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1 **Morphometric study of humpback whale mother-calf pairs in the Sainte Marie**
2 **channel, Madagascar, using a simple drone-based photogrammetric method**

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14 **Abstract**

15 Morphometric studies of humpback whales (*Megaptera novaeangliae*) occurring in the Indian
16 Ocean area have been limited by the technology currently available. In the Sainte Marie
17 channel, Madagascar, we tested a straightforward aerial single-camera photogrammetry on
18 mother-calf pairs that combines standard Unoccupied Aerial Vehicle (UAV) with free, easy-
19 to-access, and user-friendly software. Our goals were to estimate mothers' and calves' body
20 measurements and to investigate the effect of maternal parity (primiparous versus
21 multiparous, based on length) on calf's size. We estimated a mean length of 12.4 ± 1.2 m for
22 mothers ($N = 16$) and 5 ± 0.9 m for calves ($N = 16$). We found that calves' size did not depend
23 significantly on maternal parity. The photogrammetry method we used was simple and cost-
24 effective, yet produced convincing morphometric measurements with acceptable precision
25 and accuracy. The coefficients of variation (CVs) of repeated estimates and the level of error
26 were relatively low (CV = 2.31% for a known-sized object and average CV = 2.52% for
27 individual whales; average error = 1.8% for a known-sized object). We believe our results will
28 encourage more teams to study the morphometry of large marine mammals despite
29 limitations in terms of resources.

30 **Keywords:** Aerial photogrammetry; Breeding grounds; Parity; Unoccupied Aerial Vehicle
31 (UAV)

32

33 INTRODUCTION

34 Morphometric data is the numerical expression of an animal's morphological characteristics
35 that can be used to address various biological questions (Schmidt-Nielsen and Knut, 1984).
36 Previous studies have demonstrated the efficiency of using body length for determining
37 growth rate, age-structures, and population demographics in cetaceans (Chittleborough,
38 1965; Perryman and Lynn, 1993). At the individual level, morphometric data can be
39 examined to assess body condition and reproductive capacity (Perryman and Lynn, 2002;
40 Miller *et al.*, 2012; Christiansen *et al.*, 2016; Fearnbach *et al.*, 2018). In addition, a time
41 series of morphometric data can be used to assess population responses to environmental
42 and anthropogenic changes (Hanks, 1981). For example, long-term changes in size
43 distribution can provide a signal of overexploitation of a population (Stevens *et al.*, 2000).

44 Live capture-release schemes are generally not applicable to large whales due to their size.
45 Hence in the past, morphometric studies of large whales relied mainly on direct
46 measurements on stranded or commercially harvested specimens (e.g., Chittleborough,
47 1955, 1958, 1965; Omura, 1955; Nishiwaki, 1959, 1962). Later, the development of
48 photogrammetry for studying whales allowed for the extension of morphometric studies to
49 live animals. Known as the science of measuring objects using photographs,
50 photogrammetry is better than direct measurements as it does not require physical capture of
51 animals and is thus non-invasive and less opportunistic. Photogrammetry used in whale
52 studies can be divided into two main approaches: either stereo-photogrammetry or single-
53 camera photogrammetry. Stereo-photogrammetry uses overlapping photographs to estimate
54 length (Cubbage and Calambokidis, 1987; Dawson *et al.*, 1995). It allows for accurate
55 measurements of whales since the measurements are done in 3-dimensions. However, it
56 requires a complex pre-configuration such as a precise and controlled stereo-camera
57 mounting and synchronization. On the other hand, single-camera photogrammetry requires
58 only a single photograph and uses either a known-size object in the frame for scale
59 (Christiansen *et al.*, 2016) or a measurement of the range to the individual (Best and R  ther,

60 1992; Perryman and Lynn, 2002; Jaquet, 2006; Fearnbach *et al.*, 2011; Miller *et al.*, 2012;
61 Durban *et al.*, 2015; Dawson *et al.*, 2017; Christiansen *et al.*, 2018; Burnett *et al.*, 2019). To
62 achieve accurate measurements from single-photographs while optimizing the cost, a variety
63 of combinations of tools, detailed in Table 1, has been used in the field. One of the most
64 notable advances is the use of Unoccupied Aerial Vehicles (UAVs) or small aerial drones to
65 perform aerial photogrammetry.

66 UAVs have facilitated an array of methods for monitoring wildlife and studying spatial
67 ecology. They provide an ideal solution if the studied animals are scared by the presence of
68 humans in the area or if the animals are dangerous for human observers (Linchant *et al.*,
69 2015). UAVs allow researchers to observe animals in their environment from above, are less
70 invasive than Occupied Aircrafts (OA), and are significantly much more cost-effective. UAVs
71 have therefore been used for a number of marine mammal research applications (Goebel *et al.*
72 *et al.*, 2015; Fiori *et al.*, 2017), including measuring individual animals (Christiansen *et al.*, 2016,
73 2018; Durban *et al.*, 2016; Dawson *et al.*, 2017; Burnett *et al.*, 2019).

