Arctic Aerial Calibration Experiments (Arctic ACEs): Comparing Manned Aerial Surveys to Unmanned Aerial Surveys for Cetacean Monitoring in the Arctic

By

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LIST OF ABBREVIATIONS

AEWC: Alaska Eskimo Whaling Commission

AFSC: Alaska Fisheries Science Center

ASAMM: Aerial Surveys of Arctic Marine Mammals

ASAPS: Atmospheric Sensing and Predicting System

BOEM: Bureau of Ocean and Energy Management

COA: Certificate of Authorization

CS: Control Station

DEW: Defense Early Warning

EO: Electro-optical

FAA: Federal Aviation Administration

GCS: Ground control station

IFC: Interim Flight Clearance

ISO: International Organization for Standardization

ISR: Intelligence Surveillance and Reconnaissance

JISAO: Joint Institute for the Study of Atmosphere and Ocean

MML: Marine Mammal Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration

MSL: Mean Sea Level

MOA: Memorandum of Agreement

NARL: Naval Arctic Research Laboratory

NAVAIR: Naval Airs Systems Command

NOAA: National Oceanic and Atmospheric Administration

NOTAM: Notice to Airmen

NSBDWM: North Slope Borough Department of Wildlife Management

NSWCDD: Naval Surface Warfare Center Dahlgren Division

ONR: Office of Naval Research

PEMDAS: PEMDAS Technologies and Innovations

PIC: Pilots in Command

QA/QC: Quality Assurance/Quality Control

QC: Quality Control

SIMOPS: Simultaneous Operations

TCAS: Traffic Alert and Collision Avoidance System

UAS: Unmanned Aerial System

UAV: Unmanned Aerial Vehicle

ABSTRACT

Manned aerial surveys are routinely used to assess cetacean distribution and density, often over large geographic areas. Unmanned aircraft systems (UAS) have been identified as a technology that could augment or replace manned aerial surveys for marine mammals. To understand what research questions involving cetacean distribution and density can be addressed using manned and UAS technology in the Arctic, we conducted paired aerial surveys for cetaceans near Utqiaġvik (Barrow), Alaska. We present the methods and operational and analytical results from the project, and challenges encountered during the field work. Weather varied dramatically over small spatiotemporal scales and harsh environmental conditions increased the maintenance required for repeated UAS operations. Various technologies, such as a temperature and humidity sensor, a software system that provided near-term forecasts of highly variable weather, and a surface-based air traffic radar feed, directly contributed to the ability to conduct routine, successful beyond line-of-sight UAS flights under these situations. Bowhead whale abundance estimates derived from the marine mammal observer data were roughly comparable, but slightly higher than those from the Turbo Commander imagery; comparisons to the UAS imagery depended on survey sector and analytical method. Beluga abundance estimates derived from either dataset collected aboard the Turbo Commander were higher than estimates derived from the UAS imagery. Uncertainties in abundance estimates derived from the marine mammal observer data were lower than estimates derived from either imagery dataset due to the small sample sizes in the imagery. The visual line-transect aerial survey conducted by marine mammal observers aboard the Turbo Commander was considerably less expensive than the cost of the UAS survey, although we expect costs of the latter to decrease over time. We provide recommendations for future projects to help streamline project planning and enhance researchers' ability to use UAS to collect data needed for ecological research.

EXECUTIVE SUMMARY

Unmanned aircraft systems (UAS) have been identified as technology that could revolutionize the way aerial surveys for cetaceans are conducted in order to collect information on distribution, density, or abundance. During two weeks in early fall 2015, staff of the Marine Mammal Laboratory (MML), Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration conducted a comparison of manned and unmanned aircraft surveys for cetaceans near Utqiaġvik (Barrow), Alaska.

The project involved a three-way comparison among visual observations made by marine mammal observers aboard a Turbo Commander aircraft; imagery autonomously collected by a digital camera system mounted on the Turbo Commander; and imagery collected by a digital camera system on a ScanEagle® UAS (Figure 1).

Weather varied dramatically over small spatiotemporal scales and harsh environmental conditions increased the maintenance required for repeated UAS operations. Various technologies, such as a temperature and humidity sensor, a software system that provided near-term forecasts of highly variable weather, and a surface-based air traffic radar feed, directly contributed to the ability to conduct routine, successful beyond line-of-sight UAS flights under these situations.

Because the field of view visible to human observers in an aircraft is much greater than the area visible by the camera system aboard the UAS, human observers saw more cetaceans that could be identified to species than were visible in imagery from the UAS during a similar number of flight hours (Table 1); human observers saw additional cetaceans that could not be identified to species because of their distance from the aircraft. Bowhead whale abundance estimates derived using manned and UAS techniques were roughly similar, but estimates from the data collected by people in the manned aircraft were higher and had lower variance than those from the UAS, because of the smaller sample sizes in the imagery from the UAS. The visual line-transect aerial survey conducted by marine mammal observers aboard the Turbo Commander was 68.5% of the cost of the photo strip-transect survey aboard the same aircraft and 9.4% of the cost of the UAS survey; we expect the costs of using UAS for this type of project will come down over time. (Table 2).

Key outcomes:

- Overall, using UAS to collect data to estimate cetacean density or abundance is promising, but is logistically complicated and is currently considerably more expensive than a comparable manned aerial survey.
- To ensure the safety of manned aircraft flying in close proximity to UAS, precise relative position information on UAS location is essential to enable pilots to maintain separation. Visual detection of UAS by manned aircraft pilots is extremely difficult. Until a detection system is utilized, manned aircraft and UAS must be separated by pre-determined vertical and horizontal boundaries. Traffic Alert and Collision Avoidance System (TCAS) on the manned aircraft was insufficient for separation when flying within close range of the UAS with a mode C transponder.
- Until accurate and reliable software for automatically detecting cetaceans in imagery is developed, imagery collected by UAS must be processed manually, and that is a time-consuming process.
- The smaller area effectively sampled by the cameras on the UAS limits the usefulness of UAS technology for mitigation measures such as detecting all animals inside or approaching safety zones established around anthropogenic activities. To accommodate the smaller area sampled by the UAS, additional flight time or wider camera angles would be required.

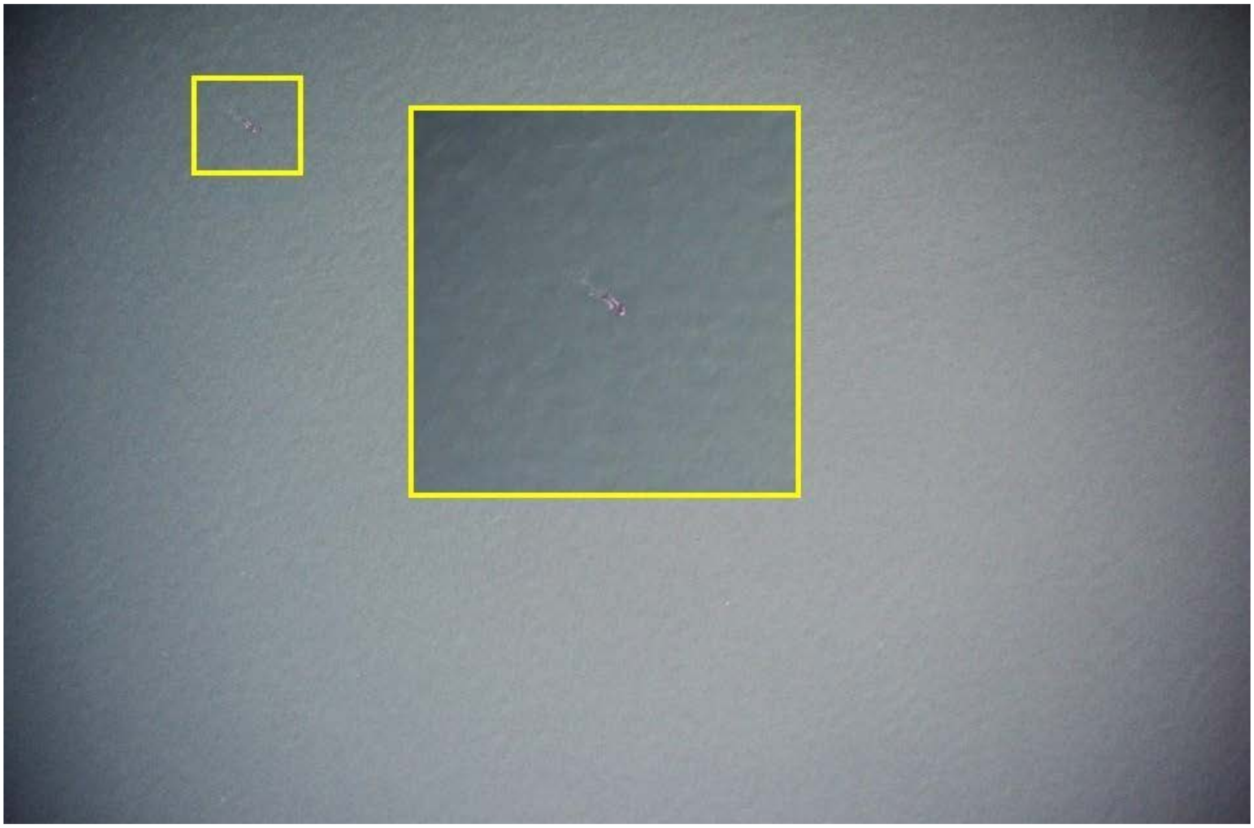

Figure 1. Sample image of a bowhead whale from the UAS imagery taken from 272 m (893 ft) altitude; the magnified section that includes the whale was added manually during post-processing.

Table 1. Summary of bowhead whales detected in images collected by the UAS and manned aircraft, and detected by marine mammal observers aboard the manned aircraft (Ferguson et al. 2018).

	West Survey Sector				East Survey Sector			
	Imagery		Marine Mammal Observers		Imagery		Marine Mammal Observers	
	UAS	Manned Aircraft	Limited Data	Historical Data	UAS	Manned aircraft	Limited Data	Historical Data
# Whales Detected	3	2	8	11	6	4	12	12
Area Covered (km)	525.4	646.0	8829.8	5927.2	448.5	645.9	7166.0	5127.3
Estimated Total # Whales	29	16	32	63	82	38	63	83
CV	0.77	0.71	0.51	0.41	0.53	0.45	0.41	0.36

Table 2. Commensurate costs required to collect, process, archive, and analyze data during the 2015 UAS and Turbo Commander strip-transect surveys that collected imagery data, and the Turbo Commander line-transect surveys conducted by marine mammal observers. $: < $150,000 US dollars (USD). $$: $150,000-250,000 USD. $$$: $250,000-1,000,000 USD. $$$$: $1,000,000-2,000,000 USD. $$$$$: >$2,000,000 USD.

	UAS Photo Strip-Transect	Turbo Commander Photo Strip-Transect	Turbo Commander Line-Transect
Field Work and Planning	$$$$	$$	$
In-kind Contributions	$$$		$
Post-field Work Expenses	$	$	$$
TOTAL	**$$$$$**	**$$**	**$$$**

BACKGROUND

Manned aerial surveys from fixed-wing aircraft have been used successfully for decades to achieve diverse scientific and wildlife management goals. Aerial line-transect surveys for marine mammals collect data that can be used to estimate density or abundance and investigate habitat use and behavior (Buckland et al. 2001, Garner et al. 1999). NOAA Fisheries, the Department of the Interior, the North Slope Borough Department of Wildlife Management, and other agencies have been involved in many marine mammal research flights in the Arctic designed to provide information on animal density and distribution important to both the agencies and to North Slope residents. These long-term datasets provide management entities with information they need on the status of the marine mammal populations.

Manned aircraft have been used successfully for decades to conduct valuable research, monitoring, and mitigation activities, and will continue to be used in the foreseeable future. However, these survey platforms do have limitations. First, there are risks inherent in flying low-altitude manned surveys that must be mitigated to reach an acceptable level of safety for the survey team. Second, observer discomfort or fatigue caused by extended periods of time aboard the aircraft can affect data collection. Third, manned aircraft, like any survey platform, have the potential to disturb wildlife. Lastly, manned aircraft burn fuel at a high rate, resulting in high costs and consumption of non-renewable resources.

Marine mammal aerial surveys conducted by unmanned aerial systems (UAS) may not be affected by some of the limitations of manned aircraft and could be a reliable, effective, and efficient way to collect data to address questions in marine mammal ecology and management. Hereafter, we refer to the combination of the airframe, control station, and pilot as a “UAS,” and to the airframe alone as an unmanned aerial vehicle (UAV). UAS have only recently been used in ecology and wildlife management, but their use is growing rapidly (Watts et al. 2010, Sarda-Palomera et al. 2012, Anderson and Gaston 2013), and includes multiple marine mammal research applications (Koski et al. 2009, Hodgson et al. 2010, Koski et al. 2010, Hodgson et al. 2013). The use of UAS to survey pinnipeds is still in its infancy, but it has been successfully used to collect images of Arctic ice seals (Cameron et al. 2009, Moreland et al. 2015) and Antarctic pinnipeds (Goebel et al. 2015) and tested for Steller sea lions (Fritz 2012). Hodgson et al. (2013) conducted strip-transect surveys for dugongs in Australia using a ScanEagle® UAS with a digital SLR camera payload and concluded that this type of UAS has “great potential as a tool for marine mammal aerial surveys.” Strip-transect surveys are based on the assumption that all animals within the area searched are detected.

While UAS have great potential, the specific data and sampling requirements for research have not been fully tested, particularly in the Arctic. Existing UAS technology integrated with a digital camera payload needs to be evaluated to determine how well it performs relative to conventional manned aerial surveys to collect data on cetaceans. The balanced use of manned and unmanned technology for implementing and evaluating management of wildlife is a priority, and this arctic mission is one of the first dedicated experiments specifically designed to understand the advantages and disadvantages of using UAS relative to manned aircraft to collect data for estimating marine mammal density.

RELEVENCE TO THE BUREAU OF OCEAN ENERGY MANAGEMENT (BOEM)

BOEM, along with NOAA Fisheries and the Office of Naval Research, supports research and technology development related to understanding the distribution and abundance of marine mammals in key areas. In addition, it is important for these agencies to quantify the number of individuals of each species that could be affected by a proposed activity; the degree to which the proposed activity is conducted within biologically important areas, such as feeding grounds and migration pathways; the age and sex class of affected species; and the types of effects on individuals and populations these activities may have.

Aerial and vessel-based line-transect surveys are widely used and broadly accepted methods for collecting data to study spatiotemporal patterns in cetacean density, abundance, distribution, habitat use, and behavior and for mitigating and monitoring the effects of oil and gas exploration or development, military activities, and other anthropogenic activities to understand potential effects and ensure environmental compliance. However, these methods are time and labor intensive and could be unsafe for human observers to implement, especially during military activities or in areas far offshore. Strip-transect surveys conducted by UAS have the potential to replace manned aerial and shipboard line-transect surveys for some combinations of species/populations, time periods, and areas, thereby minimizing risks to human life, reducing disturbance to wildlife, and possibly decreasing the logistical complexity associated with data collection. Furthermore, with reliable automatic image detectors, the labor required to process the survey data could decrease considerably, making imagery data collected by UAS valuable for mitigating risks to marine mammals. As survey and analytical efficiency increase, financial burdens decrease.

Before BOEM, the Navy, and NOAA Fisheries can accept UAS surveys in place of, or as a supplement to, conventional aerial survey methods, the performance of UAS relative to human observers in manned aircraft must be understood. This project, Arctic Aerial Calibration Experiments (Arctic ACEs), addresses this critical question. We provide recommendations on the types of cetacean study objectives that likely can be met by UAS currently and in the near future, describe improvements in UAS technology and imaging systems required to effectively study cetaceans in the Arctic (and elsewhere), and recommend adaptations to the traditional analytical processes for estimating density.

PROJECT OBJECTIVES

The goal of this study was to evaluate the ability of UAS technology (i.e., platforms, payloads, sensors, and software) to collect data to detect cetaceans, identify species, estimate group size, and identify calves and compare those results to conventional aerial surveys conducted by human observers in fixed-wing aircraft as part of the Aerial Surveys of Arctic Marine Mammals (ASAMM) project. Data collected from the UAS were used to estimate cetacean density and other parameters in the survey area and to compare these values to analogous values obtained using data from the manned aircraft. This evaluation enabled the development of recommendations for the types of cetacean study objectives that can likely be met by UAS currently and in the near future, identification of improvements in UAS technology and imaging systems required to effectively study cetaceans in the Arctic (many of which will be applicable to cetacean surveys conducted elsewhere), and recommended adaptations to the traditional analytical processes for estimating density. Our overarching objective was to conduct a 3-way comparison of data and derived statistics from the following:

- Observers in the manned aircraft;
- Digital photographs from cameras mounted to the manned aircraft;
- Digital photographs from cameras mounted to the unmanned aerial vehicle (UAV).

Specific Objectives:

1. Collect digital photographic data from small UAS (sUAS) during strip-transect surveys of cetaceans in the Arctic.
2. Collect digital photographic data from the ASAMM aircraft concurrently with line-transect ASAMM surveys.
3. Evaluate the ability of trained observers/photo-interpreters to detect marine mammals in photographic images.
4. Evaluate existing software to detect cetaceans in aerial digital photographic data collected from manned and unmanned aircraft.
5. Estimate trackline detection probability for marine mammal observers participating in the ASAMM project.
6. Estimate the trackline detection probability for photo-interpreters from imagery collected during the ASAMM project.
7. Compare the performance of manned and unmanned aircraft surveys based on metrics such as the following: i) number of sightings made by each platform, including false positive and false negative rates; ii) ability to identify sightings to species, estimate group size, and detect calves; iii) precision and bias of the resulting density

estimates; iv) relative efficiency of each platform, measured by length of trackline and duration of survey and analytical effort required to achieve target precision in the density estimate or to compute other derived parameters; v) survey and analysis cost; and vi) fuel consumption.

8. Provide recommendations to the Navy, NOAA Fisheries, and BOEM about the types of cetacean study objectives that can likely be met by UAS technology now and in the near future.
9. Describe improvements in UAS technology and imaging systems required to study cetaceans in the Arctic (and elsewhere).
10. Recommend adaptations to the traditional analytical processes for estimating density.

METHODS

Research Team

The project was initiated and managed by principal investigators (PIs; Angliss and Ferguson) from the National Marine Mammal Laboratory, now called the Marine Mammal Laboratory (MML), Alaska Fisheries Science Center, NOAA Fisheries. The PIs and others at NOAA developed the survey design, purchased the payload, designed and evaluated flight tests of the payload, led the development of the concept of operations, ensured that all Marine Mammal Protection Act and local land use permits were obtained, and ensured that both local pilots and the local community were aware of the project. In addition to the NOAA PIs, NOAA staff and contractors who played a key role in the project included:

- CAPT Phil Hall (OMAO) – advised on Certificate of Authorization (COA) preparation and beyond visual line-of-sight flight operations; served as the NOAA liaison with the Federal Aviation Administration (FAA);

- Van Helker (Oceans Associates, Inc) – drafted documents needed for clearance within NOAA and the Navy; NOAA lead for shipboard integration on the RV *Fairweather*; project liaison on the *Fairweather* during field operations;

- Amy Kennedy (Joint Institute for the Study of the Atmosphere and Ocean – JISAO) – selected and conducted pre-season evaluation of the camera payloads; lead for in-field image collection; developed imagery data processing protocol; lead for training UAS image photo analysts investigating automated image detection systems, and quality control.

The Naval Surface Warfare Center Dahlgren Division (NSWCDD) was responsible for managing all aspects of the UAS operations. The NSWCDD team submitted the request for a COA to the FAA for clearance to conduct beyond visual line-of-sight (BVLOS) operations and all paperwork (e.g., risk assessment) needed to obtain clearance from the Navy. They integrated and tested NOAA's camera payload, were responsible for most logistics for the UAS portion of the field project, and conducted UAS flights to collect imagery between August 26 and September 6, 2015. While in the field, the NSWCDD team was responsible for all pre-flight and post-flight tasks, including all maintenance needed to ensure that the full UAS system (ground control stations, communications systems, platforms, and payloads) were ready to fly each day, posting Notices to Airmen (NOTAMs), and post-flight reporting. NSWCDD staff, contractors, and associates filled the following roles:

- Site Lead/Airboss
- ScanEagle® Pilots in Command (PIC)
- Payload Integration Engineer
- Managerial Support
- ScanEagle® Launch and Recovery Technician
- ScanEagle® Subject Matter Expert / ScanEagle® Launch and Recovery Technician

We worked closely with Todd Sformo of the North Slope Borough Department of Wildlife Management (NSBDWM) because of the agency's interest in the use of new technology to study large whales and to ensure that our project could be successfully integrated into the Utqiaġvik community. The NSBDWM provided guidance about key individuals and organizations to contact to be certain that the project would not interfere with important Alaska Native subsistence harvest activities.

The ASAMM team conducted the manned aerial surveys needed for comparison to the UAS surveys funded under this award. ASAMM is funded and co-managed by BOEM, conducted by AFSC, and led by Megan Ferguson and Janet Clarke (Leidos). The ASAMM time series began in 1979 and represents one of the longest-running aerial surveys of marine mammals in the world. During the UAS field season, the ASAMM pilots and marine mammal observers were:

- Amelia Brower (JISAO) – ASAMM Flight Team Leader
- Stan Churches (Clearwater Air, Inc) – Pilot in Command
- Vicki Beaver (Ocean Associates, Inc) – Marine Mammal Observer
- Greg Pfeifer (Clearwater Air, Inc) – Second in Command
- Karen Vale (Ocean Associates, Inc) – Marine Mammal Observer

Study Area

UAS aerial surveys were conducted in airspace over the northeastern Chukchi Sea and western Beaufort Sea (Figure 2). The study area is located approximately 12-60 nmi (22.2-111.1 km) from shore on either side of Utqiaġvik, Alaska. This area was selected for UAS operations for three reasons. First, the study area lies within an area where the FAA plans to establish permanent operational areas and corridor routes (for access to coastal launch sites) in the Arctic for the operation of small UAS. We anticipated that this emphasis would enhance our chances of receiving FAA permission for beyond visual line-of-sight flights needed for the project. Second, large cetaceans, particularly gray whales and bowhead whales, are reliably found in high densities near Peard Bay and Barrow Canyon, respectively, during the open water (ice-free) season, which occurs from July to October. High densities of cetaceans are preferred in order to obtain the sample sizes (number of sightings) required to derive robust conclusions about the relative performance of manned aircraft and unmanned aircraft systems in a reasonably short amount of time. Third, the study area is located in international airspace, offshore of the coastal corridor where aircraft frequently transit between villages on the North Slope of Alaska. Operating in this low-density traffic area increases the safety margin for the project by decreasing the probability of encountering other airspace users.

The project team considered operating out of Wainwright, Alaska, due to the proximity of Wainwright to an area of high density of gray whales near Peard Bay. Conducting the project out of Wainwright was less favorable due to the high cost of chartering a commercial C130 aircraft that would be needed to transport the UAS equipment and because of the high cost and limited availability of launch and retrieval sites in Wainwright. Utqiaġvik afforded both a sufficiently large runway to allow the Navy C130 to transport the UAS gear at no cost to the project and did not require fees for access to the launch and retrieval site.

Weather during the late summer and early fall in the Arctic can range from cloud-free and sunny to snow, sometimes within the same day. Based on many years of experience conducting manned aerial surveys in the Arctic, the team expected to experience near-freezing and below-freezing temperatures, high winds, fog, low ceilings, various types of precipitation, and potential for the UAV to experience both structural and carburetor icing (which is more likely to occur with high relative humidity and low ambient temperatures). Based on the number of flight days flown historically by ASAMM, this project expected to be able to conduct flights on 5-6 days during a 17-day field season planned to occur between 14-31 August 2015.

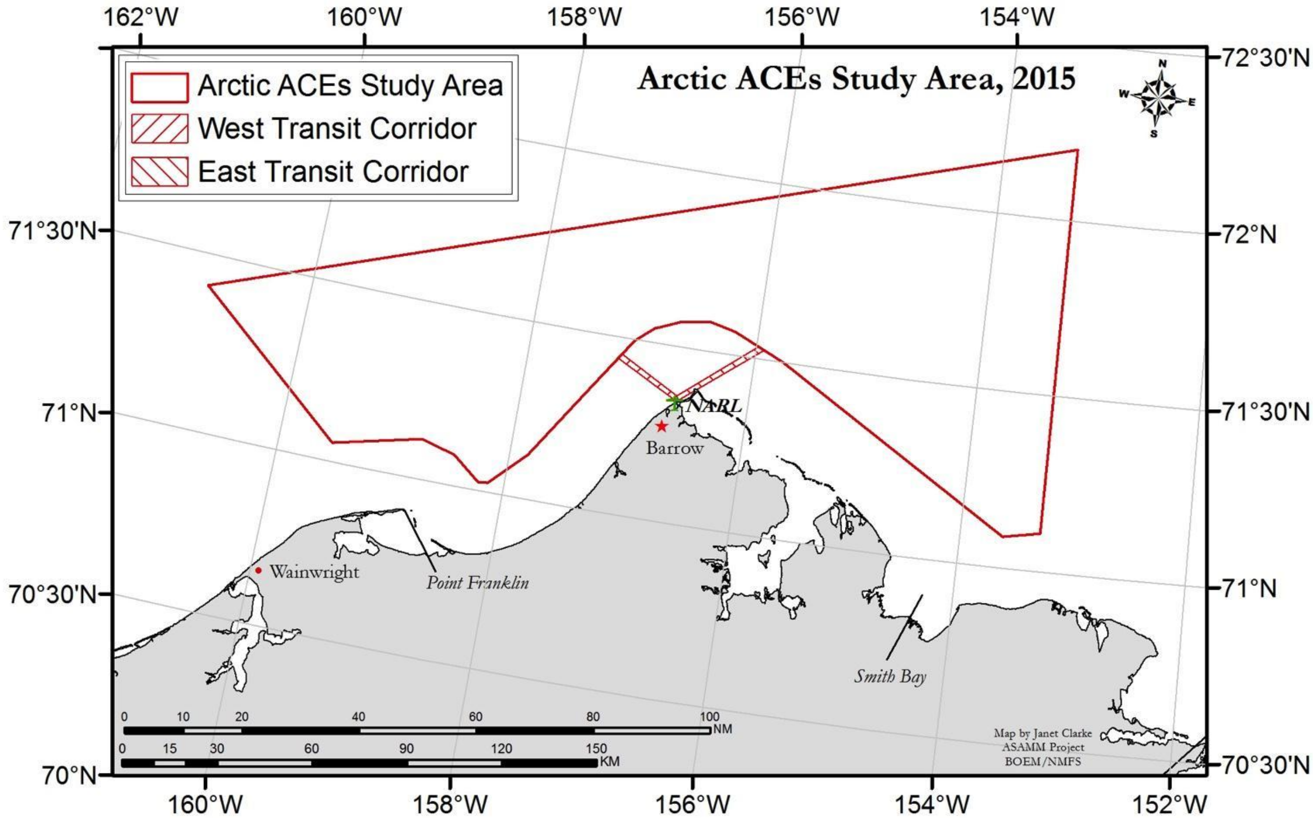

Figure 2. Study area for the Arctic Aerial Calibration Experiments (ACEs) project.

Authorizations

FAA Certificate of Authorization: The NSWCDD applied for and received a COA that authorized flights for this project. This COA was notable for the following reasons:

- The COA authorized routine beyond visual line-of-sight flights by a UAV in the National Airspace System;
- The COA included a detailed communications plan to ensure that local pilots were aware of the UAS project and could work with the UAS team to deconflict flights

Interim Flight Clearance: The NSWCD applied for and received an Interim Flight Clearance (IFC) from the Navy to authorize the flights. The IFC served as an airworthiness document for the ScanEagle® UAS in the application for the FAA COA. The IFC also included specifics regarding operational requirements for the system and the hand-off to the RV *Fairweather*.

Marine Mammal Protection Act Research Permits: The research was authorized under Marine Mammal Protection Act permit 14245-03, as amended and issued to MML by the NOAA Fisheries Office of Protected Resources. The research was also authorized under Marine

Mammal Protection Act permit 212570-1, as amended by the U.S. Fish and Wildlife Service to cover the UAS activities.

North Slope Borough Planning and Community Services Department Land Use Permit: Use of the land area north of Utqiaġvik was authorized under North Slope Borough permits 16-013 and 16-078. The permit had to be amended to accommodate shifts in the physical location of the field site, to extend the date of the project until mid-September, and to accommodate short-term restrictions of traffic near the field site to create a safety zone during launches and retrievals of the UAV.

Memorandum of Agreement between NOAA Fisheries and Shell: NOAA Fisheries and Shell signed a memorandum of agreement (MOA) on August 3, 2015, that committed the company to install a camera system in the Turbo Commander and provide images for use in this study. The MOA also specified sharing of images and allowed for use of a proprietary system for analyzing the images. Shell informed MML staff in September that they would no longer be party to the MOA due to the company's plans to abandon further work in the U.S. Arctic. A portion of the images Shell had committed to provide were sent to MML in October 2015; the remaining images were delivered to MML in November 2015.

Equipment

ScanEagle® UAS

The Insitu ScanEagle® UAS was selected for this study due to its strong airworthiness history and payload capacity. This platform was used successfully from the RV *McArthur II* in 2009 to collect imagery of ice-associated seals in the Bering Sea (Moreland et al. 2015).

The mission used two ScanEagle® UAV manufactured by Insitu, Inc. (Figure 3). All pilots were trained by Insitu and had Letters of Authorization designating them as approved ScanEagle® UAS pilots by a US Navy Squadron. ScanEagle® dimensions and performance characteristics are included in Table 3.

Figure 3. ScanEagle® on launch at Naval Surface Warfare Center – Dahlgren Division

Table 3. Performance characteristics of the ScanEagle® UAV.

Performance	
Maximum horizontal speed	80 knots (148.6 km/h)
Cruise speed	50-60 knots (92.6-111.1 km/h)
Maximum service ceiling	19,800 ft (6,035.0 m)
Endurance	24 hours
Dimensions	
Wing span	10.2 ft (3.1m)
Length (Dual bay configuration)	6.5 ft (2.0m)
Weights	
Empty structure weight	30.9-39.68 lbs
Maximum takeoff weight	48.5 lbs (22.0 kg)

Figure 4. ScanEagle® UAV

System description. The ScanEagle® UAS is configured for land- or sea-based operations, and includes the aircraft, launcher, retrieval system, control station (CS), software, and auxiliary equipment. The platform is flexible, expandable, and can be quickly reconfigured in the field.

Air vehicle. The ScanEagle® UAV is built to carry customer-supplied sensors and processors, and to provide a flexible aerial platform with power, communications, and volume for additional payloads. The aircraft is designed to handle multiple, highly persistent sensing roles, including Intelligence Surveillance and Reconnaissance (ISR) and communications relay.

The ScanEagle® UAV is a long-endurance aircraft composed of modules that are replaceable at the field site. The ScanEagle® UAV (Figure 4) is a tailless aircraft that features a high aspect ratio swept wing. It has a rear-mounted engine driving a pusher propeller. Two sets of elevons on the wings provide pitch and roll control, with rudders on the winglets at the wing tips for directional control.

Ground control station and software. Flight operations with the ScanEagle® are controlled with a stationary (land based) or mobile (ship based) CS. CS software includes operator interfaces for preflight checks, operating, flying, and monitoring multiple aircraft on independent missions.

Launch system. The SuperWedge® Laucher was used to launch the aircraft (Figure 3). The launcher is charged by an attached air compressor. The UAV is launched by removing the safety pin and then the catapult is manually activated using a pull trigger. On firing, the launcher accelerates the UAV; at the end of the rail, the UAV is launched at takeoff speed.

Figure 5. Skyhook® retrieval system, Utqiaġvik, AK.

Retrieval system. The SkyHook® retrieval system (Figure 5) captures the UAV. The SkyHook® system uses a GPS receiver and antenna to make an accurate approach via data relayed through the control station. The aircraft is captured by flying into a rope suspended approximately 45 ft (13.7 m) above the surface. A hook on the wingtip catches the line and quickly stops the aircraft.

Payloads:

The following five payloads were flown on the ScanEagle®:

1. Nikon D810 camera (Figure 6): Pictures were collected to examine cetacean distribution and estimate density. Payload details described below.

2. Atmospheric Sensing and Predicting System (ASAPS) Meteorological Sensor (Figure 6), developed by PEMDAS Innovations and Technologies (PEMDAS): Meteorological data were sent to the ground station so the UAS operators could analyze current meteorological

conditions. The sensor was used to analyze current weather conditions to determine the risk of carburetor icing.

3. Electro-optical (EO) board camera (Figure 6): The EO board camera provided the UAS operator with situational awareness during flight.

4. GPS pinger (Figure 7): The GPS pinger was intended to aid in recovery of the UAV in the event of a water landing. The GPS pinger also allowed for GPS metadata to be included with the images taken with the D810 camera.

5. Camera trigger (Figure 7): The camera trigger was intended to allow for the D810 camera to have pictures taken based on GPS distance instead of using the camera timer.

