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NOTE

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Calibration of aerial photogrammetry to estimate elephant seal mass

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Body mass measurements can provide important insights into the physiology and foraging ecology of marine mammals (Costa, Croxall, & Duck, 1989), such as linking climate anomalies like El Niño to prey abundance and predator vital rates (Abrahms et al., 2018a, 2018b; Crocker, Costa, Le Boeuf, Webb, & Houser, 2006; Derocher, Lunn, & Sterling, 2004; Robinson et al., 2012; Simmons et al., 2010; Trillmich et al., 1991). However, mass measurements can be difficult to obtain, often requiring chemical immobilization (Beltran, Ruscher-Hill, Kirkham, & Burns, 2018; Horning et al., 2019). Alternatively, animals can be lured over a platform scale using acoustic or physical stimuli, but this can be disruptive and requires extensive logistics (Deutsch, Hale, & Le Boeuf, 1990). Mass can be estimated from morphometric measurements of length, girth, height, width, and blubber thickness, but this requires chemical immobilization (Gales & Burton, 1987; Shero, Pearson, Costa, & Burns, 2014). Logistical limitations of these methods constrain the number of animals that can be weighed over a given time period (Krause, Hinke, Perryman, Goebel, & LeRoi, 2017). Additionally, these approaches may be highly disruptive for gregarious species such as eared seals (otariids) that haul out in tightly clumped groups. Further, these approaches cannot be applied to fully aquatic species such as cetaceans. As a result, most cetacean body mass data are measured in stranded or bycaught animals that might not be representative of healthy individuals.

Photogrammetry provides a promising alternative for estimating mass in numerous terrestrial and marine species (Breuer, Robbins, & Boesch, 2007; Costa, Loy, Cataudella, Davis, & Scardi, 2006; Deutsch et al., 1990; Haley, Deutsch, & Le Boeuf, 1991; Postma et al., 2015; Shrader, Ferreira, & Van Aarde, 2006). Land-based photogrammetry has used single front, top, or side photographs (Haley et al., 1991; Ireland, Garrott, Rotella, & Banfield, 2006; Meise, Krüger, Piedrahita, Mueller, & Trillmich, 2013) or combined multiple photographs into a three-dimensional model using stereoscopy (Beltran et al., 2018; de Bruyn, Bester, Carlini, & Oosthuizen, 2009; Waite, Schrader, Mellish, & Horning, 2007). However, these approaches are not suitable for species that aggregate in large groups due to the reduced visibility and accessibility of each animal which may cause disruption to the colony.

Unmanned aerial system (UAS) photogrammetry offers a method that is safer for both animals and researchers and is logistically simpler than traditional weighing methods (Fiori, Doshi, Martinez, Orams, & Bollard-Breen, 2017). Additionally, UAS photogrammetry facilitates larger sample sizes because it allows measurement at larger spatial scales, thereby increasing statistical power (Sweeney et al., 2015). However, UAS photogrammetry requires calibration and validation prior to use in order to assess the error relative to known mass measurements. Species-specific calibration of appropriate metrics (e.g., footprint area; Christiansen, Dujon, Sprogis, Arnould, & Bejder, 2016) is necessary to account for body shape differences (e.g., "peanut head" syndrome; Fearnbach, Durban, Ellifrit, & Balcomb, 2018; Joblon et al., 2014; Miller, Best, Perryman, Baumgartner, & Moore, 2012).

Northern elephant seals (*Mirounga angustirostris*) offer a unique opportunity to calibrate UAS photogrammetry to measure body mass. Elephant seals undergo dramatic changes in mass throughout the year and consistently haul out to breed and molt at Año Nuevo Natural Reserve, California, (37.11°N, 122.34°W; Le Boeuf & Laws, 1994; Figure 1). Our objectives were (1) to evaluate the accuracy of UAS photogrammetry for estimating the mass of adult female northern elephant seals and (2) to examine the effect of body position on mass estimates obtained using UAS.

