

Successful observation of orangutans in the wild with thermal-equipped drones

Claire Burke, Maisie F. Rashman, Steven N. Longmore, Owen McAree, Paul Glover-Kapfer, Marc Ancrenaz, and Serge A. Wich

Abstract: We investigated the efficacy of a drone equipped with a thermal camera as a potential survey tool to detect wild Bornean orangutans (*Pongo pygmaeus*) and other tropical primates. Using the thermal camera we successfully detected 41 orangutans and a troop of proboscis monkeys, all of which were confirmed by ground observers. We discuss the potential advantages and limitations of thermal-equipped drones as a tool to complement other methods, and the potential of this technology for use as a future survey tool.

Key words: conservation, UAVs, orangutans, thermal-infrared, sensors.

1. Introduction

1 Knowledge of the distribution and density of animal species and how these change over time is
 2 a key aspect of conservation management and has been achieved by a multitude of ground and aerial
 3 based methods (Buckland et al. 2001, 2004; Franklin 2010; MacKenzie 2006). Ground-based surveys
 4 (of animals or their signs (e.g. nests, as with orangutans)) (Buckland et al. 2001; Laing et al. 2003;
 5 Kühl et al. 2008) are inherently time consuming and can only cover small areas (Ancrenaz et al. 2004).
 6 Aerial surveys conducted by manned aircraft can cover larger areas quickly, but are generally costly,
 7 are constrained by aircraft availability, and are risky (Wich and Koh 2018; Sasse 2003).

8 As an alternative and complementary method to manned aerial surveys conservationists are in-
 9 creasingly using drones to monitor animals (Wich and Koh 2018). Detection of animals with drones in
 10 open areas has been successful for a number of species from a variety of taxa (review in Wich and Koh
 11 2018), with visible-spectrum cameras used in most cases. Being reliant on reflected sunlight, visible
 12 spectrum sensors can only be used during the day, and tend to be ineffective in cases of poor visual

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13 contrast between animals and background, or when animals are located in dense vegetation (Longmore
14 et al. 2017).

15 Thermal infrared (TIR) sensors offer an advantage over visible spectrum sensors as they detect the
16 light emitted from the animals as a result of their body heat directly. Thus they can be used at night
17 and more effectively through vegetation. Previous studies (Wich and Koh 2018; Chrétien et al. 2015,
18 2016; Witzuk et al. 2018; Kays et al. 2018) have shown that TIR cameras can indeed be used this way,
19 however they found that thermal radiation emitted by inanimate background features can confound and
20 inhibit animal detection.

21 We present the results of a pilot study to determine the effectiveness of TIR-equipped drones as
22 a tool to detect and count Bornean orangutans (*Pongo pygmaeus*) and proboscis monkeys (*Nasalis*
23 *larvatus*) in the wild, and investigate whether these species can be differentiated from each other in
24 TIR data. We discuss the advantages and limitations of this technology as a survey tool to complement
25 other methods.

26 2. Method

27 Prior to fieldwork, we developed an observing strategy and rationale to address potential challenges
28 with background temperature and thermal contrast, and determine the minimum apparent size that an
29 animal must appear in the TIR data in order for it to be effectively detected, and hence the maximum
30 drone height above that animal needed to obtain this. Details of the observing strategy and rationale
31 are provided in Appendix A.

32 Flights were conducted using a Tarot X4 drone with a custom gimbal and a dual thermal-visible
33 spectrum camera. The Thermal Capture Fusion Zoom consists of a 640x512 pixel Flir Tau 2 640 core
34 with a 19mm lens and a 1920x1080 pixel TAMRON visible spectrum (RGB) camera affixed side by
35 side (Appendix A.2).

36 We conducted 28 flights between 10-15 May 2018 with drone heights between 80–120 m above
37 ground level (AGL). Flights were performed at two sites: Sepilok Orangutan Rehabilitation Centre
38 (SORC) and the Kinabatangan Orangutan Conservation Project (KOCP) (E 118° 17' 00" to 118° 18'
39 40" - N 5° 32' 20" to 5° 33' 30") (Appendix B).

40 To ensure that we could distinguish the primates from their surroundings, we performed flights
41 before 0900 or after 1900 local time (Appendix A). Researchers with several years of experience ex-
42 amined the TIR data to visually detect the primates (similar to Kays et al. 2018). We determined the
43 robustness of these detections statistically based on the temperature of the entire scene, as detailed in
44 Appendix C.1.

45 To confirm that the objects detected in the TIR data were indeed orangutans or proboscis monkeys
46 we performed ground confirmation for all potential sightings. This was achieved in two ways. First,
47 a field team was deployed to observe the orangutans and to follow individuals until they nested. The
48 drone was flown to the nesting locations and the footage then inspected visually. Second, a blind drone
49 survey was conducted over a larger area using a grid pattern with 30% image overlap between transects.
50 Following visual inspection the GPS location of any potential detections were recorded and confirmed
51 the next morning if an orangutan or a fresh nest was found at the recorded locations. Fresh nests were
52 identified as having green leaves and the smell of urine/faeces (Appendix A.3).

53 During our observations at KOCP, we also conducted four flights over proboscis monkeys, which
54 were observed simultaneously from ground level (Appendix B for flight details).

55 3. Results

56 Examples of TIR data for our primate detections can be found in the online supplementary materi-
57 als, and are shown as still frames in appendix D.

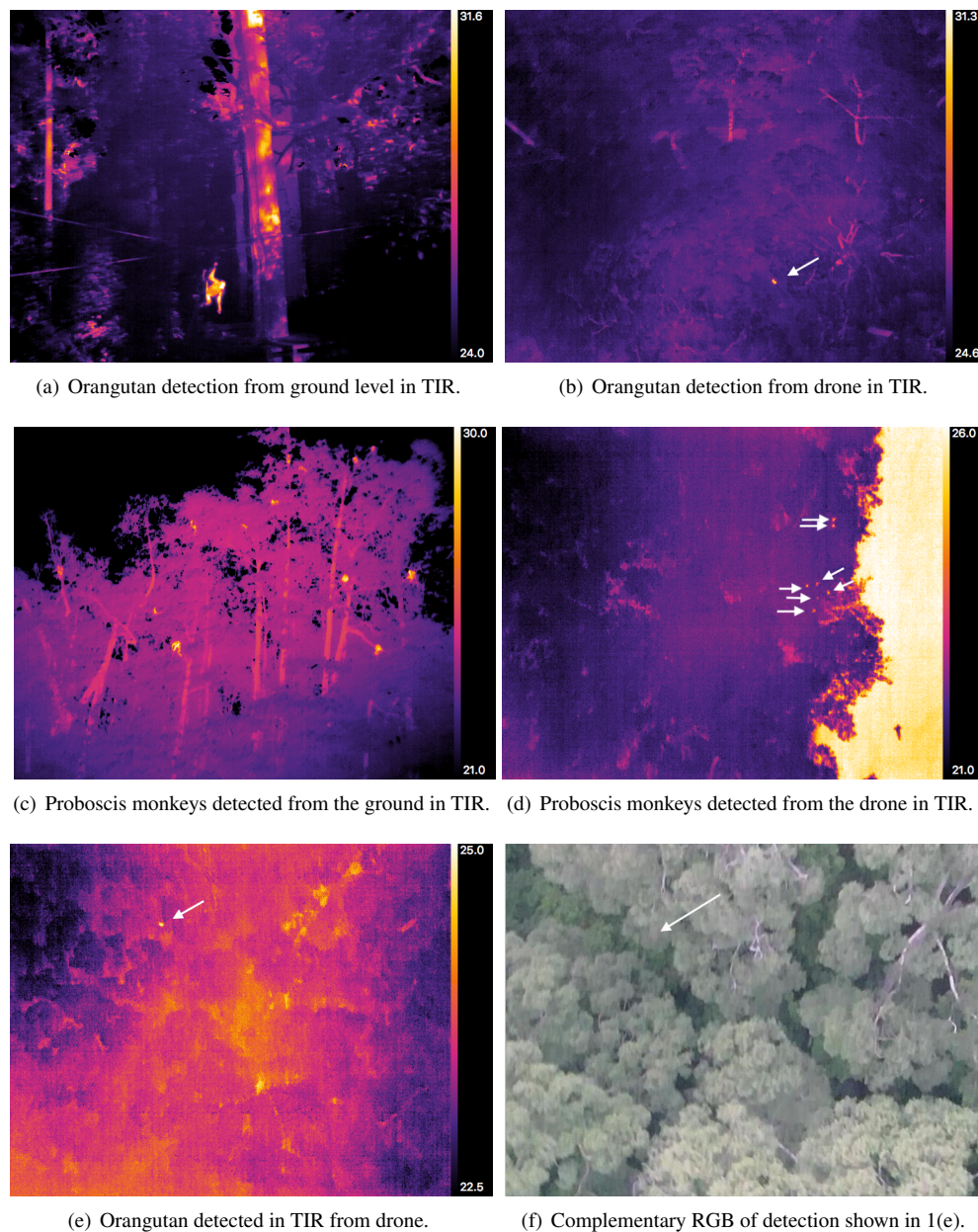


Fig. 1. Example of orangutans and proboscis monkeys observed in the TIR data from the ground and drone. The superior capacity to detect primates in TIR imagery compared to RGB imagery is illustrated in the complementary images of the same orangutan shown in frames 1(e) and 1(f).

58 In total, 28 orangutans that were originally located from the ground were detected in the TIR images
 59 from the drone (see figure 1 for examples) – every orangutan found by the ground team was identified
 60 in the drone data. Thirteen further detections were made with the blind survey flights and subsequently
 61 validated (see table C1 in Appendix B). There were no false positives identified. However, we were

62 unable to determine the number of false negatives in our data as we did not know the true number of
63 individuals present in the area surveyed.

64 During four flights we detected a troop of proboscis monkeys (Figure 1), and counted a total of 11
65 individuals in the group. The troop was also observed from ground level, but the observers were too far
66 away to count numbers with enough reliability to compare with those estimated from the drone data.

67 We compared the temperature distribution of pixels associated with animal detections to that as-
68 sociated with the environment in the same frames. We found that there was a statistically significant
69 separation between the temperatures of the animals and the surroundings, with no overlap in the two
70 temperature distributions. All orangutans and proboscis monkeys had mean temperatures separated
71 by 4–5 standard deviations from the mean temperature of the surroundings. This is equivalent to a
72 99.994% – 99.999% confidence of detection (see Appendix C.1).

