

Article

Drone-Monitoring: Improving the Detectability of Threatened Marine Megafauna

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Abstract: Unmanned aerial vehicles (UAVs; or drones) are an emerging tool to provide a safer, cheaper, and quieter alternative to traditional methods of studying marine megafauna in a natural environment. The UFES Nectology Laboratory team developed a drone-monitoring to assess the impacts on megafauna related to the Fundão dam mining tailings disaster in the Southeast Brazilian coast. We have developed a systematic pattern to optimize the available resources by covering the largest possible area. The fauna observer can monitor the environment from a privileged angle with virtual reality and subsequently analyzes each video captured in 4k, allowing to deepening behavioral ecology knowledge. Applying the drone-monitoring method, we have observed an increasing detectability by adjusting the camera angle, height, orientation, and speed of the UAV; which saved time and resources for monitoring turtles, sea birds, large fish, and especially small cetaceans efficiently and comparably.

Keywords: unmanned aerial vehicles; detectability; turtles; sea birds; large fishes; cetaceans



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1. Introduction

Usually known as marine megafauna [1], large mammals, reptiles, fish, and sea birds share ecological functions with the environment, such as the trophic-dynamic regulation of populations, storage and cycling of nutrients, community formation, and habitat provision [2]. Thus, the reduction in functional diversity within marine megafauna communities is a consequence of population decline [3]. Because of their environmental effects, marine megafauna species are considered as ecosystem sentinel [4], especially marine mammals [5]. However, studies on marine megafauna are challenging and limited due to the need of favorable metocean conditions, logistical difficulties, and short duration of visual observation, mainly in low visibility areas [6].

Traditional noninvasive techniques to study megafauna are usually limited to horizontal observations and predominately restricted to recording the surface or near-surface activity at a distance and oblique angle [7,8]. However, unmanned aerial vehicle (UAV; or drones) during the 21st century has overcome this limitation, bringing several applications for wildlife studies with very high-resolution remote sensing devices [9]. UAV is an emerging tool that is providing a safer, cheaper, and quieter alternative to traditional monitoring methods [10] and can contribute to research and management when monitoring marine protected areas [11]. In addition to the safety of operators, a main advantage of drone-monitoring is acquiring high spatial and temporal resolution of systematic and permanent data with low operational cost [12]. The drone-monitoring allows ecological patterns

analysis, such as density and abundance of marine fauna [13–15]. Drone observations can improve the understanding of animal ecology [8], with significant potential for studies of marine mammals' behavior [16] and population size [17].

Drone-monitoring has rapidly found worldwide use in cetacean research. Dolphin detection through UAV can be more accurate than traditional onboard surveys, eliminating bias caused by observer exhaustion [15]. The application ranges from studies on body condition [18] and assessing whale health [19] to sampling blow microbiome [20]. This easily accessible, low-cost tool improves existing research methods and enables novel approaches in marine turtles ecology and conservation [21], e.g., to identify sufficient morphological patterns to define individuals' sex [22]. UAVs can provide a less hazardous method for surveying wildlife and have been described to increase the efficiency and accuracy when counting seabird populations [23]. Furthermore, shark habitat use, spatial distribution, and movement speeds can also be measured [24], as well as population densities, particularly in shallow-water habitats [25], and their behaviors can be defined [26].

In 2015, over 50 million cubic meters of mining tailings were released in the Doce River basin in Eastern Brazil [27]. The incident represents one of the biggest ore dam failures [28], causing ecological and cultural damage [29,30]. For this reason, megafauna drone-monitoring was developed to evaluate the impacts in this group of organisms caused by the mining tailings dam rupture on the southeastern coast of Brazil. However, it is necessary to optimize the effort for monitoring marine megafauna with the objective to extend the knowledge about animal behavior and habitat use as environmental health parameters. Here, we have adopted a framework for adequate logistics, human resources, equipment, safety, and legislation and have developed a UAV flight pattern. In this study, we have tested different flight modes to understand which characteristics should be considered to increase monitoring marine megafauna accuracy. By applying the present drone-monitoring method, we observe an increasing detectability adjusting camera angle, height, orientation, and speed of the UAV.

2. Materials and Methods

2.1. Study Area

The study was conducted from October 2018 to March 2020 at the Doce River's region Espírito Santo (19°39' S, 39°48' W). The UAV operations were performed in the region of Doce River's mouth and the Piraquê-Açu River's mouth in Southwest Atlantic (Figure 1), a key area for a myriad of threatened taxa [31]. The sampling design was defined considering the equipment's characteristics, drone licenses for operation, and previous experiments. The elaborated drone-monitoring flight plans aimed to obtain a larger scanning area with a minimum of overlap.

