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Drones and marine mammals in Svalbard

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BIO-3950 Master's thesis in Biology - Marine Ecology and Resource Biology
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Foreword

Two years ago, I started this adventure filled with enthusiasm but with very limited knowledge on drones, marine mammals and most of the technical aspects that this project has involved. This turned the following months into a succession of challenges that I have overcome with the support and advice of many people to whom I am unquestionably grateful.

Firstly, I am thankful to my supervisors at the Norwegian Polar Institute for involving me in this project that blends my strong interest in management-applicable science with the fascination for marine mammals in a remarkable way. To make it an even greater experience, joining the fieldwork taught me invaluable lessons including the immense effort behind every number collected in the field, the importance of improvising a fourth plan when the first three options are shattered, and even methods to successfully undergo a week in a bear-proof box, under reindeer siege. Thank you for such a great opportunity.

I am especially grateful to Andy for leading me down this path while giving me enough space to practice scary critical thinking, and for all the transmitted know-how from setting appropriate study designs to selecting the best wine in the high-Arctic. I am also grateful to Kit and Christian for providing me with vast knowledge on our study species and invaluable support during the writing of this thesis; and to Rolf A. Ims for providing helpful comments on my drafts.

Many thanks to the people at the Biodiversity section at NP for the support shown in the last months, especially to Jade and Heidi, who have tirelessly made their expertise on statistics and acoustics, as well as a great deal of patience, available to me. Your help is much appreciated. To "La Caixa" foundation for providing the funding that made this experience possible through their graduate scholarship programme, and to Claes Lindqvist for putting the cherry on the cake with the great artwork on the cover.

I am also unduly grateful to my office fellow students and friends from all the kitchens where I have cooked in Tromsø, for supporting each other during this "two polar nights and a master's thesis" show and for sharing frustrations, hope and ultimately happiness. Finally, my parents, brother and Gui deserve the biggest thank you for having gone through unlimited complaints and having always replied with love and unconditional support.

This path has been as challenging as gratifying, and surely possible thanks to all of you.

Tromsø, July 2019
Albert Palomino Gonzalez

Abstract

The impact of Remote Piloted Aircraft Systems (RPAS, or drones) on marine mammals remains poorly documented despite their increasing use by hobbyists and scientists. In the High-Arctic Archipelago of Svalbard, where marine mammals are facing increasing pressure from the coupled effects of climate modification and an expanding tourism industry, the use of RPAS remains largely unregulated to date. In this study we assessed the impacts of RPAS on marine mammals, conducting experimental flights to provide science-based management advice. Our novel approach included RPAS in a range of sizes and different approach strategies, and it accounted for RPAS sound levels as well as animal behaviour prior to and after RPAS flights. Harbour seals were more sensitive during pre-breeding, reacting at distances of 80 m, than during moulting. Walruses responded at distances of 50 m. Pre-experimental levels of alertness increased sensitivity to RPAS disturbance notably. Polar bears reacted to the sound of RPAS during take-off at 300 m, although response levels were relatively low and remained so even at 60 m. Belugas reacted only visually to RPAS, when flying ahead of the pod below 15 m. Our study highlights a range of factors that can influence sensitivity to RPAS including tidal state and swell, the presence of young individuals, ambient noise levels and RPAS approach strategy. Large variations in sound levels during overhead descents and other manual flights increase RPAS disturbance potential to a greater extent than RPAS size when flying pre-programmed profiles. Physiological state and levels of alertness prior to experimentation also affected RPAS disturbance potential. We provide empirically-derived flight distances that can help management authorities establish guidelines for the use of RPAS in Svalbard.

Keywords: behaviour, distance threshold, disturbance, drone, haul-out, marine mammals, remotely piloted aircraft system (RPAS).

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1 Introduction

The recent and continued development of Remotely Piloted Aerial Systems (RPAS, or drones) has led to a rapid increase in their use by the scientific community, with researchers taking advantage of their unprecedented capabilities to film animals and landscapes (Shahbazi, Théau, and Ménard 2014). RPAS are especially useful in intermediate scale applications, when surveying particularly sensitive or aggressive species and their habitats, or to obtain observations of places that would otherwise be hard to reach (Chabot and Bird 2015). Given the rapid increase in the use of RPAS and the limited knowledge of their potential impacts on wildlife, Hodgson and Koh (2016) developed a series of guidelines for the operation of RPAS in proximity to animals. These guidelines follow a precautionary principle in order to minimize impacts, and the authors encourage researchers to report disturbance observations in their studies as well as developing experimental setups to quantify disturbance as a means for providing science-based management of these new technologies (Christie et al. 2016; Hodgson and Koh 2016).

The development in RPAS technology has benefited marine mammal research programmes, as inexpensive aircrafts improve observation capacities and make medium-scale surveys more affordable (Koski et al. 2009). Studies using RPAS have started to explore whether disturbance occurs during field operations; some, few responses from cetaceans have been reported (Domínguez-Sánchez et al. 2018). RPAS disturbances of pinniped species have also been reported in the literature (see Moreland et al. 2015; Sweeney et al. 2016; Krause et al. 2017; Arona et al. 2018), although experiments which specifically aim to assess disturbance thresholds (Pomeroy et al. 2015) are still scarce.

In the high-Arctic Archipelago of Svalbard, RPAS usage has dramatically increased as a consequence of rapid increases in tourism (Viken 2011; Viken and Jørgensen 1998) and increases in scientific research activities (Aksnes and Rørstad 2015; Misund et al. 2017). These increases in human traffic and use of RPAS brings up the question as to how strictly regulated RPAS use should be, given the concerns for nature conservation laid out in the Svalbard treaty (Svalbard Treaty - Article 2, in Miljøverndepartementet 1994-1995: 29). To date, RPAS are not subject to the same restrictions as manned aircrafts, which are not allowed to fly closer than one nautical mile from large concentrations of mammals or birds (Svalbard Environmental Protection Act - Act of 15 June 2001 No. 79). RPAS are current subject only to regulations regarding flight distances from airports, buildings or people (Section 51 on FOR-2015-11-30-

1404 by the Norwegian Civil Aviation Authority). This leaves a gap on flying restrictions over wildlife, which is only vaguely resolved by section 73 on the Svalbard Environmental Protection Act - Act of 15 June 2001 No. 79, which states that activities in Svalbard should not impact the environment or disturb wildlife unnecessarily. For recreational use, this grey zone has been generally resolved via a ban on the use of RPAS by some tour companies. Scientific use, however, remains theoretically unconstrained, although all fieldwork requires a permit issued by the Governor of Svalbard. Some countries within the Arctic, including Canada and the United States, have similar situations. Both countries have regulated the use of RPAS more generally near people, in cities and National Parks, but no clear guidelines regulate the flight of RPAS over wildlife outside protected areas. However, as in Svalbard, specific permits are requested to fly RPAS over marine mammals for scientific research, which are issued by institutions such as the Species at Risk Management Division (SARMD) in Canada and the National Oceanic and Atmospheric Administration (NOAA) in the United States.

1.1 RPAS acoustic characterisation

The recent increase in the use of RPAS in research has resulted in rising concern regarding the impacts that they can potentially pose to wildlife (Christie et al. 2016; Hodgson and Koh 2016). Smith et al. (2016) concluded that both visual and acoustic stimuli could be important in causing impacts on marine mammals and created a check-list for RPAS disturbance potentials, which included the acoustic characteristics of the area (e.g. background noise level) and of the RPAS (e.g. received sound level). However, acoustic recordings have not been undertaken in the field in association with the use of RPAS (Krause et al. 2017; Moreland et al. 2015; Pomeroy et al. 2015; Sweeney et al. 2016).

To address this gap in knowledge there have been attempts to assess potential acoustic impact of RPAS to wildlife in several experimental set-ups. Goebel et al. (2015) measured the sound level received from an APH-22 hexacopter (Aerial Imaging Solutions, LLC., Old Lyme, CT,USA) hovering at altitudes and horizontal distance levels ranging from 0 to 90m and compared it to sound levels from a penguin colony, concluding that the sound from the RPAS would likely be masked by that of the colony. Scobie and Hugenholtz (2016) measured sound levels received at 1.5 m from a SkyRanger quadcopter (Aeryon Labs, Inc., Waterloo, ON, Canada) and a fixed-wing eBee (Sensefly Ltd., Cheseaux-sur-Lausanne, Vaud, Switzerland) and compared it to the hearing thresholds of five different species, concluding that all would detect the RPAS at distances greater than 200 m without considering the effects of ambient noise. Christiansen et al. (2016) measured sound levels received on land and underwater from

a SwellPro Splashdrone (Swellpro Technology Co.,Ltd, ShenZhen, Guangdong, China) and a DJI Inspire 1 Pro (DJI Technology Co., Ltd., ShenZhen, Guangdong, China) hovering at a range of altitudes between 5 and 40 m, and concluded that acoustic impact is highly unlikely underwater unless RPAS are flown below 10 m, due to masking effect from ambient noise, but that impact is likely for animals happening on land. These conclusions support the importance of the effect of ambient sound level, although paradoxically it is rarely measured in the field.

Additionally, existing acoustic characterisations overlook an important factor by measuring sound levels emitted by RPAS fixed on a platform or hovering still: scientific use of RPAS generally involves displacing aircrafts around a specific area in order to map, record or count individuals of a species and/or their habitat (Koh and Wich 2012; Sweeney et al. 2016; Chabot and Bird 2015 and references therein), and sound produced by RPAS in movement may differ from that emitted when hovering still. Arona et al. (2018) concluded that the sound emitted by a small fixed-wing RPAS surveying a grey seal (*Halichoerus grypus*) haul-out at 80m was equivalent to ambient sound level in that environment, but different RPAS models have varying sound profile characteristics and may therefore have different effects on the animals being overflown (Pomeroy et al. 2015). In fact, sudden changes in altitude or trajectory cause increases in sound levels on multi-rotor RPAS, which have been reported to cause disturbance on Steller's sea lion (*Eumetopias jubatus*) colonies (Sweeney et al. 2016).

1.2 Study species

Two pinnipeds species were the principal subjects of this study, harbour seals (*Phoca vitulina vitulina*) and Atlantic walruses (*Odobenus rosmarus rosmarus)*, because of the high predictability of their haul-out areas.

Harbour seals are the most wide-ranging pinniped species, and Svalbard hosts the northernmost population (Prestrud and Gjertz 1990), which consists of about 2,000 individuals. The highest concentrations of animals are found around Prins Karls Forland, on the west coast of Spitsbergen (Prestrud and Gjertz 1990). In summer, their haul-out behaviour patterns are similar to those in populations from temperate areas, following both circadian and tidal cycle patterns, with numbers at colonies being highest when conditions are warm, dry and calm (Reder et al. 2003). Studies from other populations show that they are susceptible to impacts of human activity, the effect of which are well documented and can range from short-term fleeing events caused by boat traffic or humans walking (Allen et al. 1984; Brasseur 1993) or displacements at sea during construction activities (Russell et al. 2016), to spatial or temporal

shifts in their haul-out patterns in a seasonal scale with regular human activity (Henry and Hammill 2001; London et al. 2012), which can in the extreme lead to permanent abandonment of haul-out areas (Newby 1973).

RPAS impact assessments were also conducted on Atlantic walruses, which in Svalbard belong to a population shared with Franz-Josef Land, Russia (Andersen et al. 1998). There are 91 established terrestrial haul-outs around the Svalbard Archipelago (Kovacs et al. 2014), most of which consist of males only (Gjertz and Wiig 1995; Wiig et al. 1996). Recent surveys have found an increasing proportion of females and calves in north-east Svalbard, following a recovery of thins population previously hunted almost to extinction (Kovacs et al. 2014). When hauled-out on land, walruses spend over 90% of the time resting and only a very small proportion of time active, either exhibiting comfort behaviours or agonistic interactions (Salter 1979). Aircraft overflights and approaches by polar bears cause disturbance at haul-outs more often than do motorboats (Øren et al. 2018; Salter 1979). Tourist visits to haul-outs in Svalbard do not cause disturbance, likely because walruses have been protected from human hunting since 1952 (Øren et al. 2018). When disturbed, walruses commonly respond by lifting their heads, although occasionally bolder responses are elicited, such as shifting positions or eventually fleeing. In large aggregations, fleeing events are known as "stampedes", which pose serious threats due to the risk of trampling young individuals. Stampedes and concomitant calf mortalities are documented for Pacific walruses *O.r. divergens* (Fischbach, Monson, and Jay 2009; Kochnev et al. 2008)), where potential population-level effects of these events have been suggested (Udevitz et al. 2013). As for harbour seals, long-term human disturbance can cause abandonments of walrus summering grounds (Salter 1979 and references therein).

This study also explored the potential impacts of RPAS on two other Arctic marine mammal species, known to be sensitive to human disturbance: the polar bear (*Ursus maritimus*) and white whales (*Delphinapterus leucas*) during opportunistic encounters given a lower predictability in their location.

Polar bears have a circumpolar distribution and a global population size in the order of 20,000-25,000 individuals (Obbard et al. 2010). Nineteen subpopulations are recognised, with bears at Svalbard belonging to the Barents Sea subpopulation. Numbers in the Norwegian part of this population have increased since the hunting prohibition in 1973 (Derocher 2005), with the latest estimates around 973 individuals (Aars et al. 2017). Polar bears now face new threats such as ongoing sea ice declines due to global warming, which in the Barents Sea is occurring at a rate 2-4 x faster than in other Arctic areas (Laidre et al. 2015). In addition, increased tourism and

commercial activities in Svalbard could pose additional threats to polar bears via increasing encounters through human activities including wildlife-watching, snowmobile traffic and ice-breakers (Dyck and Baydack 2004; Andersen and Aars 2008; Smultea et al. 2016). Reactions to disturbances of polar bears are commonly reported as an increase in vigilance level, although factors such as sex and presence of cubs are known to influence the strength of the responses. Andersen and Aars (2008) found detection and fleeing distances were over 1 km in response to snowmobiles and suggested that such distances can be so long that disturbance would remain unnoticed by the drivers of the vehicles. For polar bears, even initiating walk is energetically expensive (Watts et al. 1991) and thus human activity can have detrimental effects, especially during the times of the year when saving energy is critical (Derocher and Stirling 1990).

Potential RPAS disturbance was also tested on white whales, or beluga whales. This species inhabits Arctic and subarctic waters, have a highly coastal distribution pattern and generally very little dispersal between different sub-populations (De March, Maiers, and Friesen 2002; O'corry-Crowe 2009). Some populations perform long-distance migrations (Suydam et al. 2001), whereas others, such as the population in Svalbard, have a very local distribution (Lydersen et al. 2001). In summer and autumn, white whales in Svalbard exhibit extremely coastal movement patterns and spend most of their time around glacier fronts, which is likely due to higher prey availability in these areas (Lydersen et al. 2001). Human disturbances in these key areas could result in animals exhibiting increasing swimming speed, compaction of groups, prolonged intervals between surfacings and also the termination of feeding (Blane and Jaakson 1994), all of which can have an effect on their energy budget. Additional documented sources of disturbance include large boats at long distances (Finley et al. 1990) and aircrafts flying below 500 m (Richardson et al. 1995).

1.3 Objective

In this study we test the disturbance effects of RPAS on marine mammals in Svalbard, with the aim of providing science-based advice for the development of regulations on the use of RPAS regionally. Our objective was to characterise visual and acoustic disturbance produced by four commercially available Vertical Take-Off and Landing (VTOL) RPAS of different sizes. In order to build upon existing knowledge, we adopt a novel approach that accounts for animal behaviour prior and after RPAS flights, while testing different approach strategies and considering additional factors that can influence animal response. In addition, we provide acoustic characterisations of the RPAS used in disturbance experiments in order to account for variations in sound emission that were likely to occur when flying in the field.

2 Methods

2.1 RPAS disturbance experiments

2.1.1 Field data collection

We conducted fieldwork at two sites in Svalbard 1) Midtøya, in Forlandsøyane (78.34ºN, 11.57ºE), a small island located Southwest of Prins Karls Forland and (Figure 1) Sarstangen (78.73ºN 11.46ºE), a natural gravel spit coming off Spitsbergen into Forlandsundet (Figure 1). The sites were selected because they were predictable haul-out sites of harbour seals and walruses, respectively.

At Midtøya, we conducted experiments on harbour seals on the 18th and 19th of August in 2017 and from the 25th to the 29th of May in 2018, during the annual moult and the pre-breeding period, respectively. The haul-out area is a boulder beach, the exposed surface of which is dependent on tidal height. Occasionally the harbour seals haul out on an intertidal reef, which is highly affected by tidal state and swell intensity.

We launched the RPAS from an observation position 120 m away from the main hauled-out group and a Sony Handycam 4k video camera (Sony Electronics Inc., San Diego, CA, USA) was used to record the behaviour of the seals from ground level. Ambient noise was recorded with a Song Meter SM4 (Wildlife Acoustics, Inc., Maynard, MA, USA), that we placed 50 m away from the seals (during the first year of the study). We increased the distance in the second year to 120 m, since the seals were then distributed differently at the haul-out site, which precluded a closer approach to the seals. We measured the distances between the observers, the acoustic recorder and the seals using a Carl Zeiss laser rangefinder (ZEISS Victory RF 8x26 PRF MONO Laser Rangefinder; Carl Zeiss AG, Oberkochen, Germany). We started and ended both acoustic and video recordings 30 minutes either side of our flight operations, providing behavioural observations of seals before and after flights. We did flights when winds were under 6m/s and when there was no precipitation. We categorised swell into three categories following Demarchi (2012): none, low and medium-high. Tidal state varied between the days of the experiments (Figure 4). Mean Sea Level (MSL) tidal information was provided as corrected values from the nearest available meteorological station, in Ny-Ålesund (78.92ºN 11.90ºE), by the Norwegian Hydrographic Service, with a vertical resolution of 10 cm and a temporal resolution of 10 minutes.

