Faculty of Science and Technology
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Unmanned aerial vehicles for marine mammal surveys in arctic and sub-arctic regions

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Unmanned Aerial Vehicles for marine mammal studies in arctic and sub-arctic regions

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Thesis for the degree of Philosophiae Doctor

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Ronald Smit

Success is not final,
Failure is not fatal:
It is the courage to continue that counts

\- Winston Churchill

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And finally, to Murphy's Law: better luck next time, buddy. You are yet to beat me.

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Preface

The work presented in this thesis is a result of a 4-year PhD project funded by the Research Center for Arctic Petroleum Exploration (ARCEx, funded by the Norwegian Research Council, project number 228107), within UiT The Arctic University of Norway. One year was dedicated to work at Akvaplan-niva, where I assisted in research and internal projects, some of which involved work in Svalbard. In addition, I attended two courses at The Center for Research into Ecological and Environmental Modelling at the University of St. Andrews (Distance Sampling introduction and Advanced courses). At UiT The Arctic University of Norway I participated in PhD-level courses, and soft-skills workshops arranged by ARCTOS (Arctic Marine Ecosystem Research Network) and ARCEx. I also assisted and trained two MSc students with their fieldwork on land-based observations of humpback and killer whales, and harbor porpoises. I attended the annual conference for the European Cetacean Society and the Society for Marine Mammalogy, and was involved in presentations for the ARCTOS Days and ARCEx conference. Within ARCTOS, I was student representative in 2017 and was involved in the planning and execution of the student forum.

The thesis presented herein discusses the use of autonomous aerial vehicles for marine mammal surveys, with a detailed evaluation of the current state of the art, field experiments, and simulation tests. The work was developed in collaboration with SMRU Consulting, the Northern Research Institute (NORUT), and the Institute of Marine Research (IMR).

SUMMARY

The environmental changes caused by climate change and the actions taken by modern societies to mitigate and to adapt to these changes are currently leading to an increased utilization of marine resources with potential effects on marine life. Baseline information on the distribution and abundance of marine species is required in order to determine the state of the marine environment in a rapidly changing world, as well as to assess the conservation status of its inhabitants. This requires effective monitoring schemes that can provide meaningful data, and detailed vulnerability assessment maps to inform policy decisions. New tools and methods are needed to monitor marine resources so that industrial activities can be conducted without (or at least minimizing) adverse impacts on species of concern. Marine mammals are particularly vulnerable because underwater noise interferes with animal behavior and physiology. This has encouraged research and development of the use of unmanned aerial vehicles (UAVs) as a new method of monitoring and detecting marine mammals. UAVs are a method of providing insights of marine mammal presence particularly in arctic and sub-arctic regions. The research conducted under this doctoral program accompanies and fills some of the knowledge gaps on the application of these systems, while highlighting the need for more detailed material on marine mammal populations, their distribution, and abundance. The three components described in this doctoral thesis involve three stages of assessment of the utility of UAV systems for marine mammal surveys in arctic and sub-arctic regions. Each of the components highlight current knowledge gaps and the need for further empirical testing of these systems. The selection of a platform and sensor depends on the research and monitoring goals. The capabilities of a system must be well understood before field trials are carried out. Platforms and sensors have different qualities and limitations, and will perform differently depending on the type of monitoring needed. It is therefore important to take these into account when planning deployments. When conducting field tests, it is important to acknowledge the many factors that may bias image analyses. Factors external to the survey equipment (such as environmental features) may affect UAV data differently than visual observer-based aerial survey data (hereby manned-surveys). Changes in pixel size due to aircraft movement may affect the resolution in which an animal is present within an image and is therefore a measure that should be included in analyses of digital imagery. The permanent record of each survey

provided by digital technology allows scientists to reduce the effect of observer bias. Certainty of detections is a measure of relevance for such analyses as it provides a better understanding of the effects of environmental and survey-related covariates on image analysts' capabilities to detect an animal. Multiple aircraft or single aircraft maneuvers are often conducted to validate observations and estimate animal availability. To increase the number of detections when using multiple aircraft, one must consider animal availability parameters that can bias estimates of abundance or density. Simulation studies considering survey features and animal behavior can be used to improve data acquisition using digital imagery (e.g., deployed by UAVs). The number of detections may be considered a time series and should be analyzed based on the frequency of occurrance, so that further analyses for correlation with whale diving cycles can be performed. The work presented here highlights the complexity of monitoring programs, and shows how technological progress is valuable not only for environmental scientists, but also for industry managers and regulators.

1. Background

Understanding distribution, abundance and health status of animals in their environment is a prerequisite to animal conservation. For marine mammals, conservation and management is largely dependent on identifying species' habitat, distributions, and monitoring of their populations (Hodgson et al. 2010, 2013).

According to the ASCOBANS report from 2009, the "state of a marine mammal population" is comprised of a range of concepts including conservation, demographic status, and health status. Conservation status is derived through comparison of current abundance and distribution data to an undisturbed initial state where populations are believed to be in equilibrium with the habitats and resources. An undisturbed initial state is however difficult to define and attain in places where there has been a long history of interactions between humans and wildlife populations. Evaluating the demographic status, on the other hand, includes a description of changes in animal vital rates, such as fecundity and mortality. Considerations taken when assessing health status are pathologies and causes of death (including nutritional state and contamination) which may determine reproduction and survival rates. This is challenging to achieve (Groom et al. 2013), as many marine mammal species are migratory with a typical migration pattern of northward movement in the summer to feed and southward movement during the winter months for breeding (Wheeler et al. 2010).

In practice, marine mammal monitoring programs aim to characterize species distribution and density in an area, monitor the status of a population, assess the impact of an anthropogenic activity or biological event, or examine the spatial and temporal habitat use in order to identify foraging or breeding grounds. Several methods have been created and developed to help characterize marine mammal populations, that with modification can be used for impact/mitigation monitoring (Macleod et al. 2010). Aircraft (e.g., Koski and Davis 1994; Harwood et al 1996; Forney and Barlow 1998; Bengtson et al 2005) and ships (e.g.,Cattanach et al 1993; Barlow 1995; Swartz et al 2003; Barlow and Forney 2007) have been the preferred platforms for documenting the distribution and abundance of marine mammals over large geographic areas (Koski et al. 2009a). Depending on the survey region, different logistical challenges may occur. Environmental changes throughout a survey may affect the number of detections and/or the capabilities of the survey equipment to record animal sightings. Such effects are of particular consideration at extreme latitudes. The arctic, for instance, remains one of the most difficult places on Earth for year-round scientific observations and research. Yet it holds the key to understanding ecosystem processes and responses to climate change, and represents an important habitat for many mammals including ice-associated seals. Logistical support is expensive and scientists frequently face hazardous, cold sea-ice conditions, that hinder ship surveys, cause aircraft icing for aerial surveys, and involve long observation periods in low temperatures (Curry et al. 2004).

In 2008, it was estimated that areas north of the Arctic Circle have 90 billion barrels of undiscovered, technically recoverable oil and 44 billion barrels of natural gas liquids. This represents 13% of the undiscovered oil in the world (Mouawad 2008, USGS 2008). Such interest for petroleum exploration in Arctic regions has highlighted the challenges present in marine mammal data acquisition in these regions. Many ship-based marine mammal mitigation programs are often conducted from seismic vessels (and other E&P platforms) used during offshore oil and gas exploration (Stone 2003, Johnson et al. 2007, Patterson et al. 2007). The focus of these programs has been to detect marine mammals within a pre-defined range of a sound source, i.e. the exclusion zone, so that mitigation measures, such as reducing or ceasing activities, may be implemented. Since some species of marine mammals react to the presence of petroleum-related operations beyond the range of visual detection (Richardson et al. 1995, Miller et al. 1999), observations from other vessels or aircraft are often used to document animal behavior. Aerial surveys have been conducted to estimate the densities of ice-dependent marine mammal species using helicopters from icebreakers (Moreland et al. 2009). However, the costs of more frequent surveys and the risks of surveying further offshore have limited the reliable assessment of the status and trends of these populations.

The information gap caused by constraints in obtaining regular and detailed data on marine mammals often limits the development of successful wildlife management plans and conservation strategies, as well as the assessment of the impacts of anthropogenic activities (e.g., bridges, marine farms, oil and gas installations) on animal populations (Groom et al. 2013). Kaschner et al (2012) concluded that even though large efforts have been made to investigate cetacean abundance and distribution, our current knowledge of many species remains limited. This will in turn hinder the ability to define concrete conservation status for many of those species (Schipper et al. 2008). Therefore, there is increasing interest and demand for marine mammal conservation and new incentives to develop technologies that can facilitate data collection.

1.1 Marine mammal survey methods

Aircraft (e.g., Koski and Davis 1994; Harwood et al 1996; Forney and Barlow 1998; Bengtson et al 2005) and ships (e.g.,Cattanach et al 1993; Barlow 1995; Swartz et al 2003; Barlow and Forney 2007) with dedicated observers onboard have been the preferred platforms for documenting marine mammal distribution and abundance over large geographic areas(Koski et al. 2009b). Traditional techniques for detection and monitoring of marine mammals focus mainly on visual observations (from land, boat or aircraft) to obtain both population (e.g., abundance estimates) and individual (e.g., behavior) information (Macleod et al. 2010).