74 The models of UAVs commonly used in aerial photogrammetry of whales vary from standard
75 UAVs, such as DJI Phantom 3, to the more expensive UAVs specifically designed for
76 scientific research and/or above-water operations. To obtain an approximation of the range
77 between the camera on the UAV and the whale, researchers generally rely on an altimeter,
78 i.e., an altitude measurements tool (as mentioned in Table 1). The altimeter can be a
79 barometric one (Durban *et al.*, 2015, 2016; Burnett *et al.*, 2019) or an external customized
80 tool such as Light Detection and Ranging technology or LIDAR (Dawson *et al.*, 2017;
81 Christiansen *et al.*, 2018). LIDAR can provide very accurate and precise altitude
82 measurements (Dawson *et al.*, 2017). However, the deployment of LIDAR on an UAV can
83 incur additional cost. Therefore, although barometric altimeters are less accurate and less
84 precise than LIDAR, they are still suitably reliable for photogrammetric purposes and are
85 commonly integrated into most UAVs (Durban *et al.*, 2015, 2016; Burnett *et al.*, 2019). It
86 should be noted that since the lens of the UAVs camera often distorts the images, some

87 photogrammetric studies incorporate prior image correction to improve photo accuracy
88 during the image processing step (Dawson *et al.*, 2017; Burnett *et al.*, 2019). Alternatively,
89 other studies follow a set of specific framing rules in order to minimize the distortion effects
90 on the image (Durban *et al.*, 2015, 2016; Christiansen *et al.*, 2016, 2018).

91 The logistical challenges in utilizing advanced research tools for studying whales may offer
92 an explanation as to why comprehensive surveys on humpback whale morphometry in some
93 regions is lacking. Adding elements to an existing UAV or designing a new UAV can be for
94 example a complex task for teams lacking of Research & Development or electronics
95 department. In this paper, we establish and validate the performance of a simple and cost-
96 efficient single-camera photogrammetry approach that combines a standard UAV (here a DJI
97 Phantom 4) with open-source software to target mother-calf pairs from the Sainte Marie
98 channel, Madagascar.

99 Humpback whales are a highly migratory species. They spend the majority of the summer in
100 their mid- or high-latitude feeding grounds. In winter, they breed and give birth in warm
101 tropical waters (Clapham, 2018). The Sainte Marie channel, located at the eastern coast of
102 Madagascar, is part of the humpback whale's breeding grounds in the South Western Indian
103 Ocean. It is an important breeding ground in terms of mother-calf pairs presence as the
104 channel is relatively calm and shallow (Trudelle *et al.*, 2018). Humpback whales arrive here
105 between June and September.

106 Female humpback whales start to calve between 5 to 9-years old (Clapham, 1992; Gabriele
107 *et al.*, 2007) where they give birth to a single calf, approximately every 2 years (Clapham,
108 2018). Humpback whale mothers are left with the responsibility of the survival of their young
109 until the calf reach the age of approximately 1-year old (Clapham, 2018). The size of sexually
110 mature females ranges between 11 m to 15 m (Omura, 1955; Nishiwaki, 1959, 1962).
111 Christiansen *et al.* (2016) reported a mean length of 12 m for females accompanied by a calf
112 off of Australia. A similar measurement has been reported by Spitz *et al.* (2000) in Hawaii.

113 The calves' mean length is about 4.2 m at birth (Chittleborough, 1965) and they have a
114 growth rate of approximately 3 cm per day (Christiansen *et al.*, 2016).

115 In pinnipeds (Bowen, 2009) and some large whale species (Laws, 1961; Gambell, 1972;
116 Best and R  ther, 1992), it has been found that primiparous mothers (females having their
117 first young and thus inexperienced mothers) tend to produce smaller offspring compared to
118 multiparous mothers (mothers that have previously calved and thus more experienced). This
119 trend may be related to numerous factors, such as a physiological change in the mother
120 following her first parturition that favours the development of future foetuses, a more
121 favourable external environment for the mother, or a behavioural change in the mother
122 gained through previous experiences (Ellis *et al.*, 2000). Female investment in offspring size
123 can be considered as a form of maternal contribution to the survival of the offspring since
124 larger offspring are known to have higher chances of survival in mammals (Ronget *et al.*,
125 2018). In humpback whales, the effect of the maternal parity on offspring size has not yet
126 been investigated. Therefore, our goals were to: 1) estimate mother's and calf's body
127 measurements (standard length and maximum width), and 2) test whether the calf's size is
128 related to the parity of its mother (primiparous or multiparous).

129 **MATERIALS AND METHODS**

130 ***Study site***

131 Field studies were conducted in the Sainte Marie channel, in Madagascar (Indian Ocean).
132 About 60 km long and 7 to 30 km wide (Trudelle *et al.*, 2018), the channel is located between
133 Sainte Marie Island (between latitudes 17° 19' and 16° 42' South, and longitudes 49° 48' and
134 50° 01' East) and the East coast of Madagascar's mainland. The data collection, conducted
135 in conjunction with ongoing study on humpback whale mother-calf interactions, were
136 completed between August to September 2018 under the national research permits #28/18
137 MRHP/SG/DGRHP.

138 ***UAV platform***

139 The DJI Phantom 4 UAV is a quadcopter weighting 1380 g, with a diameter of 350 mm. It is
140 equipped with a built-in barometer that provides real-time altitude measurements (in m), and
141 a gimbaled camera with a 3.61-mm focal length, infinite focus and 0.0015-mm pixel size.
142 Within a centred radius equivalent to 60% of the video frame height, the distortion-related
143 displacement on an image from the camera is less than five pixels (Burnett *et al.*, 2019),
144 which is low. In our study, the video resolution was set at 4096×2160-pixels (4K) with a
145 framerate of 24 frames per seconds.

