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Arctic UAS study

Arctic threats to safe design of Unmanned Aerial Systems

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Disclaimer

Summary

Unmanned Aerial Vehicles (UAV's) as they are designed today are vulnerable for arctic conditions. Both the UAV industry and the UAV operators need more knowledge about how safe design can be implemented for UAV's with regards to surviving under arctic conditions.

In order to find out what is required to survive under arctic conditions, arctic conditions must be defined.

This report describes arctic conditions and is a first attempt to establish a common toolbox for establishing a knowledge base related to safe design of UAV's for arctic conditions.

The arctic UAV study has done extensive reachout to collect data from both civilian and military UAV pilots. The result of this data collection is presented in this study.

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1. About the study

The arctic UAV study was given as a task from Ubiq Aerospace AS to NORCE Norwegian Research Center AS 17.02.2022.

This arctic UAV study had no strings attached from Ubiq Aerospace AS with regards to what type of arctic threats that should be addressed. The task was to establish a knowledge base related to arctic threats which can be addressed through improved technical design for unmanned aircraft systems (UAS).

The threats which are addressed were identified through a combination of literature studies and reachout to both military and civilian UAV end-users during the winter and spring 2022.

This arctic UAV study is intended to identify, and if possible, quantify arctic threats to UAV systems. This arctic UAV study has defined arctic conditions, and from this basis quantified the arctic threats as far as possible through data collection. Data has been collected from arctic UAV pilots and operators.

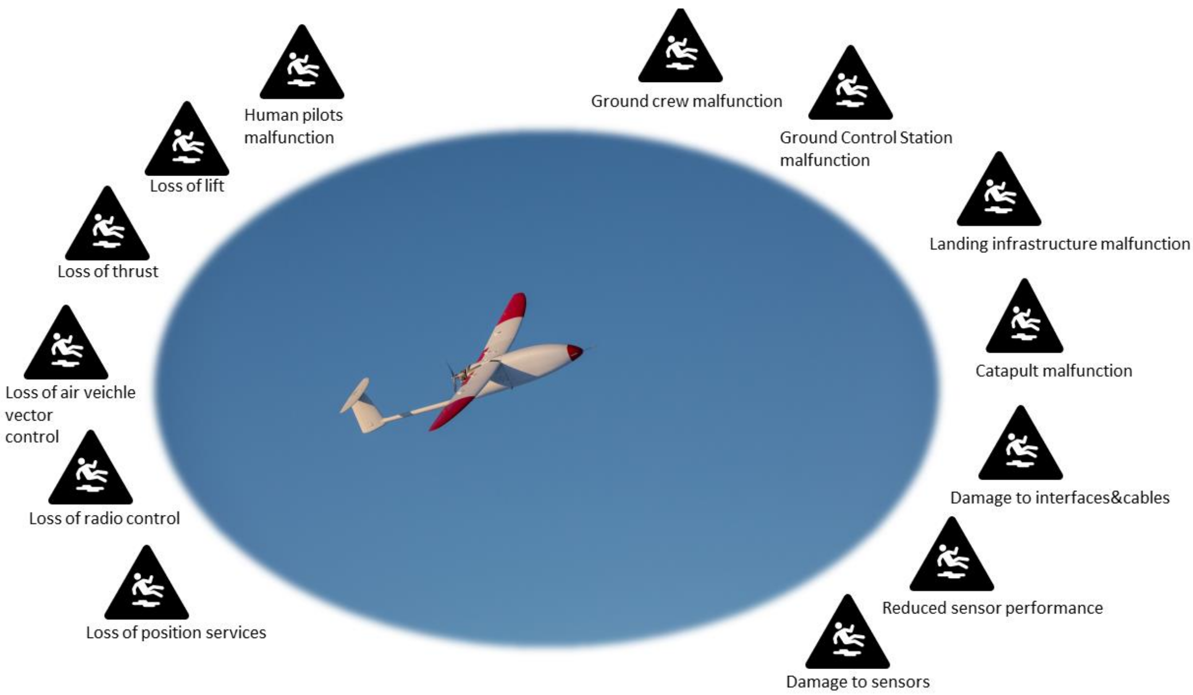


Figure 1: Arctic threats to unmanned aircraft systems (NORCE, 2022)

1.1. Background

1.1.1. Ubiq Aerospace AS

Ubiq Aerospace AS is a leading provider of solutions that enhance the capabilities of drones, air taxis, helicopters, and conventional passenger-carrying aircraft. By innovative technologies, Ubiq Aerospace combine world-leading research and highly creative engineering to deliver autonomous solutions to critical problems.

Their concept D•ICE™ is an intelligent ice detection and protection solution, designed to enhance weather robustness for drones, air taxis, and helicopters enabling operations, every day, worldwide. It allows for safe takeoff in potential icing conditions and sustained operations in icing conditions.

More information about Ubiq Aerospace AS is available through their website:
https://www.ubiqaerospace.com/

1.1.2. NORCE Norwegian Research Center AS

NORCE is Norway's leading research institute with a presence along the entire Norwegian coast. Maintaining a strong local presence facilitates close collaboration with unique specialist communities, centres of expertise, the business community and government authorities.

NORCE has led the way in UAV development since it was granted Norway's first flight permit for UAV BLOS operations in 2005. NORCE perform technical and conceptual UAV development in all perspectives of unmanned aviation, ranging from designing air vehicles via designing navigation solutions and sensors to advanced operation concepts.

What differs NORCE from all the other scientific institutes is the ability to perform physical proof of concept in all designs. (That's flyin' it, not just publishing a paper about it)

More information about NORCE is available through their website:
https://www.norceresearch.no/

1.2. Method

This arctic UAV study is based on a combination of literature studies and data collection.

Data collection is applied for justification of the threat vectors identified through dissemination of data from the literature studies.

1.2.1. Background – literature study

The topics for this arctic UAV study was established on basis of relevant literature and institutional knowledge within the Norwegian UAV BLOS community with regards to what threat vectors which can affect unmanned aircraft operations in the Arctic.

The Norwegian UAV BLOS community (The "tribe" BLOS-gjengen) is described separately by the Norwegian defence research establishment (Hansbø, 2019).

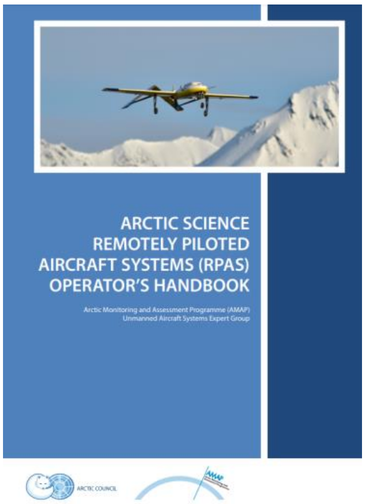
Sources additional to tribal knowledge in the Norwegian UAV BLOS community are few and scattered within the arctic landscape of science.

Searches in science databases for relevant background was done using two different approaches:

1) Keyword searches, such as: Arctic, threat, crash, operations, UAV, UAS, unmanned, drone, safe and polar.
2) When relevant science reports have been identified, the author was contacted via e-mail and/or telephone. The purpose was to find out if he/she knew if anybody else had made a report which could help this Arctic UAV study to establish background.

A few organizations have spent resources in open documentation for safe UAV design and/or operations in the arctic. Some organizations have published themselves, some have hired consultants to publish the documentation.

Examples of organizational open documentation:



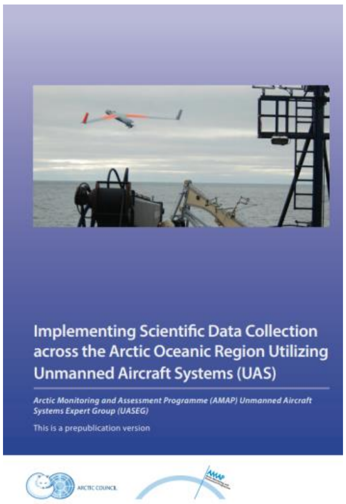


Figure 2: Handbooks by AMAP Unmanned Aircraft Systems Expert Group ((UASEG), et al., 2015)


SINTEF

2019:01284 - Åpen

Rapport

Bruk av droner i nordområdene

HMS forhold knyttet til bruk av droner i petroleumsaktiviteten i nord

Forfattere
Trond Bakken
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SINTEF Digital
Mathematics and Cybernetics
2019-12-09

Figure 3: Scientific report ordered by Petroleum Safety Authority Norway (Bakken, et al., 2019)

1.2.2. Data collection – questionnaire

Data collection for this arctic UAV study has been a combination of direct outreach to military and civilian UAV end-users in arctic countries.

Relevant respondents were identified both national and international by professional and social network, both military and civilian. An attempt to find military respondents at the 2022 “Cold response” NATO FTX was done but stranded on lack of interest from the Norwegian air force. Norwegian army and coast guard has helped a lot on collecting data from relevant respondents.

The data collection was anonymous with regards to personal information and information about the UAV end-user’s organization. It was a Microsoft forms questionnaire, shared by e-mail to relevant UAV end-users which had experience from UAV operations in the Arctic.

The questionnaire was prefixed by a definition of context for the study: **What defines arctic conditions?** (See figure 4, next page)

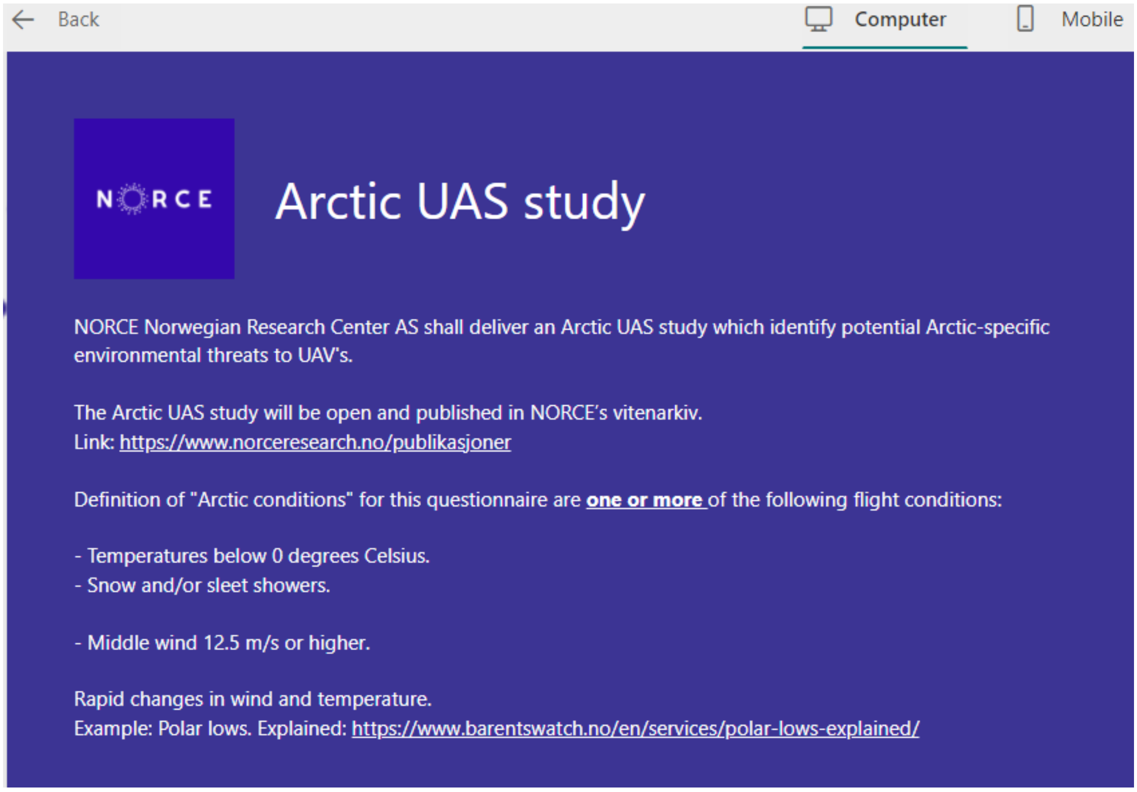


Figure 4: NORCE definition of arctic conditions (NORCE, 2022)

1.2.3. Data collection - outreach – civilian and military UAV operators in the Arctic

This arctic UAV study has collected data through outreach to UAV operators which NORCE could find through focused searches in open sources and exploring social and professional networks.

It's quite easy to locate the UAV operators which potentially can contribute. As far as NORCE has learned through the arctic UAV study there are no knowledge hubs focusing on arctic threats to safe design of UAV systems.

The (few) UAV operators which have operated in arctic conditions are both military and civilian. They both have different customers and competitors. For instance, is the enemy a competitor in the arctic UAV business for military UAV operators. The chain of command and/or your military task force are the customers for a military UAV operator.

A civilian UAV operator can provide its UAV services to different customers. Even customers who compete with each other can be customers of a civilian UAV operator.

Based on the outreach activity in this arctic UAV study we experience most UAV operators and UAV pilots are quite happy to share their experiences towards establishing a base of knowledge for safe design of UAV systems for arctic conditions.

1.2.4. Arctic knowledge – why is this important to the UAV industry?

Knowledge and leadership are key factors for solving any challenge which face organizations. If the problem at hand is important enough, the organization will lead accordingly, and resources will made available to solve the problem.

Safe design of UAV has not been an important problem to address for any of the polar states.

So far.

In January 2022 two military intellectuals put this challenge on the agenda (Chase & Hanes, 2022). They set the arctic UAV challenge into general warfare context:

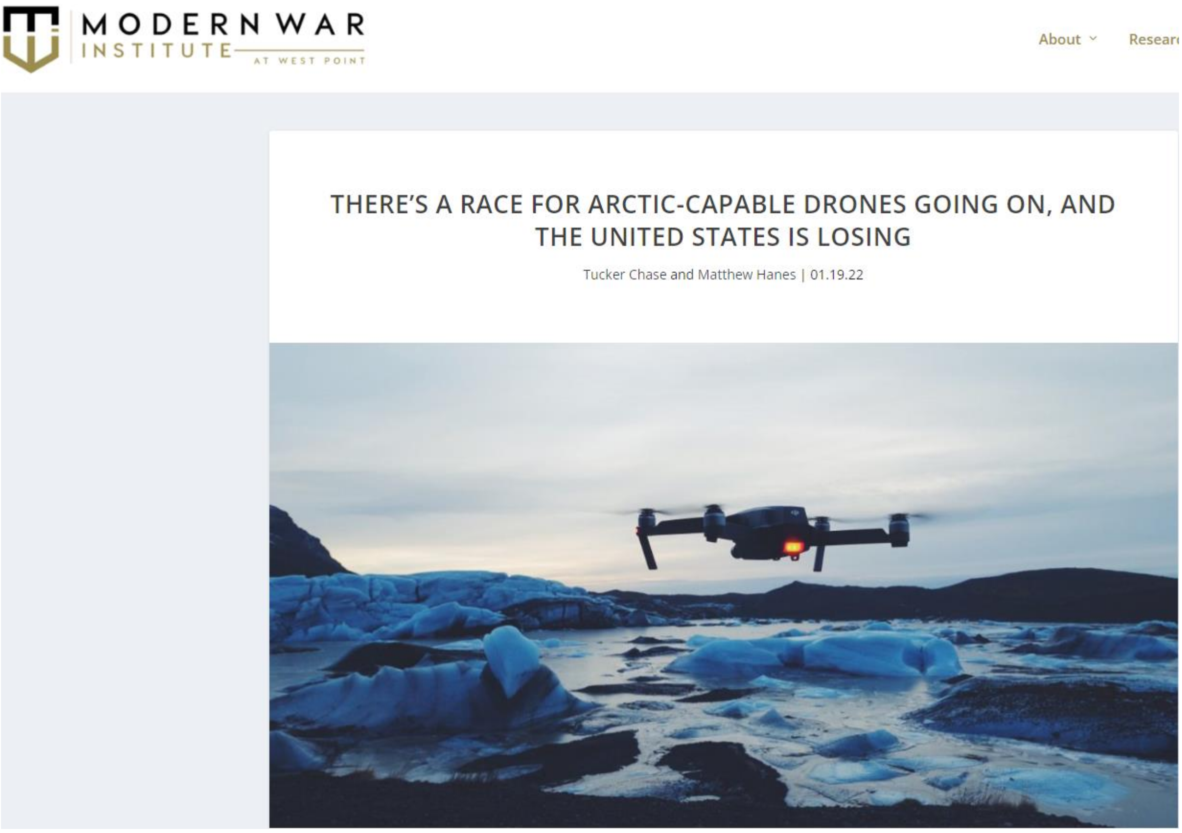


Figure 5: Military intellectual debate (Chase & Hanes, 2022)

"Right now, the unmanned aerial system is the IED of the next ten to twenty years"

-General James McConville, Chief Staff of the Army, July 30, 2021 on the Irregular Warfare Podcast (Jones & Atwell, 2022)

The US Army intellectuals identifies the problem: Russia has already focused their military capabilities to be able for operations in the Arctic. For a decade.