When conducting visual surveys of cetaceans, the most commonly used methodology is line transect surveys; where pre-determined transect lines are surveyed within a defined survey region. Observers record the perpendicular or radial distance to each of the sightings (a technique known as distance sampling), together with data on the species, group size, and environmental factors that can influence the quality of the data. Three assumptions must be fulfilled to provide unbiased estimates (e.g., Thomas et al. 2010):

1) Measurements from the observer to points of interest are accurate;
2) Animals are detected at their initial location;
3) Animals on the transect line are detected with certainty ($g(0)=1$).

To meet assumption (1), observers use reticle binoculars and inclinometers during ship and aerial surveys, respectively. Whilst not error-free, these methods should at least be bias-free. Video-range techniques (Leaper and Gordon 2001) have been developed and are an improvement on other tools though the equipment is generally more expensive and more difficult to use. Assumption (2) is particularly challenging to achieve for boat-based surveys. Many cetacean species are known to respond to the presence of boats (e.g., Aniceto et al. 2016). Animals attracted to the vessel cause positively biased abundance estimates whilst avoidance will result in negatively biased estimates. While “responsive movement” is often considered in terms of lateral movement of animals away or towards the track line, marine mammals have the capacity to submerge in response to survey platform noise that can reduce their apparent abundance (Macleod et al. 2010). Assumption 3 (*g(0)=1*) is rarely met, as it relies on observer experience and can change with distance from the observation platform. These are not insuperable constraints, but generally require auxiliary data collection, such as double-platform experiments (Hammond et al. 2002) or records of animal heading (Palka and Hammond 2001).

Moreover, when estimating animal density or abundance, scientists must understand the probability of detecting the target species. The probability of detection is based on the probability of detecting an animal, given that it is available for detection (perception bias), and on the probability of an animal being available to be detected (availability bias). The use of double-platform or double-observer surveys allow for empirical estimation for both. A constraint common to all visual surveys is that they need to be conducted under good weather conditions. The detection of cetaceans is heavily dependent on their surfacing patterns, which can become difficult to observe in harsh weather conditions, particularly at or above Beaufort Sea state 5, where the increasing number of white caps or breaking waves tends to obscure sighting cues. Additionally, surveys relying on visual cues recorded by marine mammal observers can only be conducted during daylight hours, which further impose time restrictions (Macleod et al. 2010).

With the arrival of new technologies, detection tools are moving away from using dedicated or opportunistic visual platform types (headland installations, vessels, aircraft) to improved visual (e.g., using digital tools) and acoustic systems (static and towed devices). Naturally, the most suitable monitoring approach should be chosen according to the species under study, and a mix of complementary methods should be considered (Ascobans 2009).

1.2 Autonomous vehicles

The last decades have seen a rapid development of monitoring and detection tools in terms of both field and analysis techniques to help reduce bias and uncertainties (Koski et al. 2009b) in marine mammal abundance and distribution estimates. Scientists have improved the available technologies to obtain more accurate measurements, which may result in reduction of survey time, increased data collection during periods of darkness and bad weather, and reduced risk to observers. Autonomous systems, such as unmanned aerial vehicles, gliders, and powered surface vehicles (figure 1), are revolutionizing the ability to map and monitor the marine environment (Yoerger et al. 1998, 2007, Caress et al. 2008, German et al. 2008). These platforms are unmanned, self-propelled vehicles, that can operate independently for periods of a few hours to several months (e.g., Wynn et al. 2014). They are capable of carrying a variety of sensors for environmental data, though for marine biota these are generally comprised of digital photo and video, echosounders, and passive acoustic recording devices.

These systems overcome some of the limitations of traditional survey methods by allowing greater flexibility in deployment (e.g., costs, safety, and operational range) and removing issues concerning observer bias by using digital sensors. Aerial surveys are less sensitive to weather conditions and allow for a large area to be covered over a relatively short time (Rowat et al. 2009) in relation to ship or land-based surveys. Nevertheless, they have some logistical limitations which include proximity of suitable facilities (e.g., runways and refueling stations) and appropriate aircraft. This means that isolated survey locations, or areas further offshore will not be accessible, thus surveys are generally confined to near-shore areas or offshore areas (Koski et al. 2009b, Duberstein et al. 2011). Autonomous systems provide the opportunity to conduct regular surveys across different seasons thus obtaining better information about cetacean seasonal variation and abundance. In abundance estimate studies, which often require long-term comparisons of monitoring data, detectability plays a key role. The behavior (and hence, detectability) of the animals may change (Macleod et al. 2010), affecting animal availability estimates. Aerial and underwater/surface survey technology improvements are examples of remote systems that can perform such tasks. The data analysis process is similar to traditional surveys, since there are already in place analytical tools for measuring animal presence using digital sensors. Scientists are therefore able to conduct repeated surveys using autonomous vehicles, which allow for more accurate population estimates (Sardà-Palomera et al. 2012). Survey replication is further facilitated by the ability of these platforms to consistently follow precise, predetermined tracks (Watts et al. 2012). Furthermore, they may also be an asset in mitigation activities performed around seismic operations, due to their ease of transport, few requirements in deployment and recovery, and safety of operations. With the appropriate equipment, it is possible to survey a large area for marine mammals around intense energy sources for mitigation, not restricted by the distance from land they can operate (Koski et al. 2009b).

The use of this technology in environmental research and monitoring has therefore, been recognized as a tool with the potential to revolutionize spatial ecology (Koh and Wich 2012) and conservation (Anderson and Gaston 2013). However, there is still a need to develop appropriate protocols to efficiently measure animal density and distribution.

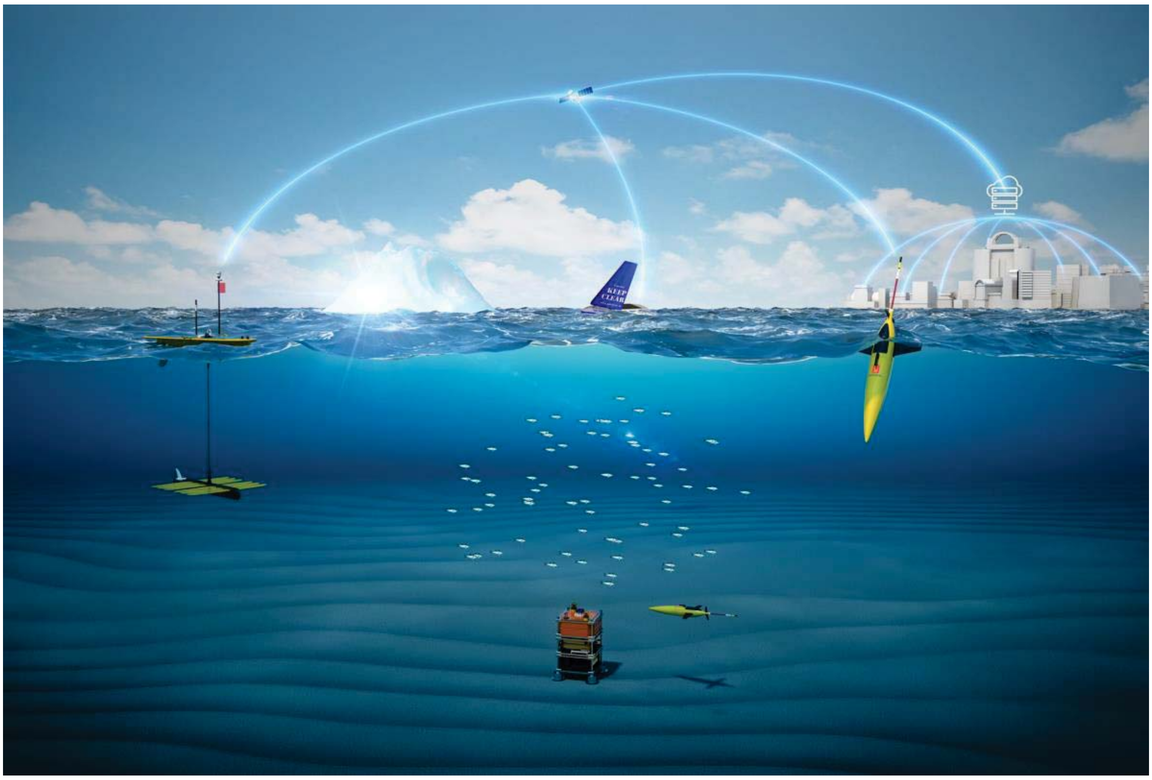

Figure 1. Autonomous systems collecting data in the marine environment. Source: Kongsberg Maritime.

Unmanned Aerial Vehicles (UAVs)

UAVs have been used for wildlife surveys in terrestrial and coastal environments (Jones et al. 2006). The range of applications for such technology in scientific exploration is rapidly expanding with the recent recycling of UAVs originally developed for military operations and the development of new UAVs of smaller size but similar capabilities. As UAVs become more accessible, numerous civilian applications have emerged: law enforcement (Finn and Wright 2012); rapid response operations (Eisenbeiss 2009); precision agriculture (Sugiura et al. 2005, Lelong et al. 2008, Hunt et al. 2010); hydrology (Niethammer et al. 2012, Westoby et al. 2012); archeology (Verhoeven et al. 2012); and environmental monitoring (Lejot et al. 2007, Hardin and Hardin 2010). These technologically-advanced so called "drones" could have the potential to replace manned aerial surveys and overcome some of their limitations (Koski et al. 2009b, 2009a, Hodgson et al. 2013).