We used a DJI Phantom 3 Advanced quadcopter with a built-in camera (20 mm aspherical lens, 12.76 megapixels) to obtain 52 photographs of 22 elephant seals that were being used in other studies requiring immobilization (Table 1). Direct mass measurements were obtained by chemically immobilizing each seal using ~1.0 mg/kg of Tiletamine/Zolazepam then enclosing the seal in a sling suspended from a tripod and Dyna-Link electronic scale (±1 kg; Robinson et al., 2012; Figure 2). One UAS photograph was obtained from directly over each seal immediately following an immobilization procedure (n = 27) or when naturally sighted within mean 2.65 ± SD 3.68 days of a procedure (n = 25). We placed a 246-cm wooden bar near and at the same elevation as the seal to provide a scale in

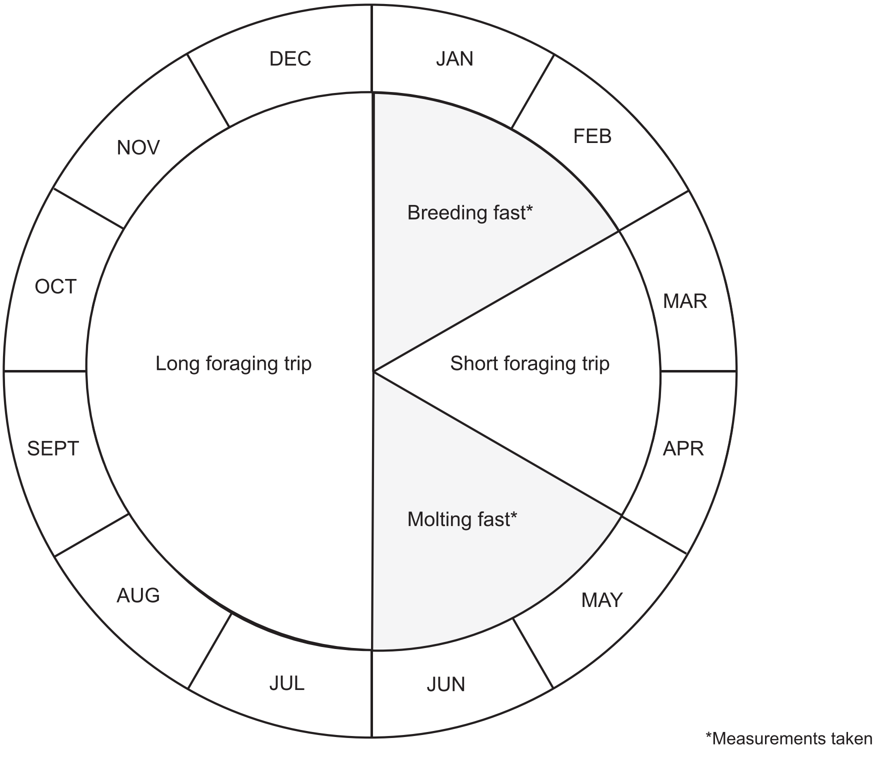

FIGURE 1 Northern elephant seals were photographed via drone and weighed on the beach during the breeding and molting fasts (gray) after returning from their foraging trips at sea (white).

each photograph. Flights were conducted at an approximate altitude of 10 m above the ground and a trained observer confirmed that the UAS did not lead to any animal disturbance. Complete body areas (hereafter, footprint areas, measured in square meters) of seals in a dorsal (laying on ventral surface, n = 45) or lateral (laying on side, n = 7) body position were measured in ImageJ using the standard polygon area selection tool (Figure 3) and compared to mass measurements. We chose to use footprint area measurement because it should account for changes in body condition by integrating length and width. Rear flippers were excluded from each trace due to the variability in positioning. Only seals with clearly visible footprints (from the tip of the nose to the tip of the tail) were included. For each animal, footprint measurements were repeated three times by one user and averaged. For seals photographed on a different day than they were weighed, we corrected mass using [MassCorrection = (0.51 + 0.0076*Mass)*DaysSinceMeasurement] (Simmons et al., 2010).