73 While relative temperature differences can robustly distinguish orangutan and proboscis monkeys
74 from the background, absolute surface temperatures cannot be used to identify or differentiate different
75 species as animal body temperatures change with that of their environment (McCafferty et al. 2015),
76 as is evident in figure C1. We measured and compared the sizes of the orangutans and proboscis mon-
77 keys (figure C2 in Appendix C.1) and found their average sizes to be distinct, in line with the expected
78 difference in size of these animals. However, there was some overlap in size between the largest pro-
79 boscis monkeys and the smaller orangutans observed, so identification based on size alone is unlikely
80 to be robust. The different behaviour of orangutans and proboscis monkeys, i.e. size of social groups,
81 nesting, is more likely to provide useful information for distinguishing one species from the other. Part
82 of the challenge of species identification is the combination of low resolution cameras with the drone
83 height necessary to avoid trees (in this case). This makes the species of animals detected difficult to
84 discern by eye (discussed in appendix A.1.3).

85 4. Discussion

86 Our results indicate that TIR-equipped drones have potential as a tool for detecting primates in a moist
87 tropical rainforest (in line with Kays et al. 2018). During this study we detected 41 orangutans and a
88 troop of proboscis monkeys using this technology and confirmed all TIR detections from the ground.

89 Using TIR-equipped drones in conjunction with existing survey methods offers several potential
90 advantages. Use of TIR sensors allows surveys to be conducted at times when traditional methods
91 are unusable. Two thirds of our orangutan detections occurred in conditions where the RGB data were
92 unusable and ground surveys would be hindered i.e. at night or during fog. Drones can cover areas more
93 quickly than ground surveys, and at lower cost and risk than manned aircraft. As such, TIR and drone
94 technology together allow animals to be located efficiently for ground follow up and identification.

95 There are a number of factors to consider and challenges when using this technology. In Ap-
96 pendix A.1.3 we calculated a theoretical maximum distance between the drone and animal of inter-
97 est for it to be robustly detected, which is 90m for orangutans and 60m for proboscis monkeys. For
98 ground dwelling species this distance informs the maximum drone flying height. However, for arbo-
99 real species, a major factor affecting drone flying strategy is canopy height. The canopy height was
100 between 30 – 50m and 10 – 30m tall for SORC and KOCP respectively, with numerous emergent trees
101 as tall as 65m and 35m, respectively. In an ideal situation the drone would be flown lower than the
102 calculated maximum height to produce data of sufficient resolution for reliable detection and species
103 identification. However, for many of the flights the drone had to be flown higher to safely avoid the
104 emergent trees. As a result, the projected size (in pixels) of the animals in the data was only sufficient
105 for detection, requiring ground follow-up to verify the species. For species identification without a
106 complementary ground survey, possible detections could be immediately confirmed during flight by
107 halting the drone and reducing its height AGL in order to resolve the animal in more detail, then re-
108 turning to its original height to continue the survey. We are currently developing a fully autonomous
109 on-board system that would allow this procedure to be executed without requiring any intervention by

110 the ground operators, which will be described in a forthcoming paper.

111 Previous studies in areas with dense canopy cover have indicated that vegetation can potentially
112 obscure animals in TIR data (Kays et al. 2018; Chrétien et al. 2016). Eleven out of 41 orangutans
113 detected in this study were in nests with $\geq 50\%$ canopy cover, estimated by looking straight up from
114 the position of the nest. Detection of animals with a high percentage of canopy cover may be possible,
115 as the angle at which an animal is viewed will change as a drone passes over. This allows some of
116 the animal's TIR emission to be observed through gaps in the vegetation. However, if an orangutan
117 is 100% obscured from above at all angles by the canopy then it will not be detected. In this case, as
118 has been noted in other studies (Buckland et al. 2004, 2001), there will be a number of individuals
119 which are missed, and the uncertainty of counts will need to reflect this. As we did not know the true
120 number of orangutans in the areas observed in this study, we were unable to estimate the number of
121 false negatives. A detailed investigation into the detection rate of animals using TIR-equipped drones,
122 and how vegetation and other environmental factors impact the detection rate is needed before this
123 technology can be used as a reliable survey tool.

124 Orangutans occur at low densities, 0.1–4 individuals per km² (Husson et al. 2008). Even with
125 a 100% detection rate, large areas would need to be surveyed to estimate orangutan numbers and
126 distribution. Multi-rotor drones are limited by their short battery life, and a typical maximum flight
127 time of 30 minutes, making them unsuitable for large area surveys. Fixed-wing drones are capable
128 of flying for longer and at higher speeds meaning larger distances can be covered. However, they are
129 limited by the requirement for suitable take-off and landing sites.

130 The necessity for ground-based confirmation of species, as in this study and Kays et al. (2018),
131 remains an unsolved challenge for large area TIR-equipped drone surveys. From our results we suggest
132 that, in its current form, the technology is suitable for surveying species that occur at high densities
133 or range over small areas, where the efficiency of ground surveys will be increased by knowing where
134 animals are located in advance. If an onboard real-time automated detection system such as the one
135 described above could consistently collect sufficiently detailed imagery to confirm primate detections
136 and species, the need for ground validation could be overcome, as well as the requirement for laborious
137 manual analysis of vast extents of imagery over large areas. Given that we have shown that the heat
138 signatures of primates can be robustly distinguished from the background, we believe the data analysis
139 process could indeed be semi-automated, e.g. with machine-learning methods (Longmore et al. 2017;
140 Chrétien et al. 2015, 2016; Lhoest et al. 2015).

141 In conclusion, in this pilot study we have shown that primates can be detected in tropical rainforests
142 using TIR-equipped drones. At present this technology can be used alongside existing methods to
143 increase the efficacy and efficiency of orangutan surveys. From the observations performed in this
144 study it was only possible to distinguish orangutans from proboscis monkeys based on size. Future
145 studies would benefit from a strategy to improve the spatial resolution of the detections.

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References

- Ancrenaz, M., Goossens, B., Gimenez, O., Sawang, A., and Lackman-Ancrenaz, I.: 2004, *Animal Conservation* **7(4)**, 375385
- Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, C. L., and Thomas, L.: 2004, *Advanced Distance Sampling: Estimating Abundance of Biological Populations.*, Oxford University Press.
- Buckland, S. T., Anderson, D. R., and Laake, J. L.: 2001, *Introduction to Distance Sampling*, Oxford University Press.
- Burke, C., Rashman, M., Wich, S., Symons, A., Theron, C., and Longmore, S.: 2018, *International Journal of Remote Sensing* in press
- Chrétien, L.-P., Théau, J., and Menard, P.: 2015, Vol. XL-1/W4
- Chrétien, L.-P., Thau, J., and Menard, P.: 2016, *Wildlife Society Bulletin* **40**, 181
- Franklin, J.: 2010, *Mapping species distributions: spatial inference and prediction*, Cambridge University Press.
- Froehlich, J. W.: 1987, *Journal of Mammalogy* **68(1)**, 200
- Husson, S. J., Wich, S. A., Marshall, A. J., Dennis, R. D., Ancrenaz, M., Brassey, R., Gumal, M., Hearn, A. J., Meijaard, E., Simorangkir, T., and Singleton, I.: 2008, *Orangutans: Geographic Variation in Behavioral Ecology and Conservation*, Oxford Scholarship
- Kays, R., Sheppard, J., Mclean, K., Welch, C., Paunescu, C., Wang, V., Kravit, G., and Crofoot, M.: 2018, *International Journal of Remote Sensing* pp 1–13
- Kühl, H., Maisels, F., Ancrenaz, M., and Williamson, E.: 2008, *Best Practice Guidelines for the Surveys and Monitoring of Great Ape Populations*, Occasional papers of the IUCN Species Survival Commission, World Conservation Union (IUCN) in collab. with the Center for Applied Biodiversity Science
- Laing, S. E., Buckland, S. T., Burn, R. W., Lambie, D., and Amphlett, A.: 2003, *Journal of Applied Ecology* **40**, 1102
- Lhoest, S., Linchant, J., Quevauvillers, S., Vermeulen, C., and Lejeune, P.: 2015, *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*
- Longmore, S. N., Collins, R. P., Pfeifer, S., Fox, S. E., Mulero-Pazmany, M., Bezombes, F., Goodwin, A., de Juan Ovelar, M., Knapen, J. H., and Wich, S. A.: 2017, *International Journal of Remote Sensing* **38**, 2623
- MacKenzie, D.: 2006, *Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence*, Academic Press.
- McCafferty, D. J., Gallon, S., and Nord, A.: 2015, *Animal Biotelemetry* **3(1)**, 33
- Mittermeier, R. A., Rylands, A. B., and Wilson, D. E.: 2013, *Handbook of the Mammals of the World - Volume 3: Primates*, Lynx Edicions
- Sasse, D. B.: 2003, *Wildlife Society Bulletin* **31(4)**, 1015

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7

Wich, S. and Koh, L.: 2018, *Conservation Drones*, Oxford University Press.

Witczuk, J., Pagacz, S., Zmarz, A., and Cypel, M.: 2018, *International Journal of Remote Sensing* **39**, 55035520

154 A. Detailed Methodology

155 A.1. Observing Rationale

156 Prior to all flights in this study, we developed an optimised strategy for observing orangutans and
 157 proboscis monkeys following the methods described in Burke et al. 2018.

158 A.1.1. Flying Times

159 Successful detection of an object relies on it being distinguishable from its surroundings. In the
 160 case of TIR data the distinguishing factor is high thermal contrast - i.e. a large temperature difference
 161 between objects of interest and their surrounding environment. To assess the likely thermal contrast
 162 between orangutan for our pilot study, we generated a land surface temperature climatology for Sabah
 163 during mid-May, Figure A1. The diurnal range for the land surface temperature at this time of year is
 164 between 22 – 33°C. Assuming animals have a fixed temperature, maximum thermal contrast is most
 165 likely when the ground is at its minimum temperature. Assuming orangutans have surface temperatures
 166 of $\sim 25^\circ$ (see figure 1), observations are most likely to provide successful detections before 09.00 or
 167 after 19.00 local time (this is consistent with the findings of Kays et al. 2018).

