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SCAR Lecture: "Satellite-based science and the changing nature of what it means to "explore" Antarctica"

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Background

Satellite imagery is a transformational technology that has radically expanded our capacity to explore and study the world's most remote places. Over just the last 30 years, the availability of publicly-available satellite imagery of Antarctica has skyrocketed, and commensurate improvements in spatial resolution now allow us to map the finest details of Antarctica's geology and even much of its biology. Newly-launched sensors now allow scientists to measure ice loss, follow the flow of glaciers, map Antarctica's bedrock, and even track the distribution and abundance of animal populations. At the same time, we can now harness satellite imagery to track human impacts on the landscape, from runways to footpaths, and more precisely design protected areas around key features. This Information Paper summarises the 2023 SCAR Lecture by Prof Heather Lynch, and describes the recent technical advances in the use of satellite imagery for Antarctic research and some of the future research areas where continued development is likely.

Antarctic geology and climate change

Many of the most notable scientific findings to emerge from Antarctica over the last several years have relied on satellite-based remote sensing in some fashion, and both active sensors (e.g., radar, LiDAR) and passive sensors (e.g., Landsat, MODIS) have been critical to our current understanding of climate change, glacial retreat, ice sheet instability, and the very nature of the Antarctic continent itself.

Of particular note are several recent studies that improve our understanding of Antarctic ice sheet dynamics and mass loss, particularly the improved mapping of Antarctic bed topography known as BedMachine (Morlighem et al. 2020) and several subsequent studies using BedMachine to understand ice sheet evolution (e.g., Seroussi et al. 2020, Velicogna et al. 2020). Satellites have also been critical in tracking the advance and retreat of ice shelves, improving our understanding of major events such as the disintegration of the Larsen A and B ice shelves (Wille et al. 2019, Christie et al. 2022) and the partial collapse of the Wilkins Ice Shelf (Rankl et al. 2017), as well as the more gradual processes that drive ice sheet dynamics (e.g., Gudmundsson et al. 2019, Wille et al. 2019) and glacial retreat (e.g., Milillo et al. 2022). One of the most advanced satellite systems measuring ice mass is the Gravity Recovery and Climate Experiment (GRACE) and its follow-on mission GRACE-FO. These two missions allow for extremely precise measurements of surface mass anomalies and have allowed us to track the loss of ice contained within the Antarctic ice sheet (Velicogna et al. 2014).

Many of these advances involved the careful synthesis of satellite-based data products with airborne or field observations, highlighting the manner in which satellite data complements, rather than replaces, field observations and measurements. For example, Schmidt et al. (2023) used an underwater vehicle to observe the grounding line of the Thwaites Glacier and the detailed topography of the ice base. These observations provide a better understanding of the processes contributing to ice melt observed using satellite imagery (e.g., Fahnestock et al. 2016, Wild et al. 2022).

Climate change is unfolding in Antarctica on both fast and slow time scales, and satellite remote sensing provides a means by which we can track tiny changes occurring over long periods of time as well as sudden events, like a collapsing ice shelf, that would otherwise be inaccessible to scientific observation. Satellites also recently marked an inauspicious record when, on February 13, 2023, Antarctic sea ice extent hit an all-time low (NSIDC 2023). These dynamics have globally-important implications for global temperature variability and sea level rise (Golledge et al. 2019, DeConto et al. 2021), and satellites have played an important role in our understanding of these future risks.

Wildlife research¹

Satellite imagery has been in regular use for earth observation and monitoring for over 40 years but much of this work has been focused on mapping the planet itself (ocean colour, sea ice, forest cover, etc.) rather than the animals that live on it. Though the idea that we could use satellites to map polar seabirds was explored early on (Schwaller et al. 1984, Schwaller et al. 1989), the last decade has seen a major expansion of these efforts in step with a rapid increase in the number and variety of sensors now currently available for wildlife research. Wildlife research in the polar regions has historically been limited by the logistical constraints of site access, but recent developments in the use of satellite imagery for animal detection has unlocked new possibilities for pan-Antarctic monitoring of animal populations. A range of different sensor systems have been used for wildlife research but most have focused on optical sensors that collect data in the visible spectrum and can be directly interpreted similar to a photograph. These include medium-resolution sensors like Landsat (30 m) and Sentinel-2 (10 m) and very high-resolution sensors such as Maxar's Worldview-2 (51 cm) and Worldview-3 (31 cm). These long-established satellite systems have been joined more recently by constellations of smaller satellites (so-called 'Small Sats') that offer imagery of comparable spatial and spectral resolution to those operated by Maxar. This rapidly-expanding portfolio of earth observation satellites offers the potential for a radical transformation of wildlife research in polar regions, but the sheer volume of data now being collected now eclipses our capacity for manual imagery interpretation. To meet this challenge, researchers are now harnessing advances in computer vision that, coupled with improvements in computing capacity, promise to deliver a new era in our ability to monitor polar wildlife.

