ARTICLE

Testing marine conservation applications of unmanned aerial systems (UAS) in a remote marine protected area[1]

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Abstract: In 2014, the United States National Oceanic and Atmospheric Administration (NOAA) utilized unique partnerships with the National Aeronautics and Space Administration (NASA), and the US Coast Guard for the first comparative testing of two unmanned aircraft systems (UAS): the *Ikhana* (an MQ-9 Predator B) and a Puma All-Environment (Puma AE). A multidisciplinary team of scientists developed missions to explore the application of the two platforms to maritime surveillance and marine resource monitoring and assessment. Testing was conducted in the Papahānaumokuākea Marine National Monument, a marine protected area in the Northwest Hawaiian Islands. Nearly 30 h of footage were collected by the test platforms, containing imagery of marine mammals, sea turtles, seabirds, marine debris, and coastal habitat. Both platforms proved capable of collecting usable data, although imagery collected using the Puma was determined to be more useful for resource monitoring purposes. Lessons learned included the need for increased camera resolution, co-location of mission scientists and UAS operators, the influence of weather on the quality of imagery collected, post-processing resource demands, and the need for pre-planning of mission targets and approach to maximize efficiency.

Key words: remotely piloted aircraft systems, unmanned aerial vehicles, marine conservation, marine protected area, image analysis.

Résumé : En 2014, le United States National Oceanic and Atmospheric Administration (NOAA) a utilisé des partenariats uniques avec la National Aeronautics and Space Administration (NASA), et la Garde côtière américaine pour les premiers essais comparatifs de deux systèmes de véhicules aériens sans pilote (UAS) : l'*Ikhana* (un MQ-9 Predator B) et le Puma All-Environment (Puma AE). Une équipe multidisciplinaire de scientifiques a mis sur pied des missions pour explorer l'application de deux plateformes aux fins de surveillance maritime, et de surveillance et d'évaluation des ressources marines. Les essais ont été effectués dans le Papahānaumokuākea Marine National Monument (PMNM), une aire marine protégée dans les îles hawaïennes du Nord-Ouest. On a, depuis les plateformes d'essais, recueilli presque 30 h de séquences, dont des images de mammifères marins, de tortues de mer, d'oiseaux de mer, de débris marins et d'habitat côtier. Il s'avère que les deux plateformes avaient la capacité de collecter des données utilisables, bien qu'on ait déterminé que les images

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recueillies par Puma soient plus utiles aux fins de la surveillance des ressources. Parmi les leçons tirées, on peut citer la nécessité d'une meilleure résolution de la caméra, la colocalisation des scientifiques de la mission et des opérateurs des UAS, l'influence des conditions météorologiques sur la qualité des images recueillies, les exigences en ressources du post-traitement et la nécessité d'une planification au préalable des objectifs et de l'approche de la mission afin d'obtenir une efficacité maximale. [Traduit par la Rédaction].

Mots-clés : systèmes d'aéronefs télécommandés, véhicules aériens sans pilote, conservation marine, aire marine protégée, analyse des images.

1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) has a complex resource management mission involving monitoring and assessment of terrestrial, aquatic, marine, and aerial environments. Agency responsibilities include monitoring and managing endangered natural resources, ensuring healthy and sustainable fisheries, predicting weather patterns, studying climate change and sea level rise, and restoring coastal habitats, among others. NOAA and other science agencies are currently exploring unmanned aerial system (UAS) technologies for their potential to support NOAA management and conservation objectives.

In June and July of 2014, NOAA had the unique opportunity to explore the capabilities of two representative fixed-wing UAS platforms; the *Ikhana* (a National Aeronautics and Space Administration (NASA) MQ-9 Predator B), a medium altitude, long-endurance aircraft with a 20 m wingspan, and a Puma All-Environment (AE) aircraft system (a small hand-launched UAS). The capabilities of these UAS were tested in an extremely remote, highly protected marine ecosystem, the Papahānaumokuākea Marine National Monument (PMNM). This was the first experience for staff working in PMNM to evaluate the capabilities of UAS for collecting data on a variety of targets, and to compare the imagery collected between platforms. These tests were made possible through partnerships with NASA, which owns the *Ikhana*, the U.S. Fish and Wildlife Service (USFWS, a co-manager of PMNM), and with support from the U.S. Coast Guard.

Generally, UAS studies are focused on obtaining data for a single type of target. Examples of recent studies on marine species include seabird studies by the USFWS in the Olympic Peninsula (USFWS 2014), by NOAA to study killer whales (*Orcinus orca*) in Puget Sound (Durban et al. 2015), and by University of Alaska and NOAA for research on Steller sea lions (*Eumetopias jubatus*) in the Aleutian Islands (Cunningham 2014). Because of the exploratory nature of this study (none of the targets have been studied using UAS in this region), and the limited opportunities to access PMNM for such research, we elected to explore the capabilities of UAS to capture data on a variety of targets, recognizing that we would lose the scientific rigor associated with single-species studies.

Post-mission, the results of UAS testing were compared between platforms and by researchers to their prior boat- and land-based work to determine utility. This experience will help to inform decisions for future operational use of unmanned aircraft by NOAA, including target-specific studies in PMNM. In addition to refining future planning efforts, lessons learned will aid NOAA and other interested marine resource managers in understanding operational considerations for specific application to marine monitoring, including coordination across multiple organizations, multi-platform observations, and integrating observations into effective management of vital marine resources.