In 2019, Russia's equivalent of the Defence Advanced Research Projects Agency announced a drone capable of four days non-stop flight in the Arctic.

In 2018, during the 8th international forum "The Arctic: the present and the future" the Kalashnikov small arms manufacturer presented the Zala arctic drones, focused on KYB-UAV which basically is a loitering munition. The KYB-UAV (figure 6) has its own GIRSAM alternative navigation system for navigation amid suppression or absence of GPS or GLONASS (TASS, 2018)

The Russian invasion of Ukraine in February 2022 gave massive media coverage for the use of uav's from both sides.

Some of the factors identified by NORCE as arctic conditions were definitely present during the winter months of the Russian invasion. Russian soldiers were reported evacuated from the frontline due to frostbite.

History will tell if the Russian focus on arctic-capable UAV-systems provided an operational edge against their opponents.

Figure 6: KYB-UAV by Kalashnikov (Kalashnikov, 2019)

1.2.5. Existing data and knowledge

Existing empiric data relevant for safe UAV design with regards to arctic conditions are few, scattered and/or not openly shared. NORCE assume this is mainly due to the following three factors:

1) Russia's military development of UAV capabilities 2000-> has not resulted in any big sales to civilian, western end users. Russian military end-users simply do not wish to share their arctic experiences and challenges to the western world.
2) NATO development of UAV capabilities 2000-> has focused on the asymmetric warfare in Afghanistan and Iraq. It has been no preparation in equipment, training or tactics for the real thing now happening in Europe. Winter warfare against a symmetric opponent in the Arctic has been no priority capability for NATO. The result being no capable equipment, training or tactics has generated the experiences needed for addressing the arctic threat vectors to safe UAV design for an arctic environment.
3) No substantial civilian governmental contracts for UAV services have been funded by any arctic states in the western world 2000->. The result being only experimental and/or demonstrator activity by UAV operators in the Arctic 2000. That's why no arctic-capable civilian UAV equipment, civilian UAV customer demands and/or UAV operator competence is present in the Arctic. The low number of operators and customers for UAV

services in the Arctic generate no technical design development, no lessons learned, or any arctic knowledge being shared.
Technical development for UAV systems 2000-> have been focused to regions where customers pay for UAV services:

- EMSA
- Military customers, activity in the Middle east

Not a lot of relevant reports could be found to help creating a fundament for this arctic UAV study. This is interesting.

Why is it so? Reasons could be:

- The few (governmental) organizations which operate UAV in the Arctic are reluctant to share their experiences and challenges.
- UAV manufacturers which deliver UAV systems to customers which operate in the Arctic are not motivated to share their technical insight which could resolve arctic problems in UAV operations.
- UAV design is driven by the market from airworthiness and robust design to low-cost design. Why spend millions of dollars for an unmanned capability if 75% of the operational window already is possible to cover by available, affordable and wastable consumer drones by the numbers because of low cost?

This arctic UAV study could be a baseline for all UAV operators and manufacturers to start methodical work towards better survivability for UAVs under arctic conditions.

1.2.6. Who’s solving the Arctic problem now, and 5-10 years to come?

As mentioned in 1.2.4 there’s a race going on for arctic-capable drones.

Russia has started this race ahead of the western world.

The U.S military branches has made their arctic strategies. None of them mention technology development focused on making the existing UAV-systems able to operate in arctic conditions.

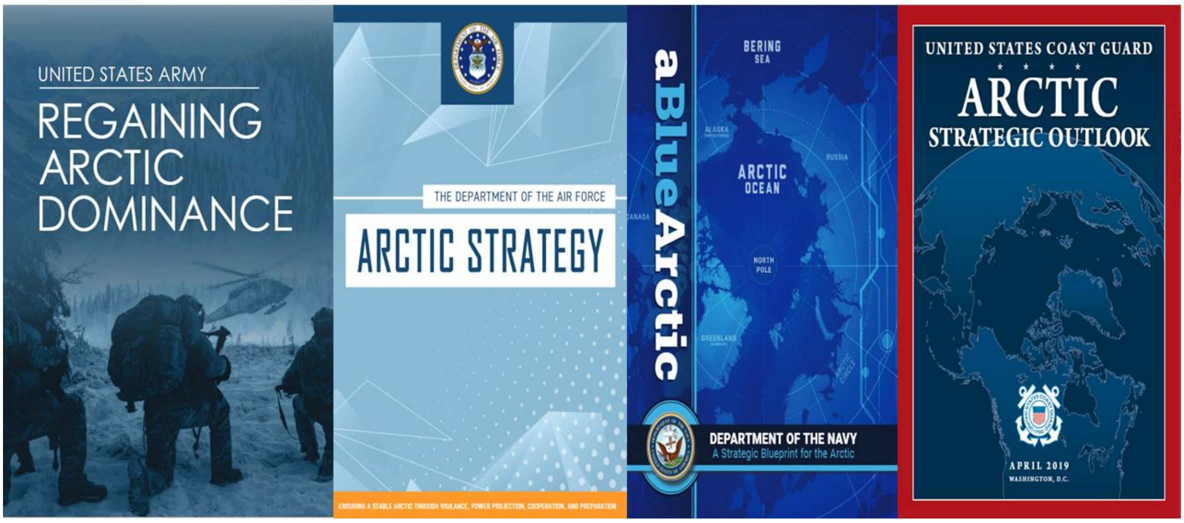


Figure 7: The U.S military branch arctic strategies (U.S government 2019-2021)

The only arctic country which has allocated funds for rendering their military forces capable to operate UAV-systems in the arctic is Denmark.

Denmark made a political decision on an arctic capability package in February 2021. Among the arctic capabilities is long-range UAV’s (750 million DKK) and smaller UAV’s (60 million DKK). See figure 8 on the next page.

FORSVARSMINISTERIET

Aftale om en Arktis-kapacitetspakke

Forsvarsforligskredsen har besluttet at styrke Forsvarets tilstedeværelse og overvågning med kapaciteter for ca. 1,5 mia. kr.

Danmark, Færøerne og Grønland har et særligt forsvars- og sikkerhedspolitisk ansvar i Arktis og Nordatlanten. Derfor har regeringen besluttet, at merbevillingen på 1,5 mia. kr. i 2023 fra Tillægsaftalen fra 2019 skal udmøntes på kapaciteter til overvågning og en øget tilstedeværelse i området.

Illustrativ oversigt over kapaciteter i pakken

Forsvarsforligskredsen har med baggrund i Forsvarets militærfaglige anbefaling aftalt, at der investeres i kapaciteter, der skal styrke luftrumsovervågning i Nordatlanten, sikre en bedre integration og analyse af overvågningsdata samt nye ubemandede kapaciteter i form af satellitter og droner til at overvåge de store hav- og landoverflader i Arktis og i Nordatlanten. Kapaciteter, der gør, at Forsvaret kommer til at være i front med den teknologiske udvikling. Samtidig imødekommes ønsker fra NATO til Danmark, der specifikt har efterspurgt langtrækkende overvågningsdroner med signalindhentningskapacitet og en luftvarslingsradar på Færøerne.

Behov for militær tilstedeværelse og overvågning i Arktis og Nordatlanten

Ruslands opbygning af militære kapaciteter i regionen medfører sammen med øget økonomisk og forskningsmæssig aktivitet en mere uklar sikkerhedspolitisk situation. Det stiller krav til Forsvarets evne til at overvåge fremmed aktivitet, håndhæve Kongerigets suverænitet og opstille bidrag i allieredes og NATO's øvelser i området. De sikkerhedspolitiske udfordringer kan kun løses i et tæt samarbejde med vores allierede. Derfor vil Forsvaret med aftalen også udstationere forbindelsesofficerer til nære arktiske allierede.

Samfundsnytte for alle dele af rigsfælleskabet

Forsvarets kapaciteter skal implementeres i samarbejde med – og være til gavn for – Færøerne og Grønland. Styrkelsen af Forsvarets overvågningskapaciteter vil samtidig medføre en bedre evne til eftersøgnings- og redningsopgaver, beredskabsopgaver, miljøovervågning, fiskerikontrol, klimaovervågning, klimaforskning mv. Med en Ny Forsvarsuddannelse i Grønland styrkes Forsvarets tilknytning til Grønland og muligheden for at flere grønlændere kan få fast ansættelse i Forsvaret. Samtidig vil uddannelsen øge de lokale beredskabskompetencer i Grønland. Etableringen af nye faciliteter i alle dele af rigsfælleskabet skal komme lokalt erhvervsliv til gode, ligesom nye faciliteter og kapaciteter skal bygges og styrkes under hensyntagen til et så lille klimaaftryk som muligt.

Kapaciteter og initiativer

- Varslingsradar på Færøerne (390 mio. kr.)
- Langtrækkende overvågningsdroner (750 mio. kr.)
- Satellitovervågning (85 mio. kr.)
- Jordstation (40 mio. kr.)
- Satellitkommunikation (drift)
- Kystradarer i Grønland (20 mio. kr.)
- Mindre droner til brug på skibe (60 mio. kr.)
- Styrket analysekapacitet (20 mio. kr.)
- Klassificeret taktisk kommunikation (40 mio. kr.)
- Ny Forsvarsuddannelse i Grønland (50 mio. kr.)
- Øvelsesaktivitet (35 mio. kr.)
- Kompetencepulje på satellitområdet (10 mio. kr.)
- Forbindelsesofficerer (drift)
- Samarbejde med institutioner i Grønland (drift)

Anskaffelser for ca. 1,5 mia. kr. og afledte driftsudgifter for ca. 300 mio. kr. årligt.

Figure 8: Denmark's Arctic capability pack (Regeringen, 2021)

The danish arctic capability package is focused among other things into *"..putting the military forces in front of the technological development"* . Adding this into an actual funded procurement of different size UAV's is de facto solving the arctic problem for danish military needs.

This excellent example of focusing establishment of arctic capability towards solving the arctic problem for UAV operators (In this case: The Danish military) is an example worth following for all other western countries which have arctic ambitions.

2. The Arctic climate

The arctic climate as a threat to safe design of Unmanned Aerial Systems is possible to identify and quantify along different threat vectors:

1) Physical environment - the arctic seasons and weather.
2) Security environment - the arctic states.

2.1. Arctic seasons and weather – physical environment

Most commonly, scientists define the Arctic as the region above the Arctic Circle, an imaginary line that circles the globe at approximately 66° 33' N (dashed blue circle in figure 7). The Arctic Circle marks the latitude above which the sun does not set on the summer solstice and does not rise on the winter solstice.

Using this definition, the arctic includes any locations in high latitudes where the average daily summer temperature does not rise above 10 degrees Celsius.

At the North Pole, the sun rises once each year and sets once each year: there are six months of continuous daylight and six months of continuous night. At lower latitudes, but north of the arctic Circle, the duration of continuous day and night are shorter. (The National Snow and Ice Data Center (NSIDC), 2022)

Scientists apply different definitions when talking about the arctic. Some scientists define the Arctic as the area north of the arctic tree line (green line in figure 9), where the landscape is frozen and dotted with shrubs and lichens. Other researchers define Arctic based on temperature.

The Arctic is mostly covered by water, a lot of which is frozen. The glaciers and icebergs in the arctic are about 20% of the planet earth’s freshwater.

Most of the water in the arctic is liquid saltwater – the Arctic Ocean. Some part of the Arctic Ocean remains frozen through all the seasons. This is what scientist define as the polar ice cap. The polar ice cap is at the smallest during September month each year (Norwegian Meteorolgical Institute, 2022)

Figure 9: The Arctic (The National Snow and Ice Data Center (NSIDC), 2022)

This map shows three definitions of the arctic:

- The treeline **(Green).**
- The 10 degrees Celsius isotherm **(Red).**
- Arctic Circle at 66° 34' North. **(Blue, dotted).**

2.1.1. The Arctic seasons

The climates – and seasons – of the arctic vary a lot, depending on their latitude, proximity to the sea, elevation and topography.

Nevertheless, they all share certain “Arctic” characteristics.

Due to the high latitudes, solar energy is limited to the summer months. Although it may be considerable, its effectiveness in raising surface temperatures is restricted by the high reflectivity of snow and ice. Only in the central polar basin does the annual net radiation fall below zero. In winter, radiative cooling at the surface is associated with extreme cold, but, at heights a few thousand feet above the surface, temperatures as much as 11 to 17 °C warmer can often be found.

Temperature inversions such as this occur more than 90 percent of the time in midwinter in northwestern Siberia and over much of the Polar Basin. They also are common over the Greenland Ice Cap and in the sheltered mountain valleys of the Yukon and Yakutia. The lowest surface temperature ever recorded in North America was observed at Snag, Yukon (−63 °C), and even lower temperatures have been observed in Yakutia (−68 °C) and northern Greenland (−70 °C).

It has been customary to divide polar climates into two large groups, those corresponding to the climate of ice caps, in which no mean monthly temperature exceeds the freezing point (0 °C), and the tundra climates, with at least one month above 0 °C but no month above 10 °C.

One other division is to classify them as polar maritime climates, located principally on the northern islands and the adjacent coasts of the Atlantic and Pacific oceans, in which winter temperatures are rarely extremely low and snowfall is high; and the polar continental climates, as in northern Alaska, Canada, and Siberia, where winters are intensely cold, and snowfall is generally light. Included in the polar continental climate type are the islands of the Canadian Arctic Archipelago, which are influenced only slightly by the sea in winter because of thick, unbroken sea ice.

In addition to these two climates, there are smaller transitional zones, limited areas of “ice” climates, the climate of the polar basin, and, on the south side of the tree line, the subarctic climates. (Dumond D. E., 2022)

2.1.2. The Arctic weather - general

The arctic region acts as a heat sink for the Earth: the arctic loses more heat to space than it absorbs from the sun's rays. In contrast, lower latitudes get more heat from the sun than they lose to space. Warm air and water move into the Arctic from tropical and temperate regions, and cold air and water moves from the arctic into lower latitudes; the constant movement of air is reflected in day-to-day changes in weather patterns.

When a winter snowstorm or cold snap hits temperate regions, people sometimes refer to the frigid temperatures as "Arctic." Cold air does in fact move from the Arctic into other regions, just as warm air from the south moves into polar regions. Storms tend to form at the boundaries between cold and warm air. Cold air moving down from the north is experienced as a cold front.