Worldwide, satellite imagery has been used to survey everything from penguins and whales to cattle and elephants (see review by LaRue et al. 2017 and references therein). Though the potential for wildlife survey by satellite imagery is global, several factors have made the polar regions a leader in the technical development and operationalization of satellite-based monitoring. For one, the polar areas are exceptionally difficult and expensive to survey using more traditional means, so alternative methods provide not only a complement to but often the only feasible means of tracking wildlife over large spatial areas. Research in the polar regions, particularly the Antarctic, is also inherently international. The confluence of multiple earth observation programmes operating in the polar regions provides the opportunity to compare and combine the strengths of different sensor programmes. The absence of trees or other woody vegetation also facilitates the use of satellite imagery for animal survey, since the simplified landscape provides little cover that might obscure animals viewed from above. Finally, the polar areas also enjoy a geographical advantage, as polar orbiting satellites pass over the Arctic and Antarctic much more frequently than they do areas at lower latitudes and the development of a very high-resolution digital elevation model for the Antarctic (Howat et al. 2019) has established in fine detail the coastline and bare rock areas on which wildlife are likely to be found.

Though the 30 m resolution precludes the direct census of animals, Landsat imagery has been used to survey Adélie penguins (Schwaller et al. 2013, Lynch & Schwaller 2014), emperor penguins (Fretwell & Trathan 2009), and Antarctic petrels (Schwaller et al. 2018), the first two

¹ Some of this text has been adapted from an article originally written for the *Marine Technology Society Journal* (Lynch [2023]).

of which are considered sentinel species for climate change and are regularly monitored as part of international efforts for Antarctic conservation. In the Antarctic, most of the work using sub-meter resolution commercial imagery to estimate animal abundance has focused on penguins (e.g., Barber-Meyer et al. 2007, Fretwell et al. 2012, Lynch et al. 2012, Lynch & LaRue 2014, LaRue et al. 2014, Strycker et al. 2020), though crabeater seals (Gonçalves et al. 2020, Gonçalves et al. 2022), Weddell seals (LaRue et al. 2011, LaRue et al. 2021), fur seals (Foley 2019), and southern elephant seals (McMahon et al. 2014, Fudala & Bialik 2022) have all been enumerated in sub-meter commercial satellite imagery as well. Pilot studies have demonstrated that even whales can be observed in satellite imagery and can be detected using automated classification models (Fretwell et al. 2014, Borowicz et al. 2019, Guirado et al. 2019).

While optical imagery has been the most promising satellite-based technology for wildlife survey, there has been some exploration of alternative data types. Radar imagery such as that provided by TerraSAR-X has been explored for penguin colonies, in the hopes that the height of penguins clustered at the colony might be distinguishable from the background substrate. Similar hopes are held for the newest generation of laser altimetry sensors, such as that on NASA's Icesat-2 satellite. While there has been some evidence that emperor penguins might be observable in this way (particularly during the winter when penguins are tightly packed together), efforts to observe colonies of the smaller nest-building species have proven unsuccessful (Mustafa et al. 2012). Thermal infrared (TIR) imagery is another intriguing technology in the polar regions because it seems as though seabirds and marine mammals should be considerably warmer than their background environment and the relative scarcity of animals in the polar regions should minimize noise in the thermal signal. Unfortunately (in this context), the most promising target for thermal surveying is emperor penguins and their body surface is actually a bit cooler than the surrounding air (McCafferty et al. 2013), and a recent study using drone imagery found no benefit in penguin abundance classification performance when including TIR data (Hinke et al. 2022). Though several polar species (e.g., polar bears, walrus, seals) have been surveyed successfully using airborne thermal sensors, satellite-based TIR imaging is captured at much lower spatial resolution (e.g., 30 m on Landsat-8; 90 m on Terra) than optical imagery, and this sets a very high threshold for the smallest detectable aggregation.

Conclusions

The number of Earth-observing satellite sensors has grown rapidly over the last several decades, and the resources available for space-based scientific research in Antarctica is sure to grow. While satellite-based research will not replace direct observations from field teams working on the ground, it can complement field observations by allowing for safer access to sites, more efficient planning of operations, and an expanded capacity to extrapolate field measurements to larger spatial areas. Full utilization of these tools will benefit from continued collaboration among countries whose assets reflect the diversity of operational capabilities and whose strengths are highly complementary. To that end, SCAR will continue to play a crucial role in coordinating these efforts for the greatest benefit of the Antarctic community.

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