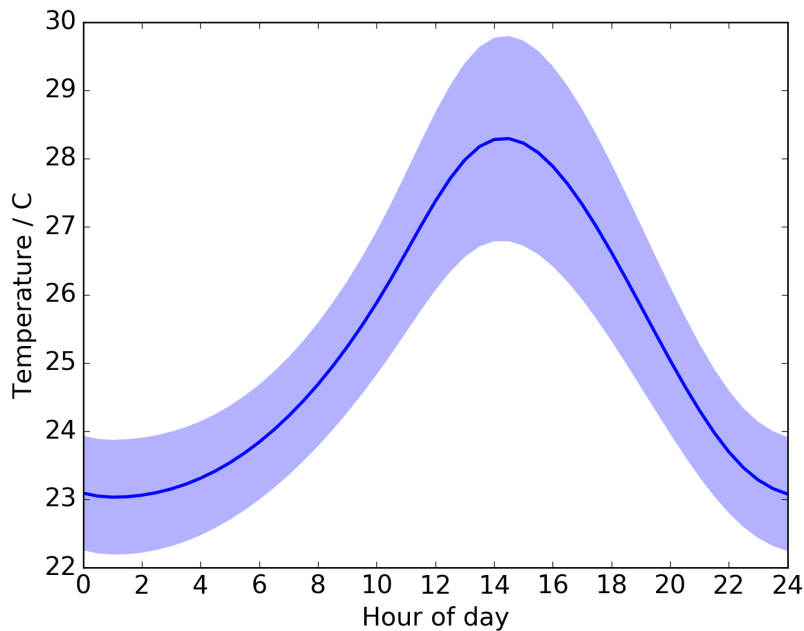


Fig. A1. The average land-surface temperature climatology of a day in mid-May in Sepilok, Sabah, constructed from historical climate observations as described in Burke et al. 2018. The thick line indicates the climatological mean and the shading shows the 2-sigma variation of observed land surface temperature at the Sepilok site.

168 A.1.2. Weather Conditions

169 The molecules which make up the atmosphere, like all objects, have an intrinsic temperature. That
 170 temperature varies from day-to-day and is often different from the ground temperature. As such the
 171 absorption and re-emission of TIR photons by the atmosphere affects the recorded temperature from
 172 objects viewed from a distance. Additionally, water vapor is a strong absorber of thermal infrared
 173 radiation. It could be expected that the typically humid environment of the Bornean rainforest will
 174 affect TIR observations.

175 Following Burke et al. 2018 we generated absorption spectra for typical weather conditions (tem-
 176 perature, pressure and humidity) in the region, and converted this to a predicted temperature change
 177 with distance - Fig A2. From this figure it is clear that for an object with surface temperature 25°C
 178 the effect of atmospheric absorption and emission is minimal at flight heights of 120m or lower, and
 179 should not significantly impact TIR data collected in this study.

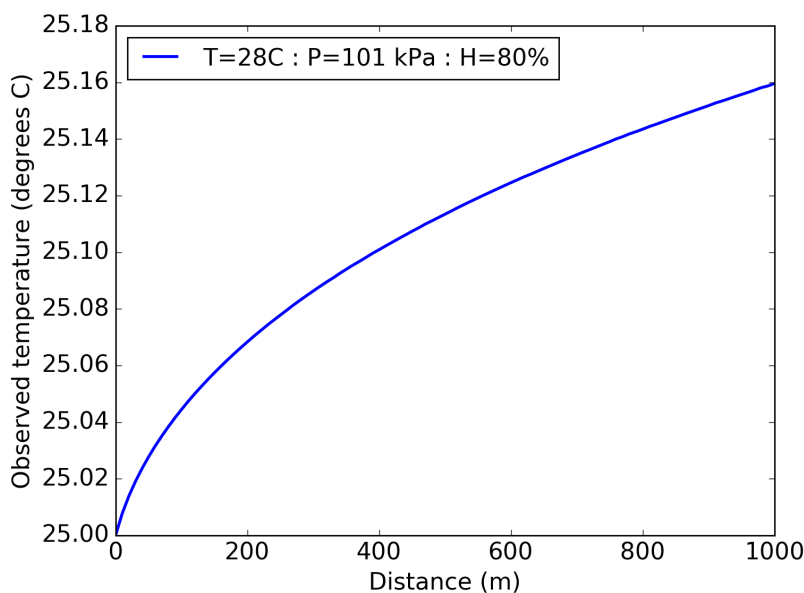


Fig. A2. The temperature which would be observed for an object of 25°C as a result of the typical 28°C air temperature, 80% humidity and 1010hPa pressure expected during May in Sabah. The expected temperature different is negligible.

180 *A.1.3. Flying Height*

181 Given the limited resolution of TIR cameras (640×512 pixels with field of view 32×26° in this
 182 case), it is often the case that an individual pixel will contain TIR emission from more than one object.
 183 In this study we are concerned about distinguishing between animals and the background. In this case
 184 the temperature measured for a single pixel in the TIR camera is a ‘blend’ of the temperatures of the
 185 animal and background imaged within the pixel. As a consequence of this, if the apparent size of an
 186 animal is sufficiently small in the field of view (FOV) of the camera, then the temperature of the pixels
 187 containing that animal can be significantly different from its true temperature - this is known as the
 188 ‘spot size effect’. As is shown in Burke et al. (2018), to minimise this effect, the animal of interest
 189 must be a minimum of 10 pixels in diameter when viewed by the TIR camera.

190 This 10 pixel minimum size can be used to set the maximum distance between object of in-
 191 terest and drone by simple geometric relations (see Burke et al. (2018)). Using this we calculated
 192 the drone-mounted TIR camera must be flown no higher than ~ 90m above an orangutan, assum-
 193 ing that adult Bornean orangutans are approximately 1.1m in length (Mittermeier et al. 2013). For
 194 proboscis monkeys, assuming adults are approximately 0.7m in length (Froehlich 1987), the maxi-
 195 mum flying height is ~ 60m (these values can be calculated using the Drone Observing Tool, http://www.astro.ljmu.ac.uk/~aricburk/uav_calc/).
 196

197 A.2. Equipment and Setup

198 The TeAx Fusion Zoom contains both TIR and RGB (visible spectrum) cameras. The FOV of the
 199 RGB and TIR cameras are centered at approximately the same point, with the FOV of the optical cam-
 200 era $\sim 2x$ larger. Any offset between images from these components can be aligned in post processing.
 201 We used a custom built gimbal to decouple the motion of the camera from that of the drone in order
 202 to provide a stable platform for data collection. High frequency oscillations are dampened by isolating
 203 the entire gimbal mechanism from the airframe by means of a tuned rubber mount. Low frequency
 204 dynamics are compensated in both the roll and pitch axis by the presence of a closed-loop brushless
 205 stabilisation mechanism which maintains the camera at a constant attitude, independent of the motion
 206 of the airframe.

207 A.3. Flight Strategy

208 As described above, maximum surface temperatures occur during the day and minimum tempera-
 209 tures at night, making night the preferable observing time for maximum thermal contrast. Due to the
 210 need to be able to see the drone for take-off and landing, it was not possible to fly the drone in full
 211 darkness, so we performed our flights as close to sunrise ($\sim 06:00$) and sunset ($\sim 18:00$) as possible.
 212 Having some amount of sunlight also meant we were able to gather data with the RGB camera.

213 Whilst our maximum flying height was set by the calculation described above, in reality other
 214 environmental factors influenced our decision on maximum flying height (see section 4). Flights were
 215 performed at heights above ground level (AGL) between 30 – 120m depending on the conditions
 216 discussed above. For most flights the camera was pointed straight down during the survey period (90° ,
 217 nadir position). However, for some flights the camera angle was changed between 45° and 90° during
 218 the flight to examine how camera angle affected detectability of animals. Upon visual examination
 219 of the TIR data, it was quickly apparent that flying with the camera at 90° made it much easier to
 220 detect the orangutans, and no animals were in fact detected with the camera pointed at 45° . All results
 221 presented are for the camera pointed at 90° .

222 The flight pattern selected – grid, line or freestyle – depended on the distance to, and visibility of,
 223 the location being surveyed from the take-off site. In general, if the pilot had a line-of-sight view of the
 224 GPS position where an orangutan had been seen from the ground, then they flew manually. At larger
 225 distances and/or with no direct line-of-sight, the flight was automated following take-off (described
 226 in appendix B, also see Table B1). Orangutan nesting sites which were identified during the evening
 227 were also surveyed the following morning using the same flight pattern. In SORC orangutan nests were
 228 found by following individuals as they left the feeding platform in the rehabilitation centre. In KOC
 229 the Hutan Orangutan field team were observing orangutans as part of ongoing research, and located
 230 known individuals and followed these until they nested. The GPS location of nesting sites was recorded
 231 and the drone flown to that location. Where distances between the launch site and the nest site were
 232 large ($> 500m$) the drone was flown at a higher height AGL to account for possible changes in terrain
 233 height and to give a wider FOV for the camera. As a result, for a small number of flights, the flying
 234 height was in the range 80 – 120m.

235 B. Detailed flight information

236 Table B1 describes the details of each flight conducted. Each flight was labelled with a unique Flight
 237 ID in the format YYYYMMDD_hhmm. For most flights the height was constant, a small number of
 238 flights had varying height and are denoted with an asterisk (*). The majority of flights were conducted
 239 at 3 m/s speed, where this value differs it is noted in the table. All recorded values denote the lowest
 240 speed travelled during the flight, occasionally a higher speed was used in order to reach the site to be
 241 surveyed, and subsequently the speed was decreased whilst covering the area of interest. We surveyed

242 the nesting sites using 3 different flight patterns; a straight line, a grid (with minimum overlap between
243 transects of 30% of the total FOV) or freestyle, where the pilot manually flew within the line of sight.

244 Because air temperature, humidity, pressure and wind speed are all environmental conditions which
245 have the potential to affect data quality, we recorded these at ground level with a handheld Kestrel 5500
246 Weather Meter prior to each flight, Table B2. Temperature, pressure and humidity are not expected to
247 vary significantly over the range of 0-100 m above ground, and small changes in these are not expected
248 to affect data quality as shown in figure A2. The only variable we expect to change noticeably is wind
249 speed. However, this should only have an impact on the stability of the drone and not temperature
250 values recorded.