The acknowledgment that UAVs have great potential in scientific research has encouraged the demand for systems that can acquire the sampling quality found in large aircrafts, with combined portability, cost advantages of smaller systems, and eliminating the risk to human life that is generally associated with manned-aerial monitoring (Koski et al. 2009a). However, small UAVs though portable and able to fly at lower altitudes in dangerous environments and over long periods of time, are susceptible to turbulence and may be affected by air-space regulatory restrictions (Gurtner 2008). Nevertheless, the permanent record of digital imagery gathered during autonomous surveys provides an objective, enduring record of the organisms of interest, that can improve data sharing, validation, and further analysis (Christie et al. 2016).

Complementary work between autonomous and traditional survey methods

Due to the UAVs' greater operational and digital sensor qualities, these systems can be used to validate, improve, or complement the data acquired by other types of marine mammal surveys. For instance, the deployment of UAVs ahead of a vessel (for either research or industrial operations) may provide a clearer understanding of an animal's responsive behavior and therefore, quantify the bias that it can cause to observations collected from that same vessel. UAVs are also capable of carrying external equipment, such as passive acoustic devices. This capability further enlarges the data collected ahead of a possible source of disturbance, i.e. collecting data on animal vocalizations in addition to visual detections. Acoustic data are less dependent on weather conditions and more dependent on the equipment's specifications regarding received frequencies and battery life. Additionally, data collection can be automated and is thus not limited by the skill of the "observer" (Macleod et al. 2010).

While acoustic recorders have several strengths, perhaps the greatest weakness is that they generally measure acoustic activity, i.e. presence/absence, rather than numbers of animals. Thus, changes in the level of acoustic activity may be due to differences in behavior, rather than true changes in density of animals (Macleod et al. 2010). Combining these with records obtained by unmanned aircraft leads to validation of detections, and/or the proportion of detections that could be missed in passive acoustics, provided that they are within the visual range of the digital sensors onboard the aircraft.

Another example of combining survey technologies is the use of telemetry data to provide information on animal behavior that can later be used to estimate the probability of an animal being available for detection (e.g., VHF transmitters fitted with time-depth recorders, and dataloggers) for surveys using UAVs. Telemetry is a widely used method for studying marine mammal movement behavior, by attaching a tag device on individual animals. The tag device (e.g., figure 2) can provide detailed information on the animals' behavior and may help identify important habitats and migration routes. More recently, telemetry studies of grey seals have been performed to create relative habitat usage maps (Matthiopoulos et al. 2004, McConnell et al. 2009), which help define protection areas. However, the use of telemetry devices alone for population abundance is generally limited (Aarts et al. 2008), since only a small number of animals can be tagged at a time, the duration of attachment of the device can vary between deployments, and recovering the data can be difficult as the device will drift with ocean currents (Macleod et al. 2010).

Figure 2: Tagged humpback whale in Kaldfjord (Northern Norway). Photo by Ana Sofia Aniceto.

In terms of animal tracking to improve the characterization of marine species spatial dynamics characterization, it is required to understand their spatial and temporal distribution, as that of their prey. Land-based observers may provide assistance in collecting information on animal availability prior or during an autonomous survey (e.g., Hodgson et al. 2017), though telemetry systems also assist in providing this information for regions or animals beyond visual line of sight. However, data on prey-species and environmental characteristics must be derived from other sources (e.g., autonomous underwater vehicles with echosounders, chlorophyll sensors and other sensors capable of measuring other environmental parameters).

A collaboration between autonomous systems, is a feasible alternative to using individual tools that could assist in increasing the resolution at which both the animal and its surrounding environment are sampled. One such example is the work developed by Sousa et al. (2016) where tagged sun fish were tracked to characterize the factors associated with their behaviour using a variety of tools that estimated the environmental drivers for both predator and prey abundance (figure 3).

All methods have their advantages and limitations. However, combining the information provided by these tools can increase the amount of data acquired and provide a more complete overview of animal behavior, abundance, and distribution in relation to their surrounding environment.

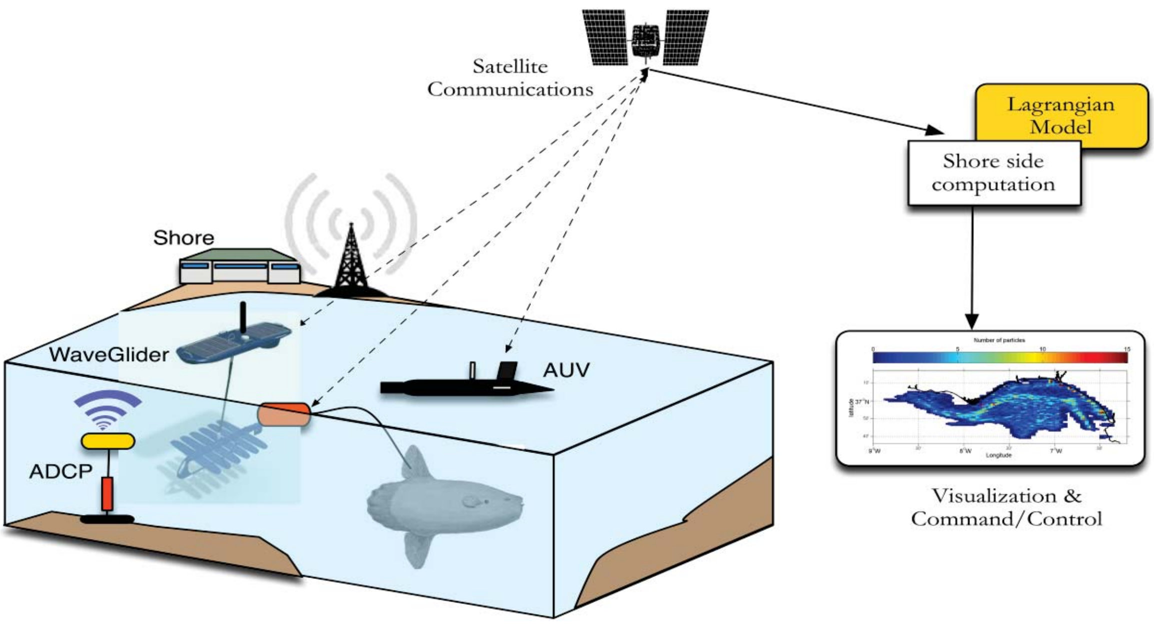

Figure 3. Example of autonomous system complementary work developed for studying sunfish.
Source: Sousa et al. (2016).

2. Knowledge gaps and study context

Top predators are key components in the Arctic ecosystem, yet it is difficult to make routine assessments of seasonal distributions and abundances, particularly for marine mammals. The interest in developing sound environmental approaches for the establishment of industrial activities in polar regions has prompted technological advances in data acquisition systems. Technological advances in UAVs, combined with increasingly sophisticated remote-sensing equipment, are facilitating ecological research that may be safer, more cost-effective, and less invasive than traditional methods (Anderson and Gaston 2013). This comparison with traditional methods has been highlighted as one area of priority when considering UAVs as alternatives to current survey methods (e.g., Koski et al. 2009b, Hodgson et al. 2010, 2017). The combination of image acquisition systems and UAVs may lead to substantial improvements in the routine assessment of top predators in their natural habitats and, in particular, in their behavioral reactions to industrial activities.

Though autonomous systems may one day prove to be an alternative to traditional monitoring methods, these systems must be systematically evaluated. The lack of "see and avoid" systems (for collision avoidance) and HD imagery analysis tools are still pending in the development of this equipment, as well as the acquisition of flight permissions for offshore locations. Establishing UAVs as survey tools for the petroleum industry means that UAV capabilities and limitations are validated, and can hence be taken into account in research and monitoring efforts. In addition, methods for interpreting the data considering possible sources of bias need to be identified and understood. Therefore, there is a need to develop appropriate protocols to efficiently measure animal density and distribution in locations of interest, which is essential for establishing appropriate regulations and mitigation measures. While this still represents a challenge for scientists, studies that focus on improving our understanding of animal behavior and surveillance will benefit not only the scientific community but also conservation and management agencies.

3. Objectives

Technological developments in autonomous aerial systems accessible to the scientific community have encouraged the need for further validation and testing in the marine environment. Particularly in polar regions, where access to isolated regions can be restricted in terms of runway platform availability, the use of such equipment can be a valuable asset in gathering large amounts of data at a lesser cost. However, only recently have there been successful studies that show that UAVs can be competitive to other survey methods, such as Hodgson et al. (2013, 2017). Such studies are still ongoing as UAV and imagery technology improve. The main research objectives of this thesis are to improve and develop the knowledge concerning surveys of marine biota using autonomous aircraft, particularly the current state of the art and its applicability in offshore regions, imagery analysis, and survey planning.

3.1 Autonomous vehicle systems and their suitability for monitoring marine biota (Paper I)

The first manuscript describes the current state of both autonomous aerial and underwater platforms as well as sensors. Understanding the qualities and limitations of different types of equipment prior to deployments is vital, particularly for mitigation of offshore industrial activities. The study is composed of a comprehensive review of different types of platforms and sensors, and their potential for future abundance estimates and focal studies. The main objectives of this study were:

- Review the current state of autonomous (aerial and underwater) technologies;
- Provide recommendations on how to improve/expand observation and detection of marine species;
- Provide recommendations on which sensors and platforms are currently most adequate for population and mitigation monitoring, and focal studies?

