 (Lynch et al. In Prep).

GPS tracklogs at Zavodoski Island (SSI) were taken with a Garmin GPSmap 60Cx on January 13, 2011. Because differential GPS data were not available to georectify GPS data, tracklogs were translated manually 65 m in a WNW direction to align with unambiguous matching features in the satellite imagery. Images were not orthorectified because sufficiently high-resolution digital elevations models (DEMs) are currently lacking for the South Sandwich Islands. Image analysis, including the overlay of GPS data and satellite imagery, was carried out in ArcMap 10.0.

Abundance calculations from satellite imagery require estimates of both colony area and nest density. For our case study of Adélie penguins at Paulet Island, we calculated colony area by manually creating polygons in ArcMap for every colony ($n = 286$) identified in the imagery obtained on February 19, 2011 (Online Resource 1). Imagery was orthorectified using the Radarsat Antarctic Mapping Project (RAMP) Digital Elevation Model and projected into the South Pole Lambert Azimuthal Equal Area projection. Nest counts for 10 of these 286 colonies were obtained by field survey on December 23, 2010, from which we obtained 10 different estimates of nest density. To extrapolate these results to the site-wide scale, abundance for each of the 286 colonies at Paulet Island was calculated by sampling with replacement from the 10 estimated nesting densities and multiplying by colony area. These abundances were then summed to produce an estimate of the total abundance of Adélie penguins at Paulet Island. We repeated the above procedure (sampling with replacement and summation) 1,000 times to generate a distribution for total abundance from which to draw inference. The 95th percentile confidence intervals were obtained from the 25th and 975th ranked values.

Table 1 Details of satellite imagery used. ORx = Online Resource x (e.g., Online Resource 1)

Location	Figure	Image date	Image details
Baily Head, Deception Island (62°58′S, 60°30′W)	1a	January 21, 2003	0.6-m resolution Quickbird-2
Bombay Island, Mikkelsen Harbor (63°54′S, 60°47′W)	1b	December 3, 2010	0.5-m resolution Worldview-2
Devil Island (63°48′S, 57°17′W)	1c	December 15, 2010	0.5-m resolution Worldview-1
Acrid Point, Zavodovski Island (56°21′S, 27°44′W)	1d, 3a	January 8, 2011	0.5-m resolution Worldview-2
Py Point, Doumer Island (64°53′S, 63°34′W)	2	October 5, 2010 & December 5, 2010	2-m resolution Geoeye-1 multispectral pansharpened using 0.5-m Geoeye-1 panchromatic
Paulet Island (63°35′S, 55°47′W)	OR1, OR2a	February 19, 2011	0.5-m resolution Worldview-2
Heroina Island (63°25′S, 54°35′W)	OR2b	January 22, 2011	0.6-m resolution Quickbird-2
Heywood Island (59°41′S, 62°19′W)	OR3a	January 11, 2011	0.6-m resolution Quickbird-2
Tetrad Islands (60°44′S, 63°55′W)	OR3b	December 3, 2010	0.5-m resolution Worldview-2
Aitcho Island (59°45′S, 62°24′W)	OR4a	January 11, 2011	0.6-m resolution Quickbird-2
Skottsberg Point (60°48′S, 63°55′W)	OR4b	December 3, 2010	0.5-m resolution Worldview-2
Salamander Point, Bellingshausen Island (59°24′S, 27°6′W)	OR5a	January 13, 2011	0.5-m resolution Worldview-1
Southwest Trinity Island (60°52′S, 63°54′W)	OR7	December 3, 2010	0.5-m resolution Worldview-2
Hope Bay (63°24′S, 57°00′W)	OR8	February 5, 2011	0.5-m resolution (panchromatic) Worldview-2 and 2-m resolution (multispectral) Worldview-2

Results

All four penguin species of interest (Adélie, chinstrap, gentoo, and macaroni penguin) can be detected using high-resolution ($\leq$2 m) satellite imagery (Fig. 1). Detection ability depends on several factors, including the timing of imagery relative to the phenology of the species, weather conditions, and nesting density. Penguin colonies are most readily identified later in the breeding season when substantial amounts of guano have been deposited, but individual penguins are most easily detected earlier in the season when penguins are resting on new snow (Fig. 2). Because they typically nest at lower densities (Stonehouse 1975), gentoo penguins appear to be the most difficult of the four Peninsula-breeding penguin species to find in satellite imagery. Additional examples of Adélie, chinstrap, and gentoo colonies as seen in satellite imagery can be found in the Supplementary Materials (Online Resources 2–4 respectively).

