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Title: Growth and opportunities for drone surveillance in pinniped research

Running head: Drone advancements in pinniped research

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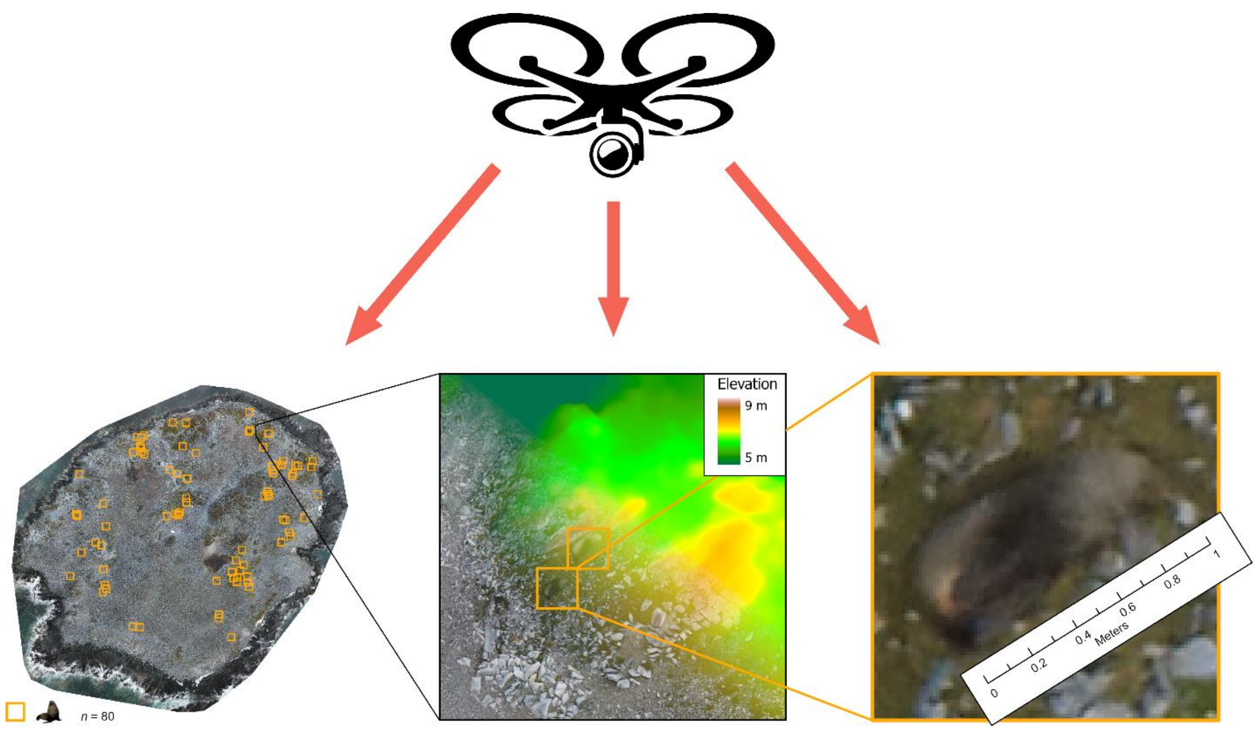
Graphical abstract



Abstract

Pinniped species undergo uniquely amphibious life histories that make them valuable subjects for many domains of research. Pinniped research has often progressed hand-in-hand with technological frontiers of wildlife biology, and drones represent a leap forward for methods of aerial remote sensing, heralding data collection and integration at new scales of biological importance. Drone methods and data types provide four key opportunities for wildlife surveillance that are already advancing pinniped research and management: (1) repeat and on-demand surveillance, (2) high-resolution coverage at large extents, (3) morphometric photogrammetry, and (4) computer vision and deep learning applications. Drone methods for pinniped research represent early stages of technological adoption and can reshape the field as they scale towards the full potential of their techniques.

Keywords

Drone, remote sensing, pinniped, wildlife technology, photogrammetry

Word count

7021

Introduction

Pinnipeds embody a variety of qualities that make many species interesting and suitable subjects for scientific research. As amphibious marine predators, all pinniped species haul out of the water, on land or ice, to breed or molt (Berta, 2018). This characteristic makes pinnipeds relatively accessible and observable among marine predators. During these major life history events, many species exhibit philopatry (returning to their place of birth), gregariousness (gathering in large groups) and general site fidelity (revisiting sites that have been visited before) to various degrees; these qualities enable scientists to reliably access predictable populations and even individuals within single seasons and across years and generations (McKnight & Boyd, 2018). Many species occupy terrestrial habitats that are accessible to humans and topographically open to on-the-ground or aerial surveillance. Finally, select species can be trained and safely housed in human care, so under appropriate ethical circumstances some pinnipeds can accommodate uniquely managed behavioral and physiological studies and assessments. Owing to these distinctive qualities, pinnipeds are often studied as sentinel species of their marine ecosystems (Bossart, 2011; Fossi & Panti, 2017), as models of marine adaptations in mammals (Hochachka, 2000), and for a variety of other scientific motivations. The equipment and methods that are used to study pinnipeds often represent the technological frontiers of wildlife science, incorporating the ongoing miniaturization of computers and sensors, faster processing speeds, and growing quantities of 'big data' (Corlett, 2017; Lahoz-Monfort & Magrath, 2021). In this vein, the use of small unoccupied aircraft systems (sUAS), or drones, represents a major frontier of wildlife technology (Linchant et al., 2015; Wirsing et al., 2022) that is poised also to unlock new methods in the study of pinnipeds.