3.2 Quantifying detection certainty in UAV surveys (Paper II)

This section of the doctoral project focuses on aircraft and environmental related-parameters that may influence image analyst detectability and certainty of detections. Understanding the effects of environmental conditions (e.g., wind speed, visibility, and light) can improve data quality, as these tend to lead to biased results. Additionally, changes in image resolution are incorporated here as a proxy for aircraft movement and its effects on image quality. To better understand the limitations of the equipment at use and what can affect the quality of the data, the objective of this study was to:

- Identify the key environmental factors affecting the reliability in detecting whales in UAV images;
- Assess the influence of UAV movement on detection certainty in Arctic waters.

3.3 Multiple aircraft and effects of survey design on detectability (Paper III)

The aim of this component of the doctoral research was to test field protocols for population estimates of cetaceans using computer simulations. Here, information from live animals using tag devices was collected in the same region where the simulation took place. The information provided by these simulations gives insights on improved survey design and data acquisition, which can be used to estimate animal abundance through a combination of field and computer-based surveys. The objectives of this study were:

- Evaluate the effects of whale directional movement on detectability given different survey transect designs;
- Estimate the optimal time lag between two UAVs that would maximize the number of detections of humpback whales.

The work is structured considering three steps in assessing the potential of unmanned vehicles in marine surveys;

First (paper I), a framework of knowledge to understand the capabilities of autonomous systems (platforms and sensors) is provided. Assessing the state-of-the-art with regards to current autonomous platforms and sensors, is of upmost importance for survey planning to obtain the best suitable system for particular type of research and monitoring objectives. Different autonomous systems can be used for monitoring, mitigation, and focal studies. Their versatility is shown in both the amount of studies performed using these systems, and in the scientific and technological innovation that arises from such studies. In addition, the outcome of this review resulted in several recommendations for future efforts that in the development and application of autonomous systems.

The second part of the evaluation (paper II) includes practical testing of UAVs for marine mammal surveys in coastal regions. Here, field trials were conducted during the winter months in Northern Norway as a test setup for the application of drones in offshore areas that can represent harsh survey conditions. The UAVs were deployed in locations where animal presence was known to identify key factors affecting the probability of detecting animals in UAV images, and to understand the underlying issues concerning the use of UAVs in sub-Arctic waters. The study was conducted at two locations, based on animal seasonal distribution (see section 4.1). By pre-planning the survey route using waypoints, the aircraft operated independently throughout the surveys, except for take-off and landing. The platforms were equipped with a digital still-photo that took consecutive images with a frame rate suitable for the level of overlap between images required to assist in species identification. The camera was connected to an onboard computer, which allowed the images to also record flight information such as GPS coordinates and altitude. Geo-referenced navigation data was obtained from the onboard flight log. Once the surveys were terminated, the images were manually reviewed for animal presence, image quality, and environmental features. Certainty of detections was the primary objective, and therefore, measures such as luminance and wave turbulence were included as possible sources of bias. As a measure of the effects of aircraft movement on image quality, changes in pixel size were evaluated across all images.

Finally, the third component (paper III) assesses issues related to detection rates based on availability, and optimizing the time gap between the deployments of multiple UAVs. This study encompasses a computer simulation that can be applied in future survey planning, with automated strip transects, and aircraft and photo settings. Telemetry data on humpback whale movement and diving behavior was recorded in the same region where the simulated surveys were to take place. The simulation measures the number of detections of humpback whales acquired by the UAVs, as well as data on detection frame, time, and operational features of the aircraft (e.g., speed, altitude). Within the framework of the simulation, it is possible to manipulate the number of realizations/replicates that are to take place for a single type of flight, as well as different combinations of settings for altitude, speed, image frame rate, and transect design. For the development of our field-optimizing simulation, the probability of detection was calculated based on the diving behavior of tagged individual humpback whales. The surveys were designed to ensure applicability for animal abundance estimates, and were tested according to the overall swimming direction of the whales. Animal detections resulting from the simulation were analyzed as a time series, and detections were correlated with each animal's diving pattern.

4.1 Area of study

In the second and third components of this project (Papers II and III), the surveys addressed animals present in fjords of the island off Kvaløya (Troms County) (figure 4). The Norwegian name for this island translates to "Whale island" and reflects the historical cetacean abundance around it. During the last seven years, unusually large aggregations of humpback and killer whales have congregated in the fjords off the northwest coast of Norway, driven there by vast amounts of herring, an important food source for the whales (Jourdain and Vongraven 2017). This provided a unique opportunity to evaluate the capabilities of UAVs to monitor marine mammal species within an area of large aggregations of whales, and to assess detection rates from UAV systems in an Arctic setting.

The number of humpback whales (*Megaptera novaeangliae*) in Arctic waters during the winter seems to symbolize a short stop in the migration between the summer feeding grounds in the Norwegian and Barents Seas, and the breeding grounds further south (Broms et al. 2015, Ryan et al. 2015). Killer whales (*Orcinus orca*) inhabit Norwegian waters year-round,

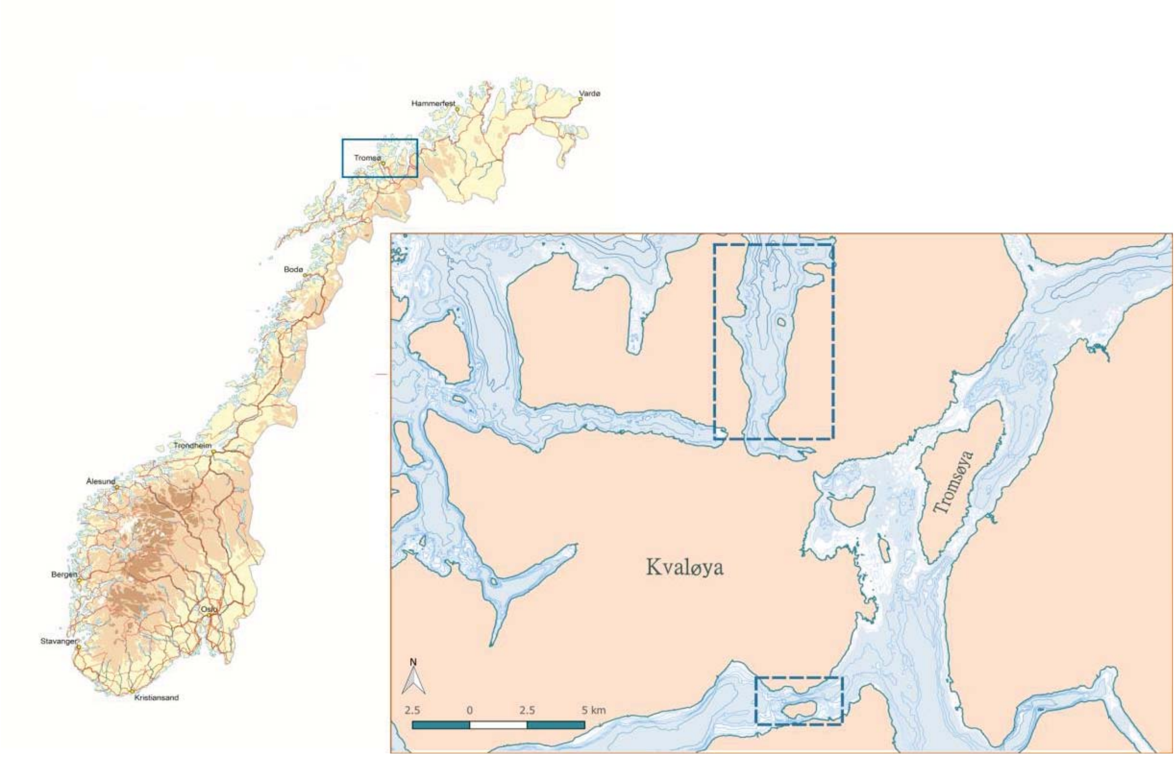

Figure 4.Map of the study regions marked with dashed lines (top: Kaldfjord, bottom: Rystraumen). Adapted from Kartverket.

migrating between offshore and nearshore areas depending on prey distribution. The primary reason for the sudden presence of humpback and killer whales in the fjords of Northern Norway is a superabundance of Norwegian spring-spawning herring (*Clupea harengus*; herein NSS herring). Although NSS herring spreads out during the summer, this species aggregates during the winter (Huse et al. 2010). The herring remains in high latitude coastal areas during the winter months. NSS herring generally begins a southward migration around January-February to spawn in southern Norway before dispersing in the open northeast Atlantic (Røttingen 1990, Vester and Hammerschmidt 2013). Between 1973 and 1986, a superabundance of NSS herring was found in various fjords in the Lofoten area (Northern Norway) during the winter. In the following 13 years (1988-2001), almost the entire winter NSS herring population could be found in Tysfjord and in the adjacent Vestfjord (Røttingen 1990), bringing with it a large gathering of killer whales (Similä et al. 1996) and the establishment of a tourism industry solely dedicated to killer whale-watching. Although the superabundance of NSS herring in the Lofoten area attracted relatively large numbers of killer whales by the end of the 20th century (Kuningas et al. 2008), there are no references of the presence of humpback whales in these fjords.

