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SYSTEMS ENGINEERING CAPSTONE REPORT

A CAPABILITY ANALYSIS OF SHIP-BASED UAS FOR ARCTIC OPERATIONS

by

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OPERATIONS**

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ABSTRACT

Operations in the Arctic pose unique challenges to the deployment of unmanned aerial systems (UAS), yet the United States Navy and United States Coast Guard both intend to utilize UAS to protect the United States' interests in the region. Previous reports show batteries become significantly less efficient in cold weather, and research on Global Positioning System (GPS) fidelity in the Arctic provides evidence of connectivity issues. This study investigates possible concepts of operations including the use of battery versus gas-powered UAS and the utilization of both line-of-sight and beyond line-of-sight communications signals. An analysis of current data on lithium-ion battery temperature sensitivity, line-of-sight transmission distances, and Arctic GPS satellite coverage is conducted. This information is used to calculate expected real-world capabilities of various commercial off-the-shelf UAS. Once expected performance metrics are established, the utility of each UAS model is determined within various anticipated missions: intelligence, surveillance, and reconnaissance; search and rescue; and deploying from various vessels, in different seasons, and at different latitudes. The findings in this report provide evidence toward the effective usage of UAS assets in the Arctic, a discussion of their deployment, and recommendations for future advancements.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACB	all-climate battery
AJ	anti-jam
BLoS	beyond line of sight
C2	command and control
CONOPS	concept of operations
COTS	commercial off the shelf
DISA	Defense Information System Agency
DOD	Department of Defense
EO	electro-optical
FIRs	flight information regions
FMV	full motion video
GCS	ground control station
GDOP	geometric dilution of precision
GEO	geostationary/geosynchronous Earth orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	graphical user interface
HAS	high accuracy service
HEO	highly elliptical orbit
IOT&E	initial operational test and evaluation
ISR	intelligence, surveillance, and reconnaissance
JACL	joint analysis for Coast Guard capabilities
JP-5	Jet Propellant-5
JP-8	Jet Propellant-8
LEO	low Earth orbit
Li-ion	lithium-ion
LoS	line of sight

MAGNA	Mayflower Multi-platform Anti-Jam GPS Navigation Antenna
MAGNA-I	MAGNA-Integrated
MEO	medium Earth orbit
MHz	megahertz
MWIR	mid-wave infrared
NM	nautical miles
RF	radio frequency
SAR	search and rescue
SATCOM	satellite communications
SATNAV	satellite navigation
SEDP	systems engineering design process
SSC	Space Systems Command
U.S.	United States
UAS	unmanned aerial systems
UAV	unmanned aerial vehicle
UHF	ultra-high frequency
USCG	United States Coast Guard
USCGC	United States Coast Guard Cutter
USN	United States Navy
USS	United States Ship
V&V	validation and verification
VHF	very high frequency
ViDAR	visual detection and ranging

EXECUTIVE SUMMARY

In recent years, the United States Navy (USN) and United States Coast Guard (USCG) have both revamped and revitalized their strategies for continued dominance within the Arctic region (Gilday et al. 2021; United States Coast Guard 2019). These strengthened policies rely not only on ongoing maritime partnerships with other Arctic nations, but in the innovative development of new strategies and technologies to continue to protect the United States' influence and interests (Gilday et al. 2021). Unmanned Aerial Systems (UAS) operations represent a dominant trend in the current technological era, and the analysis of their present and future capabilities is in the best interests of both services. Within the context of technological advancement and capabilities assessments, the Arctic region presents complex and unique challenges which must be addressed.

To inform this project, the team performed research on topics such as lithium-ion battery cold-weather performance, Global Positioning System (GPS) Arctic coverage and reliability, Arctic weather, line-of-sight communications limitations, and technology reviews for current UAS and ship types. The data attained during this process was consolidated to encompass three major sections: Arctic weather, GPS availability, and lithium ion (Li-ion) battery performance. This then led to the development of the “Arctic UAS Selector Tool.”

The “Arctic UAS Selector Tool” is based upon the previously developed “Drone Selector Tool” (Eilertsen et al. 2023). The “Drone Selector Tool” was designed to consider mission set, ship type, and flight profile characteristics such as altitude and flight time to determine the best fit asset (Eilertsen et al. 2023). Where the base tool may be used for any shipborne UAS deployment, the “Arctic UAS Selector Tool” incorporates calculations and decision points which are specific to the region. First, the tool includes a latitude-based decision gate which delineates between UAS types which rely on GPS signal and cannot operate in an austere environment versus those that may operate with GPS. This was designed due to the reduced reliability, and therefore fidelity, of GPS positional guidance north of the 55th parallel (Swaszek et al. 2018). The other primary addition to the model takes temperature into consideration when calculating the expected performance metrics

of a Li-ion battery. Figure 1 shows the charted performance expectation as a percentage of designed maximum charge which has been derived and extrapolated from numerous sources (Lei et al. 2015; Wang et al. 2016; Aris and Bahman 2017).

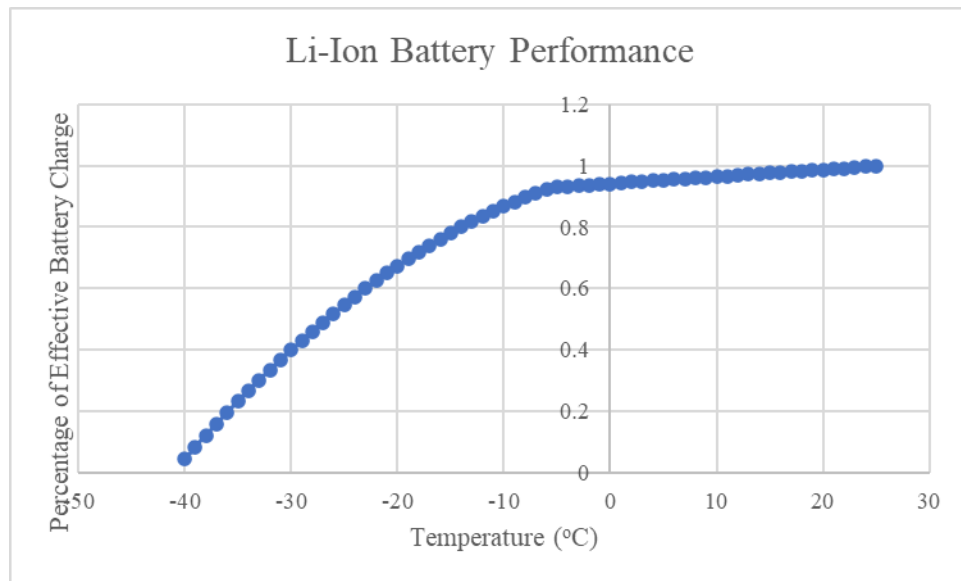


Figure 1. Thermal analysis of Li-ion battery performance.

The anticipated uses for this model are two-fold. First, the tool may be used in a pre-deployment planning scenario where the user may input average temperatures and an expected northernmost operating latitude to generate a consolidated list of UAS options which would fit the need. The second use is once on deployment, the performance calculation portion of the tool may be utilized as a mission planning aid which takes the actual temperature into account when calculating the expected endurance and range of the asset.

Upon inputting several renditions of example data to test the team's additions to the model, two conclusions became apparent. First, any asset which relies solely on GPS signal for navigation severely limits the adaptability of an Arctic mission. The 55th parallel is well below the boundary to the Arctic region on both the Pacific and Atlantic coasts of North America. As such, many of the UAS which are modeled within the tool are outright unable to deploy to the target region. Second, with the seasonal temperatures in Table 1,

an example battery-operated UAS faces a severe impact to the mission by nature of lowered battery performance, and therefore range and/or endurance. Specific to this conclusion, an analysis of alternatives was conducted to investigate external heating, internal heating via resistance, and the introduction of foam insulation to the battery pack.

Table 1. Seasonal average temperatures in Longyearbyen, Svalbard, Norway.
Adapted from Poseidon Expeditions (n.d.)

Seasonal Average Temperatures (C)				
	Spring	Summer	Fall	Winter
High	-8	5	-4	-12
Median	-11	2	-6	-16
Low	-14	-1	-9	-20

From these conclusions, the team developed several suggestions for future work. The first recommendation of note is the further development of the all-climate battery (ACB) which incorporates internal heating and was initially found to be both efficient and cost effective (Wang et al. 2016). Secondly, conducting specific GPS signal fidelity and positional reliability studies within the Arctic to further develop the model and adjust the latitude-based decision-making.

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I. INTRODUCTION

Throughout the first two quarters of CY2023, the joint analysis of Coast Guard capabilities (team JACL) capstone team investigated the implementation of unmanned aerial systems (UAS) assets within the mission sets of United States Coast Guard (USCG) cutters and United States Navy (USN) destroyers. Their work encompassed the creation of the “Drone Selector Tool” for command-level decision making, an analysis of selective mission sets in which a UAS may be used, and a discussion regarding the cost trade-off of an MH-60 with crew versus a UAS flying the same mission (Eilertsen et al. 2023).

The authors of this report (team JACL 2.0) were tasked with continuing the project as set forth by the previous team including further exploring the utilization of UAS assets within the USCG and USN. With the current emphasis on Arctic operations, the team elected to investigate the operational capabilities of UAS in this extreme region. This report focused on the unique environmental challenges and technological requirements for their effective deployment. This chapter lays out the informational baseline that the rest of the project is founded on.

A. BASIS FOR THE REPORT

In recent years, the USN and USCG have both revamped and revitalized their strategies for continued dominance within the Arctic region (Gilday et al. 2021; United States Coast Guard 2019). These strengthened policies rely not only on ongoing maritime partnerships with other Arctic nations, but in the innovative development of new strategies and technologies to continue to protect the United States’ influence and interests. UAS operations represent a dominant trend in the current technological era, and the analysis of their present and future capabilities is in the best interests of both services. Within the context of technological advancement and capabilities assessments, the Arctic region presents complex and unique challenges which must be addressed.

These challenges include radio frequency (RF) propagation, intermittent satellite communication (SATCOM) coverage, space weather, and the limited payload of group 1–3 UAS assets. Additionally, the use of lithium-ion (Li-ion) batteries is abundant in UAS

design, and these are very poor sources of power in extreme cold temperatures (Nagasubramanian 2001; Aris and Bahman 2017, 132). JACL 2.0 sought to perform a robust analysis of the unique operating conditions within the Arctic and Polar Regions with an emphasis on those aspects of UAS operations involving command and control (C2) of the assets themselves. This study's goal was to inform the future of UAS technological and policy development to best utilize the UAS fleet and aid in projecting U.S. interests in this contested region.

The team did this by focusing on two main research topics. First, SATCOM and RF constraints within the Polar Regions. These include satellite coverage, atmospheric effects, cold weather effects, and line-of-sight (LoS) limitations. Second, UAS groups 1–3, due to their wide variety of sizes, present payload challenges which must be overcome. Equipment parameters such as battery size and potential modifications to commercial off-the-shelf (COTS) assets are expected to be limited by the capacity of the systems.

The final deliverable is an extension of the drone selection tool which incorporates factors such as the environment and anticipated mission set to determine the expected performance capabilities of the selected UAS (Eilertsen et al. 2023). In addition, the team created multiple concepts of operations (CONOPS) for Arctic missions which are based on expected UAS performance in the region. These deliverables serve to provide not only a pre-mission planning system in which the most appropriate asset may be selected pre-deployment to guarantee the end-user with their desired outcome, but also a day-of-calculation for real-time environmental inputs which may be used to estimate mission operating parameters on the day of the mission. Without this real-time fidelity, missions must be flown with a wide margin of error due to the unknown actual operating parameters or risk the loss of the asset. The CONOPS provided inform the end-user of several use-cases which were determined to be of note during the investigation, from manual LoS operations all the way to extended fully automated beyond line-of-sight (BLoS) missions.

B. SCOPE

The study centers around the capabilities of UAS in the Arctic while integrated with ships within the USCG and USN inventories. The operational vision, OV-1, is represented

in Figure 1. This vision includes an asset which, when deployed from an independently operating vessel, then integrates with ground nodes, satellite communications, and other UAS in the area to complete the mission. Importantly, the OV-1 describes both LoS and BLoS communications links which are discussed in depth later in this report.

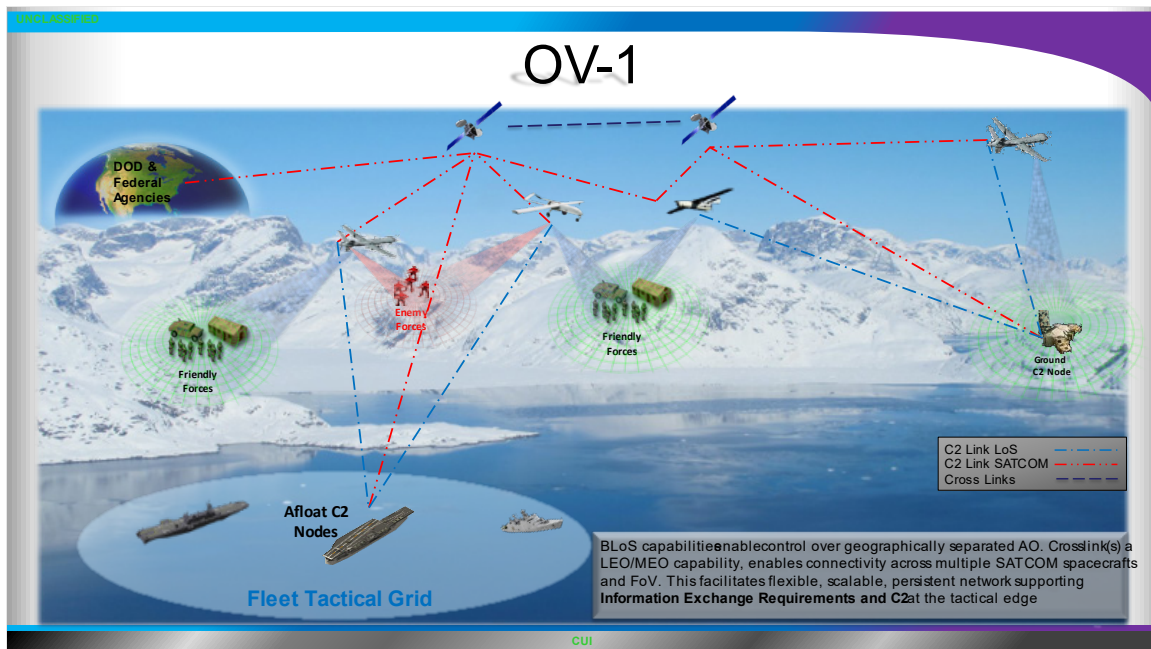


Figure 1. Operational concept for UAS integration in the Arctic

1. Requirements

Table 1 lays out the requirements recognized by the project team, and their justifications for inclusion. The requirements cover operational characteristics, acquisitions methods, and performance measures which must be met to fit the stakeholder's needs. The justifications presented alongside provide necessary amplifying information.

Table 1. Requirements for UAS integration in the Arctic. Adapted from Eilertsen et al. (2023)

	Requirement	Justification
1	Shall require minimal modification to USN/USCG ships to introduce operationally.	Ships have minimal space to spare for further modification or additional equipment.
2	Shall meet minimum requirements for flight in international airspace.	The Arctic is considered international airspace and therefore has requirements for any asset operating therein.
3	Baseline UAS shall COTS.	While portions of this report provide insight to the ideal design of an Arctic UAS, the research team's analysis was limited to COTS assets.
4	Shall be capable of communicating on frequencies which are already utilized aboard USN/USCG ships.	Communication and monitoring of the UAS may be accomplished by the ship alongside the ground controller.
5	Shall be capable of launching from a deployed ship.	This capability assessment centers on operational concepts implemented on USCG cutters or USN destroyers.
6	Shall be recoverable shipboard.	The intent of the study is to provide independently deployable solutions which do not require land-based or otherwise assisted operations.
7	Shall be of UAS group 1 to 3.	The average space available aboard the ship types discussed in this report limit the maximum size of the UAS and all support equipment to those small to medium sized assets.
8	UAS shall be capable of operating in Arctic weather conditions.	To successfully operate within the Arctic region, assets must be capable of surviving the extreme environment.

2. Assumptions

Table 2 introduces the assumptions that were made during the compilation of the report. These statements create the basis for the discussions presented and establish a description of the use case for UAS integration. If these assumptions do not prove true, the discussions and calculations here-in may become inaccurate. The justifications presented alongside provide necessary amplifying information.

Table 2. Assumptions made by the project team. Adapted from Eilertsen et al. (2023)

	Assumption	Justification
1	The requisite fuel to operate relevant UAS will be approved for transport on USN/USCG ships.	Without the ability to transport the requisite fuel for operational deployment, any UAS utilizing fuel instead of battery power is a non-starter.
2	Any battery type installed on a UAS will be approved for transport, charging, and storage onboard USN/USCG ships.	Without the ability to transport, charge, and store the required batteries for the UAS there is no operational feasibility.
3	Flight clearances will be negotiated with the appropriate authorities via letter of agreement, special use airspace coordination, or other similar routing.	Depending on the specific location, Arctic airspace is subject to air traffic control center monitoring and numerous restrictions, including many on the use of UAS assets in international airspace. Without this approval, operational feasibility is severely limited.
4	Any support equipment required for UAS operations to include ground control centers, remote monitoring and control equipment, radios, cameras etc., is approved by the cybersecurity team for use onboard USN/USCG ships.	Without access to this support or operational equipment, there is no way to operate and monitor the UAS while airborne.
5	The UAS represented on team JACL's "Drone Selector Tool" are vetted and approved by the sponsor.	To build onto the "Drone Selector Tool" there must be an assumption that the tool is well-informed and has been verified to date.
6	Requisite information necessary to accurately address the topic study is available at the UNCLAS level.	Due to the security level of this report, any information attainable at or above CUI was not addressed.
7	The missions of interest for the region are limited to those involving intelligence, surveillance, and reconnaissance (ISR); search and rescue (SAR); or research.	Research was not conducted into combat-oriented assets.
8	Significant modification to the UAS is unfeasible.	Research was conducted on COTS assets, including excessive modifications or re-design is outside the scope.

C. SPECIFIC CONTRIBUTION

First, this report acts as a centralized source for information on Arctic UAS utilization. Next, that information is integrated into an updated variation of the "Drone Selector Tool," which has been modified for Arctic specific missions and challenges, which has thus been designated the "Arctic UAS Selector Tool." Finally, the CONOPS

discussed in Chapter VI Section B act to inform the future of UAS development and operational implementation.

D. ORGANIZATION OF REPORT

This report is laid out in six chapters. Chapters I through III are used to inform the reader and build the baseline for the data analysis that follows. The first chapter has established the reasoning behind the project and the parameters by which the rest of the report operates. Chapter II provides the baseline information necessary prior to continuing with the report. The research within is used to inform the discussions throughout, as well as build the model and create the CONOPS. Finally, Chapter III lays out the required steps for using the information within the report and informs the reader of the “Arctic UAS Selector Tool’s” operability.

Chapters IV through VI build on the baseline established in the previous sections and utilize the model to inform decision-making and conceptualization of operations. Chapter IV contains a technical review of the research as well as providing example results from the model. Chapter V studies the “Arctic UAS Selector Tool” to ensure it operates as designed and provides usable outputs. Finally, Chapter VI contains the team’s conclusions, recommendations for future work, and a critical discussion of the report and its effectiveness.

II. BACKGROUND AND LITERATURE REVIEW

The operative theme of this document is focused on decomposing the compounded set of challenges that exist when operating UAS within the polar regions. This chapter reviews the background research and presents a literature review necessary for subsequent chapters.

Addressed below are the availability and viability of radio frequency (RF) technologies and RF-dependent systems in support of UAS operations, with a focus on command and control, to include telemetry tracking and control links and precision navigation requirements. The current technologies that support these vital functions include, but are not limited to, SATCOM and GPS, with the core supporting capability being reliable radio communications. In addition, topography and the physics of RF signals present considerable complications when operating within the Arctic region. This study defines those enabling technologies, their capabilities, viability, limitations, and availability within the polar regions, answers why those issues exist, and offers conceptual solutions.

In addition, there is a robust discussion on multiple ways of providing power to the UAS. From gas powered engines to batteries, there are pros and cons to each technology when considered in the context of deployed operations aboard a USCG or USN vessel, as well as when operating in subzero temperatures. Where gas engines may be more efficient, they also induce more maintenance downtime, and the necessary fuel increases the overall storage requirements (Heisel 2020). Batteries on the other hand are less efficient at low temperatures and have a lower energy density than gasoline but require fewer maintenance activities (Li et al. 2017; Heisel 2020). These trade-offs are to be understood within the context of the two main mission sets SAR and ISR, where the priorities of specific UAS capabilities may differ between missions. For example, on an ISR mission the endurance of the UAS is assumed to be the priority, where SAR missions are assumed to be shorter in both time and distance. The following section describes in detail the operations of the multiple systems which interface within the scope of Arctic UAS operations as well as other conceptual items which aid the reader in understanding the problem space.

A. SATCOM

SATCOM technologies refer to the use of satellite systems, or spacecraft outfitted with radio communication systems, to provide communication links between a sender and one or more receivers. SATCOM utility spans across a variety of societal demands which encompass television broadcasting, internet connectivity, telephone services, GPS navigation, and military operations (Rayermann 2003). It represents a means to close geographical gaps, thereby directly supporting globalization. However, it is inherently limited. To understand these limitations, one must understand the major elements of SATCOM, and how it provides BLoS connectivity. The three major elements, or segments, are the space segment (orbital structure), the ground control telemetry tracking and control segment, and the user segment which includes the ground receiving systems. In this context “ground” refers to systems on the ground, on the ocean’s surface, sub-surface, and in the air (Jo 2011).

1. Orbits

This refers to the path that space objects, such as satellites, follow as they revolve around a larger celestial body, in this case the Earth. In the context of SATCOM, orbits refer to the trajectories satellite systems take to circle the earth (Minoli 2015). Orbits consists of three physically codependent essential characteristics, which when combined help determine a satellite system’s usability: distance from earth, inclination, and field of view. Inclination describes the tilt, or angle, of the satellite’s orbit in relation to the Earth’s equator (Minoli 2015). It is the measure of the angle between the orbital plane of the satellite and the plane of the equator, from 0 to 90 degrees (Minoli 2015). A 0-degree orbit is directly over the equator, while a 90-degree orbit would bisect the poles. The explicit orbital characteristics of the satellite systems directly affect where they may best be used and where they may provide services and coverage (Albon 2021).

There are three main types of orbits: geostationary earth orbit (GEO), medium earth orbit (MEO), and low earth orbit (LEO). The fourth type is far less utilized for civil use cases, the highly elliptical orbit (HEO) (Albon 2021). These orbits occupy distances from 300 kilometers to 45,000 kilometers from earth, with an inclination from 0 to

approximately 60 degrees north/south (Albon 2021). Because of the distance, inclination, and field of view, GEO is not a very viable option to support Arctic operations:

The situation can be summarized as follows: GEO satellites cover relatively well communications needs up to 75-degree N/S, and meteorological observation needs up to 55 degrees N/S. For high latitudes, GEO satellite networks are simply insufficient or not designed to provide continuous services in terms of coverage, data rate, or communication frequencies needed for civilian and defense operations. (Trishtchenko, Garand, and Trishtchenko 2019)

They add that only HEO, LEO and MEO are viable options to provide observation over high north, stating that while GEO coverage is good up to 75 degrees, availability is sparse (Trishtchenko, Garand, and Trishtchenko 2019). Satellites within LEO, MEO and HEO constellations that provide better coverage over the Arctic make up less than 30 percent of available systems (Trishtchenko, Garand, and Trishtchenko 2019). The challenges of GEO satellites, and SATCOM within the Arctic in general have been well studied:

The challenges of communicating in this region include severe magnetic storms, the polar cap absorption phenomena, and high mountains with heavy metallic concentration-all of which are detrimental to radio signals. SATCOM [is] especially problematic because of the extremely low takeoff angle needed to access equatorial geostationary GEO satellites. Low takeoff angles are also impacted by scintillation, which is the refraction of radio signals through the atmosphere. (Mirenda and Sandler 2021)

Orbital structures and characteristics remain the key challenges limiting access in the Polar Regions, as they affect all space-based capabilities to include GPS, ISR, and others.

2. Control Segments

This is a crucial component of satellite operations, it consists of the infrastructure, facilities, and personnel responsible for tracking, controlling, and communicating with satellites in orbit. This functional construct is responsible for orbital determination, prediction, and sustainment while also maintaining communication and command links and mission planning. Without the control segment a satellite would not remain in orbit (Segura et al. 2012). These functions require infrastructure which does not exist in

abundance in the Arctic. Mirenda and Sandler had this to say about the availability of satellite communications in the Arctic:

The Defense Information System Agency's (DISA) Enhanced Mobile Satellite Service, which interfaces with the commercial Iridium satellite constellation through a DISA-controlled and secure satellite gateway, is the only current viable means of voice and limited data communications in the Arctic. (Mirenda and Sandler 2021)

There are a few commercial companies that are beginning to invest in LEO and MEO capabilities that may eventually solve these issues of availability and supportability. In the meantime, another solution must be found.

3. User Segments

This refers to the end-users, the customers outfitted or equipped with receiver and transmitter systems. This ranges from individual operators on the ground, maritime systems, surface, sub-surface, or air systems furnished with SATCOM communications terminals (Segura et al. 2012). These SATCOM systems include several key sub-components; antennas, transceivers, power supplies, and signal processors—these are cumulatively categorized as the ‘communication payload’ when in reference to UAS or aircraft systems. These components vary in size, weight, and power capabilities, depending on the structure that they are built to operate within. UAS groups 1–3 have limited payload capability, therefore selecting and outfitting these UAS with the appropriate communication payload poses a significant challenge. The nature of HEO, MEO and LEO orbits and systems require more modern systems and technologies. For example, the ability to track satellites, to be handed over between satellites without dropping connectivity, and to increase power output to combat weather effects in the Arctic (Segura et al. 2012). All these combined have the possibility to quickly increase the size, weight, and power (SWaP) required of communication payloads.

B. LINE-OF-SIGHT COMMUNICATIONS

Discussion thus far has focused on BLoS radio frequency capabilities and the inherent constraints that exist while utilizing them in the Arctic. When it comes to LoS communications, it is the lack of freedom of marine navigation which impinges upon the

deployable range for drones, making the use of otherwise viable very high frequency (VHF) and ultra-high frequency (UHF) technologies to support drone operations less straightforward (Floriani et al. 2007). Scientifically, VHF and UHF present no technical limitations and are commonly used in the Arctic already, as they are in other regions of the world. The key concern is range limited by LoS. The following factors to consider include the required supporting infrastructure capable of increasing the range of VHF and UHF LoS, and general signals characteristics.

1. Very High Frequency

VHF radio systems operate in the frequency range from 30 megahertz (MHz) to 300 MHz and are extensively employed for diverse communication purposes including maritime, aviation, and land-based applications (Floriani et al. 2007). They specifically make up part of the critical communications network in the Arctic and are used for navigation, weather updates, safety alerts, ship-to-shore, and ship-to-ship communication, aircraft to aircraft, and between aircraft and air traffic control facilities.

VHF radio communication is limited by its LoS propagation (Floriani et al. 2007). In areas with significant topography, or in this case ice obstructions, the effective range of VHF radios may be affected. In such cases, other communication methods like high-frequency radio, satellite communication, or repeater stations may be used to extend the range of communication in the Arctic.

2. Ultra-High Frequency

Ultra-high frequency radio systems operate in the frequency range from 300 MHz to 3 gigahertz (Chieftain Training 2022). UHF radio systems offer advantages over VHF in terms of signal penetration and propagation under certain conditions but have similar inherent LoS limitations. UHF radio systems are often used by military and defense agencies for communication, including naval, air, and ground operations in the Arctic region. UHF radios provide enhanced penetration through challenging terrain and offer a degree of security due to the LoS limited nature of UHF signals (Chieftain Training 2022). They support a wide array of operations ranging from remote sensing to weather monitoring, and communication services, scientific expeditions, research stations, and

environmental monitoring projects. UHF is even used for telemetry and data transmission from remote sensors, as well as communication for unmanned aerial vehicles (Chieftain Training 2022).