Some recent studies have argued that long-term changes in Arctic Sea ice and climate may have impacts on weather patterns in other parts of the world, but so far, the research remains largely inconclusive.

Over a whole year, and looking at the globe as a whole, the heat gain in lower latitudes gets balanced out, on average, by heat loss in the polar regions. (The National Snow and Ice Data Center (NSIDC), 2022)

Arctic blizzards can cause whiteouts, resulting in challenges for sensor performance when operating UAV's.

Such poor sensor performance can challenge:

- Data collection (The UAV can't see what it should see)
- Navigation (The UAV position/navigation systems which depend on passive, visual data from the ground)

2.1.3. Sources for weather data analysis

A high resolution hindcast of wind and waves for the North Sea, the Norwegian Sea and the Barents Sea can provide context for what meteorologic forces which must be taken into account when considering safe design of UAV systems.

Such meteorologic forces can be, depending on which application the UAV shall be safe designed for with regards to temperature, winds, snow/rain and waves – if the UAV is supposed to operate to and from ships.

Historic meteorologic data for such analysis are available as hindcasts, in different resolutions and from various suppliers.

One example of such hindcast data (mean wind speed) are illustrated in the figure below. (Reistad, et al., 2011)

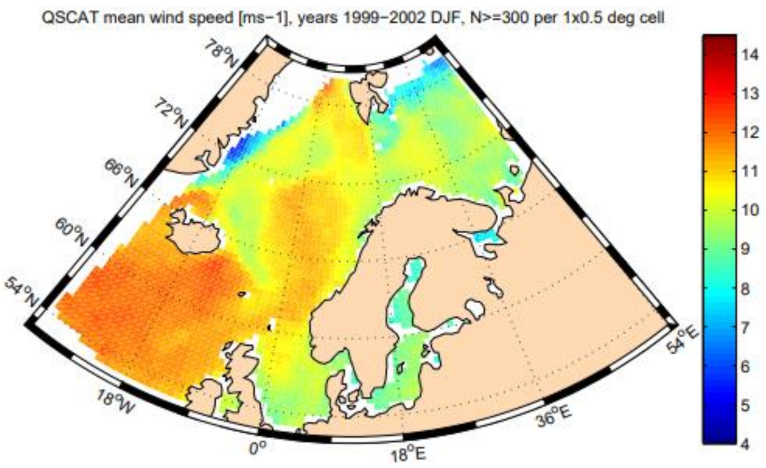


Figure 10: Hindcast, 10 m mean wind speed (Reistad, et al., 2011)

2.1.4. The Arctic weather – what's unique?

The Arctic Ocean provide energy to fuel intense mesoscale cyclones. Better known as polar lows.

Polar lows are characterized by its rapid development, strong winds, heavy precipitation (hail and snow) and rough sea states (Terpstra & Watanbe, 2020). Polar lows are primarily a winter phenomenon and is formed by excursions of polar, cold and dry air masses from the atmosphere over the polar ice cap or other cold land-areas into the open sea.

The open sea is warmer than the polar ice cap. Moisture and heat is added to the atmosphere when cold, dry air from the polar ice cap fill into the Arctic Ocean – and a polar low storm erupts. (Barentswatch, 2015)

When the dry air masses blow south from the polar ice cap into open water, the air masses close to the water are subject to massive heating and are absorbing water vapour. As warm air is lighter than cold air, it rises up like the bubbles in a kettle of boiling water.

The rising air masses are then cooled, and the water vapour condense into water droplets and/or ice crystals which turns into rain clouds.

By adding more and more heat and air from the bottom of the air masses, the water droplets and ice crystals grow until they are fall out in form of snow.

The bigger difference in temperature between sea and air, the more intense will this meteorological effect be.

If the meteorological condition in the atmosphere is present, the rising air will start to rotate. With an eye in the middle.

A polar low has started.

Figure 11: Polar low (Terpstra & Watanbe, 2020) and (Slik herjer uværet med Nordland, 2013)

2.2. Arctic security environment – the Arctic states

The arctic security enviroment is a result of the states which have an interest in dominating the arctic. Either a dominance for security purposes, a dominance for claiming the resources which are present in the arctic, or a combination of such.

The eight states (figure 12) which border the Arctic is Canada, Denmark (via Faroe Islands and Greenland), Finland, Iceland, Norway, Russia, Sweden and the United States. These eight states founded the Arctic council through the Ottawa declaration (The Arctic Council ;, 1996)

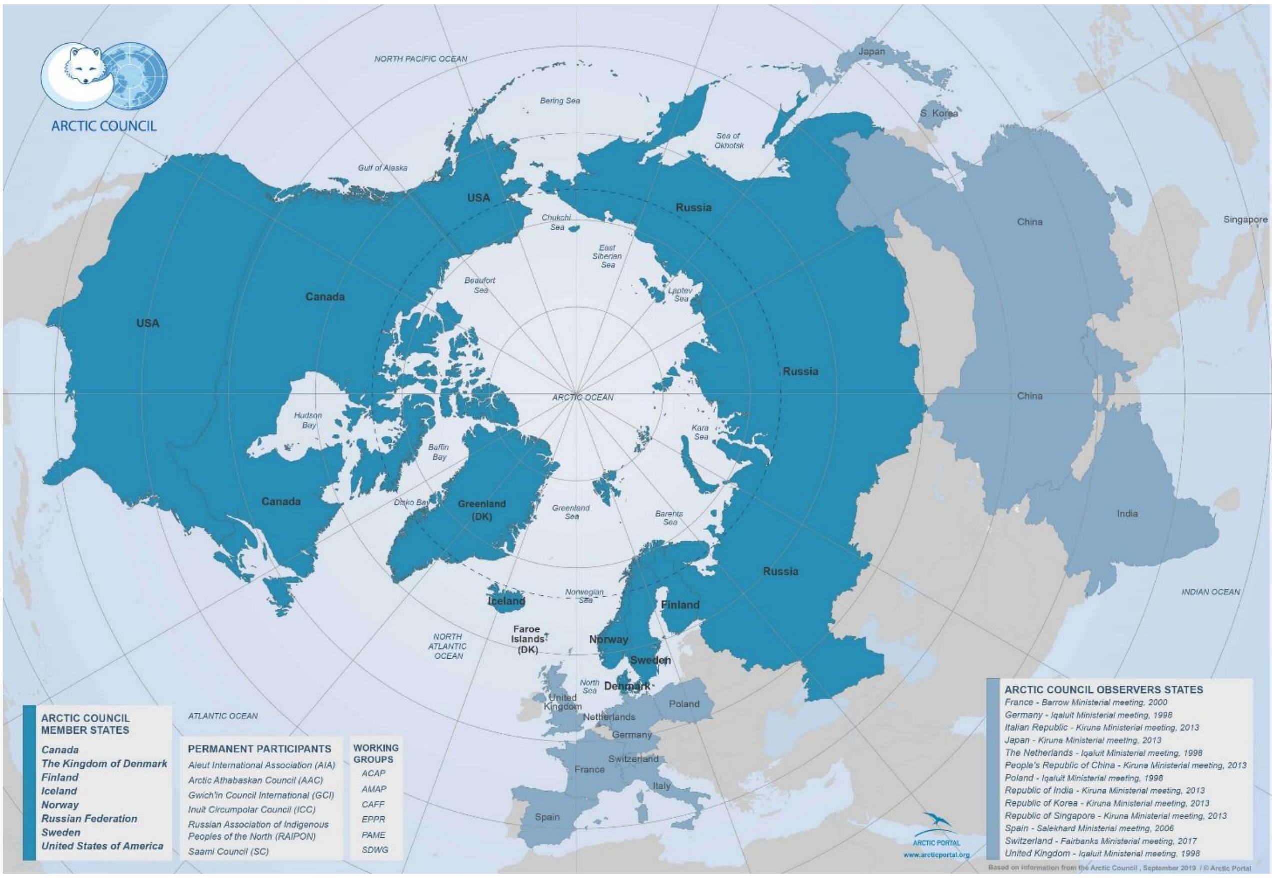


Figure 12: Arctic council member states (Arctic Portal, 2019)

2.2.1. Arctic states

The arctic's climate and geography have not seen large scale state-sentric security activities, nor has it been chosen for military conflict.

The advent of long-range missiles during the Cold War raised the profile of the arctic as an arena for superpower rivalry, but seen primarily as a space where missiles could traverse a shorter distance between the United States and the Soviet Union (Hoogensen Gjørv, Bazely, Goloviznina, & Tanentzap, 2020)

After the Cold war there was a concentrated effort among the eight states that have arctic borders to create a space often described as “*High north - Low tension*” (Hoogensen Gjørv, Bazely, Goloviznina, & Tanentzap, 2020)

The idea of “*High north - Low tension*” was to create a region here security concerns would be set aside in favor of issues related to building mutual cooperation, human development, addressing environmental change and scientific diplomacy.

The most prominent regional organization in the arctic, the Arctic Council, specifically decided to deliberately avoid debates on military security matters in its founding document, the 1996 Ottawa Declaration. (The Arctic Council ;, 1996)

Now, as the polar ice cap is changing, the Greenland ice sheet is changing it has effect on the arctic environment. Not only the physical environment as climate changes, but also its economy, development, and politics.

Some argue that the concept of the Arctic as separate from the world’s security discourses was never matched by reality. (Hoogensen Gjørv, Bazely, Goloviznina, & Tanentzap, 2020)

A hard fact is: The arctic is a militarized area of the world. The states which border the Arctic build military infrastructure in the Arctic, and they do security operations in the arctic. See e.g figure 13 (next page).

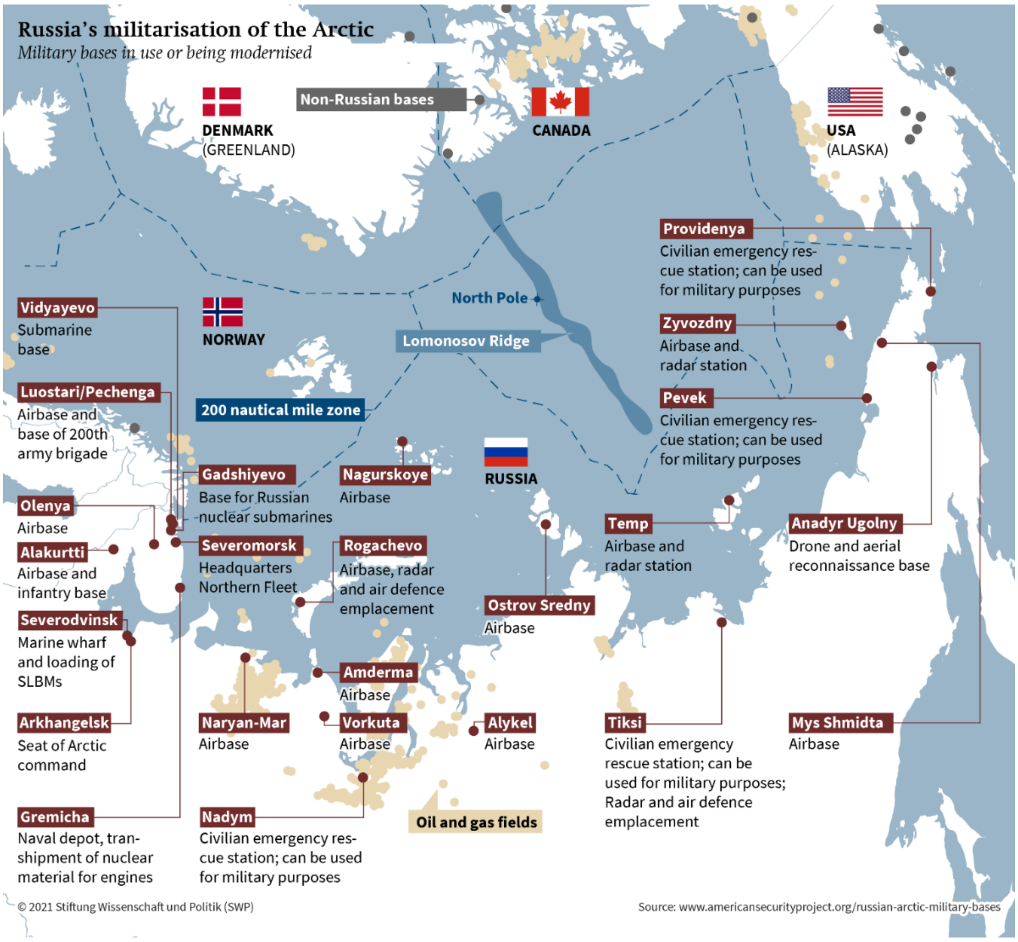


Figure 13: Russian military bases in the Arctic (Franiok, 2020)

2.2.2. Security operations – how and why does it affect safe design of UAV?

As arctic states perform security operations, they use the full spectrum of tools available in their national toolbox.

How does this affect safe design of UAV systems?

Safe design is the large contributing factor for safe UAV operations. Safe design must take into consideration the core services which provide sensor information to an autopilot onboard an UAV need, to be able to fly.

As an UAV do not have any pilot onboard, critical information requirement for the autopilot which aviate the airplane is determining where the aircraft is and how fast the aircraft travel through the air. This information requirement from the autopilot is provided by onboard sensors connected to the autopilot.

Core services for safe UAV flight is from this context are services which provide on-the fly data about the air veichle's **position** and **airspeed**.

This information is core services for the autopilot which shall operate the flight systems in order to maintain and/or restore **lift** and **thrust** for the air veihcle.

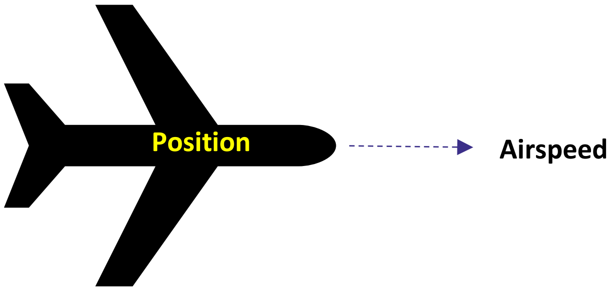


Figure 14: Core services for UAV flight (NORCE, 2022)

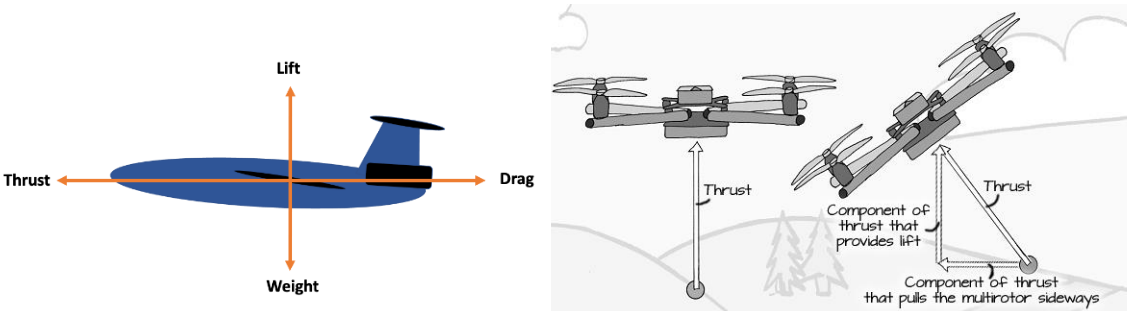


Figure 15: Theory of flight (Skybrary, 2022) and using lift to control movement (learn.parallax.com, 2022)

If the UAV autopilot have true information about the UAV's airspeed and position, it can adjust power (thrust) and rudders/wings (lift) accordingly to reach and/or maintain the UAV's flight according to what flight path it is supposed to fly.