The term "drone" most commonly refers to a variety of small robotic autonomous aircraft that are used increasingly across a variety of disciplines in environmental sciences (Floreano & Wood, 2015; Jiménez López & Mulero-Pázmány, 2019; Johnston, 2019; Wirsing et al., 2022). Drones can achieve a variety of *in situ* environmental techniques by virtue of their mobility and precise aerial positioning, including sampling of aerosols (Pirotta et al., 2017), water, soil, and invertebrates (Robinson et al., 2022), but most applications for environmental research, and wildlife in particular, use drones as versatile remote sensing platforms (Chabot & Bird, 2015; Johnston, 2019; Mo & Bonatakis, 2022; Robinson et al., 2022). With increasingly lightweight sensors and onboard processing computers, drones can collect diverse types of sensing data at a high-throughput (Jiménez López & Mulero-Pázmány, 2019), expanding both data collection and post-processing techniques for analyses that require big data.

Drones have several advantages over occupied aircraft, including simpler logistical requirements, greater safety, and lower costs (Jones et al., 2006; Linchant et al., 2015). Drones can thereby conduct operations with on-demand or repeat schedules and in sites far removed from supporting infrastructure. At the same time, low-altitude flights can collect imagery at low ground sample distances (GSDs) with precise navigation and spatially referenced metadata from global navigation satellite systems (GNSS) to achieve exhaustive spatial coverage in ultra-high (sub-decimeter) resolutions (Koh & Wich, 2012; Raoult et al., 2020). For pinnipeds, these specific advantages directly allow researchers to safely study pinnipeds in habitats that are otherwise inaccessible to alternative methods (Christie et al., 2016; Krause & Hinke, 2021). However, beyond site access, the advantages of drone surveillance also unlock new possibilities for study design and data analysis, potentially transforming downstream research and management capabilities. We discuss four key opportunities of drone methods that are already being deployed and developed for the study of pinnipeds, as well as future potential and limitations of the technology, demonstrating applications with original examples created from an open dataset of drone imagery over pinniped haul-out sites (Larsen et al., 2022a).

Repeat and on-demand deployment

Pinnipeds experience an annual cycle of physiological changes and life history events that determines their terrestrial availability to research. The annual cycles of polar species are often especially coupled to seasonally available resources, such as habitat or prey (Bowen, 2018). The mechanism of such phenology may be triggered or influenced by relatively predictable environmental attributes, like photoperiod (Temte, 1994; Temte & Temte, 1993; Trites & Antonelis, 1994), dynamic environmental cues, like climate or sea ice (Hind & Gurney, 1998), and intrinsic factors, like maternal age (Lunn & Boyd, 1993; Trites, 1991). Depending on the species, pinniped phenology unfolds with different degrees of interannual consistency (Bowen, 2018), so single scheduled population surveys might not align with their target event, like maximum on-land abundance, and additional context is often necessary to estimate where a survey occurs within the annual cycle. This concern is especially relevant for optical imagery collected by satellites, whose orbital revisit period is further limited by cloud cover (LaRue et al., 2011, 2017), and imagery collected by occupied aircraft, whose flight schedules require advanced planning and are limited to longer windows of safe weather (Sweeney et al., 2016). Drones are less limited by such logistical factors: lower infrastructure requirements allow operators to deploy drones on a more flexible and *ad hoc* schedule; rapid on-demand deployment and recovery can exploit very short weather windows; low-altitude flights can collect imagery under cloud cover; and repeat surveillance can obtain data series at frequencies and temporal ranges not practical or achievable by occupied aircraft or orbiting satellite platforms (Christie et al., 2016; Linchant et al., 2015).

On-demand deployment over pinnipeds can target expected phenological events, such as breeding and molting, or respond to contextual triggers, such as peak counts from a local index site. Repeat surveys can establish a context for temporally dynamic processes, describing trends before and after a target survey, and can functionally expand the period of sampling to increase the likelihood that targeted events are captured within the period (**Fig. 1**). High-frequency monitoring may also capture short-term temporal factors, like within-day effects of tide, weather and diel cycle, and multi-day occupancy patterns, like conspecific recruitment to haul-out sites, time-partitioned occupancy by different age–sex classes (Le Boeuf & Laws, 1994), and the balance of foraging and fasting activities among territorial males and lactating females on the rookery (Champagne et al., 2012). These advantages of repeat and on-demand drone surveys apply most obviously to research questions concerning demography, which often require temporal and phenological context to interpret counts and surveys, but high-frequency observations can also reveal the balance and budget of energetically costly behaviors across aggregated groups of pinnipeds, especially during reproductive periods (Costa, 1991). The spatial context of repeat drone imagery may still further describe spatiotemporal processes of on-land behavior, such as territoriality, sociality, and early behavioral ontogeny as they unfold across land or ice habitats. Drones can record these processes with spatial detail and at aggregate scales not typically achieved by conventional methods at ground-level.