It is vital to mention that the selection relating to VHF and UHF communication in the Arctic depends on the specific requirements of the application, the terrain, and the range needed. UHF frequencies offer advantages in terms of signal penetration through obstacles like ice and buildings, but they may have a shorter effective range compared to VHF for LoS communication (Chieftain Training 2022). Additionally, UHF satellite communication systems play a significant role in providing reliable connectivity in the Arctic, especially in remote areas where terrestrial radio infrastructure is limited.

3. Supporting Infrastructure

The primary characteristic to discuss is the range of the infrastructure. This refers to the distance between (two or more) transmitting and receiving stations. Unlike frequencies below 2 MHz, radio waves in these higher frequencies travel in straight lines, commonly referred to as LoS, and generally cannot travel beyond the horizon (Chieftain Training 2022). Without supplementary subcomponents to increase signal strength and visibility, maximum communication range for these LoS radio systems is limited to approximately 30 miles (Chieftain Training 2022). To increase range, comprehensive infrastructure(s) such as transmission towers with increased power out capabilities, and relay stations are needed to capture and repeat signal(s) in one direction, consequently increasing the normal range of communications. There are three main characteristics that can aid in extending the range: 1) increased height/clearance to compensate for the curvature of the Earth, 2) increased power output systems and antenna polarization which refers to the direction of the electric field vector in an electromagnetic wave as it propagates through space, and 3) implement retransmission component(s) between two distant sites, which refers placing a system between two or more respective sites, to receive and repeat or retransmit signal(s) between sites that are beyond LoS capabilities (Chieftain Training 2022). VHF antennas are typically either vertically polarized or horizontally polarized. Using the same polarization at both ends of the communication link helps maximize signal

strength (Chieftain Training 2022). Figure 2 provides a visual depiction of LoS and a notional Coast Guard range extension use-case.

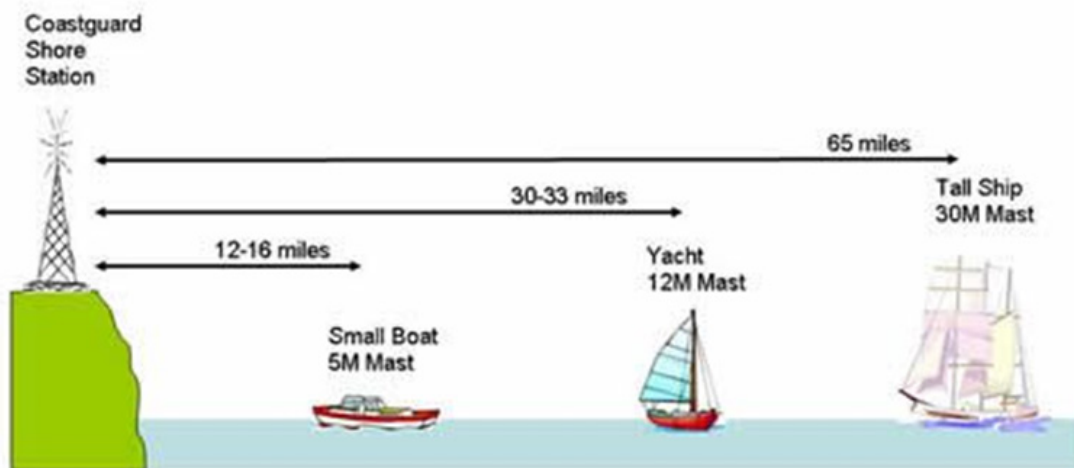


Figure 2. Notional Coast Guard range extension use-case. Source: Chieftain Training (2022).

The use case in this project requires UAS to be deployed beyond 30 miles from a control station. Given the limitations of LoS, it is evident that the use of VHF and UHF LoS systems alone to support UAS C2 operations is not feasible.

C. WEATHER

The weather in the Arctic region is known for its extreme nature. Low temperatures, high winds, and rolling seas all make for difficult operating conditions for any mission; however, in terms of UAS usage, these all introduce specific difficulties.

1. Low Temperature

The extreme low temperatures of the Arctic wreak havoc on systems of all kinds, and UAS are not immune to the effects. Cold temperature effects on batteries are established in the next section; however, fuel, flight controls, and maintenance processes are also subject to degradation. A complete discussion of Arctic weather can be found in Chapter IV Section D.2.

First, fuel is utilized in combustion engines through just that, combustion. As the temperature of the fuel lowers, combustion is more difficult to attain (Centers for Disease Control and Prevention [CDC] 2017). There are several different types of aviation gasoline routinely used in the United States military and each has its own usable range, as shown in Table 3 (CDC 2017). As the melting point and freezing point of a substance are the same temperature, this is the most pertinent line of the table. From this data, one can determine that the minimum usable temperatures of Jet Propellant-5 (JP-5), Jet Propellant-8 (JP-8), Jet A, and Jet A-1 are -46, -52, -40, and -47°C respectively. With monthly average temperatures reaching as low as -19°C, all these fuels provide a wide margin for temperature swings (Poseidon Expeditions n.d.). Importantly, this temperature is measured at the surface and does not take altitude into consideration, where temperatures are colder. As an aside, when it comes to shipboard safety, the flashpoint of the fuel is of critical importance. This table also gives evidence as to why the main fuel used aboard USN and USCG ships is JP-5, as it has a minimum flashpoint of 60°C as opposed to 38°C (CDC 2017). To achieve and maintain a usable fuel temperature, aerospace engineers utilize different techniques from fuel tank insulation to heat-exchangers which use the fuel tanks as heat-sinks (Slaubaugh, Lucht, and Lobo 2023).

Table 3. Aviation fuels. Source: CDC (2017).

Property	JP-5	JP-8	Jet A ^b
Molecular weight ^c	No data	No data	No data
Color	Clear and bright ^d	Clear and bright ^d	Clear
Physical state	Liquid ^e	Liquid ^e	Liquid
Melting point	-46°C ^d	-52°C ^d	-40°C (Jet A); -47°C (Jet A-1)
Boiling point	170°C ^f ; 150–290°C ^g	170°C ^f ; 150–290°C ^g	145–300°C
Density at 15 °C	0.788–0.845 kg/L ^f	0.775–0.840 kg/L ^f	0.775–0.840 kg/L ^h
Odor	Kerosene-like ⁱ (kerosene)	Kerosene-like ⁱ (kerosene)	Kerosene-like ⁱ (kerosene)
Odor threshold (ppm): 1i; 0.082 ^k (kerosene)	1i; 0.082 ^k (kerosene)	1i; 0.082 ^k (kerosene)	0.082 ^k (kerosene)
Solubility:			
Water at 20°C	~5 mg/L ^e (kerosene)	12.44 mg/L (unspecified temperature) ^b ~5 mg/L ^e (kerosene)	10.4 mg/L ~5 mg/L ^e (kerosene)
Organic solvents	Miscible with other petroleum solvents ^k	Miscible with other petroleum solvents ^k	Miscible with other petroleum solvents ^k
Partition coefficients:			
Log K _{ow}	3.3–7.06 ^e (kerosene)	3.3–7.06 ^e (kerosene)	3.3–7.06 ^e (kerosene)
Log K _{oc}	9.6x10 ² –5.5x10 ^{6e} (kerosene)	9.6x10 ² –5.5x10 ^{6e} (kerosene)	9.6x10 ² –5.5x10 ^{6e} (kerosene)
Vapor pressure at 21°C	2.25–25.1 mm Hg at 21°C ^b 1.12–26.4 mmHg ^e (kerosene)	2.25–25.1 mm Hg at 21°C ^b 1.12–26.4 mmHg ^e (kerosene)	>7.5 mm Hg at 37.8°C
Henry's law constant at 20°C	5.9x10 ⁻⁵ –7.4 atm-m ³ /mol ^e (kerosene)	5.9x10 ⁻⁵ –7.4 atm-m ³ /mol ^e (kerosene)	5.9x10 ⁻⁵ –7.4 atm-m ³ /mol ^e (kerosene)
Autoignition temperature	229°C ^j (kerosene)	229°C ^j (kerosene)	229°C ^j (kerosene)
Flashpoint (minimum)	60°C ^{d,i}	38°C ^{d,i}	38°C ^g
Flammability limits (% volume in air)	0.7–5% ^j (kerosene)	0.7–5% ^j (kerosene)	0.7–5% ^j (kerosene)
Conversion factors	No data	No data	No data
Explosive limits	0.7–5% ^j (kerosene)	0.7–5% ^j (kerosene)	0.7–5% ^j (kerosene)

With sub-zero temperatures comes an increased opportunity for snow and ice accumulation on the UAS and ship's surfaces. This accumulation affects all phases of flight from takeoff to landing, and even pre- and post-flight activities (National Weather Service n.d.). On the flight deck, the ice leads to an unstable launch platform, which is already a problem at sea. In flight, ice not only adds extra weight, but also increases drag (National Weather Service n.d.). This drag spoils the aerodynamics of the airfoil and reduces lift. On landing, ice accumulation on deck again leads to an unstable landing surface.

Finally, the process of maintaining the UAS is a second-order victim of the low temperatures in the Arctic. With reduced temperatures comes the requirement for more

personal protective equipment for the support personnel. With types 1 and 2 UAS, this is not likely to be as much of an issue by nature of the fact that they are more easily transported to an interior space aboard the ship. Type 3 assets, on the other hand, are almost universally too large to be stored inside a ship which is not equipped with a helicopter hangar. The introduction of physical barriers like bulky gloves, and policy barriers like limited environmental exposure times are expected to affect the operational tempo of the maintenance personnel. This degraded tempo is then expected to negatively affect the deployed operations of the UAS by increasing overall downtime. However, further analysis of these secondary effects is outside the scope of this report, and they are thus not discussed further.

2. Sea State

There is a long-standing history and precedence for ship-borne aviation both in the USN and USCG. Alongside the challenges of having a cramped operating space, smaller landing zones, and the many physiological implications of operating on an isolated platform in the sea, is the constant threat of an unsteady and randomly oscillating deck. This is a factor no matter which body of water the ship is operating in. The Arctic is not historically known for having large waves year-round, but the increasing ice-free seasons are having a large effect on the average wave heights (Liu et al. 2020). This is projected to increase drastically over the next several decades, with average wave heights increasing by two or three times by 2081–2100 (Simpkins 2020). While this modeling is based on many estimations and assumptions, it is valuable in this study as a point of discussion.

While the Arctic itself is not historically known for its extreme sea states, the pathways to the Arctic are. The waves in the North Pacific, Pacific Coastline, and the Bering Sea are all known for their stature. On the Atlantic side, the North Sea has historically produced some of the largest waves on earth (Blackledge et al. 2012). This would indicate that the final mission area may not be the limiting factor throughout a full deployment. For further discussion on sea states within the Arctic, see Chapter IV Section D.2.

3. Wind Speed

The final significant weather-related factor is the wind speed as a takeoff and landing limit. Once a UAS is airborne, the steady movement of the wind relative to the aircraft has little effect on its overall performance as an airmass tends to move in one unit (Wang et al. 2019). This is not the case, however, close to the surface or in gusty conditions. Large changes in wind velocity or direction may be catastrophic to the UAS while in close proximity to another structure, including the ship or sea (Wang et al. 2019).

To combat this risk, operating procedures for aviation-related surface assets include turning the ship into the wind and adjusting speed to increase or decrease the wind over the deck and dampen the ship's pitch and roll oscillations (Britannica 2023). This maneuverability may not always be ideal for UAS deployment, especially if the UAS deployment is to aid in SAR operations or the maneuver takes the ship out of operating range for the area of interest.

D. BATTERIES

Lithium-ion (Li-ion) batteries remain the gold standard for compact, energy dense, power solutions. They self-discharge at a slower rate, have almost no memory, and have a relatively long lifespan; all characteristics which make these batteries an ideal choice when designing a UAS (Kim et al. 2019). They do have one major drawback, however, in that they are very temperature sensitive. This fact is the focus of the battery discussions within this study.

1. Li-ion Battery Physics

Batteries work through the interaction of several internal components. These components are the anode, the cathode, and the electrolyte. Both the anode and cathode, in this case, contain lithium while the electrolyte can be any number of materials depending on the specific battery (Minos 2023). In the unenergized state, lithium is electrically neutral. When the battery is either charging or discharging, lithium ions are transferred from the cathode to the anode or vice versa. This transport is conducted within the

electrolyte, and it is the movement of these ions which generates the electricity to power the system (Minos 2023).

2. Temperature Sensitivity

Although the temperature sensitivity of Li-ion batteries has been well-documented, it was not until recently that a study had been conducted on the specific physics involved. In 2017, Li et al. published their research in the *Journal of Applied Materials and Interfaces* which described the detailed steps which occur during the charge and discharge process of a model lithium-ion battery. They then designed an experiment to measure the interaction of each of these steps and found that the desolvation of the lithium ions in the electrolyte was the physical barrier of the process at low temperatures (Li et al. 2017).

Despite this discovery, it remains true that modern Li-ion batteries show poor performance parameters while operating at sub-zero temperatures. One report suggested that battery capacity dropped by as much as 98% when below -40°C, while another study on the cold-temperature effects on lithium-ion batteries produced Table 4 (Nagasubramanian 2001; Aris and Bahman 2017, 132).

Table 4. Li-ion temperature vs. performance. Source: Aris and Bahman (2017).

Testing Temperature (T _{test})	Charge			SOC	Discharge			DOD
	Min. Temperature	Max. Temperature	Temperature Difference (ΔT)		Min. Temperature	Max. Temperature	Temperature Difference (ΔT)	
25 °C	23.6 °C	25.9 °C	2.3 °C	100%	24.9 °C	27.7 °C	2.8 °C	100%
-5 °C	-5.0 °C	-1.7 °C	3.3 °C	93%	-5.1 °C	-0.5 °C	4.4 °C	92%
-10 °C	-10.0 °C	-6.0 °C	4.0 °C	88%	-10.1 °C	-6.0 °C	4.1 °C	85%
-15 °C	-15.8 °C	-10.4 °C	5.4 °C	77%	-15.8 °C	-10.3 °C	5.3 °C	82%

Several solutions have been proposed which can mitigate this effect, from increased insulation to pre-heating the batteries, and even using the battery's own power to heat itself. Each of these solutions has shown promise within laboratory settings, but also introduce new challenges when applied to UAS technologies (Lei et al. 2015; Wang et al. 2016).

E. FUEL

There are numerous fuels used in the world of aviation, all of which have specific chemical characteristics and physical properties. For purposes of this study, JP-5 and JP-8 are the most commonly used in the United States military with JP-5 being almost exclusively used shipboard (CDC 2017, 4.1). The properties of the fuels may be found in Table 3.

With respect to Arctic operations, the lower fuel freezing point of JP-8 makes it the ideal fuel for the mission; however, JP-5's much-increased flashpoint leads to its preferred status for shipboard usage for safety reasons (CDC 2017). Not shown in the chart are various additives that are included in many fuel types which bolster secondary characteristics like lubrication and thermal stability (CDC 2017, 4.1)

F. UAS

To maintain continuity with the research carried out by Team JACL, and to achieve the goals set forth in this study, the research team utilized the same UAS provided by the "Drone Selector Tool" (Eilertsen et al. 2023). UAS are split into groups that consider the maximum weight, normal operating altitude, and speed. The first UAS category, group 1, weighs less than or equal to 20 pounds, operates less than 1,200 feet above ground level, and does not exceed 100 knots. Group 2 weighs between 21 and 55 pounds, operates at a maximum altitude of 3,500 feet above ground level, and does not exceed 250 knots. Group 3 has a maximum weight of 1320 pounds, operates below 18,000 feet mean sea level, and has a maximum airspeed of 250 knots. These groups are summarized in Table 5. UAS have proven to be some of the most reliable and efficient means of conducting auxiliary missions of ships, primarily ISR and radio relay (Eilertsen et al. 2023). The main key limiting factors of UAS productivity are the amount of power/fuel the UAS can effectively carry/maintain while simultaneously being able to carry the appropriate payload for the required mission set. These variables will inevitably affect variations in RF distance caused by power output of the UAS. Additionally, varying temperatures and air densities at geographically different areas alongside differing altitudes will likely affect the ranges of the tasked UASs as well. (Eilertsen et al. 2023)

Table 5. UAS group definitions. Source: Eilertsen et al. (2023).

UAS Group	Maximum Weight (lbs)	Normal Operating Altitude (ft)	Speed (kts)
Group 1	0-20	< 1,200 AGL	< 100
Group 2	21-55	< 3,500 AGL	< 250
Group 3	< 1320	< FL 18,000 MSL	< 250
Group 4	> 1320	< FL 18,000 MSL	Any Airspeed
Group 5	> 1320	> FL 18,000 MSL	Any Airspeed

G. DUE REGARD

Due regard is the term used to describe the operations of an aircraft outside of a state’s territorial airspace. For the United States Department of Defense (DOD), this operation is described in Flight Information Publication – General Planning, and DOD Instruction 4540.01 “Use of International Airspace by [United States] U.S. Military Aircraft and for Missile and Projectile Firings.” (National Geospatial-Intelligence Agency [NGA] 2023, 8–1; Department of Defense [DOD] 2015). These publications lay the foundation for operating aircraft outside of the purview of the international civil aviation organization procedures.

Due regard operations are named such because the aviator must operate with “due regard for the safety of navigation of all aircraft” (NGA 2023, 8–2; DOD 2015, 8). To accomplish this, the aviator must operate within visual meteorological conditions and have a safety observer, whether visually or on radar. Furthermore, UAS operators must maintain visual contact with the UAS unless it is equipped with a “Military Department-certified system that is sufficient to provide separation between them and other aircraft” (NGA 2023, 8.3; DOD 2015, 9).

H. FLIGHT INFORMATION REGIONS

Flight information regions (FIRs) refer to airspace divisions created by the international civil aviation organization to geographically divide responsibility for flight information and alerting (Federal Aviation Administration [FAA] 2023). These regions may be over a territory, such as the FIR presided over by the Houston, TX air route traffic

control center, or they may be oceanic or over several member states. Likewise, the Arctic is divided into seven FIRs, shown in Figure 3 (FAA 2010).

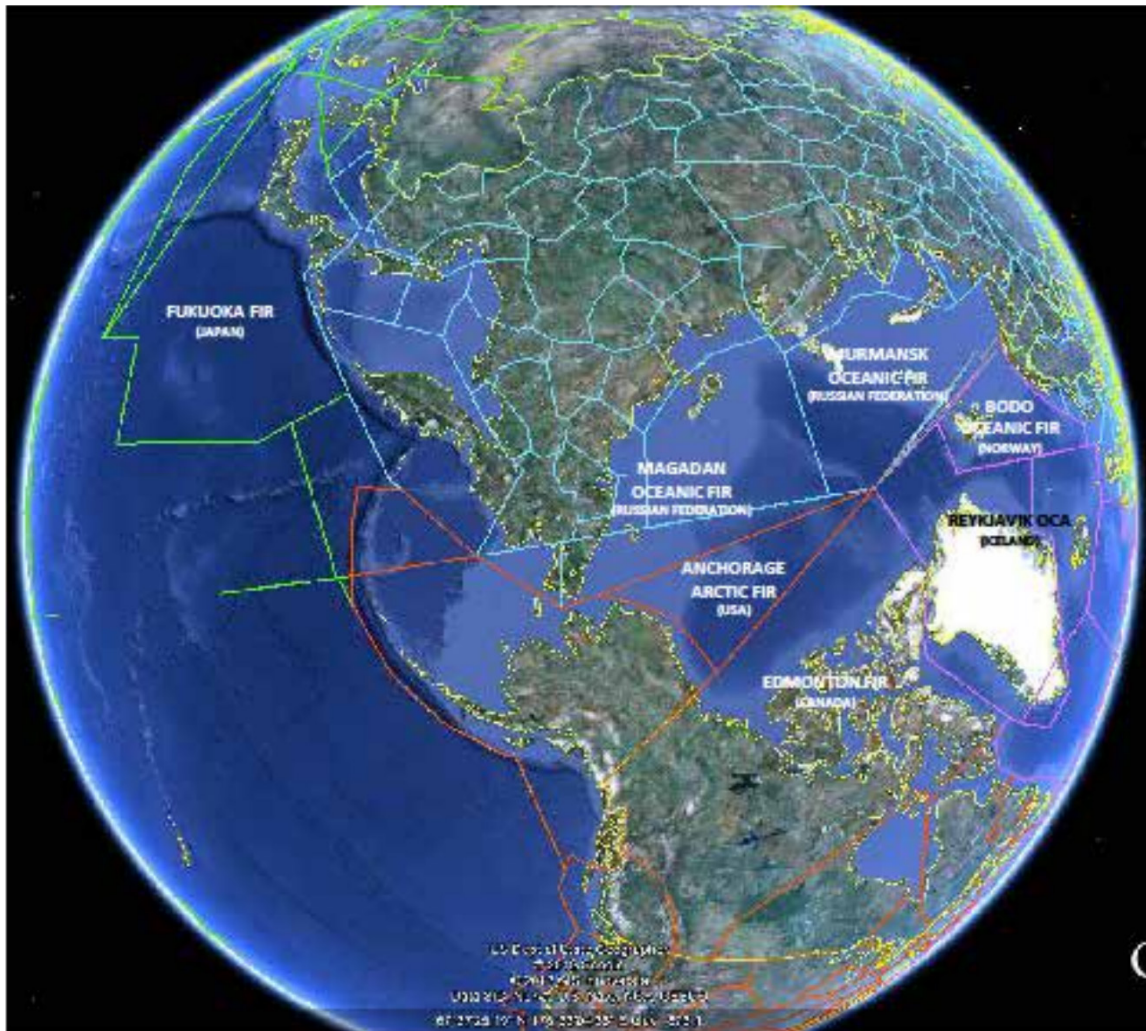


Figure 3. Map of the Arctic FIRs. Source: FAA (2010).

The importance of FIRs is that each is assigned to an individual state or organization for authority within. Therefore, each may also have its own individual set of operating procedures. This is further convoluted in the Arctic where each of the seven FIRs there-in cross boundaries with multiple nations (FAA 2010). To legally fly in this airspace, one must not only obtain authorization from the controlling agency but must also ensure

compliance with the rules and regulations of each country contained within its boundaries (FAA 2010).

I. USN/USCG SHIPS

The USN and USCG employ a wide selection of ships in support of military, civil, science, and research operations, ranging from amphibious operations, freedom of navigation at sea, military resupply operations, disaster relief, global medical support to science and technology research activities. Unique mission profiles require unique ship types with specific systems attributes to fulfill mission requirements. These ships are purpose built to support those unique operations in the corresponding conditions and environments—the USCG operates an array of specific ships which provide the capabilities to execute assigned missions. These ships are arranged into programs of record and managed by their respective requirements managers and acquisition professionals. Those include the cutter classes (lite, medium, and heavy), cruisers, patrol ships, destroyers, seaplanes, ice cutters etc.; ships to operate in every clime and place, including the Arctic regions.

In keeping with the premise of this document, the focus is on USCG missions in the Arctic, with corresponding lines of effort focused on operating UAS to support a variety of mission subsets; SAR, ISR, weather, and science and technology research. The USCG anchors on its mission statement that acknowledges the need for a “mobile and seasonal presence for Arctic Operations as levels of maritime activity require” (Jacob, Coffey, and Walker 2013). The USCG commissions a few ships to support Arctic operations that are outfitted with the technologies required to support and perform all implicit and explicit tasks supporting their core mission. Those supporting technologies include UAS systems and operations, which support SAR, ISR, and research activities. Basic UAS operation includes at least three main operation elements: control, support, and user operations element.

The overall construct of what that looks like depends on the environmental conditions, technology availability, and technology readiness level operational and mission output requirement—imposed objectives and geographic conditions and technology

readiness level dictate how operation is conducted and what capabilities are essential. The USCG has made significant strides toward realizing fully functional and adequate capabilities required to effectively perform all required missions within the Arctic regions. One of the recent capabilities, and currently employed in the Arctic is USCG Cutter (USCGC) *Healy* (WAGB-20), a cutter ship purpose-built for the Arctic. The USCGC *Healy* is instrumental in the USCG's Operation Arctic Shield, "the service's annual operation to execute U.S. Coast Guard missions, enhance maritime domain awareness, strengthen partnerships, and build preparedness, prevention, and response capabilities across the Arctic domain" (Jacobs, Coffey, and Walker 2013). Here, the USCGC *Healy* also participates in science missions to further U.S. and USCG interests in the area (Jacobs, Coffey, and Walker 2013).

The USCG continues to implement and investigate UAS capabilities from USCGC *Healy* and are having marginal to moderate successes employing and deploying UAS in support of named missions in the Arctic.

J. THE "DRONE SELECTOR TOOL"

As mentioned in Chapter I, the preceding capstone group, Team JACL, created a tool, named the "Drone Selector Tool," to allow for rapid filtering of available UAS options by ship and mission (Eilertsen et al. 2023). The inherent intent of the tool is to provide weighted best fit UAS suggestions based on mission compatibility to the user. The "Drone Selector Tool" is made up of several data sheets within an excel document that work together to create the output of drone/UAS recommendations to the user. Each data sheet has its own purpose or function, which is outlined in Table 6. The Parnell Method for utilizing swing weights was introduced and adopted by Eilertsen et al. to show ship and mission compatibility to the UAS and is one of the driving factors for creating the output.

The feature sheet, called the "Mix&Match," houses the user interface, which contains several drop-down or manual input cells that access a separate sheet called the "Backend-Mix&Match," which houses the bulk of functions needed to create the output. The user interface is designed to be simplistic while the backend sheet is much more complex, but necessary in order to effectively and efficiently output desired results. The

user interface options will first access the backend sheet and filter recommended UAS assets by absolutes. For example, if the UAS requires a runway for takeoff and landing then it is excluded from the calculations for all selected ship types which do not contain such a surface. After this immediate determination of fit, or lack thereof, the tool proceeds to perform the weighted calculations as described above for each of the other evaluated characteristics. This calculation culminates in a color-coded list of representative UAS assets to aid the user in determining the best fit for the mission and ship parameters.

Table 6. “Drone Selector Tool” sheets. Source: Eilertsen et al. (2023).

Sheet Title	Sheet Function
“Drone Specs”	Specifications of the drone/UAS data set, including things like maximum range, speed, payload weight, power type, GPS capable, and others that may be considered requirements or nice-to-haves for missions.
“Ship Specs”	Specification of the ship data set, including things like runway launch and storage space, number of operators and others that may be required for drone/UAS missions.
“ShipDroneSupportability”	Houses functions that identify if a drone/UAS and a ship are compatible based on the information provided in the specifications sheets.
“DroneMissionSupportability”	Houses functions that identify if a drone/UAS is capable of flying the different mission types (ISR/SAR and logistics)
“Parnell-ISR”	Houses the calculations for determining swing weights for each drone/UAS for ISR/SAR missions.
“Parnell-Logistics”	Houses the calculations for determining swing weights for each drone/UAS for logistics missions.
“Backend-Mix&Match”	Houses all of the additional functions and calculations used for determining the selector tool’s outputs; using functions and lookups from each of the other sheets and their calculations to create the final output chart, this sheet is the backbone of the selector tool.
“Mix&Match”	Houses the user interface and chart of output, which is the culmination of each of the other sheets in the tool.

K. LITERATURE REVIEW

The Arctic region is a dynamic environment, with ever-more opportunity for human and economic activity to increase in reduced ice conditions (United States Coast Guard 2019). Shipping routes, resource extraction, tourism, and national security interests are all drastically increasing in the region, meaning the need to continue technological advancements to meet the increased demand is increasingly important (United States Coast Guard 2019). To meet those needs, this study references similar bodies of work to provide critical information to stakeholders. While there is a significant number of studies that pertain to Arctic strategy and the unique challenges in the region, few have gone into any depth concerning UAS operations and communications challenges; the very questions being addressed throughout this study.

The report that led to the basis of this study, *“Research on Potential Unmanned Aerial Systems CONOPS for USN and USCG Ships,”* has laid the groundwork that it is not only feasible, but significantly favorable to equip surface fleets with UAS to improve SAR and ISR missions (Eilertsen et al. 2023). That report also provides the current study with the framework for pairing ships and UAS based on such characteristics as available space, launch and recovery capabilities, and qualified crewmembers aboard the ship, as well as the range, loiter time, and payload capabilities of the sampled UAS types (Eilertsen et al. 2023). Utilizing the information provided in that report allows this study to address communications, flight times, and other mission parameters, without having to make assumptions.

The same study discussed above also culminated in the “Drone Selector Tool” described in Chapter II Section J. The “Drone Selector Tool” is the predecessor to the “Arctic UAS Selector Tool,” an adapted iteration utilized for the purposes of the current study’s involvement in the Arctic arena. Most, if not all, of the functions in the adapted version carry over from the earlier version, but with additions, adaptations, or improvements for Arctic operations.