If and when the autopilot does not have true information from its onboard sensors about the UAV's airspeed and/or position, the autopilot will perform flight control on basis of false sensor data.

Examples of such flight control on basis of false sensor data for an UAV can be found in technology publications. (Corfeld, 2019) and air crash investigations (Ministry of Defence and Defence Safety Authority, 2019)

2.2.3. Security operations – military do their things also outside times of war

"Security is a concept about power, as well as a powerful concept. Invoking the concept is a political act. It makes a claim to power. The debate around what the concept means is itself a practice in power. It is a concept that has been, and continues to be, invoked to draw attention to "something" that is or should be valued above all other things." (Hoogensen Gjørv G. D., 2013)

Nations use their military force to project power. In wartime just like they do it in peacetime. One example of such projection of power is Russia's GPS-jamming into Norway, which was put on the agenda 2018-2019. See figure 16.

GPS, which is a position service and one of the core services for UAV flight will put an effective stop to any safe UAV flight if it is jammed.

In this example the state of Russia is adding an arctic risk factor for the UAV: Position services GPS is jammed.

This means the arctic security environment turns out to be one of the dimensional factors when considering safe design UAV design for arctic conditions.

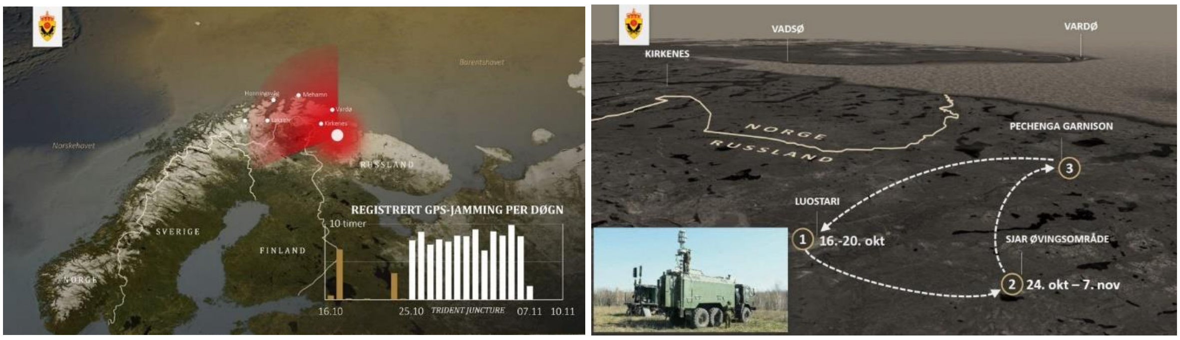


Figure 16: Russian jamming into Norway (iFinnmark, 2019)

2.2.4. Loss of GPS – what's Arctic about that?

GPS jammers are consumer goods. They are sold online, and do not require any special skills to operate.

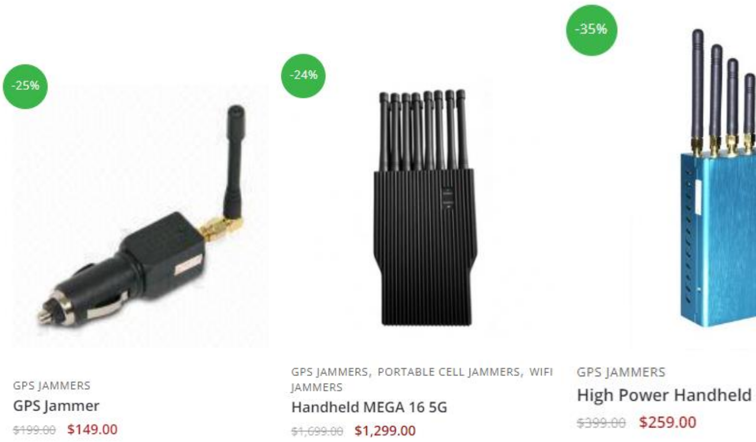


Figure 17: Examples of GPS jammers available online (GPS jammers, 2022)

Although such jammers are documented in use daily for traffic/tampering applications (Flæten, 2014), their range is very limited.

This kind of GPS jammers is not an arctic threat. They are a generic threat, available all over the world and not affecting the arctic security environment per se.

Safe design of UAV's must take such security environment threats into consideration when designing for safe flight anywhere in the world.

2.2.5. Loss of core services – how does the UAV industry handle it through current designs?

Manned aircraft are able to mitigate the loss of core services of which UAV's are dependent upon by its basic design. They have pilots onboard which are able to use their biocentric sensors to estimate the aircraft's position.

UAV's do not. UAV's depend on electronic sensors to determine all flight data which are used by the autopilot on the fly to command flight control systems. This is how the UAV maintain its thrust and lift inside its flight envelope (Skybrary, 2022).

UAV's are dependent on robustness in design through combination of different sensor technologies. Such combination of sensor technologies must be managed by onboard smart technology to operate the flight control system.

An example of such onboard smart technology is a Kalman filter algorithm (Johansen, 2014).

Kalman filters are embedded into many autopilots available on the open market today. One example is the Ardupilot Extended Kalman Filter (EKF) for Attitude and Heading Reference System (AHRS).

Such Kalman filters, which basically are algorithms is constantly developed and enhanced. For example, see evolution of Ardupilot AHRS below.

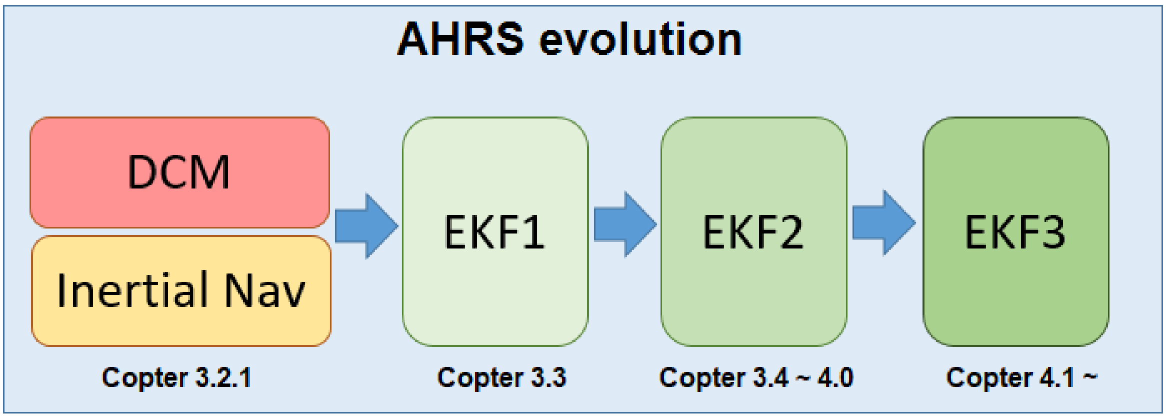


Figure 18: EKF Evolution (Ardupilot, 2022)

3. UAV systems in the arctic – threats

The arctic threats to safe design of UAV systems are well described in Oulu University of Applied Sciences ’s articles (Kramar & Määttä, UAV Arctic Challenges and the First Step: Printed Temperature Sensor, 2018) and (Kramar, UAS (drone) Arctic Challenges - Next Steps, 2019) and SAE international’s article on unsettled topics in unmanned aerial vehicle icing (Hann & Johansen, 2020)

The arctic threats can be categorized into:

1) *Technical Challenges.*
   Threats that may be addressed and the probability and/or consequences by them reduced by development of technologies and establishment of a record for its reliability.
2) *Operational Challenges.*
   Threats that may be addressed by proper planning and leadership by the UAV crew, political cooperation among arctic nations, cooperation among pan-arctic organizations and a will from any given organization to share operational experience in the Arctic open and public.

In order to identify which threats which is most relevant to address for the safe design of UAV’s, a simple categorization with regards to the negative effect on the UAV is made. See table for details.

Technical challenges		**Effect**
1	Heavy and gusty winds	Affects control of UAV
2	Rain and fog	Performance of UAV, communication degradation and optical sensor distortion.
3	Heavy clouds	Affect GPS reception and visual contact to air vehicle.
4	Dust or solid particle clouds	Temporary alter or disable visual contact to air vehicle and optical sensors.
5	Air vehicle materials	Different thermal conductivity in different materials can affect the icing accretion process on air vehicle significantly.
6	Rotor and propeller icing	Rotors and propellers generate thrust and/or lift for air vehicles. Icing degrades substantial degrade the performance of both.
7	Sensor and antenna icing	Both for flight systems sensors onboard the air vehicle and for payload sensors and/or sharing of data in real time icing degrades performance. Bad sensor data provided for instance by an iced pitot tube will provide wrong airspeed data for the autopilot onboard the air vehicle. The air vehicle will

		start compensating action to loss of airspeed, in many cases a (nose)dive to increase airspeed for restoring the lift which the autopilot think is lacking.
8	Lack of ice detection	No persons are present onboard the air vehicle to detect icing conditions and/or ice forming on the air vehicle. De-icing systems is by design either limited by onboard supply ("weeping wings") and/or adds another consumption of energy to the (reduced) availability of such onboard the air vehicle.
9	Temperature (low)	Batteries reduced performance. Voltage drop and/or loss. Solid parts become may become fragile. Liquids and lubricants may become more solid or stop supply or increase friction. Electronics may disbalance control circuits and/or take elements out of working range.
10	Ice fog	Icing. Propellers, air vehicle body and/or wings. Affect aerodynamics and the overall weight/balance of the UAV. Control surfaces and/or hinges can freeze and affect control of air vehicle.
11	Snow	Affects flying performance of air vehicle, battery life, communication ability and reception of satellite signals.
12	Accumulation of moisture and ice inside and on outer surface of air vehicle	Poor battery performance and/or failure, electronic failure and distortion of optics.
13	Lack of ground infrastructure	Snow blowing into air vehicle interior. Lack of acclimatization of air vehicle when it is taken from indoor to outdoor. Temperature shock to technical parts.
14	(lack of) Internet access	Affect communication vehicle-to-vehicle (V2V), swarm, air-to-ground (A2G) and communication to ground station (GCS)
15	Magnetic storms	Affect radio communication in general, both satellite and ground based. Affect magnetic compass on board air vehicle.
16	Magnetic compass distortion	Affected by shift of magnetic North Pole versus geographic North Pole.
17	Extreme light conditions	The Arctic has both the polar night and the midnight sun. Both are arctic seasonal varieties in light conditions and must be planned for.

		"During the cloudy days, harsh weather and night time, there may be low light or no light conditions" (Kramar & Määttä, UAV Arctic Challenges and the First Step: Printed Temperature Sensor, 2018)
18	Moving home points, like ships or a moving ice floe.	Affects air vehicle's ability to find home and safely land at home if failsafe procedures are put into effect by the autopilot.
19	Wild animals	Wild animals may attack an air vehicle when in flight. Polar bears may attack UAV crew on ground when in operation.
	Operational challenges	**Effect**
20	Complex and/or man-intensive UAV system	Complexity of the UAV system with regards to how much people which is required to launch and recover it must be addressed and planned for. *"A reasonable balance of equipment and mobility should not require having an extra team member in addition to the operational team"* (Kramar & Määttä, UAV Arctic Challenges and the First Step: Printed Temperature Sensor, 2018)
21	Lack of supply	Worsen the UAV crew's access to spare parts and tools. Reduced access to resupply of UAV crew's food, water and heat.
22	Laws, policies and regulations	For pan-Arctic operations the UAV team must encounter the Arctic security environment to be compliant to all different regulations and policies. Example: How do you issue a NOTAM in airspace which is not managed by any nation? (See illustration, figure 20, next page) If NOTAM is a requirement for the UAV operation, and no NOTAM can be issued for some of the operational area, the operation must be planned accordingly. The operation can not include the area which not can be NOTAM'ed.

Figure 19: Arctic Challenges (Kramar, UAS (drone) Arctic Challenges - Next Steps, 2019) and (Hann & Johansen, 2020)

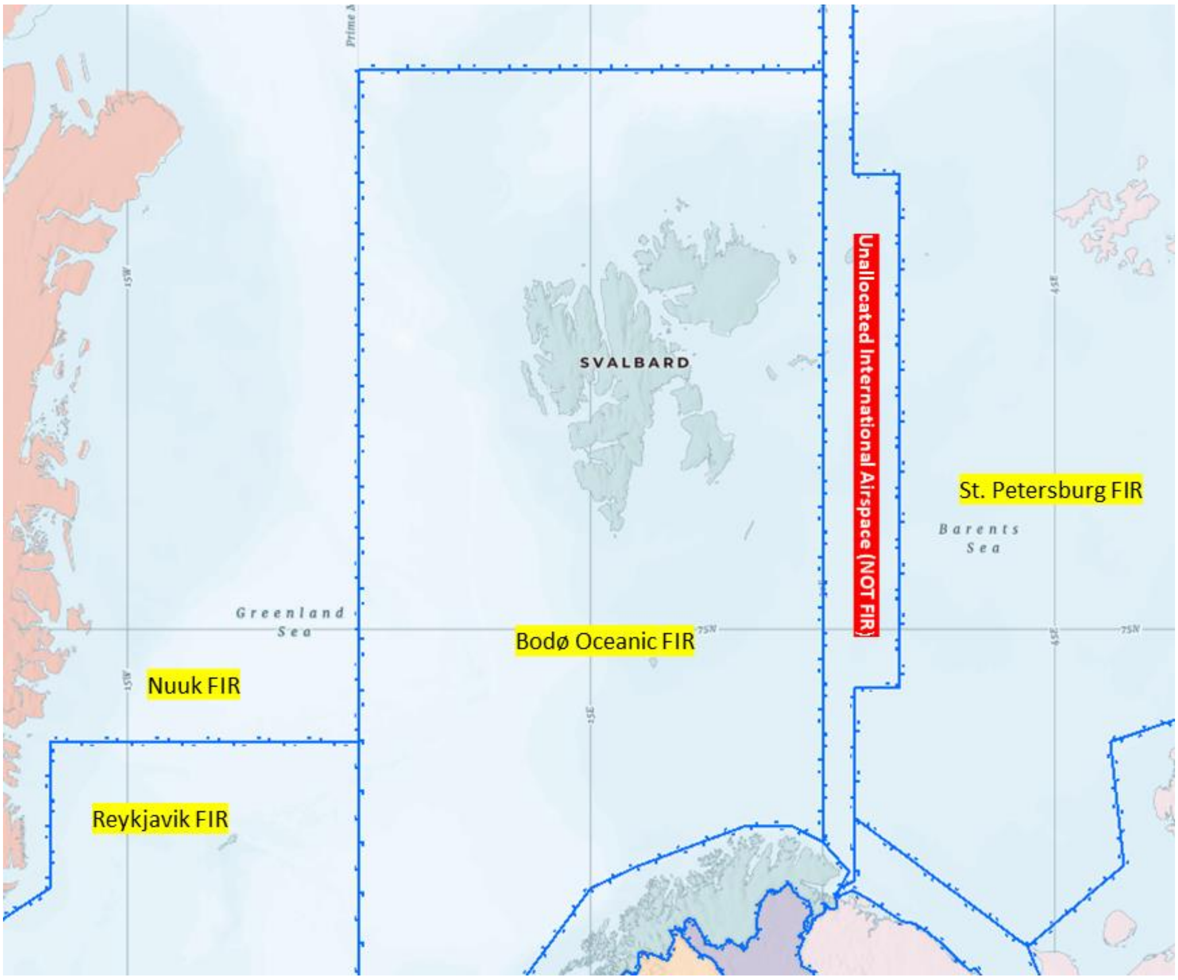


Figure 20: Unallocated Airspace, not possible to NOTAM. Example (NORCE, 2022)

3.1. Arctic threats to safe design of UAS, how to quantify?

For this arctic UAV study, a selection of the arctic threats was made, and a questionnaire for collecting data shared to relevant arctic UAV pilots.