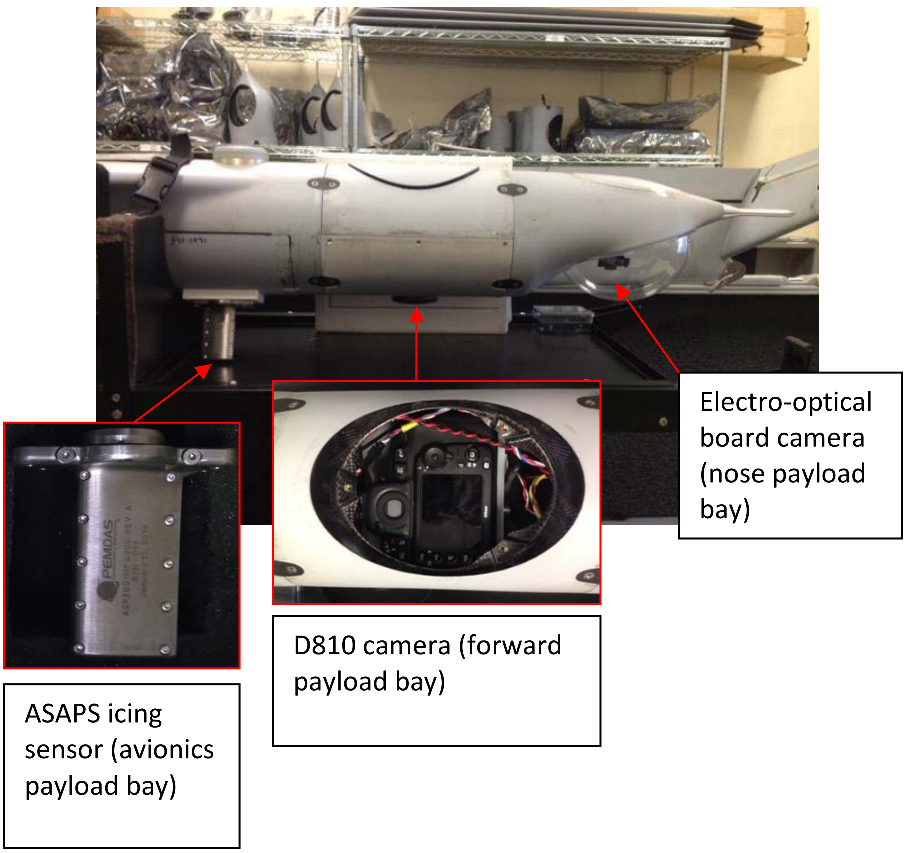

Figure 6: Forward payloads in the ScanEagle®

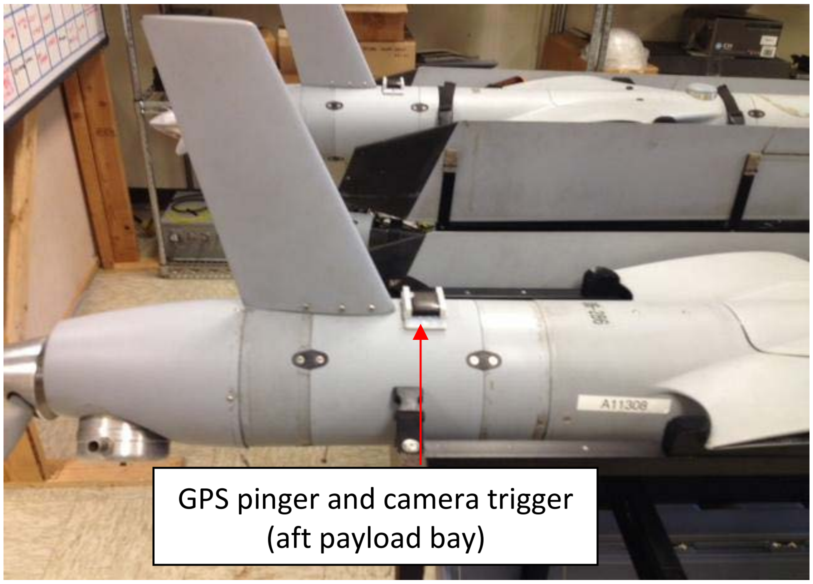

Figure 7: AFT payloads in the ScanEagle®

Digital camera payload. The UAV was equipped with a Nikon D810 high-resolution digital camera capable under ideal conditions of providing a minimum photographic ground resolution of 7 cm/pixel and a minimum photographic strip width of 400 to 600 m at 1000 m altitude. Each camera was equipped with a 20 mm Nikkor f2.8 lens. The Nikon D810 and lens were chosen for a number of reasons:

- The predecessor to the D810, the Nikon D800, had been used successfully in similar projects undertaken by LGL. The D810 contained all of the same features as the D800, but allowed for an ISO as low as 32 compared to ISO 50 on the D800.
- The 36.3 megapixel sensor provided for a 576 m swath width at survey altitude of 1050 ft (320.0 m) with a 20 mm lens.
- The camera body had slots for both a CF and SD storage card, enabling us to put 1 TB of storage in the camera. 1 TB of storage translates to roughly 10 hrs of flight time.
- Initially, a 21 mm Zeiss Distagon lens was chosen for the UAV camera in order to be consistent with the manned aircraft payload. Unfortunately, the weight and length of the Zeiss lens exceeded the UAV carrying capacity. The 20 mm Nikkor lens is shorter, lighter, and would allow for a greater swath width than the Zeiss.

Prior to integration into the ScanEagle® system, the camera and lens setup was tested on the ground to ensure that each component was functioning properly, capable of delivering the resolution specified by the manufacturer, and free of defects/aberrations that would be visible in the images. Images were taken at varying distances from an image resolution test target and with a range of settings similar to what may be used in the field. The images were then analyzed to assess resolution, focus, and uniformity.

The Nikon D810 was powered over the ScanEagle® expansion power circuit. During each picture, the amperage draw onboard the ScanEagle® would spike, allowing the operator to confirm the camera was functional and had the proper picture interval.

Digital camera payload: flight-testing. The Nikon D810 and 20 mm Nikkor lens was flight tested at NSWCDD in Dahlgren, Virginia, on 21-22 July 2015. The UAS overflew a tri-bar calibration target at pre-determined altitudes in order to assess the accuracy of the camera system. In addition, the tests were necessary to ensure that the pilots could determine

Figure 8. Image A was taken from the UAS during the test flight in Dahlgren, VA at 1050 ft AGL and 60 kts ground speed. Image B shows the calibration target at 300% zoom, with circles around the 6 cm wide and 10.8 cm wide calibration tribars.

whether the camera was firing. The bars on the calibration target ranged from 0.5 cm wide to 10.8 cm wide. During the test flights, images taken at 1050 ft (320.0 m) AGL and 60 kts (111.1 km/h) showed an image resolution of 6 cm (Figure 8).

Temperature/humidity sensor

At ONR's request, the UAV also carried an ASAPS sensor funded by ONR and designed by PEMDAS that collects and transmits information on observed temperature and relative humidity. The addition of this sensor was helpful, as it provided real-time, streaming data on environmental conditions, particularly potential for icing conditions, which might impact the flight. The information from the sensor was viewed on a laptop that could be seen by the UAS team, and the information was used to modify flight plans during the flight.

Field Operations

The shore team (5 staff from Dahlgren; 3 staff from the AFSC) was based at the runway north of the Naval Arctic Research Laboratory (NARL), approximately 5 miles (8.05 km) north of Utqiaġvik, Alaska. Portable Arctic Oven tents were used to shelter the CS, the UAS, and the survey team. The tents, along with the launch and retrieval equipment, were positioned near the defunct NARL runway in front of the northernmost hanger (Figures 9, 10, and 11).

Figure 9. View of ScanEagle® UAS ground equipment at NARL from the RV *Fairweather*

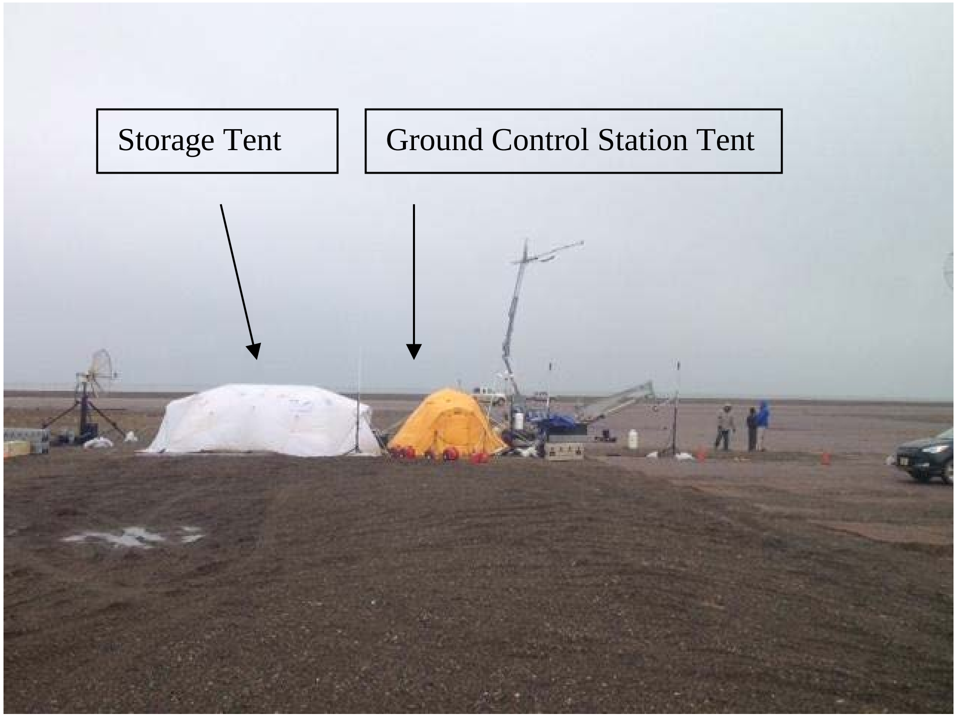

Figure 10. ScanEagle® UAS ground equipment

Figure 11. ScanEagle® on final approach

The RV *Fairweather* was positioned in the study area from August 19 through August 30 to enable full UAS coverage of the study area. The ship-based team (1 staff from Dahlgren, 1 staff from the AFSC) departed aboard the RV *Fairweather* from Nome on August 17. The ship was available to increase the situational awareness and radio communication range of the UAS pilots and provide aid in recovering the airframe in the event of a water landing. When not committed to supporting the UAS project, the ship's crew conducted hydrological surveys of the areas near Utqiaġvik, and deployed Navy wave-gliders, ensuring that vessel time in the area would be optimized.

The ScanEagle® UAVs were launched and recovered from the shore-based station at NARL and accessed the offshore study area located in international airspace through one of two transit corridors. The UAV remained at or below 400 ft mean sea level (MSL; 121 m) while inside the corridor. Once in the offshore study area, the UAV increased altitude to 1,000 ft MSL (303 m) and flew pre-programmed fine-scale (2.56 miles; 4.75 km apart) transects, collecting high-resolution digital photographic strip-transect data with a Nikon D810 with a 20mm Nikkor lens every 100 m distance over water. The UAV remained within communication line-of-sight of a CS (50-70 nmi). The pilot monitored the onboard video and PEMDAS ASAPS sensor output and altered course as necessary to avoid precipitation or clouds. Once UAS operations were complete on a particular day, the UAV descended to < 400 ft MSL (121 m) while still in international airspace offshore and entered the transit corridor inbound for recovery at NARL.

The ASAMM field team provided the manned aircraft support for the project. ASAMM observers collected both visual line-transect data on marine mammals and relevant environmental conditions, according to ASAMM survey protocols, from a fixed-wing, twin-engine turboprop Turbo Commander 690A. A Nikon D810 with a 21mm Zeiss lens was installed in the aircraft by LGL, Inc and collected images every 3 seconds. Additional camera systems were mounted in the aircraft to expand the effective swath width, but the primary comparison between imagery will be between imagery collected with the downward-looking D810 cameras in both the ScanEagle® and the Turbo Commander.

The ACEs team contracted a local company to provide both polar bear monitors and night security. Polar bear monitors were on site when a polar bear had been seen nearby in the previous 24 hours, or when the team expected to conduct UAS flights. Night security was provided by a local corporation for part of the project, and by a Navy contractor when project funds were no longer available.

In-field camera calibration

At the beginning of each flight, the manned aircraft and UAS overflew one calibration target (Figure 12) positioned on the NARL runway near the field site, at 400 ft (121.9 m) (UAV) and 1000 ft (304.8 m) (manned aircraft) MSL. The largest bars of the calibration target (Figure 12) measure 19 cm by 3.8cm. The UAV also overflew the *Fairweather* at 1000 ft (304.8 m) MSL on the first flight day (8/26). The *Fairweather* affixed a calibration target (Figure 13) to the bow of their vessel, which allowed for at-sea payload calibration. The largest bars of this target measure 53.9 cm by 10.8cm.

Assessment of the 400 ft (121.9 m) and 1000 ft (304.8 m) images showed the resolution did not meet our acceptable minimum resolution requirements. To compensate for the blur associated with these images, we increased the ISO and shutter speed and re-focused the lenses for all subsequent flights. These changes resulted in visibly higher resolution than the previous flight, yet the resolution was still poorer than the 3.02 cm we expected at 400 ft (121.9 m). We could not differentiate between the largest bars on the shore based calibration target, which were 3.8 cm wide.

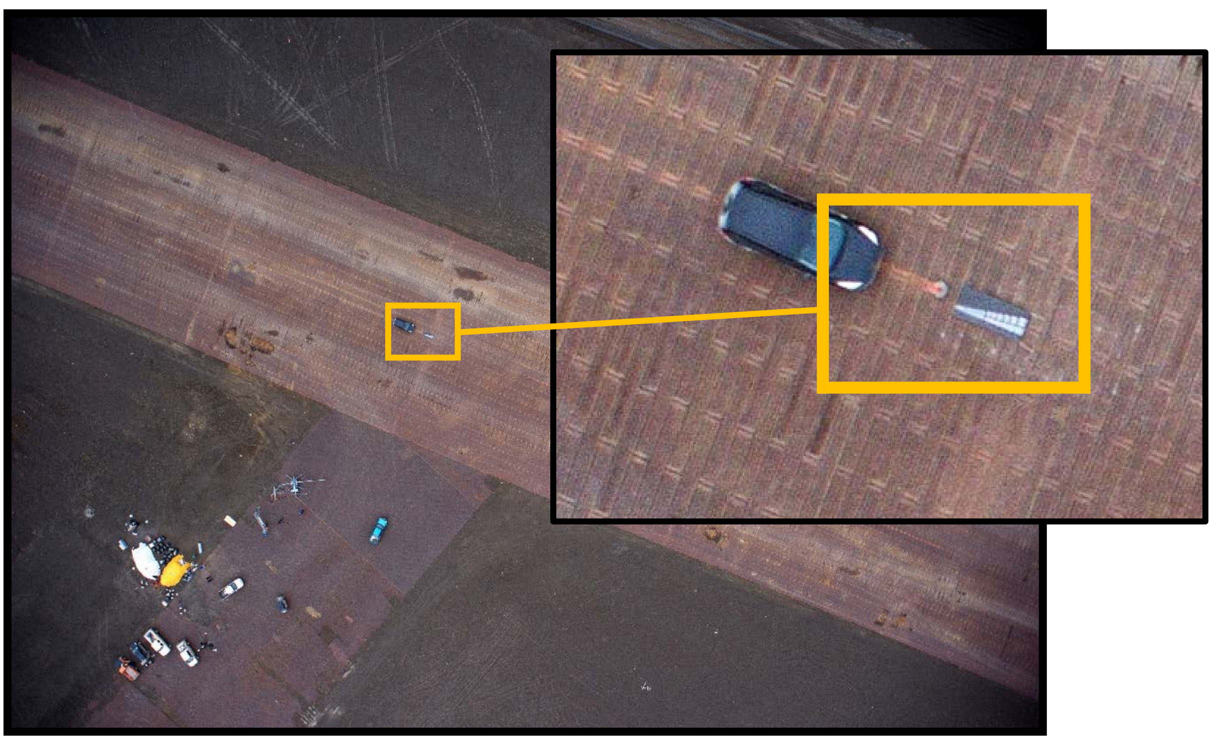

Figure 12. Calibration target at the NARL field site. Yellow boxes indicate the location of the calibration target and a zoomed insert of the target.

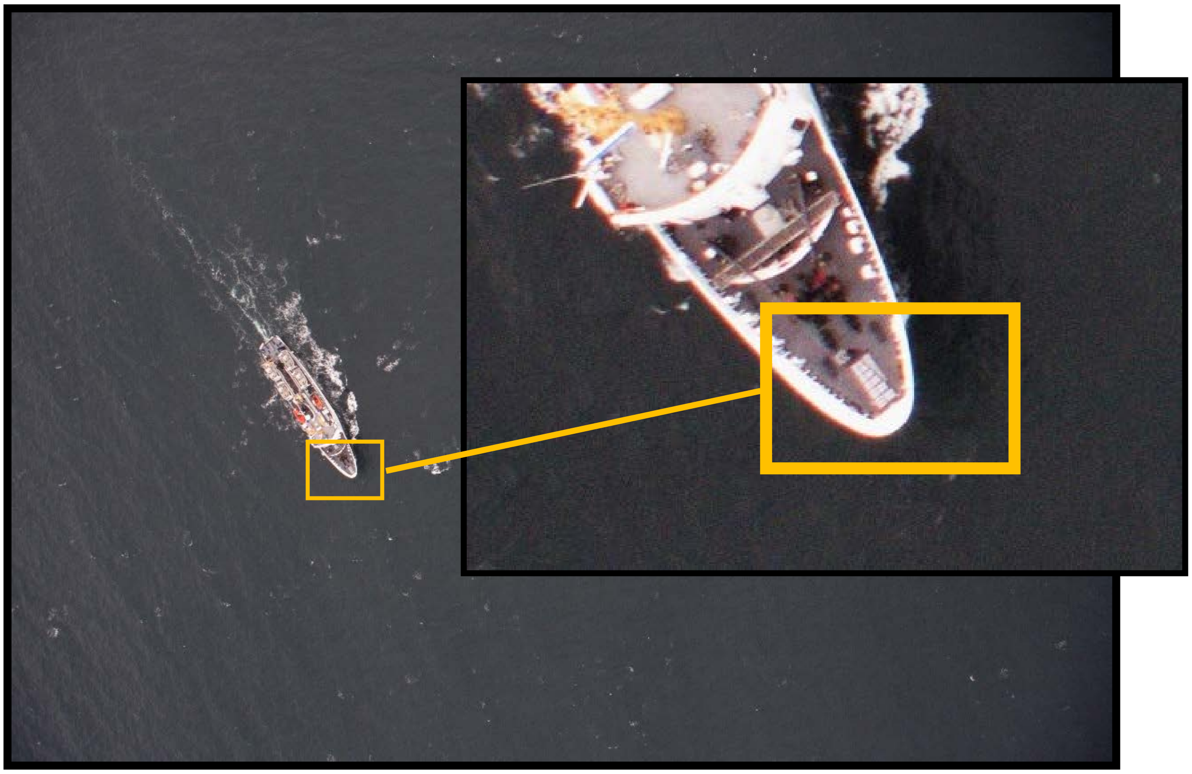

Figure 13. Calibration target on the NOAA Ship *Fairweather*, photographed from the UAV at 997 ft MSL. The yellow boxes indicate the location of the calibration target and a zoomed insert of the target.

Coordinating UAV and Manned Aerial Survey Flights

The survey design assumed that the UAV and manned flights would be synchronized in time and space to obtain independent, replicate samples of whales. There is some risk inherent in deliberately conducting simultaneous flights of manned and unmanned aircraft geographically close to each other and at the same altitude. General flight plans were discussed each morning at the 0800 hrs (local) meeting. In-flight safety was ensured by developing procedural methods by consensus among the UAS and Clearwater pilots and science leads for the two field teams, and by using technological methods required by the FAA. Technological methods included Traffic Alert and Collision Avoidance System (TCAS) for the manned aircraft, which alerts pilots of nearby aircraft that are a possible collision threat based on their range, altitude, and bearing. NOAA used an air traffic awareness tool, which allowed the UAS team to detect aircraft in the area. The two aerial survey teams flew successfully in the survey area, but there were sufficient difficulties with communications between teams that both teams decided further spatial or temporal separation was necessary after the flights on September 1. Flights on September 2 were conducted by both aircraft in the same geographic area but were offset by time: the manned aircraft conducted flights first, and then departed the area when the UAV arrived.

Aerial Survey Sampling Design

NOAA Fisheries considers abundance estimates with a coefficient of variation (the standard deviation relative to the population size) of less than or equal to 0.3 to be the desirable level of precision appropriate for making management decisions. Statistical analyses of existing aerial survey data of cetaceans in this study area suggested that a coefficient of variation of 0.3 in the estimated density of gray whales may be achieved by analyzing the data collected over approximately 50 hrs of UAS flight time. In order to collect enough data for a robust analysis, we planned to conduct daily flights of up to 14 hrs in duration on two UAVs simultaneously over a 17-day period.

Image Sampling Protocol

Image processing

Detailed image processing protocols are provided in Appendix A and associated Supplementary Data at the end of this report.

Digital images from the UAS and Turbo Commander flights were visually reviewed by three photo analysts with considerable expertise as marine mammal observers during visual aerial surveys for arctic marine mammals. Only images with midpoints located within 1-km strips centered on transects were viewed in order to simplify computation of the area sampled; images collected while transiting off transect were not analyzed. The native projection for the transects was used to determine which images were located in the transect strip; that projection was defined as a Lambert azimuthal equal area projection, with center latitude 70.0^{o}, center longitude -154.5^{o}, false easting 0.0, and false northing 0.0. Observers did not process images that showed any portion of the horizon, or where the camera angle was obviously not perpendicular to the sea surface, as these images were taken when the aircraft was turning. Because consecutive images overlapped by approximately 33% on average, photo analysts reviewed every third image from each portion of the flight that was within the study area boundaries. Ten images out of every 30 were fully analyzed at 100% zoom, while the remaining 20 were initially analyzed at 20% zoom, with instructions to selectively zoom in on any pixels containing a cue for a potential sighting. Images from 9 flights (5 manned flights and 4 UAS flights) were reviewed in detail by only a single photo analyst. Images from 1 UAS flight were reviewed independently by two photo analysts for an ongoing analysis to estimate detection probability. The lead photo analyst reviewed all images identified as containing definite or possible sightings in order to confirm species and group size, and to make a final determination on objects that were initially judged without certainty to be marine mammals.

All marine mammal sightings were confirmed by two or more experienced marine mammal observers.

The final processed imagery database included the following fields: aircraft type; image filename; latitude, longitude, and altitude; date and time (GMT); impediments to visibility, Beaufort Sea State, percent of the image covered by glare and type of glare present; whether the image was viewed at full-screen resolution or zoomed to 100% of the image size; sighting number; species identification; an ordinal variable on sighting and species identification confidence; best, high, and low estimates of group size; number of calves present; position of the sighting in x- and y-coordinates within the frame of reference of the image; length (pixels) of the animal; percentage of the image obscured by precipitation; notes if the image was not taken during level flight; and the amount of time it took to process a batch of 10 images.

Analytical Methods

For a detailed description of density analysis methods, refer to Ferguson et al. (2018) or Appendix C of this report.

Density was estimated for each combination of species (bowhead whale, gray whale, or beluga), aircraft type (Turbo Commander or UAS), and sector (west and east) of the study area. All analyses were conducted using R version 3.3.2 (R Core Team 2016). Density from imagery data collected by the UAS and by the Turbo Commander was estimated based on the number of whales found in the images relative to the total visible area in the images. Adjustments were made for each image based on the altitude of the aircraft. The coefficient of variation of the density from the images was estimated using a modified version of the approach published by Fewster et al (2009).

Whale sightings collected by human observers onboard the Turbo Commander were analyzed in a variety of ways. Density of bowhead whales and beluga whales and associated coefficients of variation were initially estimated from the traditional marine mammal observer data using a standard distance sampling approach using just survey data from the flights during this project. In addition, more complex models could be used to estimate density from the human observers because they had higher numbers of sightings of whales than seen in images, and because the historical aerial survey data could be used to improve the parametrization of the distance sampling models. Geospatial analyses were conducted using R packages sp (Pebesma and Bivand 2005, Bivand et al. 2013), maptools (Bivand and Lewin-Koh 2017), rgeos (Bivand and Rundel 2017), rgdal (Bivand et al. 2016), raster (Hijmans 2016), ncdf4 (Pierce 2015), and fields (Nychka et al. 2015). All density computations were standardized as number of animals per km^2.

For ease of comparison, density estimates (whale species per km^2) from images and from human observers were converted to estimates of the number of whales of each species present in each sector by multiplying estimated density by the corresponding sector area. Density estimates were not corrected for availability bias resulting from the animals' surfacing and diving behaviors or for the photo analysts' perception bias (Marsh and Sinclair 1989) because estimates of these parameters are not available. Additional data also need to be collected to compute correction factors for the marine mammal observers' perception bias near the trackline; therefore, this bias was not addressed. Analyses of cetacean behavior from satellite telemetry, aerial behavior studies, and aircraft field of view data are being used to compute availability bias correction factors specific to the ASAMM line-transect surveys and may be used to correct future density estimates. Investigations into adjusting the sightings in the imagery for perception or availability bias are also underway. These investigations were not part of the original research plan, but will be helpful for future surveys and analyses.

RESULTS

Planning Milestones

In FY15, the project team focused exclusively on planning and implementing the field project scheduled for August 2015. The field team met weekly via conference call and developed and tracked the various components of the project, including funds transfer, the COA application, selection of a field site, development of the outreach plan, development of risk management documents and safety plans, integration of a control station on the NOAA vessel, and logistics for the 2.5-week field project in late FY15 (Table 4).

Field Work

The Dahlgren team conducted flights of the ScanEagle® on 5 days during the study (Figure 14). Flights ranged from 1.6 to 6 hrs in duration. The ASAMM manned aerial survey team conducted flights on 5 days during the project (Figure 15). Flights by the manned aerial survey team ranged from 1.3 to 4.8 hours. One additional manned flight was conducted the day after the last UAS flight, and one flight of the manned aircraft was conducted during the study period but in an area farther south that had weather more conducive for cetacean observations. Over 70,000 images were collected during the study.

The local weather was highly variable, both spatially and temporally. The flying weather was typically worse in the morning and improved in the afternoon. On days when flights were

Table 4. Summary of milestones completed during preparation for fieldwork.

Milestone	Timing	Responsible Parties
Submit proposals for funding	Dec 2014	MML
Secure project funding for FY15	Feb 2015	ONR, BOEM, NOAA HQ offices
Commit to ship-based or shore-based project	30 Jan 2015	MML, OMAO, Navy-Dahlgren
Draft Concept of Operations (CONOPS) document presented to the FAA	Feb 2015	MML, OMAO, Navy-Dahlgren
Mission concept review for UASPO	Feb 2015	MML, Dahlgren
Initiated contract with UIC for onshore logistical support	Apr 2015	MML, Navy-Dahlgren
Outreach to communities, pilots	Feb-Aug 2015	MML, NSB
Site visit of Utqiaġvik and Wainwright; final decision on location of shore-based operations	Mar 2015	MML, Navy-Dahlgren, NSB
Initial meeting with FAA to discuss CONOPs	19 Feb 2015	OMAO, Navy-Dahlgren
Submit COA to FAA informally via Navy POC	1 May 2015	Navy-Dahlgren
Go/No-go decision based on budget targets	5 May 2015	MML, Navy-Dahlgren
Project review for UASPO	8 May 2015	MML, Navy-Dahlgren
Submit COA request to FAA	May 2015	Navy-Dahlgren, OMAO
Test camera systems on calibration targets	20-21 Jul 2015	Navy-Dahlgren, MML
Initiate contracts for bear guards	Jul 2015	MML
Development of an on-site safety plan	Jul 2015	MML, NSB
Submit cruise plan to OMAO	Jul 2015	MML
Traffic awareness application contract and testing	Jul-Aug 2015	OMAO, Navy-Dahlgren
Go/No-go decision based on COA/airspace availability	Late Jul 2015	MML
COA received	3 Aug 2015	Navy-Dahlgren, OMAO
Mission readiness review for UASPO	10 Aug 2015	MML, Navy-Dahlgren
IFC received	11 Aug 2015	Navy-Dahlgren
UAS gear arrives in Utqiaġvik	19 Aug 2015	Navy-Dahlgren
Frequency approval received from the FCC	20 Aug 2015	PEMDAS
Field operations	19 Aug – 7 Sept 2015	MML, Navy-Dahlgren, OMAO

possible, the weather within the study area was spatially and temporally variable, and there were often patches of squalls or low clouds offshore that were not apparent from the shore. The Dahlgren team kept the UAV clear of clouds and attempted to remain clear of precipitation. The team managed the UAV's interaction with the weather by monitoring the onboard video camera and the temperature/humidity data provided by the PEMDAS ASAPS sensor. The UAV frequently encountered theoretical carburetor icing conditions during flights;

the team mitigated the potential for carb icing by operating the UAV at a high RPM to keep the engine warm. The appendix provides detailed weather observations from the Utqiaġvik weather station during the project; conditions when flights were possible are highlighted in green.

The shore-based UAS team successfully handed off control of the UAS to the ship-based team during the first flight on 26 August. The hand-off to the ship allowed for the distant transects of the study area to be surveyed.

The project design relied on the expectation that two UAS could be flown simultaneously to achieve the calculated number of hours needed for a robust comparison between survey platforms. Unfortunately, the team did not have the opportunity to fly two UAS simultaneously. We elected to not attempt dual flights early in the season until the manned and UAS teams had some practice conducting coordinated flights in close proximity. Later in the season, technical issues and weather restrictions with the UAS precluded dual flights.

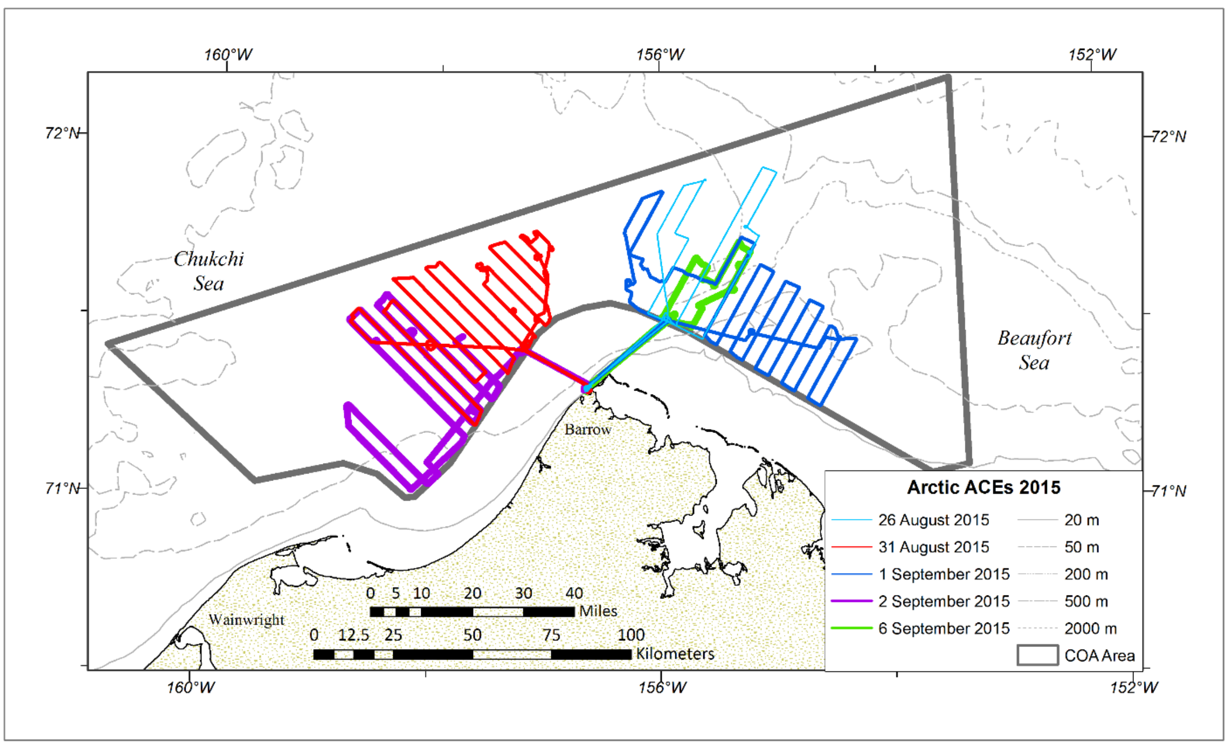

Figure 14. Flights of the UAV during the ACEs project

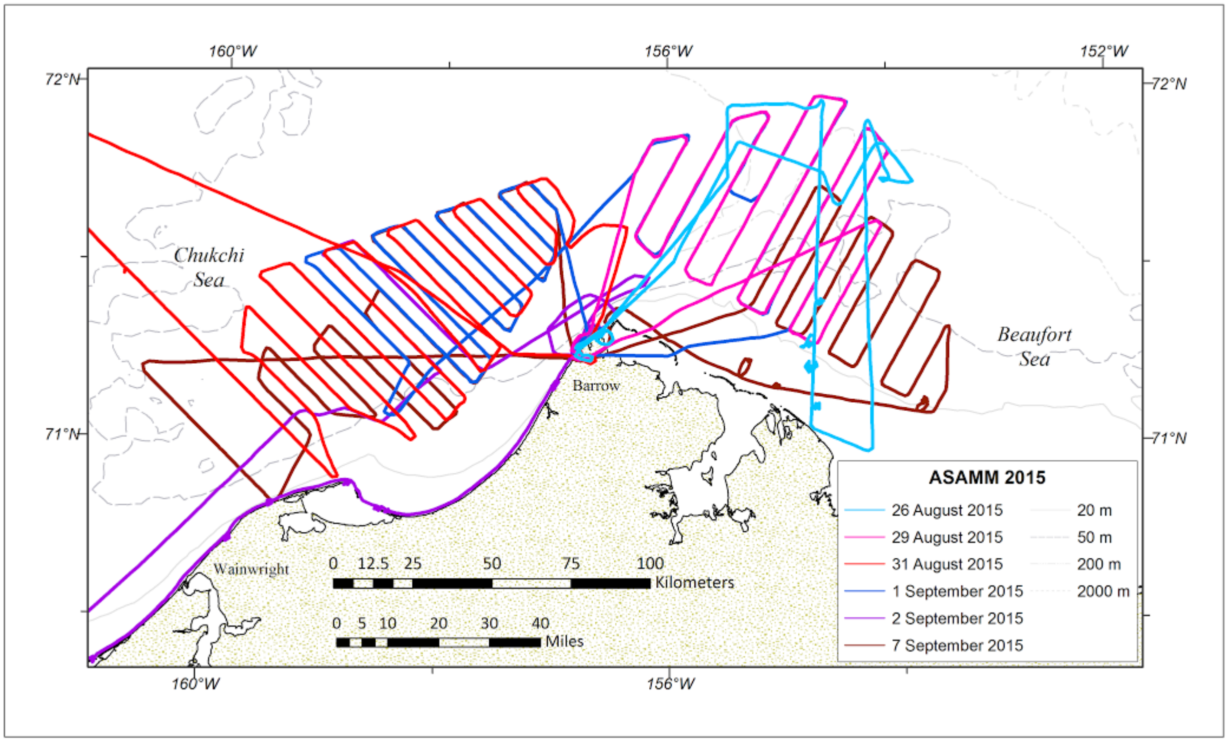

Figure 15. Flights of the ASAMM aircraft during the ACEs project.