Statistical analysis was performed in R 3.5.0. We calculated a correction factor for seal body mass estimation using a linear mixed effects model between UAS-derived footprint area and actual mass measurements with individual as a random effect using the R package lme4. We report residual error of our models by subtracting actual mass from estimated mass (mass error in kilograms) and the percent error as residual error divided by actual mass. Marginal and conditional R^2 values were calculated using the R package MuMIn. The critical level was set at α = 0.05. Values are reported as mean ± standard deviation.

TABLE 1 Sample sizes of seals and photographs from which mass was estimated and measured.

	# Photographs per season		
Seal ID (n = 22)	Breeding	Molting	# Photos per seal
5689	1	0	1
5974	2	2	4
6286	6	1	7
6564	3	3	6
6565	1	0	1
6609	1	3	4
7019	1	0	1
7694	1	0	1
7818	1	1	2
7865	1	0	1
7873	1	0	1
9454	3	1	4
9655	0	2	2
9723	0	1	1
9906	1	0	1
A728	1	0	1
B310	1	1	2
B800	1	0	1
PM695	0	1	1
U539	0	1	1
X1	3	2	5
X674	3	1	4
Total # photos	32	20	52

FIGURE 2 Mass was directly measured during immobilization procedures by enclosing adult female northern elephant seals in a sling suspended from a tripod and electronic scale. Photo credit: Daniel Costa.

FIGURE 3 Scaled photographs were taken using a DJI Phantom 3 Advanced quadcopter and analyzed using ImageJ to measure footprint area (yellow polygon, measured in m^2) of seals in a dorsal (left) or lateral (right) body position. A 246-cm wooden bar was included to provide a scale in each photograph.

Measured elephant seal mass ranged from 249.0 to 580.0 kg (402.5 ± 97.8 kg). Footprint measurements ranged from 0.92 to 1.78 m^2 (1.34 ± 0.21 m^2). Repeated footprint measurements by a single user were precise, with a range (maximum footprint – minimum footprint) of 0.014 ± 0.014 m^2 for each seal (or 1% of mean footprint area). The footprint areas ranged from 0.0008 to 0.08 m^2 across seals. We predict that this range of measurements would be similar between independent observers because the technique is simple and requires

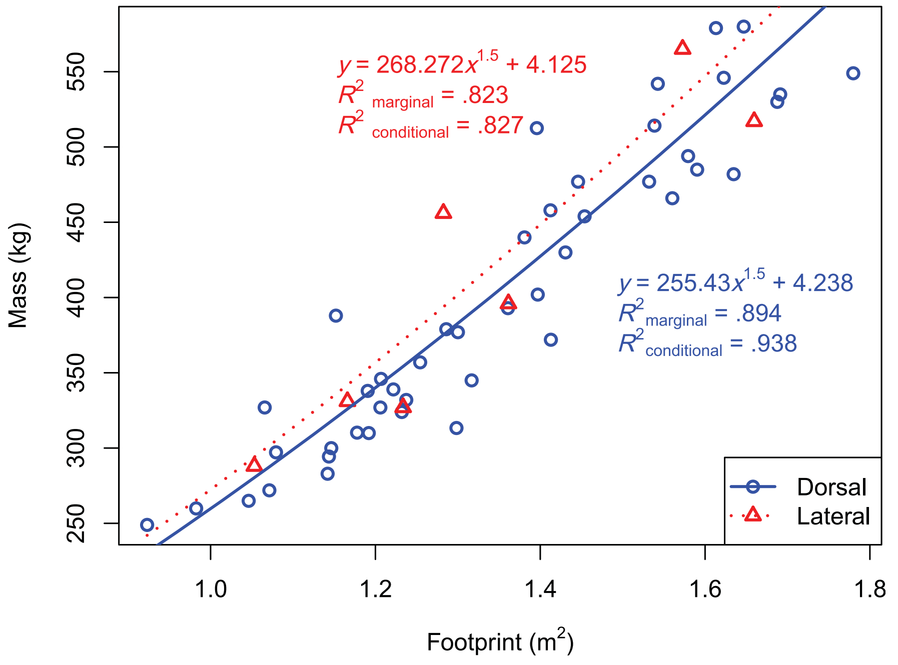

FIGURE 4 Dorsal (solid blue, *n* = 45) and lateral (dotted red, *n* = 7) footprint measurements compared to actual mass measurements in adult female elephant seals.