When real users of UAV systems with real experience from UAV operations in arctic conditions provide answers to the questionnaire, it was possible to set the different threat vectors into context.

Such context will create a perspective on the following:

1. Are the threats identified by us scientists something which are experienced by users of UAV systems in the arctic?
2. To what extent is the identified threat experienced by many of the users?
3. Do the users have any other threats/incidents which they can relate to the threat at hand they wish to share?

The collected data is in this arctic UAV study presented under each identified threat vector, see chapter 4.

Arctic Threats (Questions to respondents, see chapter 4)		**Correlation to existing knowledge** (Kramar, UAS (drone) Arctic Challenges - Next Steps, 2019) **and** (Hann & Johansen, 2020)
4.2	Arctic threats to lift.	(5) Air vehicle materials, (6) Rotor and propeller icing, (7) Sensor and antenna icing, (8) Lack of ice detection, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle.
4.3	Arctic threats to thrust.	(5) Air vehicle materials, (6) Rotor and propeller icing, (7) Sensor and antenna icing, (8) Lack of ice detection, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle.
4.4	Arctic threats to vector control of air vehicle.	(5) Air vehicle materials, (6) Rotor and propeller icing, (7) Sensor and antenna icing, (8) Lack of ice detection, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle.
4.5	Arctic threats to radio control of air vehicle.	(7) Sensor and antenna icing, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle, (14) Lack of internet access.
4.6	Arctic threats to position services for air vehicle.	(7) Sensor and antenna icing, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle, (15) Magnetic storms, (16) Magnetic compass distortion.
4.7	Loss of position services (reporting).	(22) Laws, policies and regulations.
4.8	Arctic threats to sensor performance for air vehicle.	(5) Air vehicle materials, (6) Rotor and propeller icing, (7) Sensor and antenna icing, (8) Lack of ice detection, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle.
4.9	Arctic threats to sensor robustness for air vehicle.	(5) Air vehicle materials, (6) Rotor and propeller icing, (7) Sensor and antenna icing, (8) Lack of ice detection, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle.
4.10	Arctic threats to interfaces, cables and such for air vehicle.	(5) Air vehicle materials, (7) Sensor and antenna icing, (8) Lack of ice detection, (9) Temperature, low, (10) Ice fog, (11) Snow, (12) Accumulation of moisture and ice inside and on outer surface of air vehicle.
4.11	Arctic threats to launch systems – catapult operations.	(13) Lack of ground infrastructure, (20) Complex and/or man-intensive UAV system.

4.12	Arctic threats to landing infrastructure.	(13) Lack of ground infrastructure, (20) Complex and/or man-intensive UAV system.
4.13	Arctic threats to GCS environment and GCS pilots.	(13) Lack of ground infrastructure, (20) Complex and/or man-intensive UAV system, (21) Lack of supply.
4.14	Arctic threats to GCS hardware.	(13) Lack of ground infrastructure, (20) Complex and/or man-intensive UAV system, (21) Lack of supply.
4.15	Arctic threats to ground crew.	(20) Complex and/or man-intensive UAV system

Figure 21: Data collection, correlation to literature (NORCE, 2022)

4. Collected data

4.1. Data collection – result and how to read it

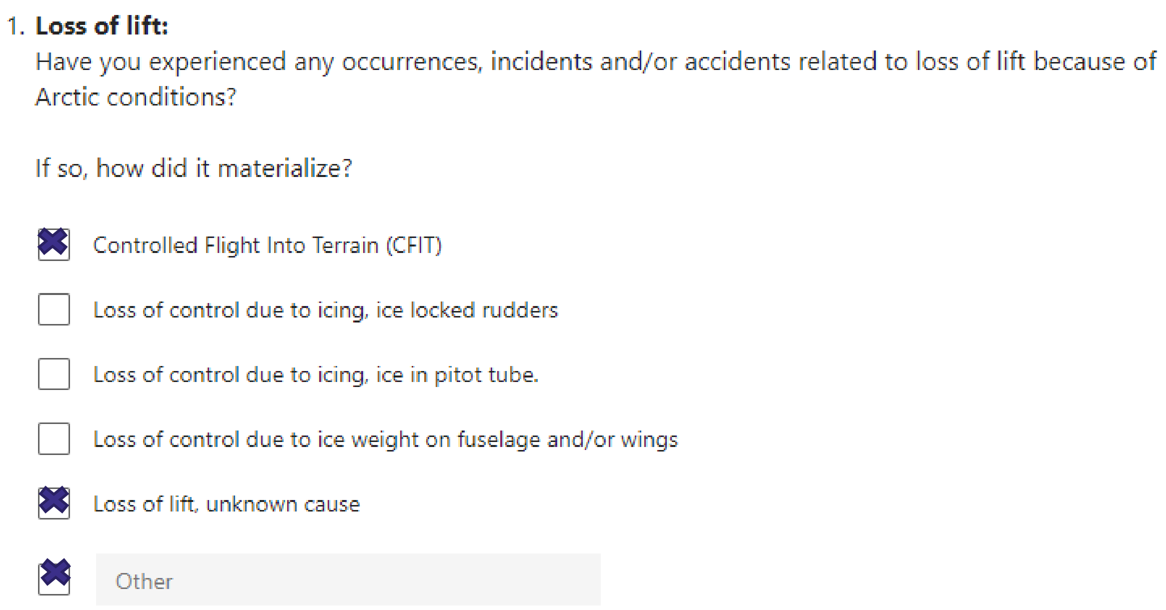
This study reached out to military and civilian organizations in Norway, Sweden, Finland and the United States. The questionnaire was answered by 33 different respondents. The respondents were both military and civilian UAV-pilots which had arctic experience.

The respondents have responded to the different optional choices for answers given in the questionnaire.

All available predefined choices for responses are listed in the graphic illustration of the results. (See 4.2 – 4.15).

If the respondent had experienced more than one of the predefined choices for response, the respondent could choose several of the predefined options.

See example (below) for hypothetical respondent's response. The respondent have in this case experienced two of the pre-defined choices, and one experience which was not described. In total three replies to this single question.


1. **Loss of lift:**
Have you experienced any occurrences, incidents and/or accidents related to loss of lift because of Arctic conditions?

If so, how did it materialize?

- [x] Controlled Flight Into Terrain (CFIT)
- [ ] Loss of control due to icing, ice locked rudders
- [ ] Loss of control due to icing, ice in pitot tube.
- [ ] Loss of control due to ice weight on fuselage and/or wings
- [x] Loss of lift, unknown cause
- [x] Other

Picture 1: Screenshot, hypothetical, from response to questionnaire (NORCE, 2022)

If none of the respondents had experienced the described option, the result is illustrated as 0 – zero.

Free text was possible to add under the option "other".

This text has been listed, respondent by respondent under the graphic illustration of responses.

4.2. Arctic threats to lift – data collection

4.2.1. Context and question to the respondents

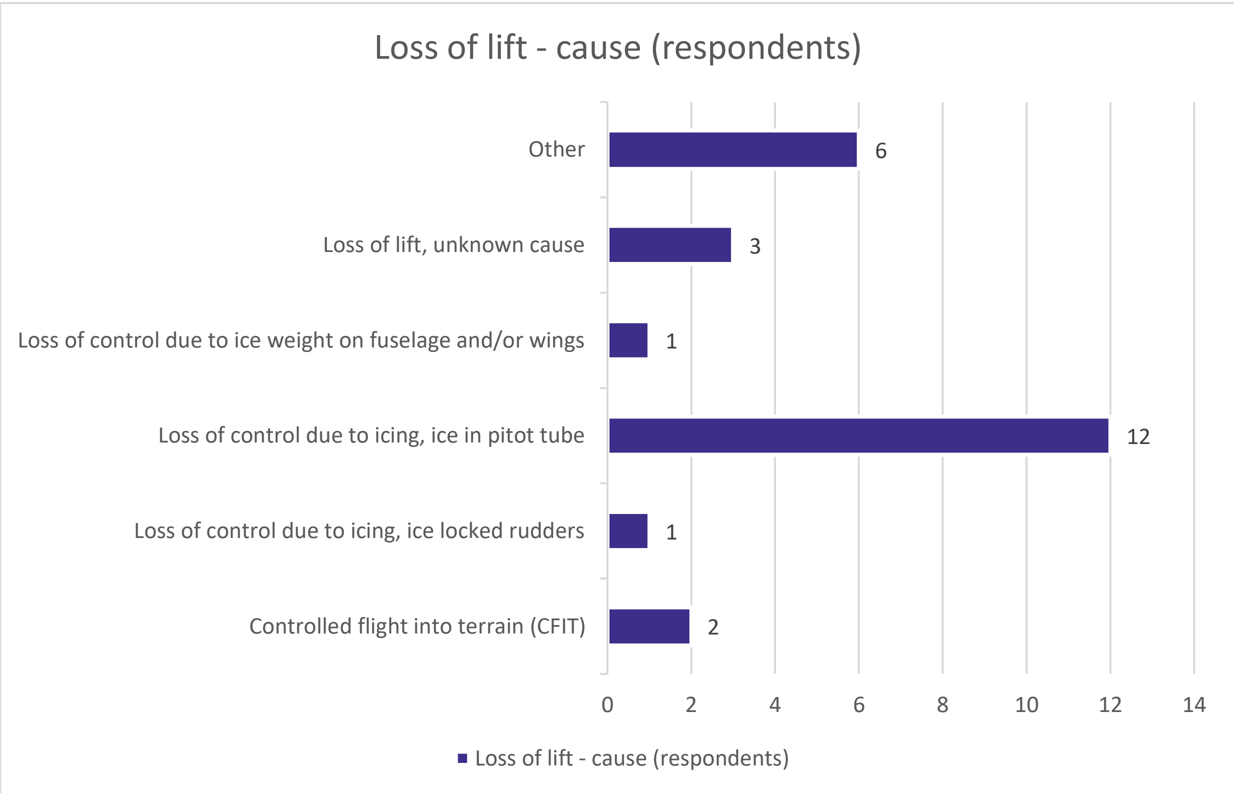
Arctic conditions were defined in the header of the questionnaire:

"Definition of "Arctic conditions" for this questionnaire are ***<u>one or more</u>*** *of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to loss of lift because of Arctic conditions*? If so, how did it materialize?"*

4.2.2. Responses – illustrated and free text

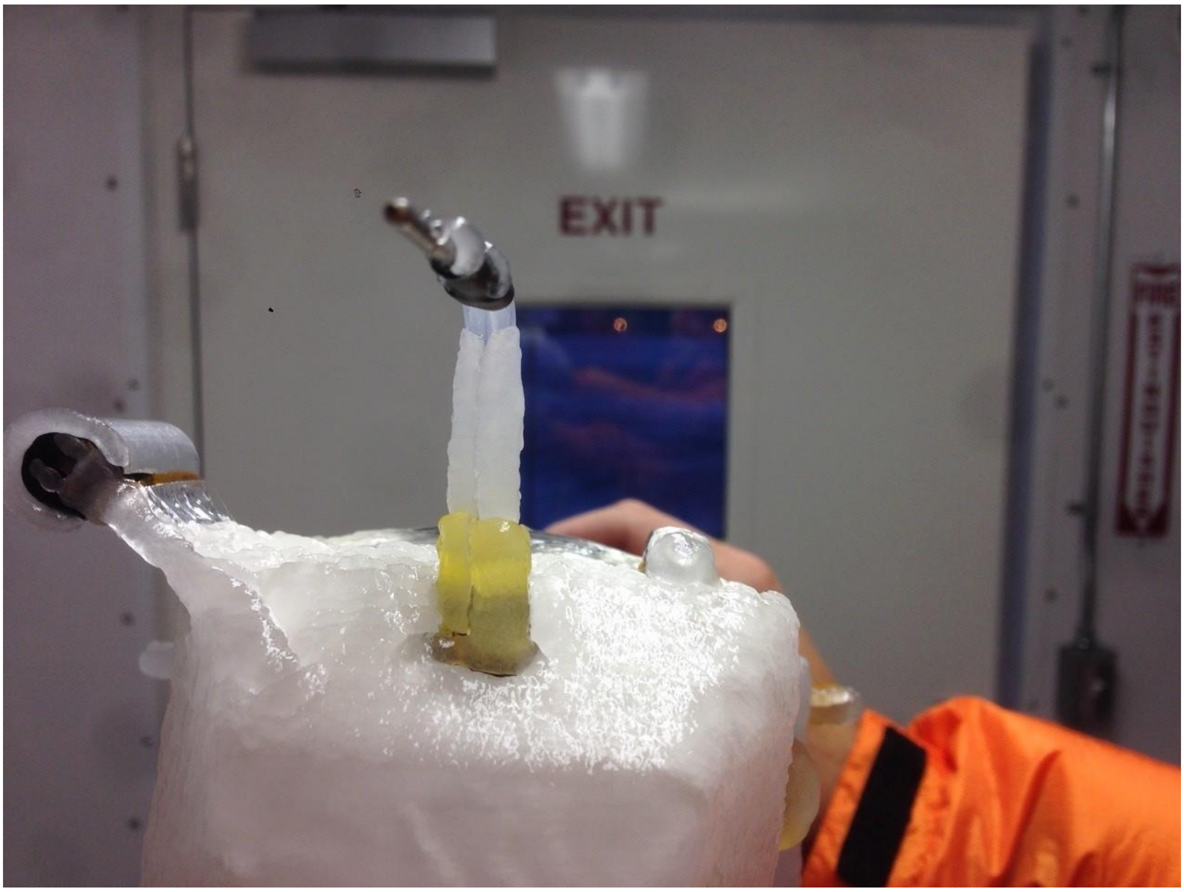


"Other" loss of lift causes (Respondent's free text)

Loss of control due to rainwater in pitot tube
Additional: Loss of lift (as the title says, and not control) on rotors/propellers.
Icing on wings, but did not loose control.