We performed a total of 88 flights over the harbour seals during 4 sessions in 2017 and 5 sessions in 2018 (Table 1), obtaining 5 and 9.5 hours of ground recording, respectively in the two study years. Each flight comprised the period between a consecutive take-off and landing operations, and it generally included a single flight profile (Appendix E: Figure E). Individual flight profiles ranged in altitude from 120 m to 20 m, decreasing at 20 m intervals, with the centre of the haul-out as a reference point. We flew at 40 km/h since the RPAS record on a high enough resolution that allow for videos to be slowed down and still images retrieved even at that speed.
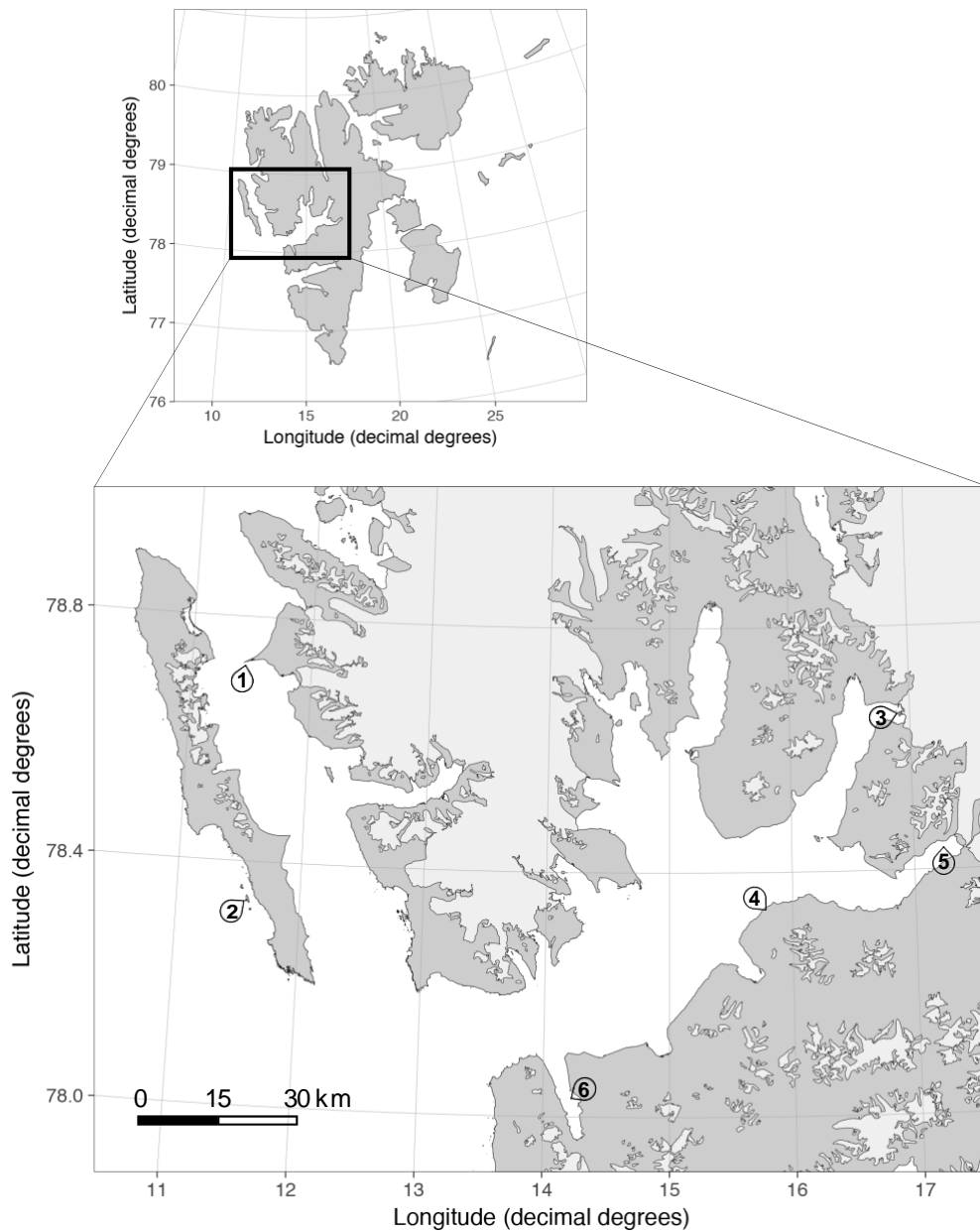

Figure 1. Sampling locations in Svalbard. We performed disturbance experiments on Atlantic walruses at Sarstangen (1) and harbour seals at Midtøya (2). Opportunistic sampling included flight tests on a female polar bear at Nordenskjöldbreen (3) and Deltaneset (4), and over two pods of white whales at Tempelfjorden (5) and Grønfjorden (6).

In addition, we followed four flight strategies that reflect different ways of approaching hauled out animals, in order to assess which causes the lowest level of disturbance. The flight strategies were: 1) Wide orbit, maintaining a minimum horizontal distance of 50 m (*Figure 2*); 2) Close orbit, maintaining a minimum of approximately 20 m in horizontal distance; 3) A direct, straight-line path from the operator crossing over the hauled out animals and ending approximately 50 m behind them (in Table 2, noted as an 'overflight' when the trajectory followed a straight line along the haul-out) and 4) Overhead descent from a maximum altitude of 120 m and ending when a fleeing response was elicited.
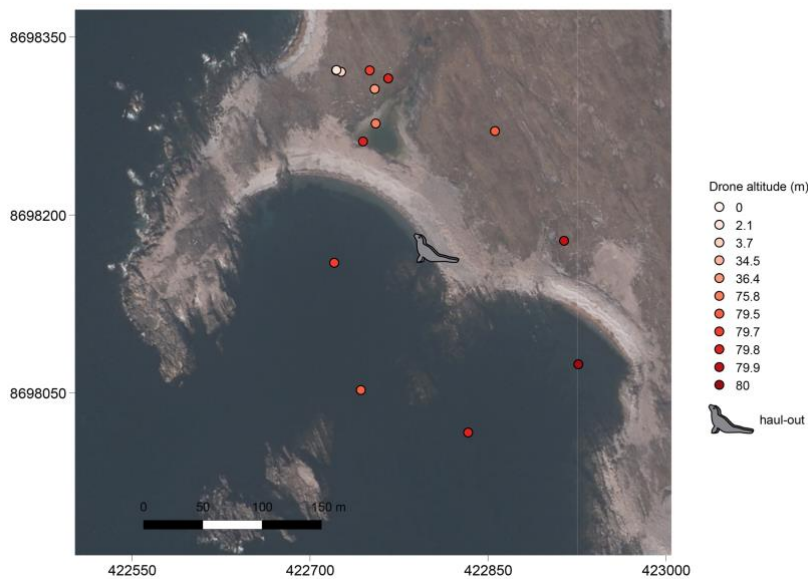

Figure 2. Example of a wide orbit profile flown at 80 m altitude over a harbour seal haul-out at Midtøya. The colour scale in the dots represents RPAS altitude, ranging from 0 at the take-off and landing point to roughly 80 m on most of the wide orbit profile. The haul-out location is represented by a seal in the centre of the flight profile.

The different RPAS models used were the DJI Inspire 2, the DJI Phantom 4 and the DJI Mavic Air (DJI™, Shenzhen, Guangdong, China; Figure 3; see specifications in Appendix A: Table A). Most wide loop and close loop profiles were pre-programmed using the Autopilot Hangar© application on an Ipad Pro 9.7" (Apple, Inc., Cupertino, CA, USA) and flown in auto-pilot mode in Visual Line of Sight (VLOS) in order to ensure repeatability across sessions. Pre-programmed flight profiles were set to maintain a constant altitude and speed and thus minimise the occurrence of abrupt moves that increase the noise signal of the aircraft (only wind gusts and occasional losses of GPS signal can cause disruptions in the trajectory).

Straight-line profiles were flown both as pre-programmed (N=12, ranging from 80 to 20 m altitude) and manual flights (N=21, ranging from 100 to 8 m altitude). All overhead descents were flown manually. In spite of the reduced stability of the trajectory in manual flights, they allowed for higher manoeuvrability and thus the possibility to fly more easily at low altitudes. Therefore, low altitude flights were generally done manually as well as segments of flights

towards the end of the flight sessions, when disturbance thresholds had not been reached with pre-programmed flights.

Figure 3. RPAS used in the study. From left to right: Inspire 2, Mavic Platinum, Mavic Air, Phantom 4 Pro.

Sampling on walruses took place in late August in 2017, because of predictable adult male aggregations at this time of year at Sarstangen. We followed a similar approach with our experiments to those employed for the harbour seals, deploying an acoustic recorder 25 m away from the aggregation and a ground camera at the operation point, 125 m away.

Altitudes, speeds and strategies of each flight profile closely followed those used for the harbour seals to simulate different drone approach strategies and to allow for comparisons across species. Over 2 sessions, we achieved a total of 39 flight profiles and 5+ hrs of ground video and acoustics. Environmental conditions and haul-out sizes are summarised in Table 1.

Table 1: Summary of flight sessions. Flights represents the total number of flights per session. The number of manual flights is shown in parentheses. Sea state was pooled into three categories: 1, flat; 2, low; and 3 for medium-high. Tide is expressed relative to the mean sea level, provided by the Norwegian hydrographic service as values corrected from the nearest station at Ny-Ålesund (78.92ºN 11.90ºE).

Date	Year	Species	Time	Season	Flights	UAS	Haul-out size	Sea state	Tide
18 Aug	2017	*P.vitulina*	am	moulting	6	Phantom 4	45	1	18 to 5
18 Aug	2017	*P.vitulina*	pm	moulting	7(1)	Phantom 4	72	1	-33 to -50
19 Aug	2017	*P.vitulina*	am	moulting	8	Phantom 4	90	1	-16 to 8
19 Aug	2017	*P.vitulina*	pm	moulting	6 (2)	Phantom 4	116	1	26 to 14
21 Aug	2017	*O.rosmarus*	pm	moulting	16 (3)	Phantom 4	13	2	41 to 55
22 Aug	2017	*O.rosmarus*	pm	moulting	15 (2)	Phantom 4	30	3	-18 to 54
25 May	2018	*P.vitulina*	am	breeding	15 (1)	Phantom 4	44	3	33 to 24
25 May	2018	*P.vitulina*	pm	breeding	9 (2)	Inspire 2, Mavic Air	55	1	-42 to -61
27 May	2018	*P.vitulina*	am	breeding	16 (1)	Phantom 4	14	3	5 to 36
28 May	2018	*P.vitulina*	am	breeding	8	Inspire 2	13	2	8 to 35
29 May	2018	*P.vitulina*	pm	breeding	14 (3)	Phantom 4, Mavic Air	47	2	14 to 40

Table 2. Summary of the profiles included in each flight over harbour seal and walrus haul-outs. Each cell contains the type of profile (wide stands for wide-orbit loops, close for close-orbit loops, descent are overhead descents, straight are straight-line profiles, and overflights are straight-line profiles performed purposely along the haul-out) together with the altitude at which it was flown. White cells are flights with Phantom 4 Pro, yellow cells with Inspire 2 and orange cells with Mavic Air.

| Flight # | Harbour seals | | | | | | | | | Walruses | |
| | Moulting season | | | | Pre-breeding season | | | | | | |
	18.8.17am	18.8.17pm	19.8.17am	19.8.17pm	25.5.18am	25.5.28pm	27.5.18	28.5.18	29.5.18	21.8.17	22.8.17
1	wide 100	wide 80	wide 100	close 40	wide 80	wide 80	wide 60	wide 40	close 20	wide 100	wide 60, 4x close 60
2	wide 120	wide 60	wide 80	close 30	wide 60	wide 40	wide 40	wide 40	close 10	straight 80-60-40	close 40
3	close 120	close 60	wide 60	close 30	wide 40	close 60	wide 40	wide 40	close 10	wide 60	close 20
4	close 100	close 40	wide 60	close 20	wide 20	close 40	wide 25	wide 20	close 40	close 60, 50, 40	close 60
5	close 80	close 30	close 100	straight 100-80-80-60-40	wide 80	wide 20	wide 40	close 20	close 20	close 80	close 40
6	close 60	close 30	close 80	descent 120-10, descent 100-20, overflight 20	wide 60	wide 10	close 40	wide 10	close 20	close 80	close 20
7		descent 120-30	close 60		wide 40	close 10	wide 40	close 10	close 20	close 60	straight 30
8		close 40			wide 20	close 10	wide 40	close 10	close 20	wide 40	straight 80
9					close 80	close 20	wide 40		wide 20	close 60	straight 60
10					close 60	descent 40-20, overflight 15	close 40		close 20	close 40	straight 40
11					close 40		close 50		close 20	close 20	straight 20
12					close 20		close 40		descent 100-30	straight 60	straight 60
13					close 40		close 20		descent 100-20, overflight 20-15	straight 50	straight 40
14					close 20		close 30		overflight 10-20-10-10-8-10-8, descent 10, overflight 10-20	straight 40	straight 20
15					descent 120-10		close 20			straight 30	descent 80-15-60-15
16						descent 100-20				descent 20-16	

10

2.1.2 Behavioural scoring

We used the video recordings from ground level to score the behaviour of harbour seals and walruses. We adopted a focal-following strategy (Altmann 1974) in order to capture variations in behaviour over the course of each flight session, i.e., between a pre-experimental control period, the flight experiments and a post-experimental period, which lasted between 1.5 to 2.5 hours (Appendix E: Figure E). We scored ten individuals across the haul-out or as many as were visible when fewer individuals were left. Focal individuals were chosen based on visibility. If we could not see them at a given moment, they were replaced by a different individual nearby. We kept walruses as focal individuals even if hidden within the haul-out, when it was clear that all the individuals were still and resting. We registered behaviour every ten seconds throughout each video, to obtain a fine scale register that could capture potential variation between the behaviour before, during and after the flight experiments.

We based behavioural categories on those used by Pomeroy et al. (2015), and complemented these with a category for comfort behaviour as in Kovacs (1987), to cover the whole spectrum of behaviour we observed. In total, seven different behavioural categories were defined:

1) Sleeping: an individual was considered to rest or sleep when it was still and had its eyes closed.

2) Comfort behaviour: when the individual was performing low intensity activities such as stretching and scratching with its flippers or against the ground.

3) Eyes open and/or head-up: it was considered when the individual kept its eyes open, possibly rising the head.

4) Side-to-side head moves: involved a higher degree of alertness, in which the individual moved the head sideways looking for any source of disturbance (related or not to RPAS flight operations).

5) Discomfort behaviour: when an individual remained highly alert while performing changes in position, excluding displacement, or other activities such as shuffling and intense scratching. Agonistic interactions with other individuals are also included in this category.

6) Locomotion: when the individual displaced itself around the aggregation or abandoned the haul-out without panicking.

7) Flee: considered to be when the individual left the haul-out in panic, individually or together with the group.

2.1.3 Calculation of RPAS-to-haul-out distances

Autopilot Hangar creates time-indexed data files of flight telemetry for each profile flown, which contain information about the aircraft and flight trajectory (summarised in Appendix B: Table B). The files were processed and the location of the RPAS (in coordinates) together with the altitude were selected for the specific seconds for which we had scored the behaviour of the animals. Horizontal distances between the RPAS and the haul-out were then calculated with the package sp (Pebesma and Bivand 2013) on RStudio version 3.4.0 (R Core Team 2017), after converting the coordinates in spatial points projected on the WGS84 datum. Subsequently, we used horizontal distance and altitude to calculate the real distance between the RPAS and haul-out using simple trigonometry.

2.1.4 Estimation of RPAS-to-haul-out distances on manual flights

Telemetry files are not available for manual flights, so we developed an indirect method to estimate RPAS-to-haul-out distances (*Distance*). First, on a set of flight videos for which telemetry distance values are available, we selected the frames that correspond to the distance values. On each frame we measured one to three individuals and calculated the average individual size (*Size*). We then log-transformed each *Size* and *Distance* pair, and we used half of the pairs to fit a mixed effects linear model that predicts *Distance* as a function of *Size*, with the flight number as a random term as in Equation 1.

$$LDist_{ij} = b_0 + b_1 LSize_{ij} + F_j + \varepsilon_{ij} \qquad (1)$$

Where $LDist_{ij}$ is the log-transformed Distance, $LSize_{ij}$ is the log-transformed Size and F_j is the random intercept for Flight number, which is normally distributed with mean 0 and variance σ_F^2. The index i refers to the flight number (i= 1, … , 22) and j to the observation within a flight (j= 1, … , 12). The residual error ε_{ij} is the within-flight variation, and it is assumed to be normally distributed with mean 0 and variance σ_ε^2.

To validate the model, we applied it to the second half of data pairs and obtained predicted *Distances*. We then plotted predicted against telemetry distances and assessed the goodness of fit of the relationship as the R^2 of a simple regression between the two variables (Appendix C: Figure A.B). Finally, we measured individual *Size* on selected frames from manual flight footage, following the same method, and obtained predicted *Distance* values by applying Equation 4 (see Appendix C).

We developed the model with flight footage from the Phantom 4 Pro on harbour seals, as we flew most flights with this RPAS, and validated it for footage recorded with the Mavic Air (Appendix C: Figure B). Flights on walruses were performed exclusively with a Phantom 4, and a model was developed and validated following the method described above for harbour seals (Appendix C: Equation 5 and Figure C).

In order to maximize the consistency of the distance-to-size ratio, we displayed all footage on the same screen and always selected the largest visible individuals. In addition, to avoid any distortion effects caused by the perspective from which an individual was viewed, we only measured individuals positioned more or less perpendicularly to the camera.

2.1.5 Analyses

To assess the disturbance effect of the RPAS, we adopted a modelling approach and analysed the data in several steps. We chose to fit models with a binomial distribution as it was the best fit to our response variable, seal behaviour (Zuur et al. 2009). Binomial models have a response variable with two possible outcomes, in our case whether the seals present a specific behaviour or not. However, we could not fit a model for each behavioural category (0-6) due to the low frequency of higher-level responses (4-6). Therefore, we merged low-level behaviour (0: sleeping, 1: comfort behaviour, 2: awake) into a single variable "low-agitation", and high-level behaviours (3: side-to-side head, 4: discomfort behaviour, 5: locomotion and 6: flee) into a "high-agitation" variable, which we then used as response variables in our models. With a binomial distribution, models fitted for low or high-agitation behaviour yield the same results, with opposed signs. Due to a more intuitive interpretation, all models presented hereafter were fitted for high-agitation level. All continuous predictor variables (tide, haul-out size, RPAS distance, flight duration, and flight number) were standardized to overcome differences in magnitude. During each model selection process, we fitted all possible variable combinations, ranked the models according to AIC values and selected the most parsimonious model with a ΔAIC<2. We did not detect strong temporal auto-correlation (Appendix D: Figure D), possibly due to the large 10 second windows between samples and the relatively short RPAS flights, so no structure was included in the models to avoid over-fitting them.