A total of 30 flights per month between October 2018 and March 2020 were performed to record megafauna habitat use patterns and behavior. At least 6 replicates of video samples in each region were performed. A total of 12 in the Doce River's mouth, 12 in Comboios, and 6 at the mouth of Piraquê-Açu (considered as a control point) videos were recorded. Data processing was performed by analyzing 10,705 min of 4k 30fps videos. When the target fauna could be identified, edits (cropping, approaching, and slow motion) were made for better viewing. The possible interference in the animals' behavior caused by the drone at the height of 50 m was visually evaluated in all videos with identified marine megafauna species.

2.2. Equipment and Licenses

The drone-monitoring operation was planned to meet all the necessary functions for observing megafauna in a remote environment with safety and efficiency. For any other airspace user's security and the safety of people and goods on the ground, the International Civil Aviation Organization (ICAO) guidelines were followed. The guidelines standardize UAV regulations worldwide through standard and recommended practices. In many countries, aircraft under 25 kg of weight at takeoff are considered small-UAV and have less

strict rules [16]. A request to the Airspace Control Department (DECEA) is through the Request for Access to Remotely Piloted Aircraft (SARPAS). These regulations are based on the rule of the National Telecommunications Agency (ANATEL) and according to the Brazilian Special Civil Aviation Regulation—RBAC—E N94 of the National Agency of Civil Aviation (ANAC, 2017).

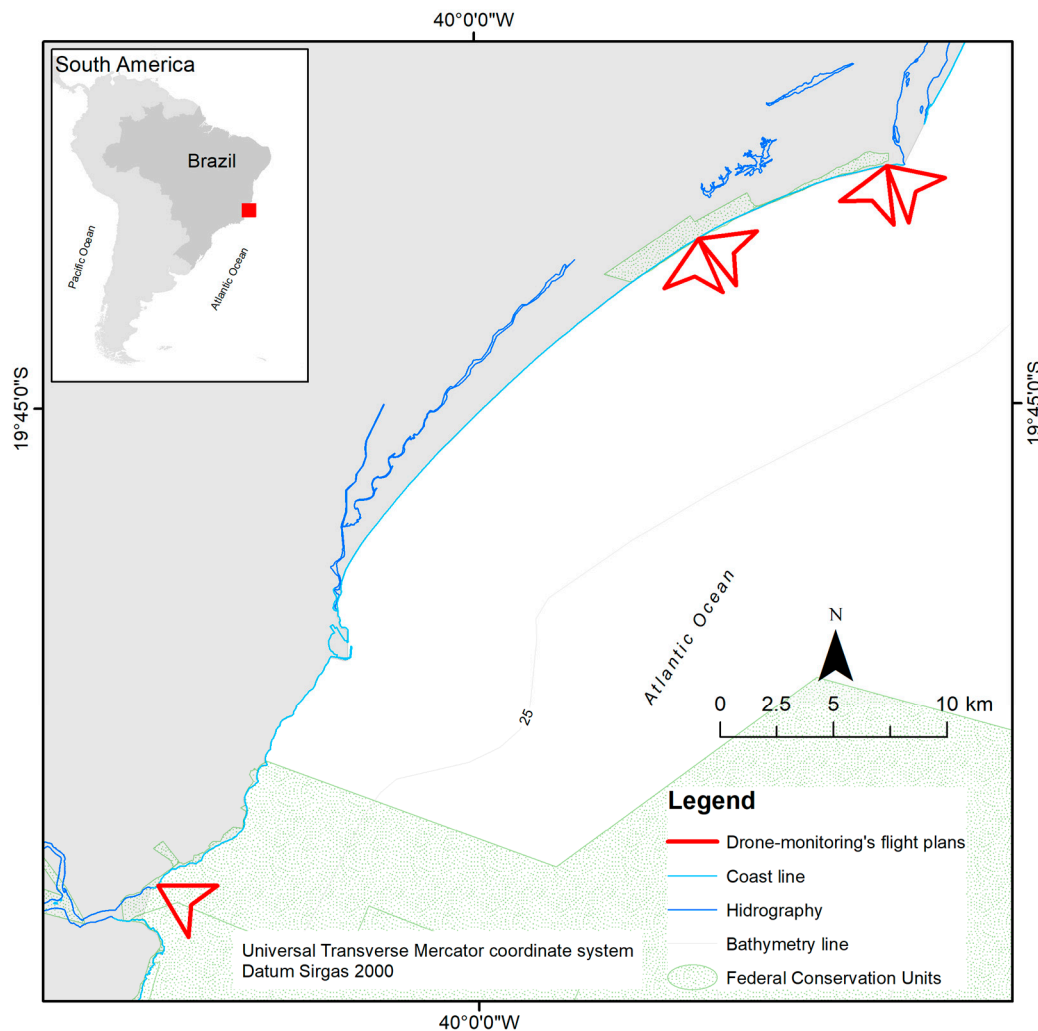


Figure 1. Sampling design of drone-monitoring of marine megafauna (flight plans in red), at three coastal monitoring points, in southeastern Brazil. In green are the limits of the Federal Conservation Units.