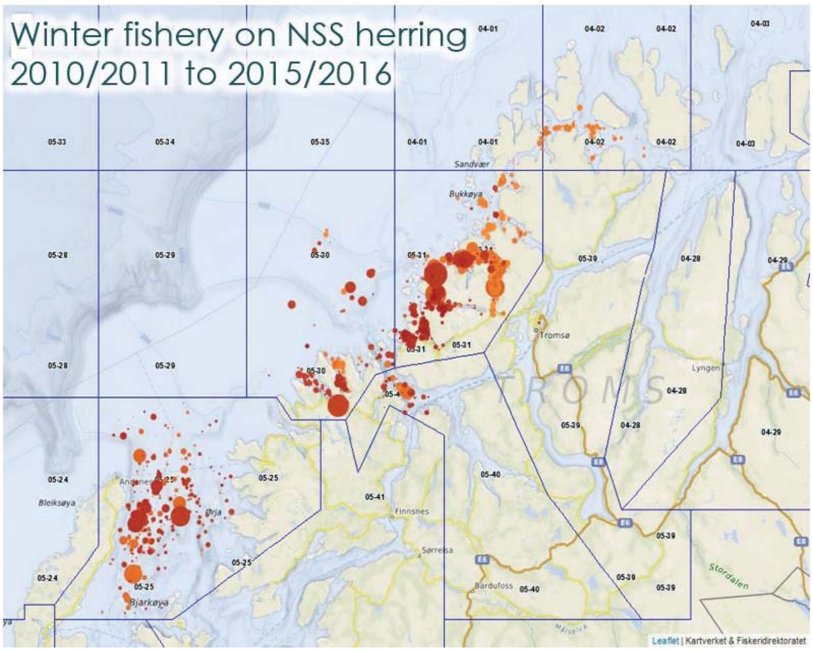

Figure 5. Distribution of herring catches in Northern Norway in the Troms and Vesterålen regions (colored in orange). Symbol size and color range represents biomass Source: Martin Biuw

The overwintering population in these areas has been declining since 2001 and the bulk of the NSS herring gradually moved north towards the Andfjord area (Vesterålen County) during winter. (Huse et al. 2010, Vester and Hammerschmidt 2013). Between 2010 and 2017, herring shoals have had a strong presence in the fjords near Tromsø during winter (November-January), as well as in the Andfjord area (December-February) (figure 5). The changes in NSS herring distribution and the proximity to open water regions is believed to influence the presence and numbers of both humpback and killer whales in the fjords near Tromsø, though the actual timing of arrival and departure of herring and whales remains unknown.

5. Main findings

When assessing the use of new technology, it is necessary to investigate the qualities of that technology in relation to current existing monitoring and research methods. Often, some of the limitations of traditional survey tools will also be applicable to new techniques, such as factors affecting detection probability. However, the extent to which these factors may affect systems such as unmanned aerial vehicles is not well understood. This chapter covers an overview of the results obtained in each component of the doctoral work.

5.1. Autonomous vehicle systems and their suitability for monitoring marine biota

Different systems will ultimately have different capabilities thus, single or multiple platforms and sensors may be designed to conduct different marine animal monitoring applications (see figure 6). This review presents critical considerations when planning marine surveys, where autonomous vehicles are the main source of data collection.

The combination of vehicle, sensor, and data relay system define the maximum size of the monitoring area that may be covered, and thus the probability of detecting a target animal. The ability to adhere to a survey design and collect relevant data to enable abundance/density estimation are the two key requirements when considering an autonomous system for population monitoring. Of the three classes of aerial platforms considered in this review, powered unmanned systems are the best candidate platform for aerial surveys using autonomous vehicles. All classes of underwater and surface vehicles are capable of conducting population monitoring. Active (AAM) and passive acoustics (PAM) sensors that are deployed onboard these systems can collect data required for detection probability estimation, though a careful survey design will be required. Some systems may have short deployment durations, thus making them more suited for focal studies and mitigation.

For the continuous real-time surveillance that is required for mitigation, platform must be continuously in contact with the shore or a support vessel. Any sensor mounted on an underwater autonomous vehicle can only send data back when at the sea surface since the amount of data that need to be transmitted for mitigation is too large to use an acoustic modem for sub surface communications. Therefore, only surface or aerial systems would be feasible in monitoring and mitigation instances when continuous real-time detection is required (figure 6). Tethered systems, such as lighter-than-air aircraft, and powered aircraft are potential candidates for performing focal animal monitoring. Though some surface and propeller-driven underwater craft have short survey duration times, these platforms, particularly those with increased maneuverability, may be suitable for individual focal animal studies. Finally, the technical and operational details of an autonomous system need to be tailored to the specific needs, e.g. the type of monitoring to be conducted, target species, area of interest, operational environment, properties of the platform that the autonomous vehicle will be deployed from, required survey length, and project budget.

These findings resulted in a set of recommendations, which include but are not limited to field comparisons between autonomous systems and traditional survey methods, and improvement of detection and classification algorithms.

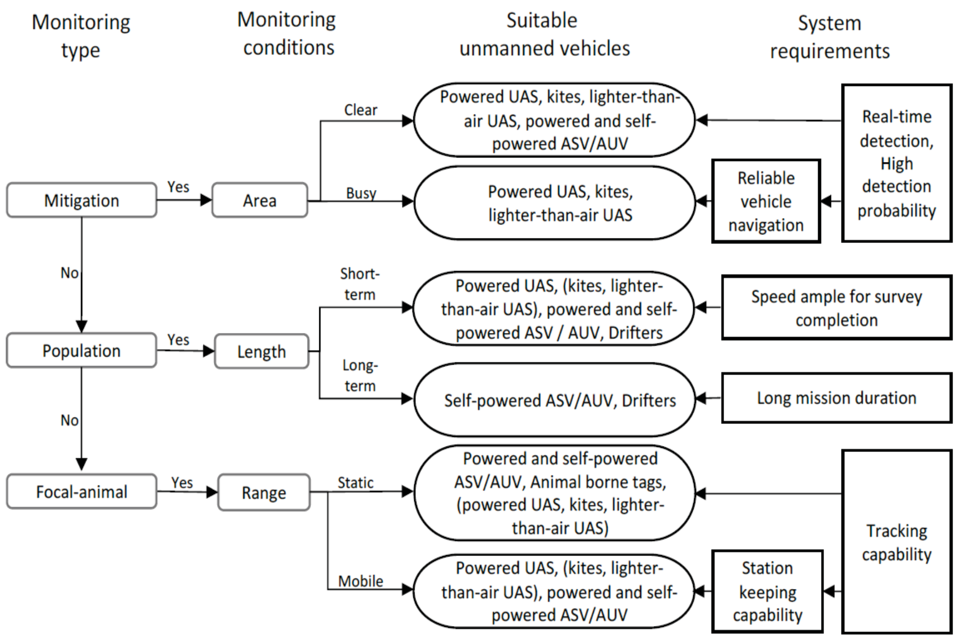

Figure 6. Decision tree for autonomous platforms according to monitoring type and conditions (Verfuss et al.2018).

5.2. Quantifying detection certainty in UAV surveys

Certainty of detection is one of the assumptions of transect sampling, and the primary metric for evaluating the utility of any animal survey method. It can be affected by environmental (e.g., sea state and glare) and survey platform (e.g., pitch and roll) conditions, which are often considered in the planning and analyses phases of a survey. For instance, sea state and glare are known to affect observers' (or image analyst) ability to detect marine mammals (e.g., Pollock et al. 2006) by limiting effective coverage of survey areas and produce false positives (Paiva et al. 2015, Kemper et al. 2016).

In Arctic and sub-Arctic regions, the effectiveness of traditional survey methods can be severely limited by cold temperatures, strong winds, and seasonally low light levels. Such environmental conditions also place limitations on UAV surveys. While UAVs as a survey platform may reduce the effect of observer bias in the data collection phase (ability to detect an animal given it is available for detection), the behavior of the animals and the probability of detection in post-survey analyses still pose some challenges. Therefore, in this study we addressed the role of such factors on the reliability of detecting humpback, killer whales and harbor porpoises in UAV images.

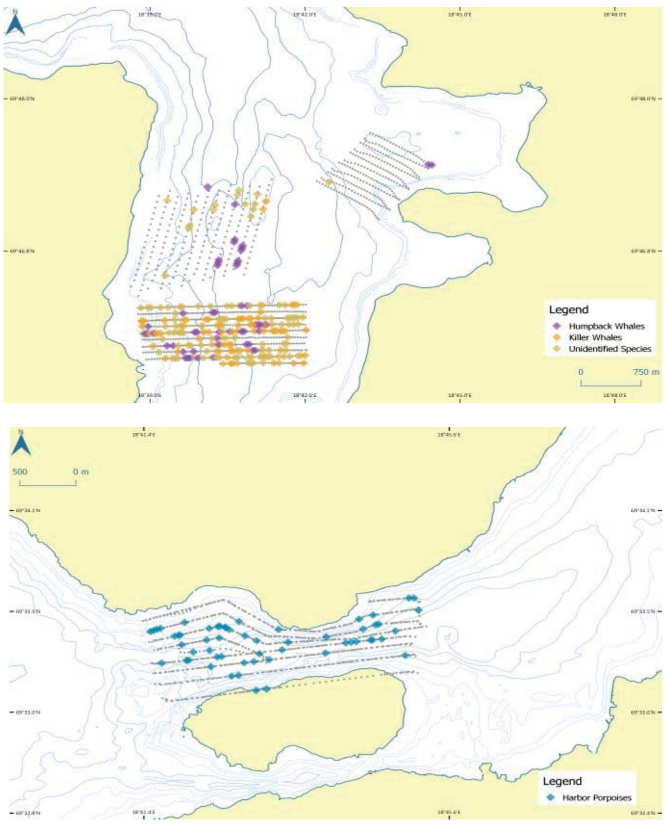

Figure 7. Detections of humpback and killer whales (top) in Kaldfjord, and harbor porpoises (bottom) in Rystraumen.