Due to high level of variation in the conditions encountered between the moulting and pre-breeding seasons (both environmental parameters and haul-out sizes, Figure 4) as well as the different biological state of the individuals, we analysed the seasons separately. For each season, we ran a two-step analysis. First, we assessed whether the presence of the drone had an

impact on behaviour. For that, we fitted binomial generalised linear mixed models (GLMMs) with seal behaviour as a response variable (either low-agitation or high-agitation) and RPAS presence as a main predictor as in Equation 2. Sea state was not included as a predictor due to high correlation with tidal state (Pearson correlation= 0.64) and the increase in parameter number.

$$Y= b_0 + b_1 RPAS_{ijk} + b_2 Tide_{ijk} + b_3 Size_{ijk} + (Session_k + ID_{jk} + \varepsilon_{ijk}) \qquad (2)$$

$$\text{where } Y = \text{logit}(p_{ijk}) = \log \left(\frac{p}{1-p}\right)$$

Finally, we included a logit link function, p_{ijk}, which is the probability that sample i on individual j of session k presents the specified outcome behaviour category, $RPAS_{ijk}$ is a categorical variable for RPAS presence (before flights / flying / after flights), $Tide_{ijk}$ is a continuous predictor, $Size_{ijk}$ is discrete and stands for the size of the haul-out, $Season_{ijk}$ is categorical (pre-breeding / moulting). $Session_k$ and ID_{jk} are random intercepts for both session and individual nested within session. These variables were assumed to be normally distributed with mean 0 and variance σ_S^2 and σ_{ID}^2, respectively. The residual error ε_{ijk} is the remaining variation within an individual, and it is assumed to be normally distributed with mean 0 and variance σ_ε^2.

If RPAS presence was included in the selected models, we proceeded to the second step, which consisted of examining whether the distance of the RPAS has an effect on behaviour. For this, we selected all subsets of the data corresponding to flight periods and applied binomial generalised mixed additive models (GAMM) with RPAS distance as a predictor, as in Equation 3:

$$Y= b_0 + f_1 Dist_{ijk} + b_1 Fnum_{ijk} + b_2 Fdur_{ijk} + b_3 Model_{ijk} + (Session_k + ID_{jk} + \varepsilon_{ijk}) \qquad (3)$$

$$\text{Where } Y = \text{logit}(p_{ijk}) = \log \left(\frac{p}{1-p}\right)$$

As with the previous model, logit stands for the logistic link function and p_{ijk} is the probability that sample i on individual j of session k presents the specified outcome behavioural category. f_1 is a non-linear function applied on RPAS distance ($Dist_{ijk}$). The fixed-effects included: flight number, considered as continuous and standardised as we expect a cumulative effect ($Fnum_{ijk}$); flight duration as a continuous variable as well ($Fdur_{ijk}$), and RPAS model as a categorical variable (Phantom 4, Inspire 2 or Mavic Air, only for the pre-breeding season). The random structure was identical to that of the GLMMs. Tide was not included in this analysis as we only used small subsets of the data, and thus little variation in tide level occurred compared to over

the time frame of the whole sessions. Haul-out size was not included in this analysis as it was not selected in any of the models from the previous step. The selection process began with a global model from which fixed effects were removed one at a time by order of significance of the p-values.

From the results on the GAMM for pre-breeding season we interpreted that manual flights, which were mostly flown towards the end of the flight sessions, had a stronger influence than pre-programmed flights on the probability of harbour seals presenting low or high-agitation behaviour. Therefore, we continued the analyses by removing the time fractions corresponding to manual flights and repeating the two-step analysis described: first, we assessed the effect of RPAS "presence" through GLMM and secondly, if the results yielded an effect, we assessed the influence of RPAS distance through GAMM.

GLMMs were fitted using package lme4 version 1.1-21 (Bates et al. 2015) and GAMMs were fitted using package gamm4 version 0.2-5 (Wood and Scheipl 2017) on RStudio version 3.4.0 (R Core Team 2017). Significance was considered at $p < 0.05$
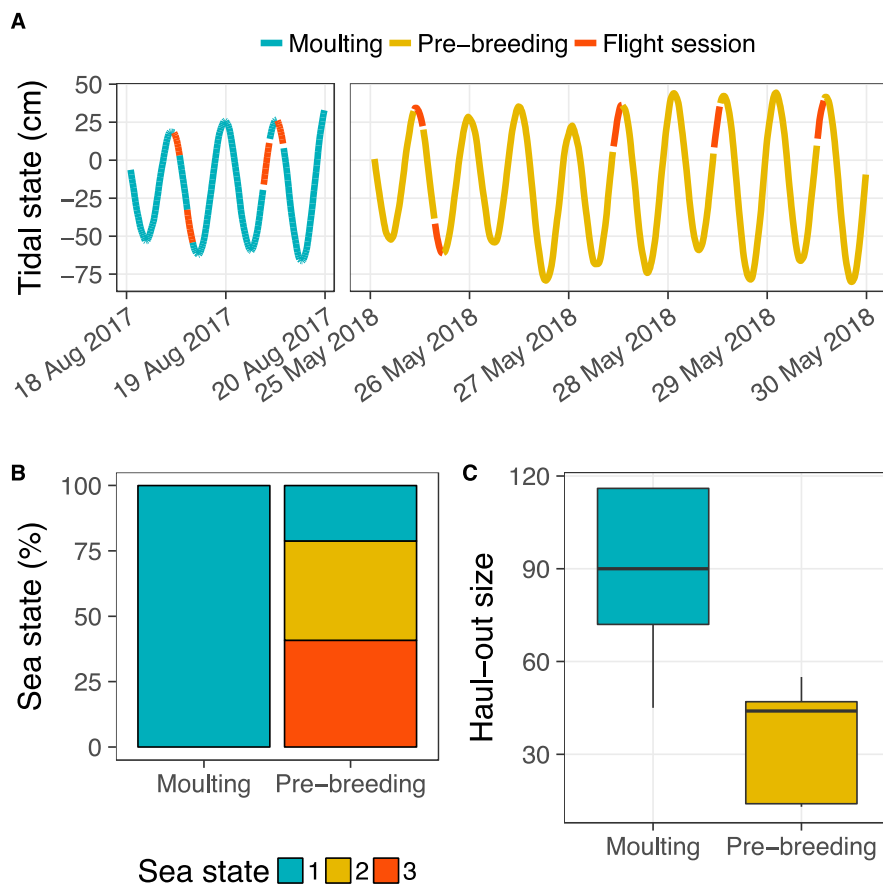

Figure 4. Environmental data gathered during flight sessions on harbour seals. A) Tidal state, expressed as a variation from mean sea level (0 cm). B) Proportion of each sea state in the moulting and pre-breeding sampling seasons as a percentage. C) Haul-out sizes in each sampling season, black line represents mean values.

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2.2 Opportunistic sampling

2.2.1 Field data collection

For species that were not as predictable spatially, we conducted daytrips from Longyearbyen to glaciers fronts within Isfjorden, which tend to be hot-spots for various marine mammal species (see Lydersen et al. 2014) between the 20th of August and the 14th of September 2018. We searched for seals, polar bears and various cetacean species. We sampled opportunistically when we encountered these animals.

We had two encounters with a female polar bear accompanied by two yearling cubs on the 20th and 27th of August 2018. During the first encounter, the female was resting on an island in front of Nordenskjöldbreen, watching the cubs who were at the shore. The second encounter happened on a narrow beach along a cliffside at Deltaneset, where the female was walking along the shore, followed by the cubs. The trials were brief, lasting 4 and 6 minutes, respectively. Upon sighting the bears, we launched a Phantom 4 Pro from the boat and ascended to an altitude of 80 and 110 m, respectively. During the first encounter we followed an overflight strategy, performing consecutive straight-line profiles over the polar bears at altitudes of 70, 50, 20 m, followed by a close approach within a radius of 5 m. During the second encounter, we alternated close-loop profiles and straight-line overflights along the beach, flying at altitudes of 90, 60, 50, 40 and 20 m. We measured polar bear responses as 1) initiation or interruption of walking and 2) head-lifting.

During the field expedition, we encountered white whales once on the 26th of August 2018 in Tempelfjorden. In this study we also include additional flights with this species, flown by the same operator performed on the 16th of June 2017 in Grønfjorden. During the first occasion, in June 2017, we performed several straight-line flights over a pod of about 15 whales, at an altitude of 1.5 m over the sea. On the second encounter, in August 2018, abundant small fragments of sea ice hindered spotting the whales, so we flew the Phantom 4 Pro at an altitude of 90 m to facilitate finding them. After spotting an individual, we descended the RPAS to altitudes of 40, 30, 25, 20 and 15 m and hovered over the area where the individual was expected to surface. We categorised reactions from white whales as no-response, with unchanged swimming trajectories, or as response, when the trajectory deviated sideways or diving deeper / longer diving was initiated.

2.3 RPAS acoustic characterisation

2.3.1 Experimental setup

We used four different RPAS in this experiment, covering a wide range of sizes and weights, all of them being vertical take-off and landing (VTOL) platforms. In order of size they were the DJI Inspire 2, the DJI Phantom 3 Standard (with similar characteristics to the Phantom 4 Pro used on field experiments), the DJI Mavic Pro Platinum and the DJI Mavic Air (see specifications in Appendix A).

In order to reproduce sound levels that overflown animals would experience, our experimental setup consisted of a SM4 placed on a platform 0.5 m above the ground, over which we performed a set of flights with each of the four RPAS models. The recordings were obtained at 16 bits with a sampling rate of 48 kHz (stereo, a frequency response from 0 to 24 kHz), with a signal-to-noise ratio of 80 dB typical at 1kHz re 1Pa.

The acoustic characterisations were carried out on a flat, open area outside of Tromsø, Norway (69.57963ºN 19.22076ºE), where external sources of noise were minimal and there were no obstacles between the SM4 and the RPAS. The experimental flights took place between 10:00 am and 12:30 pm on the 17th October 2018, when wind conditions were 0 to 1.3 m/s, thus minimizing the ambient noise. Temperature ranged between 5 and 7.6 ºC, humidity ranged from 65 to 78 % and atmospheric pressure was 997 hPa.

Tests for each RPAS model comprised two different sets of flights that we performed manually: the first set comprised straight-line transects between the take-off point and the SM4 placed 300 m away, at fixed altitudes of 10, 20, 40, 60, 80 and 100 m. We kept the speed as close as possible to 40 km/h to recreate sound levels experienced by hauled-out individuals during field disturbance experiments. The second set of flights we conduced included four vertical profiles with a continuous ascent-descent flight at a speed around 2 m/s (hereafter, V.c. ascent and descent) and a second ascent-descent flown intermittently, with accelerations from 0 to 2 m/s on each of the altitude levels as above(hereafter, V.i. ascent and descent) (Figure 5). The motivation for testing different vertical profiles was to create a record of the variation in noise levels produced when changes in altitude and speed happen, which is common during fieldwork flight missions when flying conditions are not ideal or operators are not experienced.

We retrieved information on speed, altitude and horizontal distance from take-off from screen recordings on an iPad 2 (Apple Inc., Cupertino, CA, USA) connected to the remote controller, as RPAS do not automatically record telemetry data during manual flights.
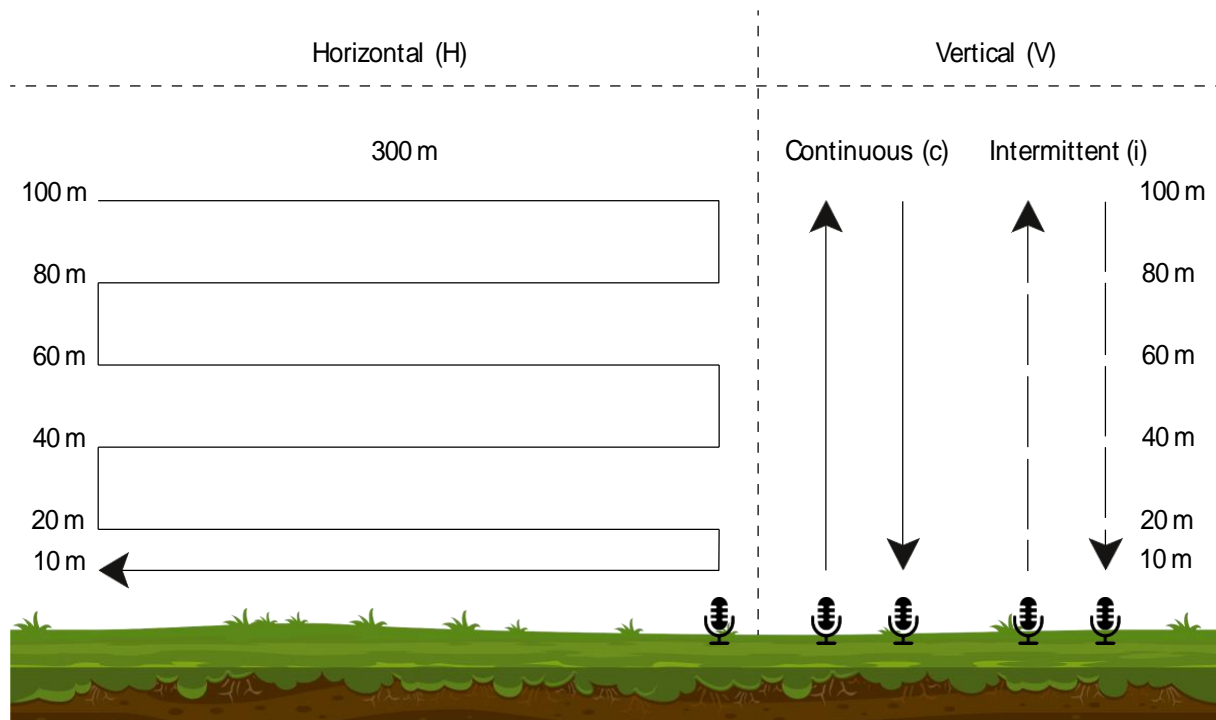
Figure 5. Flight profiles performed during the RPAS acoustic characterisations. The experiments comprised a set of horizontal flights (H) at a range of altitudes between 10 and 100 meters, as well as continuous (V.c.) and intermittent (V.i.) vertical profiles, in ascent and descent.

2.3.2 Analyses

We identified the flight recordings by synchronising sound meter and screen recordings from the iPad. We performed a preliminary analysis by visual inspection of the spectrograms on Raven Lite 2.0 (Cornell Lab of Ornithology, Ithaca, NY, USA). The spectrograms revealed that RPAS signals were visible at 0.15 kHz, below which it was masked by ambient noise, and up to 24 kHz, the highest frequency recorded. However, the strongest signal decreased steeply above 15 kHz (Figure 7). Thus, on all subsequent analyses, we excluded frequencies below 0.15 kHz. To document the noise produced by the RPAS in a simple way, we computed broadband sound pressure levels (SPL) measurements in 1 second time windows (applying half overlapping Hann window, which yields 2 values per second, and then averaging them) on all horizontal and vertical flights. Because the RPAS sound different when flying horizontally and vertically, we further examined differences across the frequency spectrum by calculating SPL for all one-third octave level (TOL) bands from 0.15 to 20 kHz for each flight trajectory (horizontal approach, V.c. ascent and descent, V.i. ascent and descent) on all RPAS models. During flight trials, we achieved more constant speeds on horizontal profiles flown at 20 than at 10 m of altitude, and the speed was more stable until just before reaching the SM4 than above

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it. Thus, with the aim of assessing differences in the characteristics of stable horizontal flights and vertical flights, we included horizontal flights at 20 m (10 m ahead of the SM4) and all four vertical profiles, also at 20 m (V.c ascent and descent and V.i. ascent and descent) in the TOL band analysis. Ambient noise consisted of a small river in the distance and occasional bird songs; nearby traffic was rare. Wind decreased from 1.3 to 0 m/s during the morning, so we calculated ambient SPL for a randomly selected minute before the start of the flights with each RPAS, both as broadband and TOL band SPL. We followed the specifications previously described except for time-averaging, which we did per-minute instead of per-second in order to avoid small scale sound variations. We computed both broadband and TOL band analyses using PAMGuide (Merchant et al. 2015) in Matlab.

2.4 Ethical statement

The study took place in Svalbard and was authorised by the Governor of Svalbard under the research project RIS-ID: 10725 Drones and marine mammals in Svalbard. No animal experimentation permit was required as the animals were not handled during RPAS flight sessions.

2.5 Author contributions

Study designed and grant held by ADL, CL and KMK. Experimental protocols established by: ADL APG. Performed the experiments: APG, ADL. Data curation: APG. Data analyses: APG, ADL. Original draft by: APG. Reviewed and edited: ADL, KMK, CL, RAI.

3 Results

3.1 Disturbance experiments on harbour seals

3.1.1 Summary of the flight sessions

A total of nine flight sessions were performed over harbour seals during two sampling seasons. The number of flights varied between sessions, depending on the availability of individuals hauling-out and their level of responsiveness, and were limited by weather conditions or RPAS battery duration(s). The period comprising RPAS flights, was 50 ± 15 minutes (mean $\pm$ SD), ranging from 23 to 70 min (on 28th and 29th May 2018, respectively Appendix E: Figure E.H and E.I). Pre-programmed flights consisted of single profiles and manual flights, i.e., straight-line or overflights and overhead descents, generally included several profiles within a flight, in order to use battery power efficiently. During the moulting season we flew 8.3 ± 2.6 profiles per session with a Phantom 4 Pro, and during the pre-breeding season we flew 15 ± 6.4 profiles, including flights with the Inspire 2 and the Mavic Air.

3.1.2 RPAS presence model

During the pre-breeding season, the relationship of tide and RPAS flight period with high-agitation behaviour was positive. The relationship with after-flight periods was negative. During the moulting season, both RPAS flight and after-flight periods showed a positive relationship with high-agitation behaviours (Table 3). Haul-out size was not included in any of the models selected.

Table 3. Estimates and standard errors of the explanatory models developed for pre-breeding and moulting seasons with high-agitation behaviour as response variable. The explanatory variable tide was standardized. ns: not selected.

	Pre-breeding		Moulting	
	Estimate	**SE**	**Estimate**	**SE**
Intercept	-2.663	0.460	-1.914	0.187
Flight	0.201	0.071	0.518	0.078
After flight	-0.452	0.074	0.253	0.081
Tide	1.125	0.176	n.s.	n.s.

3.1.3 RPAS distance models

Since RPAS presence increased the probability of individuals showing high-agitation behaviour, we tested the effect of RPAS distance on harbour seal behaviour. RPAS flight distances ranged from 10 to 300m. The relationship between seal high-agitation behaviour and RPAS distance was negative and significant in both seasons (GAMM $X^2_{smooth(distance)}$ = 90.74 and 95.93, p<0.001 for the pre-breeding and moulting season, respectively, Table 4). However, during the pre-breeding period the probability of individuals showing high-agitation behaviour increased at close distances (< 80 m) (Figure 6A) whereas during the moulting season the threshold distance was extended to > 150 m (Figure 6B). During pre-breeding, the probability of showing high-agitation behaviour decreased using Mavic Air compared to Phantom 4 Pro (estimate: -0.458, SE: 0.223) and decreased even further with Inspire 2 (estimate: -0.720, SE: 0.287). However, increasing flight numbers showed a positive relationship with high-agitation behaviour (estimate: 0.279, SE: 0.052). Conversely, the probability of showing high-agitation behaviour during moulting increased with flight duration (estimate: 0.132, SE: 0.038). The effect of flight number during the moulting season yielded high standard errors (Table 4).

