Small Unmanned Aerial Systems for Estimating Abundance of Krill-Dependent Predators: a Feasibility Study with Preliminary Results

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Abstract

Quantifying distribution and abundance of predators is an integral part of any ecosystem monitoring effort. Antarctica poses many challenges to doing so. Recent advances in the development of Unmanned Aerial Systems (UAS), particularly with vertical take-off and landing (VTOL) aircraft, have provided a new tool for addressing the challenges to estimating abundance of predators. We present preliminary results of a pilot study in the use of VTOLs for estimating abundance of krill-dependent predators. Studies in 2010/11 focused on operations, test flights, estimates of penguin abundance, comparisons to ground counts, and calculating colony area and density.

Introduction

Aerial photography has become a standard tool in wildlife assessments when scientists are faced with estimating the number of animals in large aggregations. Because manned aircraft support is not always available due to cost or logistical constraints, we investigated the applicability of small, unmanned aerial systems (UAS) as an alternative to manned platforms. We felt that there was an open niche for a platform that could be easily carried into the field, operated safely by a team of two people, and could collect images of adequate resolution to support accurate counts of small, aggregated targets in a low contrast environment. To provide the flexibility of operating in rugged terrain or from ships, we required that the aircraft be able to take off and land vertically. To reduce potential disturbance to the sampled populations and risks of pollution from fossil fuels, we restricted our search to platforms powered by batteries. We required that the UAS be capable of conducting missions under direct control of the operator or through a series of predetermined waypoints. Although our primary sampling system was to be single frame images, the aircraft would be required to transmit live video to a ground station to aid in target selection and mission planning. We envisioned these systems as tools for relatively short-range photographic missions requiring endurance on the order of 15 – 45 minutes.

After reviewing a wide range of military and commercial systems, we decided that the small, electric, multi-rotor copters were the best fit for our needs. These small UAS were designed to be photographic platforms and are exceptionally stable in flight. Their control systems incorporate input from 3-axis gyros, 3-axis accelerometers, barometric altimeters, and GPS units, making them relatively easy to fly. Because the rotors on these aircraft are directly driven by electric motors and aircraft movements are controlled by simply changing the rotation rate of one of the motors, these aircraft require none of the mechanical linkages and multiple moving parts associated with standard helicopters. In addition, the use of multiple rotors reduces the size and resultant kinetic energy in each blade, making the aircraft safer for both operators and wildlife in case of a mishap.

We selected Cape Shirreff, Livingston Island, South Shetland Islands for our field test because the habitat is rugged, remote, and scientists there work with large aggregations of penguins and fur seals. Our objectives were to:

1. Test operation of three independent vertical take-off and landing (VTOL) systems; one a large commercially-manufactured system, a second smaller custom-built quadro-copter system, and a third custom-built hexa-copter system;
2. Test range and duration for each system;
3. Monitor response of wildlife to aerial VTOL surveys;
4. Estimate abundance of gentoo penguins (*Pygoscelis papua*) and chinstrap penguins (*P. antarctica*) in colonies of various sizes and compare these to annually-collected standardized ground counts;
5. Photograph Antarctic fur seal rookery sites to determine whether image resolution is adequate to accurately count pups and to detect tags on adults;
6. Estimate areas of penguin colonies based on measurements from aerial photographs; and
7. Conduct a ship to shore sampling mission to demonstrate the feasibility of using this platform to sample otherwise inaccessible beaches.

We conclude with a discussion of the general feasibility of incorporating VTOLs as a standard monitoring tool, uses other than abundance estimation, future directions and recommendations.

Methods

Platform Selection

We took two approaches to acquisition of platforms for this project. First, we selected a new commercially available quadrocopter model (md4-1000) from Microdrones, GmbH (www.microdrones.com). Microdrones, GmbH, has been producing quadrocopters for aerial imaging since 2005. We found the md4-1000 especially appealing because it had the lift to carry heavier payloads and endurance that was advertised as up to 60 minutes.

Our second approach was to select a camera and then build an aircraft around that camera system. This process was conducted in collaboration with Aerial Imaging Solutions, Old Lyme, CT (www.aerialimagingsolutions.com). We structured this procurement of this platform in two steps. First, the contractor delivered a small, quadrocopter (APQ-16tr) that we could use for pilot training. In the second step, this same aircraft was upgraded to full sampling capabilities for field deployments at Cape Shirreff.