4.2.3. Respondent's additional info - pictures

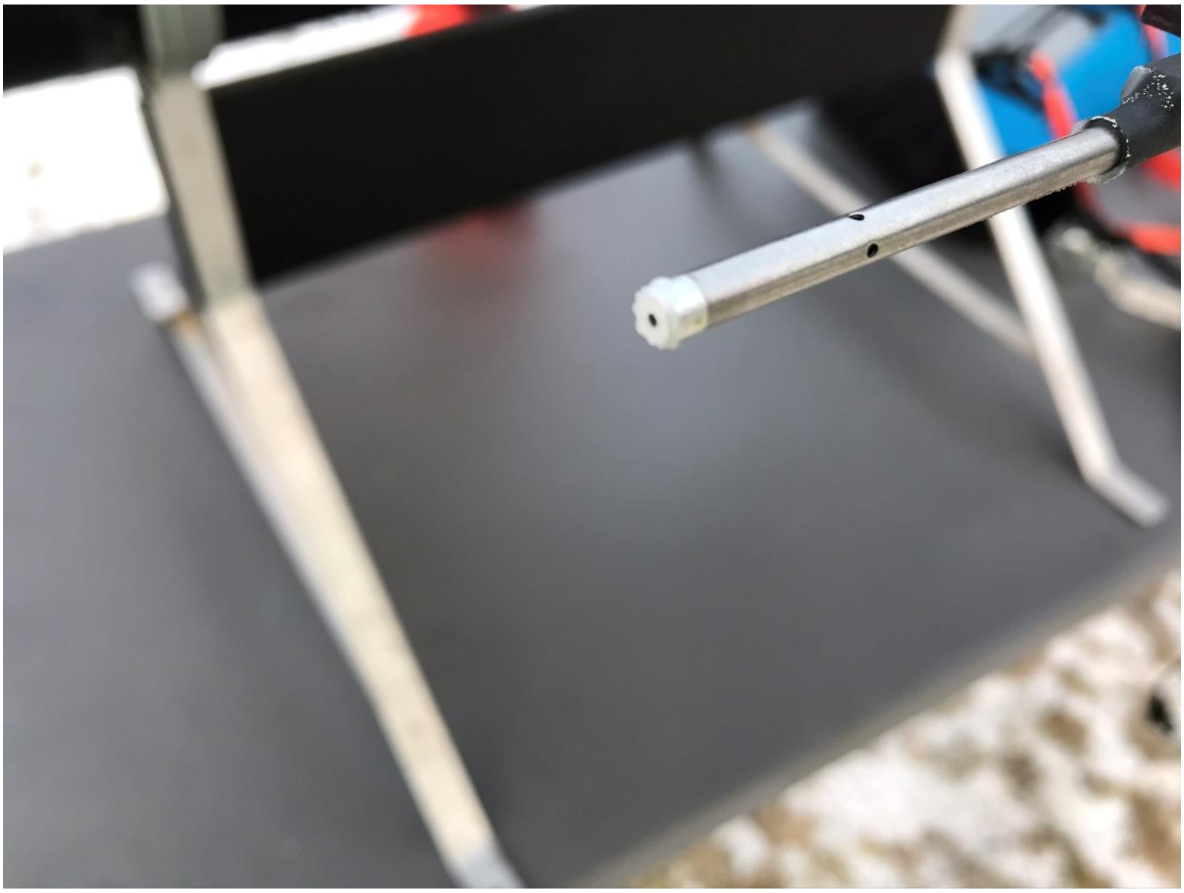
The following pictures were submitted by e-mail as additional information to replies in questionnaires.



Picture 2: Instrumentation from the Colorado DataHawk1 coated in ice during icing testing in northern Alaska. October 2014, Oliktok Point, Alaska, USA. (Photo: Gijs de Boer, University of Alaska)

Picture 3: Launch of Colorado DataHawk 2 during MOSAiC campaign, summer 2020, sentral Arctic Ocean. (Photo: Liana Nixon, University of Colorado)

Picture 4: Ice on PX-31 wings. (Photo: Carl Erik Stephansen, Maritime Robotics AS)



Picture 5: Icing on pitot tube. (Photo: Lars Semb, Maritime Robotics AS)

Picture 6: Ice on Cryowing Fox during CIRFA cruise in Fram strait 2022 (Photo: Andre Kjellstrup, NORCE)

4.3. Arctic threats to trust

4.3.1. Context and question to the respondents

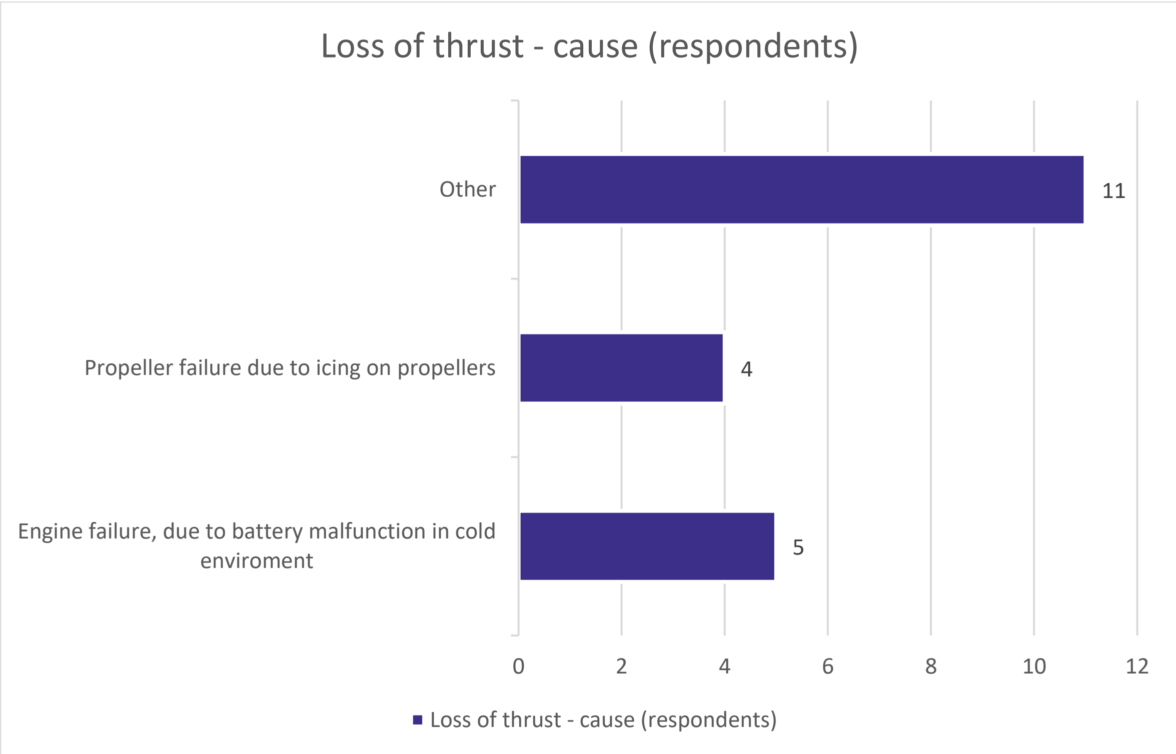
Arctic conditions were defined in the header of the questionnaire:

"Definition of "Arctic conditions" for this questionnaire are ***one or more*** *of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to loss of thrust because of Arctic conditions? If so, how did it materialize?"

4.3.2. Responses – illustrated and free text



"Other" loss of thrust causes. (Respondent's free text)
CFIT carburetor icing
Not verified: loss of thrust due to carburetor icing
Engine failure due to carburetor icing
Battery malfunction on preflight due to cold temperatures and limited heated storage possibilities.
Experienced reduced power (well within demand) and voltage that increased in flight as battery got warmer.
In-flight ESC resets due to EMI from high power military radar
Decreased thrust due to icing on propeller; was able to land safely
Icing on propeller: Propeller did not fail but autopilot complained about high vibration levels because propeller was unbalanced

4.3.3. Respondent's additional info - pictures

The following pictures were submitted by e-mail as additional information to replies in questionnaires.

Picture 7: Clear ice on Cryowing Fox multicopter during data collection on the polar ice cap, someplace between Svalbard and the North Pole 2019 (Photo: Andre Kjellstrup, NORCE)

Picture 8: Ice on fixed wing propeller. (Photo: Lars Semb, Maritime Robotics AS)

4.4. Arctic threats to vector control of vehicle

See data collected in 3.2 “arctic threats to lift” and 3.3 “arctic threats to thrust”.

4.5. Arctic threats to radio control of air vehicle

4.5.1. Context and question to the respondents

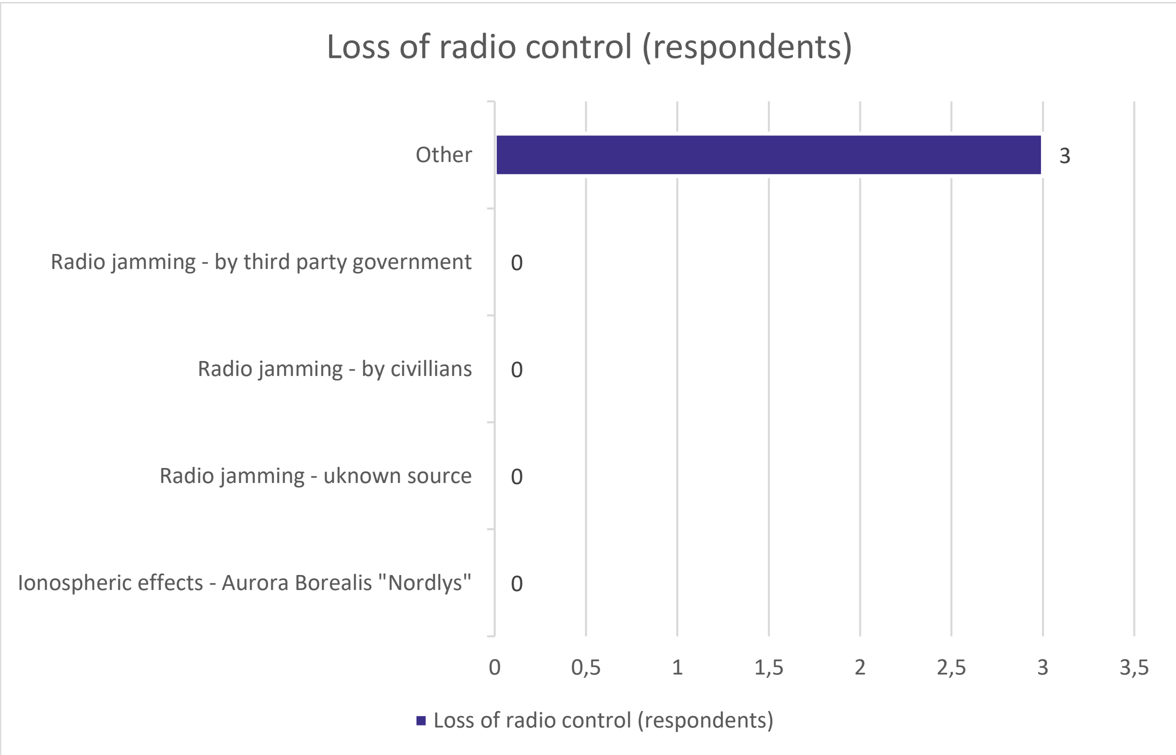
Arctic conditions were defined in the header of the questionnaire:

“Definition of "Arctic conditions" for this questionnaire are ***one or more*** *of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

“Have you experienced any occurrences, incidents and/or accidents related to loss of radio control over air vehicle because of Arctic conditions? If so, how did it materialize?”

4.5.2. Responses – illustrated and free text



"Other" loss of radio control causes. (Respondent's free text)
Local Iridium outage (1-5 hours), no reason found.
Radio jamming from own radios.
Radio jammed due to proximity to payload.

4.6. Arctic threats to position services for air vehicle

4.6.1. Context and question to the respondents

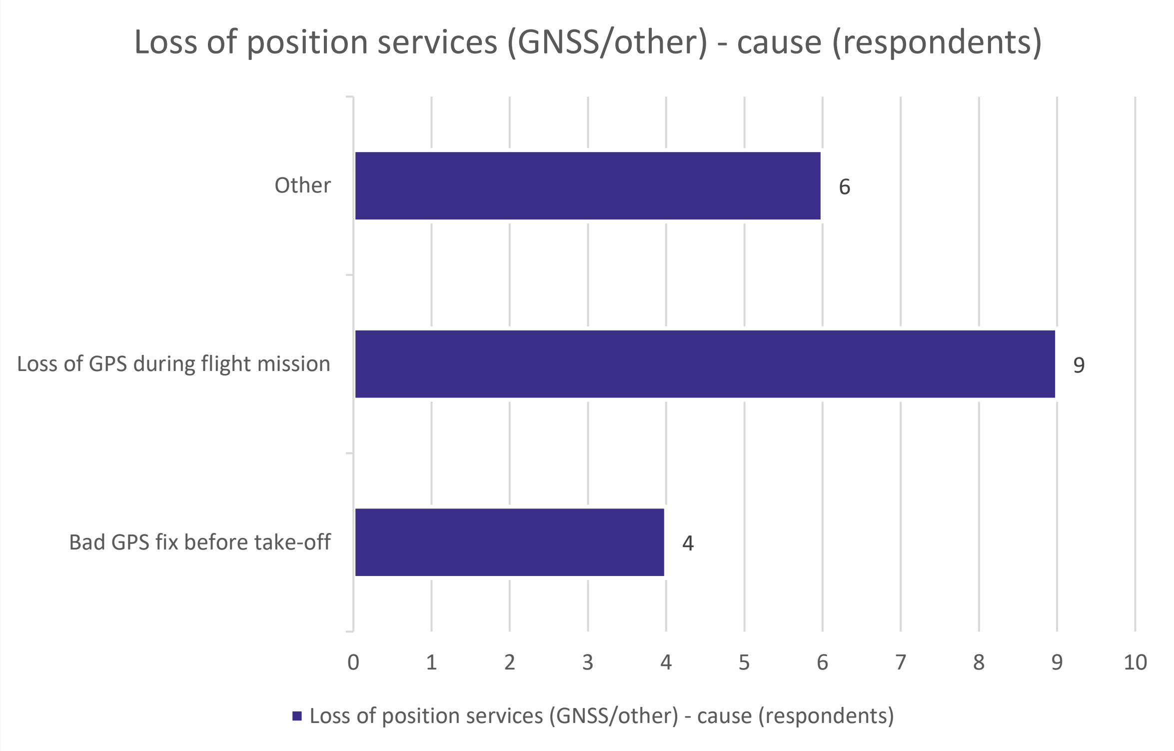
Arctic conditions were defined in the header of the questionnaire:

"Definition of "Arctic conditions" for this questionnaire are ***one or more*** *of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to loss of position services (GNSS/other) because of Arctic conditions? If so, how did it materialize?"

4.6.2. Responses – illustrated and free text



“Other” loss position services (GNSS/other) causes. (Respondent’s free text)
Magnetometer disturbances, fallback to guided mode
Svalbard, Billefjorden, on ground. Not flight. I have experienced 50 m excursions lasting 0ne to several minutes with L1 gps using egos, and smaller (10 m) L1 dGPS with remote base station about 400 m away. Such events are expected due to the high-arctic magnetosphere.
DJI systems used for photography had poor GPS quality during flight so manual control was used; other custom systems did not have issues
Unreliable compass in Svalbard region

4.7. Loss of position services – reporting

An important source for learning for the aviation industry is reports. Based on reports from aviators the different national authorities are able to determine safety performance for the aviation type at question.

As position services are regulated through different national authorities than the aviation regulators in general (civil aviation authority and/or the military aviation authority) , it is interesting to find out if the arctic aviators report to different authorities when position services are not functioning as they should.