146 ***Whale visual searches protocol***

147 All methods and approaches were carried out in accordance with relevant guidelines and
148 regulations in force in Madagascar. Dedicated visual searches for humpback whale mother-
149 calf pairs were conducted from a 6.40 m rigid motor boat during days with moderate weather
150 conditions (Beaufort scale ≤ 3 , corresponding to gentle breeze, wind speed less than 12 km
151 h^{-1} , and wave height not exceeding 0.5 m) between 0630 and 1730 hours. The crew
152 consisted of at least 3 trained observers (one on an elevated platform at the back of the boat
153 and two covering the lateral view) and 1 or 2 experimented drone pilots. When a mother-calf
154 pair was spotted, it was approached at idle speed to a distance between 100 and 200 m. All
155 mother-calf pairs were photo-identified to ensure that there is no double-sampling during the
156 study period. The ventral face of the tail fluke (visible when the whale is about to dive) and/or
157 the dorsal fin of each individual was/were photographed using a Nikon digital camera (model
158 D5600) fitted with a 50-300 mm lens. The photographs obtained within the season were then
159 manually compared in order to check that indeed no double-sampling of mother-calf pairs
160 occurred. Depending on the degree of dorsal furl, we also estimated the relative age of each
161 calf (neonate versus non-neonate, Cartwright and Sullivan, 2009; Faria *et al.*, 2013, Saloma,
162 2018). All sighting data were integrated into the local dataset ceta.net (managed by
163 Cétamada association) that gathers all marine mammals' sighting information recorded in
164 Madagascar since 2009.

165 ***UAV flight protocol for whale images acquisition***

166 The UAV was deployed from the boat to video-record the spotted mother-calf pair vertically
167 overhead from an altitude around 15 m to 60 m, at a vertical speed of approximately 0.5 m s⁻¹.
168 ¹. Sometimes the mother and the calf were not close to each other or were not at the surface
169 at the same time. In these cases, they were filmed separately. The drone initialization
170 (altitude zeroing) was performed before each flight on an on-boat platform 0.6 m above the
171 sea level (the variation of the on-boat load between outings was fairly low and assumed to
172 not have a very significant effect on this zeroing height). A maximum of two flight sessions
173 was conducted for each pair (10-15 min duration per flight). Photographs were extracted
174 afterward from the video recordings (see Images extraction and digitization).

175 ***Calibration images acquisition***

176 To estimate the whales' dimension from photographs in the absence of known size scale
177 markers in the frames and to account for systematic error in ranging, the camera needed to
178 be calibrated. This can be done using images of an object with a known length taken at
179 various distances between the object and the camera, i.e., ranges (Jaquet, 2006; Burnett *et*
180 *al.*, 2019). To perform calibration in this study, a static floating kayak of 2.75 m in length was
181 video-recorded vertically overhead at altitudes between 5 m to 45 m at the end of the study
182 period. In addition, for testing, a supplementary filming flight was performed to acquire video
183 material that is independent to the one dedicated to the calibration. The equipment, settings
184 used, and weather conditions present during calibration were consistent with the whale
185 survey flights.

186 ***Images extraction and digitization***

187 Our photogrammetric method was based on 4096×2160-pixel photographs (no cropping)
188 extracted from the collected nadir pointing video using the frame capture function in GOM
189 Player v2.3.32.5292 (GOM & Company, www.gomlab.com). Video recordings were viewed
190 frame by frame for the process. For each filmed individual, one photograph which was the

191 highest quality was extracted. A high quality photograph is one which includes the whale
192 laying flat at the surface, dorsal side facing up, emerged as much as possible, static or
193 travelling at relatively slow speed, with contour not masked by chops, and with a non-arching
194 body axis and peduncle (Figure 1a). As our unadjusted lens is likely to distort images around
195 the outside of the frame, a suitable high quality photograph was selected if the subject was
196 positioned within the 60% radius in the middle of the frame (see lens description in UAV
197 platform). For each photograph, the standard length and the maximum width of the whale
198 were measured in pixels using the software Inkscape v0.92 (www.inkscape.org) (Figure 1b).

199 With respect to the kayak video dedicated to calibration, eight photographs were extracted at
200 approximately 5 m altitude intervals (reference photographs). Only photos with clear, centred
201 frames containing the entire kayak were selected. Additionally, from the supplementary
202 independent kayak video, several photographs (tests hereafter) were taken at an altitude
203 ranging from 5 to 45 m. The length of the kayak in all photographs was then measured in
204 pixels.