Training Missions and System Testing

The initial flight training took place at Microdrones, Siegen, Germany. The course included basic familiarization of the md4-100 system, including functionality and start-up, handling of the system, and handling of rechargeable batteries. Training also included academic and hands-on flight training; items covered were theoretical requirements, physical influences, choice of airfield/ flight area, downwash and ground effect, take-off, landing, influence of wind, temperature influence, practical flight exercises, post flight check, and safety instructions. An orientation of the flight control software was conducted. Training included flight time with the md4-200 and md4-1000 in INS and GPS modes, and in RC and pre-programmed flight modes. Weather conditions for training flights were 1.5-4.5°C with winds 4.5 – 6.5 m/s. The conditions were similar to those encountered at Cape Shirreff in January-February.

All training and testing missions in the U.S. were conducted at MacDill Air Force Base, Tampa, FL, under an agreement between NOAA and the U.S. Air Force that was facilitated through the support of NOAA's Aircraft Operations Center (AOC). Flights were conducted at a recreational field that had been reserved for VTOL testing ops and were limited to altitudes under 200'. Two intensive training and testing sessions are described below.

Efforts during this first session focused on flight training using the small APQ-16tr aircraft. During these tests the APQ-16tr proved to be very reliable, responsive, and nearly indestructible. We also experienced the periphery of a tropical storm, which forced us to push our work into winds in excess of 8 m/s. We learned from this experience that while we could safely operate the smaller platform in winds up to 8 m/s, the buffeting of the aircraft from the wind significantly degraded image quality even at high shutter speeds.

We tested ground and flight resolution for the Canon S90 camera with a medium contrast (8:1) resolution target (RST-704, series C) and a simulated wildlife cluster. Although the S90 is a highly reviewed "professional" point-and-shoot camera with a 10 megapixels sensor, the results of our initial field tests were less than ideal. One problem that has been reported for the high end point-and-shoot cameras is that the increasingly high pixel density chips were beginning to reveal the limitations of the lenses on these cameras.

In all of our resolution testing, we calculated image resolution and ground resolved distances as shown below:

$$R = h/f * X \qquad \text{and} \qquad G = h/R * f$$

where R = resolution (lines/mm); f = lens focal length (mm); X = combined width of bar and space of smallest target resolved; and G = ground resolved distance (mm) (Navy 1973).

The md4-1000 aircraft was delivered with an Olympus EP1 camera. This camera is one of several new "advanced compact or micro four thirds" cameras that support higher quality interchangeable lenses and chips that are nearly six times the size of the high end point-and-shoot cameras. We reviewed other "advanced compact" cameras and selected the Sony NEX-5 camera for testing. The Olympus and Sony cameras are significantly heavier than the Canon camera we had originally targeted for the AQ aircraft. Because added weight in mission components relates directly to power requirements and thus battery life, we began investigating ways to reduce the weight of these cameras without impacting their effectiveness for our missions. Eventually, the weight of the Olympus Pen-1 camera was reduced by 27% (from 460 g to 333 g) and the Sony NEX-5 by 12% (355 g to 314 g). Once we find a way to power the Sony camera with the aircraft battery we will be able to reduce the weight of that camera by another 60 g.

Between group sessions, several training flights with both the APQ-16 and md4-1000 were conducted at MacDill AFB. During these flights both aircraft performed well, but the landing struts on the md4-1000 showed cracks after only a few landings. These were reinforced, but the design of these landing struts appeared to be inadequate to handle the mass of this platform even when landing on a grass field.

The objectives for the second field session were to conduct side-by-side resolution testing for the two aircraft (using the Sony NEX-5 on the APQ-16 platform provided by Aerial

Imaging Solutions) and to test the ground station/video link for the md4-1000. We used the same resolution target and simulated wildlife cluster as described above.

During the field testing, we experienced significant problems linking the md4-1000 video transmitter and ground control station and there were also intermittent problems in aircraft control associated with loss of RC signal by aircraft. On the final flight of the md4-1000, the lid separated from the aircraft and sailed to the ground. Because the GPS antenna is mounted in the lid, we had to fly the aircraft without GPS assistance to the ground. The aircraft received some damage to the carbon fiber lid and landing gear.

Deployment Planning

Concerns over platform stability in winds typical of Cape Shirreff (e.g., mean summer wind speed: 6.1 ± 1.3 m/s) led to a decision to build a hexacopter as a third, back-up system. The hexacopter (APH-22) provides several advantages over the small AQ platforms. Adding two motors provides more stability in flight, increases power by about 50% for a 15% increase in weight, and makes even less noise in flight than the small quadrocopters. Otherwise, the electronics and control system are essentially the same as the APQ aircraft. The basic specs for the three platforms that we took to the Antarctic are presented in Table 10.1.