The results from our 12 UAV missions in 2014-15 show that both humpback and killer whales in Kaldfjord can be detected during the polar night using UAV technology (figure 7). Despite their small size, harbor porpoise sightings were recorded in Rystraumen during the summer trials. The numbers of sightings recorded indicated that there was a strong variability between survey flights, possibly due to the animals' natural behavior.

Concerning the effect image and aircraft-related variables on detection certainty, we observed contrasting results between the two survey sites. Water turbulence, luminance, and glare were not found to have a statistically significant effect on detections of harbor porpoises (figure 8). In Kaldfjord, however, we observed that the certainty of detecting humpback and killer whales was affected by water turbulence and luminance (figure 8). This was anticipated, given that in the polar night it is difficult to identify objects at or near the sea surface. Although there was a large range in pixel size (figure 8), results from both locations show that the effect of pixel size was not significant.

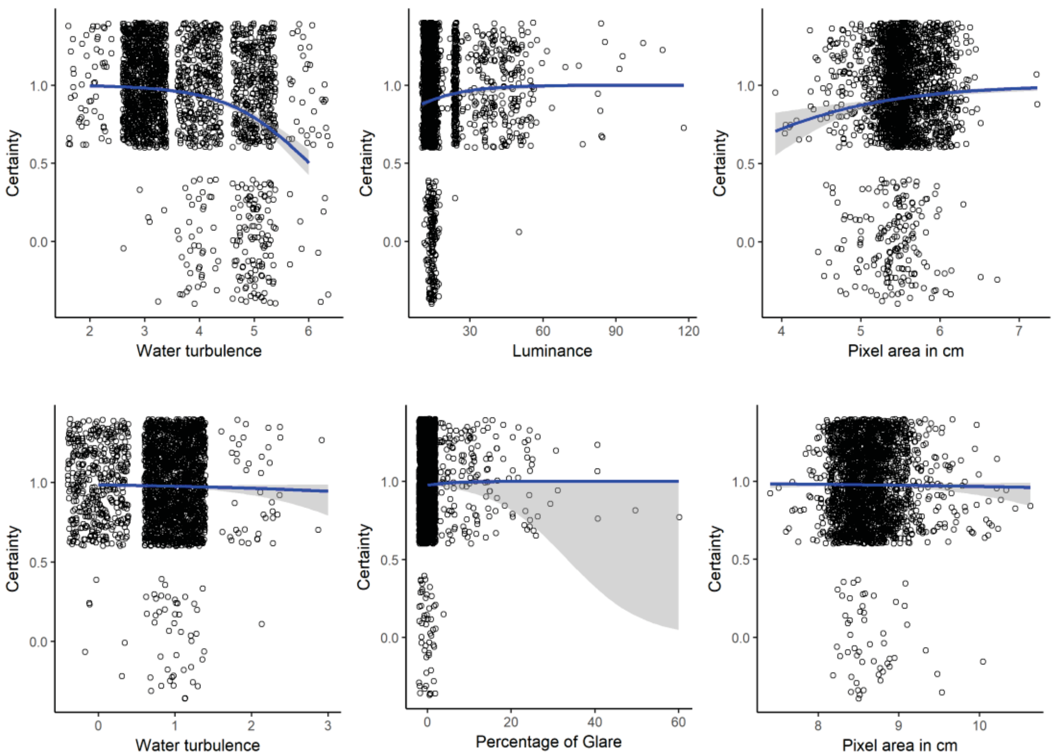

Figure 8. Image classification for the entire dataset of Kaldfjord (top) and Rystraumen (bottom), with the variables as function of certainty (0: Uncertain, 1: Certain).

The results from Rystraumen are based on a relatively small number of certain sightings, and we believe that this was the main reason for the lack of statistical significance in our results. For the effects of pixel size, the results may be explained by the fact that most of the observations fell within a relatively narrow range, while the overall range was inflated by the presence of a relatively small number of outliers (e.g., figures 8 and 9).

Our results show that UAVs, as a digital sampling platform, are affected by environmental covariates as other survey methods. Even though we did not find any significance in pixel area, for estimates of resolution required for animal detection and species identification it is still important to take special care for changes in aircraft stability that may affect it.

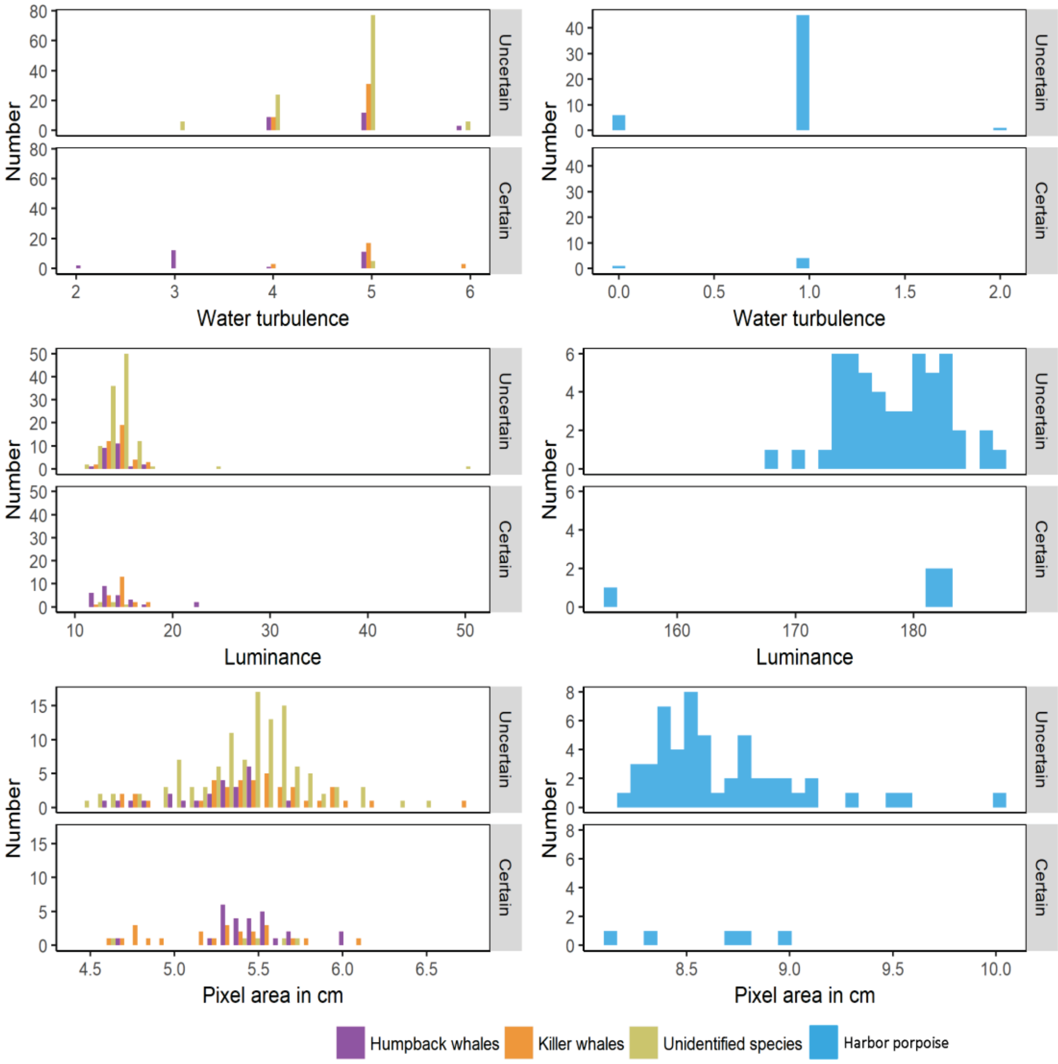

Figure 9. Animal detections for each variable considered in the model in both survey locations (Kaldfjord: left and Rystraumen: right).

5.3. Multiple aircraft and effects of survey design on detectability

Undercounting animals from aircraft represents an estimation problem for both visual and photographic aerial surveys (Caughley 1974, Williams et al. 2017). Aerial images can reduce perception bias, but not necessarily availability bias (Bayliss and Yeomans 1990, Williams et al. 2017).