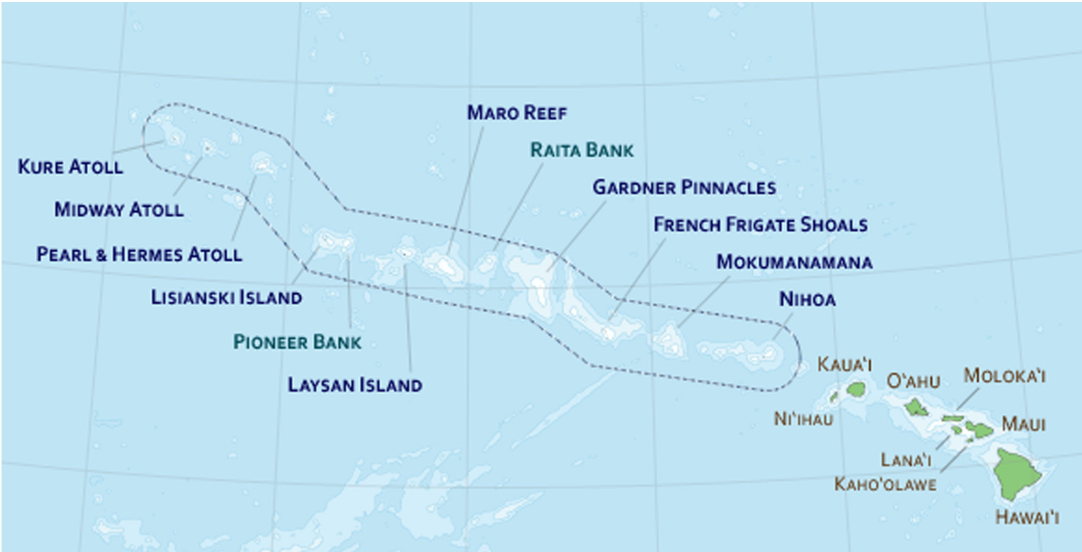
2. Materials and methods

2.1. Study location

The PMNM, established by Presidential Proclamation 8331 in 2006, protects an area of 362 073 km^2 of the Pacific Ocean in the Northwestern Hawaiian Islands (NWHI) and is one of the largest marine protected areas in the world (Fig. 1). It is also a World Heritage Site, recognized for its unique cultural and natural resources. The PMNM is home to several endangered and threatened species, including the Hawaiian monk seal (*Neomonachus schauinslandi*) and green sea turtle (*Chelonia mydas*); 98% of the world population of black-footed albatross (*Phoebastria nigripes*) nests there (USFWS 2005); and the marine environment has possibly the greatest number of endemic species of any marine area in the world (Kane et al. 2014). It also faces many threats, including marine debris, illegal fishing, global climate change (sea level rise, warming, and acidification), and potential vessel groundings.

The large and remote nature of PMNM presents unique challenges for managers tasked with protecting it. Access to PMNM is infrequent, logistically complex, and expensive. The nearest permanently inhabited island, Kauai, lies approximately 269 km to the south and east of Nihoa Island (the southernmost land mass in PMNM), and approximately 2008 km from Kure Atoll (the northernmost

Fig. 1. Papahānaumokuākea Marine National Monument (bounded by the dotted line). Map credit: NOAA.



point of PMNM). The only functional airstrip is located at Midway Atoll, which is primarily used to support USFWS operations there, and also serves as an emergency landing field for trans-Pacific commercial and military flights. All operations in PMNM must therefore be self-sufficient.

Logistics are also challenged by the PMNM's size. For comparison, planning a research mission in PMNM is equivalent in scope to planning a project that stretches from the east coast of the United States all the way to Minnesota, but in a remote location with little to no infrastructure. Currently, access occurs primarily via research vessel, approximately two to three times per year, and may include deployment of temporary field camps on some islands. Year-round staff are present on only two islands, Midway and Kure. The same circumstances that make PMNM challenging to study via traditional methods made it an ideal place to test the potential of advanced technology. This project was also the first deployment of the *Ikhana* outside of the continental United States.

2.2. Test platforms

The payloads of both platforms can be used to provide real-time and post-mission data to support multiple marine monitoring objectives.

2.2.1. Ikhana

In 2006, NASA obtained an MQ-9 Predator B unmanned aircraft system adapted for civilian missions (manufactured by General Atomics Aeronautical Systems, Inc. of San Diego, Fig. 2). The aircraft was subsequently given the name "*Ikhana*" (a Choctaw Native American word for "intelligent, conscious, or aware"). NASA initiated projects to use *Ikhana* in Earth science studies, collecting data in the atmosphere to complement measurements taken from space. *Ikhana*'s potential for other science applications was quickly realized: for example, *Ikhana*'s ability to fly long distances (over 1500 km) and capture detailed images from relatively high altitudes (minimizing potential disturbance to wildlife) offer a clear benefit to resource managers. In addition, these features make it ideal for studying remote areas, which may be difficult (or dangerous) to access using traditional means. Under NASA, the *Ikhana* has flown several successful conservation missions, including assisting the U.S. Forest Service in surveying the 2006 Yosemite and Esperanza fires and conducting a post-burn assessment of the 2009 Station fire. Recognizing the capability of *Ikhana* to support atmospheric and oceanic science, NOAA and NASA began exploring possible applications in 2005. In 2013, a formal partnership was formed that would allow *Ikhana* to be tested on NOAA missions.

The study mission in PMNM was restricted to operations below 7315 m, because of a payload requirement. The *Ikhana* flies at approximately 150 kn. For its mission in PMNM, the *Ikhana* payload included:

1. MTS-B Skyball, which incorporates electro-optical and infrared sensors into a fully gimbaled, turret-mounted sensor suite

Fig. 2. *Ikhana* aircraft. Photo credit: NOAA.

2. SeaVue Radar, which is a synthetic aperture radar that is optimized for maritime targeting
3. Automatic identification system (AIS), which is an automatic tracking system used on ships