One of the most challenging aspects to satellite-based population monitoring is differentiating penguin species where they breed contiguously or in mixed colonies. Figure 3a illustrates how macaroni penguins can be differentiated from chinstrap penguins in satellite imagery. The darker appearance of macaroni penguins in this satellite image is due to a combination of their hunched posture during brooding and higher nest density relative to the chinstrap penguin, whose more advanced phenology resulted in adults standing upright at lower density and displaying more white breast feathers to the high-altitude satellite. These differences were seen clearly in the field and can also be seen in photographs taken of Acrid Point on Zavodovki Island (Fig. 3b). Further investigation using time lapse imagery of such a colony is required to understand how these differences change over the course of the breeding season and whether differentiation of the two groups requires a specific phenological window. Similarly, we found that Adélie penguins and chinstrap penguins can be

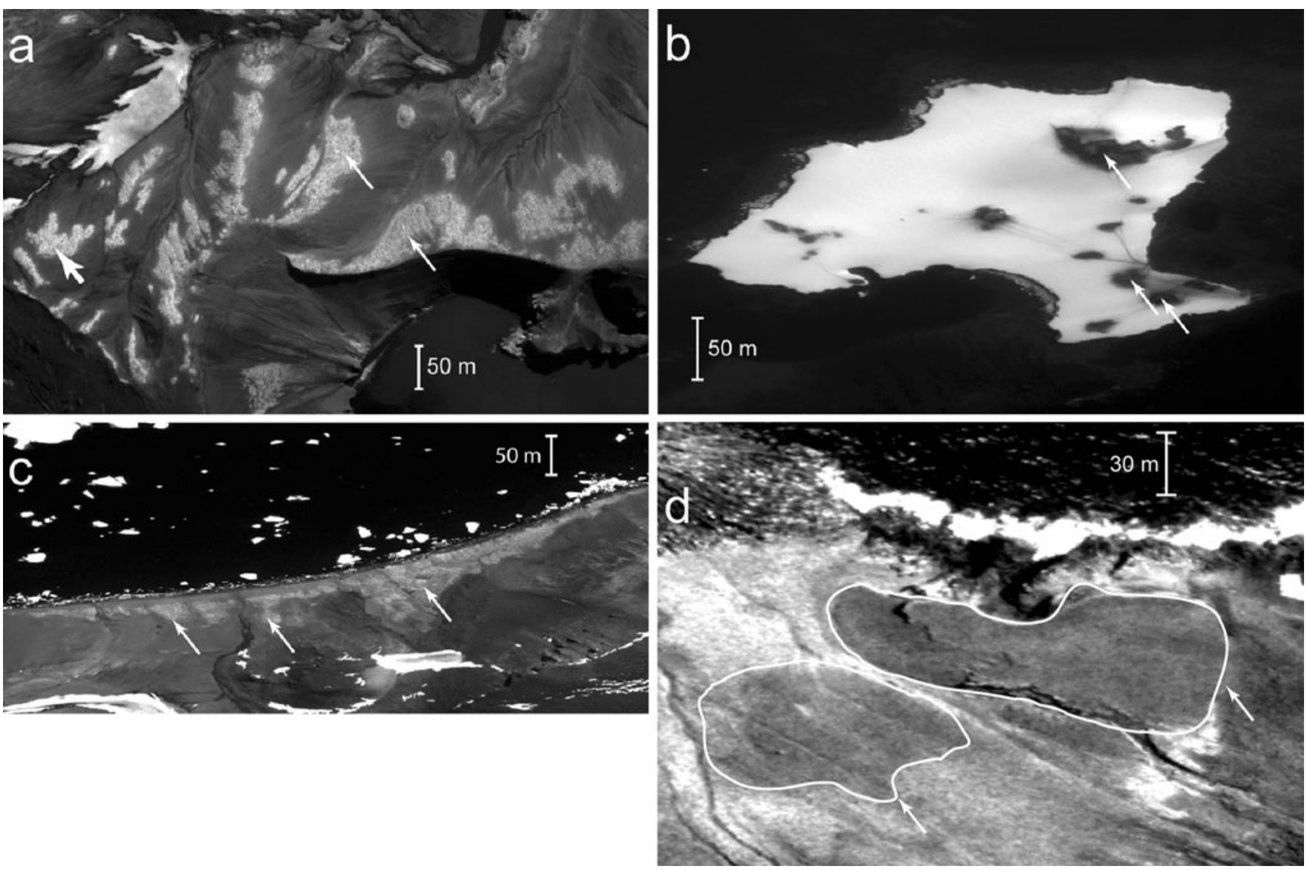

Fig. 1 Penguin colonies (indicated by *white arrows*) as they appear in panchromatic satellite imagery. Note that *arrows* indicate a representative sample of penguin colonies at this site; visually similar areas also represent penguin colonies. Imagery provided through the NGA Commercial Imagery program. **a** Chinstrap penguin colonies at Baily Head, Deception Island on January 21, 2003. Imagery copyright (2003) by DigitalGlobe, Inc. **b** Gentoo penguin colonies at Bombay Island, Mikkelsen Harbor, on December 3, 