Spatial coverage and resolution

Drone imagery expands on the legacy of aerial photography—a long-established tool of wildlife biology (Jolly, 1969; Leedy, 1948). Occupied aircraft have been used to survey and estimate pinniped populations since the era of industrial sealing (Bartlett, 1929), exploiting aerial perspectives to scout large regions of land or ice habitat at a time. Today, high-resolution satellites provide even greater spatial coverage of pinniped habitats (LaRue et al., 2011; Rodofili et al., 2022), with advantages that include automated and relatively passive data collection, once sensors are placed in orbit, and regular coverage that depends on the satellite's orbit and revisit period, though this is reduced by coincident cloud cover. Imagery from occupied aircraft regularly achieves GSDs and quality necessary to distinguish seals in their ice or land habitats (Johnston et al., 2017) and, under select circumstances, very high-resolution satellite imagery can enable the same (LaRue et al., 2017).

In this context, the spatial data that drones collect are distinguished chiefly by their resolution, coverage and topographic accuracy compared to alternative imagery. Densely structured flight plans, enabled by GNSS and the absence of a human occupant, can rapidly achieve exhaustive overhead coverage at nadir or near-nadir camera angles over an entire habitat, reconstructing complex terrain (Kyriou et al., 2021) and reducing animal occlusion behind terrain relief. Additionally, custom flight plans or manual operation can achieve oblique camera angles to locate animals inside caves, crevices or overhangs. Such robust coverage is often impossible from an orbital perspective (LaRue et al., 2017), and uncommon from occupied aircraft, which are limited by their higher operating altitudes and lower maneuverability. High-resolution sensors at low altitudes (< 400 m) document habitat, flora and fauna at GSDs sufficient for visual and automated interpretation (**Fig. 2**), and overlap between images within a survey enables structure-from-motion methods that can be used to model high-resolution 3D surface models of habitats and to orthorectify imagery to more accurately represent locations and spatial relationships among features of interest (**Fig. 3**; Nex & Remondino, 2014).

The spatial qualities of drone data provide clear benefits for demographic and abundance surveys by obviating the potential bias of undercounting in complex terrain, where animals may be partially or completely hidden from non-nadir perspectives. Additionally, high-resolution mapping products and orthorectified positional data can reveal precise, fine-scale relationships between pinnipeds and landcover or physical topography that might not resolve in comparable stereoscopic products from high-altitude aerial photography or satellite imagery (Larsen et al., 2022b). Such species–habitat relationships can reveal preferences and limitations of pinniped habitat selection that might be driven by terrestrial locomotive ability (Beentjes, 1990; Fish, 2018; Garrett & Fish, 2015) or thermoregulatory behaviors (Chaise et al., 2018; Liwanag et al., 2014; Montero-Serra et al., 2014; White & Odell, 1971), linking individual energetic costs to emergent patterns of terrestrial occupancy. The higher GSDs of drone imagery additionally facilitate the location of camouflaged species, morphs and age-classes, and discrimination between species and age-classes that can appear similar at coarser resolutions (Johnston et al., 2017; Rexer-Huber & Parker, 2020). At highest image quality, drone imagery can even be used to locate and quantify marine debris entanglements and interactions with fishing gear (McIntosh et al., 2018), and depending on animal postures, may enable identification of individuals based on brands (Sweeney et al., 2016), scarring, flipper tags (Hodgson et al., 2020), and pelage characteristics (**Fig. 2**), or the classification of pups by molt stage (den Heyer et al., 2021; Johnston et al., 2017).

Morphometric photogrammetry

Photogrammetry—measuring objects from a photograph—is a technique that predates drones and even digital photography, but has become more common, accessible and advanced in their wake (Linder, 2009). Simple 2D measurements can be estimated from a photograph, if the camera's focal length and distance-from-object are known, and drones enable this process from aerial perspectives, with distance-from-object informed by the drone's positional data from GNSS, triangulation among images with shared features, barometric altimetry, a time-linked laser range-finder, or some combination of these measurements—all of which provide different degrees of confidence that can be encoded with imagery and spatial data products (Bierlich et al., 2021). When serial imagery is captured across multiple locations, drones enable yet more complex photogrammetric analyses from derived products: many 2D measurements can be estimated from orthomosaics rectified to a known GSD, and 3D volumetry can be estimated using structure-from-motion models with a stationary individual (Postma et al., 2015).

Photogrammetry has been applied to pinnipeds at ground-level under a variety of scenarios for both 2D and 3D measurements (reviewed in Hodgson et al., 2020), but drone-specific applications remain few and experimental. First attempts have demonstrated success with 2D measurements from single photographs (Alvarado et al., 2020; Krause et al., 2017), 2D measurements from orthomosaics (**Fig. 4**, Allan et al., 2019; Hodgson et al., 2020; Infantes et al., 2022), and 3D measurements from structure-from-motion models (Hodgson et al., 2020; Shero et al., 2021). Such studies generally require validation against conventional ground-truth measurements with captured animals to confirm the veracity of photogrammetric methods (Alvarado et al., 2020; Krause et al., 2017)—though, at sufficient sample-sizes, UAS-derived measurements have been validated against archival ground-truth measurements of a comparable sample (Allan et al., 2019). Critically, most measurements are sensitive to animal posture and, depending on the technique and number of photographs needed, animal activity (Shero et al., 2021), and care is required when relating 2D indices or 3D volumetry to mass, body condition, and physiological attributes (Hodgson et al., 2020; Shero et al., 2021). Within these provisions, however, drone imagery encodes an abundance of morphometric information about imaged animals, and with increased image quality, refined photogrammetric modeling algorithms, calibrated relationships among morphometric indices, and dynamic physiological models, drone photogrammetry may become an increasingly valuable method of non-invasively canvassing pinniped populations for both focal and aggregate distributions of size and condition.