2.2.2. Puma AE

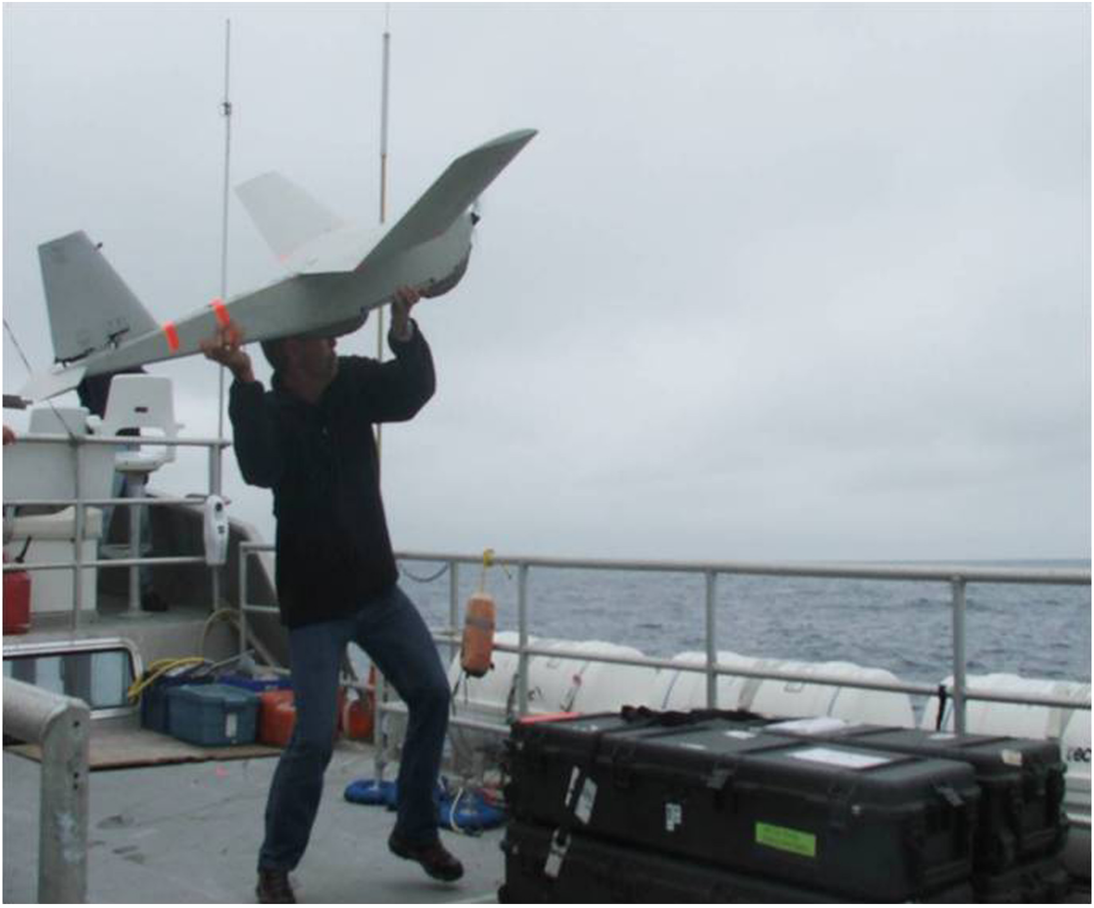
NOAA's UAS program is focused on increasing the Agency's UAS observing capabilities and developing missions with high science returns to transition UAS into cost-effective, feasible data collection systems that can be integrated into routine operations. To further these objectives, NOAA currently owns and operates two Puma AE aircraft systems (each system consists of three air vehicles, a small handheld control unit ("ground control") and telemetry equipment as well as spare parts), which are used on NOAA-specific missions (Fig. 3). The Puma AE is a small UAS designed for land-based and maritime operations. Capable of landing in the water or on land, the latest version of the Puma AE delivers more than 3.5 h of flight time per battery charge, a cruise speed of 45 kn, and a range of 15–25 km with the standard telemetry equipment. The ground control unit allows the operator to control the aircraft manually or program it for GPS-based autonomous navigation. The NOAA UAS program has successfully tested Puma on a number of previous missions. For its mission in PMNM, the Puma payload included a gimbaled and stabilized electro-optical/infrared camera.

2.3. Operations

In June 2014, the NOAA ship *Hi'ialakai* transported and served as the research platform for the Puma UAS team. Daytime Puma missions were conducted at sea from a 9 m rigid-hulled inflatable boat deployed from the *Hi'ialakai* and on land at French Frigate Shoals. Small boat teams consisted of one crew, two Puma operators, one visual observer, and from two to four scientists, while shore parties included two pilots, the visual observer, and multiple scientists. The Federal Aviation Administration (FAA) Certificate of Authorization (COA) for this study limited Puma operation to visual line of sight only. Minimum distance from the vessel for safe operation was considered to be approximately 91 m.

In July 2014, through the partnership between NOAA and NASA, two missions aboard *Ikhana* were allocated to test the ability of the platform to meet conservation objectives. Both flights were scheduled during daylight hours and departed from the Pacific Missile Range Facility, a U.S. Air Force base located in Kauai, Hawaii. The FAA COA for *Ikhana* operations limited flight altitude, and required a chase aircraft, provided by the U.S. Coast Guard Station at Barbers Point, Oahu. The *Ikhana* was

Fig. 3. Puma AE aircraft. Photo credit: NOAA.



manned by a crew of eight at the ground control station in Kauai. Several operational support staff were also present in the hangar and on the ground. A second, "mirror" ground control station was set up on the U.S. Navy base at Ford Island, where NOAA's Inouye Research Center is located. A small crew of technical personnel from NASA, Raytheon, and General Atomics staffed the mirror station, which received data in near-real time from the *Ikhana*. One project researcher was stationed at the Kauai location to relay instructions from scientists to the pilot, while the mirror station was accessed by a rotating group of scientists working on the project.

2.4. Study areas

The UAS testing activities were identified in four primary categories: maritime surveillance (*Ikhana* only), resource studies, marine debris, and coastal mapping. Study areas and requirements, identified during pre-planning stages, are described in the following subsections and summarized in Table 1.

2.4.1. Maritime surveillance

Much of the legal vessel activity in PMNM is known through multiple data sources: ship reporting requirements are in place for vessels of certain size classes, permitted vessels must carry vessel monitoring systems, the U.S. Coast Guard flies scheduled patrols in manned aircraft, and satellite-based AIS data are acquired annually. However, even with these data, the amount of unpermitted vessel activity that may be occurring in PMNM is unknown. Initial analysis of these sources indicates that only 10% of vessels transiting PMNM submit reports in compliance with the International Maritime Organization's Particularly Sensitive Sea Area regulations governing the area (Graham 2015). The *Ikhana* sensor suite for the study flights was designed specifically for maritime surveillance: as it flew over PMNM, sensors detected vessels using AIS and radar, which was compared to known traffic.

Table 1. Areas of interest and study objectives linked to potential platforms and sensors.

Area of interest	Objective	Puma sensors	*Ikhana* sensors
Maritime surveillance	• Observe vessel traffic in PMNM • Support hazard analysis and enforcement	Visual imagery; streaming video; near infrared	Visible (MTS-B Skyball); Infrared (MTS-B Skyball); SeaVue Maritime Radar AIS Receiver
Marine debris	• Support planning for the fall marine debris removal cruise • Locate marine debris ashore, in reefs, and at sea • Improve efficiency of field operations	Visual imagery; streaming video	Visible (MTS-B Skyball);
Hawaiian monk seal	• Count seals at haul-outs • Monitor haul-outs when human observers not present • Improve efficiency of field operations	Visual imagery; streaming video; near infrared	Visible (MTS-B Skyball); Infrared (MTS-B Skyball)
Green sea turtles	• Observe night-time nesting and hatching events	Near infrared	Infrared (MTS-B Skyball)
Cetaceans	• Locate and observe cetaceans • Survey populations	Visual imagery; streaming video	Visible (MTS-B Skyball); SeaVue Maritime Radar
Seabirds	• Monitor bird communities when observers not present • Improve efficiency of field operations	Visual imagery; streaming video; near infrared	Visible (MTS-B Skyball); Infrared (MTS-B Skyball)
Terrestrial and marine habitat	• Survey on-the-ground conditions • Observe dynamic changes in terrain • View reef structures and habitat	Visual imagery; streaming video; near infrared	Visible (MTS-B Skyball); Infrared (MTS-B Skyball)

NOAA ships operating in PMNM during this time were also identified for use as reference targets for close observations by radar, visual, and infrared sensors.