Another important study, *“Evaluation of a ship-based unoccupied aircraft system (UAS) for surveys of spotted ribbon seals in the Bering Sea pack ice,”* carried out by Erin

E. Moreland et al. in 2015 examined how useful UAS would be in conducting aerial surveys of marine wildlife in Arctic conditions. Their research was conducted using three Boeing ScanEagles, small UAS specifically designed for marine launches and recoveries (Moreland et al. 2015). The ScanEagle systems were launched from the *McArthur II*, a vessel operated by the National Oceanic and Atmospheric Administration, and carried out cold-weather research and telemetry missions (Moreland et al. 2015). The impact of the study provides the current research efforts tangible data on a UAS of interest, the ScanEagle, and breaks down distances flown, types of fuel used, successful launch and recovery of the UAS, and comparisons to similar missions flown by manned aerial vehicles. The research conducted by Moreland et al. also touches on command and control, flight protocols, weather effects on the UAS, and multi-agency cooperation, which are all relative subjects in the ongoing study of utilizing similar systems on USCG surface ships in the Arctic (2015).

In the article titled, “*Energy Efficiency Optimization for UAV-Assisted Backscatter Communications*,” researchers Wang et al. proposed an alternative way of relaying information that reduces battery usage compared to traditional communication patterns (2019). Their research centering on battery power and radio frequencies, though not in such extreme cases such as Arctic weather, supports this study’s objectives of addressing communications concerns. Wang et al. determined that using a backscatter technique to relay information to its parent-entity would conserve battery usage since the specified backscatter technique would require a shorter relay range to the host than typically seen within beyond LoS communications avenues (2019). It was noted that unmanned aerial vehicles (UAVs) could act as sole entities in flight to have communications with the host or multiple UAVs could be used in the C2 architecture to increase range. When multiple UAVs were utilized, the UAVs in the middle of the chain were used as relay stations to shorten the transmission range of each individual UAV (Wang et al. 2019). This information, accompanied with battery usage statistics, was helpful in addressing concerns of stakeholders, even though the targeted audience would be UAV users “for intelligent agriculture in large farms and fauna and floral protection in national parks” (Wang et al. 2019). Using this caveat, this study acknowledges that this is not research specifically

targeted towards this project's endgame; however, the information still plays a relevant roll in drawing the connection to potential energy saving alternates of UAS function in colder climates.

In conclusion of this review, it is important to note that the specifics of this study have not been previously studied with much significance. Individually, focus areas of this study have a wide array of research done on them, such as C2, group three or smaller UAS, USCG cutters and Arctic operations, and SATCOM and RF challenges in the Arctic region. When focusing the research on operating UAS in the Arctic region and compiling each of those individual topics into one, previous research is hardly existent within the defined parameters. It is the goal of this study to pave the way for research, data, and CONOPS associated with utilizing the UAS in the Arctic, a region that is rapidly gaining attention from powerful and technologically advanced nations, despite the many challenges faced.

L. SYSTEMS ENGINEERING PROCESS

This project implements tools and systems engineering processes to research, develop, and analyze utilization of UAS on USN and USCG surface ships. Due to the project's scope, the team identified an inter-disciplinary approach to the engineering process. There are aspects of both the systems engineering design process (SEDP) and model-based systems engineering. The inter-disciplinary approach has added benefits over any individual process since this project consists of many theoretical concepts as well as a need to create analytical models, while identifying requirements, functions, users, and various other systems engineering methodologies.

1. Systems Engineering Design Process

In his thesis, Jeff D. Baker describes SEDP as a strategic four-phase systems analysis approach to the engineering process, effectively focusing on a flexible, iterative, process following a structure of continuous modification, evaluation, and response (Baker 2020). When used alongside Joint Publication 5.0, *Joint Planning*, it provides “an enhanced design methodology and systems analysis approach that supports a more effective and coherent strategic design” (Baker 2020).

SEDP contains four phases, the first of which is the problem definition and is accomplished in Chapter I. Phase two, design and analysis, was an ongoing iterative step throughout the project, where framework and concepts were identified and modified as necessary. Phases three and four, decision making and implementation, respectively, extend into future work for other groups or for the stakeholders based off the research and suggestions provided by the findings of this effort (Baker 2020). These four phases are outlined in Figure 4.

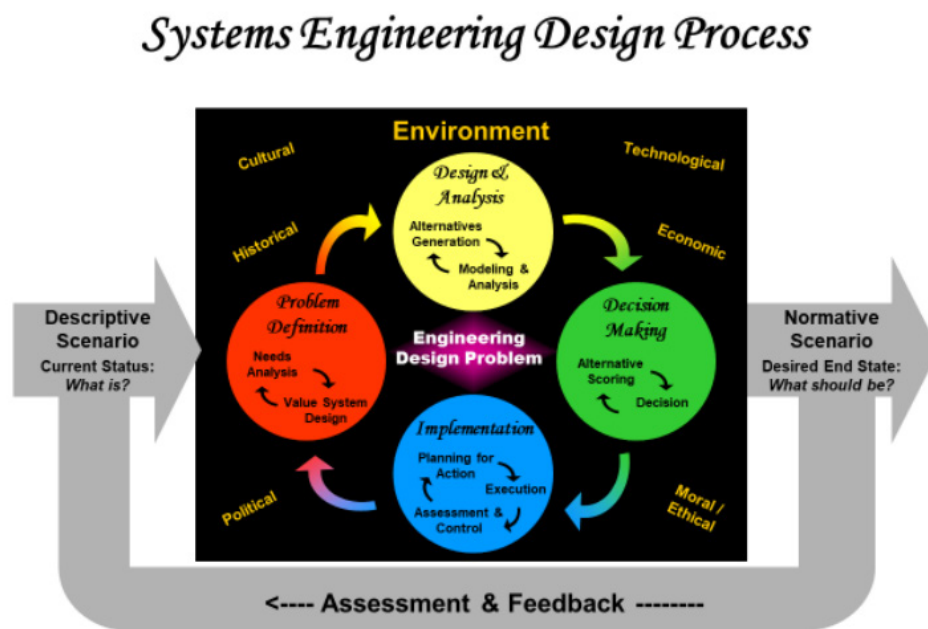


Figure 4. Systems engineering design process. Source: Baker (2020).

2. Model Based Systems Engineering

While maintaining the classic aspects of the vee model, especially as it pertains to developing a CONOPS, system requirements, initial design, and verification and validation, the MBSE approach allows for the performance of more analyses and various other techniques to deliver the optimal product to the stakeholders. Some key aspects used throughout this research process are behavioral analysis, requirement traceability, system architecture, and simulation. The models and simulations that are created maintain the

ability to be adjusted throughout this and future projects as information is updated and introduced; also, part of the iterative process (Hart 2015).

M. SUMMARY

This chapter was presented to inform the reader of the baseline information that the rest of the report builds on. The topics discussed herein will be integrated into the “Arctic UAS Selector” model, described in Chapter III, as well as be further investigated in Chapter IV, and finally be used to draw conclusions and make informed recommendations in Chapter VI. Of specific note are the Weather, UAS, Batteries, “Drone Selector Tool,” and USN/USCG Ships (Eilertsen et al. 2023).

The weather described within this chapter focused on three main topics: temperature, sea state, and winds. Temperature lends itself to many of the discussions within this report as it is a primary difference when operating in the Arctic versus elsewhere around the world. Temperature affects the combustion of fuels, performance of batteries, flight characteristics, and even maintainability of the asset (National Weather Service n.d.; CDC 2017; Wang et al. 2016). Sea state and winds are important informative items in that they are used as ‘go’ or ‘no-go’ criteria for asset deployment. Built within the model, discussed in “Chapter III, is an input for the current wind speed. This information is then cross-referenced to a programmed maximum value and the output states whether operations are physically able to be performed.

The UAS and USN/USCG ship type sections described that there are different types of each asset, which is further expounded upon in Chapter III. The characteristics of each type of UAS and ship with regards to dimensions and mission capability are the primary decision points from the previous team’s “Drone Selector Tool” (Eilertsen et al. 2023). This output is what is then fed into the Arctic selector tool for use during Arctic missions. This is where the battery discussion is implemented. Within the Arctic selector, the battery performance at different temperatures is the primary means of differentiation. From there, the battery discussion is further expounded upon in Chapter IV due to the severe impact of temperature and the need for further solutions.

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III. METHODOLOGY

This chapter is designed such that the follow-on researcher and end-user alike are capable of handling both the data gathering and modeling processes required to fully utilize the information within this report. The methodology is separated into two distinct parts. First, the model must be updated with all relevant technological and scientific developments to date. This may be in the form of new UAS or ship type, as well as new battery technologies or aviation fuels. Then, this information is used to update the model to ensure that all available assets are represented in the model and are weighed effectively.

Usage of the model is conducted in two ways. First, as a pre-deployment tool to long-range mission plan and procure the appropriate asset for the projected mission. This is accomplished by utilizing monthly or seasonal expectations of the environment as well as selection of the ship type for the deployment and the anticipated mission sets. Next, the tool may be utilized as a day-of mission planning tool by inputting actual, current, climate data for mission duration. This will provide expected performance data based on real-world conditions. This chapter introduces these concepts and the steps to be taken for both.

A. CURRENT TECHNOLOGY REVIEW

To appropriately analyze and forecast real-world UAS operational parameters, one must begin with research into the current state of technological advancements. Especially as the UAS environment is ever evolving, it is essential to ensure that new data is used.

The problem statement presents a set of multi-faced challenges that include viability of SATCOM in support of UAS operations, RF dependent systems survivability and resiliency within the Arctic, battery technology usability within the Arctic, and the overall restrictive operational environment the USCG faces in the high latitude regions. To answer those questions, to build an operationally relevant CONOP, and propose executable solution(s), material and/or non-materiel, the team conducted extensive research (open sources and peer reviewed) on the viability of known technologies and systems that are commonly used today. This document outlines the research on RF technologies, SATCOM

and the associated sectors (strengths and weaknesses, thereof), available battery technologies as workable power sources, and the operating environment.

The research processes and methods include both quantitative and qualitative research, collected factual data, factorial design analysis conducted to provide supporting substance to authors' thoughts, ideas, trends, and recommended solutions. The following paragraphs will provide in-depth views into these methods and the UAS capabilities of interest.

1. UAS

The constant competition in the UAS market leads to an increased requirement to continually update any research models with the latest technologies. The research team utilized the baseline UAS asset and capabilities lists from team JACL's 2023 report (Eilertsen et al. 2023). This listing represented the initial research burden that the project was then built around. Two new UAS types were identified as viable options for Arctic operations and were built into the model, they are discussed in Chapter IV.

2. Battery

Similar to the determination of viable UAS assets is an analysis of current technologies utilized in the manufacture of those UAS. Within the realms of power generation and propulsion, there are two main categories: gasoline and electricity. As previously discussed in Chapter II, there is a large drop in battery efficiency with a decrease in temperature (Lei et al. 2015; Wang et al. 2016). This is especially true when discussing the extreme temperatures experienced in the Arctic. As new battery capabilities are designed to incorporate lighter and more energy dense materials, or to mitigate cooling, the research contained in this report must adapt to maintain applicability. A detailed analysis of alternatives to solve for the battery temperature challenge is included in Chapter IV.

3. Fuel

In aviation, especially aviation within the DOD, there are several standardized fuel types, and even more specialty types (CDC 2017). Each of these types represents a different specific mixture of combustible fuels and additives for lubrication, temperature adaptation,

specific energy, or a combination there-of (CDC 2017). It is important to know which fuel types are available for the assigned mission and deployment platform to determine the best fit. Determining factors include fuel freeze point, fuel flashpoint, and which additives have been introduced. These factors were discussed in Chapter II and their inclusion in the model references whether the fuel is organically stored aboard the applicable type of ship.

4. Ships

Tables 7–17 serve to present the data utilized to build the “Drone Selector Tool” (Eilertsen et al. 2023). The dimensions of the ships, when compared to the dimensions of the UAS with all its supporting infrastructure, represent the first filter within the tool for creating the most beneficial asset pairing.

Table 7. Arleigh Burke class ship characteristics. Source: Eilertsen et al. (2023).

Arleigh Burke Class Guided Missile Destroyer (Flights I and II)	
Length	504.6 ft.
Width	66.6 ft.
Flight Operations Equipment	Flight Deck Only
Speed	30+ Kts
Endurance	4,400 NM at 20 kts
Sensors	SPY-1D Air Search Radar, SPS-67(V)3 Surface Search Radar, Commercial Navigation Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	Air Traffic Controllers, Anti-Air Warfare Coordinators

Table 8. Independence class ship characteristics. Source: Eilertsen et al. (2023).

Independence Class Littoral Combat Ship	
Length	421.6 ft.
Width	31.6 ft.
Flight Operations Equipment	Flight Deck and Helicopter Hangar
Speed	40+ Kts
Endurance	3,500 NM at 14 kts
Sensors	SPS-77 Air Search Radar, Sperry Bridgemaster Surface Search Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers, Anti-Air Warfare Coordinators

Table 9. John Lewis ship characteristics. Source: Eilertsen et al. (2023).

John Lewis Class Replenishment Oiler	
Length	745.7 ft.
Width	105.6 ft.
Flight Operations Equipment	Flight Deck Only
Speed	20 Kts
Endurance	6,147 NM
Sensors	Commercial Navigation Radar ¹⁰
UAS Capable Crew Type	None

Table 10. Lewis and Clark ship characteristics. Source: Eilertsen et al. (2023).

Lewis and Clark Dry Cargo Ship	
Length	689 ft.
Width	105.6 ft.
Flight Operations Equipment	Flight Deck and Helicopter Hangar
Speed	20 Kts
Endurance	14,000 NM at 20 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers

Table 11. Lewis B. Puller ship characteristics. Source: Eilertsen et al. (2023).

Lewis B. Puller Expeditionary Transfer Dock	
Length	785.1 ft.
Width	164 ft.
Flight Operations Equipment	Flight Deck and Helicopter Hangar (4)
Speed	15 Kts
Endurance	9,500 NM at 15 kts
Sensors	Sea Giraffe Air/Surface Search Radar ¹³
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers, Embarked MQ-8C and Maintainers, Operators, and Pilots

Table 12. Spearhead class ship characteristics. Source: Eilertsen et al. (2023).

Spearhead-Class Expeditionary Fast Transport Dock	
Length	337.9 ft.
Width	93.5 ft.
Flight Operations Equipment	Flight Deck Only
Speed	43 Kts
Endurance	1,200 NM at 35 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	None

Table 13. Legend class ship characteristics. Source: Eilertsen et al. (2023).

Legend-Class National Security Cutter	
Length	418 ft.
Width	54.1 ft.
Flight Operations Equipment	Flight Deck and Hangar
Speed	28 Kts
Endurance	12,000 NM at 9 kts
Sensors	Hensoldt TRS-3D/16 Surface Search Radar, Commercial Navigation Radar, SPQ-9B Surface/Air Search Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers

Table 14. Heritage class ship characteristics. Source: Eilertsen et al. (2023).

Heritage-Class Offshore Patrol Cutter	
Length	360 ft.
Width	54 ft.
Flight Operations Equipment	Flight Deck and Hangar
Speed	22.2 Kts
Endurance	9,500 NM at 14 kts
Sensors	Sea Giraffe Air/Surface Search Radar ¹⁷
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers

Table 15. Sentinel class ship characteristics. Source: Eilertsen et al. (2023).

Sentinel-Class Fast Response Cutter	
Length	153.2 ft.
Width	25.3 ft.
Flight Operations Equipment	None
Speed	28 Kts
Endurance	2,590 NM at 14 kts ¹⁹
Sensors	Commercial Navigation Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	None

Table 16. Island class ship characteristics. Source: Eilertsen et al. (2023).

Island-Class Patrol Boat	
Length	110 ft.
Width	21 ft.
Flight Operations Equipment	None
Speed	28-30 kts
Endurance	3,380 NM at 8 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	None

Table 17. Response boat characteristics. Source: Eilertsen et al. (2023).

Response Boat-Medium	
Length	44.5 ft.
Width	14.7 ft.
Flight Operations Equipment	None
Speed	45 kts
Endurance	250 NM at 30 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	None

B. CURRENT DATA REVIEW

As with technological advancements, scientific discoveries are occurring at a rapid pace. To ensure accurate outcomes, any relevant scientific advancements, edits, or discoveries must be incorporated.

1. Science and Technology Review

The discussions contained within this, or any, report must be based on current data, estimates, and informed projections. To compile this information, an investigation is required which scours available literature from peer-reviewed research to operating manuals and textbooks to determine the current state of the art in science and technology. Within the context of this report, the requisite information was determined to include LoS and BLoS technologies, GPS availability maps, and current weather trends for the Arctic and far northern latitudes.

2. Model Update

The culmination of the methodology to this point is the integration of all discovered data in the “Drone Selector Tool” first developed by the prior capstone team, Team JACL (Eilertsen et al. 2023). By design, this technology is to be treated as a living model, which may be updated as new UAS types, ship types, and technological capabilities and developments are released; and that flexibility creates opportunity for future utilization and modifications. As such, this research team has adjusted the “Drone Selector Tool” to be functional in an Arctic mission setting, and, as stated in Chapter 1, now carries the designation of the “Arctic UAS Selector Tool.”

a. UAS Data

The forefront of the “Arctic UAS Selector Tool” is the tab that houses the UAS options and specifications. Each UAS of interest is compiled into the list, along with the chosen specifications that may impact the UAS’ ability to carry out necessary mission types. The list of specifications is shown in Table 18.

Table 18. UAS parameters in the “Drone Selector Tool.” Source: Eilertsen et al. (2023).

Spec.	Units	Definition
Supports SAR Missions	Boolean	The UAS has visual or infrared sighting capabilities
Supports Logistics Missions	Boolean	The UAS can have additional payloads attached to it for delivery
Storage Size	ft. ³	The UAS’ size when in its storage configuration/in its storage case
Takeoff Size	ft. ²	The UAS’ size when in its flight-ready configuration
Runway Length Required	ft.	The length of runway required for takeoff—0 if VTOL-capable or is launched by hand/some other mechanism
Fuel Type	String	The UAS’ power source—gas or battery-powered
Swappable Payload	Boolean	The UAS’ cameras or other functionality is swappable to another device/mechanism
Encrypted Datalink	Boolean	The UAS supports encryption for the data it sends
Supports Water Landing	Boolean	The UAS can land in water and await recovery
Supports VTOL	Boolean	The UAS can takeoff from a stationary position and land without a runway

Spec.	Units	Definition
Max Transmission Range	NM	The UAS' maximum range of communication with the controller
Max Loiter Time	Minutes	The UAS' maximum time in flight
Max Altitude	ft.	The UAS' altitude ceiling
Max Payload Weight	lbs	The UAS' maximum safe operating weight
Max Speed	mph	The UAS' top speed in flight
GPS-Denied Flight	Boolean	The UAS can operate without the use of the Global Positioning System (GPS)
Autonomous Flight	Boolean	The UAS is capable of directing itself to a specified location and returning without input from the controller
Obstacle Avoidance	String	The UAS is capable of mitigating collisions
Max Effective Delivery Range	NM	The UAS' theoretical maximum range—a minimum taken of its maximum transmission range and the product of max loiter time and max speed
Sensor Quality	Integer	A value given to its visual or infrared sensors based upon the group number of the UAS

The listed set of parameters and UAS specifications that have been deemed significant for the Arctic Selector Tool are based on the previous capstone team's identified list of requirements and constraints (Eilertsen et al. 2023). It is not a complete and exhaustive list of capabilities of each UAS, but these capabilities have been identified as the most appropriate to support the mission parameters. The performance characteristics and capabilities not being specifically utilized by the tool are being accounted for so future

operations can incorporate a more robust evaluation based on those qualifications, if necessary. The rationale for each UAS capability is as follows (Eilertsen et al. 2023):

- Supports SAR Missions: Based on sponsor and mission requirements, UAS must have video capabilities, which allow them to conduct ISR and SAR missions.
- Supports logistics missions: Based on sponsor, stakeholder, and mission needs, UAS in this category should have the capability to conduct various levels of logistics-based missions. This option, to support additional payloads, is seen as a nice-to-have and not a hard requirement.
- Storage size: USCG and USN ships may contain minimal storage space for UAS. Thus, the compactness of a UAS is seen as a major determining factor in its utility.
- Takeoff size: Due to the varying sizes of ships in this arena, takeoff size could be a critical component to managing UAS on different ships, as some may not have the space or equipment to support larger UAS.
- Runway length required: Similar to the above point, if a UAS requires runway space, the number of ships that can support could be immediately limited.
- Fuel type: While this metric is not currently being utilized by the “Arctic UAS Selector Tool,” it could be used in future iterations as a requirement or nice-to-have for a ship’s UAS selection.
- Gas-powered UAS must have access to refueling, whether on board or other means of refueling UAS.
- Battery-powered UAS require access to additional battery packs, charging components, or other means of continuous battery usage.

- Swappable payload: This metric is not a hard requirement as the tool stands, however, this metric would provide favorable results due to the nature of various flight times, and visual needs, like infrared or thermal imaging.
- Encrypted datalink: Maintaining data integrity is crucial to mission sets and UAS need the capability to control sensitive data.
- Supports water landing: UAS that have ability to land in, and be retrieved from, the water provide additional capability to the mission.
- Supports VTOL: The ability of a UAS to vertically take off provides added desirability and potentially additional UAS options to smaller ships and ships with no runway space.
- Max transmission range: The max range of a UAS impacts mission sets, time on station, and potential to carry out logistical mission sets.
- Max loiter time: A UAS with longer loiter time has the capability to be on station longer, improving search areas or logistical range.
- Max altitude: A UAS search area or field of view is increased with higher altitude.
- Max payload weight: UAS that support increased payloads or have higher maximum payload capabilities have increased options for payloads, such as bigger or additional imaging systems or more logistical delivery payload potential.
- Max speed: UAS can complete mission search areas or deliveries at a greater rate, potentially improving overall mission effectiveness.
- GPS-denied flight: UAS that can go GPS-denied may provide additional capabilities in contested environments.

- Autonomous flight: UAS that can operate autonomously allow for minimal operator manipulation and minimize manpower requirements.
- Obstacle avoidance: UAS that can perform obstacle avoidance provide mission operators with less oversight, which helps expand range and operational capabilities.
- Max effective delivery range: This metric is a calculation, a product of max speed and max loiter time, giving theoretical maximum range, search area, or delivery distances.
- Sensor quality: Better imaging sensors and capabilities provide UAS with higher potential to carry out successful ISR/SAR missions by providing higher quality images to operators.
- Min Operable temp: The extreme cold can have negative effects on the performance of equipment, especially performance of Lithium-ion batteries.
- Maximum wind speed: UAS have varying wind restrictions, and wind in the Arctic region can create challenging scenarios to fly the UAS in.

Additionally, due to limitations in data discovery, some educated assumptions have been made to ensure user-friendliness and inclusion in the tool. To clearly identify the assumptions being made for the UAS, they are shown in Table 19.

Table 19. Missing UAS data assumptions. Source: Eilertsen et al. (2023).

Spec.	Assumption in Absence of Information
Storage Size	At least as large as the largest reported in its group
Takeoff Size	At least as large as the largest reported in its group
Runway Length	At least as long as the longest reported in its group
Fuel Type	No valid assumption can be made
Swappable Payload	No
Encrypted Datalink	No
Supports Water Landing	No
Supports VTOL	No
Max Altitude	At most as low as the lowest in its group
GPS-Denied Flight	No
Autonomous Flight	No
Obstacle Avoidance	No
Min Operable Temperature	0 degrees Celsius
Max Operable Wind Speed	Level 5 on the Beaufort Scale

b. Ship Data

The “Arctic UAS Selector Tool” includes ship-specific qualities to weigh into the model as well. Each ship has metrics specified to identify its compatibility and pairing potential with the UAS that were discussed in the previous section. Each ship’s metrics must match the UAS specifications and capabilities within the selector to be qualified as an option. The full list of ship metrics is represented in Table 20 (Eilertsen et al. 2023).

Table 20. Ship parameters in the UAS selector tool. Source: Eilertsen et al. (2023).

Spec.	Units	Definition
Gas Allowed	Boolean	Gasoline is approved to be aboard the vessel.
Li-Ion Batteries Allowed	Boolean	Lithium-Ion batteries are approved to be on the vessel.
Equipment Space	ft ³	The space that is available for the storage of the UAS while not in use
Launch Area	ft ²	The area that is available for launching a UAS
Runway Length	ft	The length of runway that is available or UAS that require it.
Water Recovery Support	Boolean	The vessel is capable of recovering UAS that have made a water landing/otherwise are in the water.
Due Regard Sensors	Boolean	The vessel is equipped with radar or some other means of observing the UAS while in operation to obey due regard policies.
Number of Operators	Integer	The number of crew aboard the vessel that is capable and available to operate the UAS when needed.
Number of Maintainers	Integer	The number of crew aboard the vessel that is capable and available to maintain the UAS when needed.

Like the UAS, the metrics identified for the USCG and USN potential ships are not extensive in their capabilities or definition, but rather provide qualification for the UAS' ability to be supported by them. Some examples of specifications that are not recognized as pertinent are ship speed, total ship size, and deck height, to name a few. The rationale for the parameters that have been included in the model and in Table 20 are as follows (Eilertsen et al. 2023):

- Gas allowed: Ships that have the capability to carry gasoline-powered vehicles and UAS and fuel reserves can improve the potential for a ship-to-UAS match.
- Li-Ion batteries allowed: Ships that have the capability to carry battery reserves and battery-powered UAS improve potential for matching ships and UAS.
- Equipment space: Ships with greater equipment storage capacity can support larger or more types of UAS, improving potential for ship-to-UAS matching.
- Launch area: A ship with more area to launch UAS has the ability to support a greater range of UAS.
- Runway length: A ship with any length of runway provides more opportunity for UAS matching.
- Water recovery support: If a ship can support water retrieval, there is a higher ship-to-UAS match potential.
- Due regard sensors: A ship's capability to support RADAR equipment or other UAS monitoring systems can support more UAS options, especially ones that are not equipped with obstacle avoidance systems.
- Number of operators: More crewmen on a ship provide greater mission support potential.
- Number of maintainers: More maintenance crew allow for UAS maintenance, either corrective or preventative, to follow a structured schedule, minimizing impacts on missions.

It is important to note that this tool and the parameters defined within are presented as a match-making utility for ships to support UAS and UAS missions as added operational capability. The tool does not provide a ship or offer recommendations for making

alterations or improvements to a ship’s infrastructure, but rather a way to make the most use of the infrastructure already present. Additional functionality or analysis is discussed in Chapter VI as future work.

c. User Input Data

The user input data options, presented in Table 21, sit within the “Mix & Match” tab of the “Arctic UAS Selector Tool” (Eilertsen et al. 2023). They are critical manual functions that drive the operational output of the tool. This set of cells, labeled “ISR/SAR Mission Details,” are static independent variables that provide the user the input options for the required mission specifications to help identify the best UAS match to the mission (Eilertsen et al. 2023).

Table 21. User inputs to the “Arctic UAS Selector Tool.” Adapted from Eilertsen et al. (2023)

Input	Units	Definition
Mission Type	String	A menu with dropdown mission options, including ISR/SAR or Logistics.
Ship Selection	String	A dropdown list of the available ship options, referencing the “Ship Specs” tab.
Contested	Boolean	A menu representing the mission air space as contested (“YES”) and not contested (“NO”).
Required Minimum Speed	mph	A cell that allows user to input float values representing the minimum speed the mission requires a UAS to operate. An “ON/OFF” toggle switch is present in the event a minimum speed is not a required mission parameter.
Required Minimum Loiter Time	min	A cell that allows the user to input float values representing the minimum amount of flight time the mission requires a UAS to operate. An “ON/OFF” toggle switch is present in the event a minimum loiter time is not a required mission parameter.

Input	Units	Definition
Required Minimum Altitude	ft	A cell that allows the user to input float values representing the minimum altitude the mission requires a UAS to operate. An “ON/OFF” toggle switch is present in the event a minimum altitude is not a required mission parameter.
Minimum Operable Temperature	Deg C	Inputs for this cell allow the user to identify the temperature, which affects UAS capabilities. An “ON/OFF” toggle switch is present in the event the temperature is not a required mission parameter.
Maximum Wind Level	Boolean	A cell that allows the user to input wind maximum wind levels on the Beaufort scale that affects whether a UAS can be operated. An “ON/OFF” toggle switch is present in the event wind speed is not a required mission parameter.