Antarctic Logistics

We embarked aboard the R/V *Moana Wave* in Punta Arenas, Chile, on 11 January 2011. During the transit we were able to inventory and check equipment, charge batteries, and work on the hexacopter before we encountered the rough seas of the Drake Passage. We were delivered to Cape Shirreff on 16 January. Field trials began soon after and continued weather permitting until shortly before pick up by the R/V *Moana Wave* on 6 February.

Image Analysis

All mosaics, counts, and calculations of areas for penguin colonies were performed with basic tools included in Adobe Photoshop CS5 (ver. 12.04). We determined photographic scale based on calculated differences between pressure altimeter readings recorded on takeoff and as images were captured.

Table 10.1. Aircraft specifications for two quadrocopters (APQ-16 and md4-1000) and a hexacopter (APH-22) used at Cape Shirreff, Livingston Island, Antarctica, 2010/11. The APH-22 was owned and operated by Aerial Imaging Solutions, Old Lyme, CT.

Specification	APQ-16	md4-1000	APH-22
Wing span/total length (cm)	67.1	137.2	82.3
Dry weight (kg)	1.18	3.9	1.72
Gross weight (kg)	1.68	5.08	2.72
Engine1 (size/rating)	4X90 W	4X250 W	6X110W
Power1 (Type/qty)	22.75N	peak thrust 106N	peak thrust 48.24N
Payload capacity (kg)	0.499	1.179	0.998
Payload type2	Camera	Camera	Camera
Max speed (kts)	25	25	30
Cruise speed (kts)	10	10	10
Stall speed (kts)	n/a	n/a	n/a
Endurance (min)	30	50	25

Table 10.2. Comparison of specifications and tested resolution of images from mission cameras. All resolution testing was conducted at MacDill, AFB, Tampa, FL.

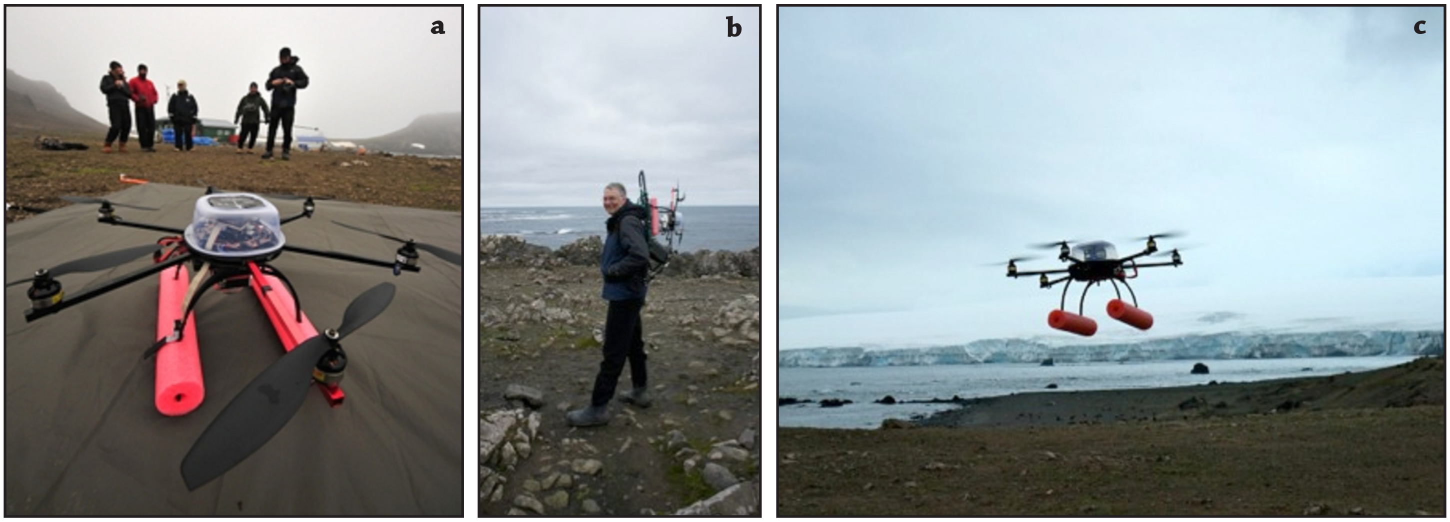
	Canon S90	Olympus EP1	Sony NEX5
Pixel Count (Mpix)	10	12	14.2
Sensor Size (mm)	7.6 x 5.7	18.0 x 13.5	23.4 x 15.6
Weight (grams)	197	460	355
Resolution (l/mm)	25	77	75

Results

Resolution and resulting ground resolved distances were excellent from all three systems (Table 10.2). Wildlife clusters were easily counted from 200’ in altitude, and for high contrast features, objects approximately one square inch could be detected from over 150’. Both cameras outperformed the S90 camera even when this camera was tested on the ground.