2.4.2. Resource monitoring

2.4.2.1. Hawaiian monk seals

Researchers' primary goal was to determine whether UAS imagery could be used to enhance population data. Population and demographic data have been collected through on-the-ground observation annually for over 30 years. This requires research teams of from two to four people conducting surveys for 2–5 months over the summer at six different atolls. The strength of the dataset is the ability to identify individual animals through a variety of marks (flipper tags, applied bleach marks, scars, etc.). During the planning sessions, it was uncertain what level of resolution would be obtainable from the *Ikhana* and Puma imagery. A resolution of approximately 2.5 cm × 6 cm would be necessary to read flipper tags, and 30 cm × 30 cm to read bleach marks. However, data collected at lower levels of resolution could still yield useful information on abundance and individual body condition (e.g., a "healthy" torpedo shaped body versus "thin" animals with well-articulated neck and obvious hips) or detect injuries or impairments (i.e., shark bites, entanglements, etc.). Both *Ikhana* and Puma platforms were used to collect imagery of monk seals on beaches at various sites in PMNM. No survey grid was set. The small size of Tern and Trig Islands (10.53 and 2.32 ha, respectively) allowed the visual capture of all animals currently using the atoll habitat. The beach and rock platforms at Nihoa Island, where seals are found, is also a small area and so could be captured in its entirety.

2.4.2.2. Cetaceans

Pre-mission planning noted that the probability of sighting cetaceans in PMNM would be low: humpback whales (*Megaptera novaeangliae*) are largely absent from PMNM between June and July, when operations were conducted. Smaller toothed whales, such as false killer whales (*Pseudorca crassidens*), are present, but at low densities. The team planned to use *Ikhana* to image cetaceans with various sensors, if sighted opportunistically. Large cetaceans are known to generate distinctive radar returns, but it was unknown whether the *Ikhana* sensors would able to detect them without specialized processing. Visual and infrared imagery were identified as collection methods for line-transect geometries between the islands of PMNM. Cetaceans occur infrequently in the areas planned for Puma operations; therefore, Puma capabilities could not be specifically tested in this mission area.

2.4.2.3. Green sea turtles

The primary need for sea turtle research in PMNM is to observe nighttime nesting at French Frigate Shoals (the primary nesting site for green sea turtles in the Hawaiian archipelago). However, nighttime operations were not planned for either mission for logistical and safety reasons. Daytime flights on both platforms to monitor monk seals were also used to capture imagery of turtles on the beach as seals and turtles co-occur. The team also planned to capture infrared imagery to determine whether seals and turtles could be differentiated. Again, no survey grid was established for Puma flights. As with monk seals, the images of turtles were examined to estimate size, determine sex, and look for injuries or entanglements.

2.4.2.4. Seabirds

Currently, data collection on seabird populations in the Monument is limited to annual counts at the two manned research sites (Kure and Midway atolls), as well as opportunistic surveys in association with research trips. Both UAS platforms hold potential to collect useful information about seabirds that are on land. If the number of birds on other islands PMNM could be counted by species with UAS, it would bolster available data sets. NOAA and USFWS successfully used UAS (Puma) in this manner on the Olympic Coast of Washington in 2013 (USFWS 2014). Although no specific survey grid was established, post-mission, USFWS researchers reviewed terrestrial footage to determine its suitability for counting and differentiating by species, as well as identification of other meaningful information, such as seabird nesting behaviors.

2.4.3. Marine debris

Current marine debris surveys rely on small boat and in-water dive operations to locate large fishing nets and marine debris caught on the reef for removal. However, the survey area is limited to the amount of area a dive team can cover and visibility to the horizontal azimuth. The ability to "look down from above" using an UAS to identify concentrations within the reef could increase the efficiency of removal operations. The areas of most concern for marine debris in PMNM include Pearl and Hermes Atoll and Maro Reef, both of which were beyond the range of planned *Ikhana* and Puma tests. Although less debris accumulates on the reefs at French Frigate Shoals, it was viewed as a useful site determining the effectiveness of aerial surveys with *Ikhana* and Puma sensors. To evaluate the potential of *Ikhana* and Puma for capturing marine debris imagery, flight plans included a generalized search of near-shore reef areas. Surveys were conducted on reefs that had previously been identified has being debris "hotspots" to increase the likelihood of detecting nets or other items.

2.4.4. Coastal and terrestrial mapping

The collection of coastal and terrestrial imagery for determination of near-shore benthic habitats, soil moisture, and vegetation cover, was a priority for NOAA and USFWS. Near-shore and terrestrial habitat mapping tests utilized the ability of the Puma to capture imagery from a single site (Tern Island, French Frigate Shoals) that could be stitched together to create photo-mosaics. The ability of the *Ikhana* and Puma sensors to penetrate the near-shore waters was unknown. During the planning stages, researchers postulated that if different habitat types were identifiable, the imagery could aid in habitat mapping. To test the sensors' capabilities, imagery was targeted from both top-down (for photo mosaics) and oblique (to analyze erosion) angles, with 30 cm resolution being the ideal goal. For *Ikhana* flights, terrestrial imagery would be captured during overflight of Nihoa Island. To test Puma capabilities, a survey pattern of overlapping passes of Tern Island was planned for one of the flights.