Computer vision and deep learning

Drone surveys of wildlife produce abundant, high-resolution image-type data that are conventionally interpreted visually by humans, but computer vision techniques can ease the burden of image interpretation (Weinstein, 2018), especially where deep learning methods can capitalize on growing archival collections for training data. Early computer-aided wildlife surveys exploited high contrast between select species and their backgrounds to locate and count animals using a simple thresholding technique (Bajzak & Piatt, 1990). Today, similar thresholding methods can be used with thermal (Beaver et al., 2020) and multispectral sensors (Colefax et al., 2021) to overcome potential lack of contrast in the visible-light spectrum, and are facilitated by the capacity of drone platforms to support modular or customizable payloads. In the absence of suitably high contrast, however, convolutional neural networks (CNNs) can be trained to detect focal objects in remotely sensed data with high success (Zhu et al., 2017), leveraging spatial context and multiscalar feature representation to extract and discriminate targets from background and alternative classes. There are many bespoke examples of CNNs achieving satisfactory or higher success in tasks of wildlife detection (reviewed in Corcoran et al., 2021; Kellenberger et al., 2018), and generalizable workflows are beginning to emerge for diverse wildlife research scenarios (Kellenberger et al., 2020; Koger et al., 2023), but implementation is often still hindered by a high threshold of requisite technological ability and mismatches of scale between demonstration scenarios and practical applications (Lyons et al., 2019).

Some current drone applications with pinnipeds leverage thermal or multispectral imagery to facilitate detection by high contrast in drone imagery (Larsen et al., 2022b; Seymour et al., 2017; Sweeney et al., 2019), but many more studies rely exclusively on visible-light photography to detect pinnipeds. With visible-light aerial imagery, deep learning techniques have already been applied to estimate aggregate pinniped counts (Hoekendijk et al., 2021), detect individual pinnipeds (Dujon et al., 2021), and classify pinnipeds by age-class (Infantes et al., 2022; Salberg, 2015), though success and generalizability vary widely between examples. Upcoming applications also include deep learning for photogrammetry, as has been demonstrated with drone-based photography of cetaceans (Gray et al., 2019) and recently with harbor seals (Infantes et al., 2022), and deep learning for individual identification, as has been demonstrated with ground-based photography of harbor seals (Birenbaum et al., 2022; Nepovinnykh et al., 2018, 2022). In this early stage of its technological deployment, deep learning for computer vision remains an experimental technique in pinniped research, and still few examples characterize its error and generalizability across large-scale applications. As implementations coalesce around useful software and prioritized research objectives, researchers will need to establish best practices to guide data acquisition and curation for model training, tuning model performance, and accurately estimating model error. In the absence of such guidance, deep learning can still enhance accuracy and efficiency by complementing, rather than replacing, human interpretation.

Future potential

New drone methodologies for pinniped research will undoubtedly emerge from these strengths and others yet to be recognized. Considering this ongoing evolution of the technology and its applications, a particular strength of drone methods is that they record a wealth of information, often far exceeding a mission's precise objective. Spatially referenced images with metadata and flight logs encode rich contextual information in digital formats that are often ready for archival or distribution before processing. If preserved, raw data products can be reprocessed and reanalyzed as downstream methods continue to improve. Best practices and standards are still emerging for collection, storage and distribution of drone data, but even within local repositories, growing collections of drone imagery and products can facilitate new analyses across spatial and temporal dimensions, satisfying methods that require large datasets for model training or rigorous statistical tests.

Limitations

Amid their promising potential, drones are not appropriate for all scenarios, and, notably, drone applications often complement rather than replace conventional and alternative methodologies. Remote sensing methods, by definition, collect data at a distance through the spectra and media that they monitor (Campbell & Wynne, 2011), and cannot replace many *in situ* methods. Drone methods have recently accomplished scientific interactions with large animals at short distances, such as tag deployment (Zak et al., 2022) and blow sampling from whales (Pirotta et al., 2017); but similar techniques have not been demonstrated for pinnipeds and would likely incur significant disturbance to target and nearby animals from a drone's acoustic and visual profile at close proximity in open air (Duporge et al., 2021).

The risk of wildlife disturbance represents a major concern in drone applications (Mulero-Pázmány et al., 2017); however, multiple studies have demonstrated drone surveillance over pinnipeds while noting little or no disturbance (Arona et al., 2018; McIntosh et al., 2018). Experimental exposures suggest that flights above 30 m are unlikely to cause significant disturbance to many species (Krause et al., 2021; Laborie et al., 2021; Mustafa et al., 2018; Pomeroy et al., 2015), and increasingly quiet drones may further reduce disturbance at closer distances (Duporge et al., 2021). Ultimately, advisable altitudes depend on the choice of drone and the choice of species, accounting for the potential sensory and behavioral sensitivity of an individual in its environment and life history stage (Duporge et al., 2021). In all scenarios, the risk of disturbance from drones should be weighed against the risk from alternative possible methodologies (Krause et al., 2021; Laborie et al., 2021; McIntosh et al., 2018; Moreland et al., 2015), and aspects of study design can further reduce the risk of disturbance from drones (Mo & Bonatakis, 2021).