205 ***Calibration process***

206 For each of the reference photographs, the measured length from the photographs (in pixels)
207 and the real length of the kayak (in m) were used to calculate the corresponding scale (in m
208 pixel⁻¹):

$$209 \text{ SCALE} = \text{REAL LENGTH} / \text{LENGTH IN PIXELS} \quad (1)$$

210 Then, the scale was regressed against the altitude at which the reference photographs were
211 taken (Figure 2):

$$212 \text{ SCALE} = 0.0004197 \times \text{ALTITUDE} + 0.0001814 \quad (2)$$

213 From (2), we then derived a formula with which we could estimate metric length from vertical
214 images taken at known altitudes:

215 ESTIMATED LENGTH = SCALE × NUMBER OF PIXELS (3)

216 **Barometric altimeter's accuracy evaluation**

217 The UAV model used did not have a suitable alternate altitude measurement for comparison.
218 Therefore, we assessed the accuracy of the barometric altimeter directly using the optical
219 properties of the camera. All of the test photographs were used to back-calculate the
220 expected distance between the camera and the object (in m) as done by Krause *et al.*
221 (2017):

222 Expected camera-object distance = (Real length × Focal length) / (Number of pixels × Pixel
223 size) (4)

224 We then compared that with the barometric altitude reading while accounting for the zeroing
225 height. To assess if the accuracy of the barometric altimeter varies with the expected altitude
226 (expected camera-object distance minus zeroing height), we performed a Spearman's
227 correlation test using the R statistical software v4.0.3 (R core team, www.R-project.org).

228 **Measurements accuracy evaluation**

229 We were unable to directly address the accuracy of our measures as it was impractical to
230 include a scale object with a known size in each photograph of whale. However, as a proxy,
231 we evaluated our measurement error based on our test photographs. From each photograph,
232 the length of the kayak was estimated and the measurement error was then calculated as the
233 percent difference as follows (Krause *et al.*, 2017):

234 % ERROR = | 1 - (REAL LENGTH / ESTIMATED LENGTH) × 100 | (4)

235 To investigate whether the error varies with the altitude at which the photographs were taken,
236 we used a Spearman's correlation test and a Kruskal-Wallis test (using three altitude
237 classes: 5 to 15 m, 15 to 25 m and > 25 m) in R.

238 **Measurements precision evaluation**

239 To indirectly assess the precision of our approach, we calculated the coefficient of variation
240 (CV) of the length estimations of our test object. Additionally, to address whether different
241 observers consistently derive similar measurements, four independent experimented
242 observers estimated the length of the test object. The results were compared among
243 observers using Kruskal-Wallis test in R.

244 **Whale data analysis**

245 The numbers of pixels of the whales were related to the estimated dimension in meter using
246 the formula (2) and (3). Based on the estimated length and considering the life history of the
247 humpback whale (Omura, 1955; Nishiwaki, 1959, 1962; Chittleborough, 1965; Clapham,
248 1992; Gabriele *et al.*, 2007; Clapham, 2018), we then sorted mothers into two categories:
249 primiparous, i.e. likely accompanied by their first calf, for mothers < 13 m, and multiparous,
250 likely already had previously one or more calves, for mothers ≥ 13 m. To assess if the body
251 lengths of calves differ between the two parity categories of mothers, we performed a
252 Wilcoxon test in R.

253 Age has previously been used to categorize females as primiparous or multiparous when
254 complete birth records for each individual were not available (Ellis *et al.*, 2000). Such
255 approach is possible when the life history of the species is known. As mentioned previously,
256 the age at which female humpback whales have their first calf is between 5-9-years old
257 (Clapham, 1992; Gabriele *et al.*, 2007) and the birth interval is about 2 years (Clapham,
258 2018). Based on these data, we can assume that females < 9 -years old whom are
259 accompanied by a calf are likely to be primiparous mothers, while those that are ≥ 9 years
260 old can be assumed to be multiparous. At age 9, a female humpback whale should reach 13
261 m (Chittleborough, 1965) and incidentally, this value is consistent with data obtained by
262 whaling operations (i.e., data from direct measurements): the average size of sexually
263 mature female humpback whales is of 13 m (Omura, 1955; Nishiwaki, 1959, 1962).
264 Therefore, we set 13 m as the threshold to define parity.

265 In some instances, it was possible to extract more than one suitable, high quality
266 photographs of individual whales. Therefore, for these whales, we were able to make
267 additional length estimations. We thus calculated the CVs on individual whales as well, to
268 obtain a more direct precision assessment.

269 **RESULTS**

270 Using a DJI Phantom 4, we photographed a total of sixteen mother-calf pairs between
271 August and September 2018. All calves had an unfurled dorsal fin, indicating that they were
272 not neonates (yet aged less than 3 months). All photographs were obtained at an altitude
273 ranging between 17 and 60 m (mean = 27 ± 11 m); the majority (29 out of 32) being obtained
274 at an altitude < 45 m. The empirical calibration formulas (2) and (3) allowed us to estimate
275 the standard length and the maximum width of mothers and calves from these photographs.

276 ***Accuracy of the barometric altimeter***

277 The absolute difference between the altitude reading provided by the barometric altimeter of
278 the UAV and the expected altitude (expected camera-object distance minus zeroing height)
279 was low (mean = 0.3 ± 0.3 m, min = 0 m, max = 1.3 m, $N = 29$; Figure 4). Furthermore, the
280 correlation between this difference and the barometric altitude was low and not statistically
281 significant (Spearman's correlation test; $\rho = 0.354$, $S = 2624$ and $p = 0.06$).

282 ***Accuracy of the method on object with a known size***

283 The results of repetitive estimations of the length of an object with a known size, a 2.75-m
284 test kayak, at an altitude between 5.8 and 40.9 m showed an average error of $1.8 \pm 1.41\%$
285 with respect to the real length (min = 0%, max = 4.56%, $N = 29$). The errors showed no
286 statistically significant variation with respect to altitude (Spearman's correlation test; $\rho = -$
287 0.16, $S = 4711$ and $p = 0.406$; Kruskal-Wallis test; $\chi^2 = 1.664$, $df = 2$ and $p = 0.435$; Figure 5).