Image Collection and Density Analysis

For complete image analysis results and figures, refer to Angliss et al. (2018) (Appendix B of this report) and Ferguson et al. (2018) (Appendix C of this report).

Of the 20,568 total images collected by the UAS in the study area (Angliss et al. 2018), 6,857 (33.3%) were processed by photo analysts. During the review of every third image from each flight, photo analysts sighted 14 bowhead whale groups (totaling 15 whales), one group of six belugas, and three gray whales. The only calf sighted in any of the imagery from either aircraft was a bowhead whale calf associated with an adult female in an image taken from the UAV while turning, and was therefore omitted from statistical analysis.

The Turbo Commander also conducted five survey flights on the UAS transect lines during five separate days: 29 and 31 August, and 1, 2, and 7 September. Survey effort in the study area ranged in duration from 1.3 to 4.8 hours, totaling 17.9 hours and 3,582 km (Angliss et al. 2018). In total, 23,580 images were collected from the vertical camera aboard the Turbo Commander in the study area (Angliss et al. 2018), and 9,776 (41.5%) were processed. The proportions of individuals of each species observed were similar across platforms, with bowhead whales generally the most frequently observed and gray whales the least. Due to the small area covered (hence, small sample sizes) in the imagery and patchy distribution of the cetaceans in the study area, the number of individuals observed and species composition were not identical across platforms and observation methods. Photo analysts detected eight lone bowhead whales and 11 beluga groups totaling 16 whales. No gray whales and no calves were detected in images from the Turbo Commander. Marine mammal observers detected 53 bowhead whale groups totaling 61 whales, 18 beluga groups totaling 54 whales, 9 gray whale groups totaling 9 whales, and 42 groups totaling 48 cetaceans that could not be identified to species. This is a considerably higher proportion of cetaceans not identified to species compared to typical ASAMM flights conducted in closing mode (when the aircraft is allowed to circle sightings). Only one of the unidentified cetacean sightings during ACEs was close to the manned aircraft, in the strip located 250-550 m parallel to the trackline. No gray whales and 17 bowhead whales were detected by airborne marine mammal observers in the 250-550 m strip. The resulting "large cetacean" species identification bias correction factor was 0.94; therefore, raw density estimates of bowhead whales from the marine mammal observer data were increased by a factor of 1/0.94=1.06, or 6%, to account for the inability to identify all large cetacean sightings to species.

Automated Marine Mammal Detection (AMMD) software comparison

Brainlike, Inc.® (www.Brainlike.com) created a proprietary version of AMMD software that was specifically calibrated for the payload used by Angliss et al. (2018)(Appendix B) and was designed to detect large whales in Arctic environments. The Brainlike, Inc.® AMMD reduces image data to single detection events (referred to as 'chips'), corresponding to potential marine mammal sightings. Each chip is saved to a separate jpg file (Figure 16). The chips may contain marine mammal sightings (a true-positive detection, Figure 16) or may not (a false-positive detection, Figures 16 and 17). Furthermore, there may be cetaceans in the images that the AMMD does not detect (a false-negative detection, Figure 17). In an attempt to limit the overall number of false positives detected by the software, the version of Brainlike's AMMD used in this study allowed a maximum of two chips to be generated per image. The software also creates an "alert map" that shows the original image with chip location boxes superimposed over each detection (Figures 16 and 17). Finally, the AMMD produces a spreadsheet listing the original filename and chip location for each image. In our study, each chip was reviewed for cetacean sightings by an experienced aerial marine mammal observer.

A detailed analysis of a representative subset of UAS imagery was conducted by three highly experienced aerial marine mammal observers (see Appendix C (Ferguson et al. 2018) for full methods). This manual review required approximately 150.4 hours of labor, or approximately 79 seconds per image. The Brainlike, Inc.® AMMD processed 20,608 images in approximately 85.9 hours of computer processing time. From those images, 39,776 chips were generated. A manual review of those chips required only 7.4 hours, or approximately 1.5 seconds per chip. Combined, the computer processing (aka: chip selection) and subsequent manual review of chips from 20,608 images required a total of approximately 93.3 hours vs. 150.4 hours of manual image review of a third of the images. If observers had analyzed each image, as the AMMD did, it would have taken at least 451 hours of labor.

Overall, the software performed remarkably well, detecting 14 out of 16 (87.5%) cetacean sightings recorded under all wind conditions, and 100% (n=14) of cetacean sightings recorded during acceptable wind conditions (≤ Beaufort 4). However, the AMMD detected only 37 out of 51 total images known to contain cetaceans (72.5%) taken during all wind conditions and 34 out of 48 images known to contain cetaceans (70.8%) taken during a Beaufort wind force of 4 or less. In all, manual observers missed only one cetacean sighting out of 16 total sightings (93.8%) that were recorded.

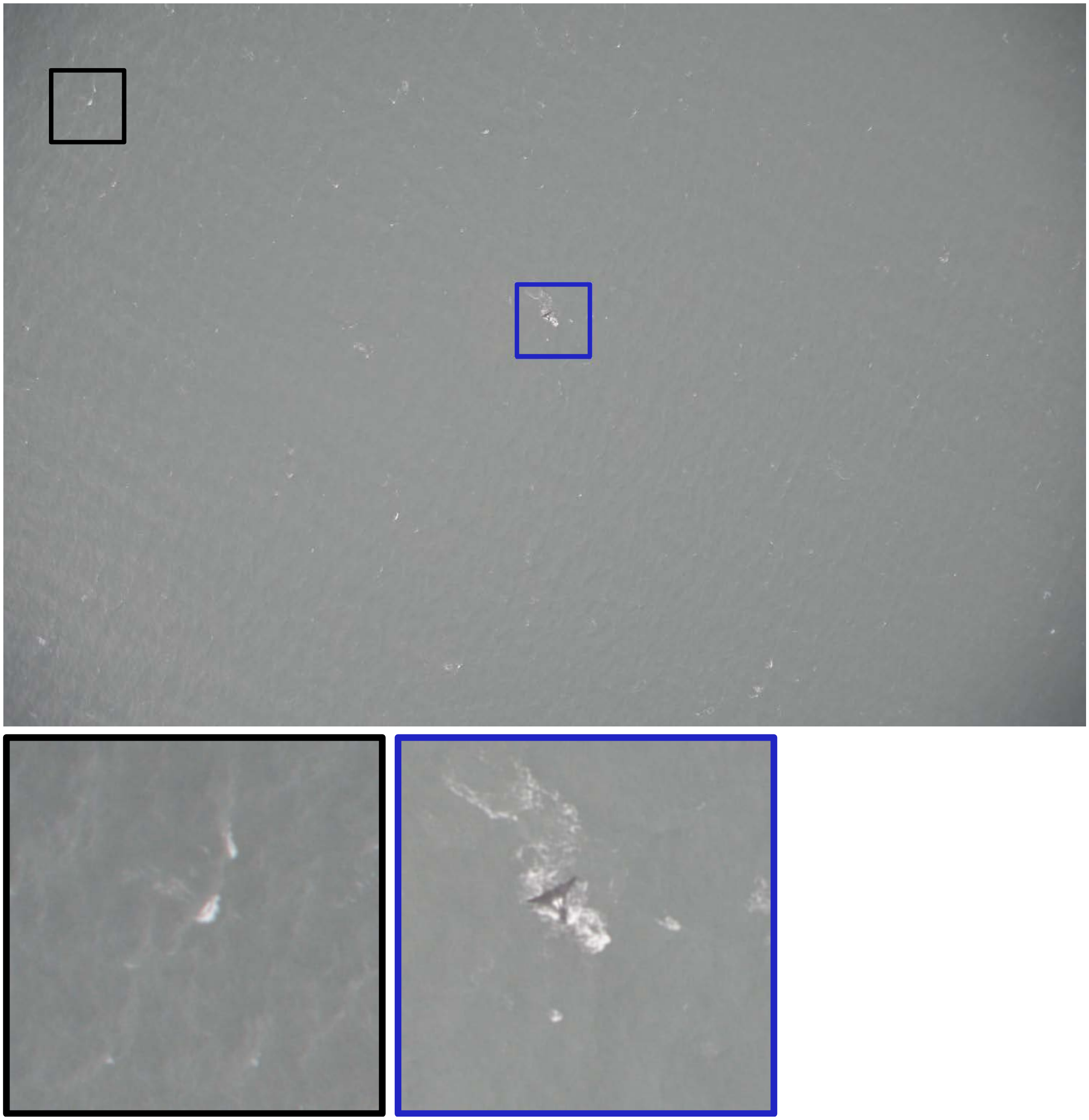

Figure 16: Top: The Brainlike, Inc.® AMMD “alert map” showing the original image with “chips” (detections), outlined in blue and black boxes. Bottom: Corresponding blue and black “chips”. The black chip (bottom left) is a false positive detection and the blue chip is a true positive detection of the dorsal fluke of a diving bowhead whale.

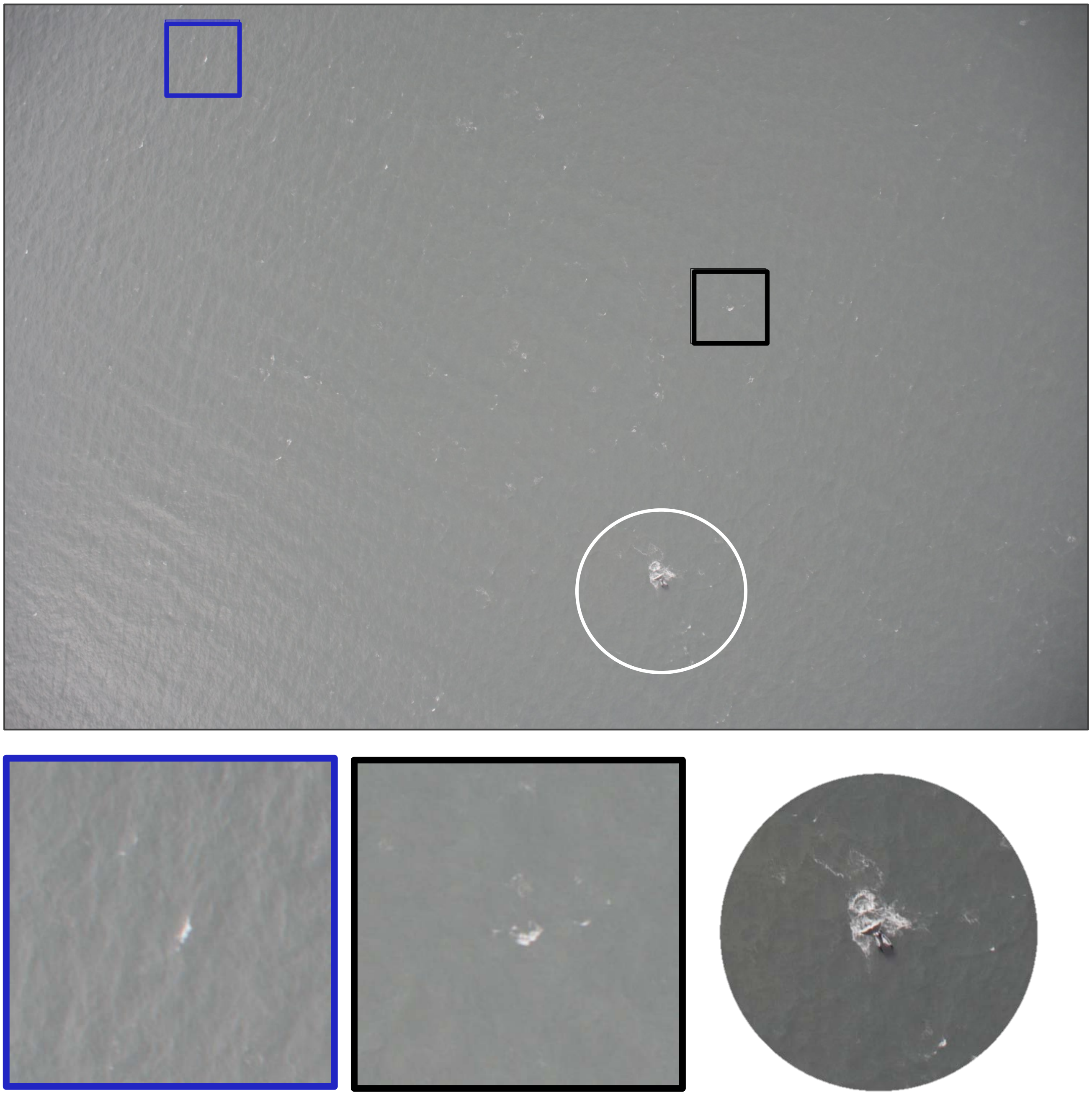

Figure 17: Top: The Brainlike, Inc.® AMMD "alert map" showing the original image with "chips" (detections), outlined in blue and black boxes. Bottom: Corresponding blue and black "chips". Both chips show false positive detections. White circle added manually during post processing highlights a bowhead whale detected during manual image analysis that was not detected by the AMMD.

Analytical Results

Estimate trackline detection probability for marine mammal observers participating in the ASAMM project and photo-interpreters

Due to the relatively low density of cetaceans in the study area, narrow strip width captured in the imagery, and relatively limited number of flight hours attained, there were too few sightings to conduct this analysis.

Compare the performance of manned and unmanned aircraft surveys based on quantitative metrics

In general, bowhead whales were found in higher densities and gray whales were found in lower densities than expected, and beluga densities were approximately consistent with previous years, based primarily on cumulative knowledge from the ASAMM historical database, which covers 37 field seasons (e.g., Clarke et al. 2017a).

Due to a broader search width, the marine mammal observers sighted approximately seven times more cetaceans than were detected in either imagery dataset during a similar number of flight hours.

All methods allowed trained observers to identify bowhead whales, gray whales, belugas, and walruses. Humpback, minke, and fin whales appear to be increasingly common in the eastern Chukchi Sea (Clarke et al. 2013; Brower et al. 2017a); improved image resolution may be needed to differentiate these species and certainly would be required to differentiate smaller cetaceans such as harbor porpoise, Dall's porpoise, or pinniped species.

Small sample sizes limited our ability to determine whether the methods affected the photo analysts' or ASAMM marine mammal observers' ability to estimate group size or detect calves.

For bowhead whales, the species with the most sightings across all methods, there was a consistent pattern in the magnitude of the estimates of uncertainty for the density estimates in the west and east sectors, with the spatial modeling methods having the lowest CVs, followed by standard distance sampling with intermediate values, and photographic strip-transect methods having the highest CVs. In this study area, lowering the CVs of the density estimates derived from the UAS imagery to be comparable to the analogous CVs from the marine mammal observer dataset would have required approximately double the number of flight hours on the UAS. This is consistent with our original study design, which included additional flight hours on the UAS.

The Turbo Commander covered more distance (3,582 km vs. 2,012 km) and ASAMM observers effectively surveyed over ten times as much area (e.g., > 11,000 km2 sampled for bowhead whales by marine mammal observers vs. ~1000 km2 analyzed in UAV imagery) in the study area compared to the UAS in approximately the same number of flight hours.

In our study, photo analysts spent a total of 332.5 hours to manually process and search every third image from the Turbo Commander and UAS imagery for large cetaceans, averaging 6.9 hours of photo processing time per flight hour. Not included in that estimate is the considerable amount of time required to download and backup the imagery. In comparison, the preliminary round of in-field editing of the ASAMM line-transect data, which involves thorough review of the database by two ASAMM personnel, is completed within 2 hours of the aircraft landing after each survey flight. At that stage, the data may be used in preliminary analyses. The final post-season quality assurance/quality control (QA/QC) of the ASAMM database takes approximately 100 hours to edit 100 flights, averaging 11.2 minutes QA/QC per flight hour.

Overall, the monetary cost of the 2015 marine mammal observer surveys was 9.4% the cost of the UAS component, and was approximately 68.5% the cost of the photo strip-transect survey aboard the Turbo Commander.

A brief consideration of fuel consumption required to conduct each type of survey suggests that the comparison is not straightforward. The Turbo Commander burns approximately 80 gallons of fuel per hour, whereas the UAS burns approximately 0.05 gallons of fuel per hour. Nevertheless, activities necessary to support our UAS operations consumed additional fuel. The research vessel *Fairweather* required a considerable amount of fuel to transit to the study area from Nome, Alaska, provide operational support for the UAS project, and return to port in Kodiak, Alaska. Furthermore, the C130 used to transport the UAS to Utqiaġvik burned fuel at a high rate. When indirect fuel consumption is considered, the manned aircraft operations required less fuel than the UAS operations.

One noteworthy difference between manned and unmanned aircraft is that the former are explicitly and painstakingly designed to safely return to land at the end of every flight, whereas the latter were designed to be expendable. This difference has implications in survey planning because it is important to have spare UAVs in the event that one has an unintentional water landing and cannot be recovered. Damage or loss to a UAV would have required a stand-down to review procedures, which could have resulted in lost survey days. In addition, the need for spare UAVs increases the overall project costs.

Provide recommendations to the Navy, NOAA Fisheries, and BOEM about the types of cetacean study objectives that can likely be met by UAS technology now and in the near future

Multiple examples exist where UAS have been highly successful and have enabled researchers to collect novel data or data in locations or times that were previously inaccessible (e.g., Acevedo-Whitehouse et al. 2010, Fritz 2012, Sweeney et al. 2016, Durban et al. 2015, Knuth et al. 2013, Curry et al. 2004). Most of these examples involve small UAS that can collect data within line of sight. However, based on the evidence encapsulated in the performance metrics summarized above, we conclude that it is premature to replace manned aerial surveys with UAS if the goal of the survey is to collect broad-scale arctic cetacean abundance or density estimates. This conclusion is based primarily on five factors: First, the technology available and used to enable manned and unmanned aircraft to fly simultaneously in close proximity in non-segregated airspace are insufficient due to the limitations of TCAS and the difficulties of visually detecting a small UAS flying at high closure rates (Angliss et al. 2018). Second, the sample sizes we obtained with the UAS were too small to reach acceptable levels of uncertainty in the density estimates. Weather and operational complexity precluded additional data collection using the UAS. Furthermore, the raw number of sightings could be a critical factor if the goal of the survey is to mitigate, via real-time detection of animals, potential risks to marine mammals due to an anthropogenic activity, such as a military exercise or commercial seismic survey. Low sample sizes could be alleviated by flying longer (pending adequate weather), or collecting data from multiple sensors on a single UAV or on multiple UAVs flying simultaneously. Nevertheless, additional data mean additional processing time, and additional UAVs result in increased air traffic and enhanced probability of mid-air collisions. Third, the financial cost of a long-range UAS survey would be prohibitive to most wildlife managers' or ecologists' budgets. Fourth, manually processing imagery takes considerable time and money, and this is a significant hurdle to overcome without reliable auto-detection algorithms for large cetaceans (although this is a subject of current research and the cost is very likely to decrease). Finally, additional weatherproofing would be required to make UAS reliable platforms in extreme environments like the Arctic (Angliss et al. 2018).

As operational and analytical efficiency of UAS-based surveys increase, financial burdens will decrease. Development and mass production of UAS that are more weather resistant and easy to transport, and development of reliable auto-detection software for cetaceans, would reduce the costs of UAS-based surveys considerably. Ultimately, the question of whether UAS can replace or augment manned aircraft for conducting aerial surveys does not have a single answer. Rather, a lengthy list of questions should be addressed to determine whether a given UAS platform will likely meet a project's safety, scientific, and logistical needs.

Recommend adaptations to the traditional analytical processes for estimating density

Ferguson et al. (2018) described a new method for estimating the uncertainty in density estimates from the imagery data that was based on the R2 estimator from Fewster et al. (2009). Ferguson et al. (2018) also helped revise the functions in the R package mrds in order to parameterize detection functions for data in which the right-truncation distance varied along the length of the trackline.

LESSONS LEARNED

Successful implementation of a multi-week UAS project in the Alaskan Arctic

Despite great interest in using UAS in the Arctic, only a handful of projects have successfully used UAS to conduct research. The use of UAS in the Arctic is challenging, particularly for beyond line-of-sight flights, and the learning curve remains steep. The following detailed list of successes and recommendations is provided to guide future UAS projects, particularly those that are directed at marine mammals or that occur in the Arctic.

Attaining required permissions and authorizations needed for a major UAS project in U.S. National Airspace

Successes

The team successfully applied for and received the following permissions and authorizations:

- FAA Certificate of Authorization for beyond visual line-of-sight flights
- Navy Interim Flight Clearance
- Amendment to a research permit issued under the Marine Mammal Protection Act addressing NOAA Fisheries-regulated marine mammal species
- Amendment to a research permit issued under the Marine Mammal Protection Act addressing USFWS-regulated marine mammal species
- Land use permit (with amendments) from the North Slope Borough

Recommendations

FAA COAs for future Arctic projects should be as flexible as possible. Pay attention specifically to weather and altitude limitations and the impact they will have on the operations. COAs should also encompass a broad range of dates to accommodate project delays due to technical or logistical problems. While these issues did not significantly impact ability to fly, they could impact future projects.

Use of a shore-based location for the primary ground control station

Successes

The team established a shore-based location for the primary ground control station. Overall, the location of the shore-based “camp” north of Utqiaġvik worked well. The area was open, and while there were some obstacles nearby (two old hangars, a few tall posts), the UAV could be launched and retrieved from multiple directions. The Arctic Oven tents (3 x 6 m) used to house the ground control stations and provide a place for storage and maintenance of the UAS were minimally adequate. On-site logistics support provided by a local contractor was outstanding. Lodging, food, and hardware supplies were located a short drive away in Utqiaġvik. NAVAIR required funds to approve an IFC for the COA for a land-based project; the cost of getting an IFC from NAVAIR for a ship-based project would have been substantially more expensive and time consuming due to the need for a custom install on the vessel available for the project.

Recommendations

A larger, hard-sided, temperature controlled workspace is preferred for housing the ground control stations and UAV equipment. The small working area inside the tents made movement of people and equipment in and out of the tents more challenging, and meant that it was more difficult for the air boss, pilots and principal investigators to communicate effectively in order to coordinate all aspects of the project. Further, the labor needed to troubleshoot various issues caused by weather was considerable. Equipment was frequently tested and found fully functional in the evening, yet during flight preparations the next morning, new technical issues would be found and have to be fixed. If a temperature controlled area were sufficiently large to allow the ScanEagles® to be placed indoors with their wings on, it would shorten the time to launch from approximately 2 hrs to 45 min after arriving at the site.

Better knowledge of potential partners located in the Utqiaġvik area might have resulted in being able to site the equipment inside a hard-sided structure. For instance, the Point Barrow Defense Early Warning (DEW) line site has lodging, kitchens and workspaces that might have been available to Department of Defense partners. NOAA and Navy staff had tried to contact DEW line staff directly and were unsuccessful via phone and email, but Navy to Air Force communications could have resulted in a different outcome.

The team was advised early in the project that polar bears would not pose a significant risk to staff at the field site, and was then counseled later that steps to ensure *polar bear safety* should be implemented at the field site. Although the bear risk was low, it was not zero; a bear safety plan was developed, distributed, and briefed to the field team. NOAA staff took firearm safety training and brought a shotgun to the field site. Bear guards were hired to stand watch during each flight, or on days when bears were sighted in the vicinity. Three bear sightings occurred near the field site during the field study, which reinforced the need for vigilance. In addition, upon arrival in Utqiaġvik, the team heard from the local police department and from other local residents that *night security* would be needed to ensure that key supplies were not compromised. A contract for night security was established for the first part of the field season; NSWCDD brought an additional team member to Utqiaġvik to perform nighttime security for the last week of the field season.

Use of a shore-based site as the location for the primary CS, launch, and retrieval of the UAS meant that the ScanEagle® system had to be transported to Barrow. This is a significant task due to the considerable size and weight of the launch and recovery equipment, and a C130 was needed to transport the gear. Because the Navy was a partner on this project, transport via Navy C130 was provided free of charge to the project. However, the Navy C130 flight was delayed for 2 weeks, which shifted the end of the field season into September and caused an avalanche of changes in staffing, personnel flight logistics, lodging, et cetera. Chartering a commercial C130 flight from the east coast and return would have cost approximately $500K; chartering a commercial flight from Fairbanks would have cost approximately $80K. *If a shore-based operation is preferred, future projects that require a fixed-wing UAV would benefit from using a UAV that could launch/land on a runway, eliminating the need for bulky launch and recovery systems*.

Beyond visual line-of-sight flights of the ScanEagle® UAV

Successes

The FAA authorized a beyond visual line-of-sight COA contingent on the use of a rigorous communications plan and using an air traffic awareness tool as a means for sense and avoid. The ScanEagle® UAV has a Mode C transponder that can be detected by airborne TCAS and with ground based air traffic radar. Through an air traffic awareness tool, the air boss was able to see the ScanEagle® UAV and other air traffic in the survey area. The air traffic awareness tool was also useful for monitoring offshore air traffic, particularly the ASAMM aircraft and Shell pilots transiting to Shell's offshore drilling area, both of which were flying at approximately the same altitude. The receipt of a COA for these flights was a notable success, as few COAs for beyond visual line-of-sight flights have been issued by the FAA.

The NSWCDD team successfully *transferred control of the UAS to a vessel* located offshore on the first flight. This allowed distant transects to be surveyed that were beyond the reach of the shore-based ground control station (GCS).

At no time did the team stand down due to predicted carburetor icing conditions prior to flight. Potential in-flight carburetor icing conditions were managed by running the engines at higher RPM and faster speeds to keep the engine warm. Additionally, the PIC recorded the command throttle and respective RPM reading every 15 to 30 mins to ensure that the engine was not exhibiting degraded performance. The use of fuel-injected engines would not have resulted in increased flight time during this project, but is recommended as a good solution for the Arctic because of the high potential for carburetor icing issues.

A detailed communications protocol was developed so local airspace users including pilots of both manned and unmanned systems – would be aware of activities in the area each day. The protocol included extensive outreach to pilots, including phone calls and meetings with local pilots working for Ravn and Shell, notices posted around Utqiaġvik and emailed directly to pilots and state/federal/local agencies who might employ pilots in the course of their work. During the field season, there were daily simultaneous operations (SIMOPS) calls.

The availability of weather information at the field site – specifically short-term, high resolution, local information on precipitation – facilitated UAS flights because it informed the pilots of local environmental conditions within at the field site in lieu of at the airport, which was 5 miles (8.0 km) away from the launch and recovery site. The PEMDAS team allowed the pilots to view "NOWcasting" software during the flights, which aided in predicting short-term variation in weather conditions. A similar system developed by the University of Washington can be seen at http://www.atmos.washington.edu/SPU/; the 1-hour forecast product provides information on highly variable weather transiting a small spatial area that would be useful for UAS operations. In addition, ONR provided a portable weather station to the team, which was used late in the field project to assess information on ceiling altitude at the field site. Due to local variability, the ceiling at the field site was often hundreds of feet higher or lower than the ceiling at the airport where the official observations were obtained; having a weather station at the field site enabled the team to measure minimum launch criteria more accurately and frequently.

Recommendations

Develop a better understanding of when carburetor icing occurs in ScanEagle® UAVs. ScanEagles® are very capable platforms but the lack of platform-specific information on the conditions under which carburetor icing may be a problem may result in pilots tending to be unnecessarily conservative about flights in conditions that the equipment manual might call "marginal". Temperature and humidity data from the ASAPS sensor will be more useful to the UAV operators if more is known about the relationship between the environmental data and the probability of icing on the ScanEagle®. Laboratory tests to evaluate carburetor icing of ScanEagles® would be helpful.

There are a number of features that could be added to a UAV to improve its capability to fly in an arctic environment. A UAV that could be flown in occasional icing conditions and be able to go through clouds could access more areas where the weather is sufficient for marine mammal surveys. Platform updates such as Iridium feeds, and modifications to handle icing such as heated pitot tubes, wing boots, and heated propellers would be helpful. For this project, weatherproofing would have been most helpful on the ground, because the team had to work on the UAS in light mist as they waited for local squalls to pass the study area, and it was clear that long-term storage in a cold, damp environment damaged the equipment over time.

Ship-based UAS operations

Requests for vessel time within NOAA must be made approximately 1.5 years in advance of when the ship is needed for a project. Early advice from ScanEagle® experts suggested that the ScanEagle® could be integrated on the RV *Rainier*, the sister ship of the *Fairweather*. The PIs requested time on the *Fairweather* for 2015 and were allocated 21 days at sea in August and September (9 days of transit, 12 days on station). Further investigation confirmed that that a standard integration on the *Fairweather* was not possible unless much of the ship's superstructure was removed from the back deck, which was not deemed feasible for the project.

Custom integration would have required significant time and funds, and would require multiple test flights before the Navy leadership would clear the installation for a project. Because of the cost and potential risk to the project (if Navy leadership did not clear a custom installation, the August 2015 field season might be canceled), the team shifted to shore-based operations, with the intent of handing off to a single ship-board control station so the full study area could be accessed. In addition, the vessel was responsible for finding and retrieving a UAV that had a water landing, and provided real-time weather observations at sea. When not being used by the UAS project, the vessel conducted hydrographic operations to make the best use of the ship's time in the area.

Successes

The team successfully transferred control of the UAV from the shore-based station to the team on R/V *Fairweather* during the first flight of the project. This was the first time the NSWCDD team had accomplished a hand-off from a land based system to a ship based system and the procedure went well.

Recommendations

NOAA should evaluate ships in the NOAA fleet that are likely to be asked to carry UAS to ascertain in advance whether and how UAS integration could occur. This review should include an assessment of deck space needed for launch/recovery, space for the CS, and space for storage and maintenance of UAS equipment. This type of information should be made available to researchers in advance of a request for vessel time.

The team felt strongly that future beyond visual line-of-sight arctic maritime operations should be based off a vessel in lieu of from a shore-based station. Basing off a vessel was considered the single operational change that would have directly and significantly improved the chances of getting the flight hours needed for the project. Often, weather conditions in Utqiaġvik were sufficiently poor to prevent launch (low ceilings, fog, or winds) but based on weather reports from the ship there were offshore areas that could have been accessed if the UAV could have been launched from a vessel. Advantages to basing off a ship for this project included:

- Ability to move to areas of good weather within the study area for launch and recovery;
- Equipment would be in a climate-controlled area;
- Long-range flights could require an Iridium link; using a mobile control station on a ship allows for additional range;
- No need to transport UAS equipment to a shore-based site;
- No need for security or bear protection contracts.

If the project were conducted from a ship, more care would be needed to set up the ScanEagle® UAV so it could be easily transported around the vessel. Because the project was land-based, NSWCDD installed the digital camera payload in a second payload bay that was less complex from an engineering perspective, but added length to the ScanEagle®, which would have made it more challenging to maneuver around a vessel.

Payload and equipment

Successes

Overall, the payloads integrated into the UAS worked well: images were successfully collected and downloaded at the end of each flight, the video camera system was useful for in-flight situational awareness, and the ASAPS sensor provided consistent data to the PEMDAS ground station.

During the test flights in Dahlgren, Virginia, on 20 and 21 July, the camera collected images at 1050 ft (320.0 m) MSL with a resolution of 6 cm, which was better than acceptable minimum resolution requirements. However, the light levels during the test flights were very high, with low to no cloud cover. This allowed for images to be taken at a much higher shutter speed and lower ISO than those collected in the Chukchi study area, resulting in higher image quality during test flights. In addition, because the camera mounts used in Utqiaġvik were damaged during the field season project, there may have been additional vibration of the camera systems that could have further impacted image quality.

Recommendations

There were two issues with the camera mounts. The mounts blocked access to the storage card slot in the camera system so that the card could not be removed from the camera. Thus, post-flight data retrieval required removing the camera from the mount, which caused wear and tear on the mount and a time-intensive transfer protocol. Future payload mounts should be designed to ensure that key payload features can be accessed during the project. Second, two camera mounts cracked upon retrieval in Utqiaġvik and had to be re-anchored in the UAV. The damage was likely due to the weight of the UAV upon retrieval and the type of plastic used for the mount. Further investigation of the type of plastic used for the mounts may help understand whether the plastic used was optimal for the environmental conditions experienced in the Arctic.