Antarctic Field Experiment

On 18 January we worked through the prelaunch checklist for the md4-1000, calibrated the magnetic compass, and performed all the preflight checks. However, on lift-off the aircraft was not responding properly to the controls and it was quickly landed it. This problem had been experienced with the md4-1000 once before in Tampa, and we found that after shutting down the system and



Figures 10.1 a-c: a. A close up of the APH-22, a hexacopter built by Aerial Imaging Systems, Old Lyme, CT, showing the utility of simple construction tools; b. portability of the APH-22 carried on a frame pack; c. the APH-22 in flight at Cape Shirreff, Livingston Island.

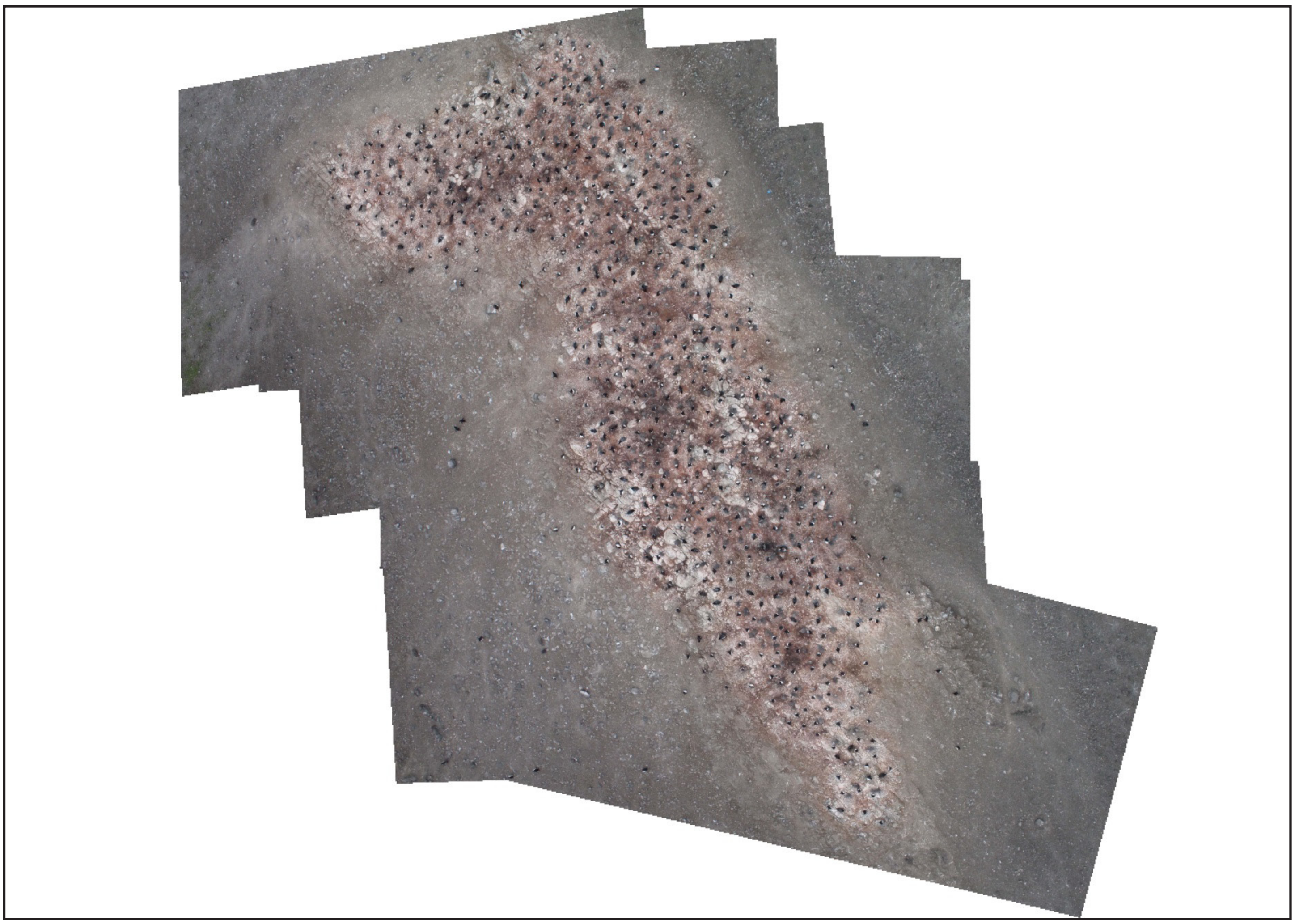


Figure 10.2. Mosaic of aerial photos of a large chinstrap penguin colony.