251 C. Detailed Results

252 Table C1 summarised the details of the orangutan detections. Where available, we include infor-
253 mation about the canopy coverage and nest height. Knowing the height of both the drone and the nest
254 increases the confidence of detections as we can verify whether the relative size (in pixels) of the ob-
255 ject detected falls within the expected size range of orangutans at that height. These quantities were
256 estimated by eye from directly below the nest on the ground, but were not recorded for all ground
257 confirmations. Nest heights were estimated to be between 8 to 20+ m AGL. Since orangutans nest and
258 travel through canopy at varying heights from the ground we believe that the orangutans were closer
259 to the drone than the minimum distance of 90m for most of our flights, and this is supported by the
260 observed nest heights. All potential detections in the TIR data corresponded to the confirmed location
261 of orangutans and/or nests; we directly observed 28 orangutans, and 10 recently vacated nests.

262 In cases where the drone was flown above 100m AGL, it became noticeably more difficult to
263 detect orangutans. For example, Flight 20180514_1830 (Table C2) was conducted at 120m to survey
264 a large area beyond the visible line of sight of the drone pilot. A mother and infant pair of orangutans
265 had previously been detected and confirmed at this site in flights 20180513_1859, 20180514_0543 and
266 20180514_0612 (see table C2). One detection was made from the TIR data from flight 20180514_1830,
267 which was verified from the ground the following morning as a recently vacated nest less than 20m
268 above ground level. However, it was noted that the height made the warm spots indicating the presence
269 of an animal particularly difficult to discern. This observation is in line with the expected result of the
270 spot size affect (see A.1.3), and supports the use of a minimum flying height of a drone for observing
271 any animal of interest in order to secure reasonable detections. A minimum height limitation will
272 likely prove challenging for large-area surveys, especially over canopy of unknown topography. For a
273 large area survey, this may be partially circumvented by carrying out a topographical canopy mapping
274 survey beforehand, which will allow drone height to follow that of the canopy for a TIR-equipped
275 drone survey.

276 Table C2 contains a brief summary of the flights conducted to observe Proboscis Monkeys.

277 C.1. Statistical differentiation of species based on temperature and sizes

278 For all frames containing orangutans we constructed histograms of the temperature of pixels con-
279 taining orangutans and all other pixels within the frame. The orangutan pixels were identified by an
280 algorithm using a temperature threshold. The threshold was set based on the height of the drone AGL,
281 and corresponding expected size of the orangutans in the data. Using an upper limit on the expected
282 size of 1.5 meters, we calculated the percentage of pixels in the FOV that this would cover. This per-
283 centage was then used as the percentile threshold for orangutan detection, i.e. the top N% of pixels in
284 the frame were counted as orangutan (or other animal) pixels. The orangutan pixels were then visually
285 confirmed for each frame. The remaining pixels make up the background or surrounding temperature.
286 The temperatures of each pixel extracted this way are shown in figure C1. The same pixels were used
287 to measure the sizes of the orangutans. This was also carried out for data from one flight contain-

Table B1. The details of flights conducted. Launch Site contains information on launch location where Sepilok Orangutan Rehabilitation Centre (SORC) is site A and the lower Kinabatangan-Segama Wetland (KOCP) site is site B. Flying height indicates the maximum height AGL for each flight with a standard error of ± 1 metres. Where flying height was varied this is denoted with an asterisk (*). Flying speed indicated is the minimum for the flight, the estimated uncertainty on this is ± 0.1 m/s. Camera angle of 90° denotes the camera pointed straight down (nadir pointing), a forwards slash (/) between two values refers to a change in angle during the flight. Launch times are in local time (Malaysian, MYT). Flight durations were recorded with an accuracy of 0.5 mins. Blue coloured rows highlight flights that were conducted to survey and image proboscis monkeys.

Flight ID (YYYYMMDD_hhmm)	Date (dd/mm/yy)	Launch site	Flying height (m)	Flying speed (m/s)	Camera angle ($^\circ$)	Launch time	Flight duration (mins)	Flight pattern
20180510_0613	10/05/18	A1	80	-	90	06:13	9	Straight Line
20180510_0622	10/05/18	A1	120	-	90	06:22	7	Straight Line
20180510_0717	10/05/18	A1	120	7	90	07:17	9	Grid
20180510_1824	10/05/18	A2	20*	-	45/90	18:24	11	Freestyle
20180510_1903	10/05/18	A2	120	-	90	19:03	13	Straight Line
20180511_0521	11/05/18	A2	70*	-	45/90	05:21	16	Freestyle
20180511_0528	11/05/18	A1	120	-	90	05:28	5	Straight Line
20180511_0535	11/05/18	A1	100	5	90	05:35	8	Grid
20180511_1744	11/05/18	A1	30*	-	45/90	17:44	4	Freestyle
20180511_1750	11/05/18	A1	30*	-	45/90	17:50	3	Freestyle
20180511_1804	11/05/18	A1	100	1	90	18:04	4	Straight Line
20180511_1830	11/05/18	A1	100	5	90	18:30	10	Grid
20180512_0521	12/05/18	A1	100	-	45/90	05:21	10	Grid
20180512_0541	12/05/18	A1	100	-	45	05:41	10	Grid
20180512_0617	12/05/18	A1	100	1	90	06:17	4	Straight Line
20180512_1804	12/05/18	A1	100	-	90	18:04	12	Freestyle
20180512_1840	12/05/18	A1	76	-	90	18:40	9	Freestyle
20180513_1828	13/05/18	B	80	-	90	18:28	10	Freestyle
20180513_1859	13/05/18	B	80	5	90	18:59	11	Grid
20180514_0543	14/05/18	B	80	5	90	05:43	12	Grid
20180514_0612	14/05/18	B	80	5	45	06:12	12	Grid
20180514_1830	14/05/18	B	120	6	90	18:30	12	Grid
20180514_2020	14/05/18	-	150*	-	45/90	20:20	14	Freestyle
20180515_0512	15/05/18	B	120	6	90	05:12	12	Grid
20180515_0539	15/05/18	B	120	6	90	05:39	4	Grid
20180515_0543	15/05/18	B	100	6	90	05:43	2	Grid
20180515_0545	15/05/18	B	80	6	90	05:45	3	Grid
20180515_0548	15/05/18	B	60	6	90	05:48	5	Grid

288 ing proboscis monkeys. The histogram of proboscis monkey temperatures is shown in figure C2. A
289 comparison of the sizes of orangutans and proboscis monkeys is shown in figure C2.

290 For all orangutans and proboscis monkeys there is a distinct gap between their temperature and that
291 of the background. The difference between the mean of each distribution was between 4 and 5 standard

Table B2. The weather data recorded at ground level with a handheld Kestrel 5500 Weather Meter for each flight. Blue coloured rows highlight any flights that were conducted to observe proboscis monkeys. All quoted errors were obtained from the Kestrel 5 series certificate of conformity.

Flight ID	Air temperature (± 0.4 °C)	Humidity ($\pm 1.0\%$)	Pressure (± 0.3 hPa)	Wind Speed (± 1.66 km/h)
20180510_0613	26.4	83.4	1011.2	1.0
20180510_0622	26.4	83.4	1011.2	1.0
20180510_0717	26.8	80.4	1011.5	2.8
20180510_1824	30.7	76.5	1008.3	0.0
20180510_1903	27.9	89.2	1009.2	0.0
20180511_0521	26.2	83.5	1008.9	1.5
20180511_0528	26.9	85.0	1009.0	0.0
20180511_0535	28.0	82.0	1010.0	0.0
20180511_1744	31.8	73.1	1007.0	0.0
20180511_1750	30.5	75.7	1007.0	0.0
20180511_1804	30.5	75.7	1007.0	0.0
20180511_1830	29.3	84.2	1007.0	0.0
20180512_0521	26.2	79.6	1008.7	0.0
20180512_0541	27.2	88.3	1009.8	0.0
20180512_0617	27.9	84.3	1009.2	0.0
20180512_1804	29.6	85.0	1007.4	1.3
20180512_1840	30.3	74.3	1008.2	1.1
20180513_1828	30.1	75.5	1011.15	1.0
20180513_1859	29.9	79.5	1011.15	1.0
20180514_0543	24.9	82.3	1011.15	1.0
20180514_0612	25.4	90.1	1011.15	1.0
20180514_1830	30.0	81.2	1011.15	1.0
20180514_2020	27.6	81.8	1011.15	1.0
20180515_0512	25.0	84.9	1011.15	1.0
20180515_0539	92.8	83.4	1011.15	1.0
20180515_0543	92.8	83.4	1011.15	1.0
20180515_0545	92.8	83.4	1011.15	1.0
20180515_0548	92.8	83.4	1011.15	1.0

292 deviations for every orangutan or monkey - equivalent to 99.994% 99.999% confidence of detection.

293 For the histograms shown in fig C1, two were constructed from morning flights and two were
 294 from evening flights. As would be expected from day to day variation in weather and conditions, the
 295 temperatures of the background differ between flights performed at the same time of day over the
 296 same general area but on different days, and the animals vary their temperature accordingly with the
 297 surroundings. As is evident in these figures it is not possible to use absolute temperature for species
 298 classification. As is also clear, the shape of distributions changes between flights, times of day, and
 299 individuals. From this we conclude that there is not enough consistency between the shape of the

Table C1. Summary of confirmed orangutan sightings from the drone. Orangutan nest heights and canopy cover above the nests are indicated where recorded. The sightings were either orangutans present in their nest, a recently built but vacant nest, or a direct observation of an orangutan not nesting.

Flight ID	Number of detections	Drone height (m)	Nest Height (\pm 2m)	Canopy coverage (%)	Sighting type
Flights at site A					
20180510-0717	1	120	-	-	Nesting orangutan
20180510-1824	1	20	8	75-100	Nesting orangutan
20180510-1903	2	120	-	75-100	2 New nests
20180511-0521	1	70	8	75-100	Nesting orangutan
20180511-0528	1	120	-	75-100	New nest
20180511-0535	2	100	-	-	2 Nesting orangutan
20180511-1744	6	30	-	-	Orangutans observed directly
20180511-1750	6	30	-	-	Orangutans observed directly
20180511-1804	1	100	12	-	New nest
20180511-1830	2	100	-	-	2 Nesting orangutan
	3		-	-	3 Orangutans observed directly
20180512-0521	2	100	> 20	0	New nest
			> 20	75	New nest
20180512-0541	2	100	> 20	0	New nest
			> 20	75-100	New nest
20180512-0617	2	100	20	75-100	Nesting mother and infant pair
			< 20	50-75	New nest
20180512-1804	3	100	-	-	Moving orangutan
			-	-	Nesting orangutan
			12	0	Nesting orangutan
20180512-1840	1	76	12	0	Nesting orangutan
Flights at site B					
20180513-1859	1	80	< 20	75-100	Nesting mother and infant pair
20180514-0543	1	80	< 20	75-100	Mother and infant pair
20180514-0612	1	80	< 20	75-100	Mother and infant pair
20180514-1830	1	120	< 20	-	New nest
20180515-0512	1	120	-	-	Mother and infant pair
Total detections	41				

300 temperature distributions for orangutans to use it to classify a species from this data. There is also not
 301 enough difference between the temperature distribution shapes of orangutans and proboscis monkeys
 302 to use this information to tell them apart.