The parameters listed in Table 21 provide the tool with the final elements needed to calculate and weigh the options for UAS output. The inclusion of each parameter in the tool is rationalized as follows (Eilertsen et al. 2023):

- Mission Type: The mission type rules out UAS that are not capable of flying the selected type of mission.
- Ship Selection: The user’s selection links the ships in the tool to its capabilities, ruling out UAS that do not meet the qualifications.
- Contested: An airspace that is contested will immediately rule out certain UAS that are not capable of flying in that type of environment due to lack of encrypted datalink or an option for GPS-denied flight.
- Required Minimum Speed: A ship, or even a mission, may require a UAS to have a minimum speed to ensure mission effectiveness, such that the

UAS can be launched, deployed, return, and be recovered in a specified amount of time.

- **Required Minimum Loiter Time:** A ship or mission may require a UAS to have a minimum loiter time to support mission parameters.
- **Required Minimum Altitude:** A ship or mission may require a UAS to support at a minimum altitude to achieve observational success or other specified tasks.
- **Minimum Temperature:** If the temperature is extremely low, it could disqualify some or all UAS from launching or hinder operational capabilities.
- **Maximum Wind Speed:** Wind speed parameters can affect when and how a UAS is utilized or affect mission parameters set forth by a ship's command.

3. “Arctic UAS Selector Tool” Methodology

In this section, the methodology of the previous capstone team, Team JACL, is reviewed, and the Arctic parameters are introduced and explained in more depth. As the “Drone Selector Tool” was introduced by the previous capstone team, the methodology, system design, output methods, weights and calculations remain largely unchanged (Eilertsen et al. 2023). The Parnell method of using swing weights to create alternative solutions based on importance is heavily relied upon for these sets of calculations (Parnell 2009). As discussed in the previous sections, the swing weight matrix is defined by the metrics and their variability. The results of the swing weights, combined with the UAS values specified for mission compatibility, create the list of UAS that fall within the mission parameters, as well as how well each UAS may perform within those parameters.

The new version of the tool, the “Arctic UAS Selector Tool,” maintains much of the methodology and functionality of the legacy version, the “Drone Selector Tool.” To properly introduce the “Arctic UAS Selector Tool,” a brief overview of the methodology

utilized in the legacy “Drone Selector Tool” is explained here, as well as an overview of the new characteristics that belong to its Arctic variation.

a. Legacy “Drone Selector Tool”

As discussed in the report by Eilertsen et al., before matching UAS to ships and providing a weighted score, the tool first conducts preliminary exclusions on a fundamental level (2023). The first way is by comparing ship specifications to UAS requirements. For example, the tool identifies a ship that cannot support carrying either fuel reserves or Li-Ion batteries, and automatically excludes UAS that require the respective power source. The second way the selector tool provides early exclusions is with UAS-to-mission supportability (Eilertsen et al. 2023). For example, if the mission area is a contested environment, then UAS that cannot operate in a GPS-denied area are excluded from the list of recommended UAS.

Once the early exclusions have been applied, the user can make selections from a menu of options to specify mission parameters, and the tool calculates the weighted measures in the background and produces the best fit UAS for the desired mission, which is displayed on the chart on the user interface. A simplified depiction of the “Drone Selector Tool” is shown in Figure 5 (Eilertsen et al. 2023).

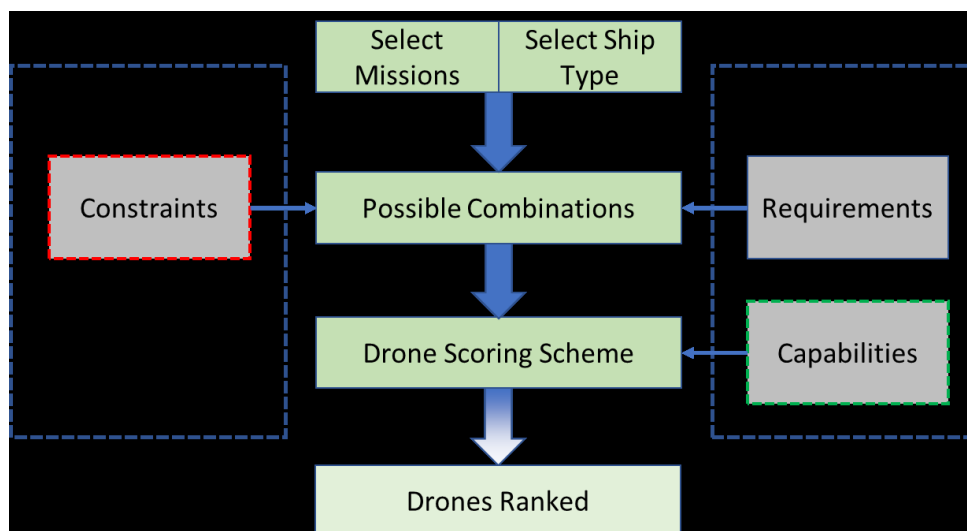


Figure 5. Simplified “Drone Selector Tool.” Source: Eilertsen et al. (2023)

b. “Arctic UAS Selector Tool”

While most functions and features of the “Arctic UAS Selector Tool” remain the same as the legacy version, some significant modifications and additions have been made to the legacy tool that this section covers in more depth. For the functionality of the “Arctic UAS Selector Tool,” the preliminary exclusion is still carried out by the “ship-to-UAS supportability” and by the “UAS-to-mission supportability.” For these portions of the tool, the baseline created by the previous capstone team and their “Drone Selector Tool” remains the same, and ensures the ship selected for use maintains the ability to carry, field, and operate the UAS that the output of the tool recommends (Eilertsen et al. 2023).

The next step of the process involves user input. The tool enables the end-user to identify the operational parameters that are necessary for their assigned mission. These mission parameters carry significant weight on which UAS may be recommended to the user, and the “Arctic UAS Selector Tool” maintains the legacy options – loiter time, minimum altitude, and minimum speed. Arctic parameters have been added to this section of the “Mix&Match” which produces an output selection of UAS that can operate in the Arctic conditions that may not necessarily be applicable to the legacy selector tool. Figure 6 shows the user input fields, next is a discussion on how to utilize them for an output.

The screenshot shows a web-based form for the Arctic UAS Selector Tool. The form is organized into sections with various input fields and dropdown menus. Callouts provide detailed explanations for specific parts of the interface:

- Checksum:** A field that displays red color when mission latitude is above the 55th parallel; red means the UAS must be capable of GPS-Denied flight, green allows all options.
- Checksum explanation:** A text box providing further clarification for the checksum field.
- GPS Availability Checksum:** A field that returns red if the checksum is red, GPS-Denied must equal "YES".
- GPS-Denied?** A dropdown menu with options "GPS-Denied?" and "GPS Unavailable Above 55 Deg LAT YES".
- Latitude:** A field where the user inputs operational latitude in degrees (e.g., 56).
- ISR/SAR Mission Details:** A section containing a legacy dropdown menu paired with the checksum and user inputs for latitude and UAS capabilities. It includes a note: "yes = UAS capable in GPS-Denied environment, no = not capable colors should match checksum".
- Speed (mph):** A field with a value of 25.
- Loiter Time (min):** A field with a value of 30.
- Altitude (ft):** A field with a value of 3000.
- Min Operable Temp:** A field where the user inputs minimum operable temperature required for a UAS in deg C (e.g., 10).
- Max Wind Level (Beaufort scale):** A field where the user inputs maximum operational wind levels using the Beaufort Wind Scale; the highest for the current data set is level 5; over that would be a no-go (e.g., 3).

Figure 6. Arctic UAS selector tool user interface. Adapted from Eilertsen et al. (2023)

Extreme temperatures can affect UAS’ duration capabilities, battery or fuel function, or ability of electronics to perform functional flights (Global Electronic Service 2023). The limits for the UAS to operate in cold weather conditions have been added to the tool to cross reference against the other operational parameters and create a recommended output that would look much different if this metric was not taken into consideration. In the tool’s data sheets, the limits of each UAS of interest have been added, and the logic to generate the output values has been added into the matrix already containing the calculations that exist from the legacy “Drone Selector Tool.” The swing weights have been adjusted and are shown in Table 23.

Another user input that has been added to the new iteration of the selector tool the maximum wind level, according to the Beaufort scale. Again, due to the harsh conditions that are regularly anticipated in the Arctic region, wind may have a large impact on a ship’s or crew’s ability to launch a UAS safely. Most of the UAS included in the tool have level 5 wind limitations (<25 mph), and for the purposes of this study condition of level 6 or above is considered a ‘no-go.’ The Beaufort scale is a known, categorized scale of wind, and the levels of interest are more clearly shown in Figure 7. Additionally, the Beaufort scale is also used for categorizing the overall sea state – things like swell, wave height, other sea activity – and is discussed as part of Chapter VI Section C to be included as another possible input to the “Arctic UAS Selector Tool.”

Beaufort Wind Scale in Miles per hour (Mph), knots and Kilometers per hour (Km/h)				
Beaufort Scale Force	Wind in MPH	Wind in Knots	Wind in Km/h	Description - Wave Heights—Visible Condition
Force 0	0-1	0-1	0-1	Calm; Ht 0.0m ~ At sea no waves - glassy like appearance of sea.
Force 1	1 - 4	1 - 3	2 – 6	Light Airs Ht 0m ~ At Sea wind makes glassy ripples on water.
Force 2	4 - 7	4 - 6	7 – 11	Light breeze Ht 0.1m ~ At Sea smooth wavelets
Force 3	8 - 12	7-10	13 - 19	Gentle breeze Ht 0.4m Slight ~ At sea slight waves no white horses.
Force 4	13 - 18	11-16	20 – 30	Moderate breeze Ht 1m - Slight to moderate ~ At Sea waves described as with occasional white horses. On land raises dust and loose paper; small branches are moved
Force 5	19 - 24	17 - 21	31- 39	Fresh breeze Ht 2m Moderate ~ At sea consistent white horses

Figure 7. Levels 1–5 of the Beaufort scale. Adapted from Classic Sailing (n.d.).

As discussed in Chapter IV, GPS coverage in the Arctic regions becomes limited north of the 55th parallel (Swaszek et al. 2018). To maintain optimal operability, a latitude designator, paired with a GPS checksum was added into the user interface of the selector tool. The latitude designator takes user input of the expected highest parallel of operation and has logic written into it that triggers the checksum to change color. Red identifies operation in GPS-Denied territory, north of the 55th parallel, and the color green identifies an operational area that is not impacted by the potentially GPS-limited area, north of the 55th parallel. The final step for latitude and the GPS-Denied user inputs is to ensure the color coding of the checksum and the dropdown option for GPS-Denied match, optimizing the validity of the selector tool's output.

Once the user inputs are complete, the function and methodology of the “Arctic UAS Selector Tool” relies on the same weighted scores as the legacy selector tool, presented in Table 22. The only difference is the addition of the logic as set forth in the above paragraphs to reflect the user mission inputs.

Table 22. “Arctic UAS Selector Tool” swing weights. Adapted from Eilertsen et al. (2023).

Specification	Swing Weight	Calculation		Measure Weight
	<i>ISR/SAR</i>			
Max Transmission Range	100	100/385		0.26
Max Loiter Time	80	80/385		0.21
Max Speed	40	40/385		0.10
Sensor Quality	60	60/385		0.12
Temperature Limit	45	50/385		0.16
Wind Limit	60	60/385		0.13
	<i>Logistics</i>			
Max Effective Delivery Range	100	100/335		0.30
Max Speed	80	80/335		0.24
Max Payload Weight	30	30/335		0.09
Temperature Limit	60	60/335		0.18
Wind Limit	65	65/335		0.19

c. Arctic Battery Performance Calculator

As has been discussed throughout the entirety of this study, one of the most recurring themes has been the affect temperature has on every aspect of Arctic operations. Lithium-Ion batteries can be severely impacted by extreme cold temperatures (Aris and Bahman 2017). Due to many UAS using battery power, especially ones that fall into UAS groups 1–3, it is critical to understand the impact cold weather may have on their operational capabilities. In conjunction with, and in an effort to continue to develop the “Arctic UAS Selector Tool” and its effectiveness, a need was identified that could help mission planning as well as mission-based UAS selection. As such, the team conducted a battery degrade analysis and a way to calculate it which would be beneficial to the improvement and overall effectiveness of the “Arctic UAS Selector Tool.”

Designed to output an operational time based on the expected percentage of battery life, the “Arctic Battery Performance Calculator” was built into the UAS selector tool. Using a trend analysis, data points were created by extrapolating percentage of battery life expected at every degree, in Celsius, that may be encountered in the Arctic arena, Figure 8. It is important to note that this calculator was designed for use with Arctic mission sets only, temperatures above 25° C are not accounted for in this model and cannot be assumed. The UAS of interest will be paired with a temperature and output an expected operational time for the specific UAS based on that temperature and expected battery life. The calculator is filtered to only offer battery powered UAS, selected by the user via a dropdown menu. When the UAS is selected, the calculator automatically populates the complementing maximum loiter time in minutes. Once that selection is complete, the user selects the expected mission temperature, and once selected, the expected battery performance percentage automatically populates. After the two dropdowns have been selected, a value of time, in minutes, will be displayed in the output box, giving the user an adjusted operational time based on the temperature’s effect on the battery. In the background of the tool, the output is calculated by multiplying the maximum loiter time by the percentage of expected battery life, Equation 1. The calculator is shown in Figure 9 with a test set of UAS and temperature and an output.

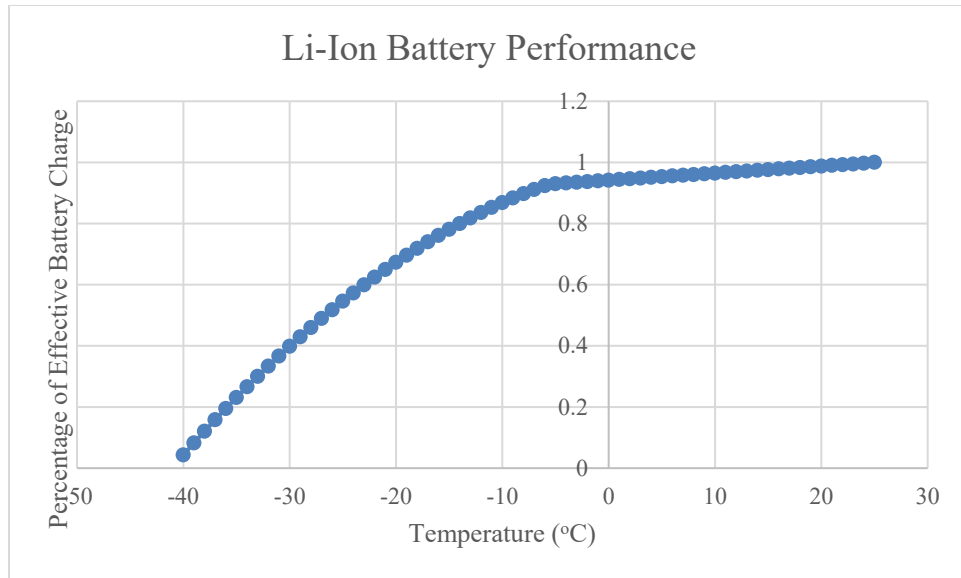


Figure 8. Li-ion battery percentage of designed capacity versus temperature graph

$$\text{Adjusted Operational Batt Life} = \text{Max Loiter Time} * \text{Temp Degrade Percentage} \quad (1)$$

Arctic Battery Performance Tool					
UAS Selection	Max Loiter Time (mins)	Temperature Selector	Battery Life Expectancy Due to Temperature	Adjusted Operational Battery Life	
Censys Sentaero BVLOS	90	-3	93%		
				84	minutes

Figure 9. Arctic battery performance calculator

C. MISSION REVIEW

With the model developed and updated, it is ready to be incorporated as both an acquisition tool as well as a pre-flight planning application. With a basic understanding of the mission parameters, one may make an informed decision on which UAS most clearly satisfies the mission requirements as well as establish day-of expectations for the operational parameters of the asset. That is to say, the deployability, operating range, loiter time, or other major characteristics of the system.

1. Mission Latitude

As established previously, the constellation of navigation-related GPS satellites is limited to a selected band of orbits around the Earth at monitored altitudes. Due to the spherical shape of the globe this creates ‘blind spots’ near the poles where GPS is either not reliable or even not available. Mission location determination may be made by considering the highest latitude expected, or the most heavily traversed latitude on the deployment. Further discussion of the GPS availability limitations is found within Chapter IV.

2. Mission Weather

Temperature, as has been discussed, is one of the main differentiators between Arctic operations and other mission areas. Determining the average mission operating temperature will allow for the most informed decision to be made regarding the prime asset for the assigned mission. Research into the average temperatures in the Arctic, and the monthly and seasonal differences, can be found in Chapter IV Section D.2.

D. PRE-DEPLOYMENT ANALYSIS

With the prior information in hand, the user is ready to select a UAS to deploy with. The more accurate the information that the user provides, the more appropriate a decision the model is likely to produce.

1. Input Expected Mission Data

Within the “Arctic UAS Selector Tool,” input the calculated values for latitude and temperature as previously discussed. The tool is designed to incorporate all the information provided.

2. Select UAS Based on Output

The product of the “Arctic UAS Selector Tool” is a weighted list of UAS assets designed to be usable at a glance to determine which UAS is most appropriate for the mission described by the user. The larger the bar on the chart, the higher the score of the UAS, and therefore the more fit for the mission.

E. REAL-TIME ANALYSIS

The final value-added solution for using the “Arctic UAS Selector Tool” is in the day-to-day operation of a selected UAS. The forecasted values for latitude and temperature are valuable for planning and acquisition, however, the actual real-time values may be utilized to determine the expected mission parameters in real-time.

1. Input Actual Pre-Mission Data

As was completed in the pre-deployment analysis, the measured values and actual mission determination may be entered into the tool for rapid decision-making. This step is for inputting day-of data, to include real latitude and temperature, to check the mission performance of the UAS.

2. Obtain Expected Performance Data

The ultimate determination of “Arctic UAS Selector Tool” is produced through the user inputting the actual values for items such as latitude, temperature, altitude, and UAS type. This information is used to calculate the expected performance characteristics of the UAS. These characteristics include the viability of deploying the selected UAS in the input conditions and the maximum loiter time, which is calculated for battery-operated UAS through the “Arctic Battery Performance Calculator.”

F. SUMMARY

Following the methodology outlined in this chapter sets up the researcher for a proper analysis of Arctic UAS operation. To accomplish this, there are two major steps: research and modeling. The research is further split into investigating technological and science-based information. The modeling is then separated into its update and usage.

First, the aggregation of usable data begins with a determination of the current USN or USCG UAS asset inventory, as well as a search of any potential COTS options which may be targets for acquisition. The model is, as of this report, up to date with all the UAS types which were discoverable by the research team. The data which could be determined from previous reports, operating manuals, and open-source literature were implemented,

and stated assumptions have been made to fill in the gaps. The technological research then must expand into ship types, fuel mixtures, and battery capabilities. The most current ship types have been implemented thus far and the model's updatability has been maximized for the future user. Fuel mixtures and battery capabilities are important for determining the operating parameters of the system and must also be updated within the model for each major advancement.

The second major portion of the methodology encompasses the usage of the model which has now been updated with the most current information. This chapter explains two separate use-cases. First, the pre-deployment utility of the Arctic drone selector lies in its ability to knowledgeably match assets by size, mission, and supportability. The first pass of the "Mix & Match" is a quick filter which determines absolute criteria such as ship space availability and UAS size requirements (Eilertsen et al. 2023). This is incorporated first to determine which assets absolutely do not apply to the user input parameters and mission requirements. The second stage of the "Mix & Match" utilizes mission equipment and support metrics to detail the most appropriate UAS for the chosen inputs (Eilertsen et al. 2023).

Once the recommended asset has been chosen, and ostensibly procured, the second usage of the "Arctic UAS Selector Tool" is the day-of mission planning calculator. The final step of the tool involves incorporating environmental data such as winds, sea states, and temperature. This data is compared to research-supported analyses of performance as well as binary determinations such as maximum wind speed for launching. This tool is designed to then provide accurate expectations of real-world performance in the given environment. Continuing to Chapter IV introduces the reader to example data sets as well as new technologies which were identified during the team's execution of the methodology here-in described.

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IV. ANALYSIS

This chapter first contains the specific research performed by the team which informed the creation of the “Arctic UAS Selector Tool” and the discussions in Chapter VI. Second, the chapter contains several examples of the model being tested with datasets designed to illustrate the operability of each of its functions. The chapter is separated into sections similar to those in Chapter III to allow for increased traceability to application.

A. CURRENT TECHNOLOGY REVIEW

This section discusses the current technologies which were researched during the project, including UAS which were added to the “Arctic UAS Selector Tool,” a new ship type which is discussed but not included in the model due to its not being operational as of this writing, and an analysis of battery heating methods which may be used to mitigate cold-weather effects.

1. UAS

Two UAS types were identified by the project team and ultimately incorporated into the “Arctic UAS Selector Tool.” The Boeing ScanEagle is already in use in the Arctic, and the RQ-21A provides a unique opportunity for the DOD to recapitalize on a program which did not serve its original purpose but could be fit for Arctic operation.

a. ScanEagle

The Boeing Company’s ScanEagle is a cost friendly and reliable UAS platform that provides a variety of capabilities for government and civilian entities, notably persistent day, and night ISR. The ScanEagle was first developed in 2001 under the purview of Insitu, a subsidiary of The Boeing Company, to be first utilized within the commercial fishing trade (Boeing, n.d.). Over the next decade, the ScanEagle has been recognized or achieved the follow milestones: utilized by most military services providing required ISR and communications support to forces in Iraq; awarded the “Top 5 Award” in the UAS platform category from C4ISR Journal; selected by the U.S. Air Force Academy as the UAS of choice to train cadets; awarded multiple contracts to DOD entities and various other nations

militaries (Boeing, n.d.). In 2013, ScanEagle was certified for commercial beyond-line-of-site operations by the FAA, the first of any UAS platform to be given this accreditation (Boeing, n.d.).

The ScanEagle has earned a distinct reputation within the UAS domain as a mission-ready platform that allows military units and various other entities to perform critical missions from land or at sea (Insitu 2020). Certain ISR capabilities are shared across all three systems, including Electro-Optical (EO), Mid-Wave Infrared (MWIR), Visual Detection and Ranging (ViDAR), and Full Motion Video (FMV) (Insitu 2020). Figures 10 to 13 and Table 23 provide a snapshot of key capabilities and limitations of the ScanEagle and RQ-21A UAS platforms that future stakeholders will need to consider prior to selecting their UAS candidate for polar operations.

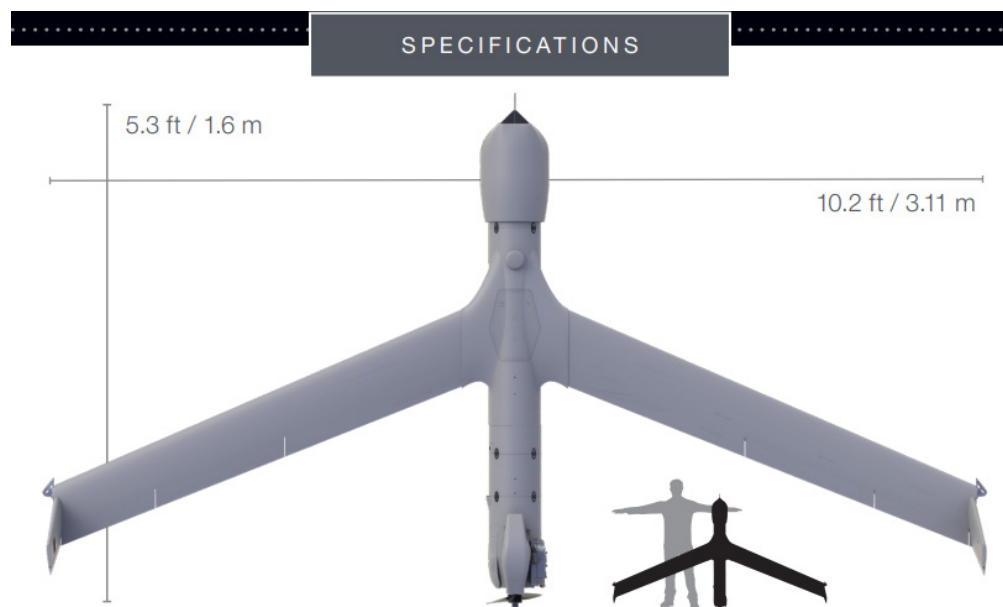


Figure 10. ScanEagle small tactical UAS. Source: Insitu (2020).



Figure 11. ScanEagle launching system. Source: Insitu (2020).

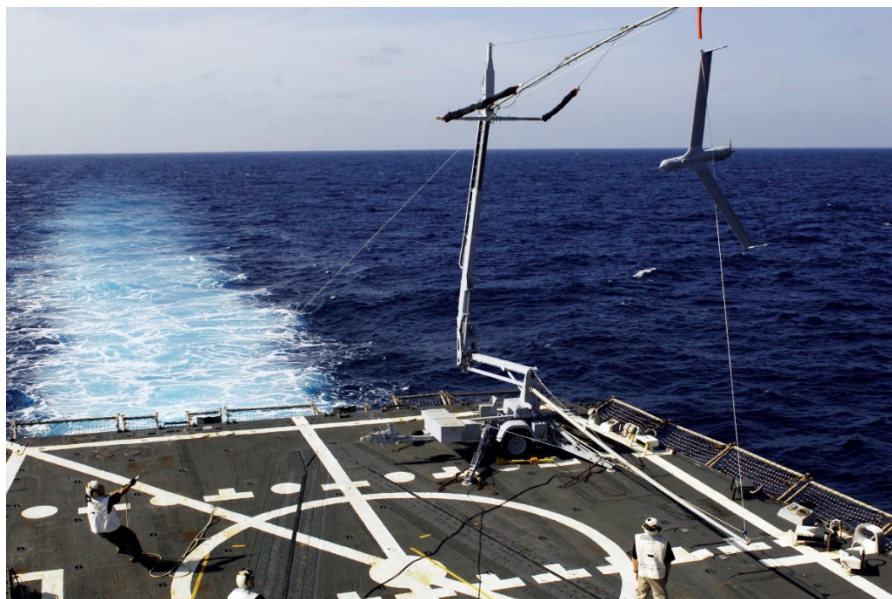


Figure 12. ScanEagle recovery system. Source: Wikipedia (2023).



Figure 13. ScanEagle 3 small tactical UAS. Source: Insitu (2020).

Table 23. UAS capabilities and specifications. Adapted from Insitu (2020 and 2021).

Specifications	ScanEagle	ScanEagle 3	RQ-21A
Length	5.6 ft	7.6 – 8.2 ft	8.2 ft
Wingspan	10.2 ft	13 ft	15.7 ft
Max Takeoff Weight	58 lb.	80 lb.	135 lb.
Max Payload Weight	11 lb.	19 lb.	*39 lb. (Reduces endurance)
On-board Power	Up to 150 Watts	Up to 170 Watts	Up to 150 Watts
Endurance	18 hrs.	18 hrs.	16 hrs.
Ceiling	19,500 ft	20,000 ft	20,000 ft
Max Speed	92 mph	92 mph	103 mph
Cruise Speed	57 – 69 mph	46 – 57 mph	69 mph
Fuel Type	JP-5 or JP-8	JP-5 or JP-8	JP-5 or JP-8
C2 Data Link	Encrypted & Unencrypted	Encrypted & Unencrypted	Encrypted & Unencrypted
Video Data Link	Encrypted	Encrypted	Encrypted
Sensors	MWIR/EO dual sensor (day & night FMV); ViDAR	MWIR/EO dual sensor (day & night FMV); ViDAR	MWIR & EO

b. RQ-21

The United States Navy and Marine Corps conducted the Initial Operational Test and Evaluation (IOT&E) of the RQ-21A Small Tactical Unmanned Aircraft system from January to December 2014 (Operational Test and Evaluation Force, 2015). The locations for the test sites during this evaluation were not in cold weather environments or arctic like conditions. The testing sites were conducted at two Marine Corps bases – Marine Corps Air Ground Combat Center Twenty-nine Palms, California and Marine Corps Base Camp Lejeune, North Carolina – while the third testing site was aboard the USS *Anchorage* (Operational Test and Evaluation Force, 2015). These testing locations have vastly different climatic conditions – desert and subtropical – compared to the northern regions of this report, but the data and outputs collected from this IOT&E report led the team towards a different UAS platform for arctic operations. The following paragraphs and pictures will describe the requirements to operate, maintain and sustain the RQ-21A for the various missions it was designed to support for the U.S. Armed Forces.