During the flight, the drone's operation in the Extended Visual mode Line-Of-Sight (EVLOS) is directly associated with the viewing distance of unmanned equipment in Visual Meteorological Conditions (VMC). The remote pilot cannot maintain direct visual contact with the aircraft without the aid of lenses or other equipment. A UAV observer must conduct the flight, following the same rules as an operation with Visual Line-Of-Sight (VLOS). The use of a binocular 25-125X80 makes it possible to safely view the drone up to 3 km away from the takeoff point. Furthermore, it is crucial to maintain a safe separation from other aircraft to avoid collisions with aircraft and obstacles.

Classification of UAV platforms for civil scientific uses generally has descriptions based upon size, flight endurance, and capabilities [32]. The DJI Mavic 2 Zoom (diagonal diameter of 354 mm, 905 g with 24–28 mm optical zoom camera, www.dji.com accessed on 19 February 2021), a quadcopter Vertical Take-Off and Landing (VTOL), was considered the most appropriate UAV for this study due to the camera's resolution capacity to record in 4k at over 30fps, with the possibility to zooming up to 4 times with the use of zoom. The Mavic

2 has an autonomy of 30 min in adverse conditions and speed up to 54 km/h. However, the manufacturer recommends that the flight plan consider 30% of the battery as a safety margin. Along with safety time, another 10% of the battery was reserved for interruptions due to the animals' sighting during the flight. No flights were performed on rainy days or during wind speed over 26 km/h, following the security margin recommended by the DJI manufacturer, and when there was Beaufort Sea State 4 or less to maximize fauna observation. The infrastructure, licenses, and staff required during the cetacean drone-monitoring operation are described in Table 1 and illustrated in Figures 2 and 3.

Table 1. Description of the infrastructure, licenses, and staff required during the drone-monitoring operation.

Operational Description for Marine Megafauna Drone-Monitoring	
Equipment	3 UAV Mavic 2 Zoom, 2 FPV DJI Goggles Racing Edition, 2 binoculars Luga Astronomical Gladiator Triplet 25-125 X 80, 3 tablet iPad mini, 10 memory cards 128 GB, 10 batteries UAV, 1 computer iMac Pro 27", 2 MacBook Pro, 1 lens filter kit PL/ND, 1 weather station, 10 HD Backup Plus Hub Seagate 8TB.
Infrastructure	Tents, tripods, chairs, tables.
Team	Remote Pilot, Copilot, Drone Observer, Fauna Observer, Logistics Operator.
License	ICAO (USA), DECEA, ANAC, ANATEL (BRAZIL)
Safety	EVLOS (3 km of radius), VMC (wind 26 km/h, no rain, no fire).



Figure 2. The drone-monitoring team comprises a drone observer, fauna observer, copilot, pilot, and logistic operator (the photographer). Monitoring of marine megafauna carried out in coastal waters adjacent to the federal protected area REBio Comboios.

2.3. Flight Parameters

We analyzed the following operating characteristics to determine a systematic flight pattern for marine megafauna's drone-monitoring: the drone's height with the sea surface, the angle of inclination of the camera to the horizon, and the availability time of a target object.



Figure 3. Main equipment used during field activities of the drone-monitoring in a natural environment: virtual reality mask—First Person View (FPV), Mavic 2 Zoom drone with extra batteries, long-range binoculars, and portable weather station.

The ground sampling distance (GSD) is an important feature to determine the accuracy of photogrammetry. Height tests were performed with an original size of an adult replicate of the franciscana dolphin (*Pontoporia blainvillei*). The object was positioned 10 cm below the water surface in the Piraquê-Açu River, and flights were performed to compare the object's visualization in FPV (First Person View) at four different heights: 100, 75, 50, and 30 m. One flight for each height was carried out with two experienced fauna observers, at different times, in which both tried to locate the object without knowing its location. The target object's size difference was calculated using the pixels' number in the image for the heights of 100 and 50 m. The zoom feature was only used to confirm the suspicion of observation, but not through the flight to avoid changing the comparison of the target object's visualization at different heights.

It is necessary to cover the largest possible area in a single flight to optimize sampling. The camera angles that provide the largest sampled area have the lowest pitch values about the horizon. We used a canvas of 1 m² to determine the camera's inclination. A total of 12 test flights were performed over the Regência beach, in Linhares, with angles ranging from -90° (nadir) to 0° (astronomical horizon). The imaged area with an angle at -27° and -31° was calculated.

Five vectors within the covered area with the different displacement positions (lateral or frontal) were simulated to understand how long the object is available to view it on the screen during the flight. The simulation occurred for a displacement at 40 km/h and a camera angle with -27° of inclination.

2.4. Detectability Tests

At 50 m above the sea level and a constant speed of 40 km/h, the different camera pitch angles (-23° , -27° , and -31°), previously determined as the most efficient, were analyzed for detectability (N/h) and UAV position (lateral or frontal) (Table 2). To check the different flight patterns' effectiveness, we compared the frequency of cetaceans (N/h) in each of the four scenarios. A total of six flights were used in one of the four experiments to perform the Mann–Whitney statistical test, a nonparametric for two independent samples at the 0.05 level of significance [33]. The analyzes were performed using the Past 4.02 statistical package [34].