303 There is a clear difference between the distribution of sizes of the proboscis monkeys and the
 304 orangutans. Whilst a small proportion of the proboscis monkey population does overlap with the
 305 orangutan distribution, generally the two are distinguishable. Since proboscis monkeys are generally
 306 found in groups, whereas orangutans tend to be solitary or in pairs, the combination of size and num-
 307 ber of animals seen could be used to distinguish the two. More data and statistical analysis would be
 308 needed to understand the possible misclassification rate using this method.

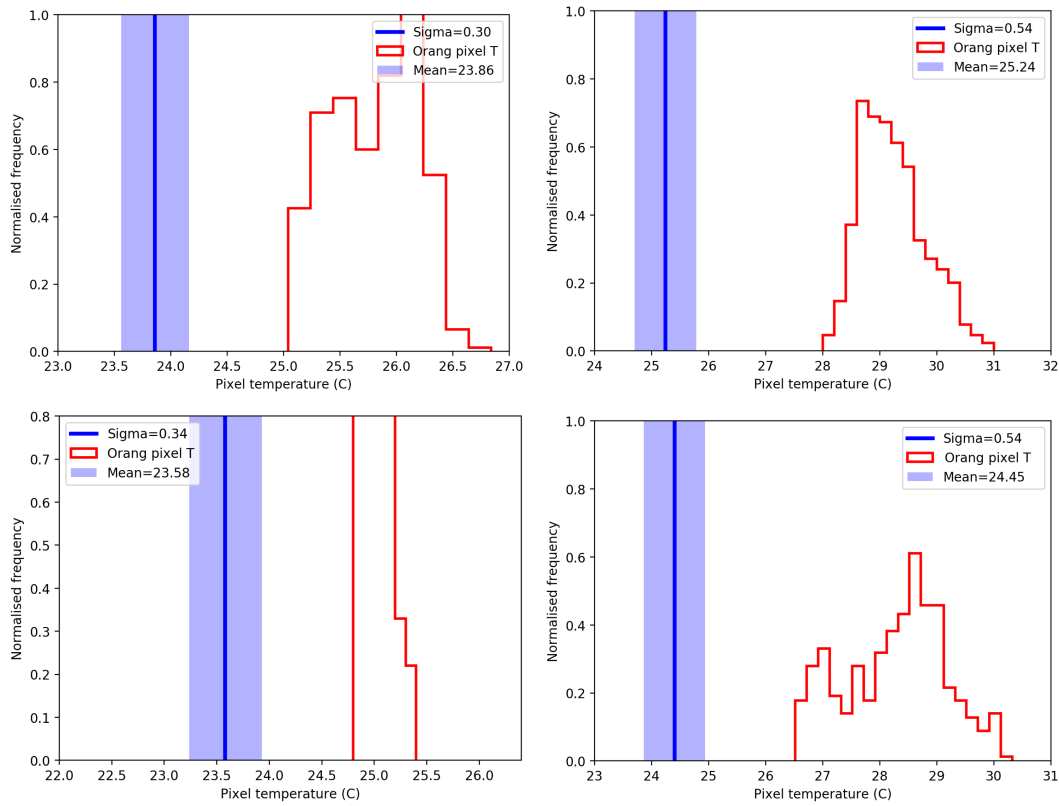


Fig. C1. Examples of temperature distributions of orangutans and their surroundings for 4 flights. Blue line and shading indicates the mean and standard deviation of background pixels respectively. Red histogram indicates the temperature of orangutan pixels. Flight IDs from top left to bottom right: 20180511_0528, 20180511_1830, 20180511_0535, 20180510_1903.

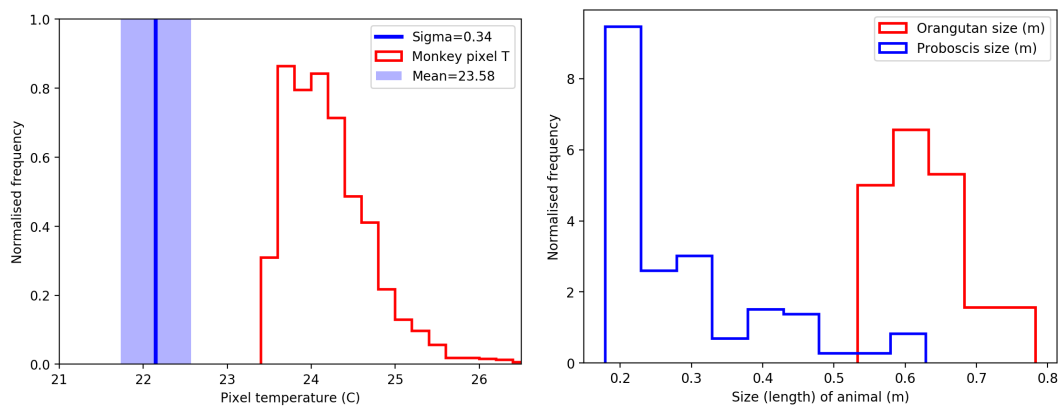


Fig. C2. [Left] Temperature distributions of proboscis monkeys and their surroundings for 1 flight. Blue line and shading indicate the mean and standard deviation of background pixels. Red histogram indicates the temperature of monkey pixels. [Right] Size comparison of orangutans [red] and proboscis monkeys [blue] when viewed from TIR drone images. Flight ID for proboscis monkeys: 20180515_0539.

Table C2. Summary of confirmed proboscis monkey sightings from the drone.

Flight ID	Height	Flight pattern
20180515_0539	120	Grid
20180515_0543	100	Grid
20180515_0545	80	Grid
20180515_0548	60	Grid

309 C.2. Optical vs thermal infrared detection

310 Endothermic homeotherms emit most of their energy in the TIR wavelength range (Wein's law).
 311 Consequently, animals such as orangutans shine brightly in TIR data, and are particularly visible when
 312 their surface temperature is warmer than that of the environment. This is evident in all of our drone
 313 observations, where the animals appear as bright objects in the thermal data and are indistinguishable
 314 in the RGB (see figures D6–D8 for an example of this).

315 Being a seasoned observer of orangutans, S.W. attempted to identify orangutans from the optical
 316 footage obtained from the drone. This was done in a blind manner, with S.W. having no prior knowl-
 317 edge of where the orangutans had been seen on the ground or in the thermal footage. S.W. found that
 318 it was impossible to detect the orangutans with the optical data.

319 The TIR was also advantageous in conditions where RGB data was unusable - i.e. at night or during
 320 fog. In these conditions it would also be difficult or impossible to see the animals from the ground.
 321 Figure D23 shows an example of data taken during fog when the optical visibility was estimated by
 322 eye from the ground to be only 20m. In this case the orangutans were still clearly visible in the TIR
 323 data.

324 The majority of our 41 TIR orangutan detections came from imaging orangutans in their nests.
 325 Orangutans are relatively easy to spot from the ground at this time as they are relatively stationary
 326 compared to their active periods during day when they can move quickly through the trees making
 327 them particularly difficult to follow on the ground. However nesting times for orangutans are generally
 328 when it is dark and they are very difficult to see with an RGB camera or from the ground. Overall we
 329 found that TIR extends the times and conditions during which surveys or observations can be conducted
 330 into times when optical cameras are unusable and reduced visibility makes ground surveys unsafe. This
 331 also makes it possible to increase the detection confidence by observing the same individual nesting in
 332 the evening and early the next morning before the nest is vacated.

333 D. Examples of all primate detections

334 D.1. SORC Detections

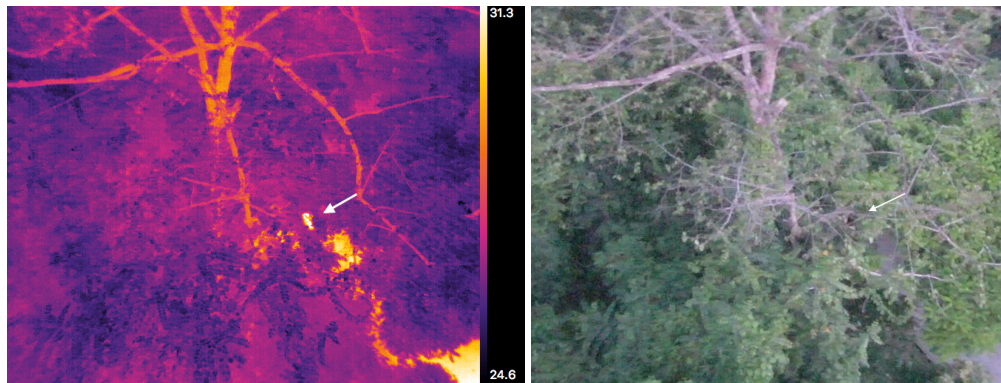


Fig. D1. Confirmed nesting Orangutan detection in Flight 20180510_1824 with camera at 45° in (L) thermal and (R) RGB. Flying height was 20m and canopy coverage was estimated at 75-100%.

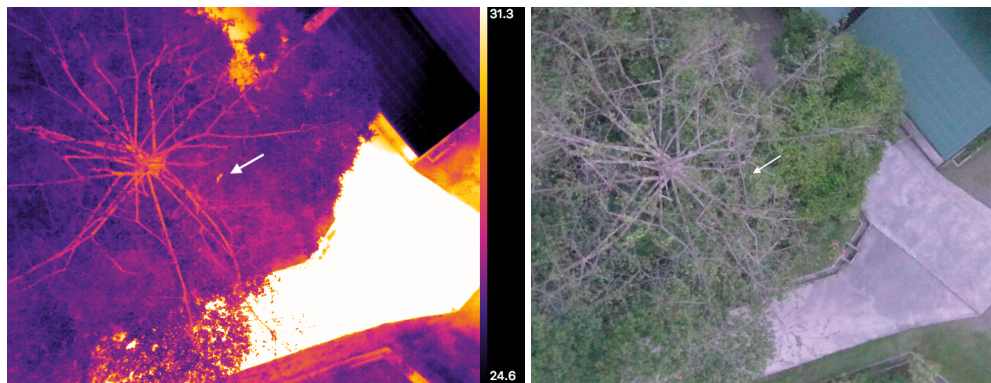


Fig. D2. Confirmed nesting Orangutan detection in Flight 20180510_1824 with camera at 90° in (L) thermal and (R) RGB. Flying height was 20m and canopy coverage was estimated at 75-100%.