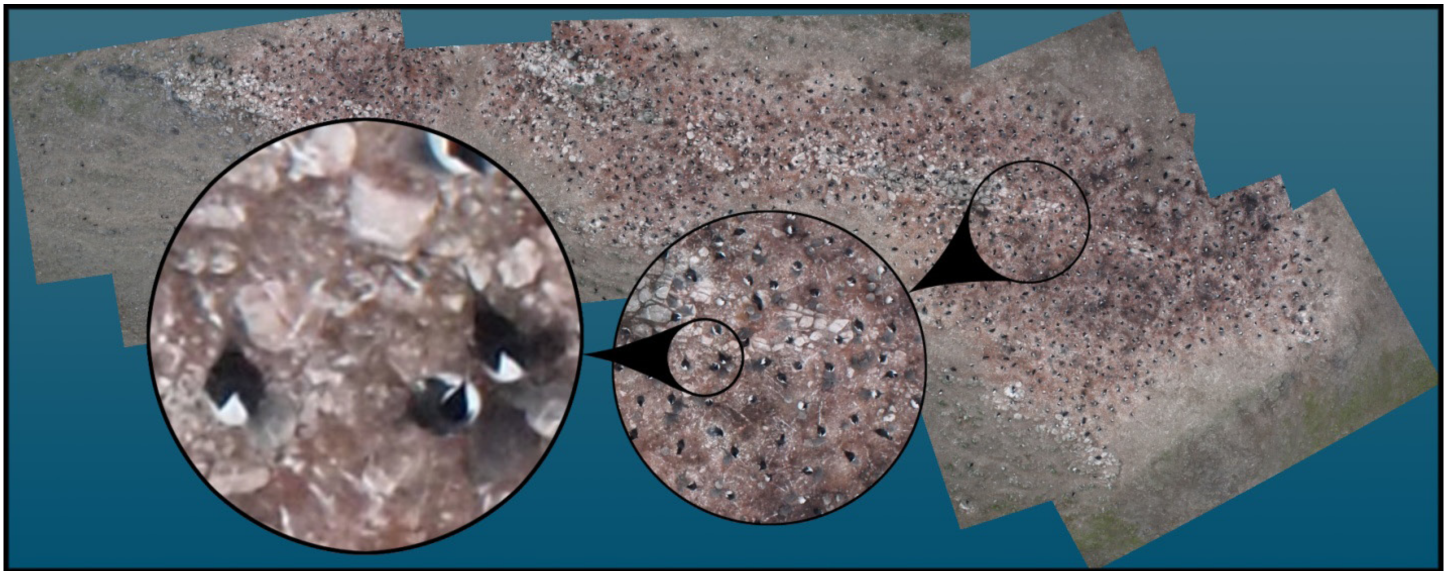


Figure 3. A chinstrap penguin colony showing visibility of both chicks and adults.

Table 10.3. Counts of penguin chinstrap and Gentoo penguin chicks made from composite aerial photographs and from the ground. Gentoo chick counts summed across common colonies due to movements of these chicks between count dates. All photographs taken from APH-22 aircraft.

Colony Number	Photo Counts	Ground Counts
3	745	848
5	102	97
8	103	106
9	27	23
10	616	618
11	617	604
12	67	32
29	970	1014
Gentoo (several)	433	429
Total counts (all)	3680	3771

Table 10.4. Calculated areas and chick densities for specific colonies based on counts and measurements from vertical aerial photographs taken from APH-22 aircraft. Some counts differ from those presented above because only well-defined nesting areas were used in area calculations.

Colony (species)	Chick Count (photo)	Colony Area (m^2)	Chick Density
3 (chinstrap)	745	886.7	0.84
5 (chinstrap)	102	49.4	2.065
5 (gentoo)	181	75.1	2.41
8 (chinstrap)	67	37.9	1.77
8 (gentoo)	138	156.9	0.88
10 (chinstrap)	580	227	2.555
11 (chinstrap)	617	512.3	1.204
29 (chinstrap)	970	933.1	1.04

restarting, the aircraft behaved normally. We tried that when we encountered the problem in the field and the second flight was worse than the first. The aircraft was almost out of control and made a hard landing, damaging the skids and breaking or cracking some carbon fiber components.