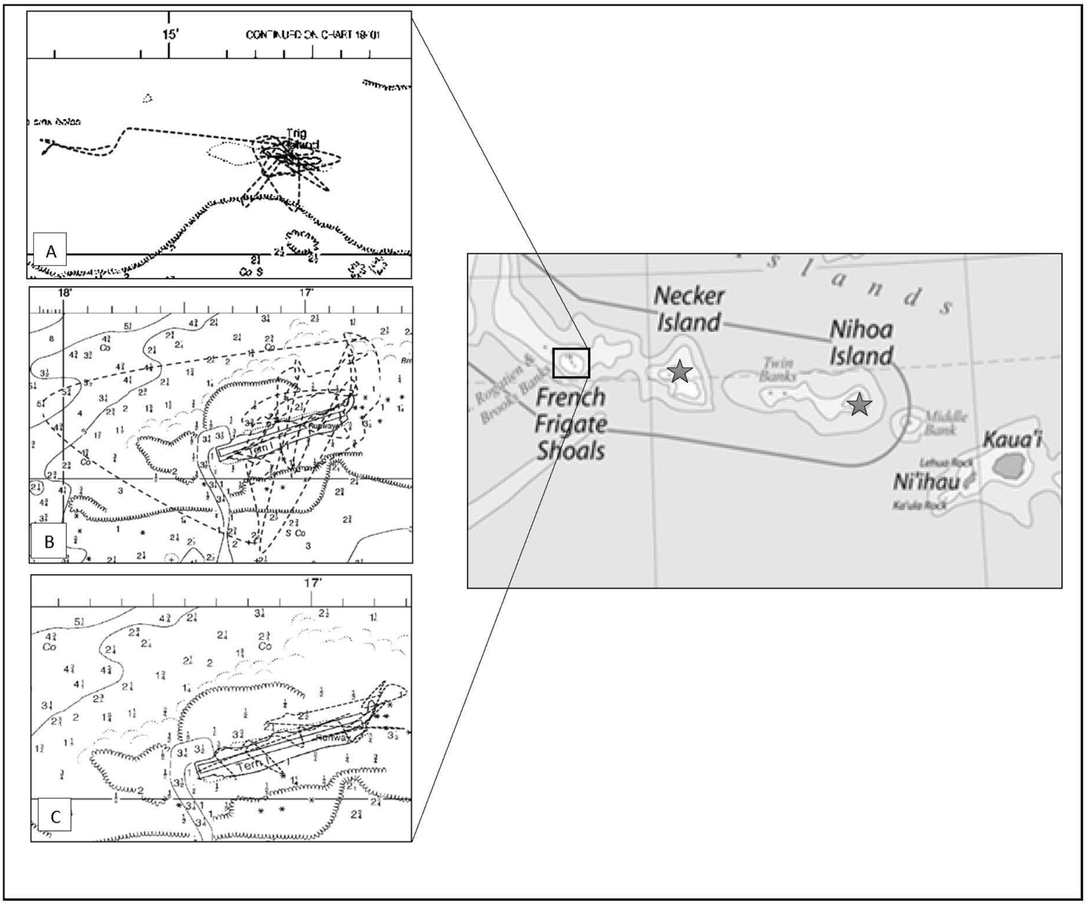
3. Results

3.1. Flight assessment

The Puma was deployed aboard the NOAA Ship *Hi'ialakai* from 16 to 23 June 2014 and flew seven missions (four from the *Hi'ialakai*, one from a small boat, and two from land). The Puma surveyed French Frigate Shoals, Nihoa Island, and Mokumanamana Island, also called Necker Island (see Fig. 4). One flight had to be aborted due to technical difficulties. Over 6 h of footage (approximately 1 h in infrared mode) were collected. The Puma was flown at an elevation of approximately 122–366 m above ground level.

Terrestrial observations with the *Ikhana* took place between 1829 and 3048 m, while maritime observations occurred at approximately 6096 m. The *Ikhana* recorded a total of 19.3 h of footage: 6 h 21 min infrared, 11 h 59 min optical, and 11 min of infrared and optical composite. Approximately 16 h of this footage was usable (contained imagery of targets). The first mission (9.9 h) flew over Nihoa Island, while the second (9.4 h) flew over Mokumanamana Island. An analogous location in the main

Fig. 4. Sample flight tracks from Puma studies. Flight tracks shown for one flight at (A) Trig Island, French Frigate Shoals, and (B) and (C) two flights at Tern Island, French Frigate Shoals. Tern Island is located at approximately 23°52′10.7″N, 166°17′4.6″W. Trig Island is located at approximately 23°52′17.8″N, 166°14′35.9″W. Map scale reference in degrees, minutes, seconds.



Hawaiian Islands was also imaged (Ni'ihau Island, with permission of the land owners, see Fig. 5 for sample track lines). Limited K_u-band satellite coverage prevented the *Ikhana* from reaching French Frigate Shoals as initially planned.

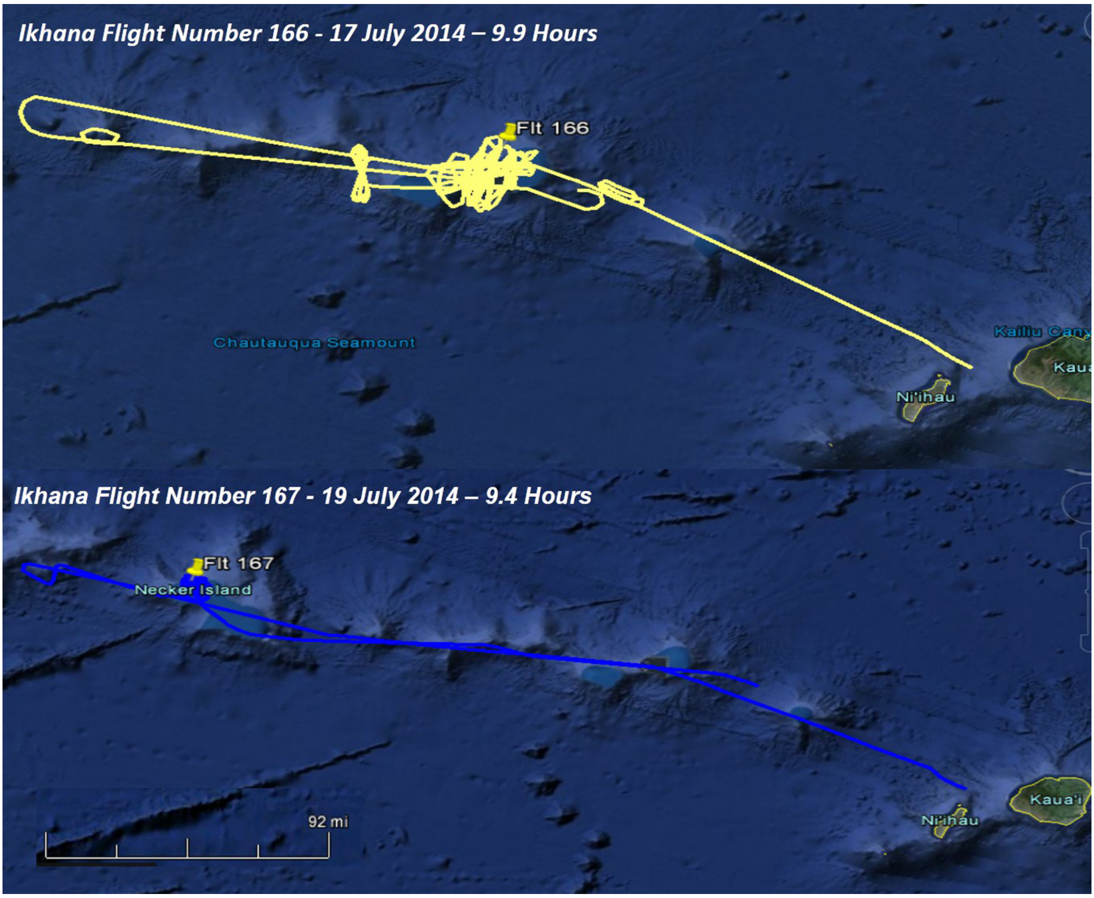
3.2. Disturbance to animals

To avoid disturbance of marine mammals and sea turtles, all Puma footage was collected from above 122 m; NOAA Fisheries biologists studying these species monitored animals for signs of disturbance. USFWS biologists monitored the flights at all times for potential bird interactions. No disturbance of monk seals or sea turtles occurred during either operation. However, some birds approached the Puma from behind and attempted to fly in formation with it, and one bird touched down momentarily on the wing in a possible attempt to attack it. Because of the high altitude at which the *Ikhana* flew, no disturbance was possible.