limited expertise. Footprint area to the 1.5 power (to account for metabolic scaling) was correlated with measured mass (Figure 4):

$$\text{EstimatedMassDorsal} = \left(255.43 * \text{Footprint}^{1.5}\right) + 4.238$$

$$\text{EstimatedMassLateral} = \left(268.272 * \text{Footprint}^{1.5}\right) + 4.125.$$

Residual error ranged from −68.7 to +69.3 kg and seal mass was estimated with a mean error of 7.7 kg, or 2.4%, of total body mass. Our error estimates were comparable to other ground-based studies that used multiple photogrammetric measurements to estimate mass (Table 2) and slightly lower than the only other overhead drone study (Krause et al., 2017). This error is similar to previous mass estimates derived from morphometric measurements obtained during manual procedures (2.8% for Weddell seals *Leptonychotes weddellii*; Shero et al., 2014 and 4% for elephant seals; Crocker, personal communication, July 19, 2019) but results in significantly less disturbance. Mass gain was estimated with a mean error of 12.2% for the postmolt foraging trip (*n* = 9 seals). We believe this large error was due to the relatively small sample size as well as the compounding of error from the pretrip and posttrip photographs.

Errors in estimated mass were marginally smaller when we used dorsal footprint area (mean error = 6.92 kg, $R^2_{marginal}$ = 0.894, $R^2_{conditional}$ = 0.938, *n* = 45) than lateral footprint area (mean error = 12.69 kg, $R^2_{marginal}$ = 0.823, $R^2_{conditional}$ = 0.827, *n* = 7). This finding agrees with Krause et al. (2017) but differs from Meise, Mueller, Zein, and Trillmich (2014) who suggested that measurements were highly sensitive to body position. Further, residuals of estimated mass were smaller when separated into the two body-position-specific models (mean error = 7.7 kg) than when combined in one model (mean error = 10 kg, $R^2_{marginal}$ = 0.885, $R^2_{conditional}$ = 0.900). Additionally, errors in estimated mass gain suggest UAS photogrammetry would be a better method for measuring mass gain over the postmolt foraging trip than the postbreeding foraging trip due to the relatively high mean error of the latter. The

TABLE 2 Mass-estimation error comparison across studies that use single photos. Error is percent mass estimation error, see details in Krause et al. (2017).

Reference	Photogrammetry method	Study species	Photogrammetry metric				Sample size	Error
			Area	Girth	Width	Length		
Bell et al. (1997)	ground	Southern elephant seal *Mirounga leonina*	✓	✓	–	–	13	4.71%
Haley et al. (1991)	ground	Northern elephant seal *Mirounga angustirostris*	✓	✓	–	✓	70	12.0%
Ireland et al. (2006)	ground	Weddell seal *Leptonychotes weddellii*	✓	–	✓	✓	73	13.8%
Meise et al. (2014)	ground	Galapagos sea lion *Zalophus wollebaeki*	–	✓	–	✓	♂ 15 ♀ 21	♂ 6.80% ♀ 14.5%
Krause et al. (2017)	aerial	Leopard seal *Hydrurga leptonyx*	–	–	✓	✓	15	4.40%
This study	aerial	Northern elephant seal	✓	–	–	–	22	2.4%

error surrounding photogrammetric mass estimates have been attributed to the influence of rigid skeletal structures (e.g., hip and thorax) and species-specific differences in body shape that could hide mass fluctuations (Krause et al., 2017; Shero et al., 2014). Additionally, a change in body composition can result in different mass but not volume due to the dissimilar densities of lipid and lean tissues (Beltran et al., 2018). This could potentially lead to differences in mass estimation error between the postmolt and postbreeding foraging trips.