Table 4. Best-fit Generalised additive mixed models (GAMMs) for high-agitation behaviour during the moulting and breeding seasons for harbour seals at Midtøya, Svalbard, Norway during RPAS test flights. Estimates for fixed effects are followed by S.E. in parentheses. Variables showed different levels of significance: p<0.01 and 0.01<p<0.05. n.a: not applicable, only Phantom 4 was used during the moulting season. n.s.: not selected

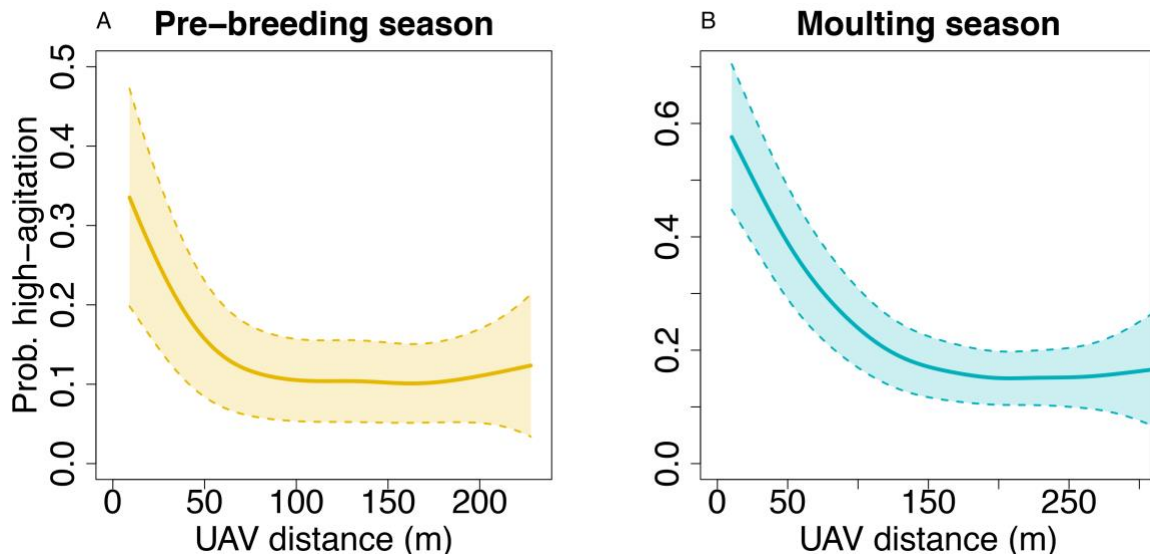|	S(distance)	Inspire 2	Mavic Air	Flight #	Flight duration
Moulting	-(x2=95.93, p<0.001)	n.a.	n.a.	-0.194 (0.096)	0.132 (0.038)
Pre-breeding	-(x2=90.74, p<0.001)	-0.720 (0.287)	-0.458 (0.223)	0.279 (0.052)	n.s.

Figure 6. Effect of RPAS distance on harbour seal behaviour by season, as the probability of an individual presenting high-agitation behaviour. A: pre-breeding season, B: moulting season. Fitted estimates from the models (solid lines) are represented along with CIs (polygons) calculated from the fitted models.

3.1.4 Effect of pre-programmed flights on harbour seal behaviour

The positive relationship of flight number with high-agitation behaviour during the pre-breeding season suggests that later flights have a stronger influence than earlier flights. Because most flights towards the end of the flight sessions were performed manually, we repeated the analysis excluding manual flights in order to test the effect of pre-programmed flights. During the moulting season, high-agitation behaviour showed a positive relationship with tide, RPAS flight number and after-flight periods (in order of importance, see Table 5). During the pre-breeding season, however, the model yielded a negative relationship with RPAS flight and after-flight periods, in order of importance; the probability of showing high-agitation behaviour was higher during control periods than during or after pre-programmed flights (Table 5). High-agitation behaviour and tide height were positively related. Haul-out size was not included in any of the selected models.

During the moulting season pre-programmed flights increased the probability of harbour seals showing high-agitation behaviour. Therefore, we tested the effect of RPAS distance. The selected model yielded significant negative relationships between RPAS distance and probability of high-agitation behaviour (GAMM X2smooth(distance) =11.83, p<0.001) and between flight number and probability of high-agitation behaviour (estimate: -0.473, SE: 0.085). This model predicted an increase in 10 % in the probability of showing high-agitation behaviour when flying at short distances (Appendix F: Figure F). This contrasts with the model

that included manual flights, which predicted a 40 % increase in the probability of showing high-agitation behaviour at the shortest distances Figure 6.B)

Table 5. Coefficients of the explanatory models excluding manual flights with high-agitation behaviour as a response variable. Explanatory variables tide and haul-out size were standardized. ns: not selected.

	Moulting		Pre-breeding	
	Estimate	**SE**	**Estimate**	**SE**
Intercept	-1.863	0.301	-2.768	0.650
Flight	0.400	0.080	-0.173	0.080
After	0.364	0.081	-0.444	0.077
Tide	0.820	0.224	1.573	0.188

3.1.5 Occurrence of fleeing events

Fleeing was the strongest response we recorded. During flight trials during the pre-breeding seasons, all or part of the haul-out fled in two occasions: during the morning session of the 25th of May, during an overhead descent that reached 20 m of altitude; and on the 27th of May, again during an overhead descent at altitudes of 38 m and 20 m (Appendix E: Figure E.E and E.G, respectively). During the moulting season, harbour seals fled once during RPAS flights on the afternoon session of the 18th of August. During an overhead descent, part of the haul-out fled at 100 m of altitude and as we kept descending, other individuals fled at 60 m of altitude (Appendix E: Figure E.B). Three additional fleeing events happened during the moulting season outside RPAS flights. Twice during the morning session on the 18th of August, and once during the afternoon session on the 19th of August (Appendix E: Figure E.A and E.D, respectively) for unknown reasons.

3.2 Disturbance experiments on Atlantic walrus

We flew two flight sessions at Atlantic walrus haul-outs, on the 21st and 22nd of August 2017. We performed 15 and 16 flights within a period of 1:45 and 1:15 h, respectively. The very different behavioural state of the walrus haul-outs in the two sessions, together with the fact that the sample size is small, prevented us from following the modelling approach we employed with analyses of the harbour seal experiments, as models failed to converge. We thus present the results in a descriptive manner.

During the first session, 13 walruses were present at the haul-out including two individuals which were young, based on the size of their tusks. The pre-experimental agitation level was high, with individuals moving between the sea and the haul-out, and as the session progressed

the individuals started to settle. Later, a straight-line flight at 60 m of altitude caused them to panic and move to the shoreline, although most did not enter the sea. The animals returned quite quickly to the top of the sand spit. After that, three close orbit profiles were flown at 60, 50 and 40 m of altitude. At 60 m, some individuals noticed the RPAS, lifting their heads and showing discomfort behaviour. At 50 m, an individual became alert and triggered another fleeing event. Similar to the first event, most individuals stopped before reaching the sea. After that, the haul-out settled down and all individuals returned to a resting state. After several profiles had been flown, with little or no reaction from the walruses, we tested the reaction to an overhead descent. After the RPAS had hovered for 20 seconds, 20 to 15 m above the haul-out, an individual became alert and caused the rest to flee. Soon after the flight experiments ended, the walruses returned to a resting state.

The second flight session yielded quite different results. The haul-out was larger, with 30 individuals, and the pre-disturbance level of agitation was very low, with most individuals resting. Soon after the session started all individuals settled down in a compact group. The walruses basically remained still, either sleeping or awake, with occasional antagonistic interactions occurring. Reactions to the RPAS were only observed during an overhead descent flown at the end of the session. At approximately 40 m of altitude an individual lifted its head, at 20 m (or lower) a number of walruses became agitated, moving their heads side to side or showing discomfort behaviour. The young individuals got startled and instigated a considerable level of reaction in the haul-out, but no fleeing occurred. While retreating, all individuals went back to resting, although quick accelerations of the RPAS around 40 m caused them to lift their heads.

Reactions to RPAS flights such as head-lifting and scratching, without locomotion, were by far the most common. On the three occasions when high-level responses were triggered on the haul-out, all we could identify a specific individual reacting first. In every case a curious adult was the first to become alert, causing the young individuals to panic and subsequently triggering the rest to flee.

3.3 Opportunistic sampling

3.3.1 Polar bear

We launched the RPAS from a distance of 300 m and lifted to 80 m of altitude during the first encounter with the female polar bear. The mother clearly noticed it as it started approaching, lifting her head. The bear was overflown at 70 m in a straight-line profile, then we lowered the

RPAS to 50 m over the island and performed a second straight-line profile. As we approached at 50 m, the bear stood up and started walking slowly towards the cubs, occasionally lifting the head to check the RPAS. A third overflight was performed at 20 m of altitude, and the female lifted the head again but did not stop walking towards the sea. Later, we lowered to RPAS to 3 m over the surface of the island and approached her within a 5 m radius. The female stopped walking and visually followed the RPAS, that we flew around her, without moving or trying to avoid it. We then lifted the RPAS to an altitude of 30 m and retreated, the polar bear continued walking towards the sea. At no time during the first encounter did she walk rapidly or attempt to flee.

During the second encounter, we launched the RPAS from a distance of 240 m to an altitude of 110 m. On this occasion, the female, that this time was accompanied by her two cubs, noticed the RPAS as it started ascending, and lifted her head when the it passed over the family unit. We then performed a close loop profile at 90 m, descended to 60 m and overflew them in a straight-line profile, and repeated the procedure at 50, 40 and 20 m. The bears did not interrupt their walk, change direction or show any other overt reactions. The mother checked her cubs regularly as she walked, lifted her head twice when the RPAS was flying at 50 and 20 m, and one of the cubs lifted the head once, when the RPAS was flying at 50 m of altitude. A few minutes after the flight trial, with the boat keeping the same distance from the shore, the polar bears did not show any signs of distress, as the cubs stopped to inspect a water stream and drink before the female kept walking along the shore.

3.3.2 White whales

On the first encounter a pod of about 15 whales was overflown several times at an altitude of 1.5 m above sea level. While flying behind or above the pod, we did not observe any reactions as the whales kept swimming straight forward. However, when the RPAS passed over them and hovered in front of the pod, the whales immediately dove and changed direction, towards a shallow bay. The second time, we lifted the RPAS to 90 m in order to spot individuals among the ice floes and descended to 40 m after spotting the first white whale. We followed the trajectory of the whale and kept the RPAS hovering at 40, 30, 25, 20 m of altitude for one surfacing, to which it showed no reaction. Then we lowered the RPAS to 15 m of altitude and placed it over the area where it surfaced two consecutive times, after which the whale dove deeply and we lost visual contact with it. A second overflown individual also dove away after surfacing twice where the RPAS was hovering at 10 m over sea level. Soon after that, the whole pod dove and we lost visual contact with all individuals.
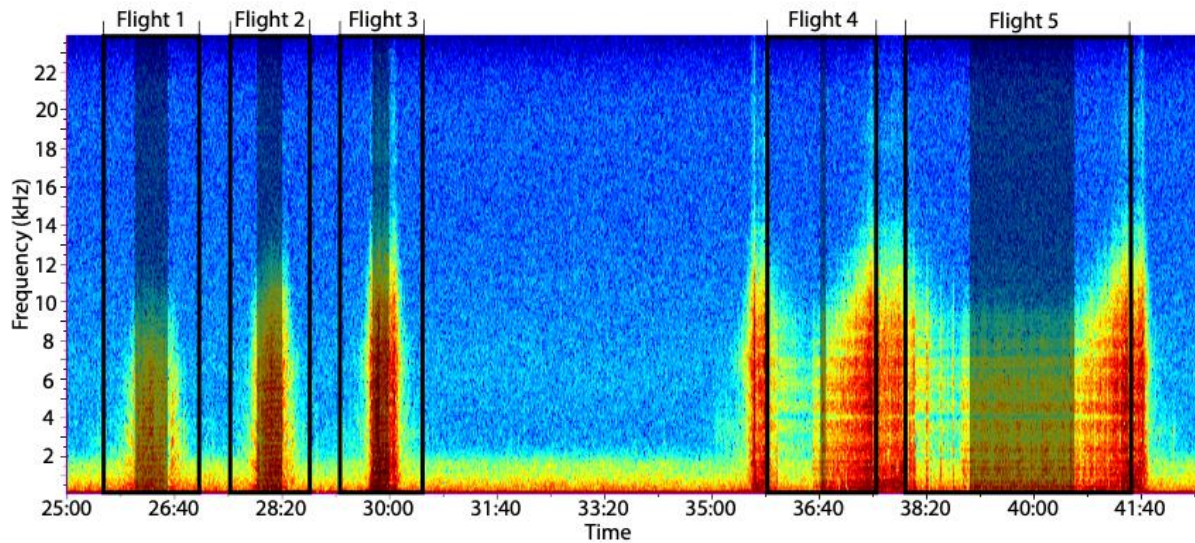
3.4 RPAS acoustic characterisation

Figure 7. Spectrogram of the profiles flown with Inspire 2. Thick boxes represent each flight and shaded areas the time hovering between consecutive profiles. From left to right: flight 1: horizontal at 100 and 80 m, flight 2: horizontal at 60 and 40 m, flight 3: horizontal at 20 and 10 m of altitude, flight 4: V.c. ascent and descent and flight 5: V.i. ascent and descent

3.4.1 Horizontal profiles

On the horizontal flights, flying at distances between 300 and 100 m to the SM4 yielded SPL under 45 dB re 20 µPa in all RPAS except Inspire 2 (slightly surpassed by Phantom 4 Pro in two points, see Appendix G). Mavic Air and Platinum, which yielded lower SPL in general, remained under 50 dB re 20µPa until a distance of 40 m (Figure 8.C, E, G, Appendix G). We observed a pattern along the range of horizontal distances: when flying at distances between 150 to 60 m from the SM4, flights at higher altitudes yielded higher SPL; at a distance of 40 m, intermediate altitudes yielded the highest SPL; and at distances shorter than 40 m, the lowest flights yielded higher SPL (Appendix G).

Profiles flown at altitudes higher than 60 m yielded a slow and constant increase in SPL, as the RPAS approached. In contrast, the approach of the RPAS at lower altitudes yielded a much steeper increase in SPL, resulting in an exponential curve (Figure 8.A, C, E, G). At horizontal distances from 20 to 0 m, profiles at lower altitudes did not consistently yield higher SPL than profiles at higher altitudes due to small variations in speed between profiles. Occasional early decelerations are reflected in lower SPL at 0 than at 10 m (Figure 8.A, C, E, G). Approaching at 10 and 20 m of altitude, all aircrafts yielded SPL around 60 dB re 20µPa (Figure 8.C, E, G, Appendix G) except the Inspire 2, that reached values over 70 dB re 20µPa (Figure 8.A, Appendix G).

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3.4.2 Vertical profiles

On vertical flights, descending profiles yielded higher SPL than ascending profiles. In addition, all RPAS showed increasing SPL al closer distances, accentuated under 40 m of altitude (Figure 8.B, D, F, H). For example, at 40 m of altitude ascending with all aircrafts yielded SPL around 5 dB re 20 µPa lower than horizontal flights at 0 m (over the SM4), which is a reduction in SPL comparable to flying horizontally at the same altitude, but at 60 to 80 m from the SM4 (Appendix H). In contrast, descending profiles with Phantom 3 Std., Mavic Air and Mavic Platinum yielded similar SPL to horizontal profiles at the same altitude, and Inspire 2 yielded higher SPL than the horizontal profile (over 66 dB re 20 µPa, which corresponds to flying horizontally at 10 m of altitude; Figure 8.B and Appendix H).

At lower altitudes, 20 and 10 m, all descents with Phantom 3 Std. and Inspire 2 yielded higher SPL than the horizontal profiles at the same altitudes. Mavic Air and Platinum maintained the same pattern as at 40 m of altitude: V.i. descents yielded similar SPL to horizontal profiles at the same altitude, and V.c. descents and both ascents yielded lower SPL than horizontal profiles (Appendix H).
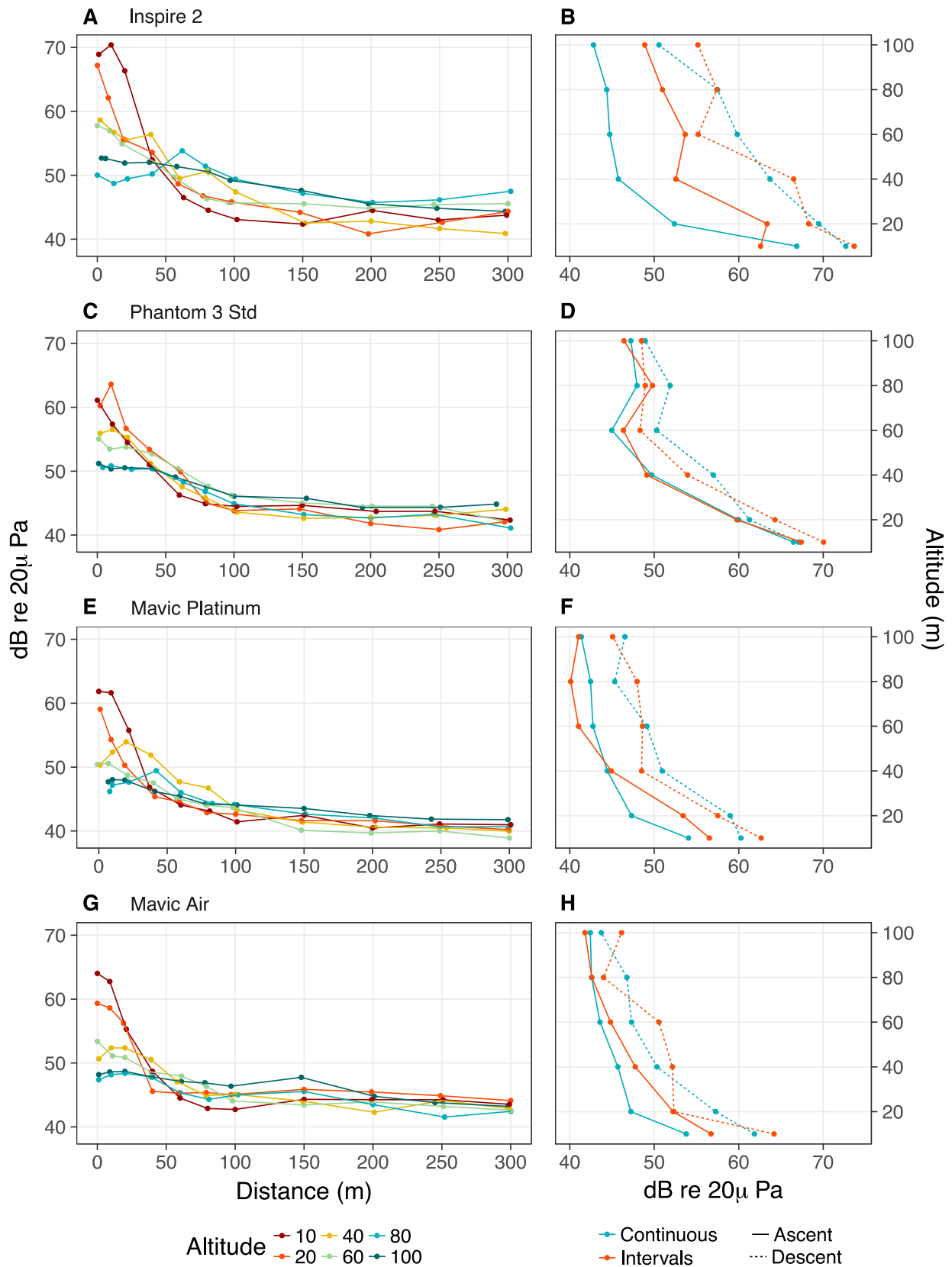
Figure 8. Broadband sound pressure level in dB re 20µPa (0.15 to 24 kHz) for profiles flown horizontally (A, C, E, G) and vertically (B, D, F, H) with Inspire 2 (A and B), Phantom 3 Std. (C and D), Mavic Platinum (E and F) and Mavic Air (G and H). A, C, E, G: Horizontal flights, each colour corresponds to a flight at a constant altitude and speeds around 40 km/h. B, D, F, H: Vertical profiles flown over the SM4 at a speed around 2 m/s. Blue lines represent vertical constant ascents (continuous line) and descents (dashed); orange lines represent vertical intermittent ascents (continuous line) and descents (dashed).