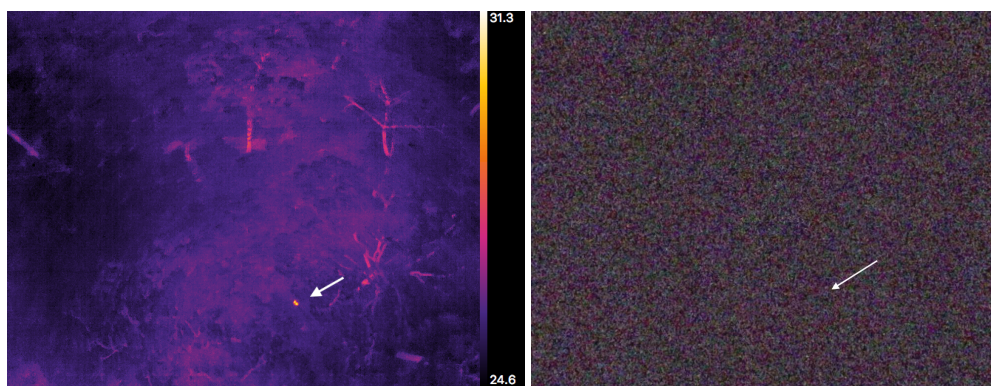


Fig. D3. Confirmed orangutan nest detection in Flight 20180510_1903 in (L) thermal and (R) RGB. Flying height was 120m and canopy coverage was estimated at 75-100%.

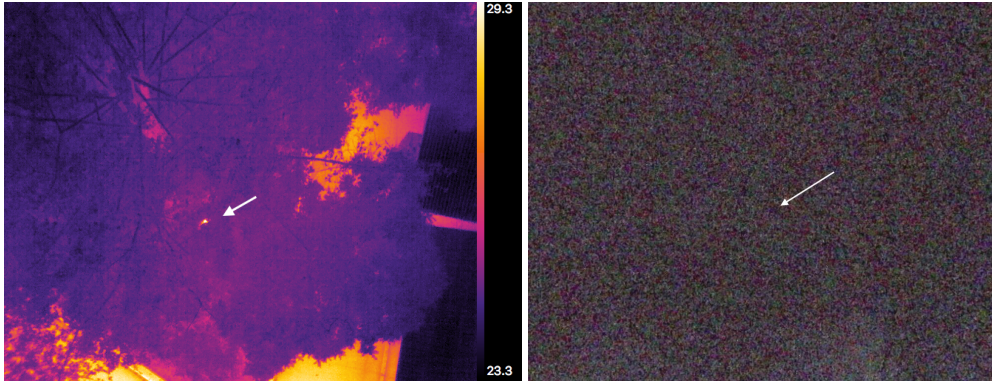


Fig. D4. Confirmed orangutan nest detection in Flight 20180511_0521 in (L) thermal and (R) RGB. Flying height was 70m and canopy coverage was estimated at 75-100%.

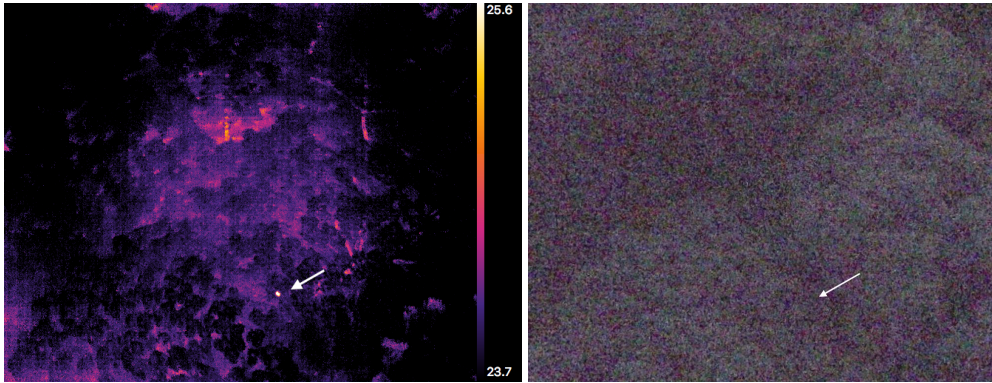


Fig. D5. Confirmed orangutan nest detection in Flight 20180511_0528 in (L) thermal and (R) RGB. Flying height was 120m and canopy coverage was estimated at 75-100%.

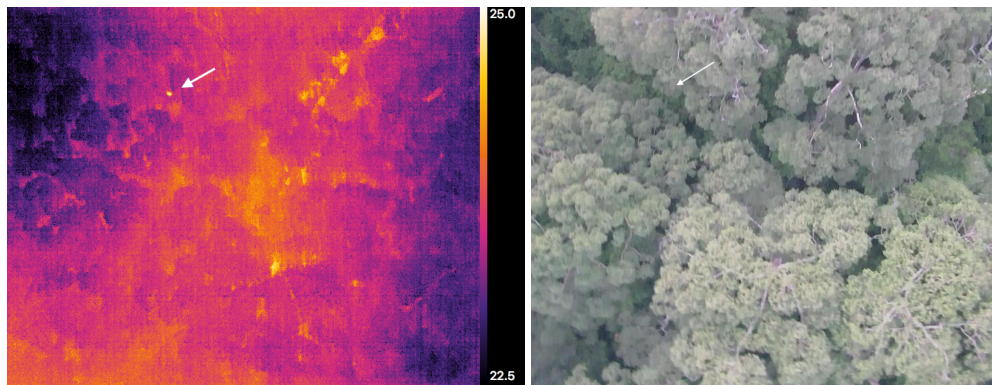


Fig. D6. Confirmed orangutan nest detection in Flight 20180511_0535 in (left) thermal and (right) RGB. Location of orangutan is indicated with an arrow in both images. Flying height was 100m.

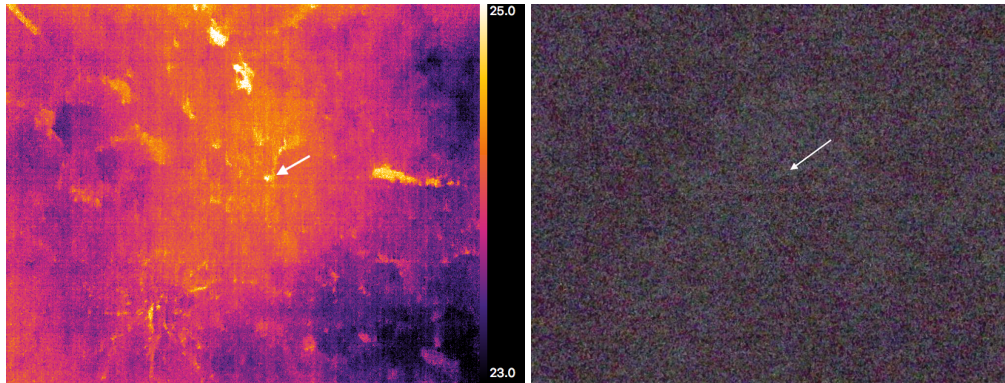


Fig. D7. An example of data from flight 20180512.0521, containing a confirmed detection of a mother and infant orangutan nesting together. Left: TIR image, Right: RGB image. Location of orangutans is indicated with an arrow in both images. This flight was performed just after dawn, making visibility difficult with the RGB. Flying height was 100m and canopy coverage was estimated at 75%.

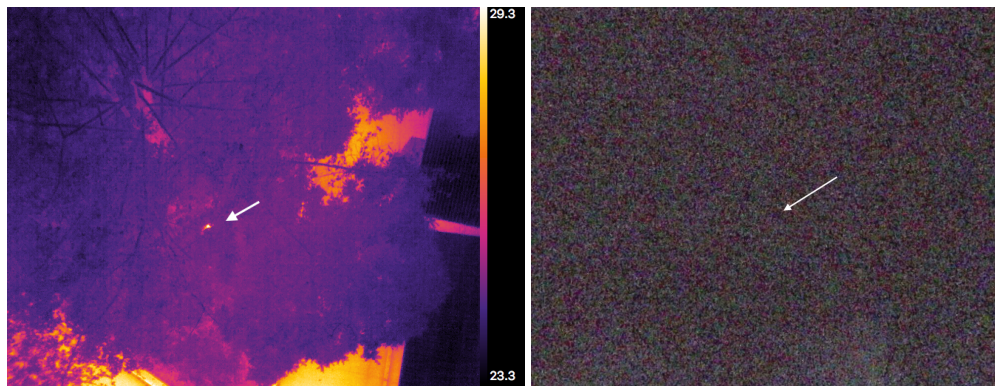


Fig. D8. Confirmed orangutan nest detection in Flight 20180511.0521 in (left) thermal and (right) RGB. This flight was performed just after dawn, making visibility difficult with the RGB. Location of orangutan is indicated with an arrow in both images. Flying height was 100m and canopy coverage was estimated as 0%.

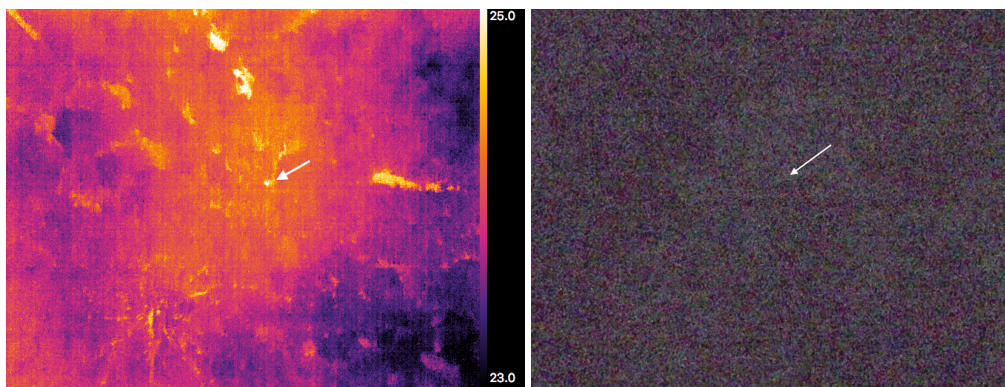


Fig. D9. Confirmed mother and infant pair detected in Flight 20180512.0521 in (L) thermal and (R) RGB. Flying height was 100m and canopy coverage was estimated at 75%.