The application of UAS photogrammetry is somewhat limited by the need to avoid wind, rain, and fog that could compromise photograph quality. However, these moderate weather conditions prohibit UAS flights to a much smaller degree than manned aircraft flights, especially in remote settings (Goebel et al., 2015; Sweeney et al., 2015). An additional consideration for UAS photogrammetry is selecting an approach for scaling each photograph. Previous studies have used a scale bar (Haley et al., 1991), custom calibration board (Hodgson, Holman, Terauds, Koh, & Goldsworthy, 2020), laser distance meter (Meise et al., 2014), or highly accurate altimeter (Krause et al., 2017). In our study, resolution of the built-in UAS GPS was insufficient for altitude measurements, which required us to use a scale bar. Additionally, while our study obtained useful measurements from flights at a 10 m altitude using an aspherical 20 mm lens without causing animal disturbance, researchers working with populations that are more sensitive to disturbance might consider using alternative measures such as higher flight altitudes and longer focal lengths.

Further work is warranted to determine the accuracy of UAS photogrammetry with other age and sex classes, particularly those too large to weigh using traditional methods (Deutsch et al., 1990). Unlike manual weighing, which can be disruptive of seal colonies and dangerous, UAS photogrammetry makes colony-wide measurements of body mass possible. For example, the mass of all seals could be estimated at the beginning of a haul-out to estimate population-wide foraging success as an index of prey availability, both within and across years. Similarly, longitudinal mass estimates of each individual could provide valuable information about reproductive energetics and ontogenetic development (Fortune et al., 2012). UAS sensors that include thermal imaging could measure seasonal changes in heat flux for individually identified animals. Integration of real-time kinematic positioning, a mode of measurement used to increase the precision of GPS signals (Lambiel & Delaloye, 2004), can increase the accuracy of altitude measurements. Newer studies have used UAS photogrammetry to obtain accurate 3-dimensional measurements; however, this method requires animals to remain stationary, which may not be ideal for active, free-ranging animals (Hodgson et al., 2020). Further evaluations could determine whether combinations of UAS photogrammetry metrics such as length to width ratios (Hodgson et al., 2020; Krause et al., 2017; Perryman & Lynn, 2002) and height to width ratios (Christiansen et al., 2019) could be used to estimate body condition (i.e., percent fat), which is a more valuable indicator of foraging success and predictor of reproductive success than mass alone (McDonald, Crocker, Burns, & Costa, 2008).

In summary, we determined the error associated with using UAS photogrammetry to estimate northern elephant seal mass. Photogrammetric measurements from a single, vertical image obtained using UAS provide a promising approach for estimating the body mass of pinnipeds and similar approaches can be used to find species-specific calibration equations. With the predictive models provided above, UAS photogrammetry will allow us to expand our knowledge of seasonal energetic intake and expenditure, especially in large-bodied and fully aquatic species in remote areas (Durban, Fearnbach, Barrett-Lennard, Perryman, & Leroi, 2015). Mass measurements can inform ecosystem-based resource management (Boyd, Wanless, & Camphuysen, 2006) by providing information about the interannual productivity of the ocean environment and in turn individual, population, and ecosystem-level health in marine mammals (Krause et al., 2017).

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AUTHOR CONTRIBUTIONS

Diana Alvarado: Funding acquisition; investigation; validation; visualization; writing-original draft; writing-review and editing. **Patrick Robinson:** Conceptualization; data curation; investigation; methodology; resources; supervision; writing-review and editing. **Nicolas Frasson:** Validation; writing-review and editing. **Daniel Costa:** Funding acquisition; resources; writing-review and editing. **Roxanne Beltran:** Conceptualization; data curation; formal analysis; methodology; resources; supervision; writing-review and editing.

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