3.4.3 1/3 Octave band analysis

In order to compare differences in SPL between horizontal and vertical flights across the frequency spectrum we calculated SPL on all TOL bands between 0.150 and 20 kHz for each flight profile at 20 m of altitude. In accordance to the results of the broadband analyses, Inspire 2 yielded the highest SPL values across the spectrum, followed by Phantom 3 Std. (Figure 9.A, B) and last by Mavic Platinum and Mavic Air.

All flight profiles yielded similar SPL on TOL bands below 0.2 kHz and over 16 k Hz, and energy levels decreased steeply over 10 kHz (Figure 9). All descending profiles showed comparable patterns across the frequency spectrum, with peaks at 0.5, 0.8, 2.5 and 6.3 kHz for all RPASs, which did not match with those on horizontal flights except for Phantom 3 Std. (Figure 9). Even if all flight profiles showed a similar SPL pattern in Phantom 3 Std., the horizontal profile yielded higher SPLs under 1.25 kHz whereas the two descending profiles dominated higher TOL bands (Figure 9.B).

The RPAS flight tests were performed in relatively calm weather conditions, when wind remained under 1.3 m/s. Figure 9 shows that ambient noise levels measured before the starting flight trials for each RPAS were lower than those from profiles flown at 20 m. Only in frequencies below 0.4 kHz its effects increased considerably, reaching values that can mask sound from some of the RPAS (Figure 9).

During disturbance experiments in Svalbard, ambient broadband SPLs reached 64 dB re 20 µPa on the 28th of May 2018 at Midtøya and on the 22nd of August 2017 at Sarstangen (calculated under the same parameters as ambient noise during RPAS acoustic characterisations). Calculated as SPL in TOL bands, ambient SPL yielded values that virtually mask Inspire 2 and Phantom 3 Std. at 20 m on frequencies below 0.5 kHz, and Mavic Platinum and Air on frequencies below 1.5 kHz (Figure 10). In TOL bands over 1.5 kHz, the masking potential of ambient noise in Svalbard was much higher than that on the site where we performed the acoustic characterisations. In frequencies between 2 and 8 kHz the difference in ambient SPL between the two sites reached nearly 20 dB re 20 µPa (Figure 10).
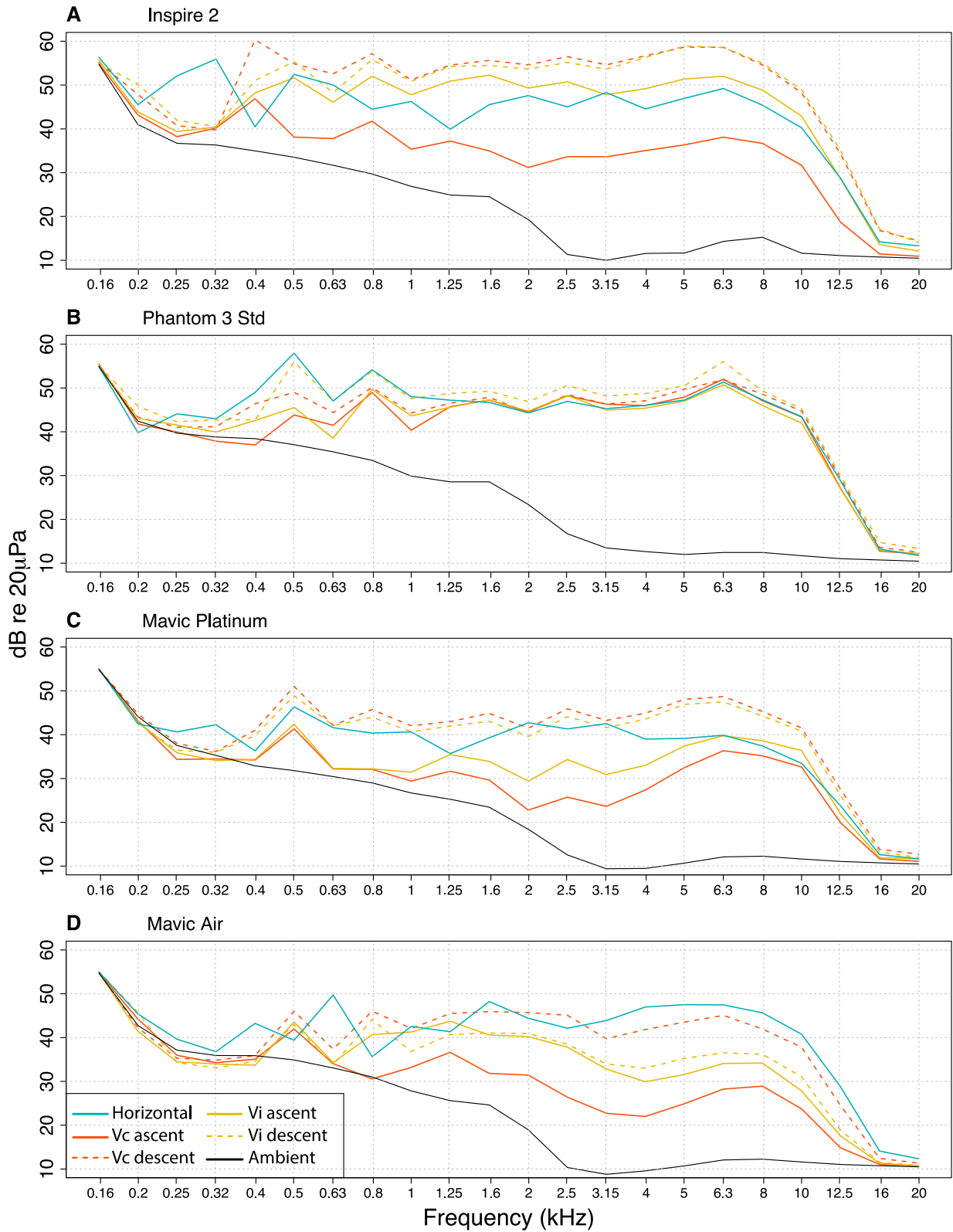
Figure 9. TOLs sound pressure level in dB re 20μPa (0.15 to 20 kHz) for profiles flown at 20 m with Inspire 2 (A), Phantom 3 Std. (B), Mavic Platinum (C) and Mavic Air (D). Blue lines represent horizontal profiles; orange represent vertical constant ascents (continuous line) and descents (dashed); yellow lines represent vertical intermittent ascents (continuous line) and descents (dashed). Background noise is plotted with a black line.
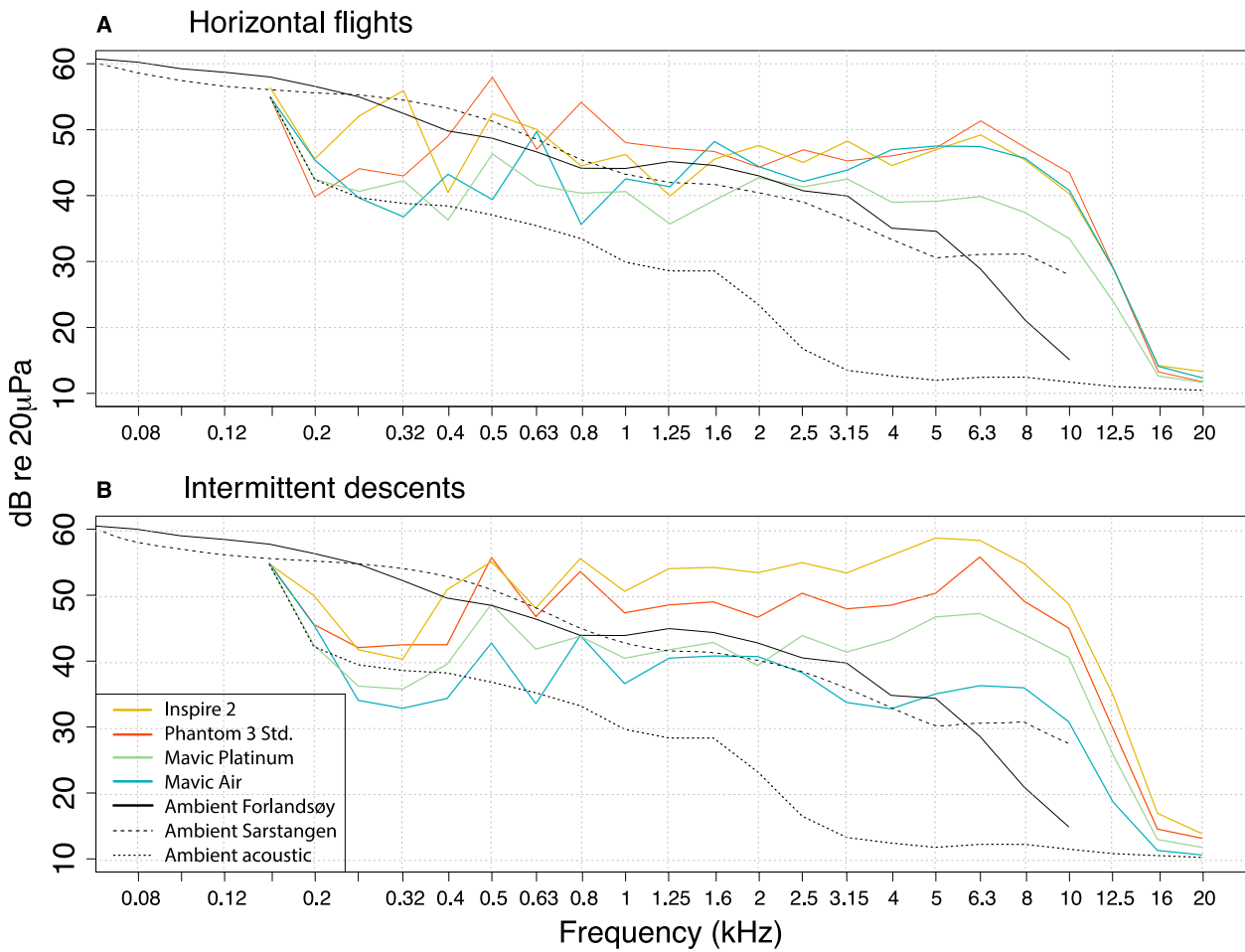
Figure 10.TOLs sound pressure level in dB re 20μPa (0.08 to 20 kHz) for Horizontal (A) and V.i. descent (B) profiles flown at 20 m with Inspire 2 (yellow), Phantom 3 Std. (orange), Mavic Platinum (green) and Mavic Air (blue). RPAS flight SPL are plotted against ambient noise at the same field site (dotted line) as well as ambient SPL at Midtøya (Forlandsøyane, solid black) on the 28th May 2018, where we conducted disturbance experiments on harbour seals, and Sarstangen (dashed black) on the 22nd August 2017, where we conducted disturbance experiments on Atlantic walruses.

4 Discussion

Several studies have stressed the need for species-specific guidelines for the use of RPAS in association with wildlife because different species show variable degrees of sensitivity to visual or acoustic disturbance (e.g. Christie et al. 2016; Hodgson and Koh 2016; Smith et al. 2016). In this study we provide an overview of the potential impacts that a variety of aircraft types and flight profiles can have on several Arctic marine mammals based on a RPAS flight experimental set-up. In addition, the acoustic characterisations of the RPAS used during the disturbance experiments in this study provide a basis for interpretation of our results and those in other studies using similar aircrafts. We have demonstrated tolerance levels for harbour seals, walruses, white whales and polar bears, that can be used to design studies using RPAS that avoid disturbance of the animals.

In addition, this study highlights the effect of multiple factors that can determine the degree of sensitivity to RPAS disturbance in wildlife. Physiological state seemed to have an influence in harbour seals as their response was not consistent between seasons. During pre-breeding period harbour seals tended to react from a threshold distance of 80 m. However, after flight experiments concluded the agitation state unexpectedly dropped to levels lower than those prior to the experiments. A combination of pre-experimental disturbance and tidal conditions might have elevated the "natural" level of alertness in the haul-out group, leading to this unexpected result. During the moulting season, animals tended to react at greater distances and maintained higher levels of agitation after the experiments had finished. However, the elevated level of alertness of the seals on the haul-out was likely caused by a polar bear visit the day prior to the flight experiments. Increased alertness, together with no wind or swell, both of which mask the sound of the RPAS, resulted in a fleeing event while the RPAS was at 100 m altitude during an overhead descent. Because of sample size is small, this single event might have biased our results for the moulting season. The increased level of alertness was likely also why the entire haul-out fled on three occasions when the RPAS was not flying. However, similar to our study, seasonal differences in responses to RPAS have been noted in other marine mammal studies (Pomeroy et al. 2015).

Other factors impacting how sensitive animals are to disturbance from RPAS included tidal state, the number of animals hauled out at a given time, the presence of juveniles and ambient noise levels. High tides resulted in increased agitation levels at harbour seal haul-outs, especially during the pre-breeding season. Rising tide exposed the seals to increasing swells

forcing individuals to either abandon the haul-out or move to higher elevations (all considered high-agitation behaviours). The lesser influence of tidal state during the moulting season is likely due to a combination of individuals at moult wanting to stay dry, and low swell during all sessions during this study period, which caused lower stress levels in the group. These results highlight the importance of accounting for tidal state when assessing disturbance on haul-outs.

Unlike harbour seals, walruses were not affected by tidal state in our study because they hauled-out well above the high tide mark on the top of a sand spit. Large swells did have an indirect influence by masking the sound from RPAS (together with the wind), as highlighted by Pomeroy et al. (2015). During the second study period at the walrus haul-out, the ambient noise was 20 dB higher than the ambient noise at the site of the acoustic characterisations we conducted outside Tromsø. The elevated background noise levels recorded at the walrus haul-out likely resulted in the noise from the RPAS being masked to a large extent. Vertical flights at 10 and 20 m of altitude would have produced loud sounds, but at greater distances the sound was likely minimal. The low levels of reaction by the walruses during our second session was likely due in part to the low levels of RPAS noise perceived.

Haul-out group size was another factor that was explored in our analyses. Other studies on harbour seals that have shown that larger groups tend to spend more time performing low-energy activities such as sleeping (Krieber and Barrette 1984; Terhune and Brillant 1996). However, our models failed to detect any effect of group size. During the pre-breeding season, the haul-outs might have been too small for the seals to benefit from group vigilance and other protective benefits of grouping (see Reder et al. 2003 for more details).During the moulting season, the higher alertness caused by a polar bear's presence in the area as well as frequent agonistic interactions due to high numbers of individuals might have masked positive effects of haul-out size (Krieber and Barrette 1984). Conversely, walruses showed the expected pattern with smaller groups reacting more to RPAS flights than larger groups.

The presence of young individuals within groups of animals has been reported to influence sensitivity to disturbance (Øren et al. 2018; Pomeroy et al. 2015; Salter 1979). However, the low numbers of juveniles in haul-outs precluded us from testing this in our study of harbour seals. Young individuals played a crucial role in triggering fleeing events at the walrus haul-outs. Young walruses did not seem to react to the RPAS directly, but rather their responses seemed to be initiated by a curious adult showing the first signs of alert behaviour. The presence of polar bear cubs during the RPAS tests with that species likely influenced our results, as females with cubs are reported to be more prone to disturbance than other sex-age classes

(Andersen and Aars 2008). Therefore, we suggest the presence of juveniles needs to be taken into account for when planning RPAS flights over walrus haul-outs or polar bears; and flight distances should be as large as possible for a given investigation.

Understanding the hearing threshold of wildlife species is critical in attempting to avoid disturbances via the use of RPAS (Smith et al. 2016). However, the ability of an animal to detect a sound does not necessarily mean that they will react to it. Most animals will respond only when a sound is loud enough that it is perceived to be a threat (Scobie and Hugenholtz 2016). The RPAS models characterised in this study presented most of their energy under 16 kHz, with a steep decline at frequencies over 10 kHz. Comparing animal audiograms with the spectrum of the sound they will be exposed to through RPAS flights will provide insight into the level of disturbance animals may experience (Grubb et al. 2007).