3.3. Utility of the platforms

Initial observations on utility of UAS for each mission area are described and summarized in Table 2, based on a preliminary review of the imagery and feedback from scientists participating in the research. A full analysis of collected data is in progress. Figures 6, 7, and 8 (and video footage linked to online version of this article) provide representative and comparative imagery captured by the platforms.

Fig. 5. Sample flight tracks for two *Ikhana* flights over the Monument. Map data: Google, SIO, NOAA, US Navy, NGA, GEBCO, LDEO-Columbia, NSF.



4. Discussion

The primary objectives of the project — to determine which targets lent themselves to further study with UAS, which UAS platforms were more useful, and to inform planning efforts for future studies, were achieved. Each UAS platform successfully demonstrated capacity to collect data on marine resources to varying degrees. Initial results described in Table 2 were based on researchers' observations and a preliminary review of the footage. They indicate success in several areas. Researchers are reviewing captured footage in more detail to refine future studies. In this section we discuss several lessons learned from the study.

Advance mission preparation was a key element to the successful completion of this project. The outcome of this preparation was a specific and detailed plan of observations that would avoid the challenges of having too many competing objectives, while providing flexibility to adapt to the observed situation. Because of the multiple objectives at each site, developing a hierarchy of targets was important. Initially, participants thought determining the size of the target objects and resolution needed would be necessary to guide the elevations at which the UAS would be flown. In practice, real-time adjustments were necessary to account for weather and to capture specific angles. Scientists and pilots were able to make adjustments in real-time during Puma operations because they were co-located. As described in the methodology section, during *Ikhana* operations scientists provided direction from a remote station to the operator. This resulted in a communications lag, which limited the group's ability to adjust to conditions on the ground (could not communicate in time to affect the observations as they were being made). A recommendation for the future would be to co-locate scientists with *Ikhana* pilots to allow for more real-time adjustments.

Table 2. Summary of results.

Area of interest	Puma	*Ikhana*	Observations
Maritime surveillance	Not tested	Tested	Although no unknown vessels were found inside of PMNM waters, a float buoy (installed) was successfully located and imaged during the study. Observers had high confidence that *Ikhana*'s sensors could be used for vessel identification based on this and previous experiences.
Hawaiian monk seals	Tested	Tested	Both platforms captured footage of monk seals and mother–pup pairs that could be used to supplement existing data on population count and population health (e.g., basic body condition information, such as healthy, torpedo-shaped animals, could be discerned form the footage). Identification markings (bleach tags of 30 cm, flipper tags of 6 cm) were not apparent in imagery from either platform. Because the vast majority of seals at the study sites are tagged, it is clear that these two platforms could not be used to capture tag data.
Cetaceans	Not tested	Not tested	To date, no cetaceans have been identified in captured footage (footage still under review).
Green sea turtles	Tested	Tested	While no nighttime footage was captured, imagery of turtles from daytime flights could be used for population counts and potential for capturing relative measurements. Infrared tests conducted during the day indicated that nighttime surveys would likely be highly successful (e.g., it was possible to differentiate between seals, (adult) sea turtles, and seabirds). The study was conducted outside of nesting season, so although turtle tracks were visible in the sand no nests were present.
Seabirds	Tested	Tested	Preliminary analysis (pers. comm., M. Kuter USFWS, 2015) of Puma footage indicated it was difficult to visually differentiate between most ground-nesting seabird species on vegetated islands, such as Nihoa and Tern islands. Conversely, on sparsely vegetated or all-sand islands, such as Trig Island, virtually all above-ground species could be determined. It was possible to positively identify the following seabird species on vegetated islands: black-footed albatross (adults), Laysan albatross (*Phoebastria immutabili;* adults), great frigatebirds (*Fregata minor*), and red-footed boobies (*Sula sula*); terns and albatross chicks could be identified with no further classification to species. The utility of the Puma was limited by the lack of sensors capable of capturing imagery of high enough resolution to successfully enlarge and identify animals of this size (approx. 30 cm). From the *Ikhana* images, great frigatebirds, red-footed boobies, and albatross chicks could be distinguished on some of the vegetated sections; white terns (*Gygis alba*) could be identified on some of the cliffs. The enhanced optics of the *Ikhana* demonstrated more promising results but further investigation is needed.
Marine debris	Tested	Tested	The primary areas of interest could not be surveyed. Neither platform clearly demonstrated the ability to detect subsurface marine debris. There may be potential for both systems to aid in the detection of floating debris but more testing is needed, as only one target was identified during these flights. A floating buoy (installed) was identifiable in Puma footage. Imagery of debris on land was captured by both sensors.
Habitat mapping	Tested	Tested	While the Puma provided high quality imagery of the terrestrial and near-shore habitat (including limited penetration of the sea surface and imagery of reef structure), *Ikhana* footage was grainy and did not penetrate the sea surface. The *Ikhana* sensor also gimbaled excessively when looking straight down, limiting its utility for constructing photo mosaics. Although resolution varied depending on angle and altitude, the best Puma images achieved better than the desired 30 cm resolution.