288 ***Precision of the method on object with a known size***

289 The repeated estimations of the length of an object with a known size showed a CV of
290 2.31%. No statistically significant differences were detected for the estimated length of the
291 object among four independent observers (Kruskal-Wallis test; $\chi^2 = 0.511$, $df = 3$ and
292 $p = 0.916$; Figure 6).

293 ***Morphometric measurements of whales***

294 All estimations are presented in Table 1. The mothers showed a mean body length of
295 12.4 ± 1.2 m (min = 10.2 m, max = 14.7 m, $N = 16$). Their average maximum width was
296 2.8 ± 0.4 m (min = 2.1 m, max = 3.6 m, $N = 16$). The calves presented a mean body length of
297 5 ± 0.9 m (min = 3.6 m, max = 7.2 m, $N = 16$) and a mean maximum width of 1 ± 0.2 m
298 (min = 0.7 m, max = 1.5 m, $N = 16$).

299 ***Relation between calves' size and parity***

300 The majority of the mothers (11 out of 16) were < 13 m in length and were classified into the
301 primiparous category. The remaining 5 individuals were classified as multiparous mothers (\geq
302 13 m in length). The length of calves from primiparous mothers was smaller than those from
303 multiparous ones on average (Figure 3). However, there was no statistically significant
304 difference (Wilcoxon test; $W = 43$ and $p = 0.084$).

305 ***Precision of the whale measurements***

306 For most individual whales ($N = 24$), we were able to extract supplementary photographs at
307 different altitudes. Including the initial whale photographs, we obtained two length
308 estimations for 23 individuals and three for one individual. With these estimations, we found
309 an average CV of $2.52 \pm 1.65\%$ (min = 0.02%, max = 5%).

310 **DISCUSSION**

311 The photogrammetric approach we used relied on a formula which was based on several
312 vertical-aerial photographs of a reference object with a known size (a 2.75-m kayak) placed
313 on the sea surface. This empirical formula allowed us to assess morphometric data of both

314 humpback whale mothers and their calves using nadir pointing aerial photographs taken at a
315 known altitude. In our method, errors are likely due to 1) the distortion of the lens, 2) the
316 human error in the digitization process 3) the accuracy of the UAV's barometric altimeter,
317 and 4) the whales' body flex and varying submersion level. To minimise lens distortion, we
318 centred all the images, with the targeted object avoiding the outer frames. With our framing,
319 the pixel displacement normally does not exceed 5 pixels (Burnett *et al.*, 2019). Thus, the
320 associated error is likely to be relatively small. Also, the contribution of human error is likely
321 to be negligible, as we found that independent observers systematically derived similar
322 estimations.

323 With the assumption that local environmental barometric pressure is relatively uniform within
324 and between individual flights in a given site (Burnett *et al.*, 2019), our tests suggest that the
325 measurements obtained with our method are relatively precise and accurate. Although higher
326 than those reported by Dawson *et al.* (2017) and by Durban *et al.* (2015, 2016), the CVs of
327 repeated estimates (2.31% for an object with a known size and 2.52% on average for
328 individual whales) and the level of error (1.8% on average, as calculated using an object with
329 a known size) did not differ greatly from those reported in Christiansen *et al.* (2016) and in
330 Burnett *et al.* (2019).

331 Regarding the barometric altimeter of our drone, the altitude it provided, used as a proxy for
332 range, was accurate to within 1.3 m. Compared to LIDAR altimeter like the one used by
333 Dawson *et al.* (2017) which is accurate to < 0.06 m, the barometric altimeter of our drone
334 was less accurate, which in turn, likely contributed greatly to the estimated errors and
335 variation over repeated measurements.

336 With respect to the contribution of the body flex and varying body submersion of free-ranging
337 whales, precise quantification is difficult as the true size of each individual is not known in
338 advance for comparison. The dorso-ventral flexing of the body may result in underestimation
339 of length if the method is based on nadir-pointing images (Cubbage and Calambokidis, 1987;

340 Dawson *et al.*, 1995). Body submersion may also contribute to additional underestimation
341 and variation because we used the altitude as a proxy for range (camera-object distance). As
342 whales are always partially submerged (at least), the range is always slightly greater when
343 photographing a whale than when photographing a kayak from the same altitude. Also,
344 because the degree of submersion may vary slightly amongst photographs and individuals,
345 there could be additional ranging imprecision which was not taken into account during this
346 study. Incidentally, this may partially explain why the CV of repeated estimates is greater for
347 whales than for our test kayak. Further studies involving at the same time our method and
348 other alternatives that can take into account the whales' body flex and body submersion
349 (e.g., stereo-photogrammetry, Cabbage and Calambokidis, 1987; Dawson *et al.*, 1995) would
350 allow the quantification of these errors and are thus encouraged. In all cases, in our method
351 we ensured that only photographs of the whale laying flat at the surface, emerged as much
352 as possible from the water, and with straight body axis and caudal peduncle were used. We
353 are thus confident that these whale related issues were minimized.