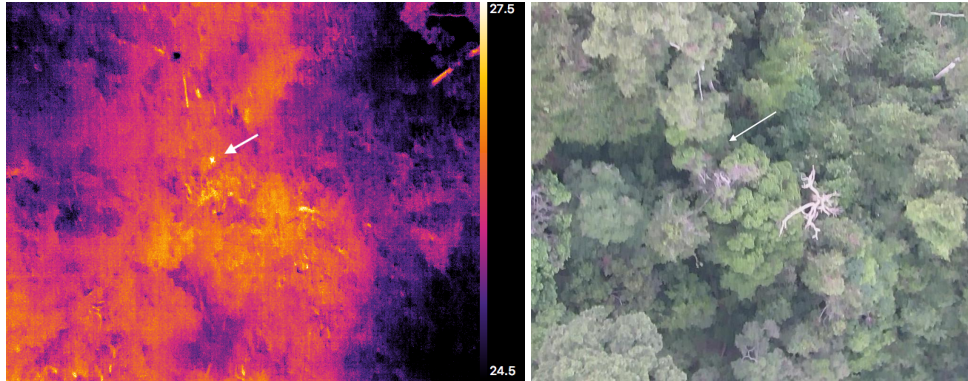


Fig. D10. Confirmed orangutan nest detection in Flight 20180511_1804 in (L) thermal and (R) RGB. Flying height was 100m.



Fig. D11. Confirmed detection of 3 Orangutans on lodge roof in Flight 20180511_1830 in (L) thermal and (R) RGB. Flying height was 100m.

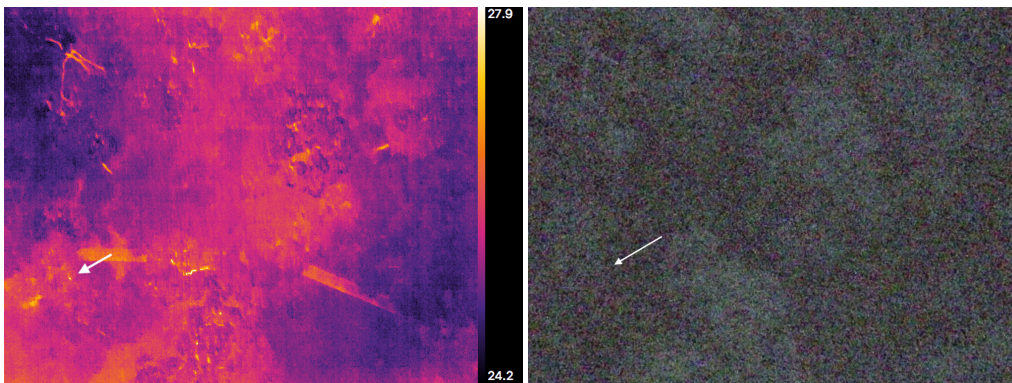


Fig. D12. Confirmed orangutan nest detection in Flight 20180511_1830 in (L) thermal and (R) RGB. Flying height was 100m

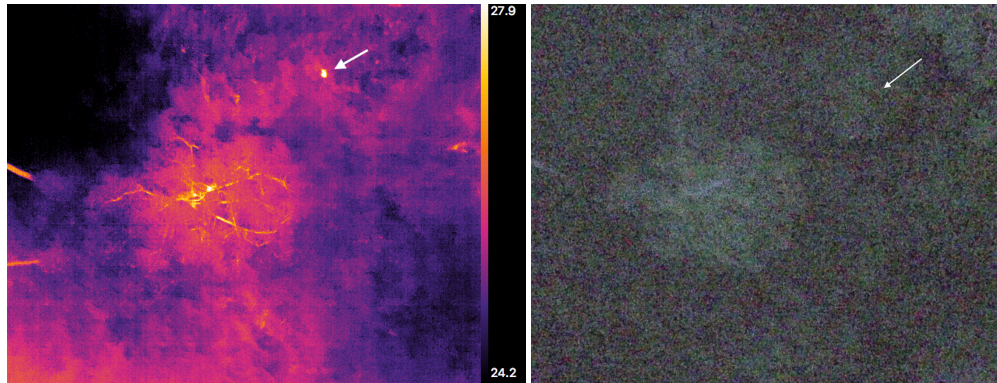


Fig. D13. Confirmed orangutan nest detection in Flight 20180511_1830 in (L) thermal and (R) RGB. Flying height was 100m.

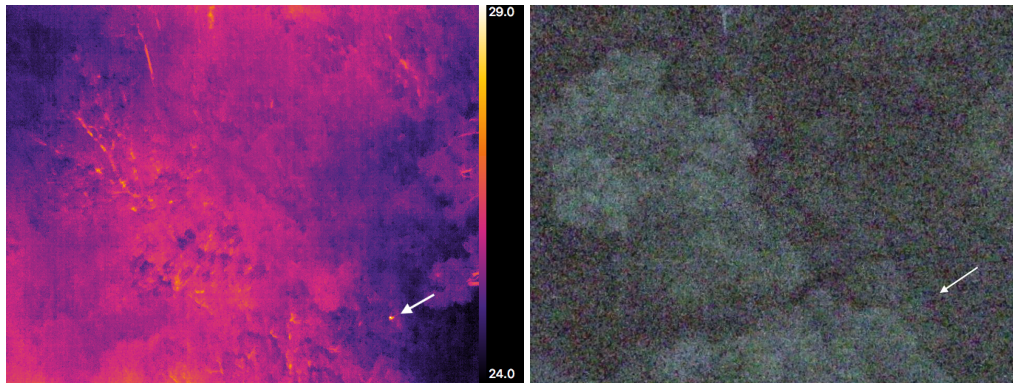


Fig. D14. Confirmed orangutan nest detection in Flight 20180511_1830 in (L) thermal and (R) RGB. Flying height was 100m.

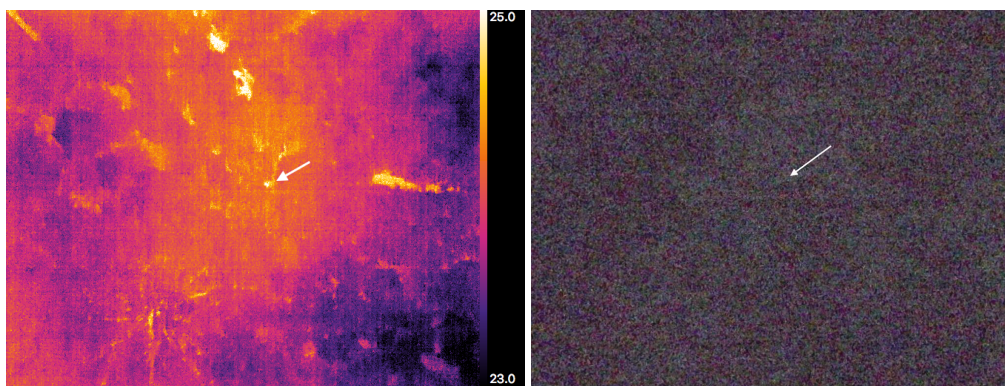


Fig. D15. Confirmed mother and infant pair detected in Flight 20180512.0521 in (L) thermal and (R) RGB. Flying height was 100m and canopy coverage was estimated at 75%.

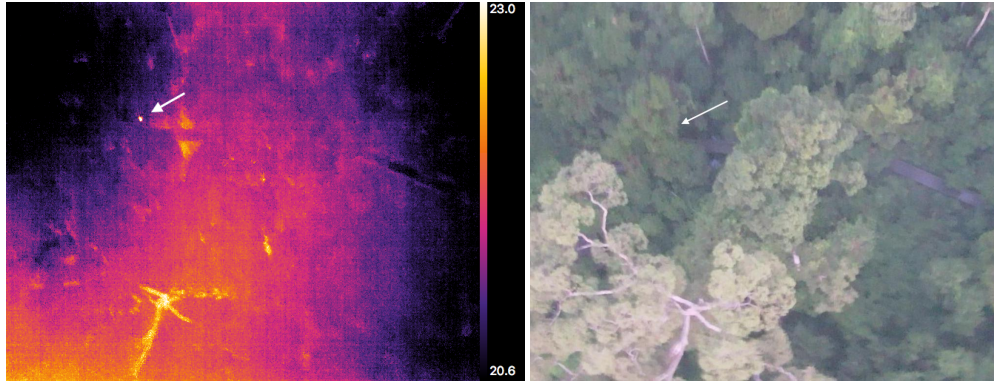


Fig. D16. Confirmed orangutan nest detection in Flight 20180512_0541 in (L) thermal and (R) RGB. Flying height was 100m and canopy coverage was estimated at 75-100%.

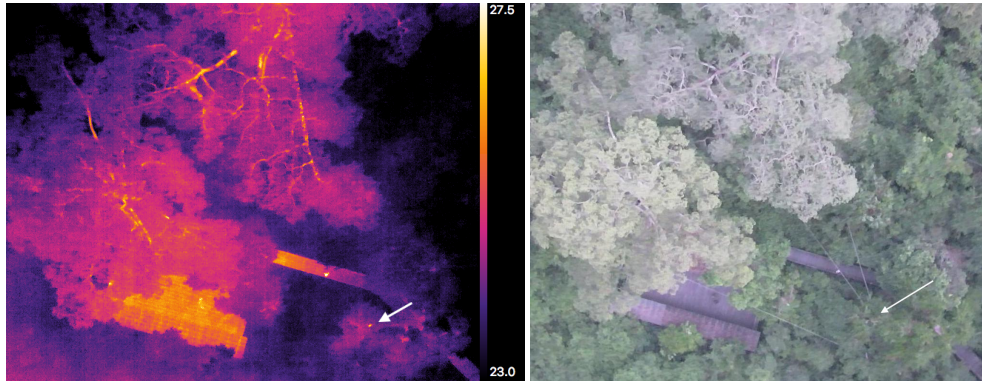


Fig. D17. Confirmed orangutan nest detection in Flight 20180512_1804 in (L) thermal and (R) RGB. Flying height was 100m.