4.7.1. Context and question to the respondents

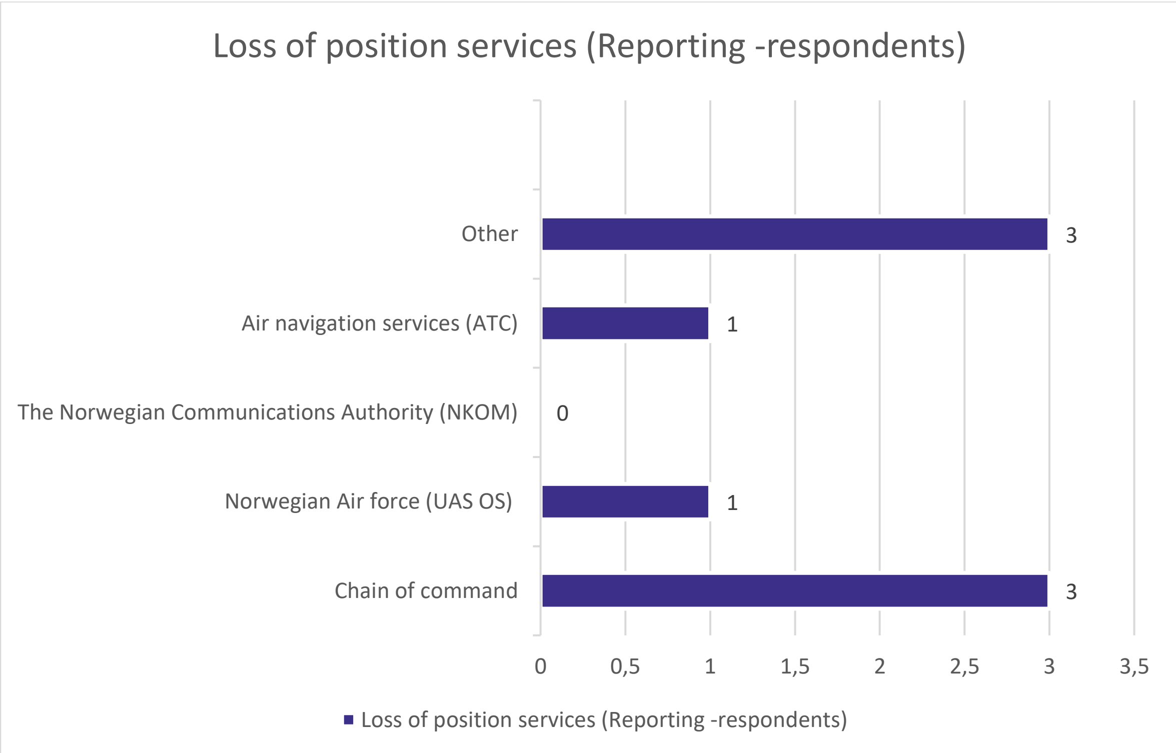
Arctic conditions are not specifically set as context.

The question asked was:

"If you experienced any occurrences, incidents and/or accidents related to loss of position services (GNSS/other), by any reason, did you report it?

If so, where did you report it"

4.7.2. Responses – illustrated and free text



Reporting – loss of position services. (Respondent's free text)
The above was discussed with the scientist in charge at EISCAT, who explained the phenomenon. There have been several continuous GPS stations operated in the Longyearbyen area which should have records of these occurrences.
No, because it was in line of sight.
I fly in manual mode (without GPS) to recover drone when I lose signal

4.8. Arctic threats to sensor performance for air vehicle

4.8.1. Context and question to the respondents

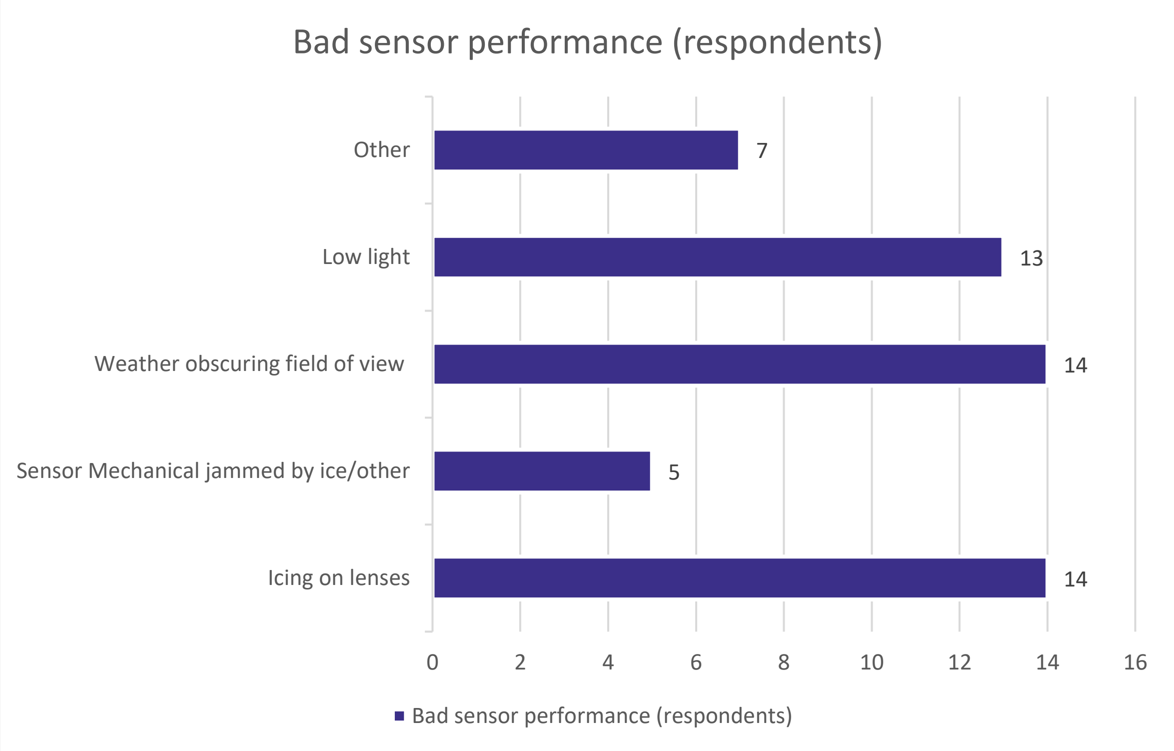
Arctic conditions were defined in the header of the questionnaire:

*"Definition of "Arctic conditions" for this questionnaire are **one or more** of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to bad sensor performance because of Arctic conditions? If so, how did it materialize?"

4.8.2. Responses – illustrated and free text



Bad sensor performance. (Respondent's free text)
Water intrusion on lenses. most likely due to manufactory faults.
Camera malfunction - image turned black.
Fog/icing inside lenses.
Condensation on the inside of the lenses due to changes in temperature.
Issues with moisture from snow and sea water intruding the sensor.
Useless magnetometer data due to high latitude near the north pole.
Low moving clouds disruption the lidar sensor, need to fly without collision control safety when this happens (fixed wing drone), for muticopter drone, problems with compass, not sure if this is related to bad GPS signal and or due to high iron in the ground n Svalbard.

4.9. Arctic threats to sensor robustness for air vehicle

4.9.1. Context and question to the respondents

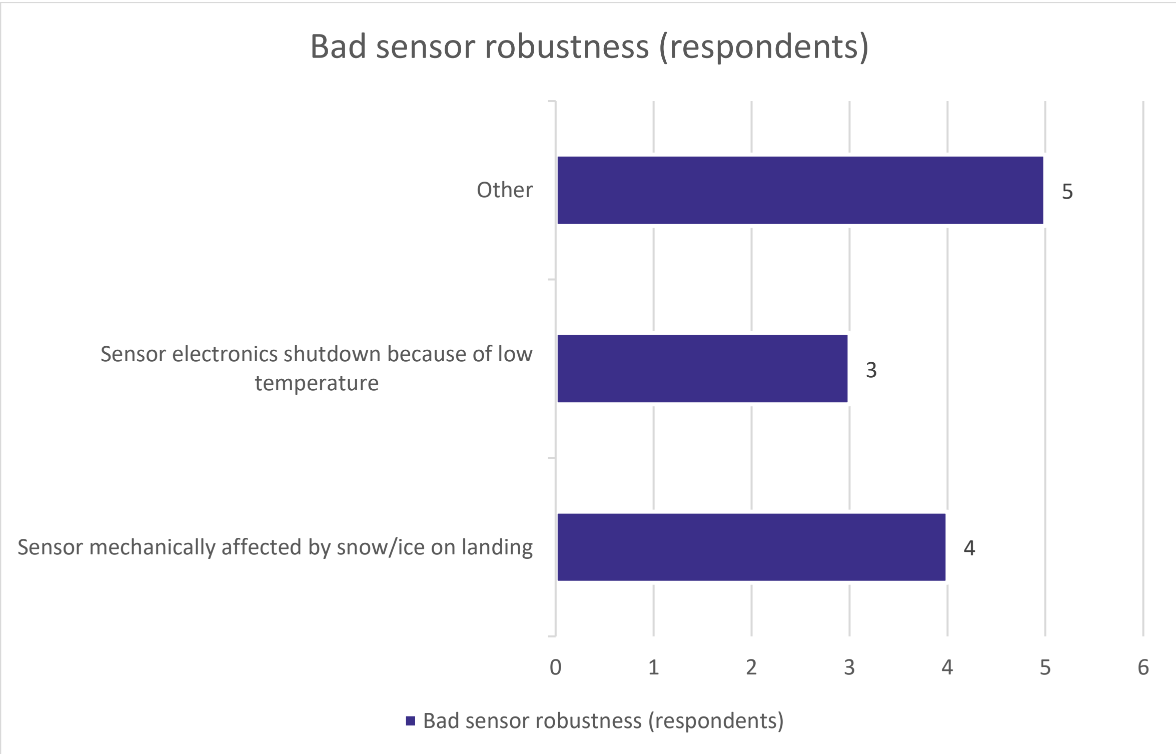
Arctic conditions were defined in the header of the questionnaire:

*"Definition of "Arctic conditions" for this questionnaire are **one or more** of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to bad sensor robustness because of Arctic conditions? If so, how did it materialize?"

4.9.2. Responses – illustrated and free text



Bad sensor robustness. (Respondent's free text)
Batteries require preheating to maintain high enough charge before launch.
If lense is warm before operation, you might get condensation when you take it outside again.
Sensor stopped booting up after landing in summer conditions.
Drones and laptop (used to fly the drone) drain un-proportionally fast, once my fixed wing almost fell out of the sky (landed with 0% left) and when laptop drains the drone does an emergency landing.
Bad gyro performance in cold weather.

4.10. Arctic threats to interfaces, cables and such for air vehicle

4.10.1. Context and question to the respondents

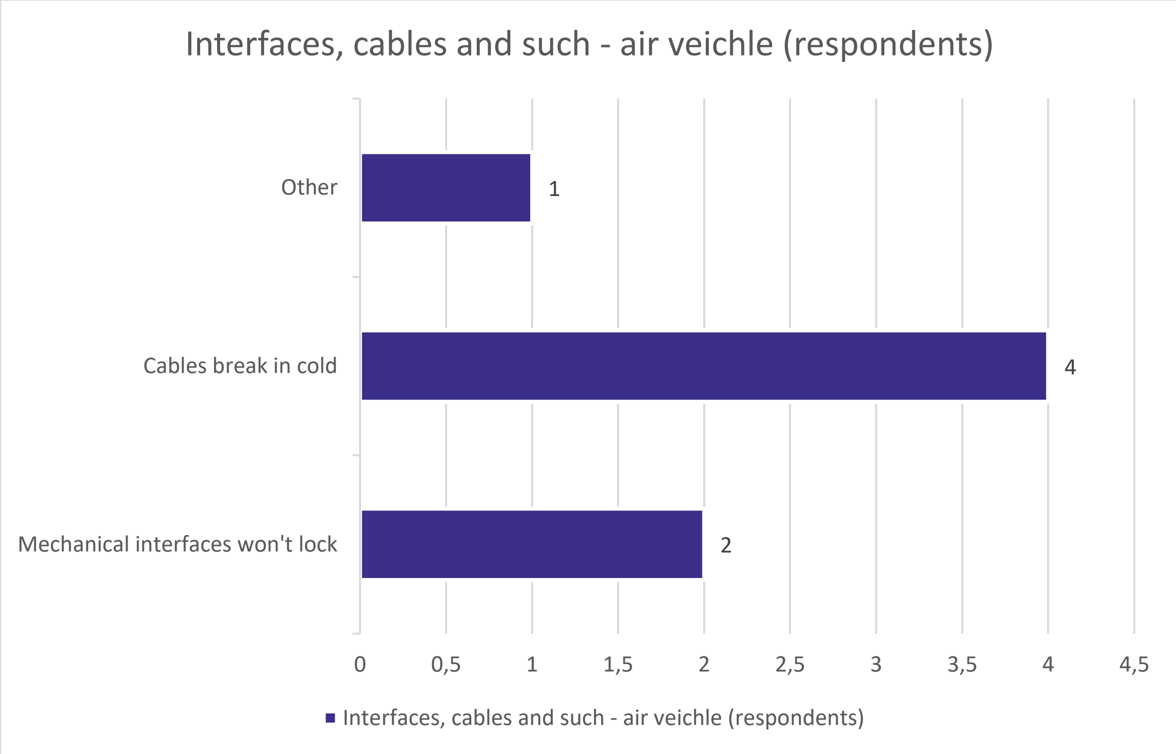
Arctic conditions were defined in the header of the questionnaire:

"Definition of "Arctic conditions" for this questionnaire are ***one or more*** *of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to interfaces, cables and such because of Arctic conditions? If so, how did it materialize?"

4.10.2. Responses – illustrated and free text



Interfaces, cables and such – air vehicle. (Respondent's free text)
Plastic connectors breaking.

4.11. Arctic threats to launch systems – catapult operations

4.11.1. Context and question to the respondents

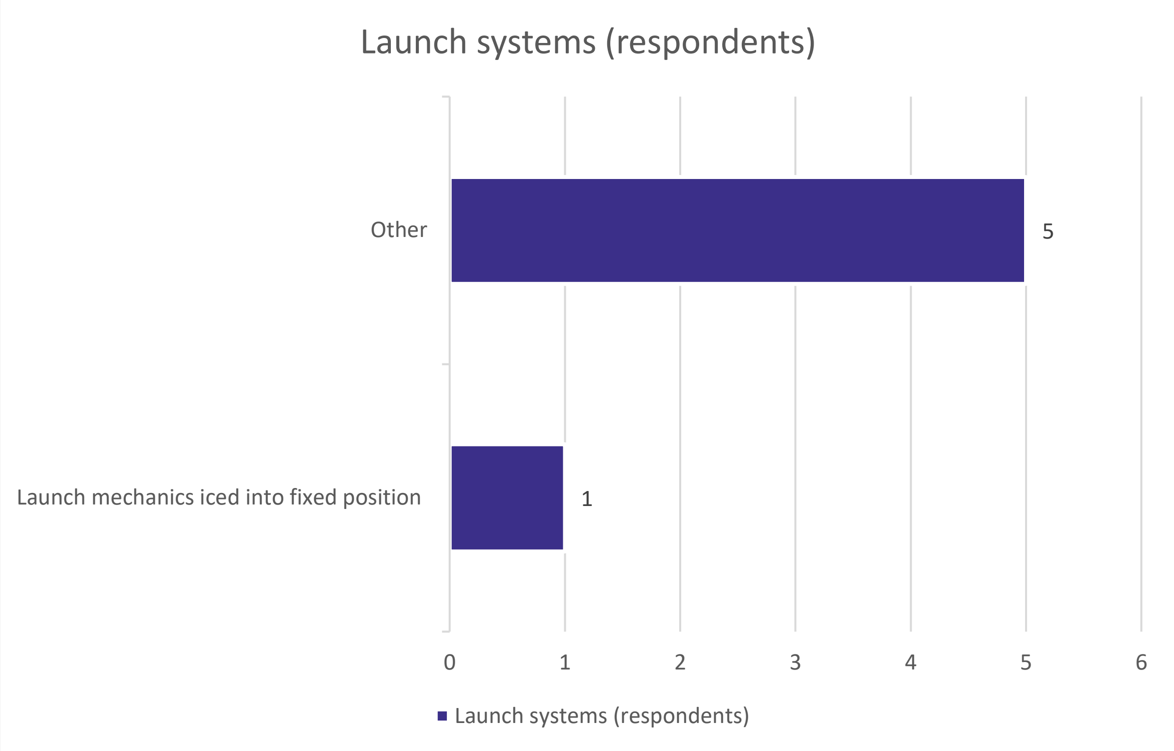
Arctic conditions were defined in the header of the questionnaire:

*"Definition of "Arctic conditions" for this questionnaire are **one or more** of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to launch systems because of Arctic conditions? If so, how did it materialize?"