2010. Imagery copyright (2010) by DigitalGlobe, Inc. **c** Adélie penguin colonies at Devil Island on December 15, 2010. Imagery copyright (2010) by DigitalGlobe, Inc. **d** Macaroni penguin colonies (white polygons) lying within a larger chinstrap penguin colony at Acrid Point, Zavodovski Island (SSI) on January 8, 2011. Imagery copyright (2011) by DigitalGlobe, Inc

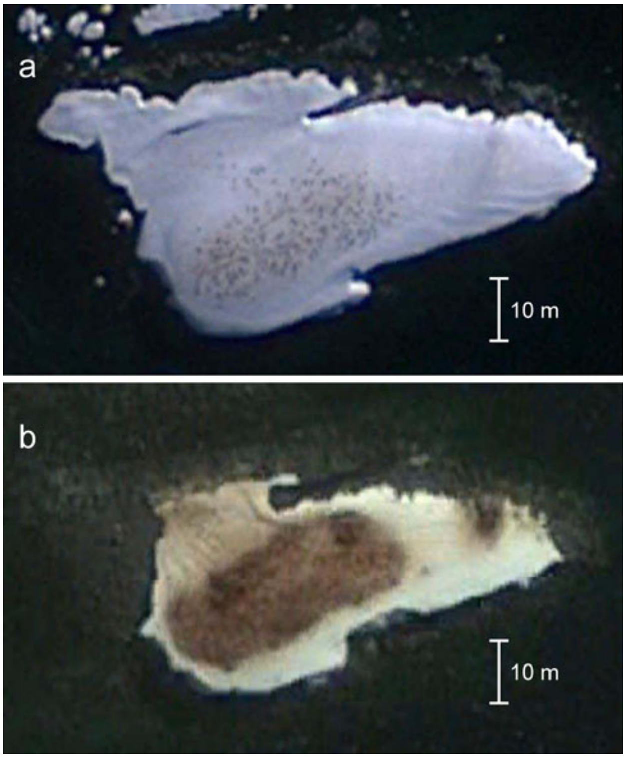

Fig. 2 Gentoo penguins on small island 35 m east of Py Point, Doumer Island on October 5, 2010 **(a)** and on December 5, 2010 **(b)**. Images captured from Google Earth, imagery copyright (2011) Google, and (2011) GeoEye, Inc

differentiated by the relatively heavier coverage of guano, and subsequently darker appearance, of Adélie-dominated areas later in the breeding season (Online Resource 5). Note that many Adélie and chinstrap chicks had crèched at the time of census and photodocumentation, and as a result, colony structure had eroded significantly. However, the delineation of Adélie-dominated areas versus chinstrap-dominated areas versus mixed areas of the colony was more apparent in the field and allowed for more unambiguous interpretation of the satellite image than is reflected in Online Resource 5.

Using manual interpretation of colony extent in the satellite imagery available (Online Resource 1), we estimate that there are 115,673 breeding pairs of Adélie penguins at Paulet Island, with a 95th percentile confidence interval of (99,222–127,203). Note that the asymmetry of the confidence intervals reflects the left skew of the abundance estimates obtained by our resampling analysis (Online Resource 6).