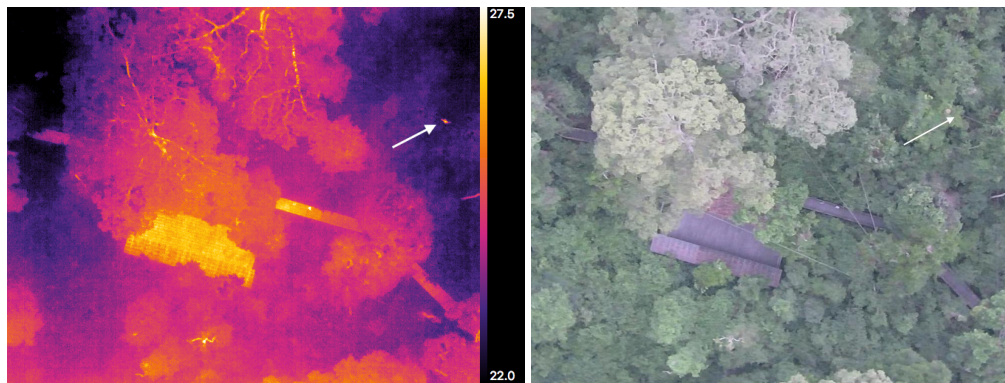


Fig. D18. Confirmed moving orangutan detection in Flight 20180512_1804 in (L) thermal and (R) RGB. Flying height was 100m.

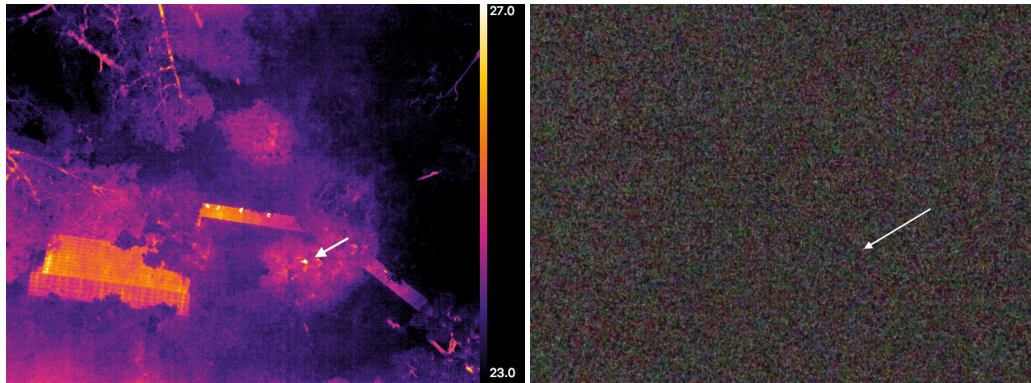


Fig. D19. Confirmed orangutan nest detection in Flight 20180512_1804 in (L) thermal and (R) RGB. Flying height was 100m and canopy coverage was estimated at 0%.

335 **D.2. KOCP Detections**

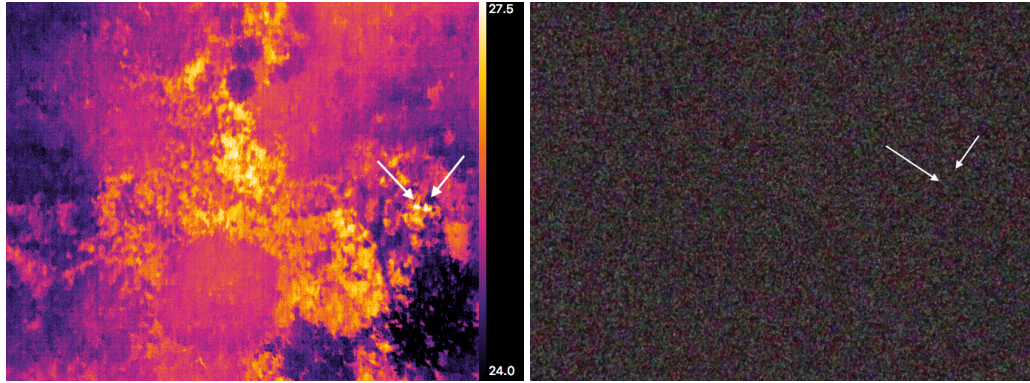


Fig. D20. Confirmed orangutan nest detection in Flight 20180513_1859 in (L) thermal and (R) RGB. Flying height was 80m and canopy coverage was estimated at 75-100%.

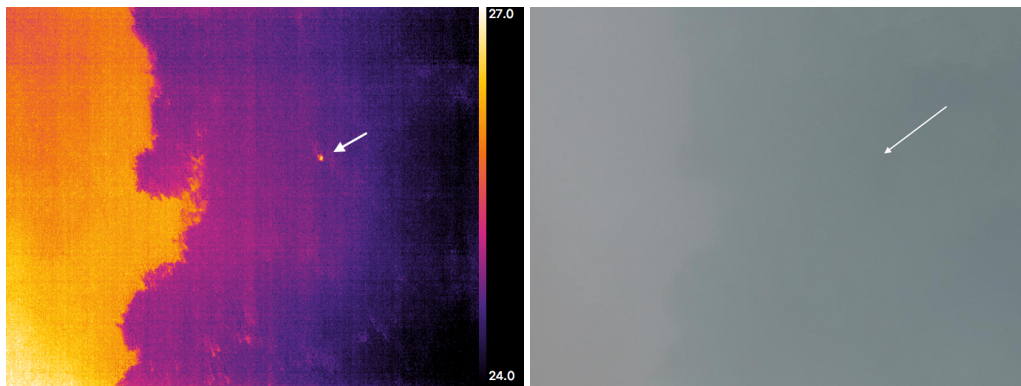


Fig. D21. Confirmed orangutan nest detection in Flight 20180514_0543 in (L) thermal and (R) RGB. Flying height was 80m and canopy coverage was estimated at 75-100%.

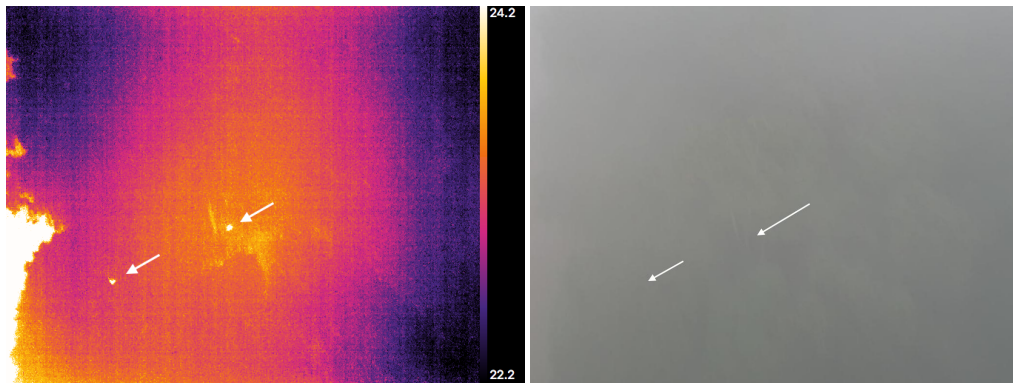


Fig. D22. Confirmed mother and infant pair detected in Flight 20180514_1612 in (L) thermal and (R) RGB. Flying height was 80m and canopy coverage was estimated at 75-100%.

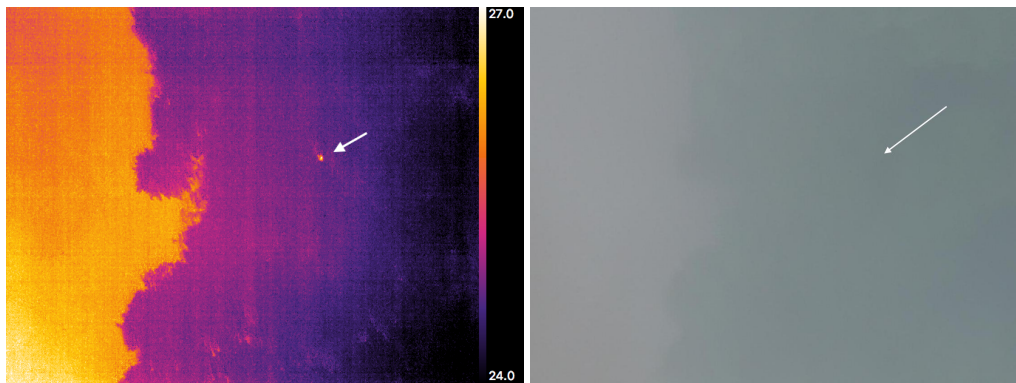


Fig. D23. Confirmed orangutan nest detection in Flight 20180514_0543 in (left) thermal and (right) RGB. This flight was performed under foggy conditions, with visibility from the ground < 20m by eye. Location of orangutan is indicated with an arrow in both images. Flying height was 80m and canopy coverage was estimated at 75-100%.

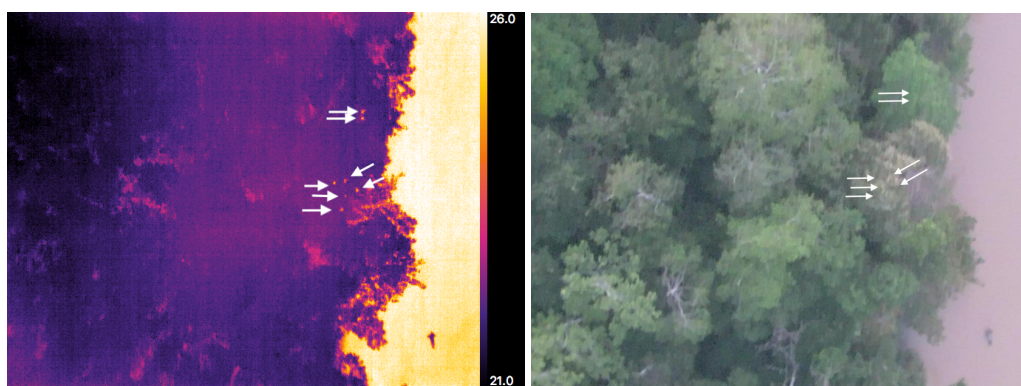


Fig. D24. Proboscis monkeys from drone at 100m with thermal camera (left) and RGB camera (right).