Audiograms for our study animals confirm that the sounds produced by the RPAS we used in this study are well within their hearing ranges. Reichmuth et al. (2013, and references therein) found that the lowest hearing threshold of harbour seals was -4 dB re 20 µPa at 3.2 kHz, and their sensitivity remained within 20 dB of this value between 0.5 and 14 kHz. Similarly, polar bears have a lowest hearing threshold of -10 dB re 20 µPa at 14 kHz remaining within 20 dB between at least 4 and 16 kHz (Owen and Bowles 2011). High hearing sensitivities have been reported elsewhere for polar bears (Andersen and Aars 2008) which reacted to snowmobiles at distances greater than 1 km and juvenile grey seals fleeing during an RPAS flight at 200m distance (Pomeroy et al. 2015). Given these hearing sensitivities, the detection of RPAS in our study by harbour seals at 100 m altitude and polar bears at a distance of 300 m is reasonable. The sound levels for the four RPAS reported in our study can provide important information for people planning to use RPAS with other wildlife, in combination with audiograms of the potential subject species to predict impacts and to avoid them. For example, given that ringed and spotted seals have very similar hearing sensitivity to those of harbour seals (Sills et al. 2014, 2015), we would expect them to detect RPAS at similar ranges.

Hearing threshold values for walruses suggest that they are sensitive to sounds at around 45 to 50 dB re 20 µPa at frequencies between 0.25 and 8 kHz at ambient noise levels of 40 dB re 20 µPa (Kastelein et al. 1993, 1996). This suggests that the walruses in our study were able to hear the RPAS descending at 20 m. However, we suggest that walruses must have better hearing sensitivity, since the haul-out fled during an overflight at 50 m. Thus, greater distances should be used for surveys and other types of flying of RPAS with walruses. During experiments on polar bears, the lack of wind enabled the female to detect the RPAS at 300 m (during launch).

Conversely, during the pre-breeding flight experiments on harbour seals, a combination of wind, big swells and large numbers of birds resulted in the RPAS not being noticed until distances were less than 40 m during some of the flight sessions. These results reinforce the relevance of accounting for ambient noise levels when planning RPAS flights over potentially sensitive species.

RPAS flying with swimming marine mammals will have different potential impacts when the animals are underwater versus at the surface. Only a small fraction of the sound energy will penetrate the water due to large impedance difference between air and salt water (Christiansen et al. 2016). Using a hydrophone at 1 m of depth, Christiansen et al. (2016) measured the underwater acoustic signal of RPAS similar to those we used in our experiments and concluded that toothed whales would likely not hear RPAS unless they were flown below 10 m of altitude in low ambient noise conditions. Our results support this low impact potential, as the white whales in our study did not react to RPAS flights as low as 1.5 m over the sea when the RPAS stayed behind them. Similar findings have been reported for humpback, blue, killer and grey whales (*Megaptera novaeangliae, Balaenoptera musculus, Orcinus orca* and *Eschrichtius robustus*, respectively), with no responses being detected when RPAS were flown at altitudes ranging from 10 to 50 m (Durban et al. 2015, 2016; Pirotta et al. 2017; Torres et al. 2018). However, contrary to our expectations, belugas dove immediately when the RPAS hovered in front of them at altitudes lower than 15 m, suggesting that RPAS can cause disturbance when they are visually detected. Domínguez-Sánchez et al. (2018) reported a similar reaction to those we saw in white whales for a blue whale when it was accidentally approached from the front at an altitude of 5 m. The sharp turn towards a nearby shallow bay in our study likely reflects anti-predator behaviour against killer whales (Karlsen et al. 2002; Lydersen et al. 2001; Vacquié-Garcia et al. 2018).

We expected little or no reaction from polar bears, because they are a top predator in the Arctic that has few if any natural predators. However, the single female in our study walked away from the RPAS on both occasions she and her cubs were exposed to the RPAS. This is similar to findings by Andersen and Aars (2008), who suggested that females with cubs are sensitive to potential disturbances. Barnas et al. (2018) reported increased vigilance but no overt flight responses by polar bears to RPAS flights at 75 and 100 m altitude with a fixed-wing aircraft; these aircraft are likely less noisy than the VTOL RPAS used in our study because they follow steadier trajectories. In addition, the study by Barnas et al. (2018) did not include tests on females with cubs and the authors highlighted the fact that bears in the area are regularly

overflown by helicopters and fixed-wing aircrafts from the tourist industry. In our study area, RPAS are a novel source of disturbance, unlike boats which polar bears are used to seeing. We suggest that the reaction that was observed in our study was a combination of high sensitivity because of the presence of cubs, and a novel stimulus increasing the propensity of the female to disturbance. Regional differences should receive further research attention as habituation to recurrent sound and visual stimuli is common in wildlife species.

Additional important factors influencing the degree of agitation included the RPAS model and the approach strategy. Manual flights, which involved overhead descents and straight-line overflights generally at low altitudes, caused more agitation than pre-programmed flights both on harbour seals and walruses. Overhead descents present rapid noise onset rates (dB/s), a sound of higher frequency and they prevent the animals from following the RPAS visually. At the same time, the speed and direction in manual flights are often not as constant as in pre-programmed flights and the resulting sudden accelerations cause variations in the pitch of sound produced. By flying orbit profiles, the Inspire 2 caused less agitation than the Phantom 4 Pro, despite the fact that it is both larger and noisier. The Mavic Air, presumably because of its small size and lower sound levels, also caused less agitation than Phantom 4 Pro, even when flown manually. In addition, flying at low altitudes yields lower noise levels at ranges over 50 m, as in wide orbit profiles, because of the acoustic profile of VTOL RPAS (Kloet et al. 2017). Importantly, our study confirms the need to maximise the predictability of the noise source by avoiding descent flights directly above animals and ideally pre-programmed flights should be used to minimise rapid noise onset rates where feasible (Bowles 1995; Sweeney et al. 2016; Vas et al. 2015).

4.1 Future research and improvements

Our study provides novel information regarding the impacts RPAS can pose to several marine mammal species. Modifications that could improve future studies include: inclusion of additional environmental and context variables such as the combined effects of tide and swell, e.g. distance from a focal individual to the sea, and inclusion of ambient noise levels as an additional predictor into the models, as it can mask RPAS sound. Such increased complexity in terms of variables will of course necessitate large sample sizes in future studies. Experiments should be conducted across a broader range of seasons, with more diversity in group sized.

Additionally, physiological responses to RPAS should be explored for marine mammal species. Ditmer et al. (2015) and Weimerskirch et al. (2018) found that black bear (*Ursus americanus*)

and especially females with cubs, as well as incubating king penguins (*Aptenodytes patagonicus*) show increased heart rates in spite of limited behavioural responses.

Finally, the statistical models employed in our study detected differences in agitation caused by different RPAS. However, larger sample sizes for Inspire 2 and Mavic Air would have allowed us to examine their effects on harbour seals more completely and possibly to provide threshold distance estimates for each RPAS. Similarly, with a larger sample size on walruses we could have applied more robust modelling approaches.

5 Conclusions

Our study provides the first science-based assessment of the impacts of RPAS on marine mammals in Svalbard. We have found that sensitivity to RPAS not only varies across species, and across seasons but also between consecutive days at the same location. Short-term temporal variations in sensitivity to disturbance can be primarily attributed to factors such as the presence of juveniles in the case of walruses or tidal state, wave effects (swell) and wind which can mask sounds from RPAS. Other factors such as moult in seals may also encourage them to avoid fleeing at flight distances that would likely stimulate a response at other times of year. However, our experiments suggest that pre-experimental levels of agitation might be among the strongest drivers of sensitivity to disturbance by RPAS.

Our study suggests that minimum distances of 50 and 80 m to walruses and harbour seal aggregations should be maintained, respectively. Polar bears showed sensitivity to RPAS as a novel stressor, despite displaying limited behavioural responses, which suggests that caution should be exhibited when flying RPAS near this species. Flight distances should be as large as possible and flights should be terminated if a walking response is elicited. Given the sensitive hearing of all of the species tested our study, it was not surprising that ambient noise played an important role in masking RPAS sound and therefore influenced the degree of sensitivity they showed in different acoustic environments. Conversely, visual cues caused significant impact on belugas, which highlights the importance of approaching this species only from behind or using high altitudes.

As expected, different RPAS yielded varying levels of sound, mostly in relation to their size, although larger RPAS caused less agitation than smaller models when flown with smoother trajectories. Manual flights, and particularly overhead descents, caused the highest levels of agitation in our study because they produced higher noise levels and variations in sound pitch. Therefore, we suggest pre-programming RPAS flights and following orbit profiles whenever the objective of the study allows for it, as well as avoiding any changes in altitude in close proximity to study animals.

6 Recommendations for management

Tourism in Svalbard has increased dramatically over the last decades, as has the number of scientific studies conducted in the archipelago (Aksnes and Rørstad 2015; Misund et al. 2017; Viken 2011). Concomitantly, RPAS are increasingly being used by hobbyists and researchers in order to film animals and landscapes (Shahbazi et al. 2014). To date, use of RPAS remains unregulated in Svalbard, although tourists are generally not allowed to use them during expeditions with most tour organisers (see AECO guidelines) and scientific use requires permission by local government authorities.

This study provides evidence that RPAS do pose disturbance risks to marine mammal species and we suggest that the following guidelines should be followed:

- A threshold distance of 80 m should be kept when flying over harbour seal haul-outs. This distance can be achieved through orbit profiles at a relatively lower altitude, e.g. 60 m, which maintains a minimum acceptable horizontal distance to a haul-out.

- The flight distance to walrus haul-outs with young individuals or adults showing pre-experimental high agitation should be 50 m or more in order to prevent fleeing events.

- We encourage the use of pre-programmed profiles for use of RPAS whenever they are used to study or film wildlife, because they reduce the chances of sudden changes in speed or direction, which increase the noise emitted by RPAS.

- Overhead descents, and vertical flights in general, should be avoided when possible. Changes in altitude should be performed as far as possible from the study animals.

- On wide orbit profiles, and any flights at distances greater than 60 m to the study animals, flights should be performed at the lowest possible altitude in order to reduce the noise levels.

- During flight sessions with no wind, the sound from RPAS is not masked and therefore flight distances should be maximized.

- Polar bears have a very sensitive hearing, so flight distances should always be kept to the maximum that the study objective permits. In addition, because they tend to show low-level responses, they should not be followed if they start walking away.

- RPAS flights over cetacean species should be flown at altitudes higher than 15 m and animals should be approached from behind to minimise responses to visual stimuli.

- All of our study species showed low in-air hearing thresholds. This stresses the importance of maximizing flight distance on species for which RPAS disturbance potential has not been tested, under a precautionary principle.
- As recommended by Bowles (1995), the exposure to acoustic stress should be restricted to the minimum time necessary, and recovery should be allowed between exposure events.
- Smaller RPAS, such as Mavic Air, should be used because of the lower impact potential they pose to wildlife.

7 Acknowledgements

8 List of references

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Appendix

Appendix A. RPAS models specifications

Table A. RPAS models used during the disturbance experiments and RPAS acoustic characterisations. All RPAS belong to DJI (DJI^{TM}, Shenzhen, Guangdong, China).

RPAS	Diameter (cm)	Weight (kg)
Inspire 2	60.5	~4
Phantom 4 Pro	45	1.4
Phantom 3 Std.	35	1.2
Mavic Platinum	33	0.73
Mavic Air	21.3	0.43

Appendix B. Telemetry data

Structure of the telemetry information recorded by the RPAS during pre-programmed flights.

Table B. Telemetry file retrieved from Flight 1 in Session 1.

AUTOPILOT			V4.1.152		
SESSION ID			2017-08-18-100440-439		
SESSION START			04:40.4		
DEVICE USER INTERFACE IDIOM			Ipad		
DEVICE OPERATING SYSTEM			IOS 10.3.3		
AIRCRAFT MODEL			Phantom 4 Pro		
DATE/TIME	Flight	Latitude (Deg)	Longitude (Deg)	Speed (kmh)	Altitude (m)
04:40.5	harbour 1	78.33651	11.580285	0	0
04:40.7		78.33651	11.580284	0	0
04:40.8		78.33651	11.580284	0	0
04:41.0		78.33651	11.580284	0	0
04:41.1		78.33651	11.580284	0	0
04:41.2		78.33651	11.580284	0	0
04:41.4		78.33651	11.580284	0	0
04:41.5		78.33651	11.580284	0	0
04:41.6		78.33651	11.580284	0	0
04:41.7		78.33651	11.580284	0	0
04:41.9		78.33651	11.580284	0	0
04:42.0		78.33651	11.580284	0	0
04:42.2		78.33651	11.580284	0	0
04:42.3		78.33651	11.580283	0	0
04:42.4		78.33651	11.580283	0	0
04:42.5		78.33651	11.580283	0	0
04:42.6		78.33651	11.580283	0	0
04:42.8		78.33651	11.580284	0.36	0
04:42.9		78.33651	11.580285	1.14	0
04:43.0		78.336509	11.580286	1.48	0
04:43.1		78.336509	11.580287	1.94	0.1
04:43.2		78.336508	11.58029	1.94	0.2
04:43.4		78.336507	11.580292	1.48	0.3
04:43.5		78.336507	11.580293	1.48	0.3
04:43.6		78.336507	11.580295	1.14	0.4
04:43.7		78.336507	11.580297	1.14	0.4
04:43.8		78.336506	11.580298	1.08	0.5
04:44.0		78.336506	11.580301	1.14	0.6
04:44.1		78.336506	11.580303	1.14	0.6
04:44.2		78.336505	11.580305	1.14	0.7
04:44.4		78.336505	11.580308	1.14	0.8
04:44.5		78.336505	11.580309	1.14	0.8
04:44.7		78.336504	11.580312	1.14	0.9
04:44.8		78.336504	11.580313	0.72	0.9
04:44.9		78.336504	11.580315	0.8	1

Appendix C. Estimation of RPAS-to-haul-out distance

By following the methodology described in Section 2.1.4 we obtained a model that predicts the distance from RPAS to a harbour seal haul-out on Phantom 4 Pro footage. The model yielded the results in Equation 4:

$$Ldist_{ij} = 5.2077 - 0.7121 S_i + F_j + \hat{\varepsilon}_{ij} \tag{4}$$

Where $Ldist_{ij}$ is the log-transformed Distance, $Lsize_{ij}$ is the log-transformed Size and F_j is the random intercept for Flight number, which is normally distributed with mean 0 and variance 0.0999^2. The index I refers to the flights (i= 1, …, 22) and j to the observation within a Flight (j= 1, … , 12). The residual error ε_{ij} is the within-flight variation, and it is assumed to be normally distributed with mean 0 and variance 0.1318^2. With a new set of measurements, we validated the model by plotting predicted distance values against telemetry values (Figure A.B) and fitting a simple regression which yielded an R^2=0.89 (t=25.308, p<2e-16).
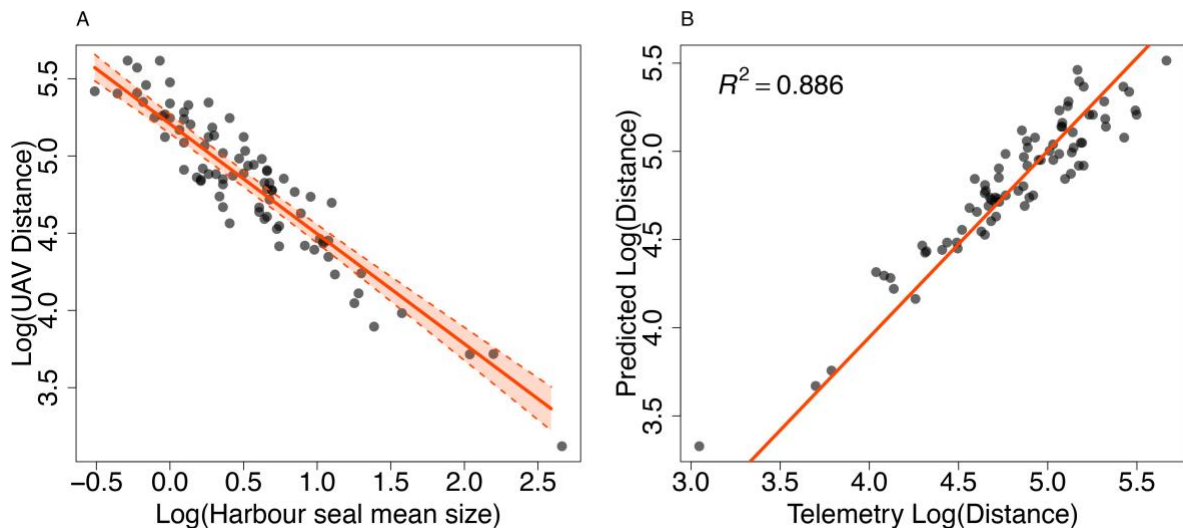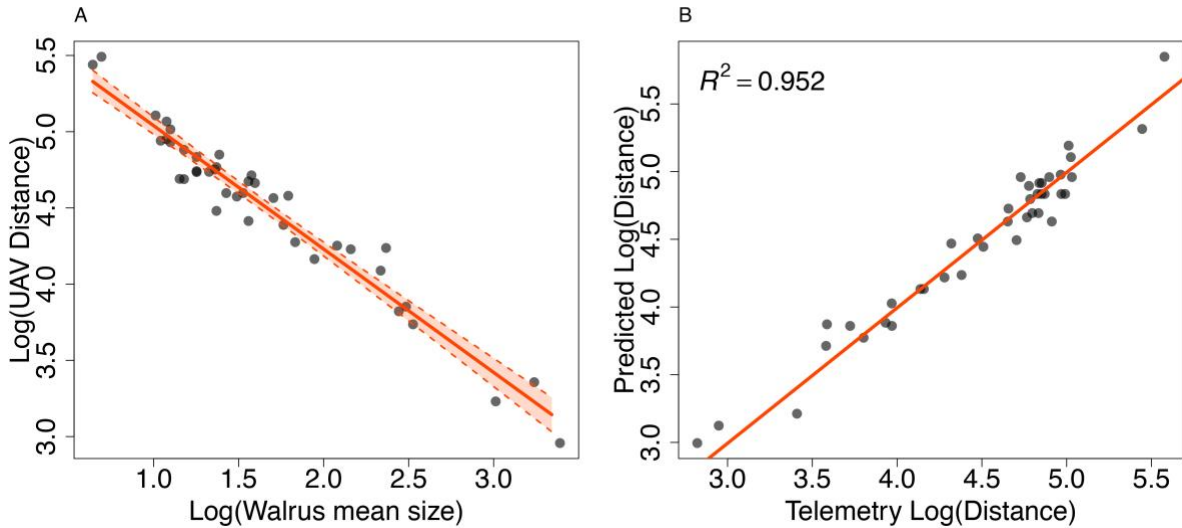

Figure A. Relationship between distance to RPAS and harbour seal size on Phantom 4 Pro footage, applying a logarithm transformation to both variables. The mixed linear model with 95% confidence intervals is plotted in red. B: Validation of the Phantom 4 Pro distance model for harbour seals, on Figure A.A. The regression line is plotted in red, yielding to an R2=0.886.