Beyond potential disturbance, many other factors can disqualify drones from a study's design. Battery life limits the range and duration of drone flights, such that most cannot achieve the larger range and extent that is commonly collected from occupied aircraft (Colefax et al., 2021). Drones often must be transported to survey sites or adjacent launch sites by boat or aircraft, potentially incurring costs and disturbance beyond that of the drone. Where drones are scientifically appropriate, local regulations may restrict the airspace, pilot qualification, or choice of aircraft for a study (Crutsinger et al., 2016; Floreano & Wood, 2015; Linchant et al., 2015; Newman, 2017). Like any complex technology, drones also require training and expertise for safe operation and maintenance. The selection of a drone-based methodology should follow careful consideration of research objectives, available expertise and resources, regulatory context, and potential risks to researchers, animals—both focal and non-target individuals—and the environment.

Conclusions

Drones constitute a new frontier in wildlife biology that, like other recent technological advancements, heralds transformative, transdisciplinary opportunities for both methods and theory in the study of pinnipeds. Though increasingly common, many drone applications remain at the scale of 'proofs of concept' or direct substitution for conventional research methods, like annual population counts. As practitioners refine and scale drone techniques toward their logistical and technological limits, pinniped researchers can begin to fully utilize the advantages of drone systems: their unique combination of large spatial coverage, ultra-fine resolution, simple and rapid deployment, and ease of customization. Downstream opportunities of drone imagery include structure-from-motion and orthorectified spatial products, precise 2D and 3D photogrammetry, computer vision and yet-to-be imagined applications for data with such rich abundance, detail, metadata, and archival potential. These advancements will complement other research themes by integrating previously independent data-streams from complementary measurement and monitoring techniques, pioneering new syntheses and transforming the field toward further integrated, multiscalar themes of research and management. Such integration is already taking place in the adjacent field of cetacean research, where drone measurements have been calibrated and integrated alongside biologging and biomechanical models to reveal new evolutionary and ecological insights (Cade et al., 2023; Goldbogen et al., 2019; Savoca et al., 2021). As new methods and standards emerge for the use of drones in research, scientists must advance applications toward the scales of management objectives and statistical rigor by validating potential methods, highlighting current limitations, and testing new applications beyond the current frontiers of pinniped research.