The envisioned use case for the RQ-21A was to provide a rapidly deployable ISR capability at the small unit level to support both sea-based and shore-based operations within the respective leader's level of control (Operational Test and Evaluation Force, 2015). Per the IOT&E report, the various types of missions the RQ-21A was designed for include:

- Target development (to include locating and tracking),
- Maritime and shore target [recognition],
- Near-shore and beach landing site and helicopter landing zone [scouting/observation],
- Area, point, and/or route reconnaissance,
- Vehicle convoy [observation],
- Riverine and small craft transit over-watch,
- Maritime/land direct action [surveillance]. (Operational Test and Evaluation Force, 2015, p. 1)

As depicted in Figure 14, the total RQ-21A system includes various amounts of air vehicles, land vehicles, trailer systems, power systems, workstations and numerous

communications systems needed to support the mission sets listed above (Operational Test and Evaluation Force, 2015).

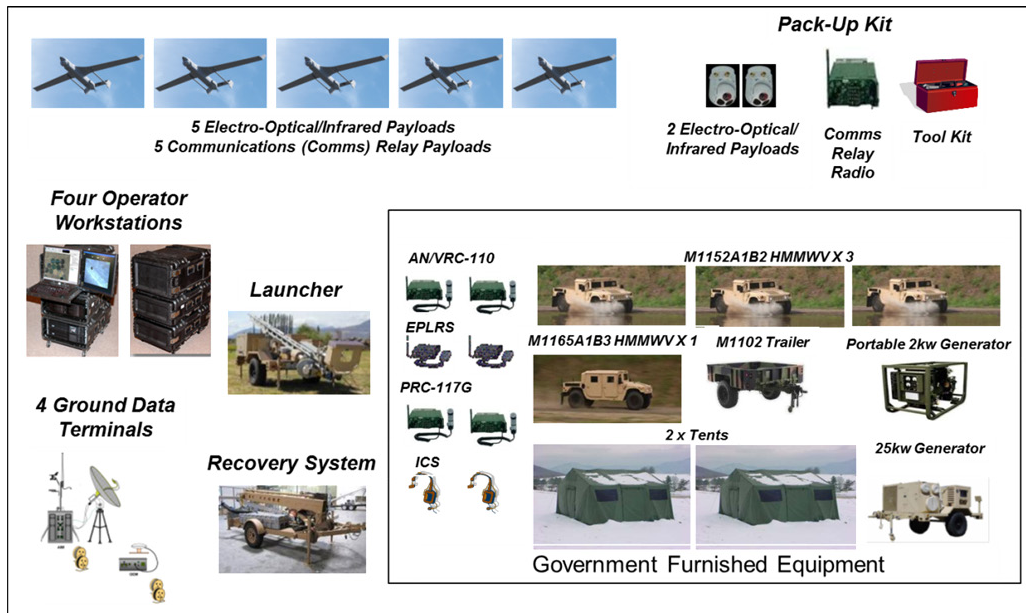


Figure 14. RQ-21A small tactical UAS. Source: Operational Test and Evaluation Force (2015).

The air vehicle is an integrated system comprised of easily replaceable parts. It is capable of organic launch and recovery procedures with the use of the associated launch and recovery infrastructure, negating the need for a runway. The air vehicle runs via a two-cylinder, electronically fuel-injected engine that functions on JP-5 or similar fuel classes (Operational Test and Evaluation Force, 2015). Figure 15 and Figure 16 display some overall specifications and a three-dimensional image of the aircraft.



Air Vehicle	Weight
Gross Takeoff Weight	135 pounds
Dry weight	110 pounds
Fuel	25 pounds
Wing Span	16.25 feet
Length	7.2 feet

Figure 15. RQ-21A Air Vehicle measurements. Source: Operational Test and Evaluation Force (2015).



Figure 16. RQ-21A Air Vehicle. Source: Operational Test and Evaluation Force (2015).

The ground control station (GCS) is the heartbeat of the RQ-21A operational employment (Operational Test and Evaluation Force, 2015). Figure 17 shows the ground control station configuration used during this evaluation in Twenty-nine Palms, CA. As the image depicts, the GCS has numerous pieces of equipment that require a considerable amount of space to operate, task, and manage the RQ-21A (Operational Test and Evaluation Force, 2015). Space available for outside systems will always be constricted on military vessels, which will be a key inhibitor (or enabler) when it comes to selecting the right UAS for the designated missions aboard USCG ships.



Figure 17. RQ-21A Tabletop Ground Control Station. Source: Operational Test and Evaluation Force (2015).

The RQ-21A launcher uses air pressure to accelerate the air vehicle to flight speed at takeoff and allows for quick engagement of the RQ-21A in various land and maritime conditions, Figure 18 (Operational Test and Evaluation Force 2015). The launcher system requires no external power source and is designed for transport by several fixed wing aircraft or be towed by a High Mobility Multipurpose Wheeled Vehicle (Operational Test and Evaluation Force 2015).



Figure 18. RQ-21A Launcher: Operational Test and Evaluation Force (2015).

The RQ-21A recovery system uses a trailer mounted mast and boom system that suspends a rope to catch the air vehicle in flight, Figure 19. After the rope catches the UAS, it glides down the rope until it reaches the ground (Operational Test and Evaluation Force, 2015). The recovery system requires a power source and communications lines to support the onboard GPS module to ensure the air vehicle descends to the correct location of the recovery system (Operational Test and Evaluation Force, 2015).



Figure 19. RQ-21A recovery system. Source: Operational test and evaluation force (2015).

The IOT&E report further explains that the results of this initial test deemed the RQ-21A not operationally effective and not operationally suitable, per Navy and Marine

Corps standards (2015). For operational effectiveness, the RQ-21A mission metrics collected during this test period resulted in 68 percent of the assigned mission-available hours (83.8 or 122.7 hours) being covered by the UAS. In other words, the RQ-21A was absent, or not able to provide the essential support, about 32 percent of the time the commander expected to have the aircraft on station to support operations (Operational Test and Evaluation Force 2015).

However, the ineffectiveness of the RQ-21A in its designed mission area may still benefit the USCG. More recent testing with upgraded GPS capabilities being integrated into the RQ-21A could provide the USCG with a protected navigation solution in the polar region (Rawlinson and Kumar, 2022). The Mayflower Multi-Platform Anti-Jam (AJ) GPS Navigation Antenna (MAGNA) device was created to align with GPS protection conditions on various land and aerial platforms, such as the RQ-21A. The MAGNA-Integrated (MAGNA-I) was an incorporated solution that reduced the size, weight, power, and cost of heavier and more costly fielded AJ systems (Rawlinson and Kumar, 2022).

After the initial installation of the MAGNA-I close to the right wing of the RQ-21A, the preliminary flight tests showed that the heat sink fins of the MAGNA-I were too close to the right wing and interfered with the right-wing flap full range of motion (Rawlinson and Kumar, 2022). Adjustments were made to the placement of the MAGNA-I antenna, depicted in Figures 20 to 22.

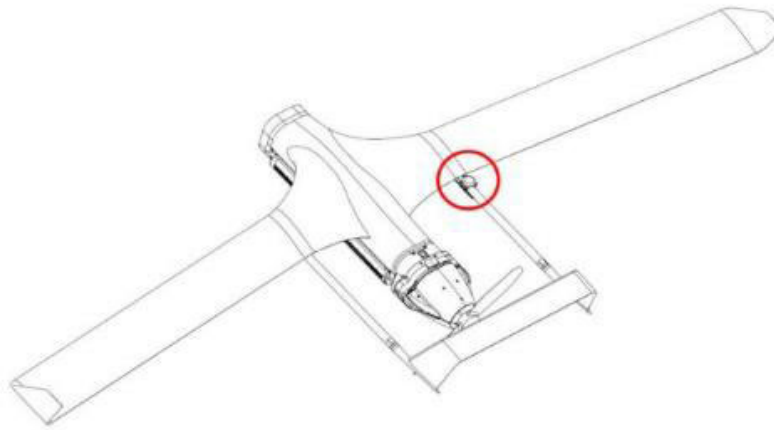


Figure 20. Phase I MAGNA-I Mounting Location. Source: Rawlinson and Kumar (2022).

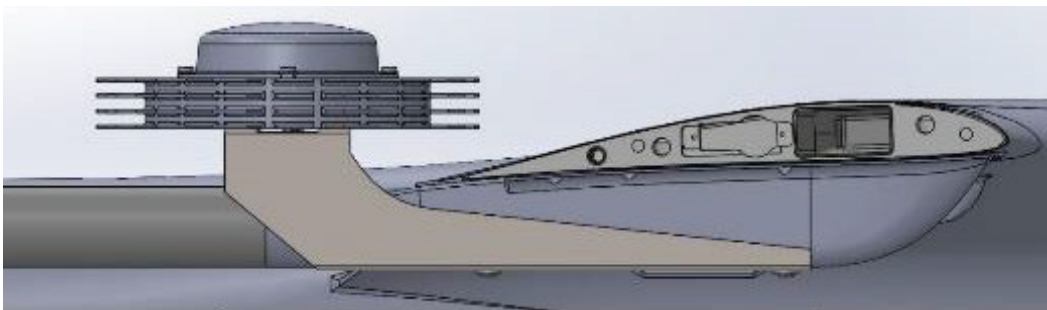


Figure 21. MAGNA-I Mounting. Source: Rawlinson and Kumar (2022).

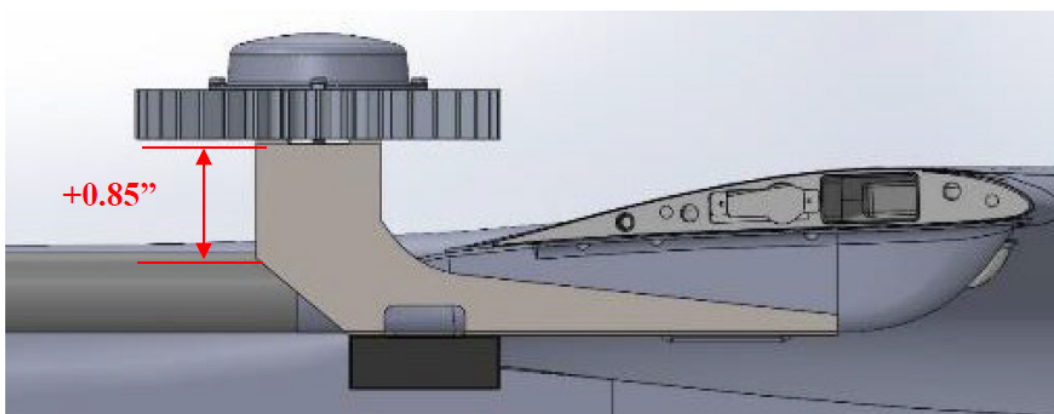


Figure 22. MAGNA-I Mounting Revision. Source: Rawlinson and Kumar (2022).

The MAGNA-I was incorporated into the RQ-21A GCS via a provided laptop that enabled the RQ-21A operator to interface with the MAGNA-I via the Mayflower Celani AJ Graphical User Interface (GUI) to remotely manipulate and observe the status of the MAGNA-I system (Rawlinson and Kumar, 2022). The Celani GUI provided the operator with various capabilities to change the GPS frequency settings, enable/disable the Anti-Jam feature, and be notified if jamming was detected. Figure 23 shows what the Celani AJ GPS GUI displayed to the operator during this field test (Rawlinson and Kumar, 2022).

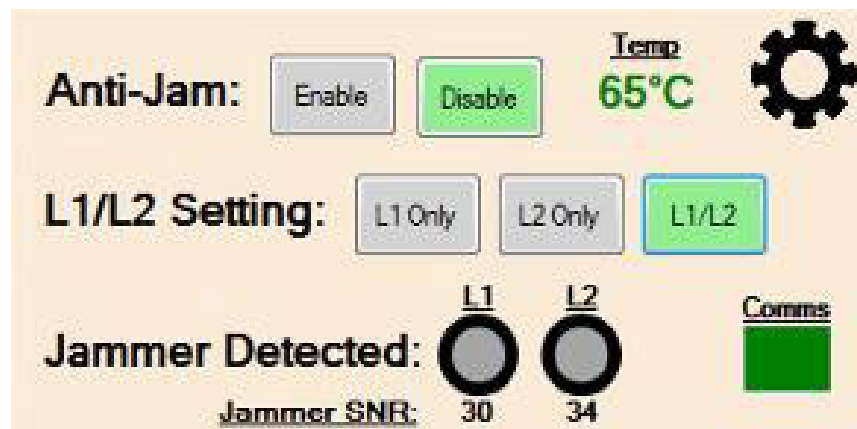


Figure 23. Mayflower Celani AJ GPS GUI. Source: Rawlinson and Kumar (2022).

The RQ-21A is a proven UAS platform within the DOD that can support a wide range of operational requirements to meet the intent of the implementing organization. Specific service components, like the Marine Corps, are moving away from the RQ-21A in favor of other Group 3 UAS systems that fit their mission objectives. More detailed testing in Polar Regions needs to be investigated via other nations that have exported the RQ-21A from the U.S. government to incorporate into their own arsenal, such as Canada (Stevenson 2016). However, given its demonstrated history over the past decade and modifications for the current environment, the RQ-21A Blackjack UAS is a potential candidate that is currently available for the USCG to employ aboard their Cutter class vessels in support of Arctic operations.

2. USCG Polar Cutter

The U.S. DOD has an objective of revolutionizing their Arctic abilities, defense, and agenda (United States Coast Guard n.d.). The spearhead of this budding ethos is the polar security cutter program. While currently having national interests in the area of concern, the USCG is assessing that the new polar security cutters will allow the U.S. to maintain a level of defensive readiness, enforce laws and treaties that support ecological and economic normalcy, and to “provide ports, waterways and coastal security; and provide logistical support—including vessel escort—to facilitate the movement of goods and personnel necessary to support scientific research, commerce, national security activities, and maritime safety” (United States Coast Guard n.d.). The United States fields only two icebreakers – the USCGC *Polar Star* and USCGC *Healy* (Mizokami 2020). Identifying a need for more modern ships with increased capabilities has led to the undertaking of the design and production of three new USCG icebreakers, the first of which will be the *Polar Sentinel*, expecting to have initial operating capability by 2028 (Lagrone 2023). The project, which was initially slated to begin in 2020, has been riddled with delays pushing that date from 2025 (Lagrone 2023).

Creating a ship hull that can withstand the brunt force of breaking through ice is incredibly difficult, but improving designs are optimized by substituting more reliable materials in the design process. Unlike the traditional steel used to make ship hulls, these new cutters will be created with an extremely strong steel known as EQ-47 (Lagrone 2023). Not only increasing the strength of the ship hull, but it is also advertised to be more tolerant of lower temperatures that will surely prove effective in colder climates like the Arctic Ocean (Lagrone 2023). While upgrading materials, newer designs have also been offered throughout the project timeline. The structural support for the *Polar Sentinel* is expected to decrease from 24–98 ft down to 16–30 ft, essentially strengthening the hull strength near the cutter’s ice belt area. (Lagrone 2023) The frame depth of the *Polar Sentinel* is assessed to increase from 10–12 ft to 15–40 ft. (Lagrone 2023) Lastly, a major change that would seem obvious is the doubling of the new cutter’s hull from $\frac{3}{4}$ ft of steel to 1.5 ft of EQ-47 steel. (Lagrone 2023)

The design was based on the German *Polarstern II*, which has dimensions of 436 ft in vessel length, 89 ft in vessel width, and 34 ft of draft (CruiseMapper n.d.). Previous editions of USCG ice breakers host a helideck that can accommodate heavy-lift cargo helicopters, military helicopters, and USCG rescue helicopters (CruiseMapper n.d.). These requirements support helicopters that range in size and utility from the CH-53 down to the MH-60 (CruiseMapper n.d.). While a hangar has not specifically been discussed, the team inferred that emplacing a helipad would likely also mean that a hangar would come with it. Using this inference, team JACL 2.0 believes that the under-construction *Polar Sentinel* would be an ideal candidate to house some of the researched UASs and employ them in the Arctic. Between the increased durability of the ship, and the supplemental aviation capabilities, the *Polar Sentinel* will likely be able to handle harsher atmospheric conditions, including ice and increasing sea states due to global warming. The *Polar Sentinel*'s size and capabilities are summarized in Table 24.

Table 24. USCG Polar cutter ship characteristics

<i>USCGC Polar Sentinel</i>	
Length	459 ft.
Width	89 ft.
Flight Operations Equipment	Flight Deck and Helicopter Hangar
Speed	16 kts.
Endurance	Unk.
Sensors	Unk.
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers

3. Battery

The main benefit to using lithium-ion batteries in small-scale applications is the energy density of the batteries themselves, which allows for a significantly smaller battery to be used without losing overall capacity. Figure 24, presented in Roberta DiLeo's thesis for the Rochester Institute of Technology provides an overall comparison of the weight and volumetric energy densities of popular rechargeable batteries (2012).

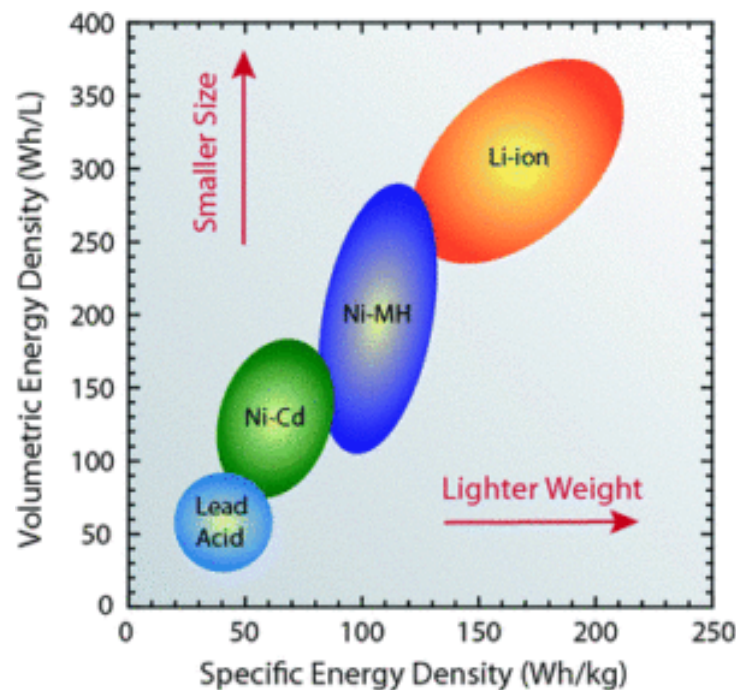


Figure 24. Battery type vs. energy densities. Source: DiLeo (2012).

Almost universally the Li-ion batteries were both lighter weight and smaller than the relevant alternatives yet could hold a higher charge (DiLeo 2012). This creates an ideal situation for the scenarios discussed in this report. Furthermore, by combining the information in Table 4 and Figure 24, one can see that, even with cold-temperature degradation, a lithium-ion battery may, in fact, still hold a better charge and the benefits of size and weight will still be present. With this substantial power-available discrepancy in mind, the most efficient heating method was studied.

a. Temperature Sensitivity Trade Analysis

A 2016 study by Wang et al. studied the ability of a battery to heat itself. They found that by introducing a thin layer of metal foil, in this case nickel, alongside the anode and cathode, they were able to introduce a self-heating ability to what they then called an all-climate battery (ACB); shown in Figure 25.

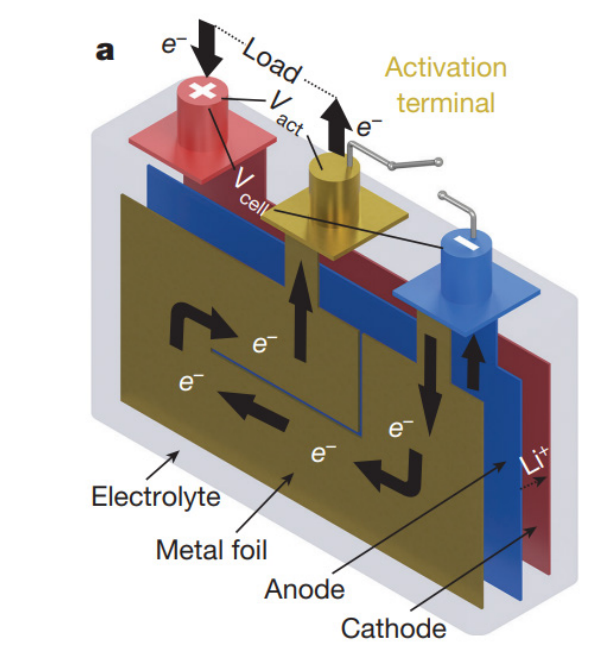


Figure 25. The All-climate battery. Source: Wang et al. (2016).

Their ACB worked by connecting one side of the nickel foil to the negative terminal and thence creating a third terminal, similar to a ground (Wang et al. 2016). This third terminal contained a switch which, when closed, allowed for free flow of electrons from the foil terminal through the negative terminal, thus effectively removing the foil from having any effect (Wang et al. 2016). However, at “low” temperatures, tested as low as -40°C in this study, the switch would open and cause electron flow across the foil (2016). The induced electrical resistance from the electron flow across the nickel foil caused the battery to heat. At 0°C the switch would close once more. Wang et al. concluded their

report with a cost-benefit analysis of the internal heating mechanism they introduced to the ACB, Figure 26 (2016).

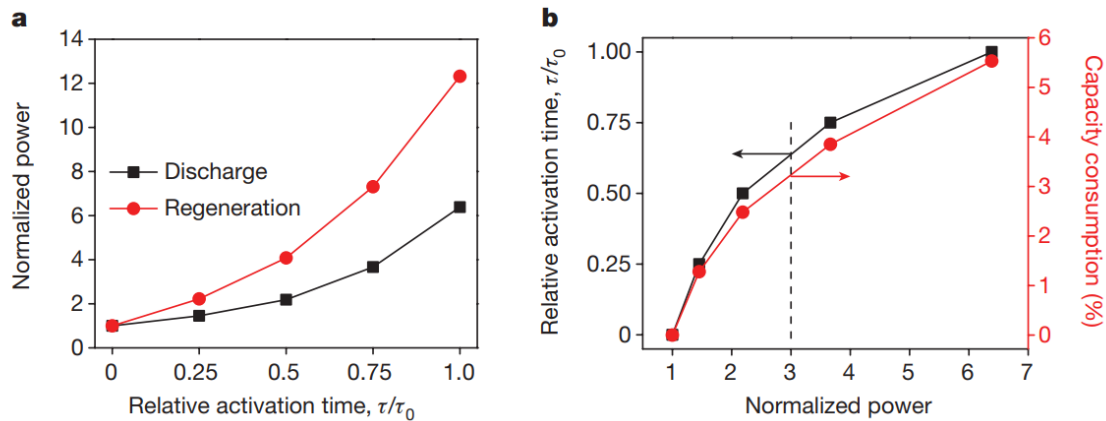


Figure 26. Normalized power and temperature curves for the ACB. Source: Wang et al. (2016).

These results show the normalized power of the batteries against the relative time that the internal heating mechanism was in use and the decrease in overall battery capacity created by the increased internal resistance of the nickel foil (Wang et al. 2016). As shown, at 100% relative activation time, the ACB had a charge capacity of greater than 12 times that of the baseline, while the discharge capacity was increased over 6 times (Wang et al. 2016). The result came at a cost of less than 6% of the battery's overall capacity. At 66% uptime, the charge and discharge powers are increased by 3 times the baseline at a cost of 3.2% (Wang et al. 2016). As far as financial cost and weight addition, their research team concluded that the cost of implementing this nickel foil solution to the average lithium-ion battery to equate to 1.5% of the overall weight of the battery and an increased cost multiple of 0.04% (2016).

b. Pre-Heating Alternative

The above-described solution is still in the nascent stages of development, however, so the team also investigated the current technological standard for electric vehicles, external pre-heating. In 2015, Lei et al. wrote about the cold-temperature susceptibility of

Li-ion batteries and studied the potential for external pre-heating. Their research included adding a copper layer to the external panels of the batteries and applying a large electrical current to create heat through electrical resistance, Figure 27.

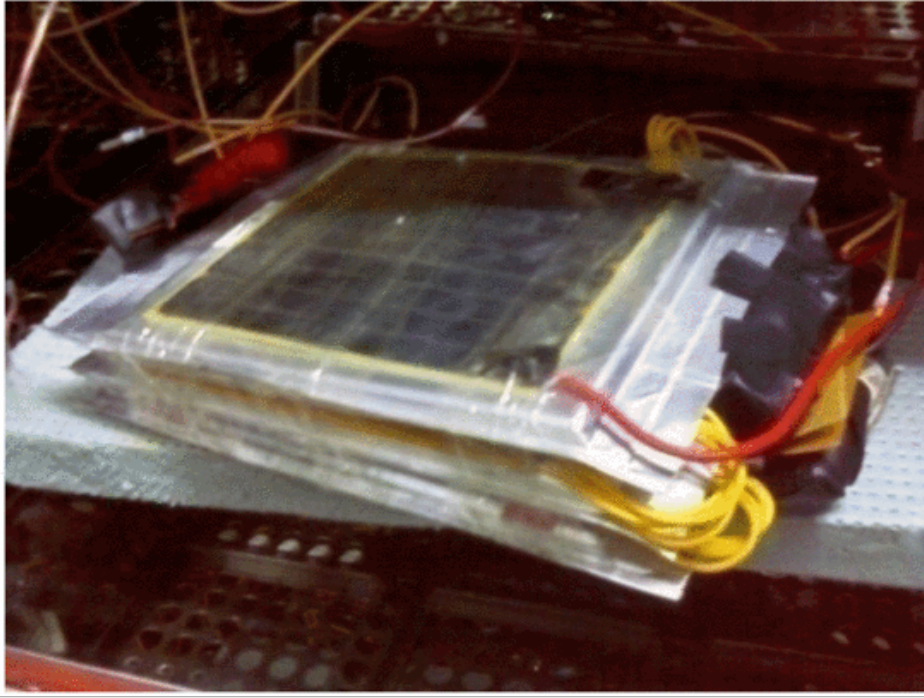


Figure 27. Externally heated battery example. Source: Lei et al. (2015)

The implication of this technology, however, is a large draw from the battery itself, in the absence of a secondary source of power. As seen in Figure 28, the experimental sample used a 35 amp-hour battery and heated using varying power applications from 90W to 240W in 15-minute increments. This converts to approximately 5–15% of the total capacity of the battery per application. The results show a large initial benefit to pre-heating the battery which dissipates over time. This decrease in effectiveness was credited to the internal temperature of the unheated batteries increasing during usage from normal internal electrical resistance. This experiment was conducted at -40°C and was determined to be highly relevant to this report.

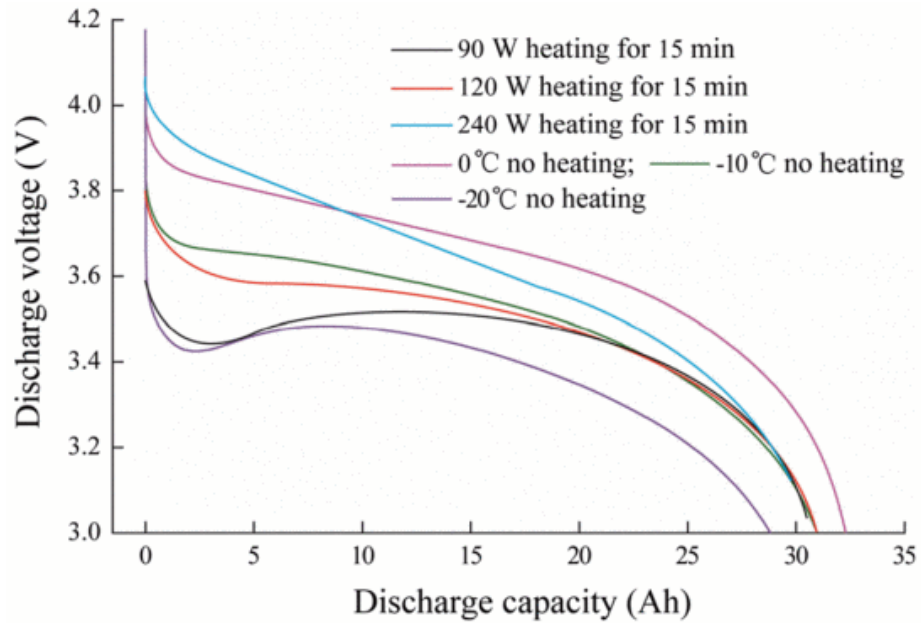


Figure 28. Discharge curves for externally heated batteries. Source: Lei et al. (2015).