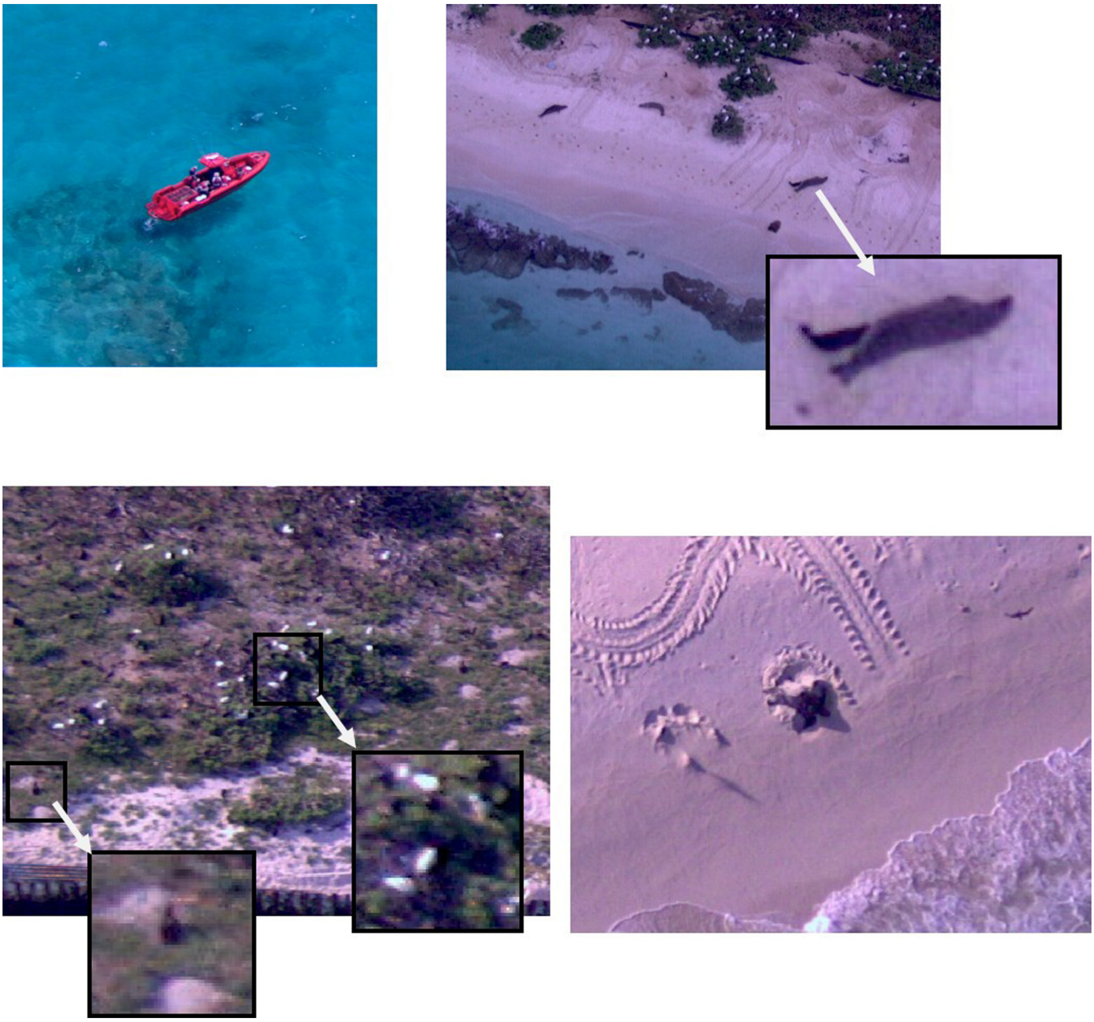
Fig. 6. Comparison between *Ikhana* (right top and bottom) and Puma (left top and bottom) imagery captured at the same Nihoa beach. Post-processing zooms (bottom photos) showing marine debris (e.g., orange buoy) and monk seals. Photo credit: NOAA.

Although our study did not utilize standard survey grids, establishing preset patterns would also improve efficiency in operations and enhance scientific rigor. Given these experiences, researchers using UAS should anticipate deviations from survey patterns and ensure a protocol is in place for documenting these changes. Further consideration in analysis methods (e.g., changes to sighting probability based on deviations) would also be necessary. Having the pilots and scientists practice prior to the mission in a simulated environment could make operations more efficient and successful. A fourth lesson learned is that providing additional training to pilots and crew on the species and habitats targeted, as well as the researchers' objectives would improve operators' situational awareness and potentially the usefulness of data captured.

Poor weather conditions (a high degree of moisture in the atmosphere) on one day of the *Ikhana* operations reduced the quality of the footage captured. Visibility also decreased over the course of the day as cloud cover increased. In the future, having a wider window in which to conduct operations would enable data to be collected during optimum conditions. Both platforms also experienced issues with shadows on the sides of Nihoa and Mokumanamana Islands' cliffs and glint on the water (Fig. 9). Lighting of the target area is clearly an important consideration.

Unfortunately, circumstances prevented comprehensive field-testing in two important areas, cetaceans and marine debris, and limited information was collected on green sea turtles. Data collected in the other mission areas indicate that both UAS platforms hold potential to provide a new source of information for these targets. In the case of cetaceans, none were sighted with UAS (likely due to overall low presence in PMNM). Using hydrophones to cue pilots in the direction of cetaceans would be one method to determine how well platforms capture imagery of various cetacean species under differing weather and sea conditions. Transiting PMNM during times of high cetacean presence (such as January–May, when humpback whales migrate through the area) or targeting known island-associated populations of spinner dolphins at Midway or Kure would be another option to increase sighting probability. For marine debris, the degree of water clarity in the captured footage also indicates that it may be possible to locate large debris items, such as fishing nets caught on the reef, identifying targets for removal in advance of putting a team in the water. Debris of multiple sizes

Fig. 7. Representative Puma images (clockwise) for surveillance, monk seals, sea turtles, and seabirds at French Frigate Shoals. Note that Puma recordings imparted a slight pinkish cast to the sand. Photo credit: NOAA.



was also clearly visible on the shoreline by both platforms, and could be targeted for later removal. This capability could be useful following large disaster events, such as the 2011 Japan tsunami, which resulted in the deposition of large debris items in the NWHI. Adding nighttime flights, which the Puma and *Ikanan* are capable of, may allow for capturing turtle nesting behavior, and is recommended for testing in the future. Use of infrared imaging during nighttime flights would also be useful in capturing data on the presence of monk seals at night, a time that is not part of current survey patterns.