The Nikon camera calibration images from the UAS indicated that the resolution was adequate for large whale detection and species identification, but was poorer (11 cm) than our initial requirements (7 cm). Image resolution was significantly impacted by higher than expected levels of blur. Upon consultation with aerial photography experts, the consensus is that the blur was caused by the camera mounting method and lack of forward motion compensation. There was no vibration dampening material inserted between the camera and the mounting bracket, which ensured that any UAV vibrations were transferred directly to the camera. After the initial flight, camera adjustments were made that decreased the image blur slightly, but these adjustments could not compensate for the lack of dampening material.

In order to avoid carburetor icing, the UAV engines were run at a faster speed and higher RPM than during the test flights at Dahlgren, VA. Higher RPM would likely cause greater vibration on the camera mount; this, coupled with lower light levels and increased precipitation between the camera and the sea surface, likely caused the greatest differences in image quality between test image and in-field image resolution.

Another factor that impacted the payload success was the rigidity and permanence of the mount. Once the camera was attached to the mount via screws and hot glue, it was very difficult to remove without damaging the mount or the camera. When adjustments to the lens focus ring were needed, as is frequently the case during the first few flights of a survey, the ring was virtually impossible to access without removal from the mount.

The Nikon D810 camera and associated lens were heavy. The weight of the camera system resulted in having to make changes to other parts of the ScanEagle® to accommodate the space and weight of the camera. To save weight, the gimballed turret was removed; it would have been helpful, although was not critical, for situational awareness to have retained the turret so the video camera could pan while the UAS was transiting in a straight line. The weight of the UAS added complexity to the launch and retrieval requirements: if a full tank of fuel were required, a wind of 10 to 15 knots (18.5 to 27.8 km/h) during launch would have been required to meet the specifications of pressurizing the launcher. Future projects collecting similar imagery data should consider modifying the camera to include only the critical mechanisms to make it lighter and easier to integrate.

Due to the location of the ASAPS sensor (protruding from the avionics) and the extended dual bay configuration, the wing had to be disconnected from the fuselage in order for the ScanEagle® to fit in the transport case. Once the wing was reconnected to the fuselage, the ScanEagle® could no longer be dropped into the transport case to allow for the case to close for shipping or on-site storage. In addition, the Arctic Oven tents were too small to allow for the wings to be installed in the tent. A different configuration of the ASAPS sensor would be helpful, and larger transport cases should be built to accommodate a ScanEagle® with an additional payload bay.

Technology that automatically broadcasts an aircraft's position and detects other aircraft in the general vicinity (such as automatic dependent surveillance – broadcast, or ADS-B) *should be installed* on both the UAS and on small aircraft that share airspace. This will improve the safety of flight by ensuring that all aircraft are visible to each other.

Overlapping survey design and historical weather conditions: Setting reasonable expectations

The total number of days during which flights could occur were roughly what was expected by the NOAA Fisheries and the NSWCDD team. In general, the weather on a "good flight day" in the Arctic would not have been considered an acceptable flight day in many other places in the U.S. The expectations of the PIs were that a 17-day project in mid-late August should result in 5-6 days of acceptable survey weather. This was estimated based on a review of the number of days that the ASAMM team surveyed during the previous 30 years. In addition, the NSWCDD team examined multiple years of data on wind, temperature, and dew point to assess whether it was reasonable to assume that flights could be conducted for a certain number of days during August. The NSWCDD team concluded independently that based on recent historical weather data, during 4 of 5 years, the project should overlap with 5-6 good flight days in a 17-day period. Thus, the 5 flight days achieved during the project were within the range of the expectations for the project.

The spatial and temporal variability in weather in the study area during the field project was more extreme than the NSWCDD expected. Weather in the study area in August can include an adequate ceiling with occasional rain and snow showers that are small in scale and highly variable. It is more challenging to operate UAS in this type of weather because available weather forecasting products do not have the necessary spatial or temporal resolution. The NSWCDD team expected rain conditions that would prohibit flights in the entire study area; instead, operations typically required “dodging” showers or low fog conditions that were transiting a portion of the study area. The NOWcasting system provided by the PEMDAS team was helpful in predicting changes in precipitation and ceiling that aided in-flight planning.

Records of daily weather observations at the Utqiaġvik airport coupled with the timing of UAS and manned aircraft flights are provided in the appendix.

Recommendations

The ship-based UAS team noted that if the survey design had targeted a lower flight altitude (e.g., 500 or 800 ft (152.4 or 243.8 m)), the UAV would have been able to collect more data for the project. However, there is a tradeoff between altitude and imagery strip width; a lower altitude produces a narrower strip width, requiring more flight time to sample the same area. In addition, decreasing the flight altitude would have further decreased the effective communications range between the CS and UAV.

Coordinating UAS and manned aerial survey flights

One of the goals of the project was to coordinate manned and UAS flights to provide a comparison of images of whales collected by the two platforms. Comparison would be facilitated by having the flights conducted at the same altitude, and preferably in close temporal and spatial proximity to decrease the chance that whale distribution and density would change in the intervening period between sampling.

Successes

In order to ensure safety during the flights, there were both technological and procedural methods for ensuring spatial separation. Written procedural methods were developed in advance of the field season by consensus by the UAS and Clearwater pilots and leads for the two teams. Technological methods included the installation of a transponder in the UAS so nearby aircraft with the TCAS would be alerted of a possible collision threat, and an air traffic awareness application, which allowed the UAS team to monitor aircraft in the vicinity.

Recommendations

During the coordinated flights on 8/26, there were deviations from the written communication protocols. After this flight, the team leads met, revised the protocols and tested the communications on the ground. On 8/31 there was a successful flight and all communication protocols worked well. During coordinated flights on 9/1, there was another deviation from the communication protocols. There was no imminent risk to human safety as a result of either occurrence; however, it became clear that the measures put in place to mitigate risk prior to the occurrence of a potential safety issue were not adequate. Thus, the leads for the manned and UAS surveys decided to cease simultaneous flights within the same survey area for the remainder of the project. Manned and UAS surveys were still conducted in the same survey areas on the same day, but not at the same time.

The manned and UAS pilots and the team leads for the various teams identified the following steps to reduce risk during a project that plans to conduct coordinated manned and unmanned surveys <u>at the same altitude and in close proximity</u>:

- Start with a simple coordination plan, and add complexity only after communications and operations are well understood and tested in the field.
- Talk through all procedures (regular and emergency) with the entire survey crew before the project starts. Make sure all parties know what mechanisms are in place to mitigate the risk to people in the coordinating aircraft. Provide the manned survey crew with site visits to the UAS operation location to become familiar with the CS and traffic awareness capabilities prior to the start of UAS operations. This would allow the manned survey crew to become familiarized with the UAS platform and comfortable with the safety and communication protocols.
- Provide all safety, communication, and documentation, and airspace authorizations to the leads for all teams. Each lead should know the safety requirements, COA restrictions, and any other requirements or restrictions for flights.
- If deconfliction is based on distance between aircraft, ensure that both teams can quickly and accurately measure the required distance using the technology they have available.
- Problems occurred primarily when either the manned or unmanned aircraft changed plans during coordinated flights. It is critical to have a way to communicate in-flight deviations from the plan. VHF communication is not always a reliable mechanism for pilots in the air and on the ground to communicate; it was not reliable for this project due to restricted VHF range at the ground-based field site. For UAS and manned aerial flights working in close proximity, good radio communications are likely the surest method of ensuring separation between UAS and manned aircraft flying in close proximity.
- During the development of deconfliction protocols and daily flight planning, talk through potential flight plans with a graphical display of the flight area. Identify any unintentional, potential points of intersection of the project aircraft. For example, for this survey, it would have been less complicated to position the entrance of transit corridors at the ends of the study area to facilitate spatial separation among survey aircraft.

- Everyone should be equally familiar with the NOTAMs issued in the vicinity of the project, particularly those NOTAMs about the project. These may be filed for either the nearshore areas, offshore areas, or both.
- Project team leads should ensure that flight services accurately enters and understands the requested NOTAMS.
- Sense and avoid technology or other onboard air traffic awareness technology (such as ADS-B and TCAS) greatly enhance situational awareness for both manned and unmanned flight crews. Continued development of technological solutions for UAS situational awareness should be a high priority for regions where manned and unmanned aircraft share airspace. A technological solution for situational awareness should be required if manned and unmanned aircraft are likely to be sharing airspace close in time, location, and altitude.
- NOAA and the Navy should develop a joint letter to the FAA asking that the NOTAMs be made available to pilots in a more user-friendly, graphical way.
- Avoid pre-flight rush and urgency to minimize the potential for error.
- Hold post-flight debriefs with all team leads.

Integrating a UAS project into an Alaskan coastal village

Successes

Because this project had a significant shore-side footprint, the PIs had to navigate a variety of expected and unexpected local concerns about the project. Due to their long history conducting research on the North Slope and established professional relationships, NOAA Fisheries staff took the lead when working with the local agencies, organizations, and individuals. The team successfully received an initial land use permit to conduct the field work in the village of Utqiaġvik, requested and received modifications to the land use permit as needed. Longstanding professional relationships and routine discussions with North Slope Borough staff helped the team understand what issues might be of concern to local residents so that potential conflicts could be mitigated well in advance of the field project.

Launching and retrieving the UAV required the creation of a “safety zone” to ensure that the UAV did not overfly people or property. Creating this “safety zone” sometimes required management of local traffic along a public road between Utqiaġvik and a popular duck hunting area north of town; this was somewhat controversial early in the field season and required a special meeting with the local planning department to explain the need for short-term traffic management.

Recommendations

Site selection for projects should be as transparent as possible. The team investigated two possible locations for the project: Wainwright and Utqiaġvik. Wainwright was initially preferred because of its proximity to an area of particularly high whale density. The team opted for Utqiaġvik because of cost: working in Wainwright would have required a chartered C130 to transport gear ($80K+) and a substantial fee for use of a gravel pad outside of town. In addition, there was some question regarding whether runway maintenance might prevent flights for part of the summer and the project could have been asked to vacate the gravel pad if an alternative user offered a higher fee. While working in Utqiaġvik instead of Wainwright was the best business decision to ensure a successful project, Wainwright officials were openly disappointed about the decision.

The team held weekly teleconferences to establish the shore-side location in Utqiaġvik, and North Slope Borough staff provided photos and measurements of the site to aid in site selection. However, an additional trip by members of the team may have expedited the selection of the specific site. This type of trip was discussed at the time, but could not be arranged due to cost and staff schedules. Maps of the site location were exchanged, but there were various opinions about whether dots on the map represented general or specific locations of equipment.

The use of UAS in populated areas is relatively new and local permitting agencies may not yet have a thorough understanding of a UAS projects' footprint and operations plans, so may not know the right questions to ask an incoming UAS team. In our case, serious concerns about "road closures" to enable a "safety zone" were raised when the team had a public service announcement read on the local radio station to announce the initiation of the project and possible short-term closures of a public road for up to 15 mins. When concerns were raised, the team immediately committed to not conducting flights until the issue was resolved. After some discussion, it seemed likely that the UAS operators could use on-site communications to minimize or eliminate having to hold traffic on an important public road; this was communicated to the permitting agency during an in-person meeting and the permitting agency was supportive. Minimum traffic delays occurred (approximately 5 personal vehicles over the course of the field season; each time vehicles were delayed for less than 3 minutes); however, it was still unclear when the project began whether delays of 1 to 2 minutes, or tens of minutes would be necessary. The need to hold traffic and the length of time that traffic would need to be held should have been identified earlier in the planning process so this could be highlighted during earlier discussions with the local permitting agency.

Researchers planning to use UAS should err on the side of providing more information to the permitting agencies so they have a thorough understanding of the operation prior to permitting.

Safety and security at the field site

Successes

Overall, the team felt that the project was both safe and secure. Polar bear guards were hired on days when there was increased polar bear risk and on days that staff were less likely to be watchful of the surrounding area because they were flying the UAS. Night security guards were hired for a portion of the season; the Navy brought their own security personnel to monitor the camp at night when funds ran short. North Slope Borough staff were routinely on polar bear patrol throughout town, attended the daily morning meetings, and called in to report bear sightings in the area.

Recommendations

During the field project, poor weather in Utqiaġvik led to a local State of Emergency due to coastal flooding that impacted multiple roads, including the only road leading to the field site. While communication between the UAS team and local Risk Management was maintained, it was not always clear when individuals were at the UAS site. Under a State of Emergency, it would have been helpful to have more frequent and detailed communications between the UAS team and the North Slope Borough so the department responsible for knowing where individuals are located could notify the team of rapidly changing road conditions and closures. In addition, since there was only one road to the UAS field site, the team should have considered contingencies such as road closures due to weather. This did not result in traffic delays or any safety risk during the project, but the implications of having only one road to the field site should have been more fully considered.

In addition, Utqiaġvik experienced a water shortage shortly after the State of Emergency occurred. This was communicated to UAS team members but not broadly disseminated. In the future, during a State of Emergency, communication with all team members would be more effective if done in a coordinated manner during the routine 0800 hrs team meetings.

Image Analysis

Successes

A detailed analysis of UAS and manned aircraft images was successfully conducted by three highly trained marine mammal observers (see Ferguson et al. 2018 for full methods). Observers were able to locate and identify cetaceans (bowhead, grey, and beluga whales) and pinnipeds (walrus and bearded seal) to species in most cases. Additionally, images were processed with Brainlike Inc.© AMMD software. Overall, the software performed remarkably well during acceptable wind conditions (≤ Beaufort 4). However, the automated marine mammal detection software detected only 37 out of 51 total images known to contain cetaceans taken during all wind conditions. In contrast, manual observers missed only one cetacean sighting out of 16 total sightings that were recorded.

Recommendations

The manual image analysis is incredibly time consuming and requires a large amount dedicated imagery management. While the AMMD software tested during this study drastically reduced the image analysis time, the results were not accurate enough for a survey in a low cetacean density region such as the Alaskan Arctic. Future manned or unmanned surveys that rely on image analysis would benefit greatly from improved AMMD software with the highest possible detection accuracy.

Lessons Learned: Summary

Table 5 provides an overview of project components that contributed to data collection and/or safety. Table 6 provides a detailed overview of which operational changes are most likely to directly improve data collection.

Table 5. Project components that were critical and directly contributed to successful data collection with the UAS, improved safety, or both.

Project component	**Comments**
Internet service	Critical for weather forecasting, access to air traffic information
Air traffic awareness application	Greatly improved flight safety because UAS team could detect local air traffic; use required by COA
NOWcasting[M1]	Increased ability to predict local weather at a spatial and temporal scale unavailable from NWS forecasts.
ASAPS sensor	Helped pilots know when they were likely approaching a cloud or measureable precipitation. Software designed to detect hypothetical carb icing conditions, not actual carb icing conditions.
Portable weather station	The cloud ceiling at the launch site was often hundreds of feet different from the ceiling at the airport.
Open land area with easy access and low traffic volume	Mitigated risks to the community of UAV flying over land.

Table 6. Recommended changes in flight operations. Critical changes are those that that would have resulted directly in increased data collection; other changes might decrease maintenance workload or improve the comfort of the working environment.

Change in operations	Critical	Not critical	Comments
Base from a ship	X		Basing from a ship would allow the team to move to where the weather is favorable for flights.
Climate-controlled storage of UAS gear	X	X	Climate-controlled facility would have minimized maintenance likely required due to near-freezing temperatures, rain, and high humidity.
Automated aircraft position broadcasting and detection technology	X		Improves safety by improving ability to avoid other air traffic; increases size of survey area.
Dampen camera to reduce vibrations	X		Would improve image ground resolution, which would aid in detecting large cetaceans, identifying them to species, estimating group size, and detecting calves.
Weatherproof UAS (IFR capability, heated pitot tubes, wing/prop deicing capability)	X	X	Would have been helpful for pre-flight preparations. May have been helpful for collecting data on some days because the UAS would have been able to better handle highly variable patches of precipitation. However, if there is visible precipitation in all areas, visibility is poor and images are not likely to be useful.
Conduct surveys at a lower altitude	X	X	May not be possible given science goals for this project; as flight altitude decreases, imagery strip width decreases, which may be inefficient.
Specify camera access requirements in advance		X	Camera mount blocked access to data port; workaround was time consuming.
Fuel-injected engine		X	The carb icing chart in the Insitu manual is general, not specific to the ScanEagle®. ScanEagle® platforms were routinely flown in icing conditions during this project with no detected effect on the project. However, if a fuel-injected engine had been used, the team would not have needed to run RPMs high to mitigate for the potential of carb icing, which might have avoided degradation of image quality.
Turret for onboard video system		X	Provides ability to see to the left and right while flying straight – aids cloud avoidance
Improve camera/camera mount		X	The camera was heavy, which required that the UAS take on less fuel. The camera mount was not built using the requested type of plastic, and turned out to be quite brittle. The combination of the heavy system and the type of plastic likely contributed to the breakage of two camera mounts.

TRANSITION TO UAS SURVEYS

One of the main goals of this project was to evaluate the situations in which UAS may be able to collect information on marine mammal density that is roughly comparable to data collected from manned aircraft. If the analysis of data from this projects indicated that UAS surveys may provide reliable information on marine mammal density within the desired timeframe, this procedure could potentially have been transitioned to limited operations by management agencies and permit holders.

However, a few key observations can be made about UAS operations designed to collect density information about cetaceans.

- This ScanEagle® UAS survey has a large physical footprint and gear had to be transported using a Navy C130, which would have been cost prohibitive if the project had been charged for the expense. In addition, the UAS survey required a team of 5 staff (an air boss, 3 staff who could serve as land-based PICs or mechanics, a dedicated mechanic, and a PIC on the associated vessel) to implement a field season. The manned aerial survey requires 5 staff (2 PICs, 3 marine mammal observers) to cover the same geographical area. Other ScanEagle® surveys have involved a smaller team of 3 (2 PICs and a mechanic; Moreland et al 2015), when only a single UAS is needed. The physical footprint and personnel needs will have to be considered early in the projects' design.
- The survey design for this project required UAS and manned aerial surveys be conducted at the same altitude and in close proximity in time and space. Communications between pilots of the manned and UAS were challenging and coordinated flights in close proximity in time, space, and altitude were discontinued after 3 flights.
- Data from human observers in manned aircraft can be edited and the number of cetaceans observed can be provided within a few hours of the survey aircraft touching down. Based on our image analysis, manual analysis of images for one hour of flight time will take approximately 7 hours to review for cetaceans. For UAS to be a viable option for assessing density or distribution over broad areas, this must be streamlined considerably.

OUTREACH

Outreach was accomplished both prior to and after the field season. Prior to the field season, outreach served two key functions: 1) mitigating potential risks to other airspace users due to flying the UAS beyond visual line-of-sight; and 2) integrating the field operations into a remote Alaskan village. During pre-field season outreach, the Alaska Eskimo Whaling Commission (AEWC) made a specific request to be updated on the project findings, and to be able to provide input on the draft final results. Thus, special care was taken to report preliminary and draft final results routinely to the AEWC.

Outreach to and communication with pilots who might be conducting flights in the area were critical components of the strategy to mitigate potential risks of operating the UAS beyond visual line-of-sight. Meetings or calls were held with the pilots actively conducting flights between Utqiaġvik and Shell's offshore operations, the commercial passenger airline company Ravn, the Alaska Air Carriers' Association, Barrow Flight Service Station, Alaska Flight Service, and the U.S. Coast Guard. Daily conference calls were conducted on a publically-accessible phone number every day at 0700 hrs (local) so local pilots for both manned and UAS operations could exchange information on their flight plans for the day.

A poster (Figure 18) was developed and electronically circulated to approximately 45 individuals prior to the field season, including local pilots, biologists in agencies or companies who commonly conduct work offshore over the Beaufort and Chukchi seas, and other interested parties. Forty copies of the flyer were posted in Utqiaġvik and Deadhorse to alert locals about the project, and it was posted to the FAA-Alaska Public Notices website. Letters and flyers were sent to big game hunting guides permitted to operate on the North Slope who might base somewhere other than Utqiaġvik, but could be flying at low altitudes along the coast.

Community outreach prior to the field season included mention of the project on a flyer that was sent to ~300 Alaska Native coastal tribal organizations, villages, and corporations approximately 6 months before the project began (the flyer is available at: http://www.afsc.noaa.gov/nmml/survey_map_2015.htm). A public service announcement was broadcast on Alaska Public Radio in Utqiaġvik for a few days starting on 18 August as the team was setting up at the NARL field site. We consulted with the NSBDWM for guidance regarding which Alaska Native community members and organizations we should meet with to provide focused information about the specifics of the project. Meetings or calls were held with the Wainwright Tribal Council, various individuals in the North Slope Borough Department of Wildlife Management, North Slope Borough Planning and Community Services Department, Inupiat Community of the Arctic Slope, Native Village of Utqiaġvik, Ukpeagvik-Inupiat Corporation, North Slope Borough Search and Rescue, Utqiaġvik Volunteer Search and Rescue, and the Utqiaġvik Department of Public Safety. The team welcomed visitors at the field site, and was able to give impromptu summaries of the project objectives and describe the equipment and procedures.

The team continued to conduct outreach activities each year after the conclusion of the field project. Initial results of the field project were presented at the Alaska Marine Science Symposium in 2016 (Angliss et al. 2016) and 2017 (Ferguson et al. 2017). A presentation about preliminary results was made to the Alaska Eskimo Whaling Commission (AEWC) in November 2016, and draft final results were presented to the AEWC in February 2018. Presentations were also made to the Alaska Beluga Whale Committee in November 2016. Preliminary results were also presented at a meeting of the Office of Naval Research Program Review (Angliss et al. 2017) and final results were presented at the POLAR2018 conference in Davos, Switzerland (Ferguson and Angliss 2018). Angliss et al (2018) and Ferguson et al (2018) were published back-to-back in the *Journal of Unmanned Vehicle Systems* to document the operational and analytical methods and results, and demonstrate completion of the objectives of this project.

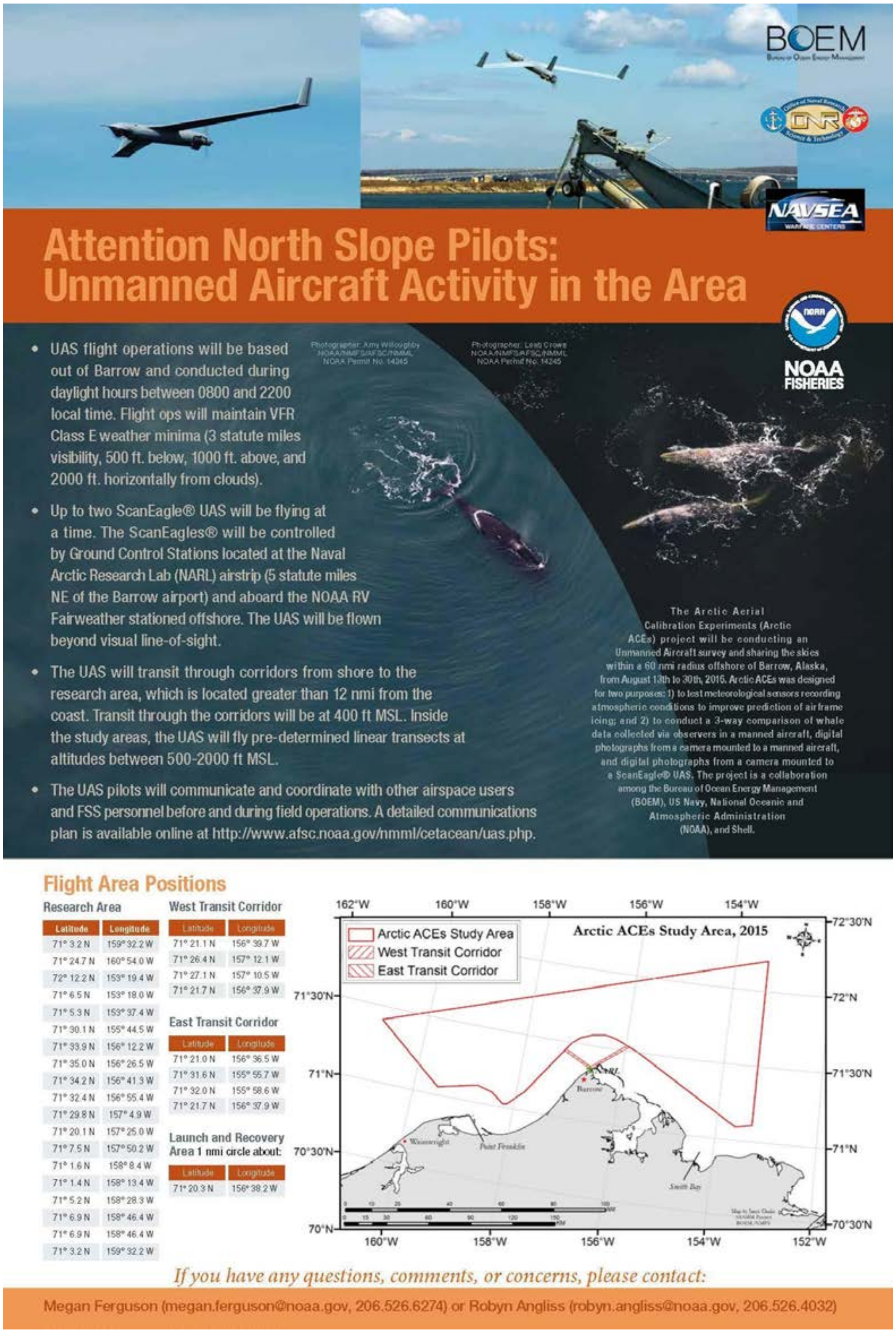

Figure 18. Flyer distributed to alert local community and pilots of the upcoming Arctic ACEs project.

COST

It is commonly believed that UAS will be less expensive than manned aircraft to meet the same goal. We compared the cost of this manual line-transect aerial surveys and the UAS surveys for this project to evaluate the cost (Table 2). The cost of the manned aerial surveys was 9.4% the cost of the manned survey. This difference was primarily due to the following:

- The cost of transporting the UAS from Virginia to Utqiaġvik, Alaska, on a C-130, which was provided by the Navy as an in-kind contribution to the project. Transportation of the sophisticated UAS to Utqiaġvik accounted for approximately 21% of the full cost of the UAS component of the project.
- The cost of staging a NOAA research vessel offshore of Utqiaġvik to enable hand-off of the UAV to a ship-based pilot so longer distance flights would be possible. The vessel was provided by NOAA as an in-kind contribution to the project and accounted for approximately 14% of the full cost of the UAS component of the project.
- Considerable manual labor was required to review images collected by the UAS to find marine mammals.
- The UAS surveys required a number of small expenses that were not required by the manned survey (bear guards; renting tents, generators, etc required for a field camp north of Utqiaġvik.

We expect that the cost of long-range UAS projects will decrease automated approaches are developed for analyzing imagery and as mid-sized UAS with a smaller footprint and lower transportation costs mature and become available for use in the challenging arctic environment.

RELATED PROJECTS

Aerial Surveys of Arctic Marine Mammals. Refer to final reports for BOEM/MML Interagency Agreement M11PG00033, M16PG00013, and M17PG00031.

PUBLICATIONS RESULTING FROM THIS STUDY

Angliss, R. P., Ferguson, M., Hall, P. G., Helker, V. T., Kennedy, A., & Sformo, T. (2018). Comparing manned to unmanned aerial surveys for cetacean monitoring in the Arctic: Methods and operational results. J. Unmanned Veh. Syst. 6(3): 109-127 doi:10.1139/juvs-2018-0001 doi:10.1139/juvs-2018-0001

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APPENDIX A: Image collection and processing protocols

Camera and lens specifications

Many factors, including airspeed, altitude, and camera focal length, can affect the size (i.e., area photographed) and quality (i.e., focus, clarity, brightness and contrast) of digital images collected from aircraft and need to be accounted for during post-processing and statistical analyses. The cruising speed for the UAS is approximately 60 kts (111.1 km/h), whereas the manned aircraft surveys are conducted at approximately 110 kts (203.7 km/h). While every attempt was made to ensure that the manned aircraft and UAS maintain the same altitude (1050 ft (320.2 m) MSL), there were instances when this was not possible. Additionally, due to UAS payload limitations described above, the camera configuration was not identical across platforms. Both the manned and unmanned aircraft used the Nikon D810 digital single-lens reflex camera with 1TB of memory, but the camera on manned aircraft used a Zeiss Distagon 21mm F2.8 ZF.2 lens, while the UAS camera will be integrated with a Nikkor 20mm F2.8 lens.

Photogrammetry terms and definition:

AGL	ALTITUDE ABOVE GROUND LEVEL (M)
SPEED	SURVEY SPEED (KTS)
FL	LENS FOCAL LENGTH (MM)
SS	SHUTTER SPEED
SI	SAMPLING INTERVAL (Sec)
GSD	GROUND SAMPLED DISTANCE (CM)
P	SENSOR PIXEL PITCH (MICRONS)
PSR	PHOTO SCALE RECIPROCAL
BLUR	IMAGE MOVEMENT (MICRONS)
IO	IMAGE OVERLAP
IMC	IMAGE MOTION CONSTANT (514773.3)
PS	PHOTO SCALE

Nikon D810 Specifications:

Sensor: 35.9mm wide by 24 mm high

Image size in FX Raw large format: 7360 pixels wide by 4912 pixels high.

Image ratio: 3:2

Blur and Photo Scale (PS) calculations for the Nikon D810:

- Photo scale is the ratio of a distance on an aerial photograph to that same distance on the ground in the real world.

IMC=IMAGE MOTION CONSTANT	514773.3
PS=FL(mm)/AGL (mm)	6.56168E-05
PSR= 1/PS	15240
BLUR=(IMC*SPEED in kts)/(SS*PSR)	1.013333268

Sensor Pixel Pitch (P) and Ground Sampled Distance (GSD) calculations for the Nikon D810:

- Pixel pitch is defined as “the center-to-center distance between individual pixels, in microns”. The area of one pixel may be calculated by squaring the pixel pitch.
- Ground sampled distance is defined as the distance between pixel centers measured on the ground. The bigger the GSD, the lower resolution. GSD is related to flight height in that higher altitude = higher GSD value.

P=(SW/IW)*1000	4.877717391 microns
GSD= ((AGL/FL)*P)/10	7.433641304 cm

Angular Field of View for Nikon D810:

This value was calculated via an online calculator:
http://www.tawbaware.com/maxlyons/calc.htm

Focal length multiplyer = 1

- **With Nikkor 20mm lens**

HORIZONTAL	84.0 degrees
VERTICAL	61.9 degrees

- **With Zeiss 21mm lens**

HORIZONTAL	81.2 degrees
VERTICAL	59.5 degrees

Coverage (aka Dimensional Field of View) for Nikon D810:

This value was calculated via an online calculator:
http://www.tawbaware.com/maxlyons/calc.htm

Focal length multiplyer = 1

- **With Nikkor 20mm lens**

HORIZONTAL	584.64 meters
VERTICAL	365.76 meters

- **With Zeiss 21mm lens**

HORIZONTAL	522.51 meters
VERTICAL	348.34 meters

Image Overlap (IO) Calculations:

DIST MOVED PER SI (M)= SI*SPEED in m/s	92.6001 meters
IO=(VERT. COVERAGE-DIST MOVED PER SI)/VERT. COVERAGE	0.746828248

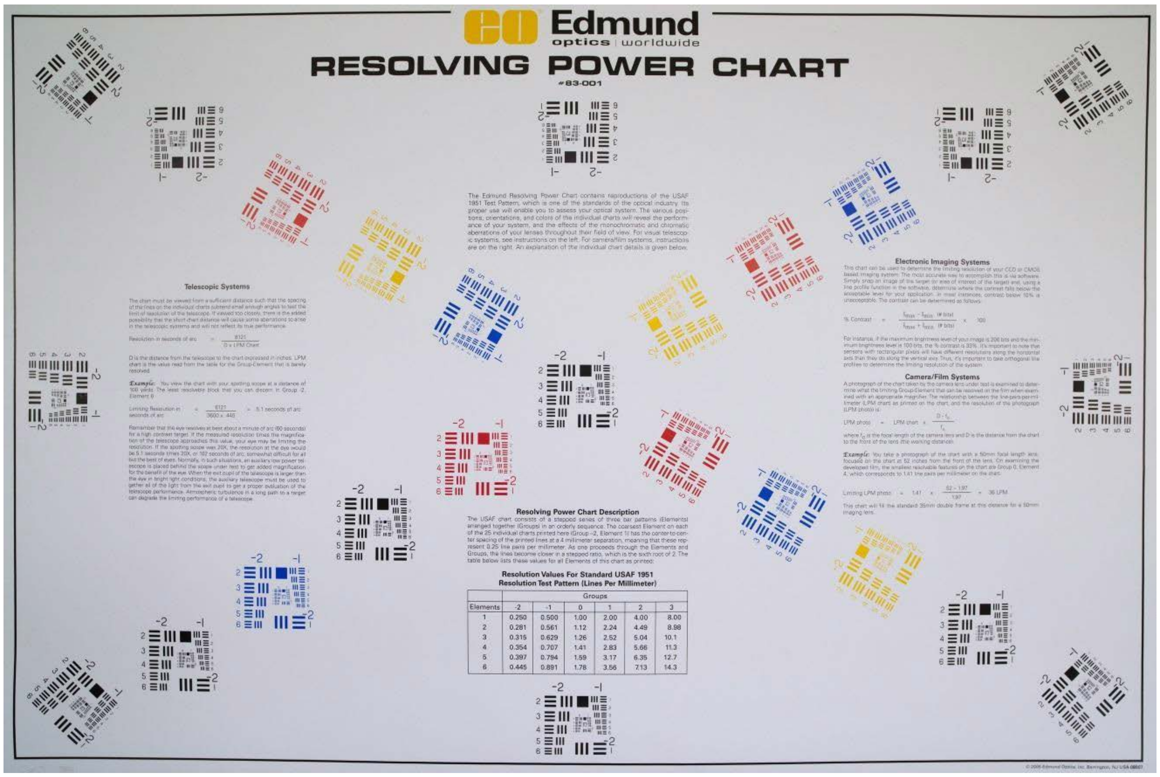
CALCULATION RESULTS SUMMARY

- NIKON D810 in FX large raw format
- Survey speed = 60kts or 30.87m/s
- Shutter speed = 2000 (1/2000th of a second)
- Sampling interval = 3 (one photo every 3 seconds)

	20mm lens	**21mm lens**
GSD	7.43 cm	7.08 cm
P	4.88 micron	4.88 micron
PSR	15240	14514
BLUR	1.01 micron	1.01 micron
IO	0.75	0.73

Comparing the Nikkor 20mm lens to the Zeiss 21mm Lens with the Nikon D810

● Mount the resolving power chart on a wall, ensuring that it is uniformly lit with enough light to use an exposure of >100th second at f/8. (http://www.edmundoptics.com/testing-targets/test-targets/resolution-test-targets/resolving-power-chart/1665/)



● Choose a lens, mount the camera on a tripod or solid surface, then:

A. Align the camera's sensor plane with the chart plane and the optical axis of the lens with the center of the rectangle. The easiest way to do this is to take a compass bearing for the plane of the target and then stand in the middle of the target and take a bearing 90° to the plane of the target. Another way to do this is to mount a long cylindrical object precisely in the center of the chart and perpendicular to it, then move the camera until you can see only the end of the object.