Rather than focusing on repairing the damaged aircraft, we decided to shift our field operations to the APH-22 (Figures 10.1a-c). We made 28 flights with the APH-22 aircraft, 18 for testing purposes and 10 for sampling, for a total of about 75 minutes of flight time (29 minutes for tests and 46 minutes for sampling).

Penguin Sampling

All of our penguin sampling flights were conducted on 21 Jan. We conducted three photographic sampling flights at the penguin blind (Figure 10.1b), each about 6 minutes in duration, at altitudes ranging between 50 and 140' (Figure 10.1c). Flight control was in direct or manual mode and passes over the colonies were made with the assistance of controllers on the ground who communicated via VHF radio to the spotter working with the aircraft pilot. We conducted the final flight of the day over the largest penguin colony on the island from the top of a 38 m hill. There were no signs of disturbance to the penguins caused by the aircraft during any of the survey flights.

We constructed a mosaic of each colony in Photoshop CS5 (Figure 10.2) from a subset of the images collected during the flights. Image resolution was consistently excellent and penguins were easily identified to species and chicks easily counted

(Figure 10.3). After our counts were completed, an independent team of seabird researchers completed ground counts of penguin chicks for the same colonies (Table 10.3). Counts from images and from the ground were not shared between teams until the counts had been completed. Although there were some small gaps in image coverage at a couple of colonies, there was no significant difference between the two data sets (paired t-test, $p < 0.05$). We also used Photoshop tools to calculate the areas of distinct colonies, converted those measurements to true areas on the ground and then calculated chick densities for each (Table 10.4). Mean density of chicks per colonies (both species) was 1.60 ± 0.07 chicks/m^2. Differences in densities probably reflect variability in survival rates of chicks to date of sampling.

Pinniped Sampling

Figure 10.4. An aggregation of Antarctic fur seals with tagged and instrumented individuals visible.

After several days of inclement weather, we conducted two test flights to evaluate the waypoint flight control and “come home” systems, and then four sampling flights over groups of leopard seals (one flight) and Antarctic fur seals (three flights). Fur seal pups were easily detected in images taken from altitudes up to 50 m, and small tags on fur seals were also visible in images (Figure 10.4). At altitudes over 23 m we saw no sign that any pinnipeds (fur seals, Weddell seals, or leopard seals) were responding to the aircraft.

Leopard Seal Photogrammetry

There were four leopard seals hauled out on the U.S. AMLR fur seal study site during our flight over this area on 1 February 2011 (Figure 10.5). We measured standard length and width at the axilla for each seal on every image in which the animal was clearly visible. The level of precision in measurements taken from multiple images was very high (Table 10.2). Average length measurements from photographs of two seals for which we had capture data were 3 and 8% higher than those recorded by scientists on the ground (Table 10.5). This difference is likely the result of bias in scale calculations from pressure altimetry data.

Discussion

Although we experienced control and other issues with the md4-1000 both during test flights and in the Antarctic, we feel that we can work through these issues and this will be an excellent platform for longer-range missions. This aircraft also needs some engineering upgrades to make it more durable in the field. The landing gear is inadequate for hard landings in irregular terrain and the locking mechanism for the lid is flimsy, making it easy to pop off in flight. Because the lid is made of carbon fiber, which is opaque to GPS signals, the GPS antenna is mounted at the top of the lid, and each time the lid is removed (to replace batteries, for instance) the fitting for the GPS must be disconnected. For field use it would be better to replace the lid with something transparent to GPS signals that would have a positive connection to the main body of the aircraft.

Because the APH-22 was still being assembled when we arrived at Cape Shirreff, we had to