Table 2. Experimental tests to assess cetaceans' detectability in drone-monitoring concerning the drone's camera angle and position during displacement in the flight.

Experiment	Camera Angle	Drone Position
1	-23°	Lateral
2	-27°	Lateral
3	-31°	Lateral
4	-27°	Frontal

3. Results

3.1. Flight Pattern

The flight pattern for the megafauna drone-monitoring was defined from experimental tests in real field conditions. Both fauna observers took less time to locate the dolphin replica at the height of 50 m, followed by 100 m. The flight with a height of 30 m was the one that obtained the longest time to locate the object. All the flights were performed with the camera at a 90° angle. For this reason, the flight at the lower height resulted in a much more restricted image coverage range. The ideal height for detecting cetaceans was determined to be 50 m height. Analyzing the video's object size, at this distance, an object of 1.5 m in length (the franciscana dolphin replica's size used in the experiment) has a pixel size of 1.97 cm. In comparison, at 100 m, this value increases by 50% (Figure 4), impairing the quality to identify the target object.

An object availability time in the image recorded during the drone's flight was determined through simulations of the drone's speed and position. At a constant speed, the position, lateral or frontal, relates to the time of an object's availability in the captured image. The image is a trapezoid. Therefore, an object remains more visible to the fauna observer when the lateral drone movement occurs. The time covered by a visually available object can vary from 10 to 94 s in a flight with a lateral position. In comparison, in a frontal flight, the time goes from 12 to 52 s (Figure 5). When flying sideways at 40 km/h, the availability time becomes 25.9% greater than when the flight speed is 54 km/h.

3.2. Detectability

The detectability of small cetaceans was tested in four experimental tests (Table 2), taking into account the configurations developed enduring the trials to define the flight pattern. Although the -23° angle has a greater scanning area (Figure 6), the camera's inclination angle to the -27° horizon showed higher efficiency in registering small cetaceans in both drone motion positions. Even with no significant difference, it is clear that the camera's inclination angle interferes with cetaceans' registration (Figure 7). However, when monitoring large cetaceans, it is recommended to change the camera angle to view part of the horizon to increase the viewing of blows and cover a bigger distance area of observations.

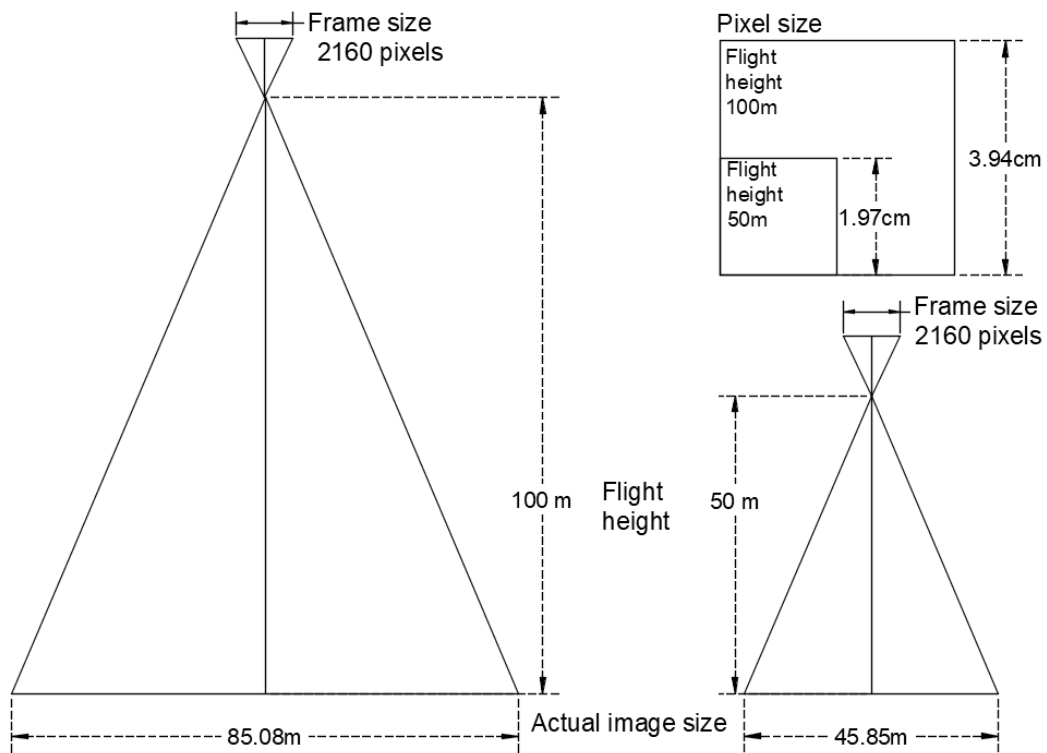


Figure 4. Representation of the image size in pixels at two different distances from the target object (100 and 50 m height of the drone to the takeoff point).