B. Adjust the distance so that the rectangle almost fills the viewfinder

C. Set the camera to aperture priority

D. Carefully focus the lens on the center target using LIVE VIEW MODE (because the apparent focus through the viewfinder is not always the actual focus)

E. Using a remote shutter release or setting the camera on a timer, make exposures at f/2.8, f/4, f/5.6, and f/8. Ensure the camera is set to collect FX-format Large RAW images.

● Repeat steps A through E for the other lens.

THEN

● Mount the calibration target we sent you on a wall or outdoors (we used a chain link fence and binder clips), ensuring that it is uniformly lit with enough light to use an exposure of >100th second at f/8

● Choose a lens, mount the camera on a tripod or solid surface, then:

A. With the camera on a tripod 400’ from the calibration target, align the camera’s sensor plane with the chart plane and the optical axis of the lens with the center of the aerial resolution chart.

B. Set the camera to aperture priority

C. Carefully focus the lens on the center target using LIVE VIEW MODE (because the apparent focus through the viewfinder is not always the actual focus)

D. Using a remote shutter release, make exposures at f/2.8, f/4, f/5.6, and f/8.

● Repeat steps A through D for the other lens.

● Stand 1000’ from the calibration target, then focus the lens using live view mode, then mark the lens with a fine point marker and tape the focus ring where the image appears sharp. Note: the bars of the target will likely not be distinguishable at this distance, but should show up after the images are downloaded.

Appendices B and C are published manuscripts. These publications are being provided as part of this report because they include substantial additional detail about the methods and results of this project.

APPENDIX B: Comparing manned to unmanned aerial surveys for cetacean monitoring in the Arctic: Methods and operational results.

NRC Research Press

ARTICLE

Comparing manned to unmanned aerial surveys for cetacean monitoring in the Arctic: methods and operational results[1]

R.P. Angliss, M.C. Ferguson, P. Hall, V. Helker, A. Kennedy, and T. Sformo

Abstract: Manned aerial surveys are routinely used to assess cetacean distribution and density, often over large geographic areas. Unmanned aircraft systems (UAS) have been identified as a technology that could augment or replace manned aerial surveys for cetaceans. To understand what research questions involving cetacean distribution and density can be addressed using manned and UAS technology in the Arctic, we conducted paired aerial surveys for cetaceans near Utqiaġvik (Barrow), Alaska. We present the methods and operational results from the project, and challenges encountered during the field work. Fall arctic weather varied dramatically over small spatiotemporal scales and harsh environmental conditions increased the maintenance required for repeated UAS operations. Various technologies, such as temperature and humidity sensors, a software system that provided near-term forecasts of highly variable weather, and a surface-based air traffic radar feed, directly contributed to the ability to conduct routine, successful, beyond line-of-sight UAS flights under these situations. We provide recommendations for future projects to help streamline project planning and enhance researchers' ability to use UAS to collect data needed for ecological research.

Key words: unmanned aerial system, UAS, cetaceans, marine mammals, aerial survey.

Résumé : Les levés réalisés au moyen d'aéronefs pilotés sont couramment utilisés pour évaluer la répartition et la densité de cétacés, souvent sur de grandes régions géographiques. Les systèmes d'aéronef sans pilote (UAS) ont été signalés comme étant une technologie qui pourrait compléter ou remplacer les levés aériens avec pilote sur les cétacés. Dans le but de comprendre quelles questions de recherche liées à la répartition et à la densité de cétacés peuvent être étudiées utilisant la technologie avec et sans pilote dans l'Arctique, nous avons réalisé des levés aériens combinés sur les cétacés près d'Utqiagvik (Barrow), en Alaska. Nous présentons les méthodes et les résultats opérationnels du projet et les défis qui se sont présentés lors du travail sur le terrain. Les conditions météorologiques automnales en Arctique variaient radicalement, et ce,

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sur de petites échelles spatio-temporelles et des conditions environnementales difficiles ont causé un entretien accru nécessaire au bon fonctionnement des opérations répétées des UAS. Les différentes technologies, comme des capteurs de température et d'humidité, le système logiciel donnant des prévisions à court terme du temps hautement variable et les informations de trafic aérien par radar au sol, ont directement contribué à la capacité d'effectuer des vols UAS de routine réussis au-delà de la ligne de vision sous ces conditions. Nous présentons des recommandations pour des projets futurs dans le but de simplifier la planification de projet et d'améliorer la capacité des chercheurs à utiliser les UAS afin de recueillir les données nécessaires pour la recherche écologique. [Traduit par la Rédaction]

Mots-clés : système d'aéronef sans pilote (UAS), cétacés, mammifères marins, levé aérien.

Introduction

Manned aerial surveys from fixed-wing aircraft have been used successfully for decades to achieve diverse scientific and wildlife management goals. Aerial surveys are of particular utility for assessing distribution and abundance of marine mammals (Garner et al. 1999; Buckland et al. 2001) because they can cover large areas in a relatively short period of time, and have been the foundation of many estimates of abundance of marine mammals; for instance, 27 of the 45 recognized marine mammal stocks in Alaska have abundance estimates based on manned aerial surveys (Muto et al. 2016). However, use of manned aircraft for marine mammal surveys does have some well-known and often-cited limitations, including impacts of observer fatigue on data collection, the potential to disturb wildlife, and cost (Hodgson et al. 2013).

Surveys conducted using unmanned aircraft systems (UAS) may be unaffected by some of the limitations of manned aircraft and could be a reliable, efficient, cost-effective, and operationally flexible alternative to surveys conducted with manned aircraft. UAS have only recently been used in ecology and wildlife research, but their use is increasing rapidly, and has increased even within the past 5 years (Chabot 2018). A search of Web of Science for publications from 2005 to 2016, followed by a search of citations included in publications found in Web of Science, documents approximately five publications per year addressing the use of UAS for wildlife studies from 2002 through 2011 (e.g., Stark et al. 2003; Acevedo-Whitehouse et al. 2009; Koski et al. 2009; Watts et al. 2010). The number of published studies found involving UAS and wildlife or marine mammal research increased gradually from 2012 to 2014 and peaked at over 25 publications in 2015 as biologists used this new technology to meet existing and new research goals (e.g., Sarda-Palomera et al. 2012; Anderson and Gaston 2013; Christie et al. 2016).

While UAS are being used successfully to collect a variety of wildlife data, the vast majority of projects have involved small, relatively inexpensive UAS that collect information relatively close to where the aircraft is launched (Barasona et al. 2014; Mulero-Pázmány et al. 2015; Christie et al. 2016; Johnston et al. 2017; Laguna et al. 2018). Despite great interest in the potential to use UAS for long-range surveys of marine mammals, studies involving long-range flights have been limited due to cost and the challenge of gaining permission to conduct beyond visual line-of-sight flights with UAS, particularly in the United States.

Over the past several years, researchers have been gradually evaluating whether UAS with the capability to fly well beyond visual line-of-sight can be used for collecting large-scale information on marine mammals that could be used to estimate density, distribution, and abundance. In 2009, Moreland et al. (2015) conducted a within line-of-sight evaluation of a UAS with beyond visual line-of-sight capability to determine if the system could provide an effective way to assess ice-associated seal distribution in the Bering Sea pack ice. In 2013, Koski et al. (2015) evaluated the use of a TD 100E UAS[2] — which has a range and payload capacity comparable to the ScanEagle® and a Nikon D800 camera — and concluded that this system would collect images of bowhead whales adequate for photo-identification of individuals when images are collected at low altitudes. Koski et al. (2013) compared the use of human observers to high definition video and fixed digital imagery to evaluate which system would most likely be helpful for marine mammal surveys when mounted in an unmanned aerial vehicle (UAV). Hodgson et al. (2013) conducted within line-of-sight strip-transect surveys using a ScanEagle® to collect observations of dugongs; Maire et al. (2013) worked with Hodgson and initiated attempts to automate the image analysis process to increase the speed of analysis.

Specific operational, data acquisition, and sampling requirements for using UAS to meet cetacean research or monitoring goals at a large scale have not been tested. Existing UAS technology integrated with a digital camera payload needs to be evaluated to determine how well it performs relative to conventional manned aerial surveys to collect large-scale data on cetaceans. This arctic mission is the first dedicated experiment specifically designed to understand the advantages and disadvantages of using a UAS with long-range capability relative to manned aircraft to collect data for estimating large scale, at-sea marine mammal density.

Our overall objectives are to evaluate the ability of ScanEagle® technology (i.e., platforms, payloads, sensors, and software) to collect data to detect cetaceans, identify species, estimate group size, and identify calves, and to compare results to conventional aerial surveys conducted by human observers in fixed-wing aircraft. The objective of this paper is to describe the field operations in August and September 2015, provide recommendations about conducting similar large-scale UAS operations in the Arctic, and provide cost comparison information for the manned and UAS survey approaches used for this study. This paper describes the materials, methods, and operational results. A comparison of the data resulting from the project is provided separately (Ferguson et al. 2018).

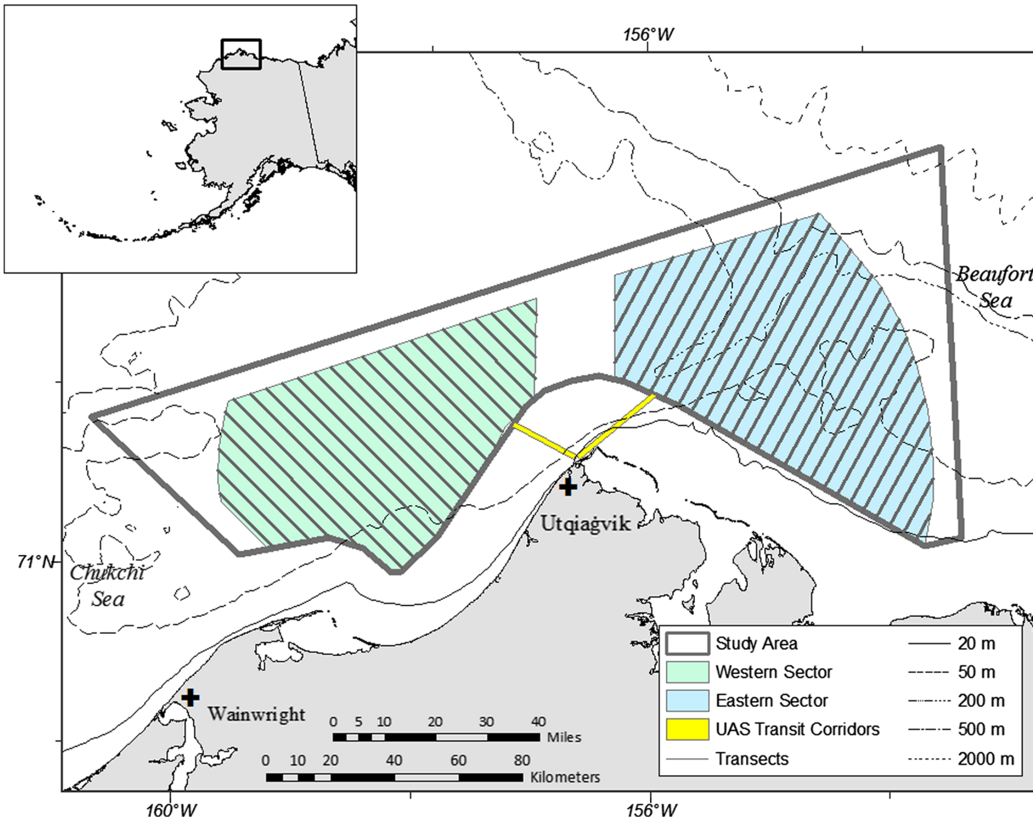
Materials and methods

Study area

Manned and UAS aerial surveys were conducted over the northeastern Chukchi Sea and western Beaufort Sea (Fig. 1). The study area is located between 22 and 111 km (12–60 nautical miles (nmi)) from shore on either side of Utqiaġvik (Barrow), Alaska. This area was selected for UAS operations for three reasons. First, the study area lies within an area where the Federal Aviation Administration (FAA) plans to establish permanent operational areas and corridor routes (for access to coastal launch sites) in the Arctic for the operation of small UAS. We anticipated that this emphasis would enhance our chances of receiving FAA permission for beyond visual line-of-sight flights needed for the project. Second, large cetaceans, particularly gray whales and bowhead whales, are reliably found in high densities in portions of this area during the open water (ice-free) season (Clarke et al. 2014; Citta et al. 2015; Brower et al. 2017). Further, modeling efforts using existing gray whale data collected during previous aerial surveys indicated that the project should be able to achieve a coefficient of variation of 0.3 in estimated gray whale density in this area with approximately 50 h of UAS flight time. Third, the study area is located in international airspace, offshore of the coastal corridor where small aircraft frequently transit between villages on the

[2]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

Fig. 1. Study area near Utqiaġvik, Alaska. Unmanned aerial system (UAS) pilots were granted permission by the Federal Aviation Administration for beyond line-of-sight UAS flights in the study area; the east and west offshore survey areas were accessed using one of two corridors that linked the launch site north of Utqiaġvik and the offshore flight areas.



North Slope of Alaska, but in general in an area of low density air traffic. Operating in this low density air traffic area increases the safety of the project by decreasing the probability of encountering other airspace users. The area was separated into east and west sectors to reflect different habitats in the Chukchi and Beaufort Seas, and to allow predetermined transect lines to be flown perpendicular to the various environmental gradients (depth, currents, and marine mammal density) in each area.

Weather during the late summer and early fall in the Arctic is highly variable both temporally and spatially, and can range from cloud-free and sunny to snow, sometimes within the same day. Based on many years of experience conducting manned aerial surveys in the Arctic, the team expected to experience near-freezing and below-freezing temperatures, strong winds, fog, low ceilings, and various types of precipitation. In the high relative humidity and low ambient temperatures common during the late summer and early fall, there is potential for the UAV to experience both structural and carburetor icing. Based on the proportion of days flown historically by the marine mammal aerial survey teams in manned aircraft, we expected to be able to conduct manned and UAS flights on 5–6 days during a 17 day field season planned to occur between 14 and 31 August 2015. We assumed that the UAS flight team could conduct two flights on every good flight day (ceiling >1000 ft, winds <20 km/h at launch) to maximize survey hours.

Outreach

Outreach served two key functions: (*i*) mitigating potential risks to other airspace users due to flying the UAS beyond visual line-of-sight, and (*ii*) ensuring that the field operations would not impact residents in Utqiaġvik. Communication with pilots who might be conducting flights in the area was a critical component of the strategy to mitigate potential risks of operating the UAS beyond visual line-of-sight. Meetings or calls were held with pilots servicing offshore petroleum exploration projects, local commercial airline companies, the Alaska Air Carrier's Association, the FAA Barrow Flight Services Station, Alaska Flight Services, and the U.S. Coast Guard. Daily conference calls were conducted on a publicly accessible phone number every day at 0700 h (local) so local pilots for both manned and UAS operations could exchange information on their flight plans for the day.

A poster (Fig. 2) was electronically circulated to all known individuals (approximately 45 parties), who commonly conduct work offshore over the Beaufort and Chukchi Seas, including local pilots, biologists in agencies or companies, and other interested parties. Forty copies of the poster were displayed in Utqiaġvik and Deadhorse, Alaska, to alert locals about the project and it was made available on the FAA-Alaska Public Notices website. Letters and flyers were sent to big game hunting guides permitted to operate on the North Slope who might base somewhere other than Utqiaġvik, but could be flying at low altitudes along the coast.

Community outreach included mention of the project on a flyer that was sent to ~300 Alaska Native coastal tribal organizations, villages, and corporations approximately 6 months before the project began. Starting at least 6 months before the project, we consulted with local government officials, local wildlife management officials, and Alaska Native community members and organizations. A public service announcement was broadcast on Alaska Public Radio in Utqiaġvik starting on 18 August as the team was setting up at the field site. The team welcomed visitors at the field site, and gave impromptu summaries of the project objectives, descriptions of the equipment, and procedures throughout the field season.

Manned aircraft and human observers

The manned aerial surveys were conducted using a Turbo Commander 690A, a fixed-wing twin-engine turboprop aircraft. Observers were experienced prior participants in surveys of arctic marine mammals, and collected visual line-transect data on marine mammals and relevant environmental conditions consistent with previous studies in the area (Clarke et al. 2014; Ferguson et al. 2018). A high-resolution camera system (see UAS payload details) mounted in a belly port of the Turbo Commander was pointed vertically downward, and collected images every 2 s. This approach is very similar to that used by Koski et al. (2013) to compare human observers to images from cameras onboard the aircraft, with the exception that our study added the direct comparison with vertical images collected by the UAS.

The UAS and payloads

The Insitu ScanEagle® UAS was selected for this study because it is a robust platform with a successful operational history and a flexible payload capability. This platform had been used successfully from the NOAA Ship *McArthur II* in 2009 to collect imagery of ice-associated seals in the Bering Sea (Moreland et al. 2015) and had been used by other projects conducting long-range surveys of marine animals (Hodgson et al. 2013).

The UAS was configured for land- or sea-based operations and includes the airframe, SuperWedge launcher, Skyhook retrieval system, ground control station (GCS), software, and auxiliary equipment. The airframe has a wingspan of 3.1 m (10.2 ft) and is 1.6 m (5.3 ft)

Fig. 2. Flyer distributed to alert local communities and pilots of the upcoming beyond line-of-sight unmanned aerial systems project.

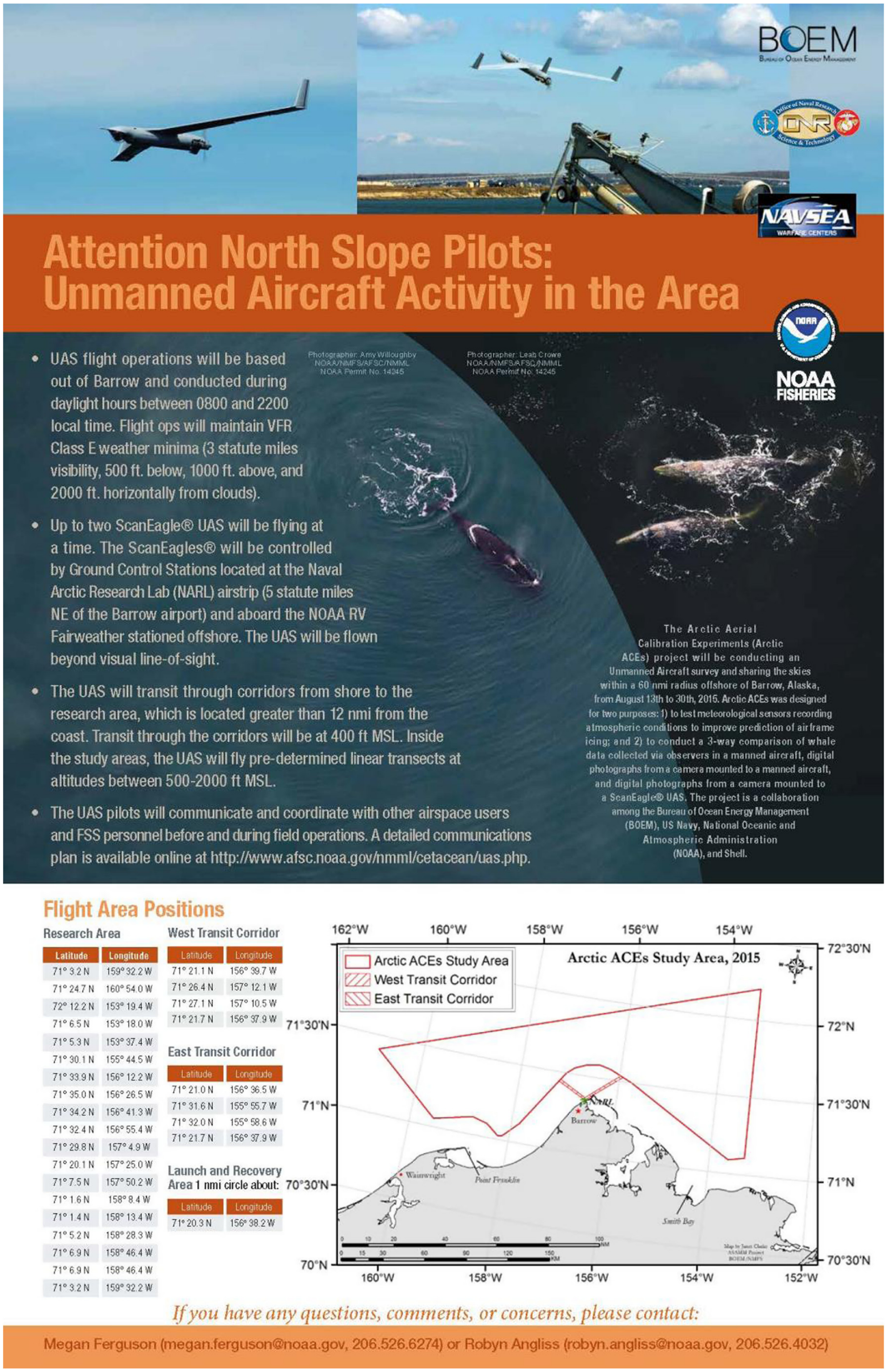


Table 1. Specifications and operations of the camera systems used in the UAV and the manned aircraft.

Specification	UAS	Manned aircraft
Camera model	Nikon D810	
Camera sensor size	35.9 mm × 24 mm	
Lens	Nikkor f2.8	Zeiss Distagon
Lens focal length	20 mm	21 mm
Target altitude	305 m (1000 ft)	320 m (1050 ft)
Target speed	111 km/h (60 kn)	203 km/h (110 kn)
Image interval	100 m (roughly every 3 s)	2 s (roughly 118 m)
Swath dimensions	576 m × 384 m	548 m × 365 m
Ground sampled distance*	7.8 cm	7.1 cm
Actual image resolution, Virginia	6 cm at 320 m (1050 ft)	n/a
Actual image resolution, Utqiaġvik	>3 cm at ~121 m (400 ft)	>11 cm at 305 m (1000 ft)
Onboard image storage	1 TB	
Metadata recorded for each image	Latitude, longitude, altitude, date/time, and various information about the camera and image exposure	

*Ground sampled distance (GSD) is the actual ground distance between the center of each pixel.

long (retrieved from the Insitu.com website on 5 September 2017); the dual-bay configuration used in this study increased the length to 2 m (6.5 ft). The maximum takeoff weight of the UAV is 22.0 kg (48.5 lb), cruise speed is 93–111 km/h (50–60 kn), maximum endurance is 24 h, and maximum altitude is 6000 m (19 000 ft). The aircraft has a rear-mounted engine driving a pusher propeller. Flight operations are controlled with a GCS that can be land-based or ship-based. The software includes pilot interfaces for preflight checks, aircraft control, and monitoring of multiple aircraft on independent missions. The SuperWedge launcher is powered by compressed air, and is manually activated using a pull cord. The launcher accelerates the aircraft to flight speed. The retrieval system captures the aircraft at the end of the flight. The aircraft uses GPS to automatically fly itself into a rope suspended approximately 13.6 m (45 ft) above the ground or deck. A hook on the aircraft wingtip catches the line and stops the aircraft.

Resolution <15 cm has been recommended as adequate for differentiating some species of large cetaceans; given the low light conditions and lack of contrast between dark bowhead whales and dark water, we chose a system that provided improved resolution so we could reliably detect large whales, identify whales to species, estimate group size, and determine whether calves were present. The UAV and Turbo Commander were each equipped with Nikon D810 high-resolution digital single lens reflex (DSLR) cameras capable of providing a minimum photographic ground resolution of 7 cm/pixel and a minimum photographic strip width of 400–600 m (1320–1980 ft) at 320 m (1050 ft) altitude. The camera mounted in the UAV was equipped with a 20 mm Nikkor f2.8 lens. The Turbo Commander camera used a 21 mm Zeiss Distagon lens. Initially, a 21 mm Zeiss Distagon lens was also chosen for the UAV camera to be consistent with the manned aircraft payload, but the weight and length of the Zeiss lens exceeded the UAS carrying capacity. The 20 mm Nikkor lens is shorter, lighter, and allowed for a greater swath width than the Zeiss lens. Table 1 includes a summary of the camera specifications for each platform.

The DSLR system was chosen because of the following:

- The predecessor to the D810, the Nikon D800, had been used successfully in a similar project in the same or similar environment (Koski et al. 2013, 2015). The D810 contained all of the same features as the D800, but allowed for a maximum ISO of twice the D800 to improve image quality in low-light conditions.

- The camera's full-frame sensor with a 20 mm lens provided for a 576 m swath width at survey altitude of 318 m (1050 ft).
- The camera body had slots for both a CF and SD storage card, enabling 1 TB of storage in the camera. 1 TB of storage translates to roughly 10 h of flight time while collecting uncompressed raw images.

In addition to the Nikon D810, the UAV carried the following four payloads:

- An Atmospheric Sensing and Prediction System (ASAPS) Meteorological Sensor, developed by PEMDAS Technologies and Innovations, provided meteorological data real-time to the UAS ground station so the UAS pilots could analyze current meteorological conditions and provide information on the risk of carburetor and airframe icing.
- An electro-optical video camera provided the UAS pilot with situational awareness during flight.
- A GPS pinger was installed to aid in recovery of the UAS in the event of a controlled water landing and to ensure GPS metadata would be included with the D810 images.
- A Mode C transponder that can be detected by airborne Traffic Alert and Collision Avoidance System (TCAS) on manned aircraft and with ground-based air traffic radar.

Digital camera payload flight-testing

The Nikon D810 and 20 mm Nikkor lens were flight tested at the Naval Surface Warfare Center Dahlgren Division (NSWCDD) in Virginia on 20–21 July 2015. The UAS overflew a tri-bar calibration target at predetermined altitudes to assess the accuracy of the camera system and to ensure that the pilots could determine whether the camera was firing. During the test flights, images taken at 320 m (1050 ft) and 111 km/h (60 kn) showed an image resolution of 6 cm; images taken at 121 m (400 ft) and 111 km/h (60 kn) showed an image resolution of 3 cm (1.2 in; Table 1).

Daily flight operations

The NSWCDD was responsible for managing and conducting all aspects of the UAS operations. The UAS ground team, GCS, launch and retrieval systems, communications systems, UAS, and backup equipment were located at a decommissioned runway approximately 8 km (5 miles) north of the Wiley Post–Will Rogers Memorial Airport in Utqiaġvik, Alaska. The NSWCDD shore-based team was staffed to provide the ability to fly two UAS simultaneously, and included an air boss, who was the lead for all UAS flight operations, three individuals who were pilots-in-command (PIC) and UAS technicians, and one individual dedicated to UAS maintenance. Portable tents designed for extreme weather were used to shelter the GCS, components of the UAS, and the survey team. An additional PIC and a second GCS were aboard the NOAA ship *Fairweather*, which was positioned in the study area from 19 August through 30 August to provide situational awareness, enable full UAS coverage of the study area through a hand-off of the UAS to the ship-based pilot, and provide aid in the event of a water landing.

All flights occurred during daylight hours, between 0800 and 2200 h local time, and during periods of favorable weather (wind less than 39 km/h and no visible precipitation).

The UAV was launched and recovered from the shore-based station and accessed the offshore study areas located in international airspace through one of two transit corridors (Fig. 1). The UAV remained at or below 121 m AMSL (400 ft) while inside the corridor. Once in the offshore study area, the UAV targeted an altitude of 305 m AMSL (1000 ft) and an airspeed of 111 km/h (60 kn). The flight tracks were preprogrammed fine-scale transects 4.75 km (2.6 mi) apart. High-resolution digital images were collected every 3 s (100 m distance) over water. The UAV remained within radio line-of-sight of a GCS (50–70 nmi). The pilot monitored the onboard video and ASAPS sensor output and altered course as necessary to avoid precipitation or clouds. Once UAS operations were complete on a particular day, the UAV descended below 400 ft AMSL (121 m) while still in international airspace offshore and entered the transit corridor inbound for recovery.

When weather permitted, the manned aerial survey team took off from the Wiley Post–Will Rogers Memorial Airport at Utqiaġvik and surveyed predetermined transects 9.5 km (5.12 mi) apart in the survey area. The manned aircraft conducted surveys at a target altitude of 320 m (1050 ft), which provided a 15 m (50 ft) buffer relative to the target flight altitude of the UAS (305 m; 1000 ft). The target flight speed of the manned aircraft was 213 km/h (115 kn). Manned aerial survey protocols detailed in Clarke et al. (2017) were followed.

At the beginning of each flight, the aircraft overflew calibration targets so the resolution of the camera systems could be evaluated after the flights. The UAV overflew a tri-bar calibration target on land near the launch and retrieval site at approximately 131 m (400 ft) altitude. The manned aircraft overflew the same tri-bar calibration target at the beginning of multiple flights at approximately 167 m (550 ft). On 26 August, the manned aircraft overflew a larger calibration target positioned on the bow of the NOAA ship *Fairweather*, at 305 m (1000 ft); the UAV overflew the larger target at approximately 121 m (400 ft).

Coordinating UAV and manned aerial survey flights

The survey design assumed that the UAV and manned flights would be synchronized in time and space to obtain independent, replicate samples of whales. There is some risk inherent in deliberately conducting simultaneous flights of manned and unmanned aircraft in close proximity. In-flight safety was ensured by developing procedural methods by consensus among the pilots and science leads for the two field teams, and by using technological methods required by the FAA. Procedural methods included daily morning meetings of both field teams to discuss the plan for the day, a detailed communications plan that involved aviation radio and satellite telephone contact, development of rules for surveying, and contingencies for communication technology failure. Technological methods included the use of TCAS for the manned aircraft, which alerts pilots of nearby aircraft of a possible collision threat based on their range, altitude, and bearing. In addition, NOAA utilized a service that provided real-time, surface-based air traffic radar feed allowing the UAS team to detect aircraft in the area.

The manned aircraft and UAV flew simultaneously and successfully in the survey area. Initial protocols designated a minimum separation distance of 12 km (7.5 mi) laterally and 15 m (50 ft) vertically. Dynamic weather and the need to adapt flight plans in flight exacerbated the complexities of airspace coordination. After a few simultaneous flights of both platforms, the teams opted to increase the spatial separation, allowing only one project aircraft in a sector at a time.

Authorizations

Unmanned aircraft systems surveys were conducted under a FAA Certificate of Authorization (COA) that authorized beyond visual line-of-sight flights in the National Airspace System and international airspace managed by FAA. Navy Interim Flight Clearance was granted to the NSWCDD, which served as the airworthiness document for the ScanEagle® UAS. The marine mammal research was authorized under Marine Mammal Protect Act permit 14245-03, as amended and issued to the Marine Mammal Laboratory by the NOAA Fisheries Office of Protected Resources. The incidental harassment of polar bears and walrus caused by the UAS flights were authorized by permit 212570-1 from the U.S. Fish and Wildlife Service. Use of the area north of Utqiaġvik was authorized under North Slope Borough permits 16-013 and 16-078.

Table 2. Summary of hours flown and number of images collected in the survey area during each flight of the unmanned aerial systems (UAS) and the manned aircraft useful for the density comparison.