In the case of UAS, this introduces a new challenge in that a secondary power source would be necessary at the beginning of a mission to pre-heat the battery for flight. During longer flights, once cold soaking has occurred from ambient air temperature, the batteries would either need to be reheated by themselves or continue to operate in a degraded state. The substantial battery draw used to heat the battery through external means would be expected to have severe impacts on range and endurance.

c. *Insulation Alternative*

The team's analysis of alternatives also included research into insulating materials and their ability to mitigate heat dissipating from a pre-heated battery in flight. Table 25 shows an extensive list of possible insulating materials, however the team focused on polystyrene and polyurethane foams (Cengel and Gharjan 2010). These materials are extremely light weight, and have excellent insulative properties, as evidenced by the table.

Table 25. Insulating materials thermal properties. Source: Cengel and Gharjan (2010).

Properties of insulating materials
(at a mean temperature of 24°C)

Material	Thickness, <i>L</i> mm	Density, ρ kg/m ³	Thermal Conductivity, <i>k</i> W/m·K	Specific Heat, c_p kJ/kg·K	<i>R</i> -value (for listed thickness, <i>L/k</i>), K·m ² /W
Blanket and Batt					
Mineral fiber (fibrous form)	50 to 70 mm	4.8–32	—	0.71–0.96	1.23
processed from rock, slag, or glass)	75 to 90 mm	4.8–32	—	0.71–0.96	1.94
	135 to 165 mm	4.8–32	—	0.71–0.96	3.32
Board and Slab					
Cellular glass		136	0.055	1.0	—
Glass fiber (organic bonded)		64–144	0.036	0.96	—
Expanded polystyrene (molded beads)		16	0.040	1.2	—
Expanded polyurethane (<i>R</i> -11 expanded)		24	0.023	1.6	—
Expanded perlite (organic bonded)		16	0.052	1.26	—
Expanded rubber (rigid)		72	0.032	1.68	—
Mineral fiber with resin binder		240	0.042	0.71	—
Cork		120	0.039	1.80	—
Sprayed or Formed in Place					
Polyurethane foam		24–40	0.023–0.026	—	—
Glass fiber		56–72	0.038–0.039	—	—
Urethane, two-part mixture (rigid foam)		70	0.026	1.045	—
Mineral wool granules with asbestos/ inorganic binders (sprayed)		190	0.046	—	—
Loose Fill					
Mineral fiber (rock, slag, or glass)	~75 to 125 mm	9.6–32	—	0.71	1.94
	~165 to 222 mm	9.6–32	—	0.71	3.35
	~191 to 254 mm	—	—	0.71	3.87
	~185 mm	—	—	0.71	5.28
Silica aerogel		122	0.025	—	—
Vermiculite (expanded)		122	0.068	—	—
Perlite, expanded		32–66	0.039–0.045	1.09	—
Sawdust or shavings		128–240	0.065	1.38	—
Cellulosic insulation (milled paper or wood pulp)		37–51	0.039–0.046	—	—
Roof Insulation					
Cellular glass	—	144	0.058	1.0	—
Preformed, for use above deck	13 mm	—	—	1.0	0.24
	25 mm	—	—	2.1	0.49
	50 mm	—	—	3.9	0.93
Reflective Insulation					
Silica powder (evacuated)		160	0.0017	—	—
Aluminum foil separating fluffy glass mats; 10–12 layers (evacuated); for cryogenic applications (150 K)		40	0.00016	—	—
Aluminum foil and glass paper laminate; 75–150 layers (evacuated); for cryogenic applications (150 K)		120	0.000017	—	—

For the purposes of this analysis, there are two important metrics included in this information. First, the density of the material. Being that weight is such a crucial characteristic of any aviation-related component, the density of the material is of critical

importance. This metric was simply seen as a lower-is-better calculation and used as a first-pass filter. Second, the thermal conductivity values, k , provide the true measure of a materials insulative ability (LibreTexts 2022; Burger 2018).

To calculate the energy dissipation of the battery with and without insulation, two equations were required. First, Equation 2, where R is the thermal resistance of the material, L is the length of the material that the energy is traversing, k is the thermal conductivity value from Table 25, and A is the surface area of the material (Cengel and Gharjan 2010; Burger 2018). With R calculated, Equation 3 generates Q , the heat transfer rate of the material where ΔT is the difference in temperatures between the hot and cold parts of the system (LibreTexts 2022; Burger 2018).

$$R = L/k*A \quad (2)$$

$$Q = \Delta T/R \quad (3)$$

Using Equations 2 and 3, Table 26 was generated showing the thermal performance of an uninsulated battery alongside a battery insulated by 1 centimeter of polyurethane or polystyrene foam. Thermal dissipation is shown in both Watts and British thermal units (BTU). Although future work is necessary to determine the exact temperature differential of the material as it reaches equilibrium with the ambient air temperature, it is evident by these calculations that even one centimeter of installed foam insulation will decrease the heat loss of the battery system by ~50%. These results were calculated using a battery initial internal temperature of 25°C and an external temperature of -20°C.

Table 26. Heat transfer calculations.

Material	L (Distance m)	A (Area m ²)	K (Thermal Constant)	R (Conductivity)	Q (Heat Transfer Rate W)	Thermal Transfer (BTU)
Unprotected Battery	0.05	0.5	0.14	0.71	63	214.83
1 cm Polyurethane Foam	0.01	0.5	0.023	0.870	28.411	96.88
1 cm Polystyrene Foam	0.01	0.5	0.04	0.5	37.06	126.37

B. CURRENT SCIENCE REVIEW

Military SATCOM and GPS are sustained and necessary capabilities, controlled and operated by DOD, now exclusively Space Force, under the command and control of Space Systems Command. They are aging capabilities with known deficits and vulnerabilities. Space Systems Command (SSC) has funded developmental plans and roadmap(s) to modernize the capabilities, in order to fulfill current DOD needs – considering factors like growing global operational needs, and pacing adversary threats (DeLaPena 2022).

Figure 29 depicts the current overall SATCOM and GPS ecosystem which includes the three previously discussed space, ground, and user segments.



Figure 29. SSC Space Map. Source: Military Communications & Positioning, Navigation, and Timing Overview with GPS Update (2022).

To meet the current needs, SSC has established campaign(s) to modernize the ecosystems by year 2030, in order to accomplish their assigned mission, “Rapidly deliver premier MiComm and PNT capabilities resilient to the threat by the relentless pursuit of warfighter needs and acquisition excellence” (DeLaPena 2022). The overall goal and vision: “World-class space professionals connecting people and systems, any time any place, to enable unity of efforts across all warfighting functions” (DeLaPena 2022). Which presumably include locations such as the Arctic region. Figure 30 depicts the current overall SATCOM and GPS ecosystem, and the vision for the future.

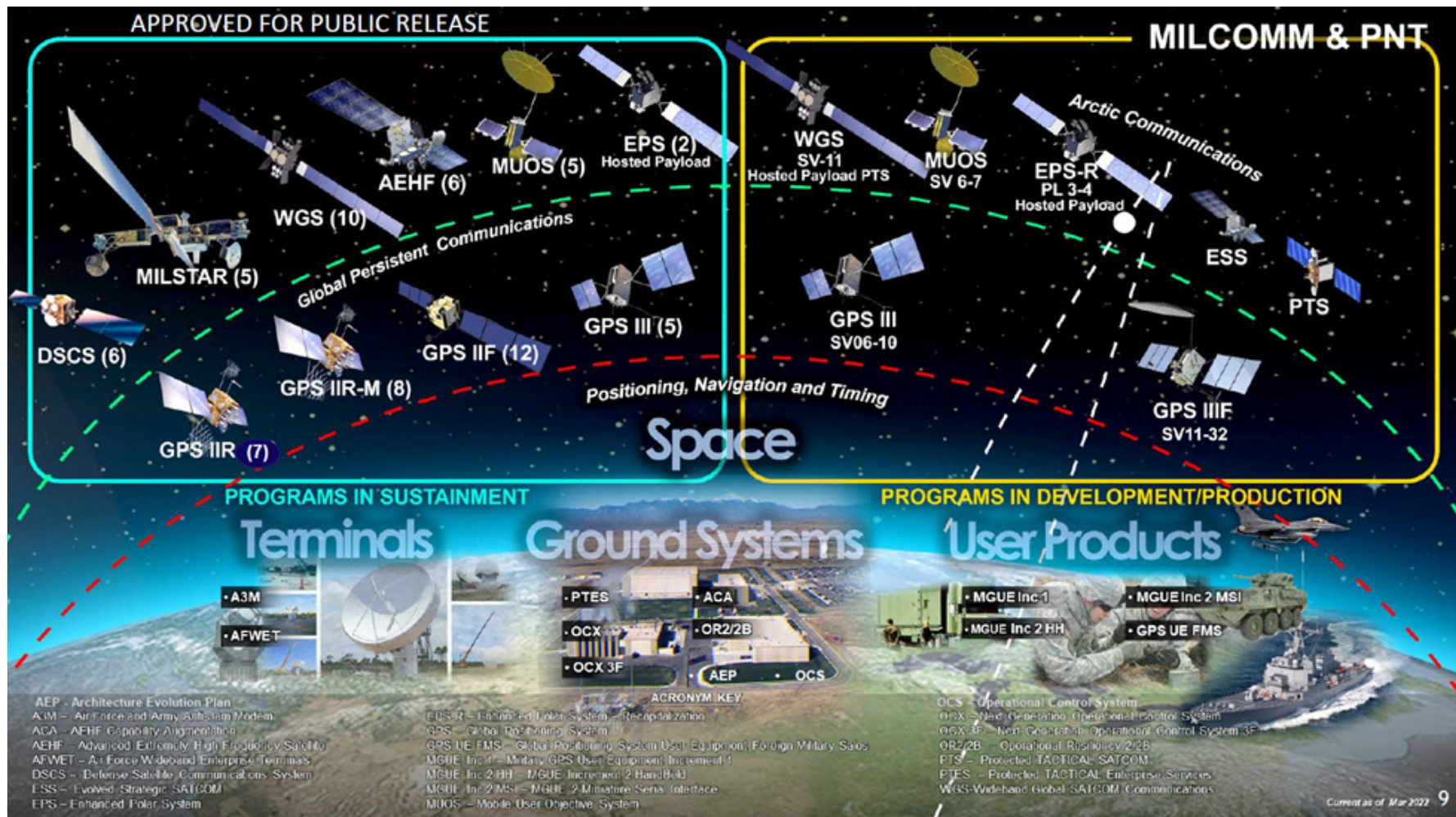


Figure 30. SSC space map (present and future). Source: Military Communications & Positioning, Navigation, and Timing Overview with GPS Update (2022)

As discussed throughout this report, the Arctic region presents multiple challenges for a variety of applications for UAS operations and naval navigation. Geometric Dilution of Precision (GDOP) is a measure of the relationship between the ground receiver and the Global Navigation Satellite System (GNSS) satellite's beam pointing (Swaszek et al. 2018). Given that the orbital inclination of the GPS constellation is 55 degrees, this latitude appears to become the point of a gradual degradation of the GDOP between the satellite and GPS receiver (Jensen and Sicard, 2010; Swaszek et al. 2018). Figure 31 shows an increase in GDOP values after the GNSS receiver moves north of 55 degrees.

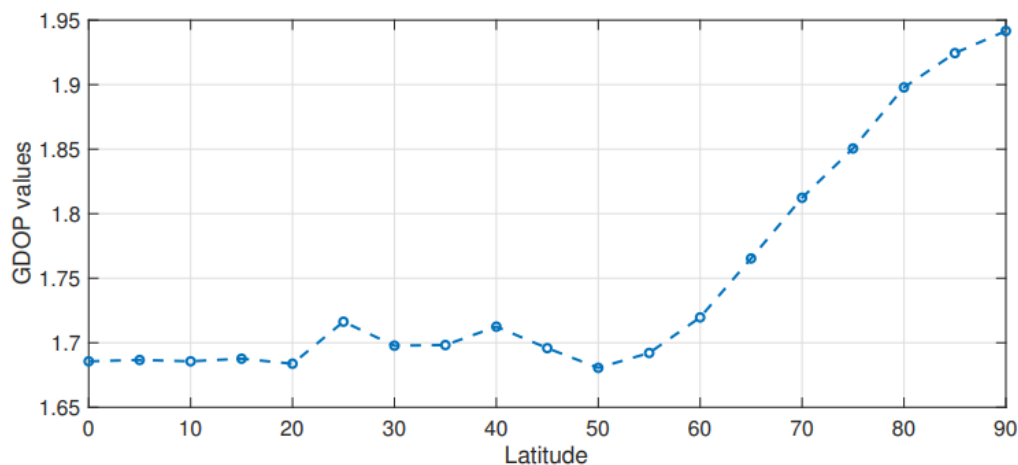


Figure 31. The best GDOP for 7 GPS satellites over a 24-hour period, versus receiver latitude. Source: Swaszek et al. (2018).

C. MODEL UPDATE

With all the aforementioned information in hand, the model was updated. Within the “Mix & Match” section of the “Arctic UAS Selector Tool” the team added the RQ-21A and the Boeing ScanEagle 1, 2, and 3 UAS models. Along with these new models, two new UAS characteristics were added to the data table, maximum wind speed and minimum temperature. Although not explicitly discussed within the rest of the report, these metrics make logical sense based on the discussion of the high wind speed in the Arctic as well as the obviously low temperatures. All other updates to the model are consistent with discussions within Chapter III.

D. MISSION REVIEW

The two major implications of the mission, as outlined in the current model, are due to the temperature of the operating area and the maximum latitude expected. These are discussed in this section.

1. Mission Latitude

The latitude portion of the mission review, for the purposes of understanding and utilizing the “Arctic UAS Selector Tool” is a determination of the expected maximum northern latitude that the mission is expected to cover. As discussed in Chapter IV there is a drop in GPS availability and reliability starting at 55 degrees north (Swaszek et al. 2018). As such, this furthest northern point is used in the model as described in Chapter III, where 55 degrees is a hard cut-off for any UAS which is incapable of flying in a GPS denied environment.

2. Mission Weather

The team conducted climate analysis for the efficacy of UAS use from historical nautical publications by the maritime safety information sector of the National Geospatial-Intelligence Agency. This resource details winds, currents, sea/air temperatures, wave heights, ice limits, visibility, barometric pressure, and weather conditions at different times of the year (Maritime Safety Information 1994, 2002). Out of these data sets, the team utilized winds, air temperatures, and wave heights to make its assessments. While the database does not have a specific section detailing Arctic Ocean weather/climate, the team used both the North Pacific Ocean data as well as the North Atlantic Ocean data to build out a next best data set that meets the team’s requirements and provides information necessary to make educated decisions on UAS use. While specific data is not in abundance, the team made assumptions with the given information to be able to give the team data that is plausible to act in place of missing information.

When analyzing the wind data, most of it was interpreted using the Beaufort scales. The Beaufort wind scale is “one of the first scales to estimate wind speeds” and its effects (National Weather Service n.d.). The scale has established force categories which each

represent a range of wind speeds. The data primarily uses forces one through eight and is most effectively separated out by month due to seasonal variations. Beginning in January, the wind speed was most often observed to be between 11 and 16 knots for both the North Pacific and North Atlantic, while the extreme was 21 knots in the North Pacific and 27 knots in the North Atlantic (MSI 1994, 2002). In February, stark contrasts were observed between the highest wind speeds. The North Atlantic showed the ability to produce 40 knot winds with average winds being 17 to 27 knots (MSI 2002). The North Pacific Ocean, however, averaged 11 to 16 knot winds, with a high of 21 knots (MSI 1994). March again showed high winds of 40 knots with 11 to 21 knot averages in the North Atlantic while the North Pacific averaged between 11 and 16 knots with 16 being the highest (MSI 1994). Furthermore, in the North Atlantic, April, May, and December showed maximum observed wind speeds of 33 knots, while October and November were slightly slower at 27 knots (MSI 2002). In the North Pacific Ocean, the two most noteworthy months were October and November hosting 33 and 27 knot highs, respectively (MSI 1994). The annual wind speed data is compiled in Tables 27 and 28.

Also contained within these same tables is data on Arctic regional sea states. This data differs slightly in that it is a variable affecting the ship itself, and not directly affecting the UAS. Sea states induce pitch and roll tendencies which have the potential to create an unsafe launch/recovery surface (McDonald 1993, A-9). Using sea state 5 as the benchmark for being able to safely launch UASs, the team conducted analysis on two centuries worth of sea state data in the North Pacific and North Atlantic Oceans. The Pacific Ocean was consistent across all the months with a standard 90% of days having a sea state of 5 or less (MSI 1994). The variation and scrutiny came when analyzing the North Atlantic Ocean. January and February had 70% of days that had sea state 5 or less (MSI 2002). Once the weather began to subside, March and April had 80% of its days under sea state 5 (MSI 2002). Consistent with fair weather in the temperature and wind metrics, May through September had 90% of its days less than or equal to sea state 5, with October, November, and December going back to 80% as the weather began to turn again (MSI 2002).

Arctic temperatures have varied ranges across the months as well as in differing environments (over land and over water). The team sourced over-land averages for a 12-

month period at Longyearbyen, Svalbard, Norway to show average temperatures and temperatures that were the highest and lowest recorded, Table 29 and Figure 32. Most of the recorded temperatures fall within operating parameters for the identified UASs. The months that are concerning at first glance are October through April. These are all months that produce mostly subzero temperatures. October's average temperature is -6.5 degrees Celsius with a high of -4 and a low of -9 (Poseidon Expeditions n.d.). November averages -11 degrees with a high of -8 degrees and a low of -14 degrees (Poseidon Expeditions n.d.). December begins to hit double digit negative temperatures with an average of -14.5 degrees and highs of -11 degrees and lows of -18 degrees (Poseidon Expeditions n.d.). January, February, and March all average between -16 and -17 degrees Celsius with highs of -13 degrees and lows between -20 and -21 degrees Celsius (Poseidon Expeditions n.d.). These are of particular note when deciding whether or not icing could occur onboard the UAS with the majority of icing occurring between zero and -10 degrees Celsius (Weather n.d.). As this report is intended to inform future decision makers, it is important to note that these temperatures will only increase because of the rapid warming rate being experienced in the Arctic, known as Arctic amplification (Copernicus n.d.). In 2022 alone, Arctic temperatures were 0.73 degrees Celsius warmer than the average of temperatures between 1991 and 2020 (Ballinger et al. 2022).

Table 27. North Pacific wind speed data. Adapted from MSI NGA (1994)

North Pacific Wind (kts)												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Highest	21	21	16	16	21	21	21	16	21	33	27	16
+Mean	16	16	16	10	16	16	16	16	16	16	6	10
-Mean	11	11	11	7	7	11	11	7	11	11	4	7
Lowest	1	4	1	1	1	4	4	1	4	1	4	4
% Days Below Sea State 5	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%

Table 28. North Atlantic wind speed data. Adapted from MSI NGA (2002)

North Atlantic Wind (kts)												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Highest	27	40	40	33	33	21	21	21	21	27	27	33
+Mean	16	27	21	16	21	16	16	16	16	21	27	27
-Mean	11	17	11	7	11	11	7	11	11	11	17	11
Lowest	4	7	4	4	7	4	1	1	4	7	7	7
% Days Below Sea State 5	70%	70%	80%	80%	90%	90%	90%	90%	90%	80%	80%	80%

Table 29. Arctic temperatures across Longyearbyen, Svalbard, Norway.
Adapted from Poseidon Expedition (n.d.)

Arctic Temperature (°C)												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
High	-13	-13	-13	-9	-3	3	7	6	1	-4	-8	-11
Median	-16.5	-17	-16.5	-12.5	-5	-2	5	4	-1	-6.5	-11	-14.5
Low	-20	-21	-20	-16	-7	-7	3	2	-3	-9	-14	-18

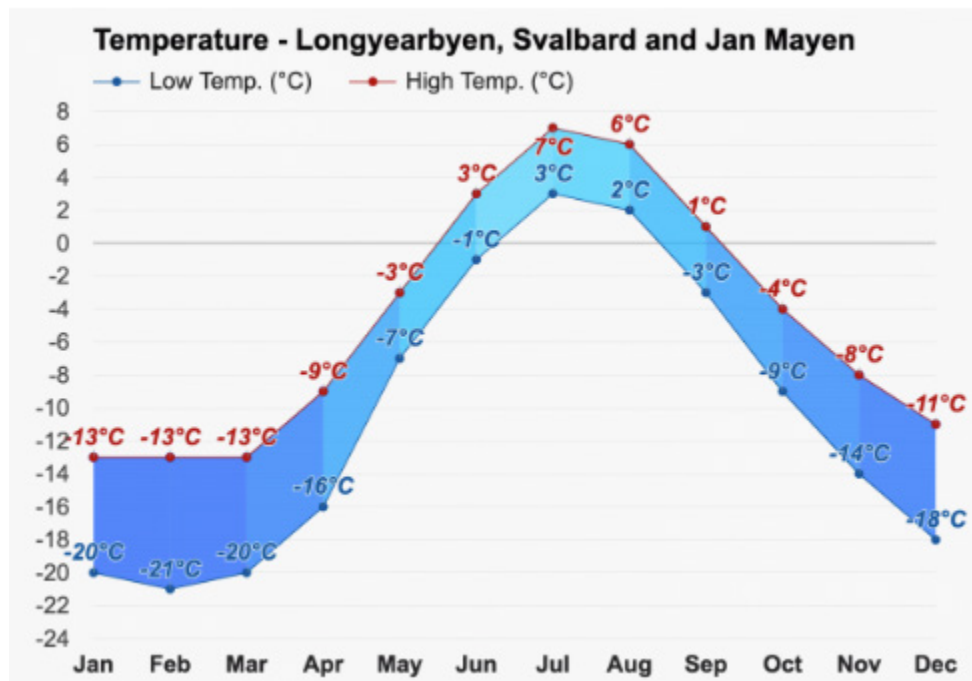


Figure 32. Annual high and low temperatures measured at Longyearbyen, Svalbard, Norway. Source: Poseidon Expeditions (n.d.)

To test the validity of the model in regard to mission capable temperatures, the team used seasonal averages of the areas of Longyearbyen, Svalbard, Norway in Figure 32. This data was derived from a figure from Poseidon Expeditions that gave highs and lows for each month in the specific area of interest. The team then took these averages and used the median across each month as a quantitative inference of what the averages could plausibly be across the months. This would have less of an effect in totality because of the small differences in temperature changes that a dedicated Arctic weather station would be able to provide. Seasons in the Arctic region are slightly shifted from the seasons as most experience them. Spring consists of March through May (Seasons of the Year n.d.). June through August complete summer (Seasons of the Year n.d.). September through November make up fall (Seasons of the Year n.d.). Lastly, winter comprises of December through February (Seasons of the Year n.d.). Summer is, as expected, the warmest season and poses no complications to getting the UAS in the sky. Spring and winter, however, begin to become extremely cold, showing -11 and -16 degrees Celsius, respectively, as average temperatures (Poseidon Expeditions n.d.). Spring typically has highs around -8 degrees Celsius and lows of -14 degrees Celsius (Poseidon Expeditions n.d.). Winter stands out having highs of -12 degrees Celsius and lows of an astonishing -20 degrees Celsius (Poseidon Expeditions n.d.). Table 30 was generated using the information in Table 29 and averaging each row in their respective months. This information was entered into the “Arctic UAS Selector Tool” to gauge how each UAS would fare in different operating seasons. This data is presented in Chapter IV Section E.

Table 30. Seasonal average temperatures in Longyearbyen, Svalbard, Norway. Adapted from Poseidon Expeditions (n.d.)

Seasonal Average Temperatures (C)				
	Spring	Summer	Fall	Winter
High	-8	5	-4	-12
Median	-11	2	-6	-16
Low	-14	-1	-9	-20

E. PRE-DEPLOYMENT ANALYSIS

The pre-deployment analysis is designed to be the user's opportunity to adjust UAS acquisition based on the nature of the scheduled deployment. Variables introduced during this process include ship type, latitude, minimum acceptable speed, loiter time, altitude, temperature, and the estimated wind speed on the Beaufort scale.

1. Input Expected Mission Data

Below are examples of how the team used the "Arctic UAS Selector Tool" in accordance with mission details that were identified as high priority intelligence requirements pre-flight. For most inputs, the team kept everything constant to show how each mission detail independently influenced the model output. First, the team used the tool to show which UAS performs the best under GPS denied environments. GPS denied environments, during peace time, were characterized as latitudes north of 55N (Swaszek et al. 2018). The team used 54N and 56N as placeholders to show the stark contrast in which UASs were competitive during the selection process. Figures 33 and 35 show how the latitude relates with the GPS availability checksum with actual results being shown in Figures 34 and 36. For the sake of seeing the effects that each input plays in the overall selection of the UAS, the team kept constants throughout the inputs with Latitude being 56N, GPS-denied being yes, required minimum speed being 25 knots, required minimum loiter time being 30 minutes, required minimum altitude being 3000 ft, minimum operable temperature being 10 degrees Celsius, and maximum wind level being 3 on the Beaufort scale. Outputs are rendered on a graph depicting a scale from 0–300 on how effective each drone type is, though, no drone exceeds 250 on the scale. For conciseness, the team cut the graphic off at 250.

When analyzing the output data from "Arctic UAS Selector Tool" as it relates to latitude and GPS enabled versus denied environments, as expected, GPS-enabled environments have more qualified candidates to embark on missions than a GPS-denied environment. The UASs that stay consistent through both environments, and thus are more prone to being selected for missions, are the RQ-21A, Shield VBAT, and all three Boeing ScanEagles with scores of approximately 240. The Aerosonde Textron HQ comes in fourth

at a score of approximately 120. The Takeover AR3 Catapult also scored extremely well to perform in the GPS enabled environment with a score of just over 200.