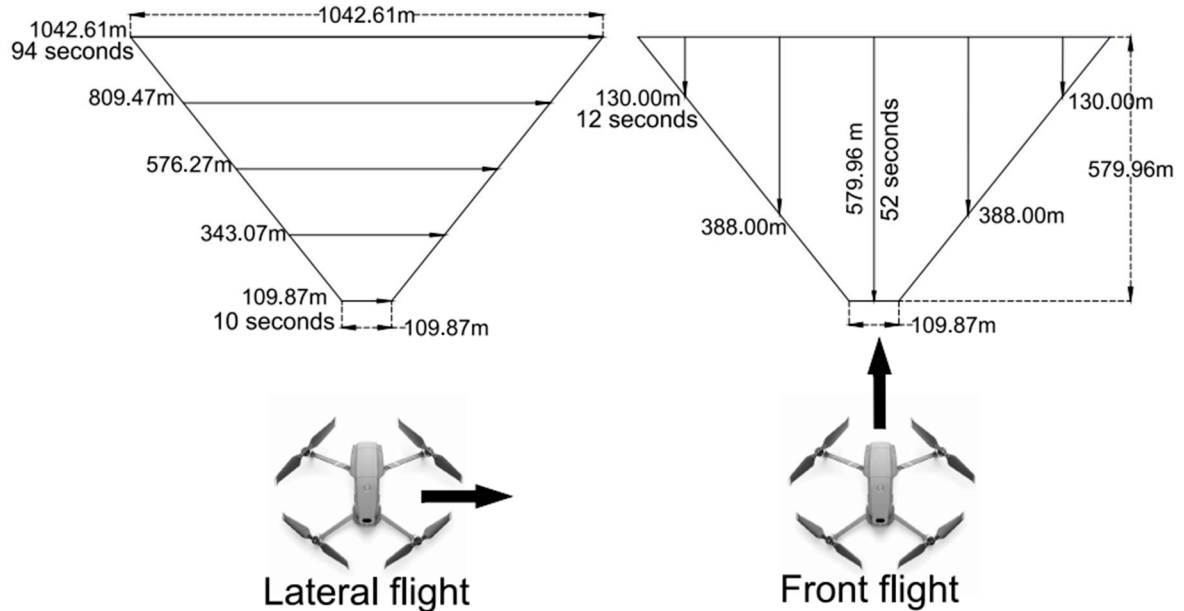


Figure 5. Vectors with object availability simulations. The continuous black lines represent the imaged area's boundary; dashed arrows represent the time spent hypothetically traveled by an object available in the image in lateral and frontal flight.

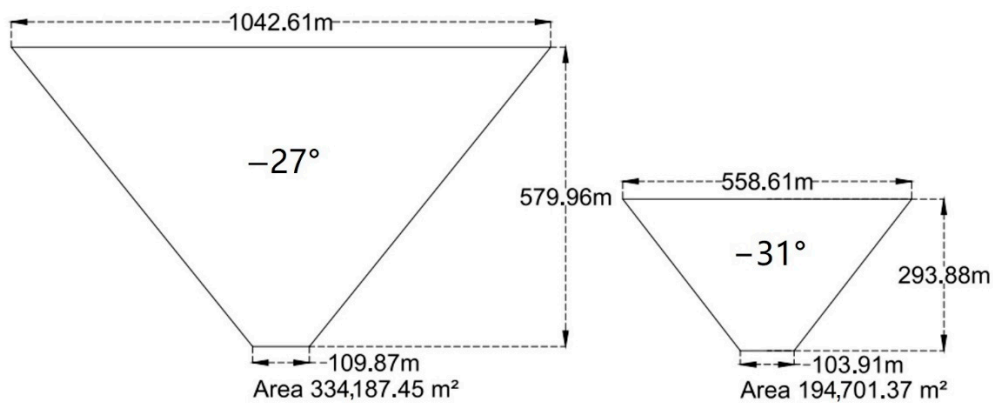


Figure 6. Imaged area sizes at different angles of inclination of the camera to the horizon. The image on the left represents the angle of -27° (imaged area: $334,187\text{m}^2$) and on the right represents the camera angle at -31° (imaged area: $194,701\text{m}^2$) angle to the horizon.