	UAV flights		Manned flights		
Date	Flight hours	No. of images	Flight hours	No. of images	Comments
26 August	3.7	2 736	—	—	Successful hand-off of UAS from shore- to ship-based team. Project transects not flown by manned survey team.
29 August	—	—	3.2	5 103	—
30 August	—	—	—	—	Manned flights attempted but aborted due to low ceiling and poor observing conditions.
31 August	6.0	6 246	3.3	4 212	Camera mount damaged on retrieval.
1 September	5.5	5 460	4.8	4 896	—
2 September	5.0	4 995	1.3	1 368	Most manned aircraft flight time outside of survey area due to poor conditions.
6 September	1.6	1 131	—	—	Manned aircraft conducted reconnaissance to assess conditions for UAV flights; retrieval of the UAS damaged boom on the skyhook.
7 September	UAS team packed gear		5.4	8 001	Manned survey team completed all transects in the study area.
Total	21.8	20 568	17.9	23 580	Total images = 44 148 on transect.

Results

The UAS team conducted five flights of the ScanEagle® during the study (Table 2). UAS flight duration in the survey area ranged from 1.6 to 6 h and 20 568 images were collected during the flights. The manned aerial survey team conducted flights on 7 days during the project (Table 2); flight duration in the survey area ranged from 1.3 to 4.8 h and 23 580 images were collected during the flights. The manned aircraft conducted additional surveys outside the survey area when the weather was too poor for effective observations in the survey area. There were 3 days when flights were conducted by both the UAS and the manned aerial survey teams.

The local weather was highly variable, both spatially and temporally. There were often patches of squalls or low clouds offshore that were not apparent from the shore, but could be seen using the live video feed from the UAV and by the crew of the Turbo Commander. The ScanEagle® team kept the UAV away from clouds and attempted to remain clear of precipitation. The team managed the UAV's interaction with the weather by monitoring the onboard video camera and the temperature and humidity data provided by the ASAPS sensor. The UAV frequently encountered theoretical carburetor icing conditions during flights; the team mitigated the potential for carburetor icing by operating the UAV at high revolutions per minute (RPM) to keep the engine warm.

The project design relied on the expectation that two UAS could survey simultaneously to accumulate the estimated number of hours needed for a robust analytical comparison between survey platforms. Unfortunately, due to the complications of coordinating manned and UAV flights, weather, and technical issues, the team did not have the opportunity to fly two UAVs simultaneously. Science results are found in Ferguson et al. (2018).

Observations and recommendations

Despite great interest in using UAS in the Arctic, only a handful of projects have successfully used UAS to conduct research beyond line-of-sight. The use of UAS in the Arctic remains in its infancy and the learning curve is still relatively steep. The following observations and recommendations are provided to guide future UAS projects, particularly those that are directed at marine mammals, occur beyond line-of-sight or that occur in the Arctic.

Use of a shore-based location for the primary GCS

Overall, the location of the shore-based camp north of Utqiaġvik was acceptable for launch and recovery of the UAS. The area was open, and while there were some obstacles nearby, the UAV could be launched and retrieved from multiple directions. The large tents (3 m × 6 m) used to house the GCSs and provide a place for storage and maintenance of the UAS were minimally adequate. Lodging, food, and hardware supplies were located a short drive away in Utqiaġvik, and logistics support was provided by a local company, Ukpeaġvik Iñupiat Corporation (UIC), that specializes in arctic science support. In the planning stages of the project, the initial evaluation was that it would have been substantially more complicated to integrate the UAS on the NOAA research vessel than to stage on the shore. UIC provided polar bear guard services and night security for the site.

We recommend using a hard-sided, temperature controlled workspace for housing the GCS and UAV equipment. The working area inside the tents was minimally adequate but challenging. Equipment was frequently tested and found fully functional in the evening, yet during flight preparations the next morning, new technical issues were discovered and had to be fixed. Many of the technical issues were believed to be caused by low temperatures and high humidity at the field site. If a temperature-controlled area were sufficiently large to allow the UAV to be placed indoors with their wings on, it would shorten the time to launch from approximately 2 h to 45 min after arriving at the site.

Use of a shore-based site as the location for the primary GCS, launch, and retrieval of the UAS meant that the UAS system had to be transported to Utqiaġvik. This is a significant task due to the considerable size and weight of the UAS launch and recovery equipment, and a C130 was needed to transport the gear. Because the U.S. Navy was a partner on this project, transport via C130 was provided free of charge to the project. However, if this had not been available, chartering a commercial C130 flight from the U.S. east coast to Utqiaġvik would have cost approximately $580K (USD). If a shore-based operation is preferred, future projects that require a fixed-wing UAV would benefit from using a UAV that could launch and (or) land on a runway, eliminating the need for bulky launch and recovery systems, or a UAS already staged in the area of interest.

Beyond visual line-of-sight flights of the UAV

The receipt of a COA for these flights was a notable success as the FAA had issued few COAs for beyond visual line-of-sight flights by UAS.

Flying beyond visual line-of-sight is required to collect some types of environmental data, and the permitting and logistical requirements are significant for beyond visual line-of-sight flights in U.S. airspace. The FAA authorized a beyond visual line-of-sight COA for this project based on an air traffic density study and operations were contingent on the implementation of a rigorous communications plan for exchanging critical information with other airspace users and continuously monitoring the surface-based air traffic radar for any aircraft approaching the operations area. The communications protocol proposed to the FAA ensured that local airspace users — including pilots of both manned and unmanned systems — would be aware of our beyond line-of-sight activities in the area each day. The protocol included extensive preseason outreach to pilots.

The UAV has a Mode C transponder that can be detected by airborne TCAS and with ground-based air traffic radar. Through the surface-based air traffic radar feed, the air boss, who was the lead for all flight operations, was able to see the UAV and other air traffic in the survey area. The surface-based air traffic radar was also useful for monitoring offshore air traffic, particularly the project aircraft and local pilots transiting to an offshore drilling area, both of which were flying at approximately the same altitude as the UAV.

The air traffic density study, communications protocols, and air traffic radar were useful in reducing risk to manned aircraft in airspace shared by manned and unmanned aircraft, particularly when UAS were operating beyond visual line-of-sight in areas and at altitudes where manned aircraft also occur.

Operations in arctic fall weather conditions

Icing of the airframe and carburetor are a well-known problem for UAS and can significantly restrict flights. UAS were first flown in the Arctic in the spring of 1999 (Curry et al. 2004); airframe icing and carburetor icing caused the project to lose three aircraft after 16 h of flight time. While fall conditions for this project were substantially warmer than those typical of April, the combination of low temperatures and high humidity meant that icing was a potential problem on many days that were otherwise good flight days. The UAS flight team managed potential in-flight carburetor icing conditions by running the engines at relatively high RPM and faster speeds to keep the engine warm. Additionally, the PIC recorded the commanded throttle and respective RPM reading every 15–30 min to ensure that the engine was not exhibiting degraded performance. The use of fuel-injected engines would not have resulted in increased flight time during this project, but they are a recommended solution for the Arctic because of the high potential for carburetor icing issues. At no time did the team stand down due to predicted carburetor icing conditions prior to flight.

We recommend that UAS manufacturers and operators develop a more precise understanding of when carburetur icing occurs in UAVs. The lack of platform-specific information on the conditions under which carburetor icing may be a problem for a particular UAV will mean that pilots may tend to be unnecessarily conservative about flights in conditions that the equipment manual might call “marginal”. Temperature and humidity data provided real-time by an onboard sensor on the platform will be more useful to the UAV pilots if the relationship between the environmental data and the probability of icing on a particular UAV is better understood. Laboratory tests to verify the conditions under which carburetor icing of various UAVs actually occurs would be helpful.

There are a number of features that could be added to a UAV to improve its capability to fly in an arctic environment. A UAS that could be flown in occasional icing conditions and be approved to go through clouds could access more areas where the weather is sufficient for marine mammal surveys. Platform updates, such as satellite-linked monitoring and control, and modifications to handle icing such as heated pitot tubes, wing boots, and heated propellers would be helpful. For this project, weatherproofing would have been most helpful for the shore-based team because the team had to work on the UAS in light mist as they waited for local squalls to pass the study area, and it was clear that long-term storage in a cold, damp environment damaged the equipment over time.

The availability of weather information at the field site — specifically short-term, high resolution, local information on precipitation — facilitated UAS flights because it informed the pilots of local environmental conditions at the field site, located 8 km (5 mi from the airport, where official FAA weather observations were measured). A portable weather station was used late in the field project to assess information on ceiling altitude at the field site. Due to local variability, the ceiling at the field site was often hundreds of metres higher or lower than the ceiling at the airport; having a weather station at the field site enabled the team to measure minimum launch criteria more accurately and frequently. “NOWcasting” software that provides immediate or short-term forecasts, such as that designed by PEMDAS and used for this project, was helpful to predict short-term variation in weather conditions.

Ship-based UAS operations

The ability to conduct ship-based UAS operations may be helpful to many researchers, but UAS may not integrate readily on vessels commonly used by researchers. A highly customized integration for our project would have required significant time and funds, and multiple test flights.

When not committed to supporting the UAS project, the ship's crew optimized vessel time in the area by conducting hydrological surveys of the coastal areas near Utqiaġvik and deploying U.S. Navy wave-gliders. The ability to conduct multiple important projects simultaneously improves the cost-efficiency of the vessel time.

We recommend vessels used for arctic research be assessed to provide potential users with information relevant to understanding what types of UAS operations are compatible with each vessel. This assessment should include measurements of deck space available for launch and recovery, space for the GCS, and space for storage and maintenance of UAS equipment.

Future beyond visual line-of-sight arctic maritime operations should be based off a vessel in lieu of from a shore-based station. This may limit the vessel–UAS combinations that can be easily implemented, as integrating some UAS on some vessels will be complicated and expensive. However, basing off a vessel was considered the single operational change that would have directly and significantly improved the chances of getting the flight hours needed for the project. Often, weather conditions in Utqiaġvik were sufficiently poor to prevent launch (low ceilings, fog, or winds); however, based on weather reports from the affiliated ship there were offshore areas that could have been accessed if the UAV could have been launched from a vessel. Advantages to basing off a ship for this project included

- ability to move to areas of good weather within the study area for launch and recovery;
- equipment would be stored in a climate-controlled area;
- long-range flights based from shore could require a satellite link; using a mobile GCS on a ship provides a larger range without the need for satellite link;
- no need to transport UAS equipment to a shore-based site; and
- no need for security or bear protection contracts.

Camera resolution

During the test flights prior to the field season, the camera collected images at 318 m (1050 ft) AMSL with a resolution of 6 cm (2.36 in), which was better than the acceptable minimum resolution requirements (7 cm) needed to achieve the project's objectives. However, the light levels at Dahlgren, Va., during the test flights were very high, with low to no cloud cover. This allowed for images to be taken at a much higher shutter speed and lower ISO than those collected in the study area, resulting in higher image quality during test flights. The Nikon camera calibration images from the UAS in the field indicated that the resolution was adequate for large whale detection and species identification, but was poorer (>10 cm) than the initial minimum requirements and testing done in Virginia prior to the field effort. In addition, vibration of the camera systems likely impacted image quality. The camera mounts used in Utqiaġvik were constructed with a cold-intolerant material and became damaged over time upon platform retrieval. While the achieved resolution was adequate to identify large whales, a higher resolution would be needed in area with greater species diversity or smaller target animals.

We recommend investigating structural improvements to the camera mounting system, such as cold-tolerant material for the camera mount and vibration-dampening material between the camera mount and bracket.

If payload weight is a concern, modify the camera to include only the critical mechanisms to make it lighter and easier to integrate. The Nikon D810 camera and associated lens were relatively heavy for the UAV. The weight of the camera system (1.3 kg; 2.8 lb) resulted in having to adjust other components of the UAV to accommodate the camera system. To save weight, the gimbaled turret was removed. Although not critical, it would have been helpful for situational awareness to have retained the turret so the video camera could pan while the UAS was transiting in a straight line. The weight of the UAS also added complexity to the launch and retrieval requirements: if a full tank of fuel were required, a wind of 18.6–27.8 km/h (10–15 kn) during launch would have been required to meet the specifications of pressurizing the launcher.

Non-camera payloads

Due to the location of the ASAPS sensor and the extended dual bay configuration, the wing had to be disconnected from the fuselage for the ScanEagle® to fit in the transport case. Once the wing was reconnected to the fuselage, the ScanEagle® could no longer be placed in the transport case for shipping or on-site storage.

A different configuration of the ASAPS sensor would be helpful, and larger transport cases should be built to accommodate a ScanEagle® with an additional payload bay.

Coordinating UAS and manned aerial survey flights

One of the goals of the project was to conduct coordinated manned and UAS flights simultaneously in close proximity to provide a comparison of whales detected by sensors on the two platforms. To ensure safety during the flights, there were both technological and procedural methods for ensuring spatial separation in flight. Written procedural methods were developed in advance of the field season by consensus by team pilots and project leads. Technological methods included the installation of a transponder in the UAS so nearby aircraft with the TCAS would be alerted of a possible collision threat, and monitoring a surface-based air traffic radar, which allowed the UAS team to monitor aircraft in the vicinity.

For coordinating UAS and manned aircraft flights, TCAS alone is not sufficient for ensuring safe separation due to the limitations of TCAS and difficulties in visually detecting a small UAS flying at high closure rates. A detection and ranging available to the manned aircraft and UAS would increase safety when operations are being conducted in nonsegregated airspace. It is essential that precise relative position information be utilized when there is a future requirement for manned aircraft and UAS to fly in close proximity. UAS-based detect and avoid system would increase safety when UAS operations are being conducted in nonsegregated airspace. Without precise relative position information, manned aircraft and UAS must be separated by predetermined vertical and horizontal boundaries for each aircraft. These boundaries will depend on UAS type (VTOL or fixed-wing), performance (vertical and horizontal velocities), reliability, and flight conditions.

During the project, after a few coordinated UAS and manned flights at the same altitude and as close as ~15 km, the teams increased the spatial buffer between the project aircraft to maintain a level of safety acceptable to the flight teams. The following were the factors that resulted in this change in protocol. Both the airboss at the GCS and the pilots of both the unmanned and manned aircraft could detect each other's location using the surface-based air traffic radar feed and TCAS, respectively, but neither system allowed the pilots

Table 3. Critical project components that directly contributed to successful data collection with the UAS, improved safety, or both.

Project component	Comments
Internet service	Critical for weather forecasting, access to air traffic information.
Surface-based air traffic radar feed	Greatly improved flight safety because the UAS pilots could detect local air traffic; use required by the certificate of authorization.
NOWcasting	Increased ability to predict local weather at a spatial and temporal scale unavailable from NWS forecasts.
ASAPS sensor	Helped UAS pilots know when they were likely approaching a cloud or measureable precipitation. Associated software designed to detect hypothetical carburetor icing conditions, not actual carburetor icing conditions.
Portable weather station	The cloud ceiling at the launch site was often hundreds of metres different from the ceiling at the airport.
Open land area with easy access and low traffic volume	Mitigated risks to the community of UAV flying over land.

to precisely measure the distance between the platforms, so distance was a poor metric for triggering real-time flight decisions. The size of the UAV made it impossible to visually detect at distances beyond 1 or 2 km; the survey team in the manned aircraft never detected the UAV visually.

In addition, because of the limited capabilities of the TCAS I system used in the project, it was not operationally feasible for the manned aircraft pilots to make independent decisions about changing their flight path in response to the UAS flight path until the UAS was within <2 miles of the manned aircraft.

In-flight communications need to be more reliable. The weather in the study area was dynamic, which resulted in frequent changes to flight plans by pilots of both aircraft to find areas conducive to surveying. The pilots used satellite phones to discuss real-time changes in flight plans, but satellite phone coverage in the study area can be intermittent. A relatively user-friendly alternative communications approach was VHF radio; however, VHF communications are limited by the ability to transmit and receive the radio signal, which is affected by weather and the altitude and strength of the broadcasting signal.

Integrating a UAS project into an Alaskan coastal village

Discussions about the proposed UAS project with individuals in the local community began 2 years before the project was funded to identify potential problems with sufficient lead time to mitigate any concerns. A directed outreach effort to local governments, offices, and organizations was initiated at least 6 months before the project started. Longstanding professional relationships and routine discussions with North Slope Borough staff helped the survey team understand what issues might be of concern to local residents so that potential conflicts could be mitigated well in advance of the field project.

Researchers planning to use UAS near a populated area should err on the side of providing more information to the permitting agencies so they have a thorough understanding of the operation prior to permitting, and be prepared to cease operations immediately and discuss concerns if issues are raised. The use of UAS near coastal Alaska villages is relatively new and both UAS operators and local permitting agencies may not yet have a thorough understanding of a UAS projects' footprint in rural and remote areas, so all parties may not know the best questions to ask prior to the project. UAS teams should be prepared to be flexible and adapt their operations to conform to local land use needs.

Table 4. Recommended changes in flight operations for a comparable Arctic survey.

Change in operations	Critical	Not critical	Comments
Base from a ship	X		Basing from a ship would allow the UAS team to move to where the weather is favorable for flights.
Climate-controlled storage of UAS gear	X		Climate-controlled facility would have minimized maintenance likely required due to near-freezing temperatures, rain, and high humidity.
Automated aircraft position broadcasting and detection technology	X		Improves safety by improving ability to avoid other air traffic; enables increased size of survey area.
Dampen camera to reduce vibrations	X		Would improve ground resolution, which would aid in detecting large cetaceans, identifying them to species, estimating group size, and detecting calves.
Weatherproof UAS (instrument flight rules capability, heated pitot tubes, and wing/prop deicing capability)	X	X	Would have been helpful for preflight preparations. May have been helpful for collecting data on some days because the UAS would have been able to better handle highly variable patches of precipitation. However, if there is visible precipitation in all areas, visibility is poor and images are not likely to be useful. Lack of a weatherproof UAS did not severely limit the success of the project, but it would have been helpful for preflight preparations.
Conduct surveys at a lower altitude	X	X	May not be possible given science goals for this project; as flight altitude decreases, swath width decreases, which may be inefficient. Future projects must consider the balance between expected cloud ceiling, platform altitude and swath width.
Use a fuel-injected engine		X	The carb icing chart in the Insitu manual is general, not specific to the ScanEagle®. ScanEagle® platforms were routinely flown in icing conditions during this project with no detected effect on the project. However, if a fuel-injected engine had been used, the team would not have needed to run RPMs high to mitigate for the potential of carb icing, which might have avoided degradation of image quality.
Turret for onboard video system		X	Provides ability to see to the left and right while flying straight — aids cloud avoidance.
Improve camera/camera mount		X	The camera was heavy, which required that the UAS take on less fuel. The camera mount was not built using the requested type of plastic, and turned out to be quite brittle. The combination of the heavy system and the type of plastic likely contributed to the breakage of two camera mounts.

Note: Critical changes are those that that would have resulted directly in increased data collection; other changes might decrease maintenance workload or improve the comfort of the working environment. Changes identified as both critical and not critical were those that did not limit success of our project, but should be considered in the design of similar projects facing challenging weather.

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Conclusions

We identified many project successes and provided detailed recommendations about how we could have better met various operational and technological challenges. Table 3 summarizes the aspects of the project that were critical to successful data collection from UAS, improved safety, or both. Table 4 summarizes the operational changes that are most likely to directly improve data collection by future projects.

Unmanned aircraft systems are sometimes marketed as a "transformative" or "disruptive" technology that will dramatically change how wildlife researchers collect data. This is clearly true in some situations: after a few field seasons of evaluation, NOAA Fisheries is now routinely using a hexacopter UAS to collect mission-critical information on penguins (Goebel et al. 2015), killer whales (Durban et al. 2015), and Steller sea lions (Sweeney et al. 2016).

Analytical results of this project (Ferguson et al. 2018) indicate that long-range UAS surveys provide reliable information on marine mammal density that is comparable to the information collected by manned aerial surveys. However, for long-range surveys for marine mammals, at this time, the use of UAS is promising, but considerably more expensive and logistically complicated than manned aerial surveys. A future project's risk tolerances, scientific objectives, physical footprint, personnel needs, and cost will have to be considered early in the projects' design.

Many researchers are interested in UAS as simply a new and effective means to transport a sensor to an area of interest and are less interested in the UAS technology. At this stage in the process of evaluating UAS and associated technology for use in ecology and other nonmilitary disciplines, it is particularly helpful to highlight operational challenges and possible solutions (Curry et al. 2004; Koski et al. 2015) in addition to reporting research results. Direct comparisons of the ability of different UAS to collect the same or similar data (Johnston et al. 2017) is also particularly helpful. By decribing in detail the unique operational challenges involved in using UAS for beyond line-of-sight flights to study animals in the wild, we hope that others may build on our experience and effectively find similar and broader use of this technology.

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APPENDIX C: Performance of manned and unmanned aerial surveys to collect visual data and imagery for estimating arctic cetacean density and associated uncertainty.

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ARTICLE

Performance of manned and unmanned aerial surveys to collect visual data and imagery for estimating arctic cetacean density and associated uncertainty[1]

M.C. Ferguson, R.P. Angliss, A. Kennedy, B. Lynch, A. Willoughby, V. Helker, A.A. Brower, and J.T. Clarke

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Abstract: Manned aerial surveys have been used successfully for decades to collect data to infer cetacean distribution, density (number of whales/km^2), and abundance. Unmanned aircraft systems (UAS) have potential to augment or replace some manned aerial surveys for cetaceans. We conducted a three-way comparison among visual observations made by marine mammal observers aboard a Turbo Commander aircraft; imagery autonomously collected by a Nikon D810 camera system mounted to a belly port on the Turbo Commander; and imagery collected by a similar camera system on a remotely controlled ScanEagle® UAS operated by the US Navy. Bowhead whale density estimates derived from the marine mammal observer data were higher than those from the Turbo Commander imagery; comparisons to the UAS imagery depended on survey sector and analytical method. Beluga density estimates derived from either dataset collected aboard the Turbo Commander were higher than estimates derived from the UAS imagery. Uncertainties in density estimates derived from the marine mammal observer data were lower than estimates derived from either imagery dataset due to the small sample sizes in the imagery. The visual line-transect aerial survey conducted by marine mammal observers aboard the Turbo Commander was 68.5% of the cost of the photo strip-transect survey aboard the same aircraft and 9.4% of the cost of the UAS survey.

Key words: UAS, bowhead whale, gray whale, beluga, Beaufort Sea, Chukchi Sea.

Résumé : Les levés réalisés au moyen d'aéronefs pilotés ont été utilisés avec succès pendant des décennies pour recueillir des données afin de déduire la répartition, la densité (nombre de baleines/km^2) et l'abondance des cétacés. Les systèmes d'aéronef sans pilote (UAS) pourraient compléter ou remplacer certains levés aériens avec pilote sur les cétacés. Nous avons effectué

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une comparaison entre trois types de levés, soit des observations visuelles de mammifères marins faites par des chercheurs à bord d'un aéronef Turbo Commander ; des images recueillies de façon autonome par un système photographique Nikon D810 monté dans un hublot sous le Turbo Commander; et des images recueillies par un système photographique semblable sur un UAS ScanEagle® télécommandé utilisé par les Forces navales des États-Unis. Les estimations de densité de baleines boréales provenant des données des observateurs de mammifères marins étaient plus élevées que celles des images à partir du Turbo Commander; les comparaisons avec l'imagerie UAS variaient selon le secteur du levé et la méthode analytique. Les estimations de densité de bélugas provenant de l'un ou l'autre des ensembles de données recueillies à bord du Turbo Commander étaient plus élevées que les estimations provenant de l'imagerie UAS. Les incertitudes au niveau des estimations de densité provenant des données des observateurs de mammifères marins étaient inférieures aux estimations provenant de l'un ou l'autre des ensembles de données d'imagerie en raison des petites tailles des échantillons au niveau de l'imagerie. Le levé aérien par transect effectué visuellement par des observateurs à bord du Turbo était 68,5 % du coût du levé par transect de bande de photos à bord du même aéronef et 9,4 % du coût du levé UAS. [Traduit par la Rédaction]

Mots-clés : système d'aéronef sans pilote (UAS), baleine boréale, baleine grise, béluga, mer de Beaufort, mer des Tchouktches.

Introduction

In recent years, there has been increasing interest in understanding the degree to which unmanned aircraft systems (UAS) could be used to augment or replace manned aerial surveys for studying cetaceans. A UAS comprises an aircraft without a human pilot onboard, a ground- or ship-based controller (pilot), and the communication system connecting the aircraft to the pilot. The aircraft is referred to as an unmanned aerial vehicle (UAV). If successful, using UAS to address questions in marine mammal ecology and management may decrease risk to personnel, increase survey efficiency, and minimize disturbance to wildlife.

In general, to further our understanding of cetacean ecology, the following questions are representative of what needs to be answered. How many individuals of each species or population are found in a given area and time period, and how does that density (number of animals per unit area) vary on time scales spanning hours to decades? Are the animals distributed as large groups, small groups, or single individuals? Where and when do the animals feed, migrate, and reproduce? Is the species or population segregated by age or sex? The data required to address these questions are also required to address conservation and management issues relevant to management agencies and to entities, such as the military and industry, who are required to obtain authorization from management agencies to conduct certain activities in the marine environment. Furthermore, the issues of human safety, animal disturbance, project cost, efficiency, precision, and accuracy are common to both the scientific and management realms.

Manned aerial surveys from fixed-wing aircraft can efficiently and quickly survey large or remote areas, and have been used successfully for decades to achieve diverse scientific and wildlife management goals. In some cases, animal visibility is better from an aircraft than from a vessel or land. Additionally, due to the increased survey speed relative to marine mammals, aerial survey platforms reduce or eliminate potential biases in abundance or density estimates arising from animal movement (Buckland et al. 2001). Aerial line-transect surveys for marine mammals (Garner et al. 1999; Buckland et al. 2001) collect data that can be used to infer distribution, estimate density or abundance, and investigate habitat use and behavior. The National Oceanic and Atmospheric Administration (NOAA), Bureau of Ocean Energy Management (BOEM), US Navy (hereinafter referred to as Navy), petroleum industry, and others have relied on manned aerial line-transect surveys to collect large-scale information on cetaceans for stock assessment purposes (e.g., Muto et al. 2017) and to evaluate the impacts of specific human activities on cetaceans (e.g., Clarke et al. 2017*b*).

There are numerous examples of the successful application of manned aerial surveys to study marine mammals in the Arctic. The Aerial Surveys of Arctic Marine Mammals (ASAMM) project, funded and co-managed by BOEM and conducted and co-managed by NOAA Fisheries, is one of the longest-term surveys for marine mammals in the world (Clarke et al. 2017*b*), with annual line-transect surveys dating back to 1979. Multiple federal and state agencies, academic institutions, and private companies rely on data in the ASAMM historical database to make decisions regarding marine mammal conservation and management, and to better understand marine mammal roles in the arctic ecosystem. In addition, aerial survey methods have been used successfully off Point Barrow, Alaska, to collect photo-identification data to estimate the abundance of the Western Arctic bowhead whale stock (Schweder 2003; Koski et al. 2010; Schweder et al. 2010; Mocklin et al. 2012*a*; Vate Brattström et al. 2016). Numerous studies of bowhead whale feeding behavior in the Alaska Arctic, specifically in the Barrow Canyon area (Mocklin et al. 2012*b*) and in the eastern Alaska Beaufort Sea (Richardson and Thomson 2002), have been conducted from aircraft. Furthermore, aerial surveys have been used regularly to mitigate and monitor the effects of anthropogenic activities, such as petroleum exploration operations (e.g., Richardson et al. 1985, 1986, 1987; Schick and Urban 2000).

Although decades of valuable research, monitoring, and mitigation activities have been successfully conducted from manned aircraft, these survey platforms have some specific limitations. First, observer discomfort or fatigue caused by extended periods of time aboard the aircraft can affect data collection. Second, there are risks inherent in manned aerial operations that must be mitigated to reach an acceptable level of safety for the survey team. Third, manned aircraft have the potential to disturb wildlife. Lastly, manned aircraft burn fuel at a relatively high rate, resulting in high costs and consumption of non-renewable resources.

UAS have only recently been used to study ecology and inform wildlife management, but their use is growing rapidly (e.g., Watts et al. 2010; Sarda-Palomera et al. 2012; Anderson and Gaston 2013; Vermeulen et al. 2013; Barasona et al. 2014; Chabot et al. 2015; Mulero-Pázmány et al. 2015; Vas et al. 2015; Rümmler et al. 2016), including marine mammal research applications. Hodgson et al. (2013) conducted within line-of-sight strip-transect surveys with a ScanEagle® to collect observations of dugongs (*Dugong dugon*), and Maire et al. (2013) initiated attempts to automate analysis of the resulting images. UAS are also used to survey pinnipeds. UAS have been successfully used to collect images of spotted (*Phoca largha*) and ribbon (*Phoca fasciata*) seals in the Bering Sea pack ice (Moreland et al. 2015), to survey leopard seals (*Hydrurga leptonyx*) and Antarctic fur seals (*Arctocephalus gazella*) in Antarctica (Goebel et al. 2015), and to collect images to assess abundance and pup production of Steller sea lions (*Eumetopias jubatus*) in the western Aleutian Islands (Fritz 2012; Sweeney et al. 2016). Koski et al. (2015) evaluated the use of UAS in the Canadian Arctic to collect high-resolution photographs to identify individual bowhead whales and they monitored the whales' observed reactions to UAS overflights.

The performance of existing UAS technology and sensors versus human observers in manned aircraft for collecting data on cetaceans across broad study areas is unknown but must be understood prior to using UAS to augment or replace manned aircraft surveys. In late summer 2015, BOEM, the Navy, and NOAA, in collaboration with Shell Oil and the North Slope Borough Department of Wildlife Management, conducted field operations in the northeastern Chukchi Sea and western Beaufort Sea. The objectives were to evaluate the ability of UAS technology (i.e., platforms, payloads, sensors, and software) to collect data to detect cetaceans, identify individuals to species, estimate group size, and identify calves relative to conventional aerial line-transect surveys by human observers and digital photographic surveys conducted from fixed-wing manned aircraft. The target species were gray whales, bowhead whales, and belugas. All three species are protected under the US Marine Mammal Protection Act, the bowhead whale is granted additional protection as an endangered species under the US Endangered Species Act, and bowhead whales and belugas are of substantial interest and concern because they are hunted for subsistence. We estimated cetacean density and abundance in the survey area, and associated uncertainties in those estimates, and compared those values across all three datasets. Additionally, we compared the following performance metrics across datasets: number of sightings; ability to identify sightings to species; relative efficiency of each platform, measured by length of trackline and area covered, and the duration of survey and analytical effort required to achieve a pre-specified level of precision in the density estimate; and survey and analytical costs in both dollars and fuel consumption. Here, we provide recommendations for the types of cetacean study objectives that can likely be met by UAS currently and in the near future. Operational results and recommendations are described in a companion paper by Angliss et al. (2018).

Methods

Study area and survey timing

The study area encompasses approximately 16 800 km^2 of the northeastern Chukchi and western Beaufort seas (Fig. 1) (Angliss et al. 2018). Pre-determined transect lines, spaced 4.75 km apart, were located west (24 transects) and east (26 transects) of Point Barrow. The study area was partitioned into west (5140 km^2) and east (6149 km^2) sectors due to logistical (Angliss et al. 2018) and ecological considerations. Field operations occurred in 2015, beginning with the arrival of the UAS equipment aboard a Navy C130 aircraft on 19 August and ending with the last flight of the manned aircraft in the study area on 7 September (Angliss et al. 2018). The project was conducted during the time of year with documented peak cetacean abundance and weather conditions most conducive to flight operations in the study area.

The survey area provides important feeding grounds and migration pathways for gray whales, bowhead whales, and belugas, which use the area seasonally (e.g., Citta et al. 2015; Clarke et al. 2015, 2016, 2018; Stafford et al. 2016; Brower et al. 2017*b*). Gray whales are reliably found in high densities in the west sector during the open water (ice-free) season, which occurs from July to October. In some years, bowhead whales and belugas are found in high densities in the east sector, especially in the vicinity of Barrow Canyon. Known high-density areas were targeted to obtain the number of sightings required to derive robust analytical conclusions about the relative performance of manned aircraft and UAS in a reasonably short period. A sighting was defined as either a group (i.e., cluster) of closely associated animals, typically located within five body lengths of each other, or a single individual detected alone.

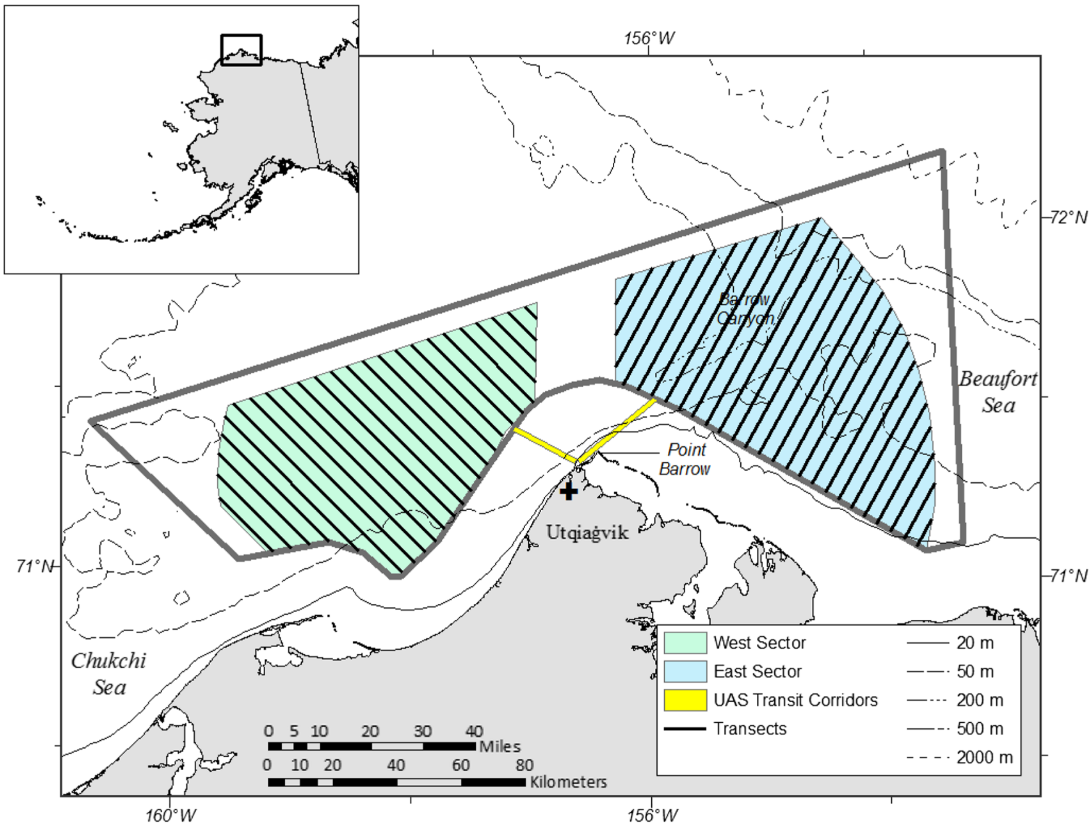
Field methods

UAS aerial surveys

Here, we provide a summary of our 2015 field methods. A more comprehensive and detailed description of field methods and aviation safety protocols for the UAS is provided in Angliss et al. (2018).