354 The estimated standard lengths of the mothers were consistent with those obtained from
355 underwater images by Spitz *et al.* (2000) in Hawaii and from aerial vertical photographs by
356 Christiansen *et al.* (2016) off of Australia. Using a threshold that we defined according to the
357 known life history of humpback whales, we categorized the mothers as primiparous (< 13-m
358 mothers) or multiparous (\geq 13-m mothers). The calves produced by mothers categorized as
359 multiparous seemed larger than those produced by mothers categorized as primiparous. It
360 has been reported that novice (primiparous) females generally produce smaller offspring
361 (Clutton-Brock, 1991), while multiparous females are capable of producing larger offspring,
362 as they are physically and physiologically more mature than primiparous females (Ellis *et al.*,
363 2000). For both fin whales (*Balaenoptera physalus*) and sperm whales (*Physeter*
364 *macrocephalus*), it has been documented that the offspring of primiparous females are
365 smaller than those of multiparous females examined at the same time (Laws, 1961; Gambell,
366 1972). For right whales (*Eubalaena australis*), calves from primiparous females have a

367 smaller mean length than calves from older females (Best and R  ther, 1992). In our study,
368 the difference in size between calves from multiparous mothers and primiparous mothers
369 was however not statistically significant. It should be considered that our study was
370 conducted at the end of the breeding season, and all calves we observed had an unfurled
371 dorsal fin and were longer on average compared to the mean length at birth (4.3 m;
372 Chittleborough, 1965). This means that the calves have already grown significantly since
373 birth. The difference in size, while likely evident and fragrant at birth, is likely less evident
374 with time as calves may grow throughout the season at different rates depending on various
375 external factors, as seen in pinnipeds (Bowen, 2009). Milk intake by humpback whale calves
376 and the milk production from each mother may for example differ amongst mother-offspring
377 pairs, meaning the postnatal growth rate may vary. Although our sample size was relatively
378 small, our results provide a first assessment of the morphometry of the South Western Indian
379 Ocean's female humpback whales and their calf.

380 In conclusion, we were able to estimate the body measurements of humpback whale mother-
381 calf pairs and to investigate the effect of maternal parity on calf's size using a relatively
382 straightforward photogrammetric method that combined a standard UAV and free, easy-to-
383 access and user-friendly software. Our method was not as precise and as accurate as
384 methods involving more advanced equipment and tools such as drone equipped with acute
385 altimeter (Durban *et al.*, 2015, 2016; Dawson *et al.*, 2017) and paid software (Dawson *et al.*,
386 2017; Burnett *et al.*, 2019). However, we demonstrated that our methods produce convincing
387 morphometric measurements with both satisfactory precision and accuracy. While the level
388 of error limits the suitability of this method for comparing individuals, our methods still have
389 potential applications to study the global morphometric trend of a population. Our methods
390 can be further adapted for studying population structures or for investigating population
391 responses to changing environment as has been done previously (Chittleborough, 1958;
392 Hanks, 1981; Stevens *et al.*, 2000; Perryman and Lynn, 2002). We hope that this study will
393 encourage more teams to study the morphometry of large marine mammals despite

394 limitations in terms of resources. Such studies would especially help in conservation
395 decision-making as it may help identifying environmental issues.

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516 ground at Sainte Marie Channel, Madagascar. *African Journal of Marine Science* 40:
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518 **TABLES AND FIGURES**

519 **Table 1**

520 Non-exhaustive list of photogrammetric approaches used for measuring whales at sea. For
521 Aerial vehicle: (***) expensive, time and resource consuming aerial vehicle. (**)
522 efficient/specialized but expensive aerial vehicle. (*) Low price/standard vehicle. (.) Aerial
523 vehicle not required. For Range measurement tool: (***) Efficient/specialized but expensive
524 tool. (**) Moderate price/standard tool or pre-integrated in the vehicle. For Image
525 measurement tool: (***) highly specialized scientific tool. (**) Paid software/Script available
526 for free but requiring paid software. (*) Free software/Script and software available for free.
527 (a) Based on linear measurements of a known-sized object. (b) Based on linear
528 measurements of individual adult whales. (c) Based on measurements of the surface area of
529 individual whales.

Reference	Aerial vehicle	Type	Range measurement tool	Scale basis	Lens distortion correction	Image measurement tool	CV (%)	Error (%)
Cubbage & Calambokidis (1987)	Airplane (OA) ***	Stereo-photogrammetry	Radar altimeter **	Independent reference object	No	Stereoplotter ***	1.7 (a)	0.5 (a)
Best and R�ther (1992)	Helicopter (OA) ***	Single-camera-photogrammetry	Radar altimeter **	Independent reference object	No	Stereoplotter ***	1.3 (b)	-
Dawson <i>et al.</i> (1995)	(Not required) .	Stereo-photogrammetry	(Not required)	Camera characteristics (obtained from calibration)	No	Stereoplotter ***	4.4 (b)	< 2.5 (a)
Spitz <i>et al.</i> (2000)	(Not required) .	Single-camera-photogrammetry	Sonar **	Camera characteristics (obtained from calibration)	Yes	Adobe Photoshop software (Adobe) **	4.3 (a)	4.6 (a)
Perryman & Lynn (2002)	Airplane (OA) ***	Single-camera-photogrammetry	Radar altimeter **	Camera characteristics (factory specifications)	No	Image Pro Plus (Media Cybernetics) **	2 (b)	1 (a)
Jaquet (2006)	(Not required)	Single-camera-photogrammetry	Laser range finder **	Independent reference object	No	Adobe Photoshop software (Adobe) **	1.3 (b)	0.27 (a)
Fearnbach <i>et al.</i> (2011)	Helicopter (OA) ***	Single-camera-photogrammetry	GPS ***	Camera characteristics (factory specifications)	No	ImageJ software (NIH) *	-	< 3.2 (a)
Miller <i>et al.</i> (2012)	Airplane (OA) ***	Single-camera-photogrammetry	Radar altimeter **	Independent reference object	No	Image Pro Plus (Media Cybernetics) **	1.7 (b)	-