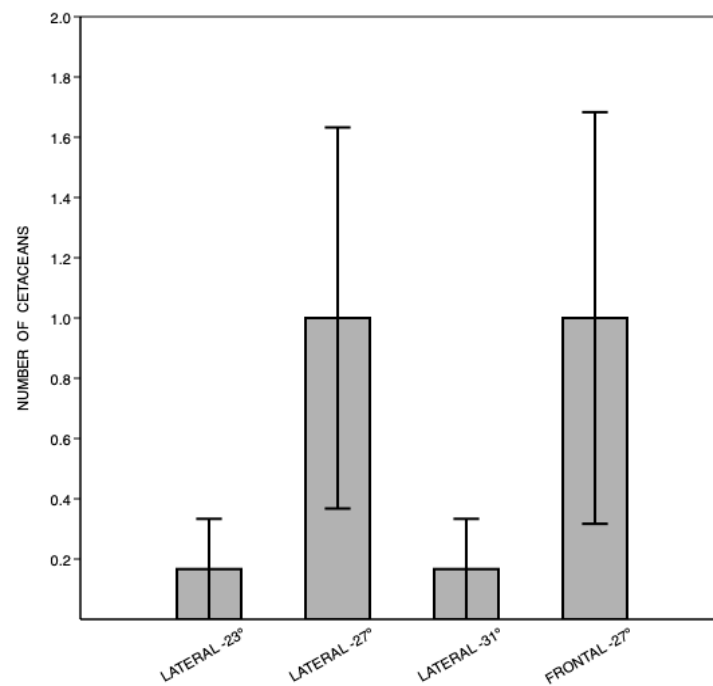


Figure 7. Detectability of cetaceans per flight in the four experiments performed. No significant differences were found between the experiments according to the Mann–Whitney–Wilcoxon non-parametric test.

Besides being a noninvasive method [15], which provides considerable information, the high-resolution videos (4K) recorded allow researchers to review in the laboratory multiple times and are deposited in a bank of permanent samples. The present study showed that almost one-fourth of the cetaceans' sightings were recorded after analyzing the videos. It is evident (Figure 7) that the angle is a more critical factor for the detectability of small cetaceans than the drone position (lateral or frontal). Nevertheless, the drone's lateral position during the flight will always be more promising when the camera's width is higher than the height (Figure 5).

3.3. Marine Megafauna Recorded

After defining the most efficient flight pattern for detecting marine megafauna, a total of 729 regular flights were carried out, with an average time of 882 s (S.D. ± 211 s), over 18 months. We registered 4838 sightings distributed in 14 marine megafauna species

by analyzing of videos recorded during the drone-monitoring. In the case study, it was possible to record 3743 occurrences of seabirds in 1393 groups from 6 families, 224 sightings of sea turtles from 2 families, and 964 sightings of cetaceans in 256 groups (3 species were successfully identified). Besides, sharks and rays, other large fishes were registered (Figure 8 and Table 3).

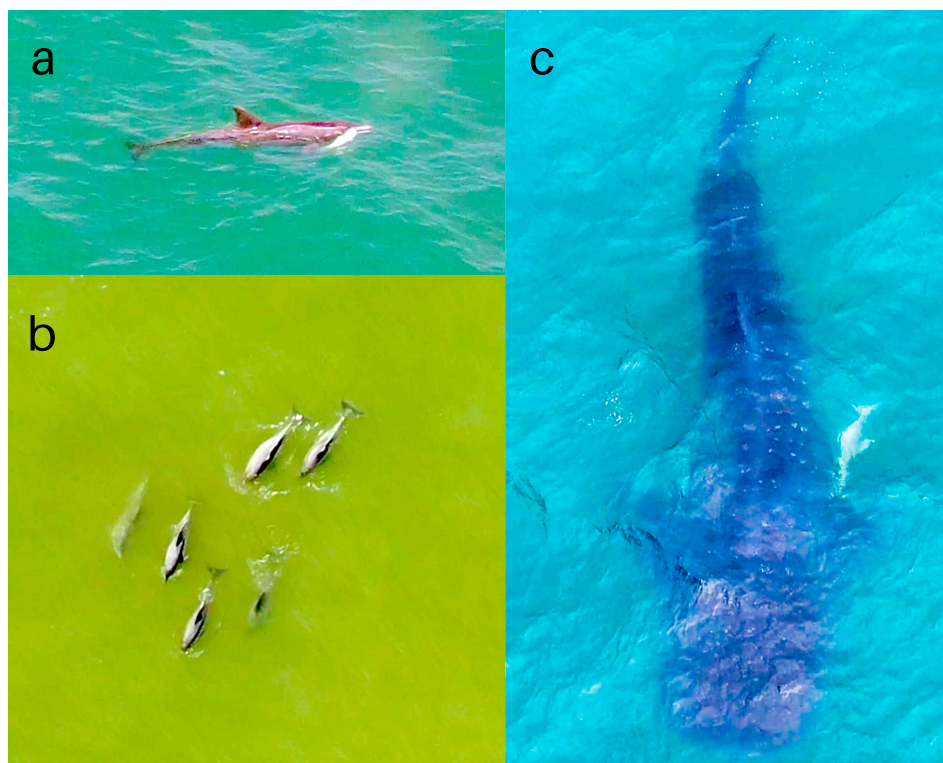


Figure 8. Marine megafauna recorded during drone-monitoring. Frames captured from 4k 30fps videos. (a) Rough-toothed Dolphin (*Steno bredanensis*) eating a fish. (b) Group with six adult Guiana Dolphin (*Sotalia guianensis*) individuals. (c) Whale Shark (*Rhincodon typus*) with an associated Common Remora (*Remora* sp.).