Discussion

While high-resolution satellite imagery represents a transformative technology for biological monitoring in polar regions, several challenges to image classification remain. Pervasive cloud-cover over the Antarctic Peninsula and sub-Antarctic islands limits ground visibility on most days. Even when cloud-free images are obtained, the visibility of breeding populations depends sensitively on matching the timing of imagery to the phenology of the target species. Target visibility may peak before or after peak abundance depending on whether the goal is to identify individual animals, which often appear more sharply against snow earlier in spring or early summer, or to identify colonies, which are highlighted later in the breeding season by the accumulation of guano at the site. Moreover, heavy snowfall can obscure all evidence of breeding temporarily. Although multispectral imagery may provide additional information (e.g., the composition of penguin diet as reflected in the spectral signature of guano) and is particularly useful when looking for the existence of colonies in unknown locations, it is possible to identify penguin colonies using only panchromatic (gray-scale) images. In addition to the wider availability of panchromatic images (Worldview-1 only includes panchromatic), the higher resolution of panchromatic (0.5–0.6 m) relative to multispectral (2.0 m) images affords greater detail on colony size and shape.

The use of satellite imagery to differentiate among species is still in the exploratory stages and appears even more sensitive to the timing of imagery relative to breeding phenology as the demarcation between species' breeding areas can become ambiguous as colonies erode following chick crèche. Changes in breeding substrate, particularly areas of volcanic ash that can mimic penguin colonies, can also confuse image interpretation. Very small colonies are difficult to detect, although the precise lower bounds of detectability and, by extension, the speed with which new colonies can be identified remains an area for future research. For these reasons, the reliability of image interpretation is significantly enhanced by ground-truth GPS data, photodocumentation, or personal experience at the site.

Our experience has suggested the following guidelines for the detection and differentiation of penguin colonies in high-resolution satellite imagery:

1. While breeding phenology is species- and location-specific and subject to significant interannual variability (Lynch et al. 2012), useful imagery can be obtained between November and March.
2. Repeated imagery of the site facilitates the matching of imagery to the phenology of the target species and allows for redundancy in case of cloud-cover, heavy snowfall, or other factors that may affect image interpretation. Although we were not able to explore this with the imagery available, it may be possible to estimate the relative coverage of different species breeding in mixed or adjacent colonies by their staggered arrival