The ScanEagle® UAS was selected for this project based on its strong airworthiness history, relatively large payload capacity, and long endurance (24 h). A Nikon D810 high-resolution digital camera with 20-mm Nikkor f 2.8 lens, capable under ideal conditions of providing a minimum photographic ground resolution of 7 cm/pixel and minimum photographic strip width of 400–600 m at survey altitude, was directly exposed to the outside air. We expected this resolution would be sufficient for detecting individual large whales,

Fig. 1. Study area for the manned and unmanned aerial surveys of cetaceans conducted in late summer 2015. Transects shown were flown by both the manned and unmanned aircraft.



identifying animals to species, estimating group size, and determining whether calves were present. A global positioning system (GPS) pinger allowed position metadata to be simultaneously recorded with the images taken by the D810. Metadata automatically recorded for each image included latitude, longitude, and altitude. A camera trigger automatically collected photographs at pre-set distance intervals throughout the duration of each flight, based on position data from the GPS.

In a typical UAS flight, the UAV was launched and recovered from the shore-based station and accessed the offshore study area located in international airspace through one of two transit corridors (Fig. 1). The UAV remained at or below 122 m above mean sea level (AMSL) while inside the corridor to increase vertical separation with typical nearshore air traffic. Once in the offshore study area, the UAV increased altitude to the target altitude of 305 m AMSL and flew pre-programmed fine-scale (4.75 km apart) transects (Fig. 1) at 93–111 km/h, collecting high-resolution digital photographic strip-transect data every 100 m distance. Therefore, a given parcel of water on the surface of the ocean was visible in at least three consecutive images from the UAV. Occasionally, the UAV operated at lower altitudes, as necessary, to remain below the cloud bases. Transects were flown in passing mode, wherein the aircraft did not divert from the transect line or circle to investigate sightings. Once UAS operations were complete on a particular day, the UAV descended below 121 m AMSL while still in international airspace in the offshore study area and entered the transit corridor inbound for recovery at the shore-based station.

Aerial Surveys of Arctic Marine Mammals

ASAMM manned aerial line-transect surveys have been conducted annually in the western Beaufort Sea since 1979. Survey protocols have remained essentially constant since 1982 (Clarke et al. 2017*a*). These surveys were conducted from 1 July to 31 October 2015 over a larger expanse of the eastern Chukchi and western Beaufort seas (67°–72° latitude, –140° to –169° longitude, encompassing 240 000 km^2; Clarke et al. 2017*a*). In 2015, flight protocols were altered between 26 August and 7 September to follow the fine-scale transects in the UAS survey area (Fig. 1) and to provide a comparison between the UAS and manned aircraft surveys. Comprehensive and detailed field methods for the ASAMM project in 2015 are provided in Clarke et al. (2017*a*).

ASAMM marine mammal observers collected visual line-transect data on marine mammals and relevant environmental conditions from a fixed-wing, twin engine Turbo Commander aircraft flown by two pilots from Clearwater Air, Inc. ASAMM visual survey protocols followed standard line-transect procedures (Buckland et al. 2001). Crew positions and responsibilities, and recording of environmental, effort, and sighting data were identical to that described in Clarke et al. (2017*a*). The ASAMM aircraft surveyed at approximately 213 km/h at a target altitude of 320 m. All ASAMM surveys conducted in the UAS study area during the UAS field season implemented passing mode protocols to be consistent with the UAS surveys. Because of the observers' ability to detect large cetaceans located farther than 9 km from the aircraft, the Turbo Commander flew every-other transect line, resulting in 9.5 km spacing.

A downward-pointing Nikon D810 high-resolution digital camera with a 21-mm Zeiss Distagon lens was attached to a mount installed in the belly port of the Turbo Commander. The lens was directly exposed to the outside air. The camera automatically collected images every 2 s, during which time the aircraft traveled approximately 118 m. A parcel of water on the surface of the ocean was visible in at least three consecutive images, depending on aircraft altitude. Metadata automatically recorded for each image included latitude, longitude, and altitude. The Zeiss lens is capable of achieving a sharper focus than the Nikkor lens used on the UAV due to high-quality glass and anti-glare coating on the former. However, the differences between the lenses at the distances to our targets were negligible in terms of the ability to detect or identify animals. The Zeiss lens was too heavy and long to use in the UAV.

Aviation safety

Safety was the primary concern of project personnel. Several tools were used to enhance the safety of, and minimize risk to, non-participating and participating aircraft during field operations; these tools are comprehensively discussed in Angliss et al. (2018). The UAS and ASAMM Turbo Commander flights were synchronized in time and space to obtain independent, replicate samples of cetaceans in the study area. Surveys from manned and unmanned platforms did not directly overlap spatially and temporally to maintain safety of flight. The two platforms operated as close as safely possible (Angliss et al. 2018).

Image processing methods

Detailed image processing protocols are provided in supplementary data A.[2] Digital images from the UAS and Turbo Commander flights were visually reviewed by three photo analysts with considerable expertise as marine mammal observers during visual aerial surveys for arctic marine mammals. Only images with midpoints located within

[2]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/juvs-2018-0002.

1 km strips centered on transects were viewed to simplify computation of the area sampled; images collected while transiting off transect were not analyzed. The native projection for the transects was used to determine which images were located in the transect strip; that projection was defined as a Lambert azimuthal equal area projection, with center latitude 70.0°, center longitude −154.5°, false easting 0.0, and false northing 0.0. Observers did not process images that showed any portion of the horizon, or where the camera angle was obviously not perpendicular to the sea surface, as these images were taken when the aircraft was turning. Because consecutive images overlapped by approximately 33% on average, photo analysts reviewed every third image from each portion of the flight that was within the study area boundaries. Ten images out of every 30 were fully analyzed at 100% zoom, while the remaining 20 were initially analyzed at 20% zoom, with instructions to selectively zoom in on any pixels containing a cue for a potential sighting. Images from nine flights (five manned flights and four UAS flights) were reviewed in detail by only a single photo analyst. Images from one UAS flight were reviewed independently by two photo analysts for an ongoing analysis to estimate detection probability. The lead photo analyst reviewed all images identified as containing definite or possible sightings to confirm species and group size, and to make a final determination on objects that were initially judged without certainty to be marine mammals. All marine mammal sightings were confirmed by two or more experienced marine mammal observers.

The final processed imagery database included the following fields: aircraft type; image filename; latitude, longitude, and altitude; date and time (GMT); impediments to visibility, Beaufort Sea State, percent of the image covered by glare, and type of glare present; whether the image was viewed at full-screen resolution or zoomed to 100% of the image size; sighting number; species identification; an ordinal variable on sighting and species identification confidence; best, high, and low estimates of group size; number of calves present; position of the sighting in *x*- and *y*-coordinates within the frame of reference of the image; length (pixels) of the animal; percentage of the image obscured by precipitation; notes if the image was not taken during level flight; and the amount of time it took to process a batch of 10 images.

Analytical methods

All analyses were conducted using R version 3.3.2 (R Core Team 2016). Geospatial analyses were conducted using R packages sp (Pebesma and Bivand 2005; Bivand et al. 2013), maptools (Bivand and Lewin-Koh 2017), rgeos (Bivand and Rundel 2017), rgdal (Bivand et al. 2016), raster (Hijmans 2016), ncdf4 (Pierce 2015), and fields (Nychka et al. 2015).

Throughout the text, we refer to "density"; however, results are presented both in terms of density and number of individual animals to facilitate interpretation. All density computations were standardized as number of animals per square kilometre. Density estimates were converted to estimates of the number of whales of each species present in each sector by multiplying estimated density by the corresponding sector area.

Density estimates were not corrected for availability bias resulting from the animals' surfacing and diving behaviors or for the photo analysts' perception bias (Marsh and Sinclair 1989). Additional data need to be collected to compute correction factors for the marine mammal observers' perception bias near the trackline; therefore, this bias was not addressed. Analyses of cetacean behavior from satellite telemetry and aerial behavior studies, and aircraft field of view data are being used to compute availability bias correction factors specific to the ASAMM line-transect surveys. Investigations into adjusting the sightings in the imagery for perception or availability bias are also underway.

Density estimation from the UAS and Turbo Commander imagery

Density was estimated separately for each combination of: species (bowhead whale, gray whale, or beluga), aircraft type (Turbo Commander or UAS), and sector (west or east) of the study area. Separate density estimates were derived for the east and west sectors because they were known a priori to represent distinct habitats, and it was assumed that densities would not be constant throughout the entire UAS study area. Spatial modeling methods can incorporate sightings and effort off transects; however, the sample sizes in our imagery were not large enough to create spatial models that would enable use of off-transect data.

Density estimates were based on the total visible area in each image, which was calculated as the total image area multiplied by the proportion of the surface area visible. Images with <50% surface area visible (due to precipitation) were considered to contain minimal information and could potentially introduce biases into the analysis, so they were omitted from the density analyses. Because of the relatively small sample size, we were unable to examine the effects of Beaufort Sea State or glare on detection probabilities.

The total area of each image was calculated as the product of the horizontal coverage (coverage.h, in metres) and vertical coverage (coverage.v, in metres), divided by 1×10^6 to produce a value in square kilometres. Horizontal and vertical coverage were calculated as follows:

$$\text{(1)} \quad \text{coverage.h} = \left(\frac{\text{sensor.h}}{f}\right)\text{alt}$$

$$\text{(2)} \quad \text{coverage.v} = \left(\frac{\text{sensor.v}}{f}\right)\text{alt}$$

where sensor.h is the horizontal dimension (mm) of the camera's sensor, sensor.v is the vertical dimension (mm) of the camera's sensor, f is the focal length (mm) of the lens, and alt is the survey altitude (m).

Density estimates were derived for each species from the imagery as

$$\text{(3)} \quad \hat{D}_{p,\,\text{sp}} = \frac{\sum_{i=1}^{k}\sum_{j=1}^{m} n_{i,j,p,\,\text{sp}}}{\sum_{i=1}^{k}\sum_{j=1}^{m} a_{p,i,j}}$$

where $\hat{D}$ is the estimated density; p is the platform type (UAS or Turbo Commander); sp is the species; k is the total number of unique transect lines covered by each platform;[3] m is the total number of replicates of transect line i covered by each platform; $n_{i,j,p,\text{sp}}$ is the number of individuals of species sp in imagery collected by platform p on replicate j of transect i; and $a_{p,i,j}$ is the total visible area in replicate j of transect i from platform p.

Coefficients of variation (CV) for the density estimates were estimated using a modified version of the R2 estimator from Fewster et al. (2009), based on input from Fewster (R. Fewster personal communication to M. Ferguson on 7 October 2016). The R2 variances in the density estimates for each species × platform × sector were estimated as

$$\text{(4)} \quad \widehat{\text{var}_{\text{R2}}}(D) = \frac{k}{A^2(k-1)}\sum_{i=1}^{k}\left(\sum_{j=1}^{m} a_{i,j}\right)^2\left(\frac{\sum_{j=1}^{m} n_{i,j}}{\sum_{j=1}^{m} a_{i,j}} - \frac{n_{\text{tot}}}{A}\right)^2$$

[3]The variables k and m are platform-specific, but the "p" subscript is omitted from k and m throughout the manuscript for simplicity.

where $A = \sum_{i=1}^{k} \sum_{j=1}^{m} a_{p,i,j}$ is the total visible area covered by platform p and $n_{\mathrm{tot}} = \sum_{i=1}^{k} \sum_{j=1}^{m} n_{i,j,p,\mathrm{sp}}$ is the total number of individuals of species sp detected in imagery from platform p.

The $\widehat{\mathrm{CV}(D)}$ for each species and platform was estimated as

$$(5) \quad \widehat{\mathrm{CV}(D)} = \frac{\sqrt{\widehat{\mathrm{var}_{\mathrm{R2}}(D)}}}{\hat{D}_{p,\mathrm{sp}}}$$

Because sector area is a constant, $\widehat{\mathrm{CV}(D)}$ equals $\widehat{\mathrm{CV}(N)}$, where $\hat{N}$ is the estimated number of whales.

Density estimation from ASAMM marine mammal observer data

Density and corresponding CV estimates were derived for bowhead whales and belugas using standard distance sampling methods, and for bowhead whales using both standard distance sampling and density surface modeling methods. There were no sightings of gray whales that met the data filter criteria for these analyses (supplementary data B[2]). There were too few beluga sightings, and they were too tightly clustered to construct a density surface model. The data filters used for each of the methods described herein are illustrated in supplementary data B (Fig. B1).[2]

Geospatial analyses used to estimate density from the ASAMM data were conducted in an equidistant conic projection defined as follows: first standard parallel 71.17°, second standard parallel 71.86°, latitude of origin 71.51°, longitude of origin −156.64°, false easting 0.0, and false northing 0.0.

Standard distance sampling methods for line transects extrapolate from the sightings observed on transect lines to an estimate of the number or density of animals in the study area or geographic strata by fitting a detection function to estimate the effective area surveyed and using design-based inference to extrapolate to the survey region (Buckland et al. 2001; Thomas et al. 2010). The detection function acknowledges that observers' ability to detect animals decreases with distance from the trackline and possibly other factors (Marques and Buckland 2003). Assuming that the probability of detecting animals located directly on the trackline is certain (i.e., $g(0) = 1.0$), the standard distance sampling density estimator for animals located in groups (Buckland et al. 2001) is

$$(6) \quad \hat{D} = \frac{n\widehat{E(s)}}{2L\hat{\mu}} = \frac{n\widehat{E(s)}}{2Lw\hat{p}_{\mathrm{a}}}$$

where $\widehat{E(s)}$ is the expected group size, L is the total transect length surveyed, $\hat{\mu}$ is the estimated effective strip half-width, w is the right-truncation distance used to fit the detection function, and $\hat{p}_{\mathrm{a}}$ is the estimated unconditional probability of detecting an animal in a strip of area $2wL$.

The effective strip half-width is the distance on one side of the trackline that would contain the same number of sightings if detection probability were equal to 1.0 as were actually detected during the survey. $\hat{\mu}$ equals the integral of the detection function over the range of the distance surveyed on each side of the trackline. For analyses that accounted for variable visibility range due to precipitation, which effectively resulted in a variable width searched along transects (quantified by VisX.km), $\hat{\mu}$ and $\hat{p}_{\mathrm{a}}$ were computed using the modified methods described in Buckland et al. (2001, eq. (6.42)) and in supplementary data B.[2] The numeric variable VisX.km was derived for each record in the ASAMM database by first converting the categorical values for the left and right side visibility ranges into numeric values corresponding to the maximum range for the category (e.g., "2–3 km" became 3.0 km), and then averaging the numeric values on both sides of the aircraft.

The number of sightings that met the relevant data filtering criteria (supplementary data B, Fig. B1[2]) during the five ASAMM flights conducted in the UAS survey area during this study (37 bowhead whale groups and 12 beluga groups) were insufficient to estimate reliable detection functions for bowhead whales and belugas. Buckland et al. (2001) note that it is the absolute size of the sample, not the fraction of the population sampled, that is the relevant sample size, and suggest that a practical minimum for reliable estimation of the detection function is 60–80 sightings. Nevertheless, for illustrative purposes, we present bowhead whale density estimates derived using standard distance sampling methods and density surface models that incorporated detection functions created using the limited dataset (supplementary data B[2]).

The historical ASAMM dataset was used to create more reliable detection function models for both bowhead whales and belugas (supplementary data B[2]). From 2009 through 2015, ASAMM surveys were conducted using comparable Turbo Commander aircraft, the same standardized line-transect survey protocols, and many of the same observers as ASAMM used during the UAS survey period. Detection functions built with the historical data incorporated sightings from across the entire ASAMM study area. The best bowhead whale detection function model based on the historical dataset, which was used to derive density estimates using both standard distance sampling methods and density surface modeling methods, included depth and group size covariates. The best beluga detection function model included longitude, a categorical variable related to percent cover of sea ice, and a categorical variable distinguishing between group sizes ≤10 versus >10. Depth and longitude variables were considered proxies for unmeasured variables related to differences in habitat or behavior across the ASAMM study area that affected detectability.

In the standard distance sampling analysis, density and CV(D) were estimated using the mrds package (Laake et al. 2016) in R. Data filters used to estimate density via standard distance sampling methods were identical to those used to construct the detection function models (supplementary data B[2]), with the exception that only transect sightings collected during ASAMM survey flights in the UAS study area, following the UAS transect lines, during the UAS field season were used (supplementary data B, Fig. B1[2]). In the analyses that accounted for the variable width searched along transects, the area sampled was calculated as the product of transect length and VisX.km (e.g., eq. (10)). Encounter rate variance calculations used the R2 estimator (Fewster et al. 2009). The sample unit used in this analysis was transect; therefore, effort and sighting data collected on a single transect over multiple days were pooled.

Density surface modeling incorporates spatially referenced data to model the variation in animal density across a spatial grid comprising high-resolution cells (e.g., squares or hexagons). The only spatially referenced data we considered were projected geographic coordinates because we were interested in explaining the observed spatial variation in density within a well-sampled study area rather than directly investigating ecological factors shaping that variability or extrapolating the predictions beyond the spatial or temporal extent of the surveys.

We implemented two-stage density surface modeling methods, wherein the detection function is parameterized independent of the spatial model used to estimate density (Miller et al. 2013). The detection functions used in the density surface models were the same models used in the standard distance sampling analysis (supplementary data B[2]). Data filters used to generate the data subset for spatial modeling were identical to those used to estimate density in the standard distance sampling analysis, with the exception that sightings and effort from both transect and search survey modes were included in the spatial models (supplementary data B, Fig. B1[2]). Spatial models were created using generalized additive modeling methods from package mgcv (Wood 2006), parameterized by a negative binomial distribution (function "negbin" in the language of mgcv) with a natural logarithmic link function. The generalized cross-validation score was used for smoothing parameter estimation, with the gamma parameter set to 1.4 to control for overfitting (Wood 2006). Quasi-Poisson and Tweedie (Tweedie 1984; Dunn and Smith 2005) models, and negative binomial models based on the "nb" function were also considered, but examination of model residuals (Ver Hoef and Boveng 2007) and maps of predictions suggested that the negbin function provided a better fit to the data.

Miller et al. (2013) describe methods in which the analytical sample unit for constructing spatial models is a transect segment created by sequentially chopping transects into equidistant pieces, beginning with the start of a given transect and continuing to its endpoint. Effort and sightings in one transect segment compose a single sample unit. The parameterized spatial model is then applied to a georeferenced grid to extrapolate density predictions across the entire surface. We defined an analytical sample unit for constructing our spatial models to be one 5 km hexagonal cell of the spatial grid encompassing the study area; therefore, the sample units used to construct the spatial model were identical to those for which predictions are needed. In this case, survey effort and sightings were summarized into cells as if a honeycomb matching the spatial grid were dropped onto the georeferenced survey data, and all of the sightings and effort contained within each cell made up one sample.

Two types of spatial models were built, depending on whether information specific to each sample unit (i.e., hexagonal cell) or each sighting was used to parameterize the detection function (Miller et al. 2013). For analyses using the limited dataset, when only cell-level covariates were used in the detection function and it was assumed that the search width was constant, the count-response spatial model was used to estimate density

$$(7)\quad \ln(E(\text{ind}_c)) = \beta_0 + f(X_c, Y_c) + \text{offset}(\ln(2\hat{\mu}_c L_c))$$

where ind_c is the random variable for the number of individual whales in cell c, with ind_c referring to the associated observations and $E(\text{ind}_c)$ the expected value (mean) of ind_c; β_0 is the intercept; X_c is the projected longitude of the midpoint of cell c; Y_c is the projected latitude of the midpoint of cell c; $f(\cdot)$ is the smooth function (Wood et al. 2008) of location covariates used to describe whale density (this function is parameterized in the model-fitting process); $\hat{\mu}_c$ is the estimated effective strip half-width of cell c; and L_c is the length (km) of transect effort in cell c.

The smooth function used in the best model was a thin plate regression spline with extra shrinkage. The extra shrinkage allows the spline parameters to shrink to zero, if necessary, during estimation (Wood 2006). The offset term accounts for spatially heterogeneous survey effort across the study area and is treated as a constant during the model-fitting process. Models based on tensor products and soap film smooths were evaluated but did not perform as well as the thin plate regression spline models, presumably because of data sparsity.

For analyses using the historical dataset, when covariates specific to each sighting were used in the detection function or the variable search width was incorporated into the detection function model, the abundance-response model was used

$$(8)\quad \ln(E(\hat{N}_c)) = \beta_0 + f(X_c, Y_c) + \text{offset}(\ln(a_c))$$

where $\hat{N}_c$ is the estimated abundance in cell c

$$(9)\quad \hat{N}_c = \sum_r \frac{\text{ind}_{cr}}{\hat{p}_{cr}}$$

where r is the an index identifying unique sightings; $\hat{p}_{cr}$ is the estimated unconditional probability of detecting sighting r located within w distance of the trackline in cell c; and a_c is the area sampled in cell c, computed as

$$(10)\quad a_c = 2\sum_v \text{VisX.km}_v L_{cv}$$

where v is an index identifying unique values of VisX.km and L_{cv} is the length of survey effort covered in cell c under visibility conditions VisX.km_v.

The predicted number of bowhead whales in each sector was computed by multiplying the area of each hexagonal cell contained within each sector by the corresponding density estimate for the cell, and then summing across cells in each sector.

Estimates of CV(D) for the spatial model predictions were made using the delta method to combine uncertainty from the spatial model with that from the detection function, based on the assumption that these models are independent (Buckland et al. 2001). Estimates of spatial model uncertainty, CV(gam), were calculated using the dsm.var.gam function from the dsm package (Miller et al. 2017). Detection function uncertainty, represented by CV($\hat{p}_a$), was computed as the standard error of $\hat{p}_a$ divided by $\hat{p}_a$. Applying the delta method,

$$(11)\quad \text{CV}(D) = \sqrt{[\text{CV}(\text{gam})]^2 + [\text{CV}(\hat{p}_a)]^2}$$

Sightings of large cetaceans unidentified to species were used to compute a "large cetacean" species identification bias correction factor, $p(\text{ID}) = 1 - p(\text{unid})$ (J. Laake, AFSC, personal communication to M. Ferguson on 3 May 2016). The variable p(unid) is the probability of recording an unidentified large cetacean in the strip (dx) located parallel to the trackline in which detectability is similar across all large cetacean species. Based on the histograms of bowhead and gray whale sightings made by ASAMM observers from 2009 through 2015 (supplementary data B[2] and MML unpublished data), dx was defined as the strip spanning 250–550 m perpendicular to the trackline. p(unid) was computed as follows:

$$(12)\quad p(\text{unid}) = \frac{n_{\text{unid, dx}}}{\sum_i n_{i,\text{dx}}}$$

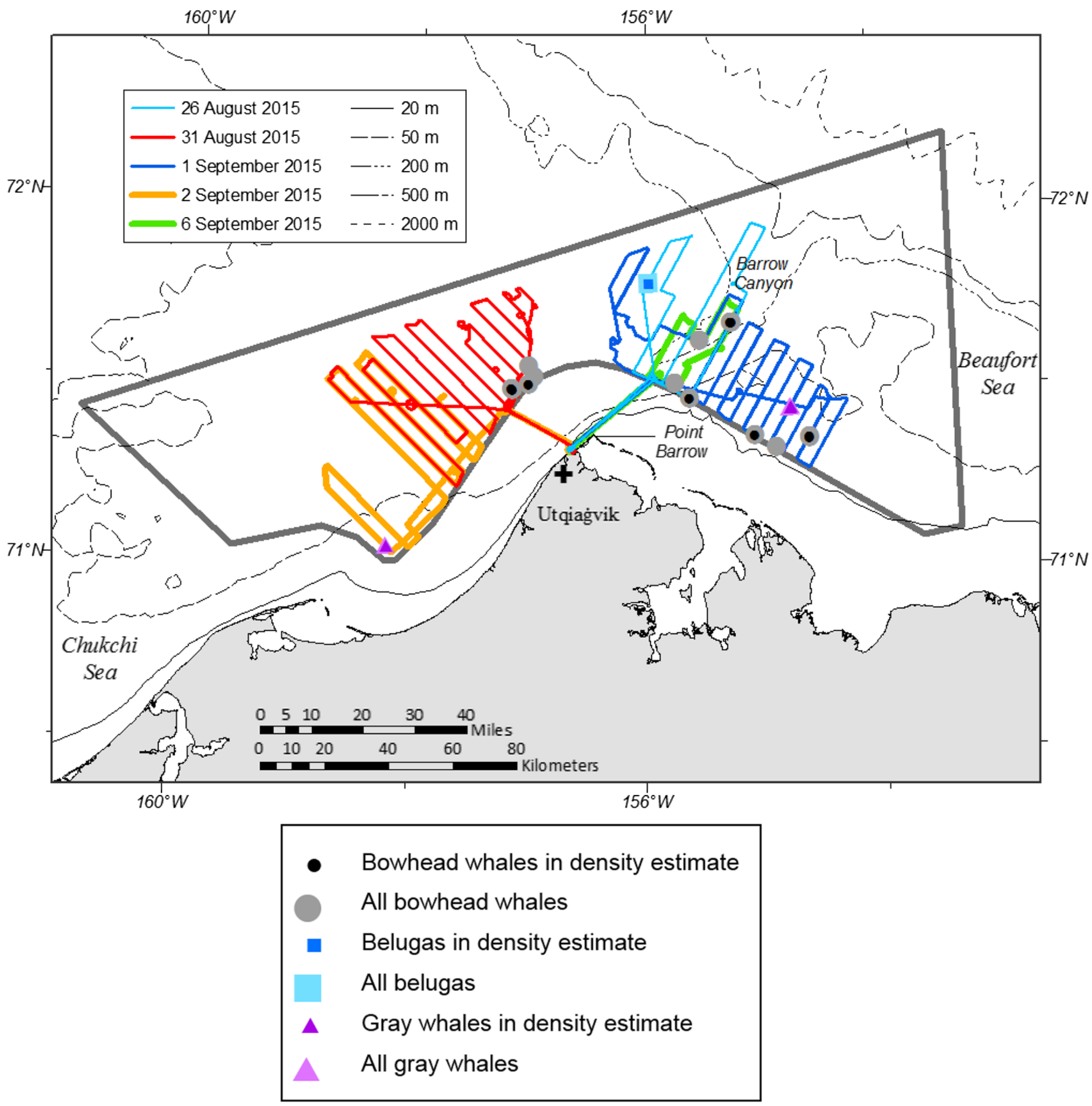
where i is the species category corresponding to bowhead whale, gray whale, or unidentified large cetacean; dx is the strip located near the trackline in which detectability is similar across all species; and n is the number of sightings by airborne marine mammal observers during the UAS survey period.

To correct for species identification bias, the estimated densities of bowhead whales derived from the standard distance analysis and both spatial models were each divided by p(ID).

Results

Weather was conducive to surveying on six (35%) out of the 18 days spanning 21 August to 7 September 2015, beginning with when the UAS was operational (Angliss et al. 2018). The weather in the study area was highly variable in space and time. Conditions included fog, haze, mist, drizzle, rain and snow squalls, low cloud ceilings, and coastal flooding resulting in the declaration of a State of Emergency, with occasional periods of acceptable

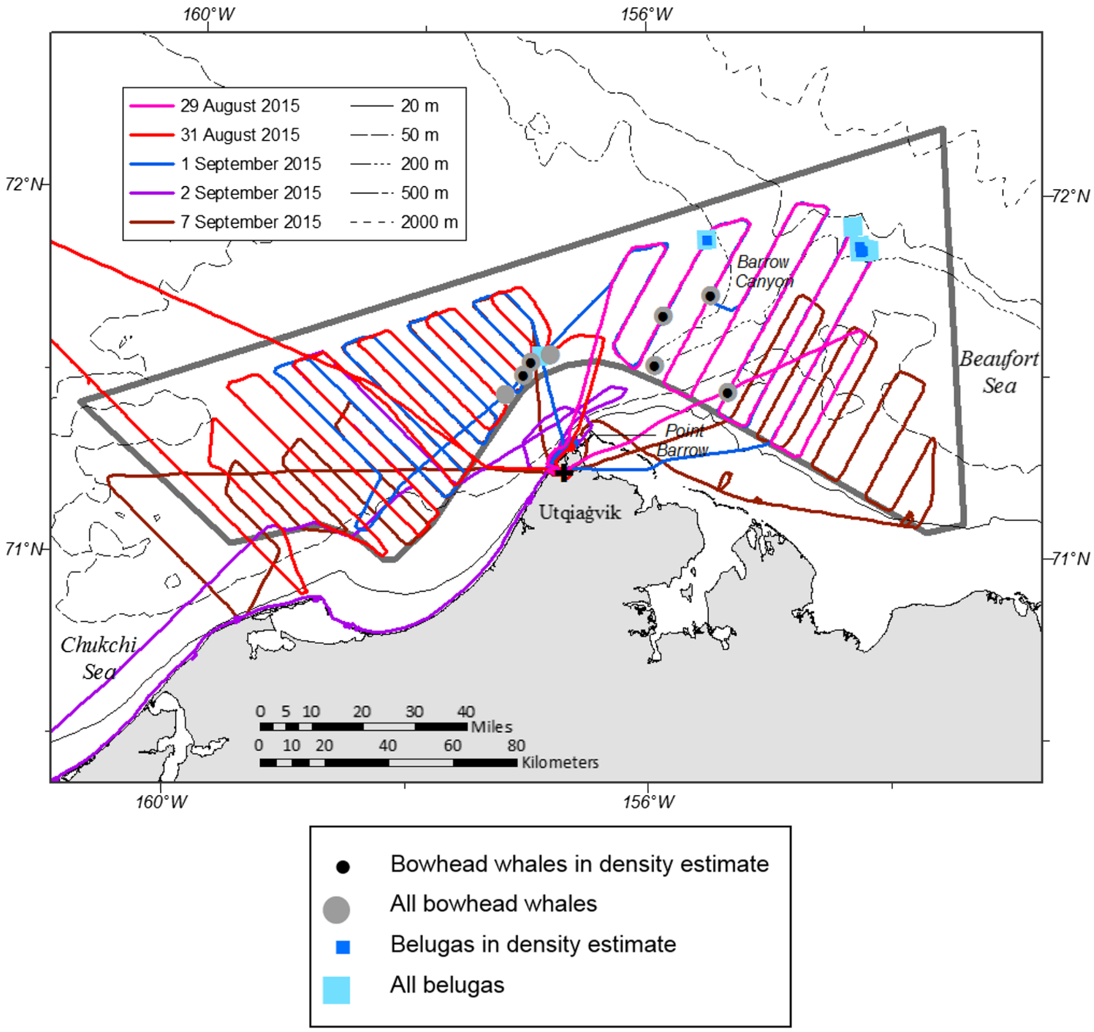
Fig. 2. Location of UAS survey effort, total sightings from the UAS imagery database (Table 1), and sightings from the UAS imagery database that were used to estimate density (Table 2). Symbols overlap for nearby sightings.



ceilings and no precipitation when flights could be conducted (Angliss et al. 2018). Although one of the project's field objectives was to cover each transect line at least once by each aircraft, weather limitations resulted in some lines being sampled multiple times and others not being sampled at all (Figs. 2, 3, and 4).

The UAS conducted five survey flights consisting of a single flight each day on five days: 26 and 31 August, and 1, 2, and 6 September. UAS flights ranged from 1.6 to 6.0 h duration, for a total of 21.8 flight hours covering 2012 km in the study area (Fig. 2) (Angliss et al. 2018). At no time were two UAVs airborne simultaneously. Of the 20 568 total images collected by the UAS in the study area (Angliss et al. 2018), 6857 (33.3%) were processed by photo analysts. During the review of every third image from each flight, photo analysts sighted 14 bowhead whale groups (totaling 15 whales), one group of six belugas, and three lone gray whales

Fig. 3. Location of Turbo Commander survey effort, total sightings from the aircraft's imagery database (Table 1), and sightings from the aircraft's imagery database that were used to estimate density (Table 2). Symbols overlap for nearby sightings.



(Table 1; Fig. 2). The only calf sighted in any of the imagery from either aircraft was a bowhead whale calf associated with an adult female in an image taken from the UAS while turning, and was therefore omitted from statistical analysis.