Despite the high number of seabirds, it was possible to identify, at the species level, in 92.3 % of the records. The Sternidae family had the highest documented numbers, with 53.6 % of the records. Birds of the family Apodidae were registered but were not identified at the species level. These were the species that showed the most significant interaction with the drone. During the takeoff and landing, some curious individuals approached the equipment. Furthermore, during two sightings at the Doce River's mouth, a flock of the Sternidae family showed to change behavior, such as taking flight collectively, when the drone approached.

Green turtle (*Chelonia mydas*) was the most observed sea turtle species, with 83.9 % of the records. The remaining records were equally distributed among the loggerhead turtle (*Caretta caretta*), leatherback turtle (*Dermochelys coriacea*), and olive turtle (*Lepidochelys olivacea*), all identified as adult individuals. Among all the cetaceans observed, the Guiana dolphin (*Sotalia guianensis*) was the species with the highest number of records (180 groups), followed by the franciscana dolphin (*Pontoporia blainvillei*) with 45 groups registered and the rough-toothed dolphin (*Steno bredanensis*) with 4 groups. No observable behavior response to the drone flying at 50 m altitude overhead sea turtles and dolphins was observed.

Table 3. Number of sightings of marine tetrapods identified at genus or species level during marine megafauna drone-monitoring, between October 2018 and March 2020, in the southeastern South Atlantic. International Union for Conservation of Nature (IUCN) threat categories.

Tetrapods Group	Order	Family	Species	Popular Name	Threatened Category (IUCN)	Number of Sightings
Sea birds	Suliformes	Fregatidae	<i>Fregata magnificens</i>	Magnificent frigatebird	Least concern	1
	Suliformes	Sulidae	<i>Sula leucogaster</i>	Brown booby	Least concern	96
	Suliformes	Sulidae	<i>Sula dactylatra</i>	Masked booby	Least concern	2
	Procellariiformes	Procellariidae	<i>Thalassarche</i> sp.	Albatross	–	1
	Charadriiformes	Sternidae	<i>Sterna hirundo</i>	Common tern	Least concern	30
	Charadriiformes	Sternidae	<i>Phaetusa simplex</i>	Large-billed tern	Least concern	158
	Pelecaniformes	Ardeidae	<i>Egretta thula</i>	Snowy egret	Least concern	1
Sea turtles	Testudinata	Cheloniidae	<i>Caretta caretta</i>	Loggerhead	Vulnerable	2
	Testudinata	Cheloniidae	<i>Lepidochelys olivacea</i>	Olive ridley	Vulnerable	2
	Testudinata	Cheloniidae	<i>Chelonia mydas</i>	Green turtle	Endangered	188
	Testudinata	Dermochelyidae	<i>Dermochelys coriacea</i>	Leatherback	Vulnerable	2
Marine mammals	Cetartiodactyla	Delphinidae	<i>Steno bredanensis</i>	Rough-toothed dolphin	Least concern	10
	Cetartiodactyla	Delphinidae	<i>Sotalia guianensis</i>	Guiana dolphin	Near threatened	640
	Cetartiodactyla	Pontoporiidae	<i>Pontoporia blainvillei</i>	Franciscana	Vulnerable	153
Large fishes	Perciformes	Carangidae	<i>Caranx lugubris</i>	Black jack	Least concern	2
	Perciformes	Echeneidae	<i>Remora</i> sp.	Common remora	–	1
	Orectolobiformes	Rhincodontidae	<i>Rhincodon typus</i>	Whale shark	Endangered	1
	Myliobatiformes	Myliobatidae	<i>Aetobatus narinari</i>	Spotted eagle ray	Near threatened	1
	Myliobatiformes	Rhinopterae	<i>Rhinoptera bonasus</i>	American cownose ray	Near threatened	8

4. Discussion

Our study showed that the ideal flight pattern for monitoring cetaceans in a natural environment was when the drone was flying at 50 m height, with a camera angle of -27° of inclination. The drones move in the lateral position, with a speed of 40 km/h. Despite the limitations pointed out for monitoring marine wildlife with drones, this study demonstrated that it is possible to monitor small cetaceans and other marine groups with low-cost drones, increasing the method's efficiency significantly when adopting optimized parameters such as the flight height, position, and camera tilt angle. Raoult et al. [26] suggest that researchers knowing the target fauna's specific characteristics and the impact of drones on the species studied can choose the appropriate equipment for that location. The authors also suggest that flight patterns should be established to optimize the collection of information. Joyce et al. [35] highlight the importance of knowing the drone's capacity and the current licenses and regulations in place, the data processing capacity, and the required logistical and administrative possibilities.