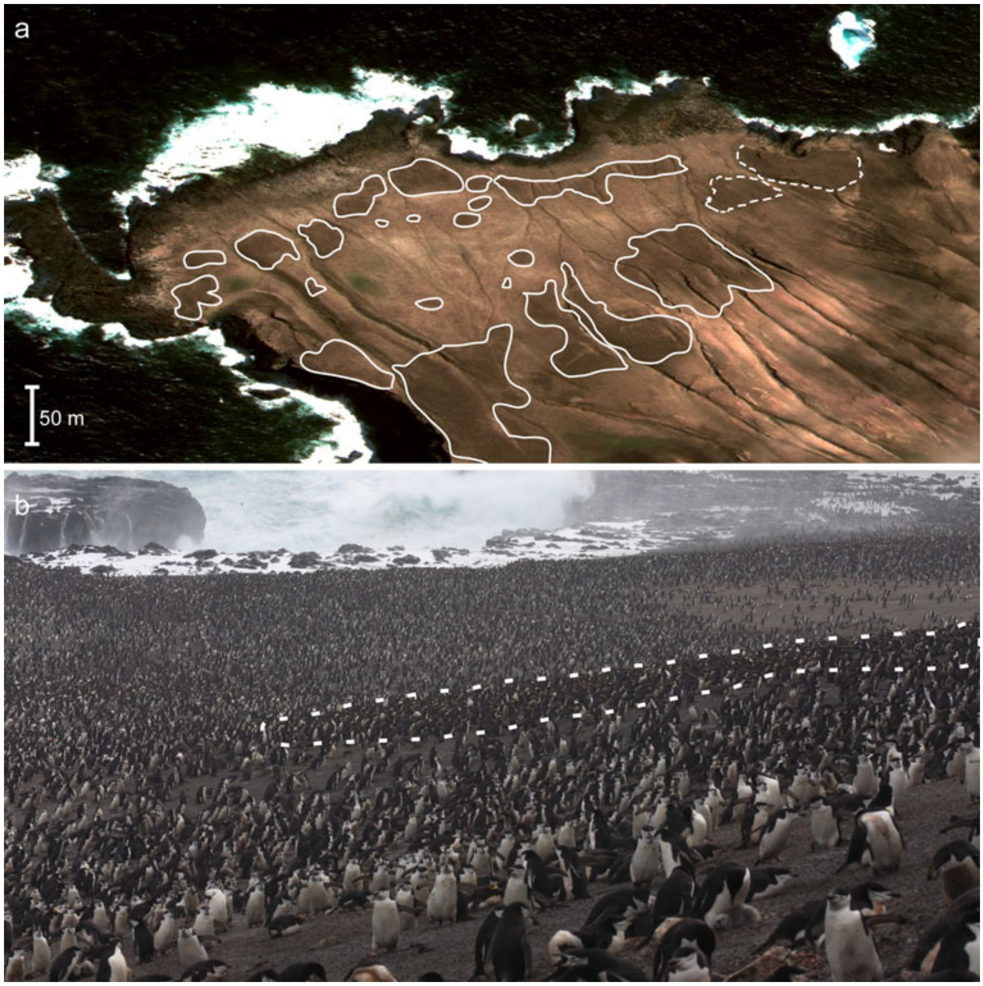

Fig. 3 **a** Chinstrap and macaroni penguins at Acrid Point, Zavodovski Island (SSI) on January 8, 2011. Image provided by the National Geospatial-Intelligence Agency (NGA) Commercial Imagery Program and copyright (2011) by DigitalGlobe, Inc. *Dashed white lines* denote GPS tracklogs of macaroni colonies within the larger chinstrap penguin colony obtained January 12–13, 2011. *Solid white lines* indicate other areas of Acrid Point identified as macaroni penguins in the imagery and verified through field notes and photodocumentation. Visually similar areas not circled may represent macaroni penguins not visible in the photodocumentation or may represent landscape features that are visually similar but unidentified. **b** Photograph of a portion of Acrid Point colony showing how macaroni penguins (enclosed by *dashed polygon*) appear darker relative to the surrounding chinstrap colony due to their hunched posture and higher density

(particularly in differentiating Adélie penguins and chinstrap penguins), a technique that would require multiple images during the period of colony establishment (3–4 weeks). A review of previously captured images in the DigitalGlobe archive found that the percentage of cloud-free images (<5% cloud-cover) ranges from a low of 4% in the South Orkney Islands to a high of 22% in the region including the Tabarin Peninsula and Joinville Island, with an overall average of 10%. Therefore, it may take several years to acquire the imagery required to clearly establish spatial patterns of occupancy, particularly where differential breeding phenology is used in the interpretation of mixed-species colonies.

3. Both clouds and shadows can complicate image interpretation (Online Resource 7). Images should be essentially cloud-free (<5% cloud-cover) as patchy clouds can mimic guano staining for an inexperienced analyst. Low sun-angle can produce dark shadows that, while easily identified in the context of adjacent topography, may preclude assessment of shaded areas.
4. While higher resolution panchromatic imagery provides the best detail for mapping colony structure, multispectral imagery can be helpful in resolving ambiguities where patchy snow may mimic a penguin colony (as demonstrated in Online Resource 8).
5. Image interpretation of unknown locations should be done with caution, particularly if colony structure is ambiguous or the breeding site is topographically complex or involves multiple substrates.
6. Penguin colony detection is highly influenced by nesting density. For this reason, gentoo penguins are often

the most challenging of the four studied species to map accurately, particularly when nests are sparsely scattered.

7. Ground control points, unambiguously visible in the imagery and of known geographic location, would allow for georectification and more precise alignment of GPS data obtained in the field. In addition to aiding qualitative assessment of the imagery, orthorectification using high-resolution DEMs would permit more accurate quantitative estimation of colony area.

While our case study of Adélie penguins at Paulet Island relied on a small sample (10) of nest density estimates and would be improved by more sophisticated modeling of nest density (including better digital elevation models for orthorectification), our estimated abundance of 115,673 (99,222–127,203) was remarkably close to the 95,000–105,000 (±25%) estimate of Naveen et al. (2000), especially considering the time elapsed between our estimate, reflecting the 2010/2011 population and the 1998/1999 population reflected in Naveen et al.'s earlier estimate. Despite its limitations, this demonstrates the potential for satellite image analysis to produce reasonable abundance estimates in addition to the establishment of simple presence or absence of breeding activity.

Commercial high-resolution satellite imagery offers the potential for population monitoring that scales from an individual colony to the entire continent, and while ground-truth data remain critical to accurate interpretation, phenologically sensitive algorithms for interpretation will eventually provide a cost-effective complement to more traditional field-based population study. Of particular interest is the use of satellite imagery to discover unknown or newly established colonies in areas not currently being monitored, a process which is prohibitively expensive using traditional vessel-based survey methods. In addition, satellite imagery provides one of the only available methods for estimating populations of very large penguin colonies like Paulet Island which are, by virtue of their size, extremely difficult to survey on the ground.

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