5. Conclusion

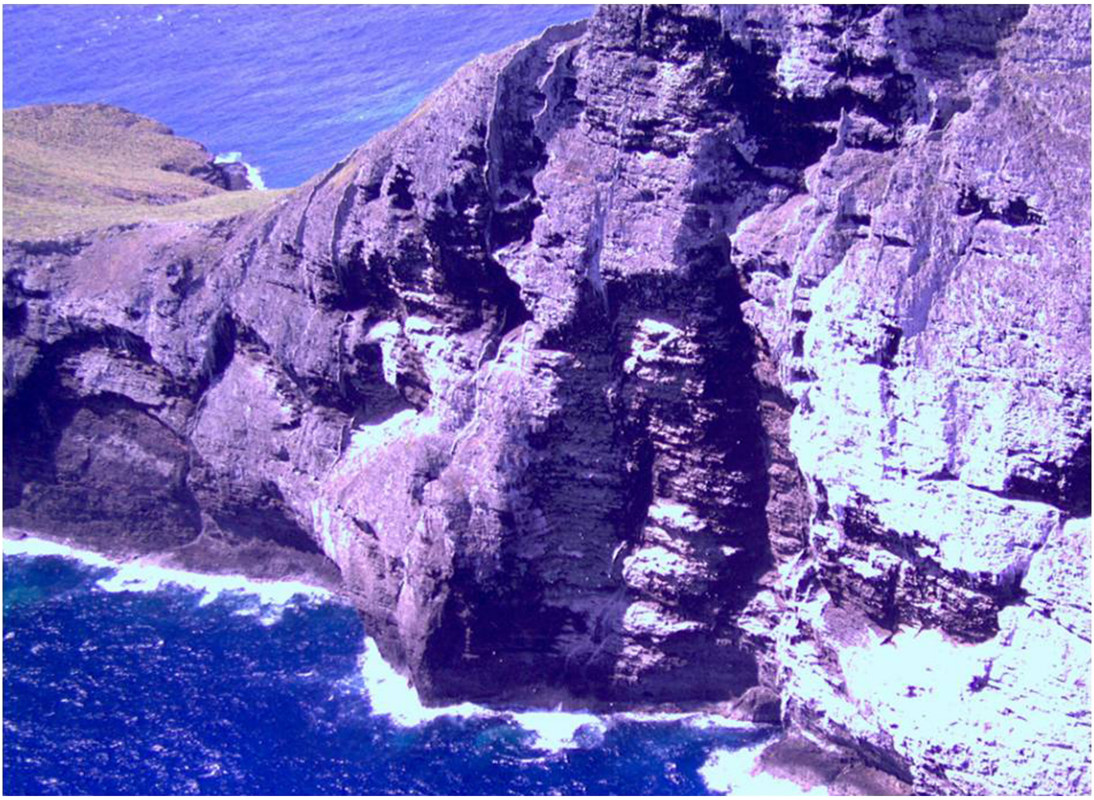
Testing new technologies, documenting, and sharing the results is becoming increasingly important to scientists and resource managers as they struggle to respond to escalating threats to marine and terrestrial resources. This exchange is particularly relevant given the resources needed to evaluate them. Importantly, post-processing resource demands are also high: appropriate staff and technology are necessary to transform UAS data into accessible formats. Scientists must then review many hours of footage and associated data logs to derive useful data products.

In this study, the potential of UAS platforms to contribute to research and management objectives was confirmed to varying degrees. Both Puma and *Ikhana* provided useful population data for larger species on shore (e.g., seals and turtles), as well as limited information on birds and vegetation.

Fig. 8. Near-shore imagery of subsurface reef structure at French Frigate Shoals, captured by Puma. Photo credit: NOAA.

Puma provided better imagery for use in studies of terrestrial and near-shore environments. Long-range UAS, such as *Ikhana*, can provide a vital leap in awareness of the risk to fragile marine resources from unauthorized access to PMNM waters, and could also aid in quickly evaluating the impact and response need to unusual mortality events and to natural or anthropogenic disasters, such as an tsunamis, storms, or oil spills. Additionally, they provide observation capabilities when human access is limited. For example, a future *Ikhana* mission in PMNM would be most useful in the winter months, when NMFS field crews are not present in the NWHI and limited data on seal presence have been collected.

Fig. 9. Example image of lighting effects. Some areas of the cliffs (Nihoa Island) are washed out, while others are in shadow. Photo credit: NOAA.



Although their utility is now documented, cost and feasibility aspects of UAS may continue to limit further testing and methodology refinements. Smaller UAS platforms, such as the Puma or vertical take-off and landing (VTOL) systems, may be more affordable for science programs. A personal UAS can be purchased for approximately $1000, while more advanced platforms like Puma cost much more. The availability of UAS like the *Ikhana* is much more limited and extremely costly. There is potential that leveraging multi-purpose missions (for example, the NASA–NOAA partnership described here) will allow for resource agencies to take advantage of these systems. As demonstrated by this study, the imagery captured using UAS can potentially be used by researchers working on more than one subject. Multi-purpose missions are often cost-effective and more efficiently leverage the limited opportunities to access remote areas like PMNM, as not all researchers have to be present to benefit from data collected.

Other methods of conducting research in remote places are also often at high cost (e.g., land-based surveys for monk seals, fixed-wing aircraft for cetacean or enforcement surveillance), and may be comparable with UAS costs over time. Additionally, operation of small UAS still requires ship access to PMNM. Because of the remote nature and limited opportunities for access, each trip is multi-purpose in nature, so a side-by-side comparison of the costs for obtaining data using ship versus UAS platforms is not possible. Further, in PMNM, UAS can never fully replace the work of human researchers. For example, field teams must still access PMNM to conduct the interventions (vaccinations, disentanglements, translocations, etc.) that are critical to Hawaiian monk seal recovery. Similarly, marine debris must still be removed by divers and snorkelers, and transported out of PMNM by vessels. Therefore, UAS will provide useful augmentation and increased efficiency through its inclusion in these projects, but is not sufficient by itself for all objectives.

In the future, capabilities of UAS may be increased to maximize their utility and appeal to researchers. For example, scientists participating in this study recommended addition of sensor payloads that capture hyperspectral imagery and LiDAR, which would be useful for habitat mapping and analyzing sea level rise. Increased resolution cameras that support capture of more detailed imagery are already being tested. Automatic image recognition software could further speed processing times. Additionally, as scientists and managers become more aware of the research environment, we can better direct the development of new sensors. For example, NASA and Remote Sensing Solutions, Inc. are currently working on interferometric synthetic aperture radar techniques to provide extremely high resolution single-pass three-dimensional imagery. Post-processing of original data is another option for the future: this analysis may reveal additional information when geo-referenced using geographic information systems software.

Although not an exhaustive examination of the capabilities of all UAS platforms, the results of this study have applications to researchers working on other topics and with other systems. Locations that would potentially benefit from use of UAS include very remote locations as well as those identified as particularly hazardous for manned aviation (for example, the Aleutian island chain and the North Atlantic) or where field team safety is a concern (e.g., Nihoa Island in PMNM, which has a small area where seals are found, but a very difficult landing site). Areas where disturbance of wildlife is a concern or that are difficult to access (e.g., birds nesting in cliffs) may also make good candidates for UAS study.

Researchers and managers interested in UAS as a potential tool should consider costs, efficiencies, and appropriateness of the proposed platform, because capabilities vary widely. Sharing research results will also be critical to identifying best practices and to increase the likelihood that UAS will become tools of choice. NOAA's Pacific Islands Region plans to continue UAS testing in PMNM during 2015, expanding platforms to include VTOL systems, informed by the preliminary studies documented herein.

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