The ground sampling distance (GSD) obtained with a given sensor varies at different flight heights [35]. The closer the drone is to the ground, the higher is the image resolution, and the smaller area will be captured. The present study used the best available camera resolution (4k), which is a fundamental factor in determining the flight height since the objective is to monitor the largest area possible, in the shortest time, with sufficient quality

to identify the target fauna. Because of the rapid technological advance and the consequent quality of captured images, it is expected that the height of unmanned flights can be increased exponentially, maintaining the same resolution and capturing a larger area.

The speed and position during the flight depend on the study area size, the animal size to be monitored, and the available time. The values adopted in this study proved valid for small cetaceans with coastal distribution, such as *S. guianensis* [36]. With lateral detachment and speed below the equipment's maximum limit, it allowed the target fauna to spend more time available for sighting. These values are crucial for species with little time available on the sea surface, such as *P. blainvillei* [37]. Nevertheless, the drone's lateral position during the flight will always be more promising when the camera's width is higher than the height.

The camera's tilt angle at -27° proved to be efficient for monitoring small cetacean species. However, for monitoring large cetaceans, it is recommended to change the camera angle to view part of the horizon since studies with large whales scan at the level of the horizon to increase the area of viewing blows and to allow greater distance observations. Besides, as there is a sharp decrease in observation in the upper area of the image, small animals with shy behavior and/or a color similar to the environment are more difficult to observe when very distant. Therefore, increasing the distance from the horizon to close to -90° of camera tilt reduces this problem. Although there is a decrease in the scanned area with the increase in the camera tilt towards the nadir, the captured image has greater clarity at all screen positions. When defining the best camera tilt angle, it is recommended to consider the target fauna's behavior and the time available to sample the desired study area.

Detailed behavioral study of marine mammals is a challenge [38]. Studies of individuals' behavior and their intraspecific interactions are only possible in the environment if there is ample visualization time. Drone-monitoring makes it possible to identify more specific behaviors and age classification than other methods since VTOL UAVs potentially do not directly impact dolphins when flying over 25–30 m [7,39,40]. Cetaceans are only visible at the surface for brief timeframes. Only a portion of the entire group is usually seen at any specific time, so visual estimates of group size are regularly underestimated [41]. That is why determining the number of individuals in a group is incredibly hard for this order [42]. All cetaceans recorded during this study were successfully identified at the species level, and group size could be recorded during the video analyses. This shows that the camera's features can help estimate the number of individuals in a group, with slow video speed and zoom [43].

UAV diffuse use's significant limitations include limited survey range, difficulties obtaining permits for use, and data-processing time [10]. The license for EVLOS flights, e.g., limits the operation to a maximum distance of approximately 3 km, preventing not coastal cetaceans from being observed in operations from the land. To date, small, battery-powered multicopters, due to their low costs, are easy to operate but with limited energy efficiency. Batteries usually need to be recharged or replaced approximately every 20 min, restricting the survey range [10]. Still, drones demonstrate the potential to provide new insights into marine animals' behavior linked to abundance, distribution, and population density [44]. Drones allow intense smaller spatial scale sampling, in addition to accessing isolated locations [45].

The ideal conditions for performing drone-monitoring have scope for adaptations, depending on the circumstances and infrastructure that existed at the drone's takeoff location. As the technology advances fast, concerning the availability of new equipment, the type of drone to be adopted must have superior features to those used in this study (autonomy, distance, and cost–benefit ratio). As drones evolve towards longer flight times and better sensor packages, it will be possible to rapidly identify sea turtles [46] or whales in aerial imagery [47]. The increase in innovative ways of using drones enhances environmental research and conservation [48] and can even describe which whale populations are healthier [49]. They can change our perspective on the environment. Identifying critical habitats for the conservation of highly mobile marine vertebrates is essential [50]. Therefore,

the combination of lightweight UAVs with image processing techniques in increasingly efficient software can provide products applicable in several ecological studies [51]. Incorporating drones as research tools will empower scientists worldwide to collect relevant data for various terrestrial, marine, and freshwater habitats [35].

5. Conclusions

This study provided unprecedented information that will serve as a foundation for developing research with marine megafauna using drones. We developed a method that optimized efforts to monitor marine megafauna and extend knowledge about these groups' behavior that serves as a sentinel of the environments. By applying the drone-monitoring techniques we presented, observations of the target marine fauna are increased, using all the resources provided by the equipment safely and efficiently. Regardless of the equipment used, evaluating the best angle of inclination of the camera, flight altitude, speed, and position of the drone, are essential to increase efficiency in detecting marine megafauna, especially small cetaceans. With this systematic monitoring, it will be possible to understand the local populations' dynamics and maintain research to evaluate the impact of mining tailings released on the Doce River. Future studies are necessary for the evolution of the method with specific species, taking into account the region and the animals' behavior, such as the time of availability and probability of detection.

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