4.11.2. Responses – illustrated and free text



Launch systems. (Respondent's free text)
Bungy coords not bungy cords due to temperature.
Moisture in pistons when compressed air expands.
Bungee strength reduced.
Bungee for launch became brittle and lost tension.
Bungee rubber looses elastic in cold weather.

4.12. Arctic threats to landing infrastructure

4.12.1. Context and question to the respondents

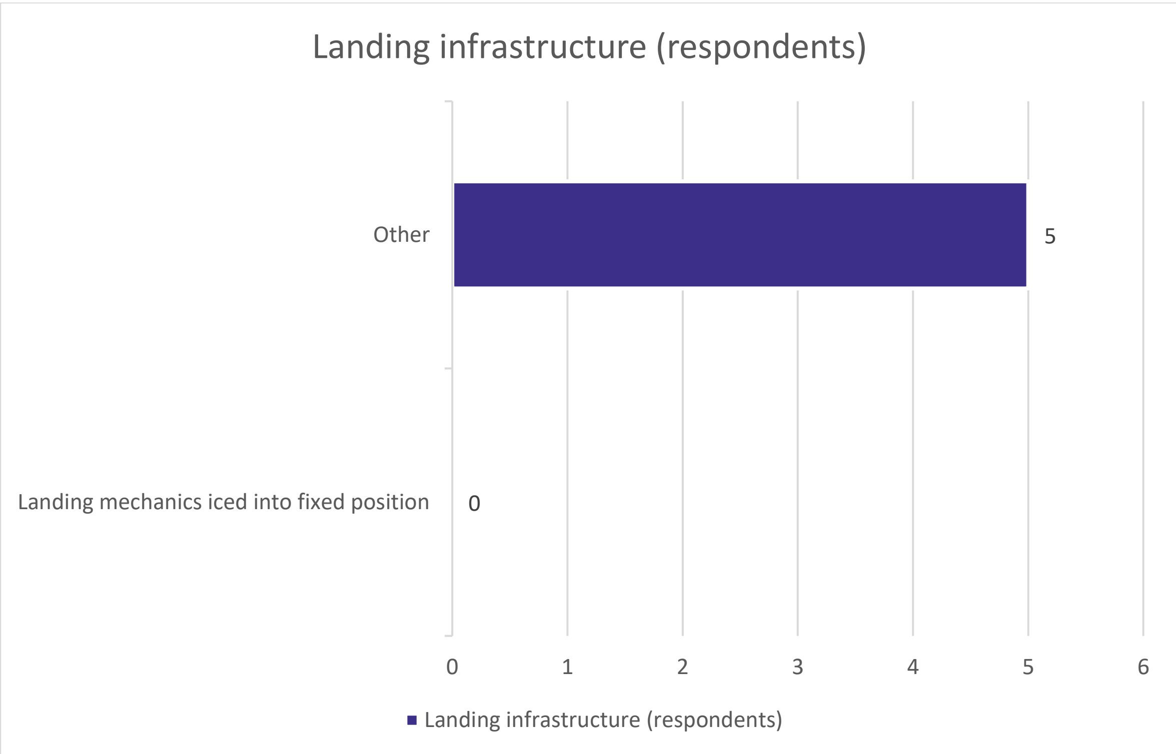
Arctic conditions were defined in the header of the questionnaire:

*"Definition of "Arctic conditions" for this questionnaire are **one or more** of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

"Have you experienced any occurrences, incidents and/or accidents related to landing infrastructure because of Arctic conditions? If so, how did it materialize?"

4.12.2. Responses – illustrated and free text



Landing infrastructure. (Respondent's free text)
Landing failure because of snowpile. Snow got in to drone and break it.

4.13. Arctic threats to GCS environment and GCS pilots

4.13.1. Context and question to the respondents

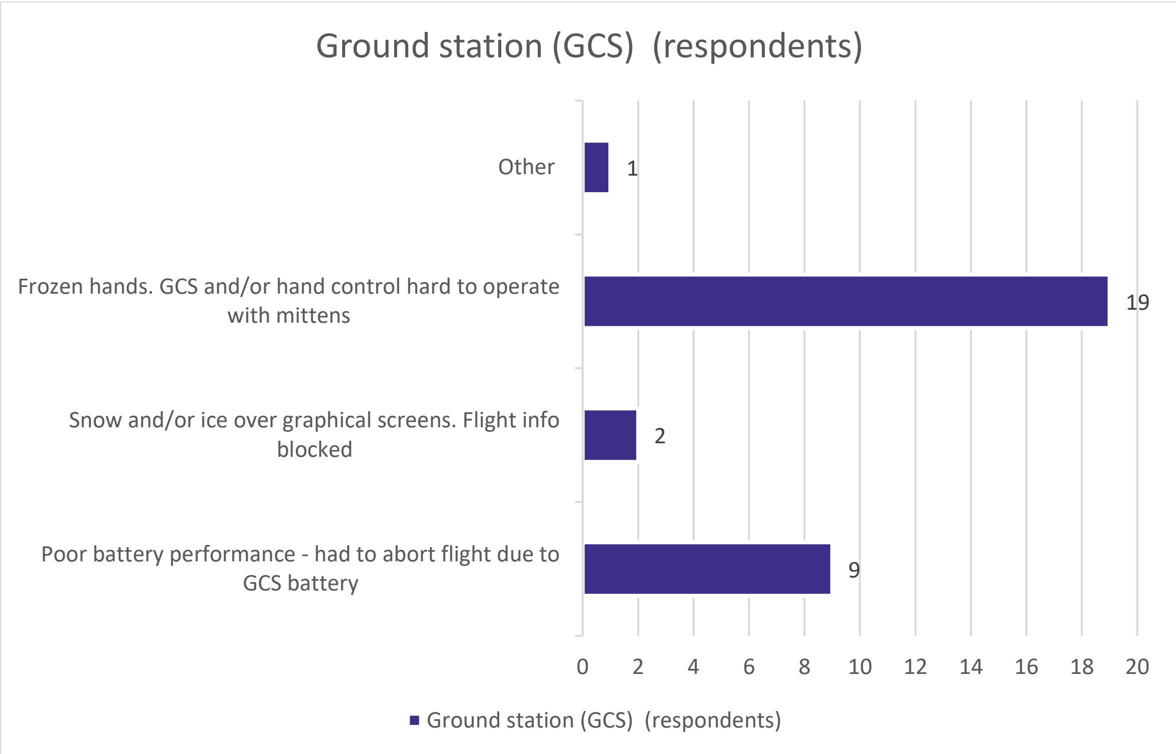
Arctic conditions were defined in the header of the questionnaire:

"Definition of "Arctic conditions" for this questionnaire are ***one or more*** *of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

***"Have you experienced any occurrences, incidents and/or accidents related ground station environment (GCS)* because *of Arctic conditions?* If so, how did it materialize?"**

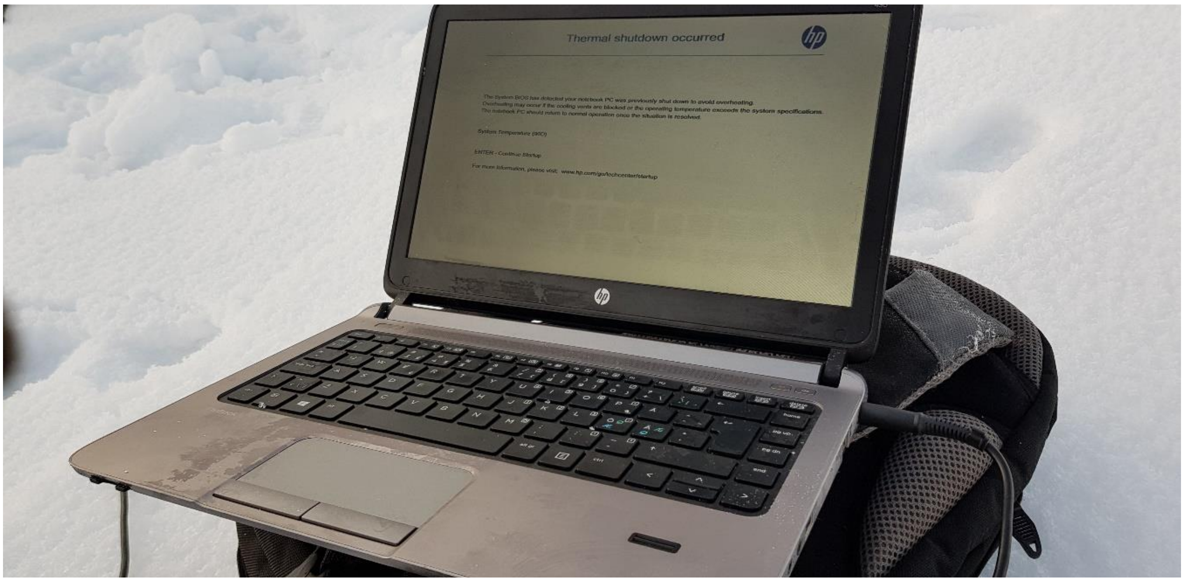
4.13.2. Responses – illustrated and free text



Ground station (GCS) . (Respondent's free text)
GCS as laptop BIOS would not start as thought it was overheating in low temperature (HP).

4.13.3. Respondent's additional info - pictures

The following pictures were submitted by e-mail as additional information to replies in questionnaires.



Picture 9: GCS for Cryowing Fox multicopter in thermal shutdown during data collection on the polar ice cap, someplace between Svalbard and the North Pole 2019 (Photo: Andre Kjellstrup, NORCE)

4.14. Arctic threats to GCS hardware

See 4.13 Arctic threats to GCS environment and GCS pilots.

4.15. Arctic threats to ground crew

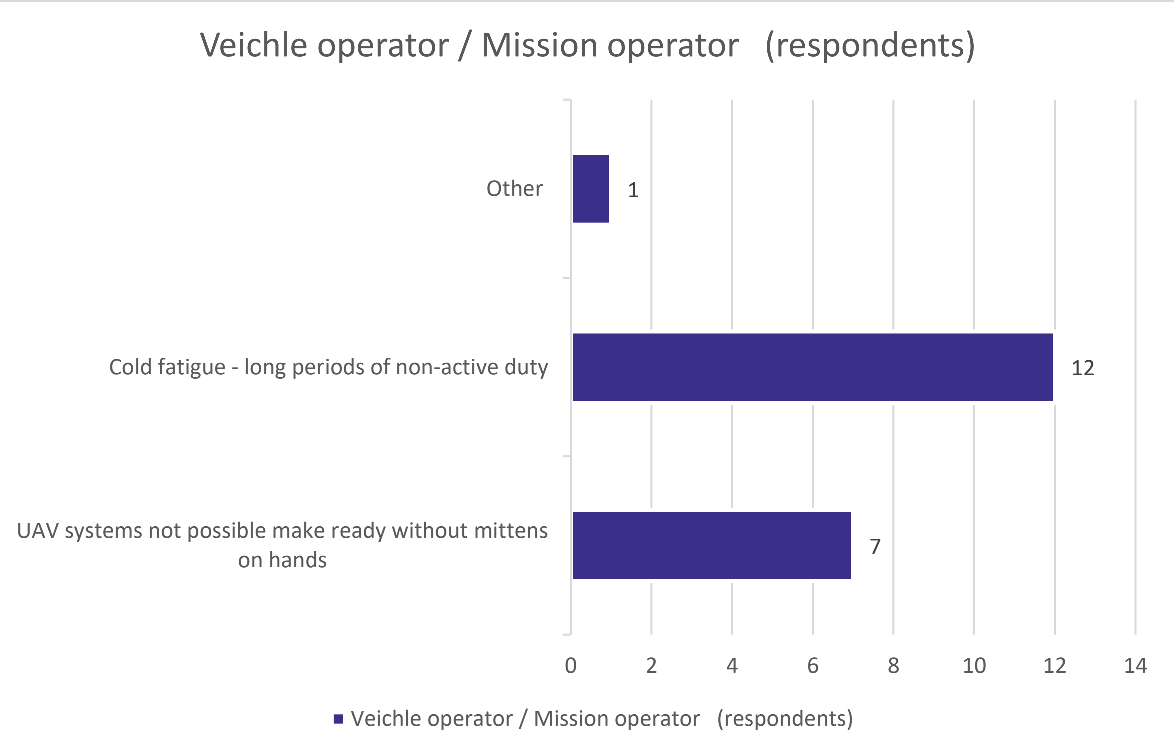
4.15.1. Context and question to the respondents

Arctic conditions were defined in the header of the questionnaire:

*"Definition of "Arctic conditions" for this questionnaire are **one or more** of the following flight conditions:*
- Temperatures below 0 degrees Celsius.
- Snow and/or sleet showers.
- Middle wind 12.5 m/s or higher.
Rapid changes in wind and temperature.
Example: Polar lows. Explained: https://www.barentswatch.no/en/services/polar-lows-explained/

The question asked was:

***"Have you experienced any occurrences, incidents and/or accidents the human beings operating the UAV because of Arctic conditions?* If so, how did it materialize?"**



Vehicle operator / Mission operator. (Respondent's free text)
Propellers have eaten into downjackets when starting them.

5. Conclusion

This arctic UAV study has been a start. It has identified some areas of the UAS as system and how it is vulnerable to arctic conditions.

The literature describes different threat vectors against a safe design of UAV systems in general.

Very few, if any, has done the job to find common ground between the UAV technology producers and the UAV technology users.

Such simple things as common understanding of what "arctic conditions" are, and what technological issues the UAV producers must address first in order to mature their products even more with regards to surviving in the arctic has not been addressed by the UAV customers.

To solve this problem the arctic states must invest in UAV systems as an arctic capability. Either as product investments and/or investments in UAV services.

Denmark's military arctic capability package is an excellent example for one small start for such.

The other arctic countries which plan to implement UAV's in their military capabilities can follow this example for enabling UAV as an arctic capability, and cooperate with Denmark on how to resolve the arctic challenge for UAV's.

Cadet Tucker Chase and major Matthew Hanes illustrated this fact in their article "*There's a race for arctic-capable drones going on, and the United States is losing*" (Modern war institute/West Point/January 2022)

This arctic UAV study has gathered some anonymous responses from both military and civilian UAV pilots which have arctic experience.

It supports many of the vulnerability factors for UAV's in the arctic already identified and published by others.

5.1. Recommendations for further science work

Recommendations for further scientific work with regards to safe design of UAV's for arctic conditions is:

1. Continue establishing a common understanding of what arctic conditions are, and how a safe design of UAV's can increase both the operational envelope for the unmanned systems, the involved personnel and increase an acceptance from third parties for UAV operations in the Arctic.
2. Continue collecting data (user experiences) from UAV operators and UAV pilots which has arctic experience.
3. Start collecting data from established UAV user groups which already are present and operate UAV's in the Arctic. Both military and civilian.

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5.2. Glossary, abbreviations, and definitions

Word	Definition
The Arctic	The northernmost region of Earth, centred on the North Pole and characterized by distinctively polar conditions of climate, plant and animal life, and other physical features.
BLOS	Beyond visual Line of Sight
FTX	Field Training Exercise
EMSA	European Maritime Safety Agency
GPS	Global Positioning Service
Military Intellectuals	Military personnel who think and express themselves in an academic manner.
UAS	Unmanned Aerial System. Both air vehicle and other systems required to operate.
UAV	Unmanned Aerial Vehicle. An airplane which does not have a pilot on board.
UAV operator	Organization which operates UAV
UAV pilot	Person who pilots an UAV.