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Figures

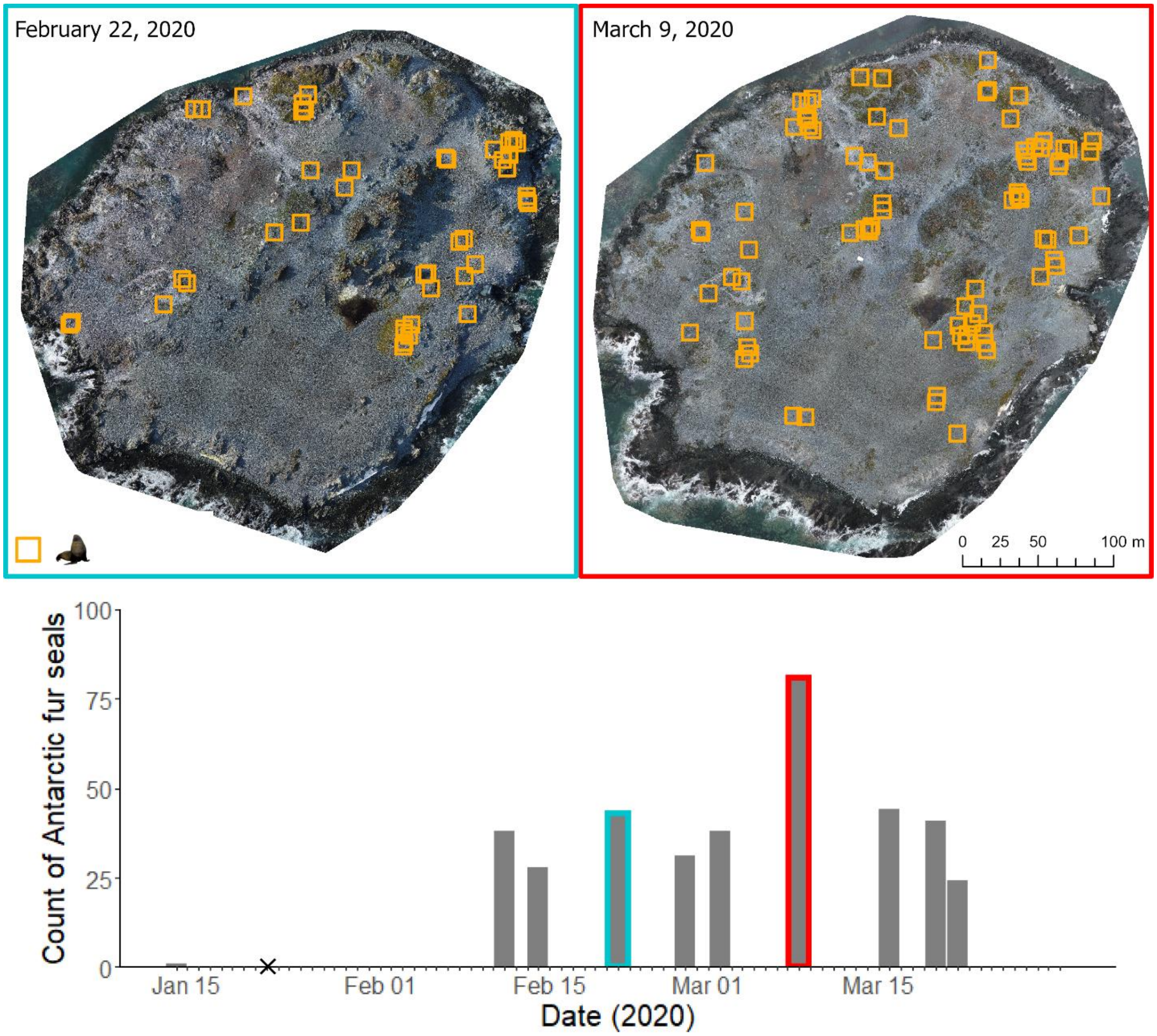

FIGURE 1 | Example drone orthomosaics (top) describe changes in abundance and occupancy of Antarctic fur seals (*Arctocephalus gazella*, orange squares) on Torgersen Island, Antarctica (64° 44' 49''S, 64° 4' 24''W) in summer 2020. Orthomosaics show imagery from February 22 and March 9 with total counts (bottom) from 11 drone surveys during January– March 2020 . Repeat drone surveys, here, provide temporal context that informs estimates of both the timing and abundance of seals at this site.