To validate the Phantom 4 Pro model on footage from Mavic Air, we obtained predicted distance values from a set of size measurements and plotted them against the corresponding telemetry distance values, obtaining an R2=0.94 in the linear regression (t=17.382, p=2.92e-12) (Figure B).

Following the methodology described for harbour seal Phantom 4 Pro footage, we fitted a model for walrus footage from Phantom 4 Pro, presented in Equation 5 (Figure C.A).

Similarly, we validated the model by plotting predicted distance values against telemetry values in a new set of data points and fitted a single regression, which yielded an $R^2=0.95$ (t=28.309, p<2e-16), (Figure C.B).
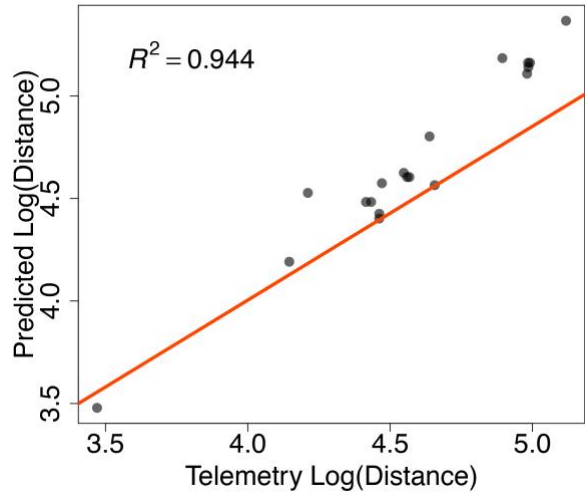
$$LDist_{ij} = 5.8484 - 0.8092\ LSize_{ij} + F_j + \varepsilon_{ij} \qquad (5)$$

$$\text{where } f \sim N\ (0,\ 1.693e\text{-}06^2)$$

$$\text{and } \varepsilon \sim N\ (0,\ 0.127^2)$$

Figure C. A: Relationship between distance to RPAS and walrus size on Phantom 4 Pro footage, applying a logarithm transformation to both variables. The mixed linear model is plotted in red with a 95% CI. B: validation of the Phantom 4 distance model for walruses, on Figure C.A. The regression line is plotted in red (R²=0.95).

Appendix D. Autocorrelation plots

The selected GLMMs for harbour seals yielded low autocorrelation likely because of the relatively long time-windows between samples, 10 seconds, compared to the length of most flights, between two and three minutes.
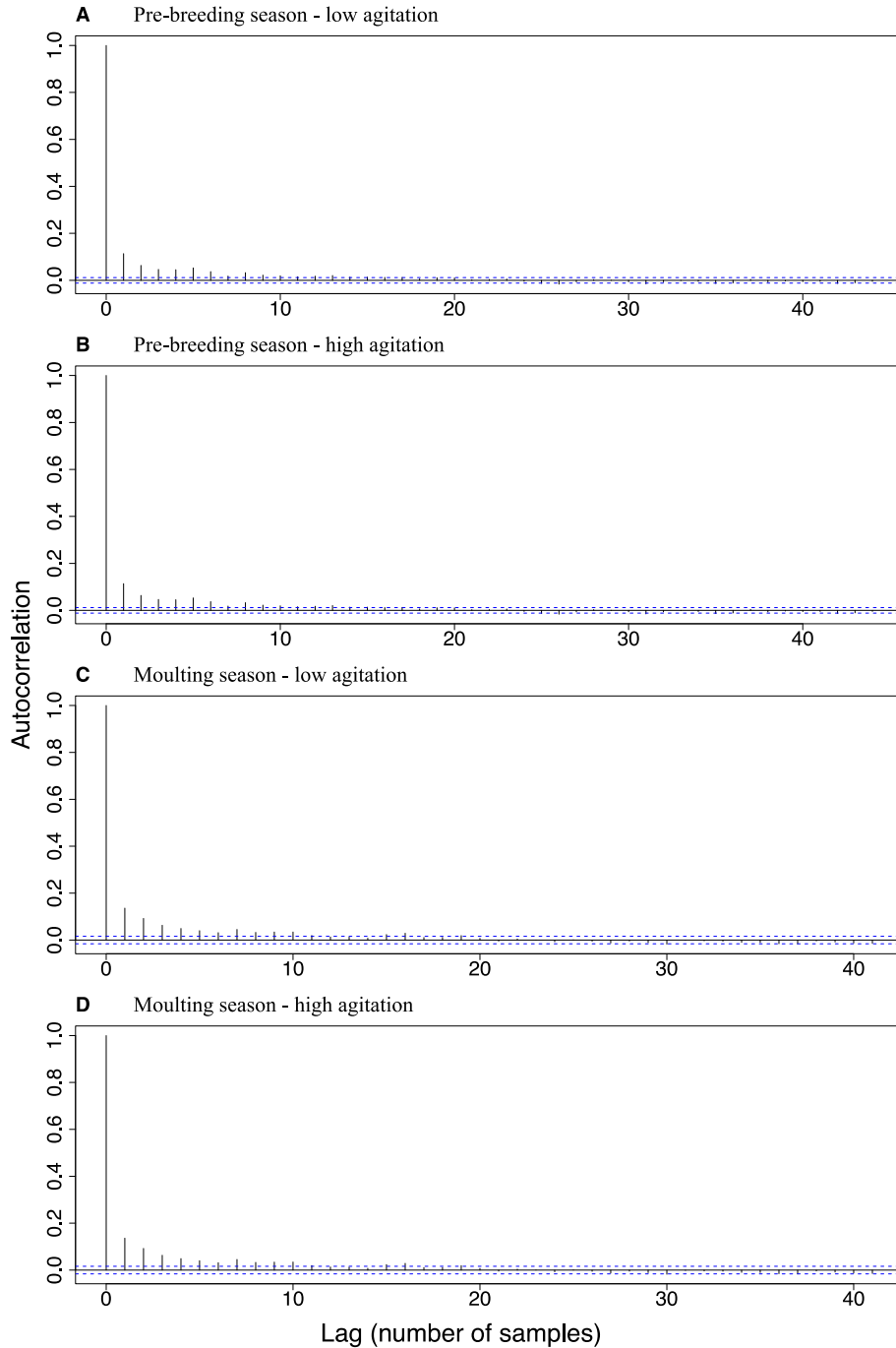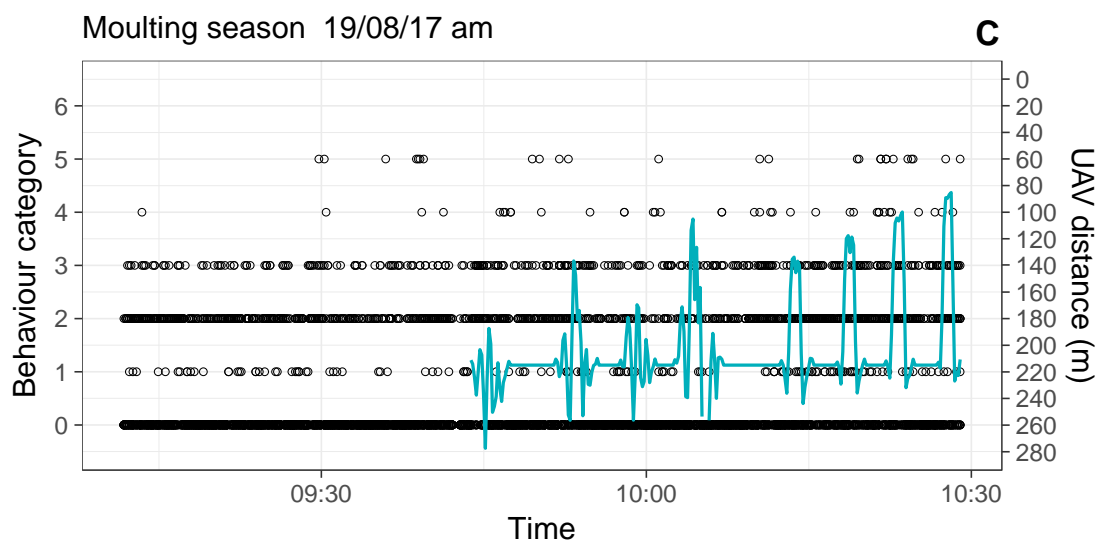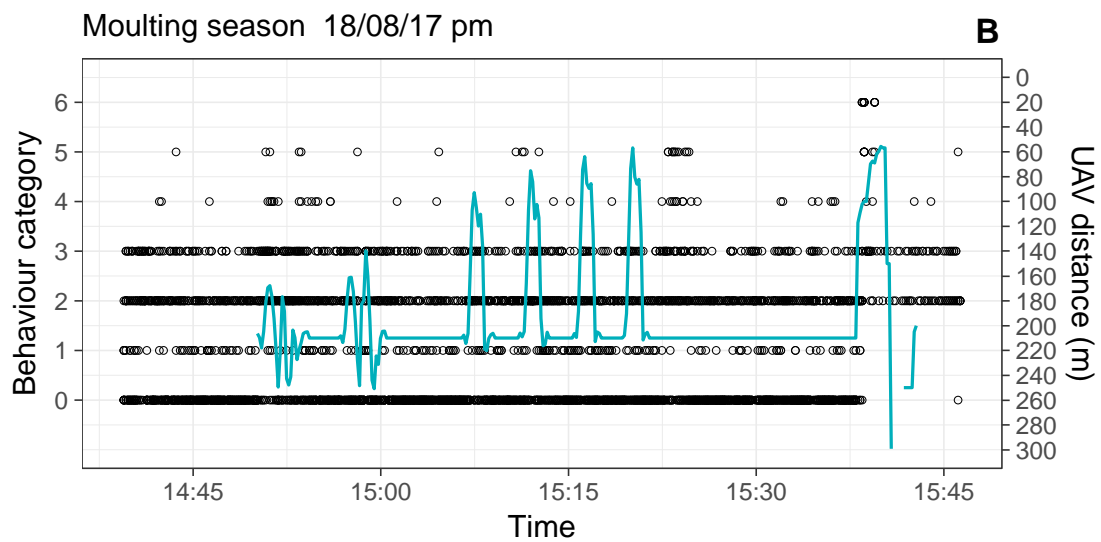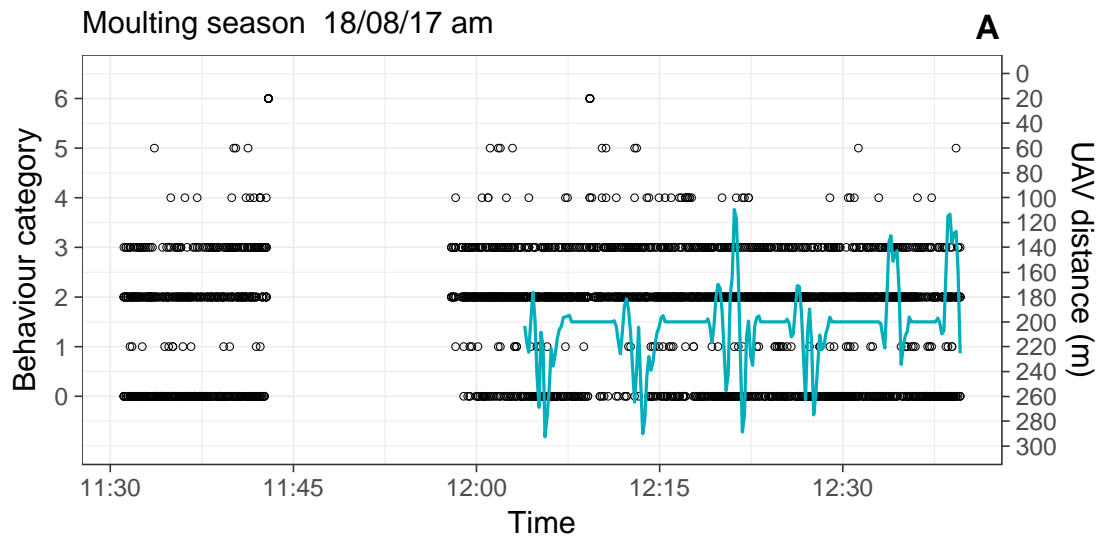

Figure D. Auto-correlation plots for the harbour selected models. A and B correspond to the selected models for the pre-breeding season with low and high agitation behaviour as a response variable, respectively. C and D correspond to the selected models for the moulting season with low and high agitation behaviour as a response variable, respectively.
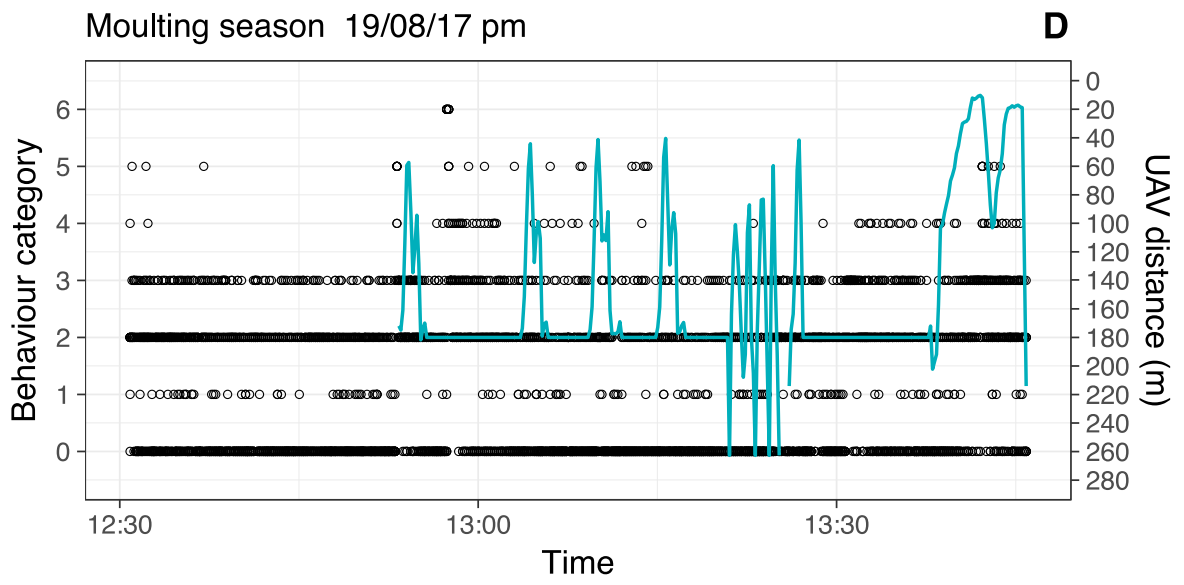
Appendix E. Raw data: behaviour scores and RPAS distance

Behaviour data for all flight sessions on harbour seal and walrus disturbance experiments, alongside with the corresponding RPAS flight distances.