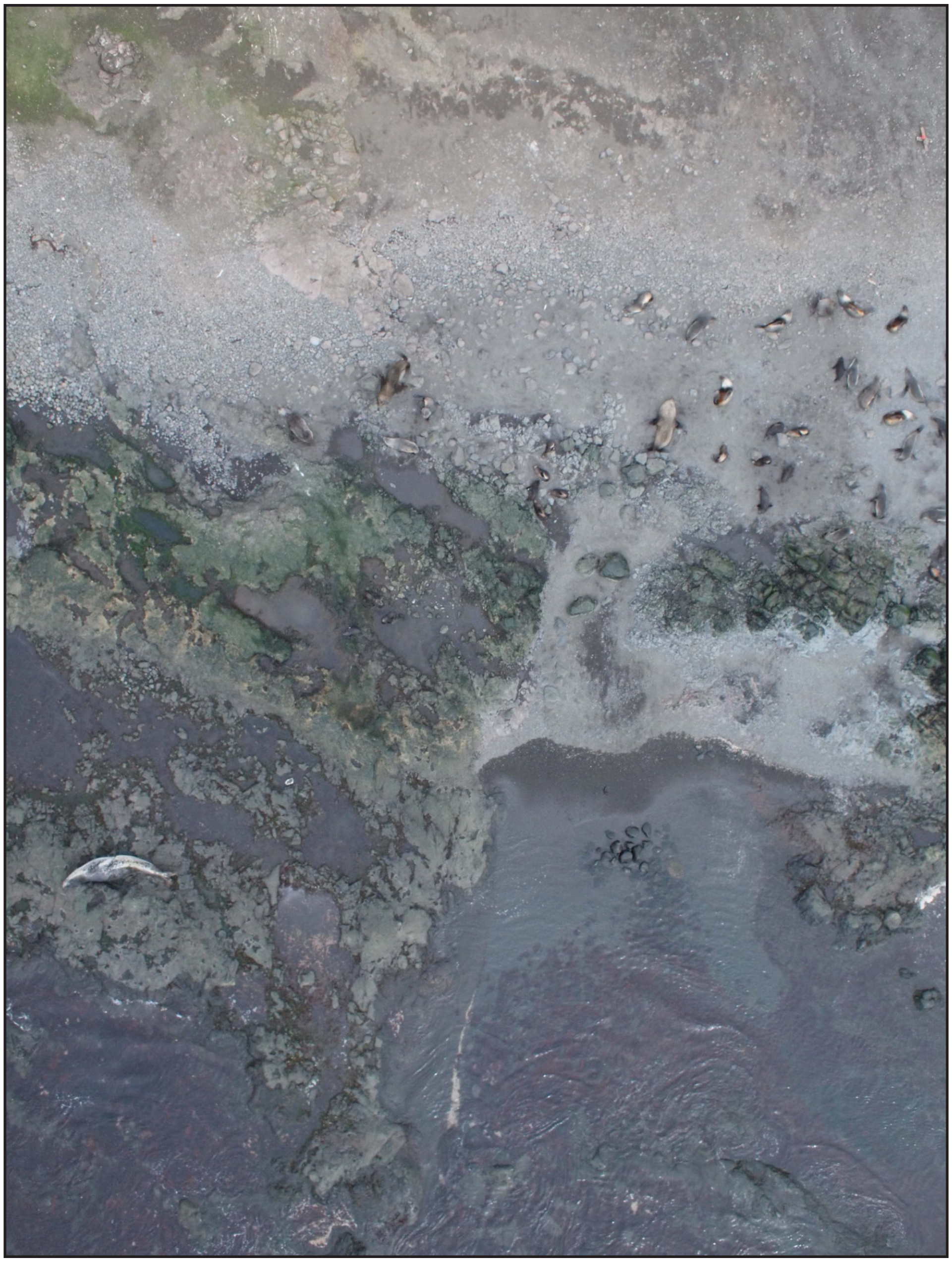


Figure 10.5. An aerial photo of a leopard seal (lower left) and fur seals (upper right).

blend a slow and methodical testing regime with the necessity of taking advantage of good weather conditions as they occurred. Almost all of our flying was done in the manual control mode, although we performed some waypoint and "come home" tests in the autonomous control option. Our sampling flights were all approximately six minutes, and we carefully inspected the aircraft after each flight. Batteries were changed after two flights and batteries were not allowed to go below a 50% charge level. For this small aircraft, we found that the pilot, with the aid of a spotter, could comfortably maintain visual contact with the aircraft out to about 150 meters.

Although we had to move rapidly through testing to sampling applications, this aircraft performed flawlessly. Images collected from this platform met all of our requirements, allowing us to accurately count penguin chicks, identify penguin adults and chicks to species, easily detect Antarctic fur seal pups, and remotely detect tagged fur seals. Originally, we had planned to use the images to count penguin nests, but by the time we arrived on the Island the crèche was well under way. Crèche refers to the transition from the period when an adult remains with the chicks to protect them from predators to the stage in which both adults must go to sea to feed to meet the demands of the rapidly growing chicks. Once both of the

Table 10.5. Length and width measurements for four leopard seals hauled out during test surveys of pinniped haul outs. N is the number of photos. Standard length measurements made during captures are in parentheses after mean length derived through photogrammetry.