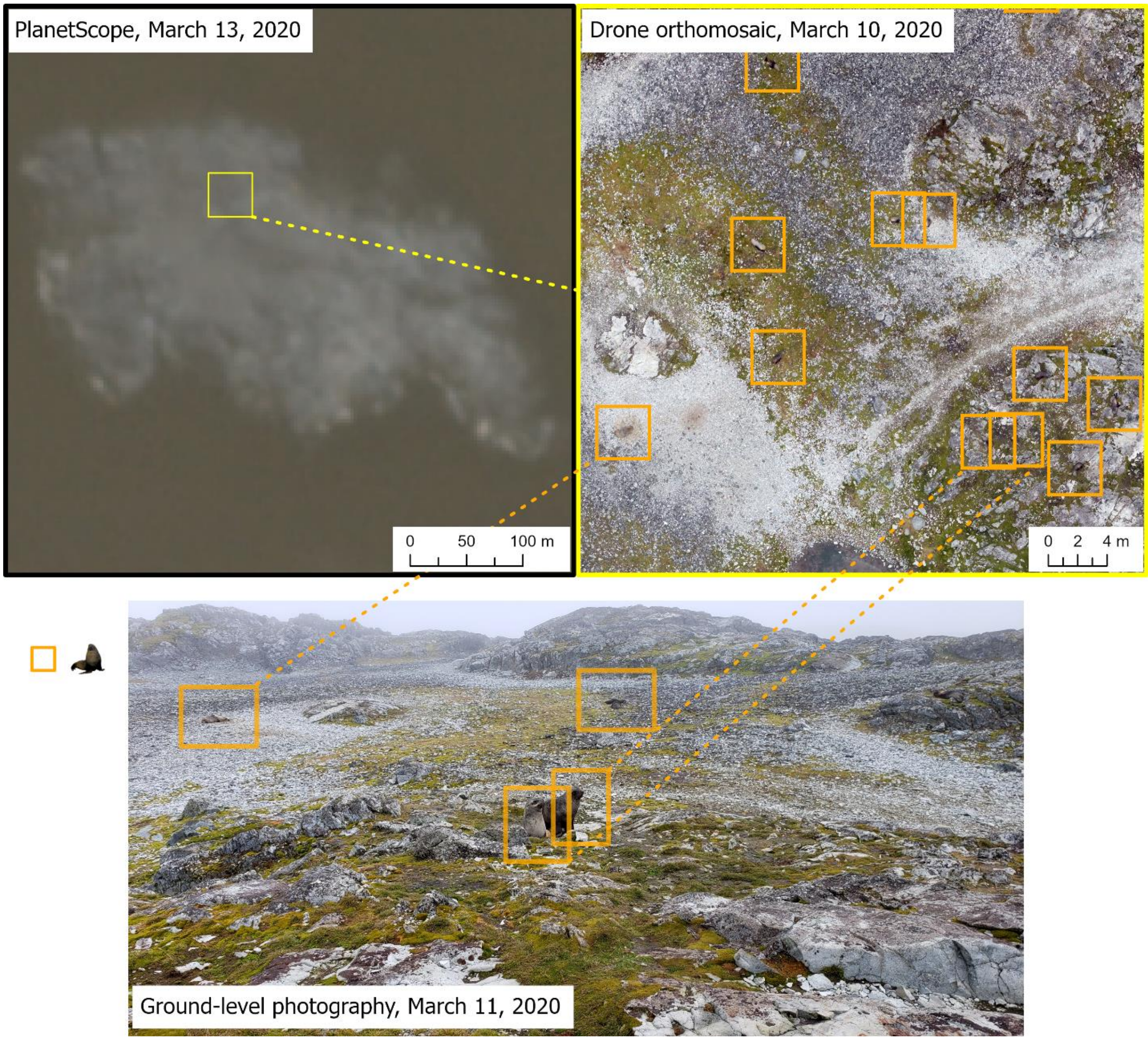

FIGURE 2 | Near-contemporaneous satellite, drone and ground photography demonstrate differences in resolution and spatial context between imaging modes. A PlanetScope image (top left) describes Humble Island (64°44' 20"S, 64°5'9"W) in 3.125 m GSD, here subset from a 25-km swath-width that can provide regional context. A drone orthomosaic (top right) describes landforms, flora and Antarctic fur seals (orange boxes) in 1.3 cm GSD, here subset from a survey of the entire island . A ground-level photograph, captured on a Samsung Galaxy S9+ smartphone camera, shows Antarctic fur seals within the landscape at varying distances. Individual seals can be identified with high confidence in both drone imagery and ground imagery (orange dashed lines) based on their pelage and locations. PlanetScope image ID: 3226192_2009012_2020-03-13_1054.

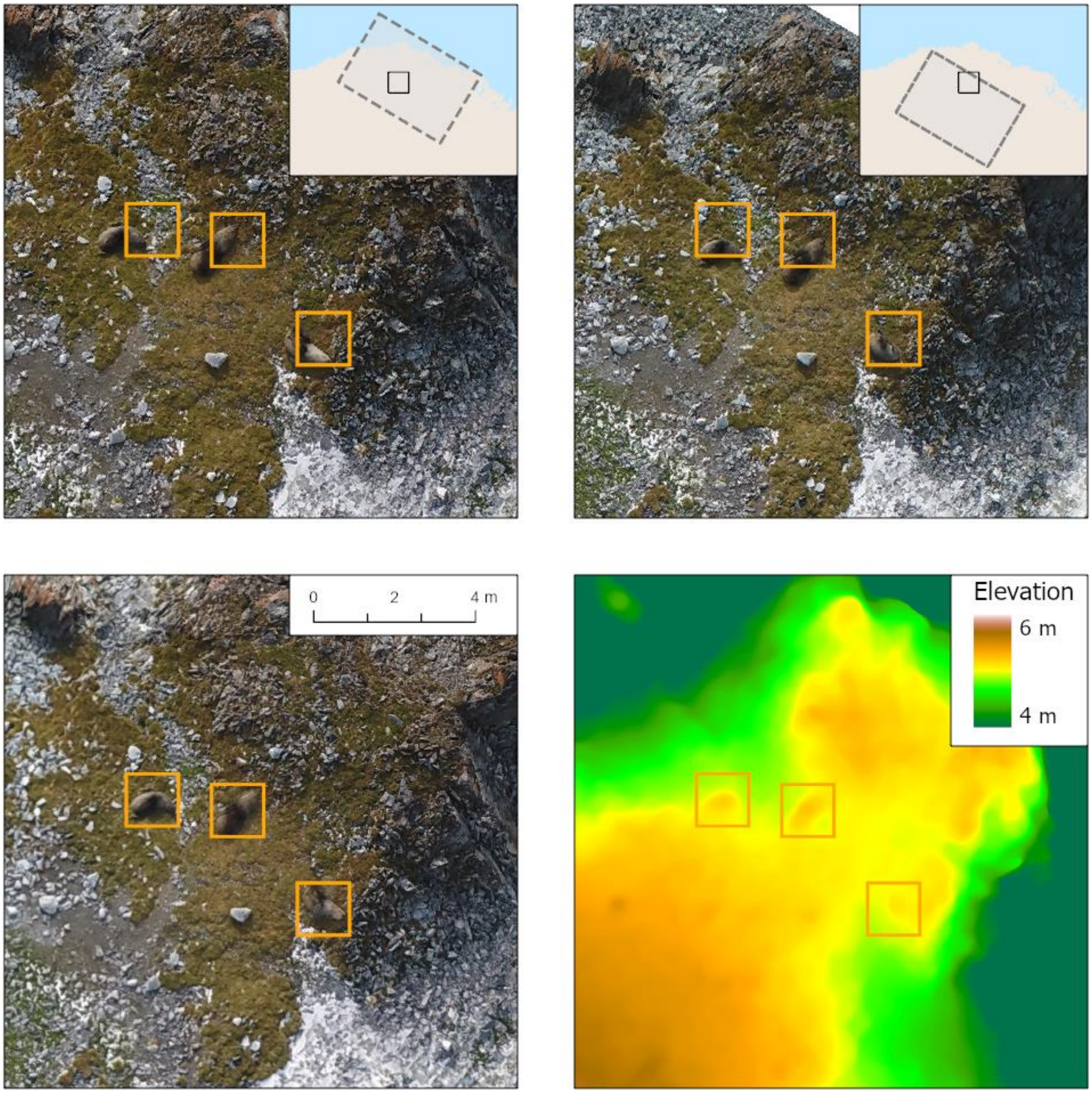

FIGURE 3 | Unprocessed drone imagery and corrected photogrammetric products illustrate orthorectification at ultra-fine scales. Uncorrected photographs (top) show visible displacement of seals from their true locations (orange boxes) resulting from the parallax between different camera perspectives. Insets shows the subset location (black square) within the footprint of its source photograph (gray dashed rectangle). Orthorectified imagery (bottom left) shows the true relationships among features in Euclidean space. A derived DEM (bottom right) describes the topography of those features. Imagery is subsetted from a survey of Torgersen Island (64° 44' 49"S, 64° 4' 24"W), captured on March 23, 2020 .