One of the principal methods for estimating availability in aerial surveys is to use multiple aircraft in tandem, where observers in each aircraft count animals independently (Hiby and Lovell 1998). Using aircraft in tandem is twice as expensive as using single aircraft, and transects might not overlap due to error in GPS locations and misaligned flight paths. Further, methods for using aircraft in tandem have relied on identifying individual animals (i.e. duplicates seen by each aircraft) which is often problematic (Hiby and Lovell 1998, Borchers and Langrock 2015, Williams et al. 2017). UAVs may overcome these limitations, as they are more likely to maintain flight tracks and, depending on the system deployed, cheaper to operate. Therefore, we used a design-based method as an example of field sampling where the survey design is controlled and followed by a design-based analysis. Behavioral data collected from seven data-loggers was included to provide a realistic setting of humpback whale movement in foraging grounds in fjord systems. We assessed whale movement to define strip-transect designs following standard aerial survey methods, and investigated the effect of different simulated time lags between two aircrafts on the number of detections recorded. A total of 1000 simulations were conducted for each individual tagged animal present in Kaldfjord (figure 4). The majority of the recordings showed that the whales tended to move in a North-South direction, which led us to place transects perpendicularly to this trend (i.e., East-West).

The underlying assumption behind this analysis is that the temporal dynamics in the detections as a function of time lags between flights is related to the whales diving cycle. Figure 10 shows the temporal dynamics in detections, as a function of time lags between two flights (every minute for a maximum lag of 60 minutes), in seven humpback whales. The results show that there is a large variation in detection numbers and diving cycles between the whales

This indicates that even in regions where animals may behave similarly, such as foraging hotspots, strong variation may occur which should be taken into account in survey planning. To further explore the cyclic behavior of the detections, time series analyses using a frequency domain method for spectral density estimation were conducted. For this, a Thomson multitaper method (Thomson 1982) was used to estimate the power spectrum of the periodic signals (the analysis process is described in figure 11). This showed peaks of periodicity for detections of each animal ranging from 2.9 to 9.85 (mean 5.863) (e.g., figure 11). The same analysis for the whales' dive cycles resulted in peaks of periodicity between 2.0 and 9.14 (mean 5.409), indicating that a flight interval of 5 minutes would be the most adequate for maximizing detection rates. Correlation test between the periodicity of detections and dive cycle showed a non-significant correlation (e.g., figure 12). Nevertheless, these results demonstrate the importance of implementing prior knowledge on species behavior into survey planning. Particularly, the diving behavior of the target species should be considered when modifying the interval between flights to maximize the number of detections recorded.

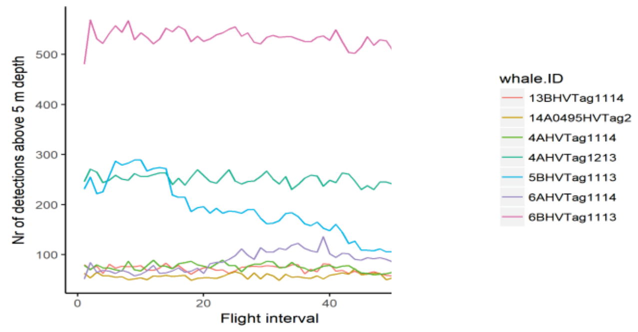

Figure 10. Detections for each humpback whale obtained by two simulated UAVs at time lags of one minute up to a maximum of 60 minutes between aircrafts.

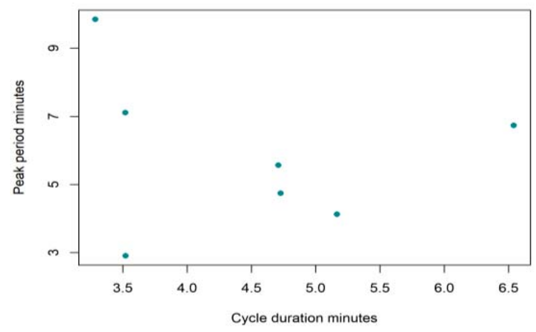

Figure 12. Period peaks for whale detections as a function of period peaks in dive cycle duration.

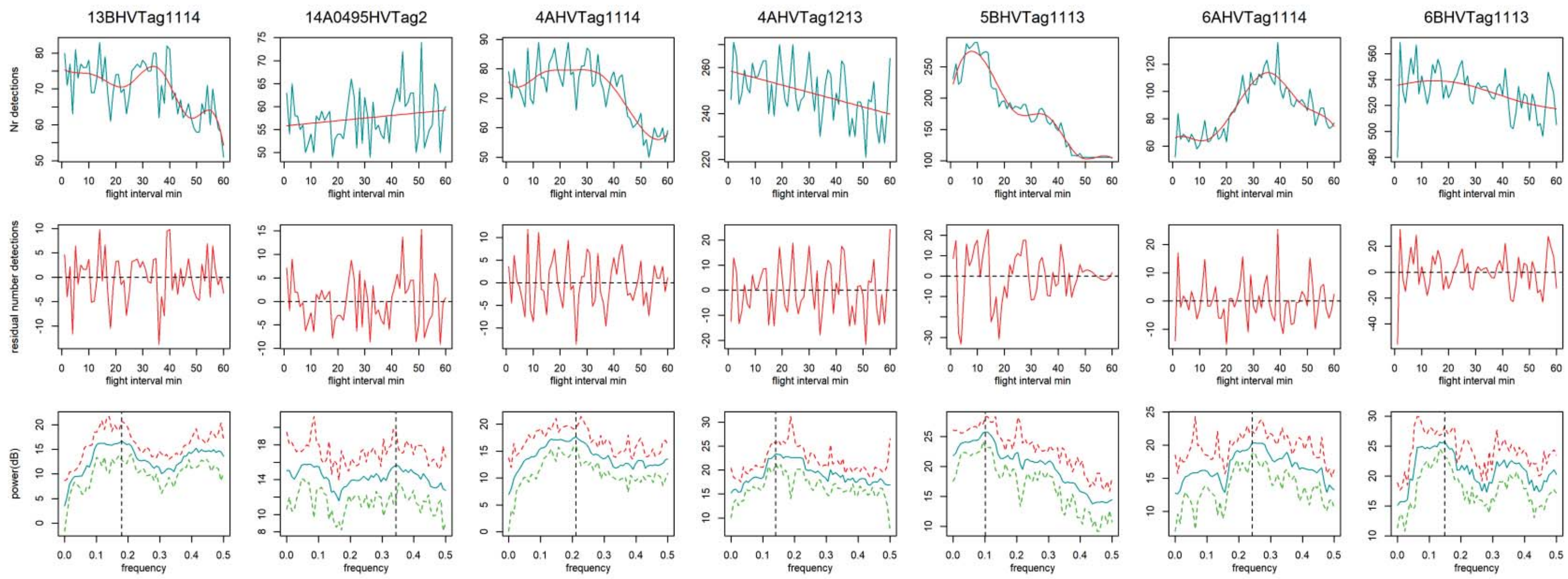

Figure 11. Multitaper analysis process for whale detections provided by the UAVs. Top: Detections for each tagged animal fitted with a smooth curve. Middle: Residual detections, from a smoothing spline. Bottom: Multitaper spectrogram with jackknifed confidence intervals (at the 95% level, marked in green and red) with peak frequency (Hz) marked with vertical dashed line.

6. Synthesis

Autonomous technology is continuously evolving as new complementary tools and applications are discovered and evaluated. The technological progress in autonomous aerial, underwater, and surface vehicles has allowed for different categorization of the various platforms and sensors, which may in turn assist in the collection of data valuable for monitoring purposes. Three monitoring categories were defined in this study: population, mitigation, and focal monitoring. Aerial, underwater, and surface vehicles will ultimately have different capabilities due to the sensors that they can carry and the endurance of the platform/vehicle.

Due to the nature of the data required, population surveys generally need systems with high endurance capabilities. This is a major benefit of self-powered underwater and surface vehicles, though these are sensitive to environmental conditions, particularly ocean currents. Long-term deployment is not a requirement for mitigation or focal monitoring (i.e., monitoring the behavior of the animals), which demand real-time detection and tracking abilities, respectively. In this case, only surface or aerial systems are currently suitable. The process of detecting an animal using these platforms will depend mainly on the target species, which may require different onboard sensors. The number of considerations required when designing individual, population, and mitigation-monitoring surveys can therefore be quite large, though mainly depend on survey objectives and cost-benefit trade-offs. It is, for these reasons, advised that surveys should be designed for particular regions specifically to suit the problems associated with each region, the expected type of species present, causes of behavioral disturbance, and distance from land. Overall, there is no one-fits-all autonomous system solution for marine animal monitoring, and the combination of platform and sensor should be made considering market options for off-shelf/ready-made systems and manual assembly.

Beyond the comprehension of the currently available autonomous systems, one should consider carefully the quality of the data that is required. UAVs and associated developing technologies have the potential to improve on data reliability compared to manned aircraft (recording visual observations) in marine fauna surveys, as they are able to remove much of the observer bias and can reduce perception biases. The use of digital sensors rather than relying on human observers to detect and identify species is in itself an improvement over traditional methods. However, it is still necessary to understand the effects of environmental and technical factors on data acquisition that may affect perception bias from an analyst standpoint. Marine mammal surveys generally consider sea state effects on the Beaufort scale, glare, and visibility, as measures that can bias estimates. In UAV surveys, these effects may also occur but will depend on a variety of factors that not only depend on analyst assessment qualities, but also on the sensors deployed onboard the aircraft. The environmental factors considered in this study include water turbulence, luminance (winter surveys during the polar night), and glare (summer surveys). Water turbulence and luminance were found to have a significant effect on certainty of detections of humpback and killer whales. The same was not observed for harbor porpoises, though lack of variance in the levels encountered and in animal detections appears to be the leading cause. Moreover, for accurate classification and species identification, adequate image resolution is a requirement for any digital survey. Changes in pixel size derived from aircraft movement (particularly changes in pitch and roll) represent another consideration when assessing sensor and platform suitability. None of the surveys conducted reflected significant changes in pixel area that could affect certainty of detections. Nevertheless, variations in pixel size are an important measure to consider when planning and analysing data from digital surveys, since it can provide detailed information that would not be otherwise acquired using other parameters in isolation. Developments in imagery systems and post-processing image correction algorithms may reduce surface optical distortion and provide clearer images, while also improving current sightability errors and limitations. Therefore, empirical testing of UAVs and associated technologies aimed at increasing sampling and post-processing efficiencies, and reducing sightability errors will ultimately enable UAVs to deliver efficient and reliable marine aerial survey data (Colefax et al. 2017).