Select Mission	ISR/SAR	ISR/SAR Mission Details	
Select Ship	Ship 8	Toggle	Required Min Speed (mph)
		ON	25
GPS Availability Checksum	GPS-Denied?	Toggle	Required Min Loiter Time (min)
GPS Available	NO	ON	30
If Checksum returns red, GPS-Denied must equal "YES"	Latitude	Toggle	Required Min Altitude (ft)
	54	ON	3000
		Toggle	Min Operable Temp
		ON	10
		Toggle	Max Wind Level (Beaufort scale)
		ON	3

Figure 33. Arctic UAS Selector Tool input data (GPS Enabled)

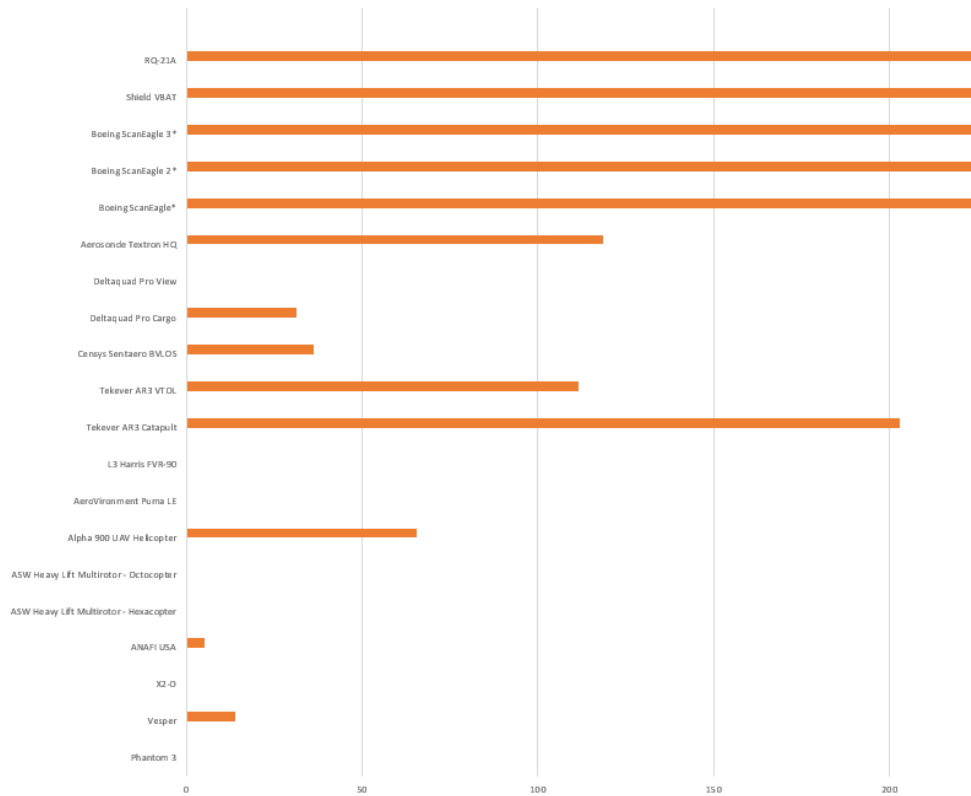


Figure 34. Arctic UAS Selector Tool output data (GPS enabled)

	Select Mission			ISR/SAR Mission Details
	ISR/SAR			
			Toggle	Required Min Speed (mph)
	Select Ship		ON	25
	Ship 8			
			Toggle	Required Min Loiter Time (min)
GPS Availability Checksum	GPS-Denied?		ON	30
GPS Unavailable Above 55 Deg	YES			
If Checksum returns red, GPS-Denied must equal "YES"			Toggle	Required Min Altitude (ft)
	Latitude		ON	3000
	56			
	.		Toggle	Min Operable Temp
			ON	10
			Toggle	Max Wind Level (Beaufort scale)
			ON	3

Figure 35. Arctic UAS Selector Tool input data (GPS denied)

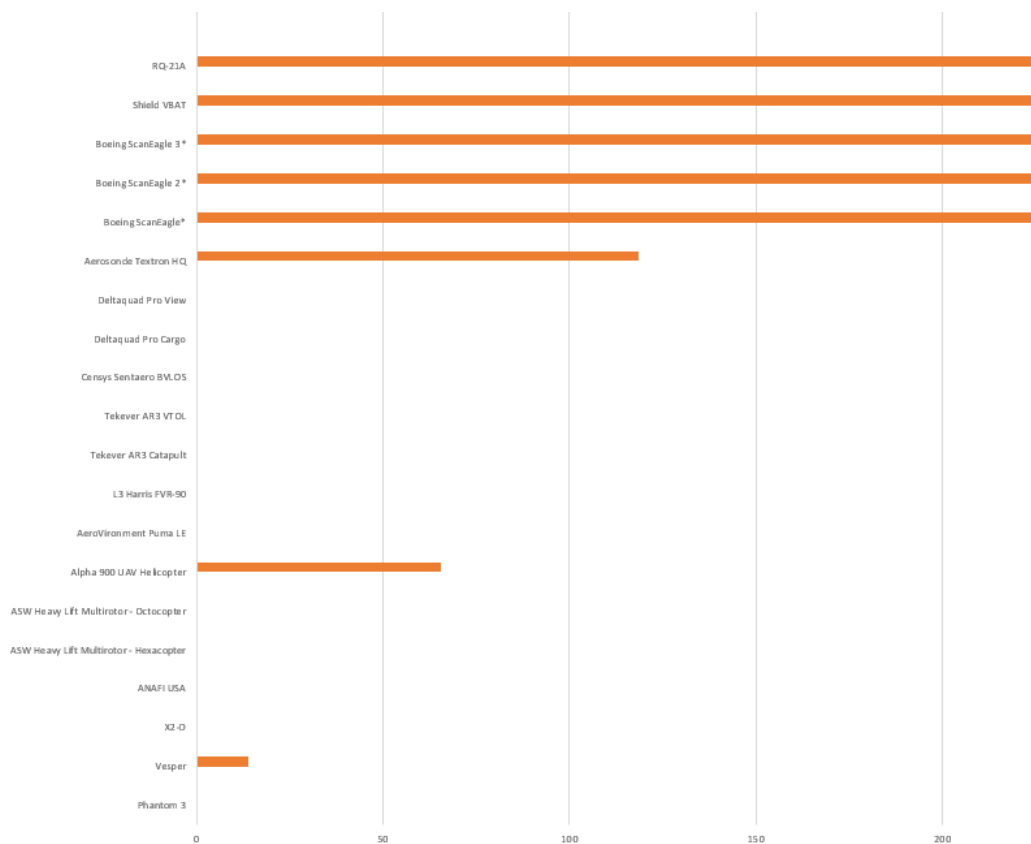


Figure 36. Arctic UAS Selector Tool output data (GPS denied)

Next, the team analyzed how the UASs perform in different climates and temperatures. Figures 37 to 44 show the analysis between the average temperatures of each season, -11 degrees Celsius for spring, 2 degrees Celsius for summer, -6 degrees Celsius for fall, and -16 degrees Celsius for winter. All seasons considered, the RQ-21A, the Shield VBAT, and the three ScanEagles once again proved to be superior performers across all average temperatures in each of the four seasons. The Aerosonde Textron HQ showed that it is usable during the summer months as well.

Select Mission		ISR/SAR Mission Details	
ISR/SAR			
		Toggle	Required Min Speed (mph)
		ON	25
Select Ship			
Ship 8			
		Toggle	Required Min Loiter Time (min)
		ON	30
GPS Availability Checksum	GPS-Denied?		
GPS Unavailable Above 55 Deg	YES		
		Toggle	Required Min Altitude (ft)
		ON	3000
		Toggle	Min Operable Temp
		ON	-11
		Toggle	Max Wind Level (Beaufort scale)
		ON	3

If Checksum returns red, GPS-Denied must equal "YES"

Figure 37. Arctic UAS Selector Tool input data (spring average temperature)

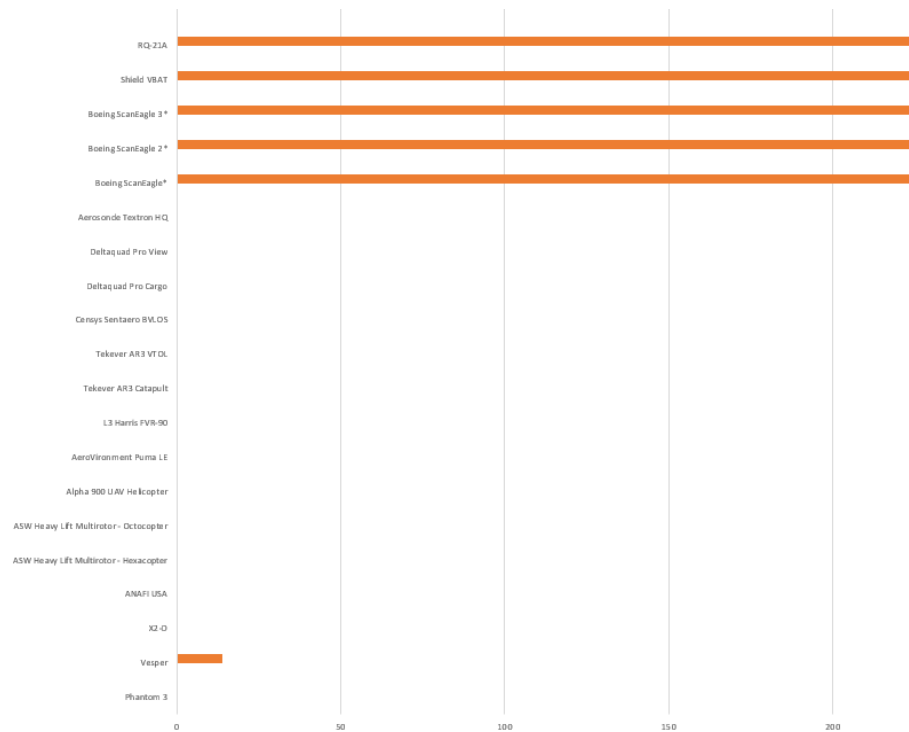


Figure 38. Arctic UAS Selector Tool output data (spring average temperature)

Select Mission		ISR/SAR Mission Details	
ISR/SAR			
		Toggle	Required Min Speed (mph)
		ON	25
		Toggle	Required Min Loiter Time (min)
		ON	30
GPS Availability Checksum	GPS-Denied?		
GPS Unavailable Above 55 Deg	YES		
		Toggle	Required Min Altitude (ft)
		ON	3000
		Toggle	Min Operable Temp
		ON	2
		Toggle	Max Wind Level (Beaufort scale)
		ON	3

Figure 39. Arctic UAS Selector Tool input data (summer average temperature)

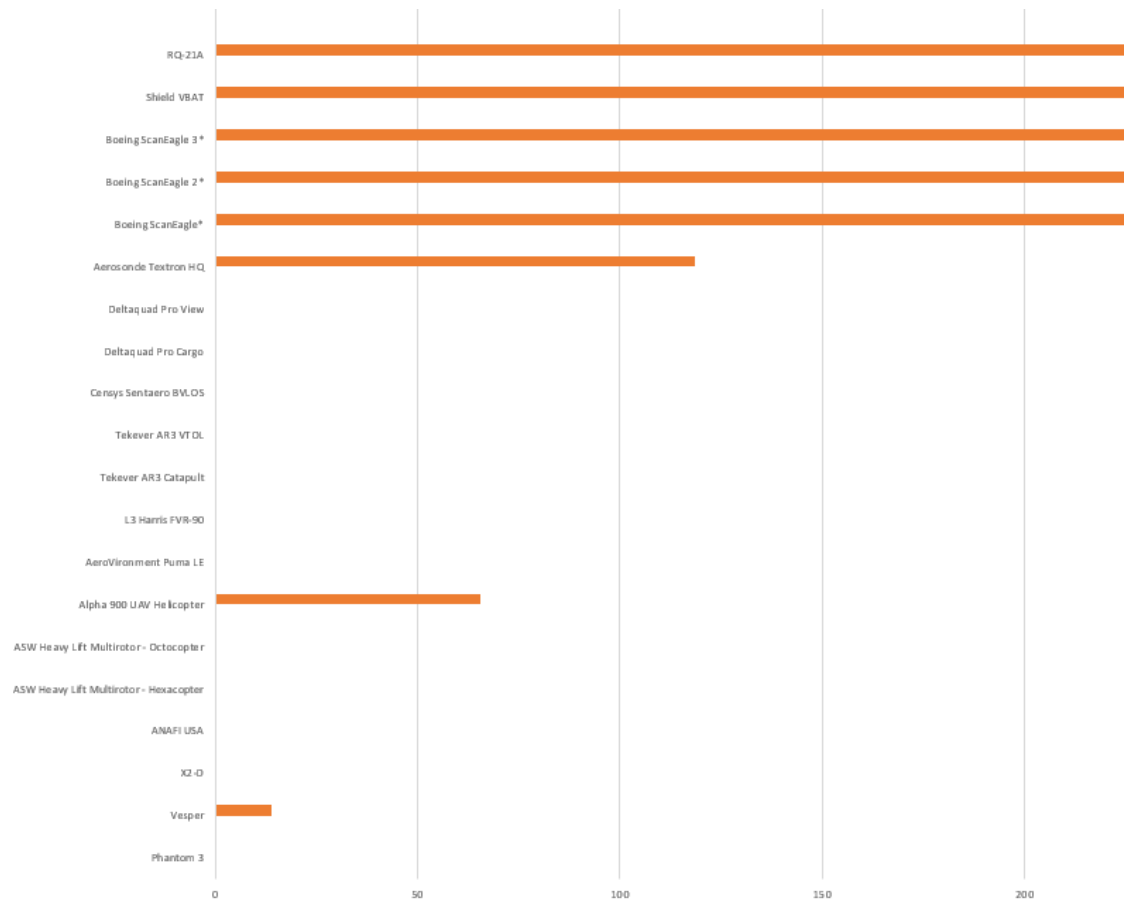


Figure 40. Arctic UAS Selector Tool output data (summer average temperature)

Select Mission		ISR/SAR Mission Details	
ISR/SAR			
		Toggle	Required Min Speed (mph)
		ON	25
Select Ship			
Ship 8			
		Toggle	Required Min Loiter Time (min)
		ON	30
GPS Availability Checksum	GPS-Denied?		
GPS Unavailable Above 55 Deg	YES		
		Toggle	Required Min Altitude (ft)
		ON	3000
		Toggle	Min Operable Temp
		ON	-6
		Toggle	Max Wind Level (Beaufort scale)
		ON	3

Figure 41. Arctic UAS Selector Tool input data (fall average temperature)

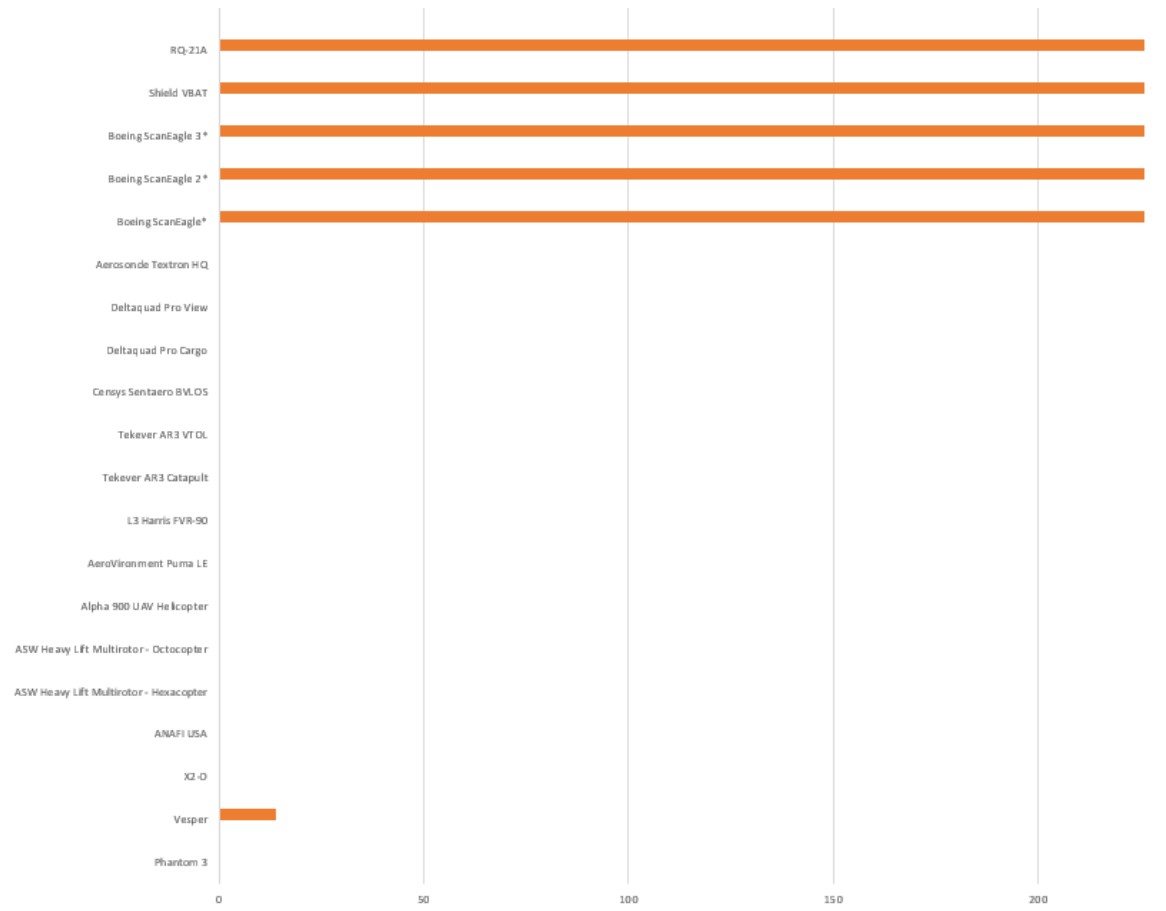


Figure 42. Arctic UAS Selector Tool output data (fall average temperature)

Select Mission		ISR/SAR Mission Details	
ISR/SAR			
		Toggle	Required Min Speed (mph)
		ON	25
Select Ship			
Ship 8			
		Toggle	Required Min Loiter Time (min)
		ON	30
GPS Availability Checksum	GPS-Denied?		
GPS Unavailable Above 55 Deg	YES		
If Checksum returns red, GPS-Denied must equal "YES"		Toggle	Required Min Altitude (ft)
		ON	3000
		Toggle	Min Operable Temp
		ON	-16
		Toggle	Max Wind Level (Beaufort scale)
		ON	3

Figure 43. Arctic UAS Selector Tool input data (winter average temperature)

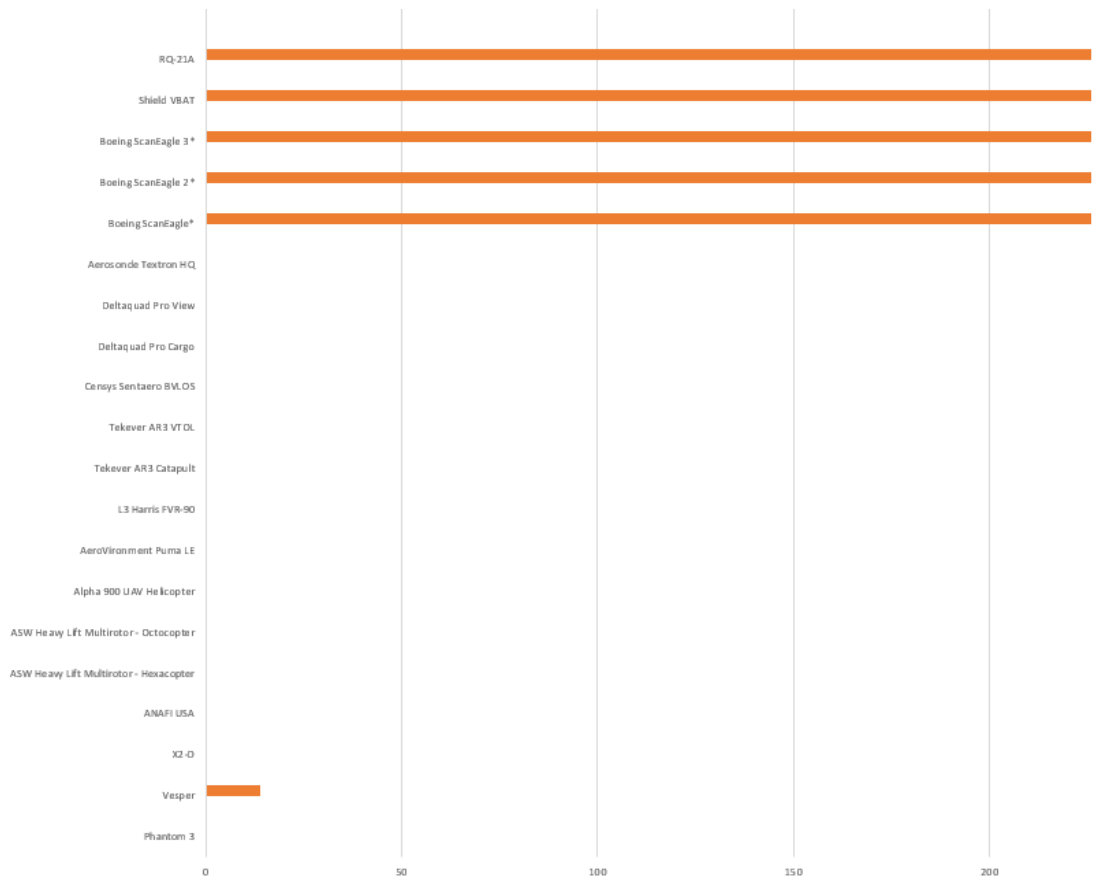


Figure 44. Arctic UAS Selector Tool output data (winter average temperature)

When looking at wind speeds as a determining factor for UAS usage, the team broke it down between three wind speeds as it relates to the Beaufort Scale. The team used force 1, force 5, and force 6 shown in Figures 45 to 50. To keep it concise, the team forewent using forces 2, 3, and 4 since any UAS output differential was marginal. Between the outputs produced by forces 1 and 5, the RQ-21A, Shield VBAT, three ScanEagles, and the Aerosonde Textron HQ produce scores similar to every other test ran. The Alpha 900 UAS Helicopter and the Vesper produce scores of 70 and 20, respectively. The consistent scores across both wind forces makes sense since most aerial assets are rated to be able to perform in standard military operating conditions across branches and uses. Figure 50 is used to show that none of the UASs are rated to be able to perform in climates and environments that contain force 6 or higher wind speeds, the graph is focused in to emphasize that zero points were scored by any asset.

	Select Mission			ISR/SAR Mission Details
	ISR/SAR			
			Toggle	Required Min Speed (mph)
	Select Ship	ON		25
	Ship 8			
			Toggle	Required Min Loiter Time (min)
GPS Availability Checksum	GPS-Denied?	ON		30
GPS Unavailable Above 55 Deg	YES			
If Checksum returns red, GPS-Denied must equal "YES"			Toggle	Required Min Altitude (ft)
	Latitude	ON		3000
	56			
			Toggle	Min Operable Temp
		ON		10
			Toggle	Max Wind Level (Beaufort scale)
		ON		1

Figure 45. Arctic UAS Selector Tool input data (force 1 wind)

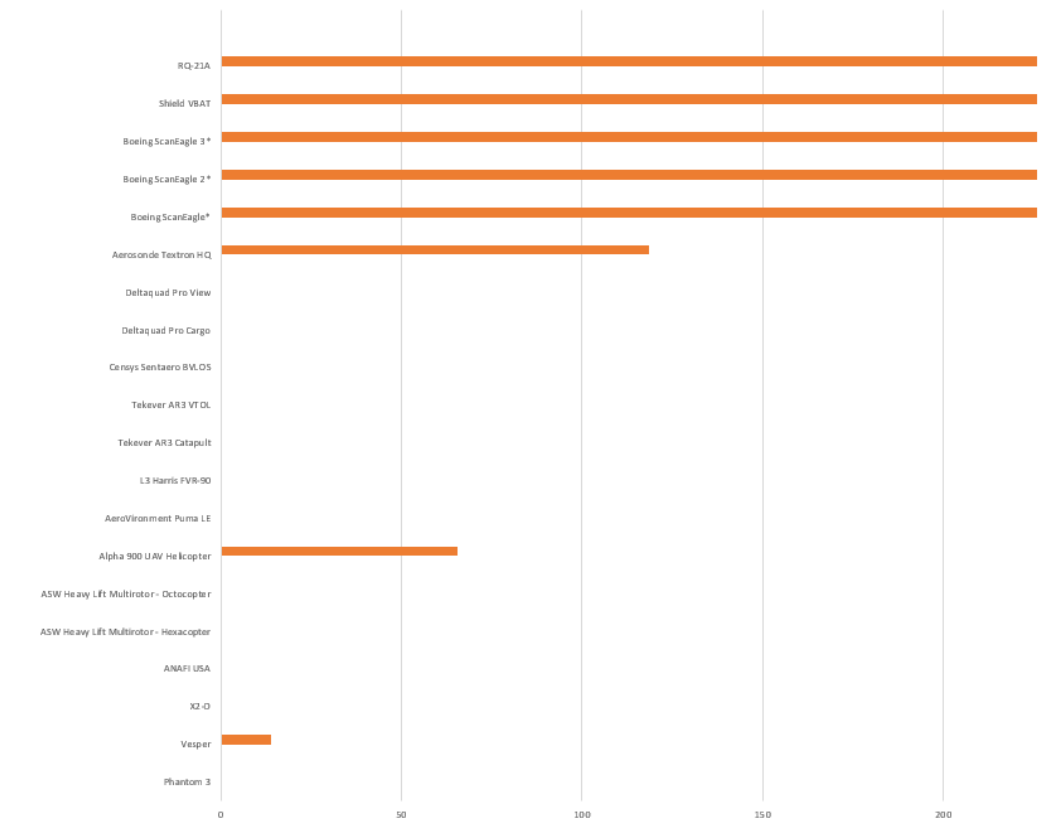


Figure 46. Arctic UAS Selector Tool output data (force 1 wind)

	Select Mission		ISR/SAR Mission Details
	ISR/SAR		
		Toggle	Required Min Speed (mph)
	Select Ship	ON	25
	Ship 8		
		Toggle	Required Min Loiter Time (min)
GPS Availability Checksum	GPS-Denied?	ON	30
GPS Unavailable Above 55 Deg	YES		
If Checksum returns red, GPS-Denied must equal "YES"		Toggle	Required Min Altitude (ft)
	Latitude	ON	3000
	56		
		Toggle	Min Operable Temp
		ON	10
		Toggle	Max Wind Level (Beaufort scale)
		ON	5

Figure 47. Arctic UAS Selector Tool input data (force 5 wind)

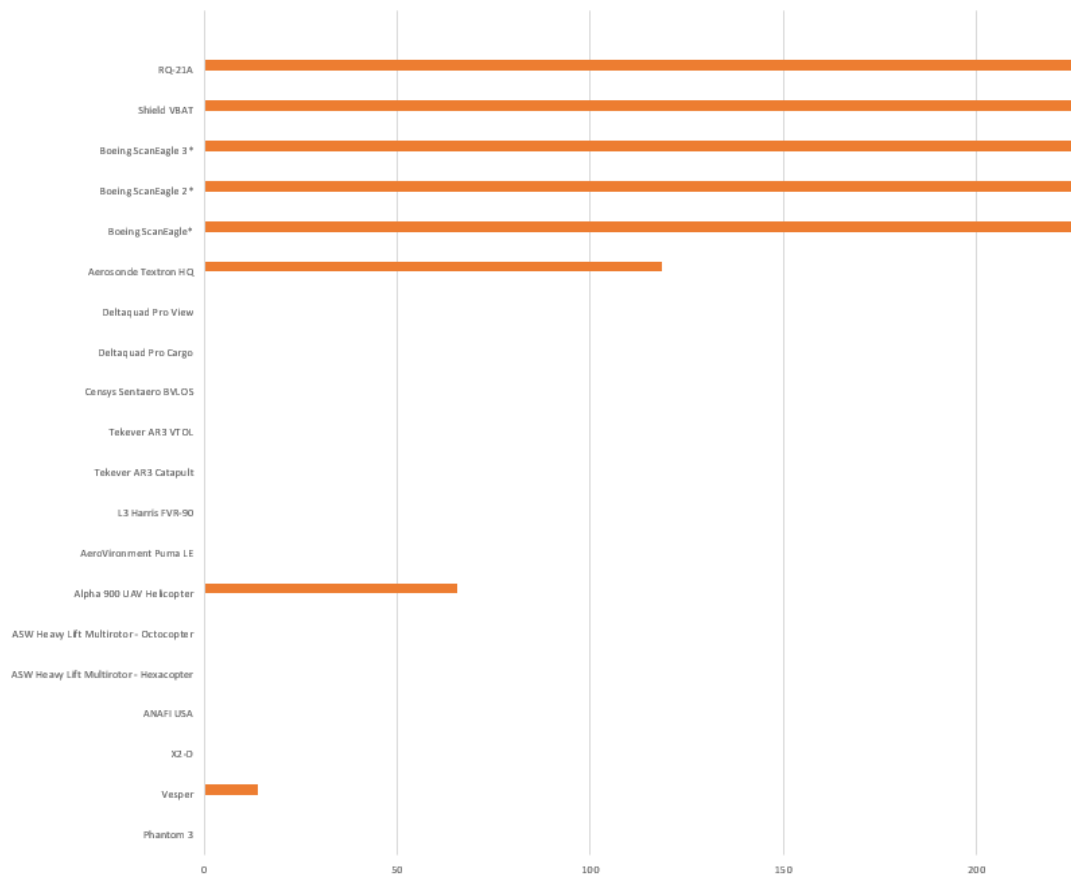


Figure 48. Arctic UAS Selector Tool output data (force 5 wind)

	Select Mission			ISR/SAR Mission Details
	ISR/SAR			
			Toggle	Required Min Speed (mph)
	Select Ship	ON		25
	Ship 8			
			Toggle	Required Min Loiter Time (min)
GPS Availability Checksum	GPS-Denied?	ON		30
GPS Unavailable Above 55 Deg	YES			
If Checksum returns red, GPS-Denied must equal "YES"			Toggle	Required Min Altitude (ft)
	Latitude	ON		3000
	56			
			Toggle	Min Operable Temp
		ON		10
			Toggle	Max Wind Level (Beaufort scale)
		ON		6

Figure 49. Arctic UAS Selector Tool input data (force 6 wind)

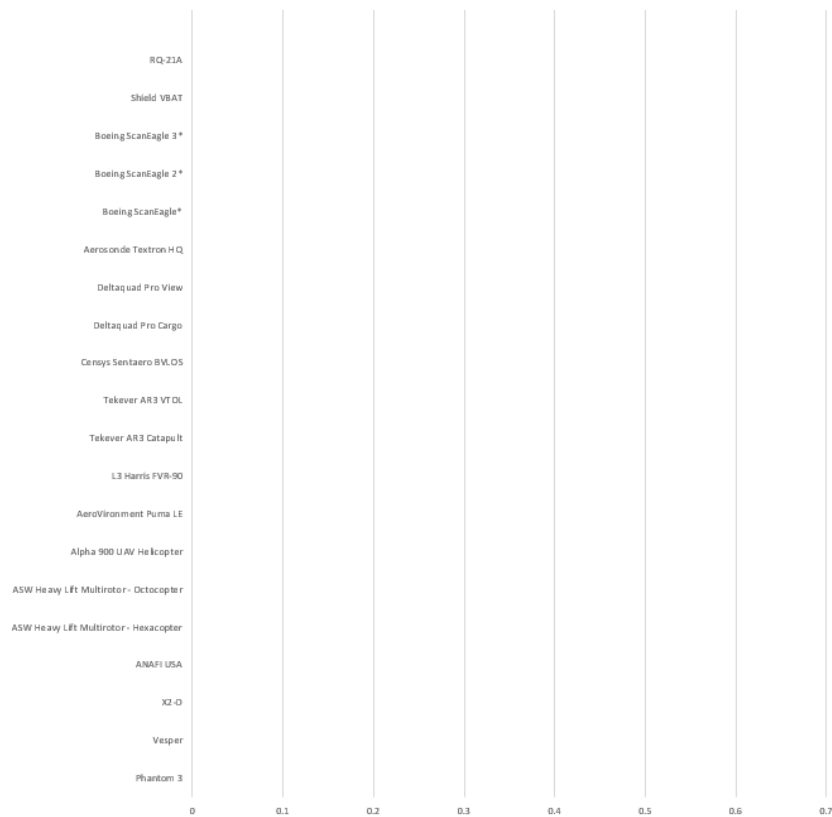


Figure emphasizing the lack of UAS operability at force 6 by model design. As UAS and ships become more resistant to wind and sea state the model may be adjusted to accommodate.