The Turbo Commander also conducted five survey flights on the UAS transect lines during five separate days: 29 and 31 August, and 1, 2, and 7 September (Figs. 3 and 4). Survey effort in the study area ranged in duration from 1.3 to 4.8 h, totaling 17.9 h and 3582 km (Angliss et al. 2018). In total, 23 580 images were collected from the vertical camera aboard the Turbo Commander in the study area (Angliss et al. 2018), and 9776 (41.5%) were processed. The proportions of individuals of each species observed were similar across platforms, with bowhead whales generally the most frequently observed and gray whales the least. Because of the small area covered (hence, small sample sizes) in the imagery and patchy distribution of the cetaceans in the study area, the number of individuals observed and species composition were not identical across platforms and observation methods.

Fig. 4. Location of Turbo Commander survey effort, total sightings from the marine mammal observers' database (Table 1), and sightings from the observers' database that were used to estimate density by standard distance sampling methods using either the historical or limited dataset for the detection function (Table 2). Symbols overlap for nearby sightings.

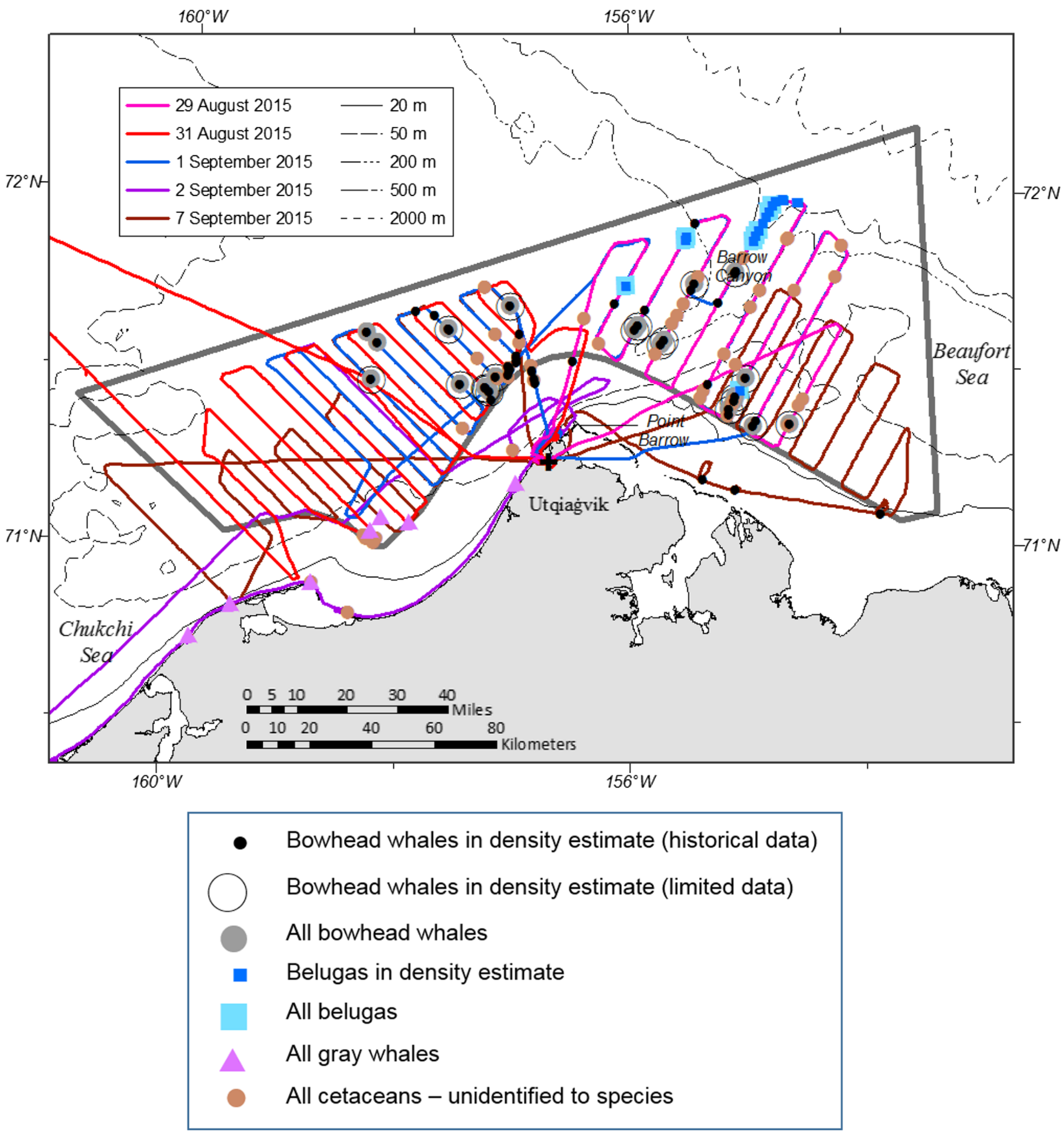


Photo analysts detected eight lone bowhead whales and 11 beluga groups totaling 16 whales (Table 1; Fig. 3). No gray whales and no calves were detected in images from the Turbo Commander. Marine mammal observers detected 53 bowhead whale groups totaling 61 whales, 18 beluga groups totaling 54 whales, 9 gray whale groups totaling 9 whales, and 42 groups totaling 48 cetaceans that could not be identified to species (Table 1; Fig. 4). This is a considerably higher proportion of cetaceans not identified to species compared to typical ASAMM flights conducted in closing mode (when the aircraft is allowed to circle sightings), but only one of those sightings was close to the aircraft, in the strip located

Table 1. Total number of whale sightings and individual whales detected in imagery from the UAS and Turbo Commander and by the marine mammal observers aboard the Turbo Commander during all survey effort (i.e., while transiting and on transect).

Species	UAS images		Turbo Commander images		Marine mammal observer data	
	No. of sightings	No. of whales	No. of sightings	No. of whales	No. of sightings	No. of whales
Beluga	1	6	11	16	18	54
Bowhead whale	14	15	8	8	53	61
Gray whale	3	3	0	0	9	9
Unidentified cetacean	0	0	0	0	42	48

250–550 m parallel to the trackline. No gray whales and 17 bowhead whales were detected in the 250–550-m strip. The resulting "large cetacean" species identification bias correction factor was 0.94; therefore, raw density estimates of bowhead whales from the marine mammal observer data were increased by a factor of 1/0.94 = 1.06, or 6%, to account for the inability to identify all large cetacean sightings to species.

Because of the different assumptions and, therefore, data filters used to construct bowhead whale detection functions from the limited versus historical dataset, sample sizes used to build the density surface models differed slightly between the count-response and the abundance-response models. The count-response spatial model was constructed from a total of 488 hexagonal cells with non-zero survey effort; 25 of those cells had bowhead whale sightings, resulting in a total of 32 bowhead whale sightings comprising 35 total whales in the model. Single whales were found in 29 of the sightings used in the count-response model, and three sightings had two whales each. The abundance-response spatial model was constructed from a total of 492 hexagonal cells with non-zero survey effort; 25 of those cells had bowhead whale sightings, and 32 bowhead whale sightings comprising 34 total whales were incorporated into the model. Single whales were found in 30 of the sightings used in the abundance-response model and two sightings had two whales each.

Bowhead whales were consistently predicted to be more numerous in the east sector than the west sector (Table 2). The patterns in predicted density were similar in the count-response (Fig. 5) and abundance-response (Fig. 6) spatial models, with the highest densities located near shore in the vicinity of Point Barrow, decreasing with increasing distance from shore. The spatial models also predicted relatively high densities over Barrow Canyon. The highest densities were shoreward of the 200 m isobath. The count-response model predicted an area of high density in the southeastern corner of the study area, due to one sighting of two whales that was filtered out of the dataset used for the abundance-response model. It is worth noting that the spatial models used information on sightings and effort from the east and west sectors to fill in the gap in survey coverage north of Utqiaġvik to generate density estimates for those cells. We believe this was reasonable because the gap in coverage was located in the middle of the survey area, comprising a relatively small area compared to the entire study area, and is known from historical studies to have cetacean habitat that is consistent with the east and west sectors, which were thoroughly surveyed. In the west sector, the estimated number of bowhead whales ranged from a low of 16 whales (based on the imagery from the Turbo Commander) to a high of 63 whales (based on standard distance sampling methods using the historical dataset). In the east sector, the estimates ranged from 38 whales (based on the imagery from the Turbo Commander) to 83 whales (based on standard distance sampling methods using the historical dataset). Variability in estimated uncertainty among analytical methods was consistent between

Table 2. Summary of density and abundance estimates for bowhead whales, belugas, and gray whales in the west and east sectors, based on imagery data from the UAS and Turbo Commander, and from marine mammal observer data collected aboard the Turbo Commander.

	West sector						East sector					
	Imagery		Marine mammal observers				Imagery		Marine mammal observers			
	UAS	Manned aircraft	Standard distance sampling (limited data)	Standard distance sampling (historical data)	Count model (limited data)	Abundance model (historical data)	UAS	Manned aircraft	Standard distance sampling (limited data)	Standard distance sampling (historical data)	Count model (limited data)	Abundance model (historical data)
Bowhead whale												
No. of whales	3	2	8	11	—	—	6	4	12	12	—	—
Area covered (km^2)	525.4	646.0	8829.8	5927.2	—	—	448.5	645.9	7166.0	5127.3	—	—
Estimated whale density	0.006	0.003	0.006	0.012	—	—	0.013	0.006	0.010	0.014	—	—
Estimated total no. of whales	29	16	32	63	35	50	82	38	63	83	60	65
CV	0.77	0.71	0.51	0.41	0.28	0.20	0.53	0.45	0.41	0.36	0.28	0.20
Beluga												
No. of whales	0	0	—	0	—	—	6	11	—	22	—	—
Area covered (km^2)	525.4	646.0	—	2207.0	—	—	448.5	645.9	—	1692.3	—	—
Estimated whale density	0.000	0.000	—	0.000	—	—	0.013	0.017	—	0.025	—	—
Estimated total no. of whales	0	0	—	0	—	—	82	105	—	152	—	—
CV	NA	NA	—	NA	—	—	1.02	0.67	—	0.72	—	—
Gray whale												
No. of whales	1	0	—	0	—	—	2	0	—	0	—	—
Area covered (km^2)	525.4	646.0	—	NA	—	—	448.5	645.9	—	NA	—	—
Estimated whale density	0.002	0.000	—	0.000	—	—	0.004	0.000	—	0.000	—	—
Estimated total no. of whales	10	0	—	0	—	—	27	0	—	0	—	—
CV	1.04	NA	—	NA	—	—	1.01	NA	—	NA	—	—

Note: Bowhead whale density estimates based on the standard distance sampling methods were adjusted for species identification bias. None of the density estimates have been adjusted for perception or availability bias. The number of whales represents the subset of whales from the sightings that met the data filter criteria for each method (supplementary data B, Fig. B1[1]). Because the marine mammal observers did not observe any gray whales within the necessary data filtering criteria, the effective area covered based on standard distance sampling methods could not be computed for gray whales. For a given species, sector, dataset, and analytical method, the coefficient of variation in estimated density (CV(*D*)) equals that for the estimated total number of whales (CV(*N*)).

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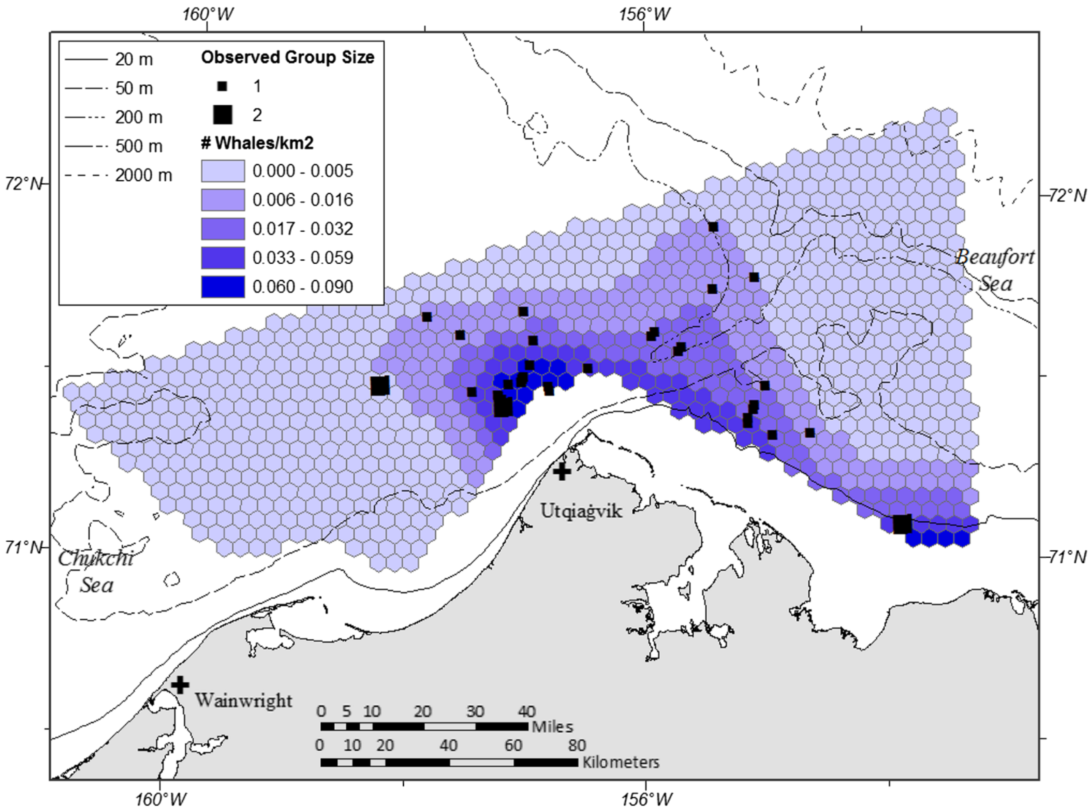
Fig. 5. Bowhead whale density predictions from the count-response spatial model. The locations of the bowhead whale sightings used to build the model are also shown, according to observed group size.

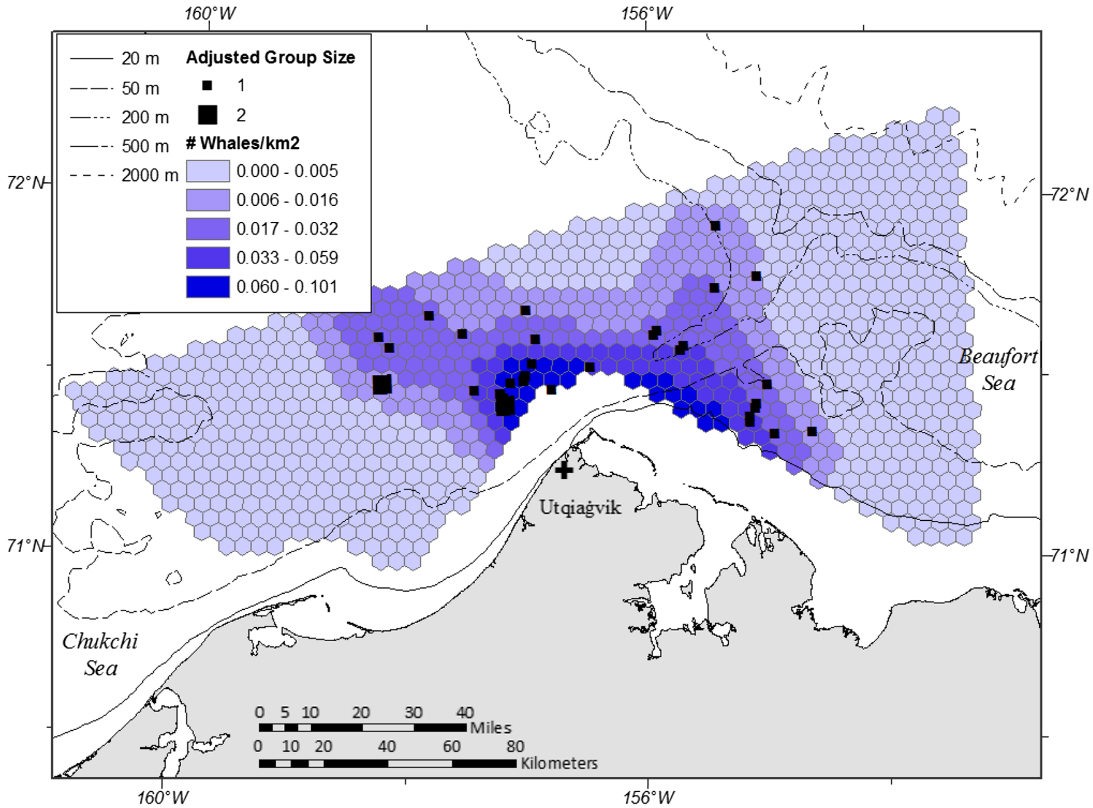


both sectors, with the spatial models having the lowest CVs (0.28 for the count-response spatial model and 0.20 for the abundance-response spatial model), standard distance sampling models having intermediate values (0.36–0.51), and estimates derived from the imagery having the highest values (0.45–0.77) (Table 2). The CVs for the spatial models can be decomposed into contributions from the spatial model and the detection function model. For the count-response model, the uncertainty due to the spatial model (CV = 0.16) was less than that from the associated detection function (CV = 0.23). For the abundance-response model, the uncertainty due to the spatial model (CV = 0.16) was greater than that from the detection function (CV = 0.11). The effective area searched, based on percentage of the water's surface visible in the imagery and sampled area for the marine mammal observers, was approximately 10 times greater for human observers than for aerial imagery (Table 2); the larger effective search area resulted in more detections and lower CVs.

Belugas were sighted in only the east sector (Table 2, Figs. 2–4). The estimated number of belugas was smallest (82 whales) for the UAS imagery and largest (152 whales) for the marine mammal observer dataset in the standard distance sampling analysis that incorporated historical data into the detection function. Estimated coefficients of variation in the density estimates were similar for the Turbo Commander imagery (0.67) and marine mammal observer dataset (0.72), and highest for the UAS dataset (1.02) (Table 2).

Gray whales were detected only in the UAS imagery (Fig. 2) and by the marine mammal observers aboard the Turbo Commander (Fig. 4); however, there were no marine mammal

Fig. 6. Bowhead whale density predictions from the abundance-response spatial model. The locations of the bowhead whale sightings used to build the model are also shown, according to group size, adjusted for the estimated unconditional detection probability, $\hat{p}_a$.

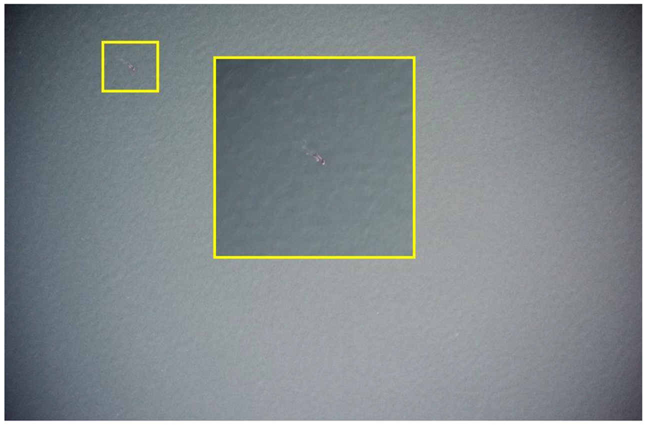


observer sightings that fit the analytical criteria for density estimation (supplementary data B and Fig. B1[2]). Therefore, estimates of the number of gray whales present were computed only from the UAS imagery, resulting in an estimate of 10 whales in the west sector and 27 whales in the east sector (Table 2). The estimated coefficients of variation in the estimated number of whales were high in the west and east sectors (1.04 and 1.01, respectively) (Table 2), reflecting the very small sample size.

Discussion

The results presented herein represent the first report of a field experiment involving simultaneous manned and unmanned aerial survey operations targeting cetaceans that provide a direct comparison among line-transect data collected by marine mammal observers onboard an aircraft, and digital photographic strip-transect data from the manned aircraft and UAV. The surveys were conducted during late summer in the Alaska Arctic, when migratory cetaceans are typically found in high abundance and weather conditions are dynamic, ranging from gale force winds, flooding rain, snow, fog, or clear skies with no measurable wind, potentially all in the course of 24 h. We analyzed each dataset separately to independently compare each method; however, a unified model that included all three sources of data could be explored as a way to utilize the strengths of each dataset to derive density estimates if a single best estimate were preferred for each species. Our

Fig. 7. Sample image of a bowhead whale from the UAS imagery taken from 272 m altitude. This whale was observed in the east sector (71.37°, −154.59°).



overall assessment of the methods was based on 10 performance metrics: (*i*) number of sightings made by each method; (*ii*) ability to identify sightings to species; (*iii*) ability to estimate group size; (*iv*) ability to detect calves; (*v*) precision and bias of the resulting density estimates; (*vi*) length of trackline and area sampled; (*vii*) duration of survey effort; (*viii*) analytical effort required to achieve target precision in the density estimates or to compute other derived parameters; (*ix*) monetary cost; and (*x*) non-renewable energy consumed. Each metric is discussed in this section.

The ability to study cetacean ecology unites the first five of the 10 performance metrics. In general, bowhead whales were found in higher densities and gray whales were found in lower densities than expected, and beluga densities were approximately consistent with previous years, based primarily on cumulative knowledge from the ASAMM historical database, which covers 37 field seasons (e.g., Clarke et al. 2017*a*). Due to a broader search width, the marine mammal observers sighted approximately seven times more cetaceans than were detected in either imagery dataset during a similar number of flight hours.

All methods allowed trained observers to identify bowhead whales, gray whales, belugas, and walruses. Based on the large proportion of sightings that the marine mammal observers aboard the Turbo Commander could not identify to species relative to the analogous proportion during ASAMM surveys that are conducted in closing mode (e.g., Clarke et al. 2017*a*), it is evident that implementation of passing mode line-transect surveys affected observers' ability to positively identify sightings to species. The resolutions of both imagery datasets were lower than expected due to a combination of wind, precipitation, low light, camera vibration, and the need to operate the UAV at high RPMs to mitigate icing (Angliss et al. 2018) (Fig. 7). Humpback, minke, and fin whales appear to be increasingly common in the eastern Chukchi Sea (Clarke et al. 2013; Brower et al. 2017*a*); improved image resolution may be needed to differentiate these species and certainly would be required to differentiate smaller cetaceans, such as harbor porpoise, Dall's porpoise, or pinniped species. Higher resolution could be achieved by modifying the camera mounting system to dampen vibrations. A lens with a longer focal length would also produce a higher resolution image, although at the expense of a narrower strip width and, hence, a smaller sampled area.

Small sample sizes limited our ability to determine whether the methods affected the photo analysts' or ASAMM marine mammal observers' ability to estimate group size or detect calves. In the imagery, whale group sizes ranged from one to six whales (belugas were found in the largest groups), and only one calf, a bowhead whale, was detected. Group size estimates for cetacean sightings made by the ASAMM observers during the study period ranged from one to seven animals, with the largest groups being belugas. The ASAMM observers sighted eight beluga calves and one bowhead whale calf during the study period. Based on information in the ASAMM historical database, we know that observers detect only approximately 25% of bowhead whale calves present upon initially sighting bowhead whales (e.g., Clarke et al. 2017*a*); in other words, in 75% of the bowhead whale sightings that included at least one calf, the calf was detected only after the aircraft circled the sighting. Therefore, conducting the line-transect surveys in passing mode during this experiment likely resulted in biased estimates of calf numbers for the marine mammal observers, and possibly also in the imagery.

For bowhead whales, the species with the most sightings across all methods, there was a consistent pattern in the magnitude of the estimates of uncertainty for the density estimates in the west and east sectors, with the spatial modeling methods having the lowest CVs, followed by standard distance sampling with intermediate values, and photographic strip-transect methods having the highest CVs. In this study area, lowering the CVs of the density estimates derived from the UAS imagery to be comparable to the analogous CVs from the marine mammal observer dataset would have required approximately double the number of flight hours on the UAS. This study had planned to meet that target number of flight hours by conducting flights with two UAS simultaneously, but dual operations were not possible due to weather and logistical limitations. We adapted Fewster et al.'s (2009) R2 estimator for encounter rate variance to compute the CVs in the density estimates derived from the imagery. This was necessary because the area captured in the digital images was not consistent throughout each transect because the UAS had to vary its altitude to avoid clouds. Estimation of availability and perception biases in the density estimates from all three methods is in progress, but requires collection of additional data.

The next three performance metrics address the relative efficiency of each method: (*vi*) length of trackline and area sampled; (*vii*) duration of survey effort; and (*viii*) analytical effort required to achieve target precision in the density estimates or to compute other derived parameters. The Turbo Commander covered more distance (3582 km versus 2012 km) and ASAMM observers effectively surveyed over 10 times as much area (e.g., >11 000 km^2 sampled for bowhead whales by marine mammal observers versus ~1000 km^2 analyzed in UAV imagery) in the study area compared to the UAS in approximately the same number of flight hours.

Although photographic data provide an excellent permanent record of the strip-transect survey and allow observers unlimited time to review each snapshot, analyzing the photos to determine whether animals are present, identify sightings to species, and determine group size is labor- and time-intensive if done manually (Hodgson et al. 2013; Koski et al. 2013; Taylor et al. 2014). Simultaneous collection of infrared and high-resolution electro-optical digital imagery has successfully accelerated the processing time of the latter for detecting ice seals hauled out on ice (Sigler et al. 2015) because reliable auto-detection algorithms based on the infrared signals have been developed. However, infrared sensors are not yet able to reliably detect bowhead whales due to their thick blubber, which insulates their core from the arctic environment. In our study, photo analysts spent a total of 332.5 h to manually process and search every third image from the Turbo Commander and UAS imagery for large cetaceans, averaging 6.9 h of photo processing time per flight hour. Not included in that estimate is the considerable amount of time required to download and backup the imagery. In comparison, the preliminary round of in-field editing of the ASAMM line-transect data, which involves thorough review of the database by two

Table 3. Commensurate costs required to collect, process, archive, and analyze data during the 2015 UAS and Turbo Commander strip-transect, and Turbo Commander line-transect aerial surveys.

	UAS photo strip-transect	Turbo Commander photo strip-transect	Turbo Commander line-transect
Field work and planning	$$$$	$$	$
In-kind contributions	$$$	—	$
Post-field work expenses	$	$	$$
Total	$$$$$	$$	$$$

Note: $, <$150 000 US dollars (USD); $$, $150 000–250 000 USD; $$$, $250 000–1 000 000 USD; $$$$, $1 000 000–2 000 000 USD; $$$$$, >$2 000 000 USD.

ASAMM personnel, is completed within 2 h of the aircraft landing after each survey flight. At that stage, the data may be used in preliminary analyses. The final post-season quality assurance/quality control of the ASAMM database takes approximately 100 h to edit 100 flights, averaging 11.2 min quality assurance/quality control per flight hour.

A common belief is that UAS will be less expensive than manned aircraft to meet the same goal. Therefore, the final performance metrics we evaluated were the commensurate costs required to collect, process, archive, and analyze data to derive estimates of cetacean density and associated uncertainty. These costs could be based on time, as presented above, money (Table 3), or non-renewable energy. To compute the monetary cost of the line-transect marine mammal observer surveys, we included the following items: labor, travel, and per diem for the science crew, including pre-season preparation, field work, and post-season wrap-up; aircraft usage fees (e.g., pilot labor, travel, and per diem; aircraft maintenance and repair) and fuel; and scientific communications and equipment (e.g., survey laptop, satellite telephone service). The cost estimate for the photo strip-transect survey aboard the Turbo Commander included the following: aircraft usage fees (e.g., pilot labor, travel, and per diem; aircraft maintenance and repair) and fuel; camera mount; scientific equipment (e.g., cameras, lenses, data storage, computers, monitors, software, resolution targets); and labor for post-season image analysis and archiving. The cost estimate for the UAS survey included the following: outreach; bear guards and bear spray; landing craft to offload personnel and equipment from the ship; logistics for Utqiaġvik field work; scientific equipment and communications (e.g., cameras, lenses, data storage, computers, monitors, software, resolution targets, satellite and cellular telephone services); materials for UAS shipboard and land operations and payload integration; UAS usage fees; in-kind contributions provided by the Navy and NOAA to transport UAS equipment between Dahlgren and Utqiaġvik and use the RV *Fairweather*, respectively; and labor for post-season image analysis and archiving. Overall, the monetary cost of the 2015 marine mammal observer surveys was 9.4% the cost of the UAS component, and was approximately 68.5% the cost of the photo strip-transect survey aboard the Turbo Commander. We expect that the costs of long-range UAS surveys will come down over time as equipment becomes less expensive and less logistically complicated, and as some of the workflow becomes automated. For this project, in terms of information collected per dollar spent, using marine mammal observers to collect line-transect survey data while airborne was considerably less expensive, generated many more sightings, and resulted in more precise density estimates than either image-based method in this study.

A brief consideration of fuel consumption required to conduct each type of survey suggests that the comparison is not straightforward. The Turbo Commander burns approximately 80 gallons of fuel per hour, whereas the UAS burns approximately 0.05 gallons of fuel per hour. Nevertheless, activities necessary to support our UAS operations consumed additional fuel. The research vessel *Fairweather* required a considerable amount of fuel to transit to the study area from Nome, Alaska; provide operational support for the UAS project; and return to port in Kodiak, Alaska. Furthermore, the C130 used to transport the UAS to Utqiaġvik burned fuel at a high rate. When indirect fuel consumption is considered, the manned aircraft operations required less fuel than the UAS operations.

One noteworthy difference between manned and unmanned aircraft is that the former are explicitly and painstakingly designed to safely return to land at the end of every flight, whereas the latter were designed to be expendable. This difference has implications in survey planning because it is important to have spare UAVs in the event that one has an unintentional water landing and cannot be recovered. Damage or loss to a UAV would have required a stand-down to review procedures, which could have resulted in lost survey days. In addition, the need for spare UAVs increases the overall project costs.

Multiple examples exist where UAS have been highly successful and have enabled researchers to collect novel data or data in locations or times that were previously inaccessible (e.g., Curry et al. 2004; Acevedo-Whitehouse et al. 2010; Fritz 2012; Knuth et al. 2013; Durban et al. 2015; Sweeney et al. 2016). However, based on the evidence encapsulated in the performance metrics summarized above, we conclude that it is premature to replace manned aerial surveys with UAS if the goal of the survey is to collect broad-scale arctic cetacean abundance or density estimates. This conclusion is based primarily on five factors: First, the technology available and used to enable manned and unmanned aircraft to fly simultaneously in close proximity in non-segregated airspace are insufficient due to the limitations of TCAS and the difficulties of visually detecting a small UAS flying at high closure rates (Angliss et al. 2018). Second, the sample sizes we obtained with the UAS were too small to reach acceptable levels of uncertainty in the density estimates. Furthermore, the raw number of sightings could be a critical factor if the goal of the survey is to mitigate, via real-time detection of animals, potential risks to marine mammals due to an anthropogenic activity, such as a military exercise or commercial seismic survey. Low sample sizes could be alleviated by flying longer (pending adequate weather), or collecting data from multiple sensors on a single UAV or on multiple UAVs flying simultaneously. Nevertheless, additional data mean additional processing time, and additional UAVs result in increased air traffic and enhanced probability of mid-air collisions. Third, the financial cost of a long-range UAS survey would be prohibitive to most wildlife managers' or ecologists' budgets. Fourth, manually processing imagery takes considerable time and money, and this is a significant hurdle to overcome without reliable auto-detection algorithms for large cetaceans (although this is a subject of current research and the cost is very likely to decrease). Finally, additional weatherproofing would be required to make UAS reliable platforms in extreme environments like the Arctic (Angliss et al. 2018).

As operational and analytical efficiency of UAS-based surveys increase, financial burdens will decrease. Development and mass production of UAS that are more weather resistant and easy to transport, and development of reliable auto-detection software for cetaceans, would reduce the costs of UAS-based surveys considerably. Ultimately, the question of whether UAS can replace or augment manned aircraft for conducting aerial surveys does not have a single answer. Rather, a lengthy list of questions should be addressed to determine whether a given UAS platform will likely meet a project's safety, scientific, and logistical needs.

Conclusions

Marine mammal observers' ability to detect motion, perceive patterns and colors, recognize target images in a visually complex field of view, and focus near and far are unmatched by currently available optical sensors and software packages. Pilots and marine mammal observers in conventional aircraft provide real-time situational awareness of the survey process, allowing first-hand assessment of environmental conditions, their location relative to other traffic in the airspace, and the surrounding ecosystem. This situational awareness increases the probability of success by minimizing time spent in poor weather conditions that impede data collection and can affect aircraft performance. Furthermore, over a century of technology and knowledge are available to facilitate coordinating airspace among manned aircraft operating simultaneously, relying in large part on the pilot's ability to detect and avoid other aircraft. The survey crew onboard an aircraft are able to quickly integrate information from their surroundings and assess novel situations, which can lead to expedited decision-making that may affect flight safety or the value of the data being collected. Humans are impressive multi-purpose sensors. Their abilities to learn, process information, adapt to new situations, and quickly make decisions enable the survey teams to collect multiple types of data using a wide variety of tools, thereby making manned aerial surveys efficient with respect to cost and time.

At this time, the use of UAS for long-range cetacean surveys is promising, but also experimental and expensive. Further investment of time and money is required to advance technology and implement necessary safety precautions, and these improvements may shift the balance in favor of UAS for certain types of scientific aerial missions in the future.

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