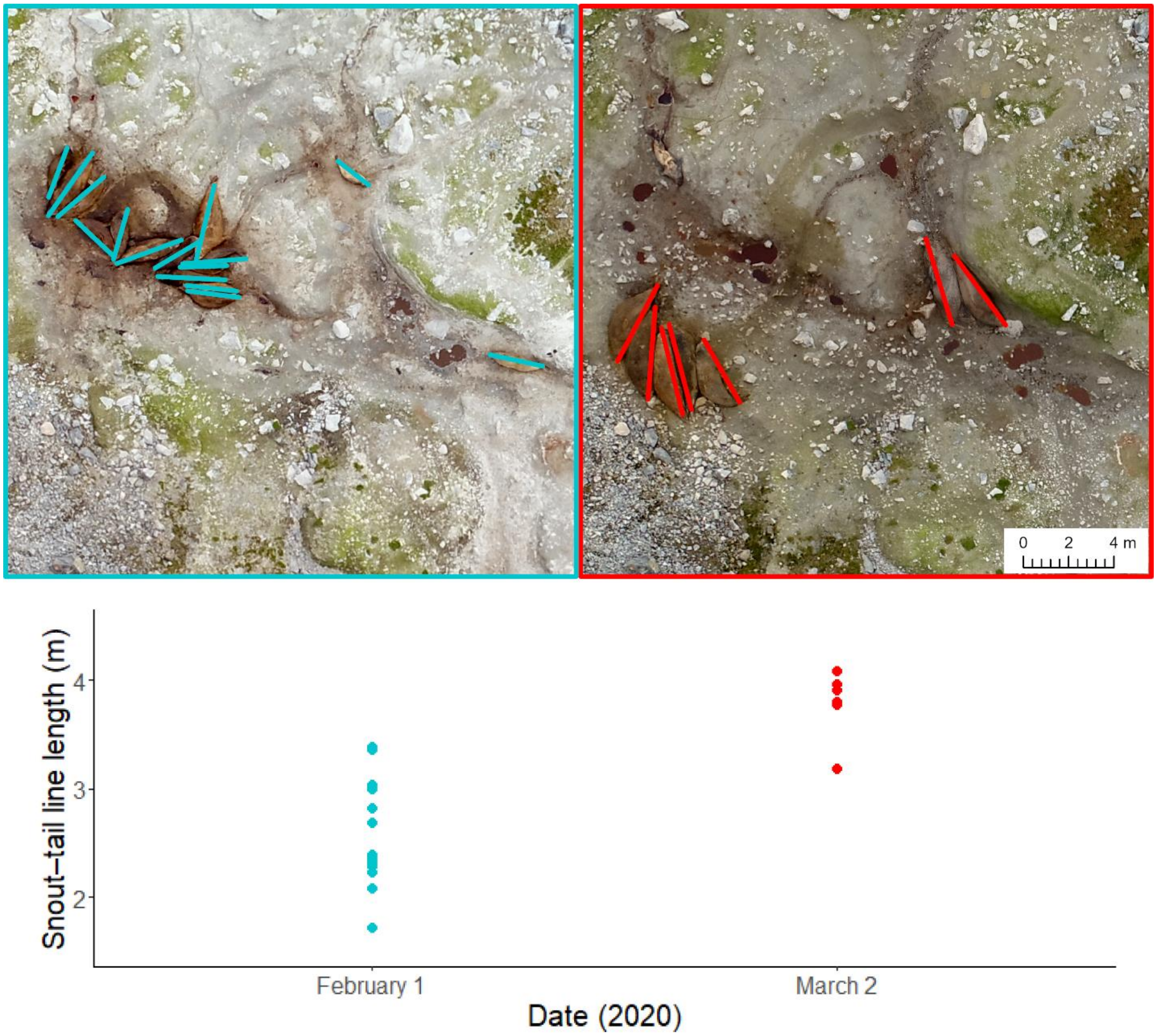

FIGURE 4 | Example orthomosaic imagery (top) describes the presence and approximate lengths of southern elephant seals (*Mirounga leonina*) across multiple drone surveys of Amsler Island, Antarctica (64° 44' 16"S, 64° 3' 55"W) in summer 2020 . Orthomosaics allow measurements of seals, here a coarse snout–tail straight line, based on the known GSD of the imagery. Repeat measurements at the same site reveal potential differences in occupancy with respect to abundance and age-classes as the region shifted from the peak molting period of cows and juveniles (late-December to early-February) toward the peak molting period of bulls (early-March to late April), as has been described previously for more northerly rookeries .