Durban <i>et al.</i> (2015, 2016)	APH-22 hexacopter (UAV) **	Single-camera- photogrammetry	High precision barometer **	Camera characteristics (factory specifications)	No	-	-	< 1 (a)
Christiansen <i>et al.</i> (2016)	Splashdrone quadcopter (UAV) **	Single-camera- photogrammetry	(Not required)	Reference object in the same frame as the target animal	No	Custom-written script in R *	< 12 (c)	-
Dawson <i>et al.</i> (2017)	DJI Inspire Pro (UAV) **	Single-camera- photogrammetry	LIDAR ***	Camera characteristics, (obtained from calibration)	Yes	Custom-written script in MATLAB **	1.2 (b)	1 (a)
Christiansen <i>et al.</i> (2018)	DJI Inspire Pro (UAV) **	Single-camera- photogrammetry	LIDAR ***	Camera characteristics (factory specifications)	No	Custom-written script in R *	0.3 (b)	4.75 (b)
Burnett <i>et al.</i> (2019)	DJI Phantom 3 Pro/4/4 Pro (UAV) *	Single-camera- photogrammetry	Barometer **	Independent reference object	Yes	Custom-written script in MATLAB **	< 5 (b)	-

531 **Table 2**

532 Morphometric measurements of mothers and calves from photogrammetry and reproductive
 533 category of the mothers based on their estimated length. Length corresponds to standard
 534 length, i.e., length from the tip of the snout to the notch of the tail fluke. Width represents the
 535 maximum body width.

Pair ID	Mother			Calf	
	Length (m)	Width (m)	Category	Length (m)	Width (m)
1	12.8	2.9	Multiparous	4.9	0.9
2	14	3.6	Multiparous	4.8	1.1
3	13.1	2.9	Primiparous	4.9	0.9
4	14.7	3.2	Multiparous	7.2	1.5
5	12.7	3.1	Primiparous	4.6	1
6	10.2	2.3	Primiparous	3.6	0.7
7	12.1	3	Primiparous	5	1.1
8	12.1	2.6	Primiparous	4.9	1
9	12.4	2.7	Primiparous	4.6	0.9
10	13.7	3	Multiparous	6.6	1.4
11	12.1	2.8	Primiparous	4.3	1
12	10.7	2.2	Primiparous	4.4	1
13	12.4	2.6	Primiparous	4.9	1
14	11.2	2.7	Primiparous	4.9	1
15	12.6	3	Primiparous	4.6	1
16	11	2.1	Primiparous	5.3	1

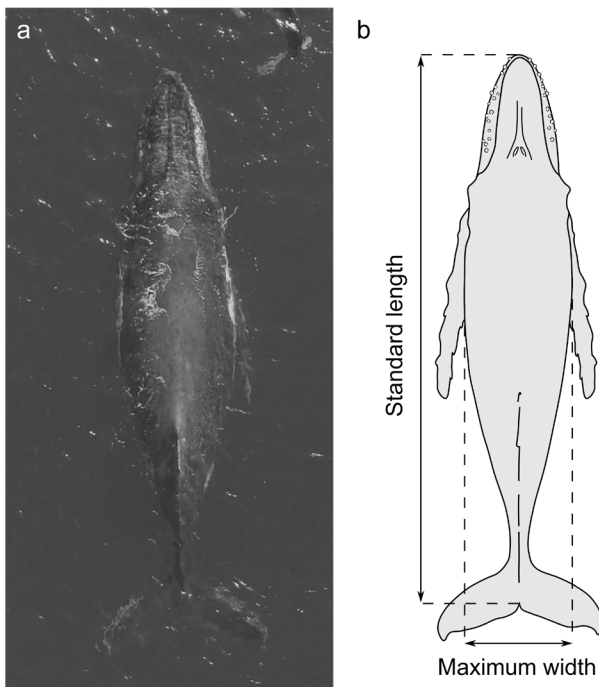
536

537 **Figure 1**

538

539 Figure 1. (a) Example of acceptable aerial photograph of humpback whale extracted from the
540 video recording and used for photogrammetry. The original image was of 4096×2160-pixel
541 but was cropped in this figure to highlight the fixed criteria. The whale must be flat at the
542 surface, dorsal side facing up, emerged as much as possible, static or travelling at relatively
543 slow speed, with a contour not masked by chops and with a non-arching body axis and
544 peduncle. (b) Measurements in pixel recorded for each photograph.