For the analysis of abundance and distribution, a key issue is detectability. This study used photo reviewer certainty as a response, as opposed to other possible measures of detectability (i.e. comparing count rates, or independent observation from another platform). Often, standard detectability is evaluated based on animal habitat preference, which is difficult to compare between studies and when other platforms are used. Detectability certainty measured in UAV images was therefore included as a proxy for actual detectability. Certainty and detectability may be correlated, but could react to covariates differently. For instance, as photo detectability certainty is conditional on a potential sighting being made, there will be unknown numbers of animals that would have been missed completely which are not considered in the certainty metric. These two concepts should not be confused with one another, but seen as complementary. Even though observer detectability may remain the same, under different environmental conditions, certainty may be reduced and therefore should be included as a metric in future surveys. The probability of detecting an animal on the transect line, or in this case within an image, may depend not only on the environmental and aircraft features, but also on the probability of an animal being available for detection (availability). During manned aerial surveys, the deployment of multiple aircraft is generally connected to estimates of animal availability and group size. Aircrafts follow the same track line in tandem or a single aircraft is used that can then circle back on the track (the “race-track” method) (Hiby and Lovell 1998, Hiby 1999). In the case of UAVs, a single aircraft is capable of conducting both tasks by either using image overlap or by locking the target animal/group's position and loitering. However, this would require long battery life and large data storage capacity, and real-time data transmission. The deployment of multiple UAVs can therefore provide a cheaper and valuable alternative. Still, even though data acquisition and technology reliability may be underway understood, issues concerning animal movement and availability measurements remain a challenge.

The positioning of the transect lines may affect the probability of double counting. During manned-surveys, line-transects are generally positioned perpendicular to the shoreline and the expected natural swimming direction of the animals to minimize this effect and obtain uniform coverage of the survey area (Buckland et al. 2001, Strindberg and Buckland 2004, Hodgson et al. 2017). Often, the assessment of animal movement is not validated, particularly in complex survey regions, and therefore it is important to consider it in survey planning. Humpback whale movement trends were calculated and used to define the tracks that were to be flown by two simulated UAVs. Additionally, the telemetry data was used in the analyses to provide a realistic setting of humpback whale diving behavior in foraging grounds in fjord systems. This allowed for an assessment of the effect of different simulated time delays between the two aircrafts on the number of detections recorded.

Unmanned aircraft synchronization to determine the validity of their abilities is a field of investigation that is expected to gain more recognition as onboard systems are further developed. To achieve maximum detection rates in UAV surveys, the deployment of multiple aircrafts should take place to ensure that the animals are detected in at least one of the vehicles. This would imply an approximation to a time interval that corresponds to half duration time of a dive. The variability in detections between the time delays appeared to be associated with humpback whale diving cycles, where higher detections at a particular time lag represented extended periods at the surface. Analyses of individual diving cycle and detection frequencies showed that, on average, the time interval between the two aircrafts should be 5 minutes. However, it is important to note that an animal's behavior does not remain constant since the effect of environmental traits on an animal's preference will largely depend on its biological requirements. Thus, it is necessary to acquire prior knowledge of the movement patterns in order to determine the adequacy of survey methods and resulting availability estimates. In this study, simulations were conducted individually for each tagged animal, and resulted in a variety of detections throughout the surveys. Though the number of detections within each simulation (out of 1000) was not taken into account, such detail should be included in further UAV survey planning efforts. Understanding of animal behavior may assist in estimates of double counting, which is often not considered an issue as long as transects are placed perpendicularly to trends of movement and the platform speed is higher than the animals'. The correlation in the resulting detections with diving cycles show that this could be an issue, and should be further explored.

This study has proven that UAVs have many useful qualities over traditional methods which, when combining empirical and simulation studies can become a valuable asset in planning and conducting digital surveys.

7. Remarks and conclusion

Marine mammal surveys can be logistically demanding and expensive, particularly in remote or large study areas. Knowledge on new technological developments and analysis tools are therefore imperative to ensure the effective use of autonomous systems. These systems will likely become increasingly popular in ecological research, as technological improvements allow for long-distance, accurate trajectories and diverse payloads (Christie et al. 2016). Thus, autonomous systems provide an opportunity to improve estimates of the status of marine mammal populations, as long as researchers adapt survey methodologies and analysis techniques to suit this new technology.

UAVs may be more efficient in acquiring data given their survey planning software and the need for less resources for deployment (with possibly the exception of larger systems that require a team of experts to conduct the same tasks). However, the effectiveness of UAVs in replicating results obtained by traditional surveys of wildlife is currently being debated, and the accuracy and precision of UAS-derived population estimates is being tested. Therefore, further assessments and studies should be made before UAVs' efficiency and efficacy can be fully understood. These include issues related to field deployments and considerations for the acquisition of data from UAV imagery, and how to process the acquired data.

7.1 Sampling remarks

The permanent record of digital imagery originating from ecological or wildlife surveys provides an objective, enduring record of the organism of interest for future reference, data sharing, and further analysis (Christie et al. 2016). Processing of large amounts of digital photos, video, and other remote-sensing data from UAV surveys often require a substantial time investment for data organizating and processing. Additionally, image analysis will often rely on the expertise and training of analysts. Research investment into the development of image analysis and auto-recognition software is beginning to improve UAV post-processing efficacy (Schoonmaker et al. 2011, Colefax et al. 2017, Seymour et al. 2017) which, together with alternative sensors such as thermal infrared imagery, can facilitate animal detection (Gonzalez et al. 2016, Seymour et al. 2017).

Environmental conditions may affect image quality even when measures are taken to operate in favorable settings. It is therefore advisable, to collect all information available representing environmental effects within images or video. No surveys were conducted at wind speeds higher than 7 m/s in the field study (paper II). However, there were found large variations in the pixel sizes obtained from changes in aircraft altitude, pitch and roll. Image overlap may help validate sightings (Hodgson et al. 2013, 2017) when external factors to the survey are expected to have an effect on detectability, though it may require larger data storage and battery capacities. The amount of overlap chosen is subjective, and can also be used to increase detectability of species that do not spend a large proportion of time at the surface and to improve group size estimates. Therefore, there should be a clear link between decisions made concerning the amount of overlap and survey method chosen, and species behavior, since for abundance estimates it can influence on data analyses.

In the simulated study (paper III), the survey areas were centered to the distribution of each animal. The focus was on improving detection rates rather than evaluating the UAV's potential for providing accurate abundance estimates, which often requires uniform and random coverage of the survey area. Too much effort in nearshore strata can hurt the quality of inference when quantifying the abundance of Arctic marine mammals in sea-ice environments Conn et al. (2016). This is another issue that should be taken into account when planning future surveys for estimates of animal abundance.

7.2 Data analysis remarks

Image overlap may lead spatial to autocorrelation in animal abundance estimates. It can lead to low variance between close observations and higher standard errors of mean estimates, which will affect significance levels in parametric statistical models (Ferguson and Bester 2002). Efforts should be made to incorporate these effects in statistical analyses. Few studies have shown how to integrate spatial autocorrelation in digital surveys (e.g., (Salberg et al. 2009, Paiva et al. 2015, Conn et al. 2016). Given the nature of the data sampled during field deployments, this was not found to represent an issue for certainty of detections. In the time series obtained from simulated flights, the correlation with animal behavior was clear, though the number of double counts for each animal was not under focus. Nevertheless, it is important to take into consideration the possible effects of autocorrelation in estimates of abundance resulting from digital surveys with overlapping imagery. Also, when replicating surveys, the probability of detecting animals may change between survey periods, and should be assessed accordingly. This is particularly relevant for highly social species, where swimming synchronization may occur. For species where this probability is not likely to change through time, pilot studies could be conducted to examine availability bias, and then used as an informative prior distribution for future aerial surveys, precluding the necessity to conduct replicate surveys during each sampling period (Williams et al. 2017).

Overall, the work presented here provides critical factors to be considered when planning marine surveys using autonomous aerial systems as the main source of marine mammal data collection. This study shows that UAV technology can be used to monitor sea mammals of a variety of sizes. For UAV deployments, some considerations should be made following standard practice for aerial surveys while having in mind the specifications of the equipment at hand. Particularly at high latitudes, whether during summer or winter, environmental and biological context can be limiting, and should be incorporated into survey planning and data analyses.

"We are stuck with technology when what we really want is just stuff that works."

- *Douglas Adams*

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PAPERS

Understanding the current state of autonomous technologies to improve/expand observation and detection of marine species

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Monitoring marine mammals using unmanned aerial vehicles (UAVs): quantifying detection certainty

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Unmanned aerial vehicles in whale research: using multiple aircraft

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