	Length (cm)				**Width (cm)**				**Width/Length**			
Seal ID	**N**	**mean**	**stdev**	**cv**	**N**	**mean**	**stdev**	**cv**	**N**	**mean**	**stdev**	**cv**
White 8	1	302.4	na	na	1	86.3	na	na	1	0.285	na	na
Orange 36	8	324.4 (300)	5.54	0.017	8	74.6	1.44	0.019	8	0.23	0	0.019
Red/white 005	10	306.8 (297)	6.36	0.021	10	68.9	2.86	0.04	10	0.214	0.006	0.027
No Tag	13	285.9	5.96	0.021	9	68.9	2.86	0.042	9	0.241	0.006	0.024

adults begin making foraging trips, the chicks clump together for protection from predators (primarily skuas) and the nesting colonies begin to break down. Some of the differences in chick counts between photographs and the ground teams likely resulted from movements of groups of chicks between geographically defined colony sites.

These images also appear to provide a disturbance-free alternative for measuring size and shape of leopard seals. This will take some significant calibration efforts before the remote technique could be considered as a primary field-sampling tool. If photogrammetric sampling became a sampling focus in areas of very irregular terrain like we experienced in the Antarctic, a radar or laser altimetry system would be a valuable addition.

One of our requirements from the beginning was for a system that could be easily carried into remote locations by one or two people. The APH-22 is ideal for field applications that require a small team to carry all the sampling equipment and plenty of spare batteries into the field for a full day of work. This system is still being fine-tuned, but it is essentially ready to go into the field.

Our final objective was to conduct a mission from our support ship, the R/V Moana Wave, but at the end of the clearance process it was decided that a separate risk assessment was necessary before at-sea launch and recovery could be conducted. The md4-1000 has had some problems, but this is still an excellent long-range platform and the primary platform for sampling from ships. With some continued development and structural engineering support, this aircraft or one with similar endurance characteristics has great potential for sampling in the Antarctic.

Platform assessments

The APQ-16 was first designed as a primary sampling platform, but proved so effective as a trainer that this became its primary role. As we shifted to a heavier camera, this small quadrocopter became our third option for field operations.

The md4-1000 brings long endurance and greater lift capabilities that make it still the type of system that is well suited for ship to shore missions. We have had both reliability and structural issues with this system that need to be resolved before we decide how to move forward with this mission.

The APH-22 is an excellent shore-based sampling platform. It was reliable, rugged and has the lift to carry the larger cameras we selected for this project. It is a field ready system that meets all the required specifications for future work at Cape Shirreff and the South Shetlands.

These small UAS platforms are relatively easy to fly because computer chips integrate information from the pilot with data from onboard accelerometers, compasses, an altimeter, and a GPS unit. Changes in direction, speed, and altitude are made by simply changing the speed of the electrical motors attached to the propellers. To be successful in the field, the operator of one of these platforms must be able to fly the aircraft and thoroughly understand and test the components that interact to make flight relatively easy. In the case of the md4-1000, we had one of the first of this model to be built, the manual had not yet been completed, thorough test procedures and techniques were not provided, and we did not have the necessary information to truly understand how this system worked. When everything goes well, the aircraft is exceptionally stable in flight and flies well. If we had a better understanding of how the components of this aircraft interacted we would have been better equipped to troubleshoot problems.

With the APQ-16 and the APH-22, one person can hold the aircraft and test the responses to controls and stabilization systems with the motors running. The md4-1000 is too large and too powerful to do this safely by hand. A flexible test bed to hold the aircraft in place while systems are checked is required.

Wildlife Applications

The UAS systems we tested are exceptionally suitable for wildlife photogrammetry because of their portability, exceedingly quiet operation, stability in flight, hover ability and their ability to fly without disturbance to the animals. They are simple enough to fly that personnel with a modest amount of training can safely fly and operate the systems. Video capability provides an added element of flexibility and will no doubt be useful for longer missions from ship to shore. Programmability for pre-programmed flight operations to known locations provides additional benefits. With additional study these platforms will be useful to estimate size and mass of leopard seals without capture. With time and further development they should become a standard tool in monitoring wildlife populations.

Acknowledgments

We would not have been successful in this project without the insight and support of Robbie Hood, NOAA, UAS Program Director. She understood our mission and approach and consistently stood with us as we reached decision points in this process. Dr. George Watters, Director of the Antarctic Ecosystem Research Division, and his staff provided financial, scientific, and logistical support, with-

out which the field effort could not have been attempted.

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NOAA Technical Memorandum NMFS
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FEBRUARY 2014

AMLR 2010-2011 FIELD SEASON REPORT

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La Jolla, CA 92037

NOAA-TM-NMFS-SWFSC-524

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