545



546

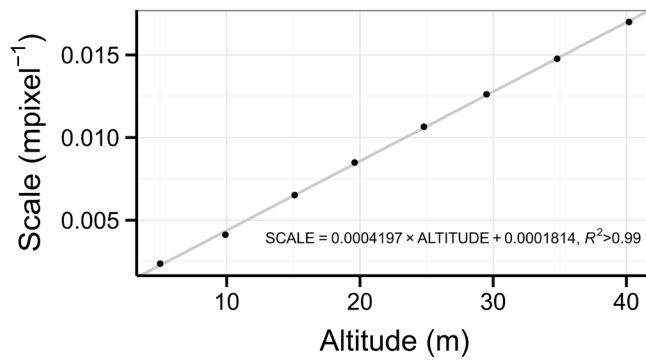
547

548 **Figure 2**

549

550 Figure 2. Relationship between photographic scale and height at which the photos were
551 taken. Multiplied by the number of pixels, the regression equation gives length in meter.

552



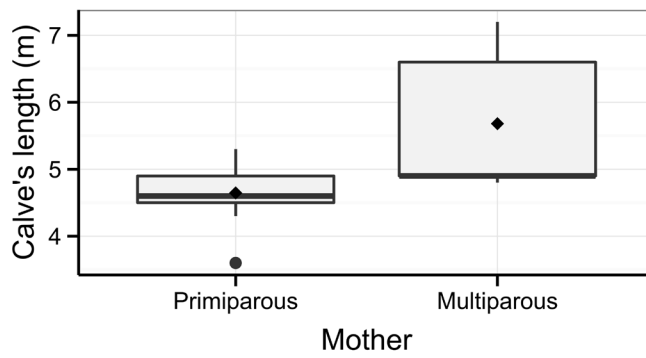
553

554 **Figure 3**

555

556 Figure 3. Calves' estimated standard body length according to the parity of their mother. The
557 bold black lines represent the median and the diamonds represent the mean. The difference
558 found was not statistically significant (Wilcoxon test; $W = 43$ and $p = 0.084$).

559



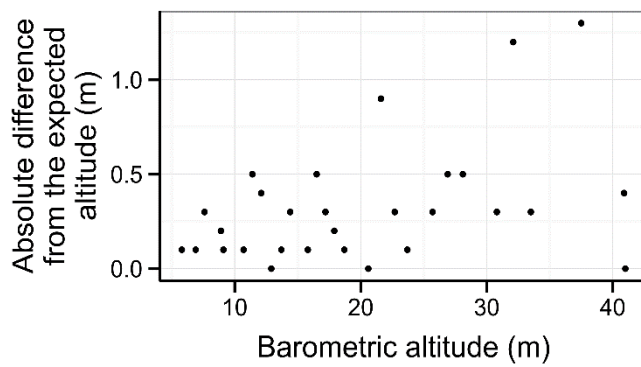
560

561 **Figure 4**

562

563 Figure 4. Barometric altitude reading versus its absolute difference from the expected
564 altitude. The correlation was low and not statistically significant (Spearman's correlation test;
565 $\rho = 0.354$, $S = 2624$ and $p = 0.06$).

566



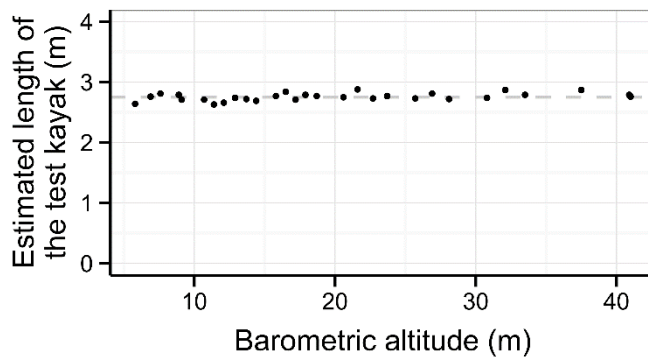
567

568 **Figure 5**

569

570 Figure 5. Repetitive estimation ($N = 29$) of the length of the test kayak at an altitude from
571 5.8 m to 40.9 m. The grey horizontal dashed line indicates the real length of the kayak
572 (2.75 m). The coefficient of variation (CV) of the estimations was of 2.31%.

573



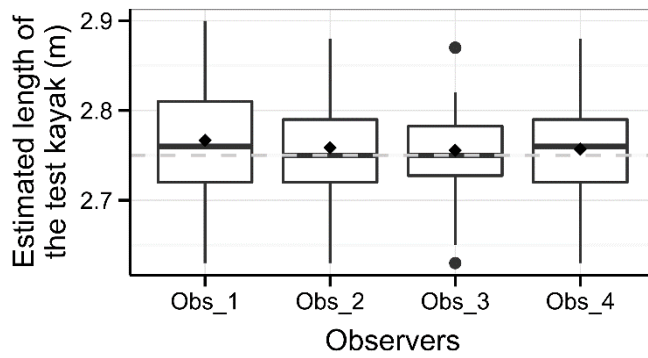
574

575 **Figure 6**

576

577 Figure 6. Repetitive estimation ($N = 29$) of the length of the test kayak compared between
578 four independent observers. The grey horizontal dashed line indicates the real length of the
579 kayak (2.75 m). The difference found was not statistically significant (Kruskal-Wallis test;
580 $\chi^2 = 0.511$, $df = 3$ and $p = 0.916$).

581



582