Moulting season 19/08/17 pm **D**

Pre-breeding season 25/05/18 am **E**

Pre-breeding season 25/05/18 pm **F**

VII

Pre−breeding season 27/05/18 **G**

Pre−breeding season 28/05/18 **H**

Pre−breeding season 29/05/18 **I**

VIII
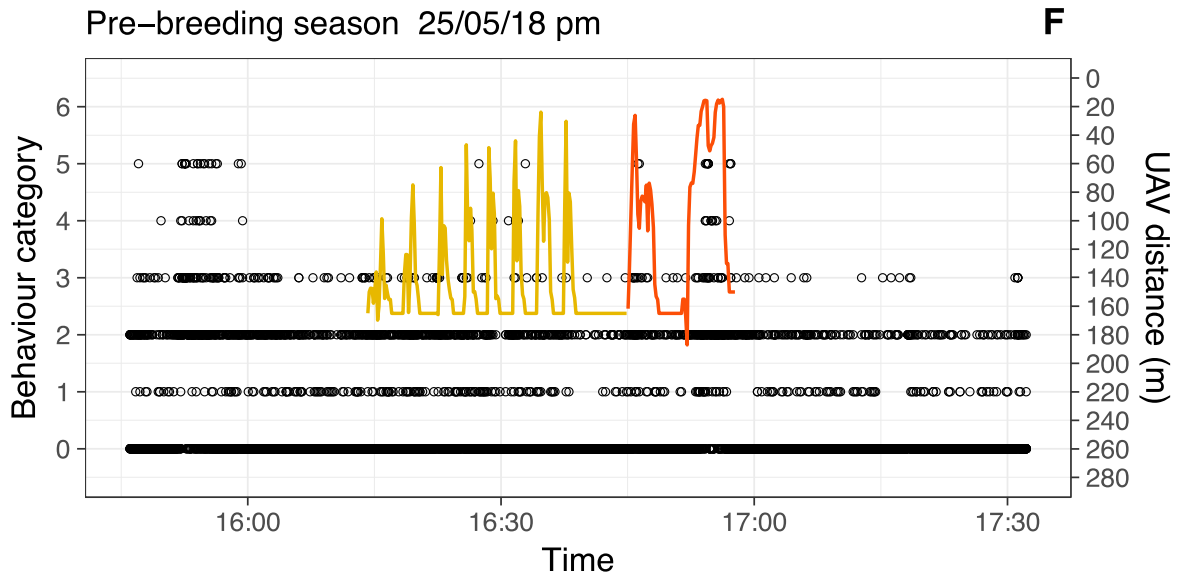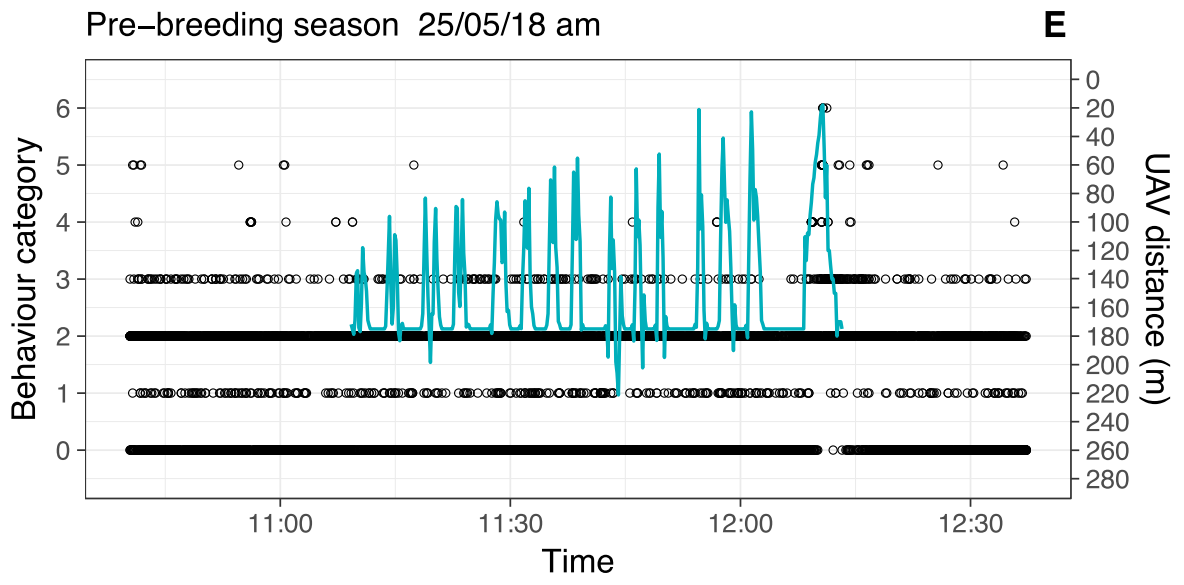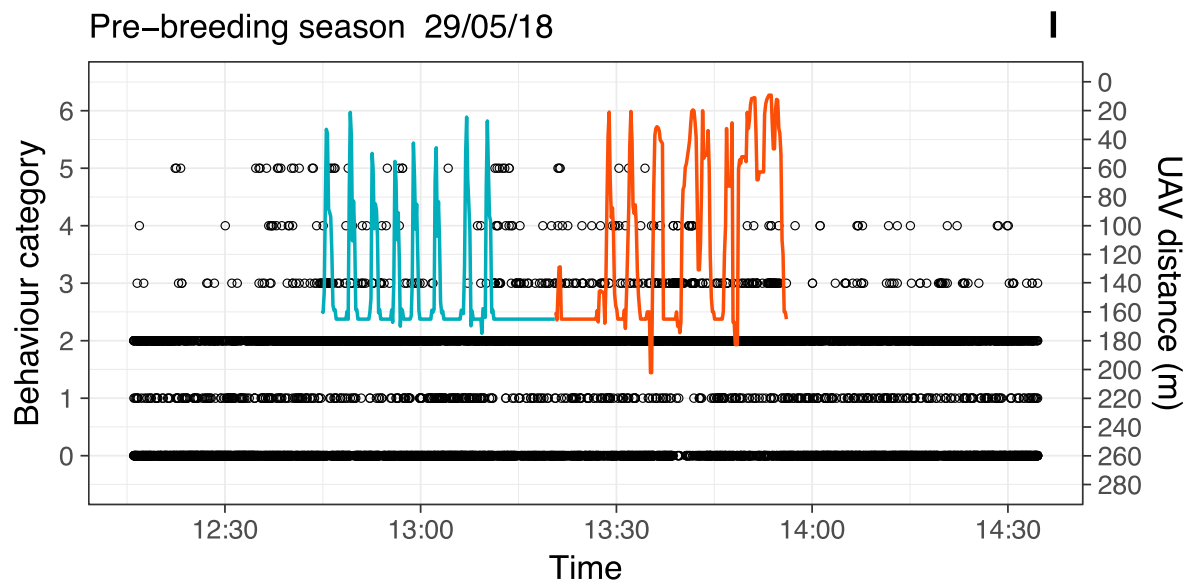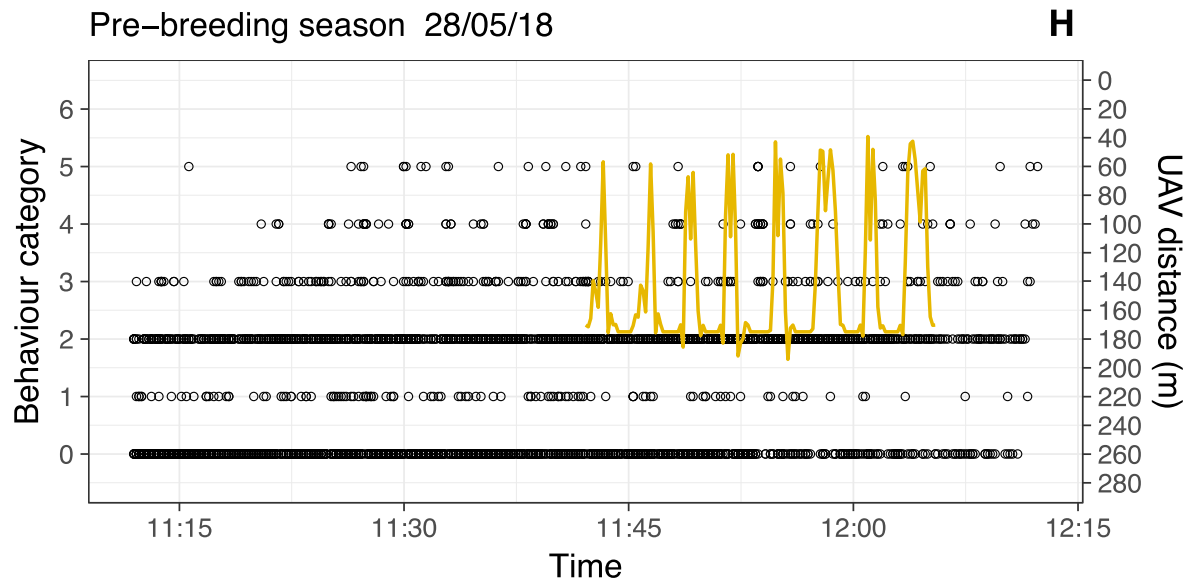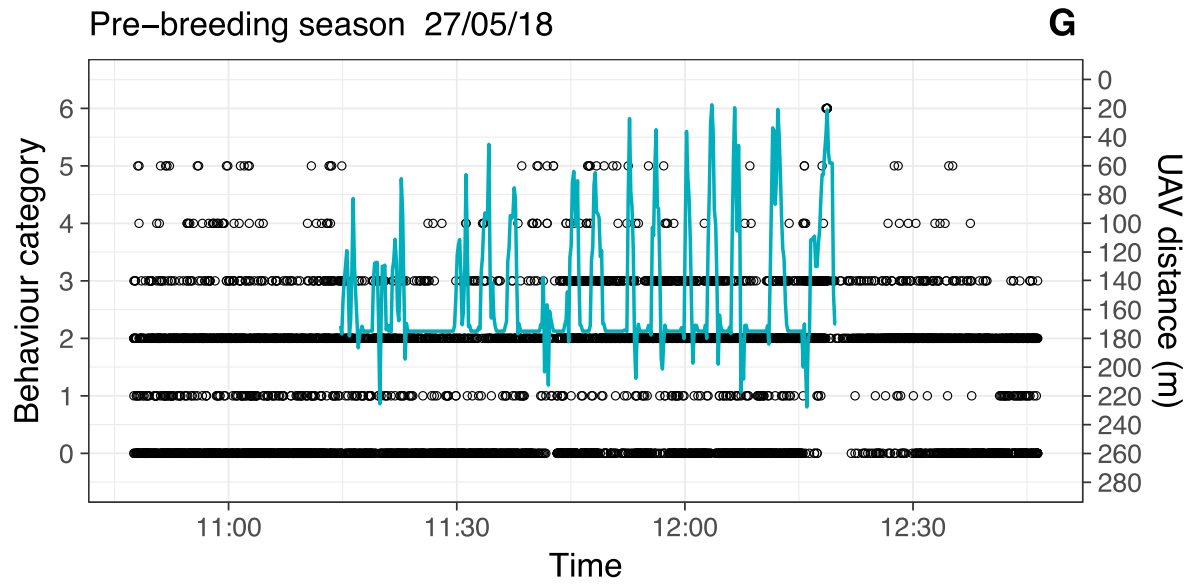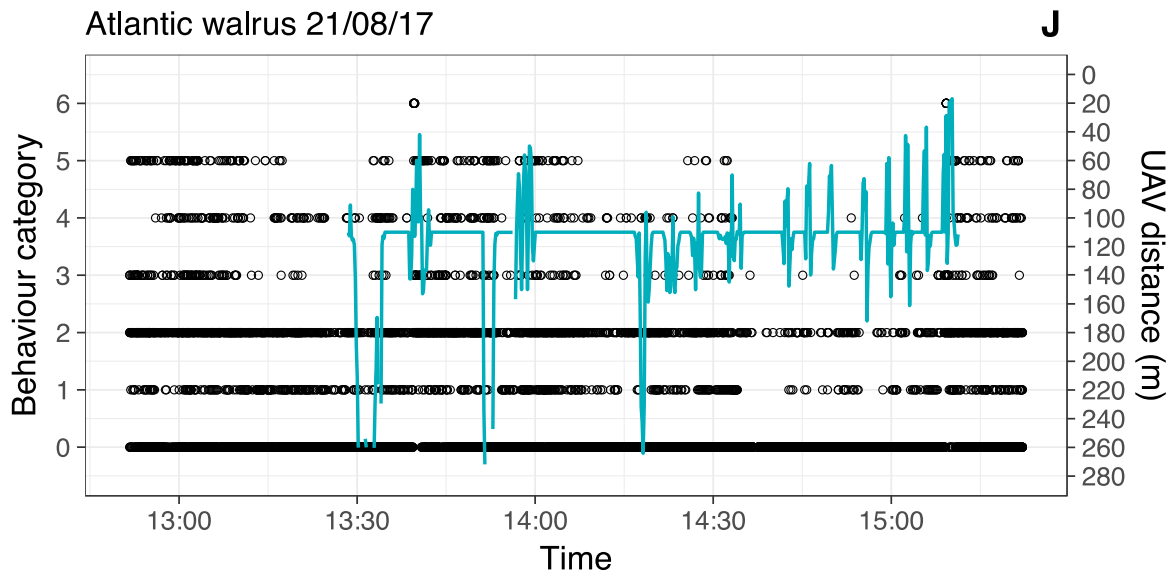
Figure E. Experimental flight sessions over harbour seals and Atlantic walruses. The scatterplots represent behaviour scores for all fo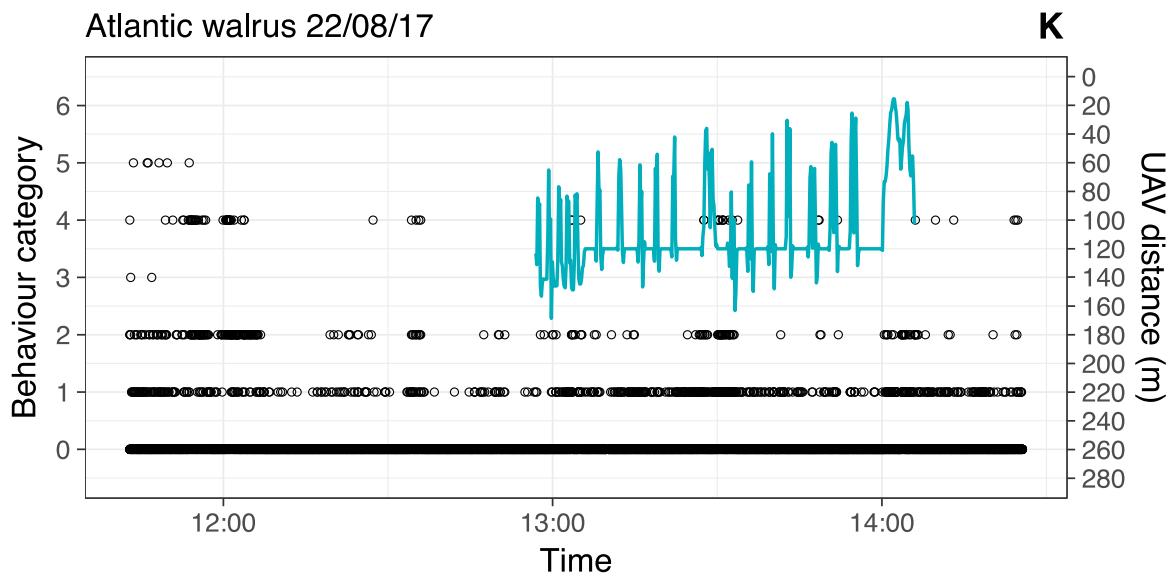cal individuals in each session. RPAS distance to the haul-outs is shown on the secondary y-axis. Blue profiles correspond to flights with Phantom 4 Pro, yellow profiles to Inspire 2 and orange profiles to flights with Mavic Air.

Appendix F. Effect of pre-programmed flights on harbour seal behaviour

This appendix contains the plot for the model that excludes the effect of manual flights during the moulting season, presented in Section 3.1.4.

Figure F. Effect of RPAS distance for the pre-programmed flights during the moulting season on (A) high-agitation behaviour and (B) low-agitation behaviour of harbour seals. Fitted estimates from the models (solid lines) are represented along with CIs (polygons) calculated from the fitted models.
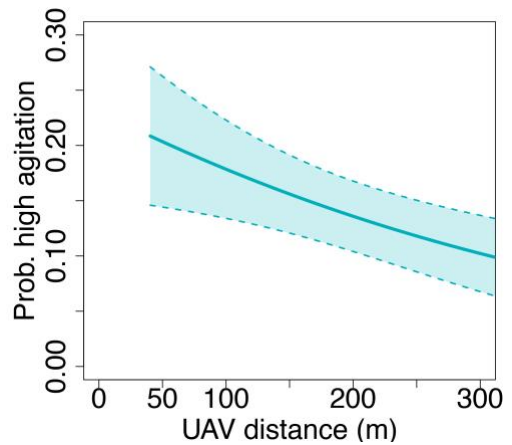
Appendix G. RPAS acoustic characterisations: horizontal flights

Table A. Broadband sound pressure levels (SPL) (dB re 20 µPa) calculated at frequencies between 0.15 and 24 kHz for 1 s periods for horizontal flights during RPAS acoustic characterisations. For each flight at altitudes of 100, 80, 60, 40, 20 and 10 m, SPL were retrieved for 1s flight periods corresponding to horizontal distances of 300, 250, 200, 150, 100, 80, 60, 40, 20, 10 and 0 m to the SM4. Flights were performed with four different RPAS: Inspire 2, Phantom 3 Standard, Mavic Platinum and Mavic Air.

					Horizontal distance to SM4 (m)						
Inspire 2	**300**	**250**	**200**	**150**	**100**	**80**	**60**	**40**	**20**	**10**	**0**
100	44.34	44.83	45.54	47.63	49.20	50.56	51.36	52.02	51.91	52.62	52.69
80	47.49	46.15	45.74	47.17	49.37	51.41	53.81	50.20	49.44	48.71	50.02
60	45.56	45.41	44.81	45.54	45.68	46.34	49.71	52.17	54.91	56.99	57.76
40	40.88	41.65	42.81	42.53	47.39	50.62	49.48	56.38	55.51	56.73	58.64
20	44.34	42.62	40.83	44.20	45.83	46.78	48.65	53.59	55.62	62.11	67.19
10	43.75	42.99	44.50	42.36	43.07	44.52	46.50	52.41	66.34	70.39	68.91
Phantom 3 Std											
100	44.84	44.34	44.31	45.75	46.08	47.49	49.08	50.43	50.53	50.36	51.20
80	41.09	43.24	42.66	43.21	44.91	46.82	48.28	50.38	50.29	50.83	50.57
60	42.20	44.52	44.52	45.03	46.21	47.63	50.38	52.70	53.77	53.46	55.04
40	44.04	43.07	42.78	42.63	43.59	45.83	47.55	51.21	55.29	56.52	55.91
20	42.07	40.85	41.82	44.10	43.83	45.02	48.89	53.40	56.67	63.60	60.24
10	42.35	43.73	43.70	44.65	44.48	44.92	46.26	51.03	54.51	57.35	61.10
Mavic Platinum											
100	41.77	41.86	42.42	43.52	44.06	44.23	45.43	46.17	47.97	48.04	47.70
80	40.68	40.64	42.01	42.64	44.14	44.31	46.00	49.43	47.63	47.19	46.18
60	38.90	40.00	39.69	40.12	43.67	44.02	45.09	47.52	48.71	50.57	50.40
40	39.96	40.47	40.59	41.39	43.27	46.72	47.69	51.89	53.94	52.35	50.35
20	40.23	40.79	41.61	41.62	42.62	42.87	44.54	45.37	50.28	54.31	59.05
10	40.98	41.09	40.47	42.45	41.43	43.12	44.06	46.83	55.73	61.62	61.84
Mavic Air											
100	43.21	43.81	44.78	47.75	46.37	46.90	47.10	47.81	48.69	48.61	48.18
80	42.43	41.55	43.50	45.53	45.02	44.31	45.34	47.80	48.39	48.17	47.38
60	42.60	43.21	43.91	43.44	44.07	46.35	47.95	48.59	50.86	51.12	53.39
40	42.88	44.14	42.30	44.03	45.10	44.90	47.07	50.53	52.36	52.37	50.66
20	44.12	44.88	45.46	45.87	45.04	45.38	45.27	45.57	56.23	58.62	59.34
10	43.54	44.24	44.26	44.32	42.73	42.89	44.52	48.70	55.28	62.75	64.02

IX

Altitude (m)

Appendix H. RPAS acoustic characterisations: vertical flights

Table D. Broadband sound pressure levels (SPL) (dB re 20 µpa) calculated at frequencies between 0.15 and 24 kHz for 1 second periods for vertical flights during RPAS acoustic characterisations. We flew four vertical profiles: an ascent and descent flown at a constant speed of 2m/s (V.c ascent and descent), and an intermittent ascent and descent, with sudden accelerations from 0 to 2 m/s at altitudes of 100, 80, 60, 40, 20 and 10 m over the SM4 (V.i. ascent and descent). SPL were retrieved for each 1 s flight period corresponding to the altitude levels indicated. Flights were performed with four different RPAS: Inspire 2, Phantom 3 Standard, Mavic Platinum and Mavic Air.

Inspire 2	V.c. Ascent	V.c. Descent	V.i. ascent	V.i. Descent
100	42.8	50.55	48.87	55.17
80	44.37	57.5	50.97	57.41
60	44.73	59.82	53.66	55.20
40	45.76	63.7	52.55	66.50
20	52.37	69.47	63.36	68.28
10	66.87	72.67	62.58	73.67
Phantom 3 Std				
100	47.23	48.92	46.42	48.48
80	47.96	51.88	49.79	48.93
60	44.97	50.28	46.34	48.31
40	49.70	56.99	49.12	53.94
20	59.99	61.28	59.77	64.29
10	66.48	67.09	67.40	70.04
Mavic Platinum				
100	41.37	46.52	41.05	45.07
80	42.46	45.32	40.1	47.96
60	42.74	49.13	41.03	48.6
40	44.44	50.94	44.92	48.5
20	47.32	58.99	53.42	57.52
10	54.04	60.27	56.52	62.65
Mavic Air				
100	42.43	43.72	41.8	46.13
80	42.57	46.76	42.61	43.99
60	43.57	47.31	44.82	50.55
40	45.69	50.32	47.75	52.15
20	47.23	57.26	52.23	52.31
10	53.78	61.86	56.72	64.18

Altitude (m)