Figure 50. Arctic UAS Selector Tool output data (force 6 wind)

2. Select UAS Based on Output

Using the inputs from above, discuss the selection of the appropriate UAS. This determination is ultimately informed by several factors, only a few of which are modeled in this report. At this point in the process, however, the user has the results of the mission data analysis and is ready to determine the UAS best fit for the mission.

F. REAL-TIME ANALYSIS

The real-time analysis differs from the pre-deployment analysis in that it uses actual data to calculate for the best UAS for the flight and, if battery operated, what the actual performance that can be expected from the UAS is.

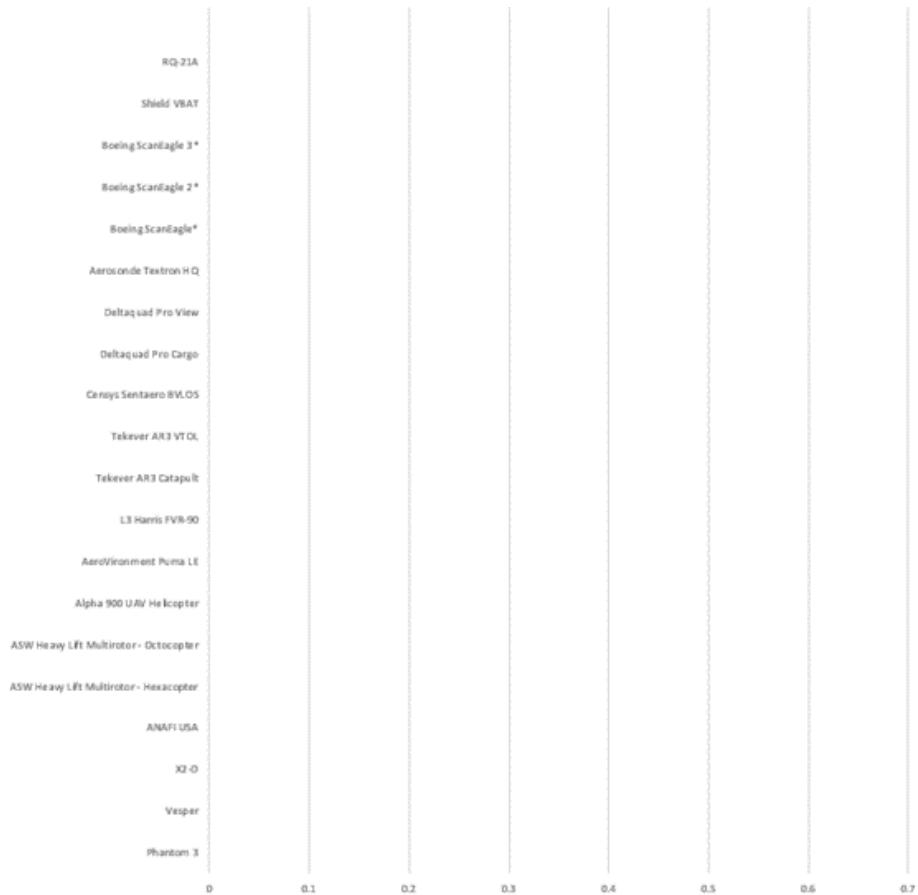
1. Input Actual Pre-Mission Data

In accordance with standard mission planning protocol, the team used Windy.com to gather meteorology and oceanography data for the Arctic region for a notional mission for the night of 20NOV2023. Gathered data included 30–35 knot winds, a 7 on the Beaufort Scale, and temperatures that were ranging from –5 to 5 degrees Celsius. The team settled on using –5 degrees Celsius since it was the worst-case scenario variable. Using these data points to input into the “Arctic UAS Selector Tool,” the outputs produced show that no UASs were capable of performing even the bare minimum of requirements for an ISR mission, mainly due to the wind level that was to be expected during the mission.

As was seen earlier in the report, anything after 6 on the Beaufort Scale provides marginal returns, if any at all. A 7 on the Beaufort Scale follows the same trend as there were no UASs available that could safely launch, perform the mission, and be recovered for a 20NOV2023 ‘Night Go’ as shown in Figures 51 and 52. When an arbitrary battery powered UAS was selected from the prospective list and tested in cold weather conditions, Figure 53 shows that at –5 degrees Celsius, the Vesper’s battery performance slightly decreases from the advertised 55 minutes down to 51 minutes.

	Select Mission			ISR/SAR Mission Details
	ISR/SAR			
			Toggle	Required Min Speed (mph)
	Select Ship		ON	25
	Ship 8			
			Toggle	Required Min Loiter Time (min)
GPS Availability Checksum	GPS-Denied?		ON	30
GPS Unavailable Above 55 Deg LAT	YES			
If Checksum returns red, GPS-Denied must equal "YES"			Toggle	Required Min Altitude (ft)
	Latitude		ON	3000
	56			
	.		Toggle	Min Operable Temp
			ON	-5
			Toggle	Max Wind Level (Beaufort scale)
			ON	7

Figure 51. Arctic UAS Selector Tool input data (real-time)



As with Figure 50, the real-time wind analysis produced a wind of force 7 and, therefore, the model returned zero results. This emphasizes the potential for Arctic weather to negate all UAS operability at a given time.

Figure 52. Arctic UAS Selector Tool output data (real-time)

Arctic Battery Performance Tool					
UAS Selection	Max Loiter Time (mins)	Temperature Selector	Battery Life Expectancy Due to Temperature	Adjusted Operational Battery Life	
Vesper	55	-5	93%		
				51	minutes

Figure 53. Arctic Battery Performance Calculator (real-time)

2. Obtain Expected Performance Data

Continuing to use the Vesper UAS to test the battery performance tool, the team once again used the average temperatures for each season as a variable for tool utilization. Figure 54 shows the second largest drop in operational battery life, dropping from a 55-minute advertised loiter time to 46 minutes of projected loiter time.

Arctic Battery Performance Tool					
UAS Selection	Max Loiter Time (mins)	Temperature Selector	Battery Life Expectancy Due to Temperature	Adjusted Operational Battery Life	
Vesper	55	-11	85%		
				46	minutes

Figure 54. Arctic Battery Performance Calculator (spring average temperature)

Figures 55 and 56 show minimal decreases in battery performance in cold temperatures of 2 and -6 degrees Celsius. The Vesper UAS only loses approximately three and five minutes of operational battery time, respectively, in summer and fall.

Arctic Battery Performance Tool					
UAS Selection	Max Loiter Time (mins)	Temperature Selector	Battery Life Expectancy Due to Temperature	Adjusted Operational Battery Life	
Vesper	55	2	95%		
				52	minutes

Figure 55. Arctic Battery Performance Calculator (summer average temperature)

Arctic Battery Performance Tool					
UAS Selection	Max Loiter Time (mins)	Temperature Selector	Battery Life Expectancy Due to Temperature	Adjusted Operational Battery Life	
Vesper	55	-6	92%		
				50	minutes

Figure 56. Arctic Battery Performance Calculator (fall average temperature)

Figure 57 shows the starkest decrease in operational battery life. This is expected as winter traditionally has the coldest temperatures. The “Arctic Battery Performance Calculator” shows that a -16 degree Celsius climate produces a 24% battery degradation to the Vesper UAS, decreasing its operational battery life 14 minutes from 55 minutes down to 41 minutes.

Arctic Battery Performance Tool					
UAS Selection	Max Loiter Time (mins)	Temperature Selector	Battery Life Expectancy Due to Temperature	Adjusted Operational Battery Life	
Vesper	55	-16	76%		
				41	minutes

Figure 57. Arctic Battery Performance Calculator (winter average temperature)

V. VALIDATION AND VERIFICATION

The validation and verification (V&V) performed in this chapter is a stepwise process which begins with a common-sense analysis of the model and progressed through the framework set forth in “*The Validation Square: How Does One Verify and Validate a Design Method*” (Seepersad et al. 2006). Figure 58 outlines the validation process, aligning V&V with a determination of methodological usefulness.

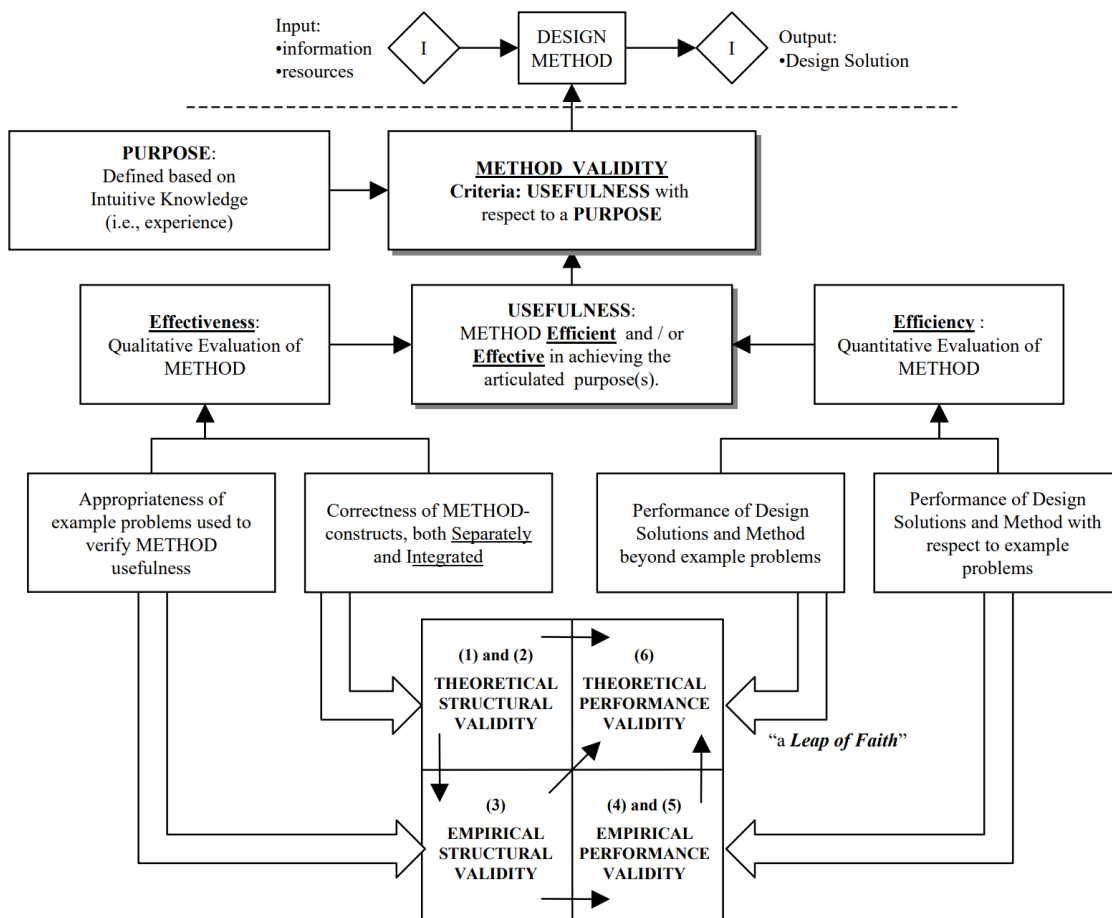


Figure 58. Validation process. Source: Seepersad et al. (2006).

As seen within the V&V square located at the bottom of the figure, there are six segments internal to the V&V process (Seepersad et al. 2006). The authors list these six steps as:

1. Accepting the construct's validity
2. Accepting the method's consistency
3. Accepting the example problems
4. Accepting usefulness of method for some example problems
5. Accepting that usefulness is linked to applying the method
6. Accepting usefulness of method beyond example problems (Seepersad et al. 2006)

A. ACCEPTING THE CONSTRUCT'S VALIDITY

This first step in the V&V process began as early as the literature review and background chapter. It was during this period that the team determined the need for an “Arctic UAS Selector Tool” and the factors which were most appropriate to determine UAS utility in the region. This need is first highlighted within the USN and USCG Arctic strategy publications (United States Coast Guard 2019; Gilday et al. 2021). These publications outlined a need for increased presence in the Arctic regions, which inherently includes UAS assets. From a technical perspective, the team determined that temperature and latitude were major determining factors to add to the model from studying lithium-ion battery performance and GPS availability maps (Aris and Bahman 2017; Trishtchenko, Garand and Trishtchenko 2019).

The model that was edited in the creation of the “Arctic UAS Selector Tool” had been previously V&Ved during its development and it was deemed appropriate to accept the accuracy of the model as a basis for update (Eilertsen et al. 2023).

B. ACCEPTING METHOD'S CONSISTENCY

The model's consistency was determined through a thorough analysis of the raw data, cell look-ups, and conditional formatting used within. The traceability of the information is always available for user inspection due to its nature as an Excel model. This fact alone was not determined to be enough to consider the consistency of the model to be verified, however, so the team elected to execute a systematic review of each table

and cell entry for accuracy as well as proper referencing within the model. This included the use of null data to isolate certain outputs, thus verifying the correct constructs were operational and traceable.

C. ACCEPTING THE EXAMPLE PROBLEMS

Throughout Chapter III of this report, the model is outlined in detail from a discussion of the data used to inform the model itself to the user inputs required for operation. These inputs entail such information as the type of mission being flown, the type of ship being deployed from, and the mission location as it pertains to latitude and average temperature.

The example problems within Chapter IV Section E.1 are admittedly agnostic to type of ship and mission, as the true developments made during this project are unrelated to those two metrics. The addition of the temperature and battery performance correlations as well as the GPS availability cut-off at 55 degrees of latitude are the major modeling additions which had to be run through the V&V process for this report. As such, example problems were designed around deployments in each season throughout the year. Average temperatures throughout the year were sourced and calculated to simulate this data. The model was then tested with a deployment which crossed the 55th parallel, as well as one that did not, to ensure proper determination. Other V&V steps within the model were deemed to have been completed when the initial “Drone Selector Tool” was designed.

D. ACCEPTING USEFULNESS OF METHODS FOR SOME EXAMPLE PROBLEMS

As discussed previously, the example data presented in the Chapter IV was designed to evaluate the main additions to the “Arctic UAS Selector Tool;” the expected Li-ion battery performance metrics in response to Arctic temperatures, and the limited UAS deployment options due to GPS unavailability in the northern-most portions of the region.

E. ACCEPTING THAT USEFULNESS IS LINKED TO APPLYING THE METHOD

The example problems were designed to evaluate each of the individual constructs that the team added to the previously validated model (Eilertsen et al. 2023). The baseline model was already successful at determining an appropriate UAS given a set of mission requirements and the type of ship on which it would be deploying (Eilertsen et al. 2023). The “Arctic UAS Selector Tool” was thus an amendment and addition to this baseline which incorporated decision metrics based on latitude and temperature as well as including four new UAS models to the tool.

As shown in Chapter IV, the example problems evaluated the tool’s ability to differentiate between a mission north of the 55th parallel and one south of it, which was determined to be a justifiable line in the sand for reliable GPS availability. The model is designed to search for UAS assets which require GPS to operate, and filter those out given any latitude north of 55° latitude. This filter was tested in both directions to ensure proper filtering and the results were correct in both cases.

The other evaluated decision metric utilized mission temperature. To prove the utility of this method, the team created four sets of data which represented seasonal averages throughout a calendar year. These temperatures were then all passed through the UAS performance calculator for a singular asset to demonstrate the range of battery performance expected throughout the year. As the only determination for asset performance in the model, this method was found to be consistent with expected results by means of manual calculation.

F. ACCEPTING USEFULNESS OF METHOD BEYOND EXAMPLE PROBLEMS

The final V&V step is a culmination of the previous five and, by Seepersad et al.’s own admission, incorporates a “leap of faith” (2006). This is due to the inherent inability to test all scenarios during method design and the assumption that, if the method has indeed been tested in enough variations, any utilization of the tool thereafter will also provide appropriate results (Seepersad et al. 2006).

In the case of this project, the “Arctic UAS Selector Tool” has been duly V&Ved at multiple levels. First, the team utilized a baseline tool which itself had been subject to a thorough V&V process itself (Eilertsen et al. 2023). Then, the team established a need for additional methodologies specific to Arctic UAS utilization. This determination satisfied step one in the validation square process (Seepersad et al. 2006). Once the decision was made to design an “Arctic UAS Selector Tool,” and the model was built, the consistency of the model was tested through scrupulous review of each section. Finally, multiple sets of test data were run through the model to determine the accuracy of the model’s decision-making given control information. This process has given the team confidence that the model is both relevant to current work, and accurate in its ability to inform the user of both appropriate UAS selection and Arctic utilization.

G. SUMMARY

The V&V process utilized by the project team centered on the validation square framework proposed by Seepersad et al. (2006). Their report highlights six steps in the process of V&Ving a new “construct” (2006). These six steps were followed by the team, with the addition of basic common-sense analysis of the model. While the first four steps of the process can be empirically determined using the team’s model and example data, steps five and six refer to theoretical model analysis. While at a basic level these were performed as well, there is still work to be done in this avenue.

The “Arctic UAS Selector Tool” is in its infancy, and many assumptions were necessary in its design due to the unclassified and open-source nature of its development. Future groups may find that they have increased access to UAS specifics which better inform the decision-making process embedded in the tool. As the tool’s fidelity is increased by the nature of its inputs, the V&V process may be fully realized.

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VI. DISCUSSION, CONCLUSION, AND FUTURE WORK

The final chapter of this report contains the team's final thoughts on the modeling performed as well as the research conducted within the report. Section A amplifies the results of the test data being modeled in Chapter IV. Section B discusses suggested CONOPS for the near-term utilization of UAS in the Arctic. Finally, Section C provides a list of opportunities which the team has identified as relevant to the progression of the field.

A. DISCUSSION

As discussed in the Chapter V, the experimentation for this report was performed on two main metrics which constitute the creation of the "Arctic UAS Selector Tool." These were the addition of latitude as a determining factor for UAS selection, and the creation of the "Arctic Battery Performance Calculator" for computing expected real-world performance of Li-ion batteries in Arctic temperatures. During the analysis phase of the report these two additions were tested via specifically designed data sets, the results of which are discussed here.

With regards to the latitude input for the tool, the logic is based around GPS availability drop-off north of 55 degrees. For any of the UAS which were determined to require GPS connectivity to operate, this input acted as a filter and blocked those results from the output. As the final version of this design acted as 'go/no-go' determination, the results of the testing matched the hypothesis. This is not to say that the experimental design was perfect, however the filter worked as expected. There may be GPS availability north of this cut-off at any given time, and it is possible that different UAS require different levels of precision to operate. As such, the tool's absolute cut-off is unlikely to match actual performance perfectly, but it is seen as a planning tool with outputs on the safe side by using a more restrictive latitude than may be required. To better inform this operation, a higher fidelity understanding of GPS availability and precision at a given time would be necessary, but this information is not available at the unclassified and open-source levels.

The "Arctic Battery Performance Calculator" utilizes a chart which was designed from the results of previous research into the temperature sensitivity of Li-ion batteries.

This data was extrapolated to include the range of temperatures expected to be experienced in the Arctic. Test data was then derived from the seasonal average temperatures of the region and a sample UAS was used to calculate expected performance in each. The results show an expected range of performance with the lowest calculated occurring in the winter, when it is coldest, and the highest performance occurring in the summer when it is warmest. These match the hypothesized results. This model, while accurate for the specific test it is designed for, does not present the entire picture with regards to true thermal analysis. This is because batteries, through usage, heat themselves from the inside, as well as the expected mission design starting with batteries which are at room temperature from inside a storage space instead of prematurely cold-soaked to ambient temperature. These adjustments, however, were beyond the scope and abilities of the team to model appropriately. As such, this tool is again seen as one which provides outputs on the safe side by assuming the battery starts at, and remains at, the coldest temperature throughout the entire mission.

B. CONCLUSION

This report has explored many different facets of utilizing UAS in the Arctic region from C2 capabilities with regard to VHF/UHF LoS technologies as well as GPS and SATCOM BLoS technologies to temperatures, winds, and sea state analyses to better understand the operating environment. Ultimately, the team modified the “Drone Selector Tool” and created the “Arctic UAS Selector Tool” which incorporated several new models of UAS, a new filter for mission latitude, and an “Arctic Battery Performance Calculator” for determining the utility of Li-ion batteries throughout a range of temperatures. As promised at the beginning of the project, the team has identified key factors that should be considered when designing a mission into this region.

1. Batteries

As many COTS UAS are designed around the use of Li-ion batteries, this was selected as one of the main research avenues for this project. The team performed an analysis of alternatives with regards to battery thermal protection, as well as built a calculator to estimate real-world battery performance. These results all show a drastic need for an efficient and effective solution to the dilemma. While there are suggestions laid out

in Section C for researching new technologies, or developing the leading edge of current projects, there are immediate options available which will help.

The first is to simply store, charge, and maintain the batteries in a warm environment until necessary to install prior to the mission. In this way, the thermal mass of the battery is at its peak, and ‘cold soaking’ of the battery is delayed to the maximum extent possible.

The second solution is based on the insulation alternative discussed in Chapter IV where one centimeter of insulating foam was added to the design and the thermal loss of the battery was reduced by ~50%. This solution was determined to be viable, though it does assume that the battery has room around it for the installation. This is expected to only apply to the larger UAS where there is more room to work.

2. GPS

Although the discussion of satellite navigation (SATNAV) within earlier sections of this report has focused on GPS specifically, there are numerous other navigational constellations in orbit. Many UAS are capable of utilizing more than one constellation for navigational purposes, and it is recommended that they do so if the mission is beyond the 55th parallel. This concept is further discussed within Section C as a technology worth developing, however it does come with risks to security that are inherent within using systems designed by other countries. For this reason, this solution may be relevant to some areas of the USCG and USN but not the entire gambit of possible operations.

3. VHF/UHF Communications

The discussion of LoS communications within this document has all assumed that the sole communications node was aboard the vessel from which the UAS deployed. In real-world operations this may not always be the case. In areas where a ground presence is established, there is likely to be a secondary system capable of maintaining communications with the asset. In this way, the UAS C2 may be passed between nodes during a mission and LoS communications maintained throughout.

C. FUTURE WORK

The team has identified numerous opportunities for future work based on information that was unavailable, or experiments that were not feasible given the constraints. These research ventures include everything from expeditionary data to better inform the assumptions made herein to amplifying the model to at least the controlled unclassified information level to incorporate the appropriate flight data. The suggestions for future work are separated into the same categories as have been used throughout the report.

1. UAS

The UAS analysis focused primarily on established programs of record UAS platforms from vetted companies with longstanding DOD contracts. Listed below are some suggestions into other systems that might meet future stakeholder requirements to support Arctic operations:

1. The V-Bat drone has been recently developed by Shield Artificial Intelligence and was awarded to be the Medium Tactical Unmanned Aerial System of choice for Special Operations Command (Shield AI 2023).
2. The L3 Harris FVR-90 UAS is another vertical lift takeoff system that has been developed in the last three years and has comparable capabilities to the ScanEagle and RQ-21A platforms (L3Harris 2020). L3 Harris is another well recognized corporation that has several existing contracts within DOD, which could provide some advantages over commercial companies.
3. Deliberate coordination and testing of the UAS described in the artic region to validate the system capabilities and findings within this report. These operational tests should be scoped in a way that will allow the owning company for each UAS an opportunity to test the limits of their system, while also validating any requirements from the stakeholders.

2. Ships

The team's discussion of the forthcoming USCG Polar Cutter was not implemented into the model due to its status as a future technology. As such, when it is a more appropriate time to do so nearer its operational release, the team suggests adding the new ship type to the model.

The team also made assumptions based on the ships carrying appropriate fuel and allowing Li-ion batteries aboard, as such it may be of value to conduct a review of the current fleet to ensure this is true.

3. Batteries

The battery analysis resulted in the discovery of several prominent gaps in previous research, as well as the need for future technological developments:

1. The further development of the ACB modification to Li-ion batteries (Wang et al. 2016). Whether by evaluating new materials for the most efficient use of electrical resistance for internal heating or by optimizing the thermal switch temperature triggers and overall uptime, the ACB provides an opportunity for enhancing Li-ion batteries' self-sustaining cold weather capabilities (Wang et al. 2016).
2. Research into battery types which are more resistant to extreme temperatures. As shown in Figure 24, there are many different combinations of materials used for battery design (DiLeo 2012). Further research may identify new battery types which have an acceptable trade-off between energy density and operating temperature range.
3. A thermal analysis of Li-ion batteries for more detailed insulation calculations. Important information includes the thermal mass of the batteries, the size of the batteries, and the specific materials used to build them.
4. More specific research into the low-temperature performance capabilities of Li-ion batteries and appropriate ways to address this challenge.

5. Combined research into how mission specifics affect battery life with a focus on ISR capabilities. This is to include the endurance impacts of real-time video versus storage and download options as well as manual control versus fully autonomous flight regimes, as applicable to individual UAS models.

4. Communications

The team discusses recent research being undertaken by various civil and government entities that provide insight into enhancements to satellite navigation in the arctic and improvements to LoS communications within the U.S. military. The research examined below offers a baseline for future research into advancements for critical communications capabilities in the arctic region.

a. GPS

The GPS constellation is just one of several SATNAV systems used by different countries around the Earth (Kaplan and Hegarty 2017). “The term Global Navigation Satellite System (GNSS) is defined as the collection of all SATNAV systems and their augmentations” (Kaplan and Hegarty 2017). China, Russia, India, Japan, and the European Union operate and maintain their own independent GNSS infrastructures (Kaplan and Hegarty 2017).

Over the past couple of years, researchers in Europe have been conducting experiments with new developments in GNSS technologies that are supported by its Galileo GNSS. The Galileo High Accuracy Service (HAS) is a GNSS reinforcement that delivers precise satellite improvements to users across the world free of charge via Galileo’s E6 signal (Naciri et al. 2023). Beginning in early 2021 and going into 2022, scientists have conducted experiments aboard vessels and on land with this enhanced capability provided by the Galileo GNSS. Figure 59 shows the antenna placement aboard a Norwegian vessel during testing along the coast of Norway in early 2021. Figure 60 is a depiction of the physical location of where the test was conducted along the norther coast of Norway (Susi et al. 2021).



Figure 59. GNSS antenna mounted on board the Hurtigruten vessel sailing from Bergen to Kirkenes, Norway. Source: Susi, M. et al. (2021).

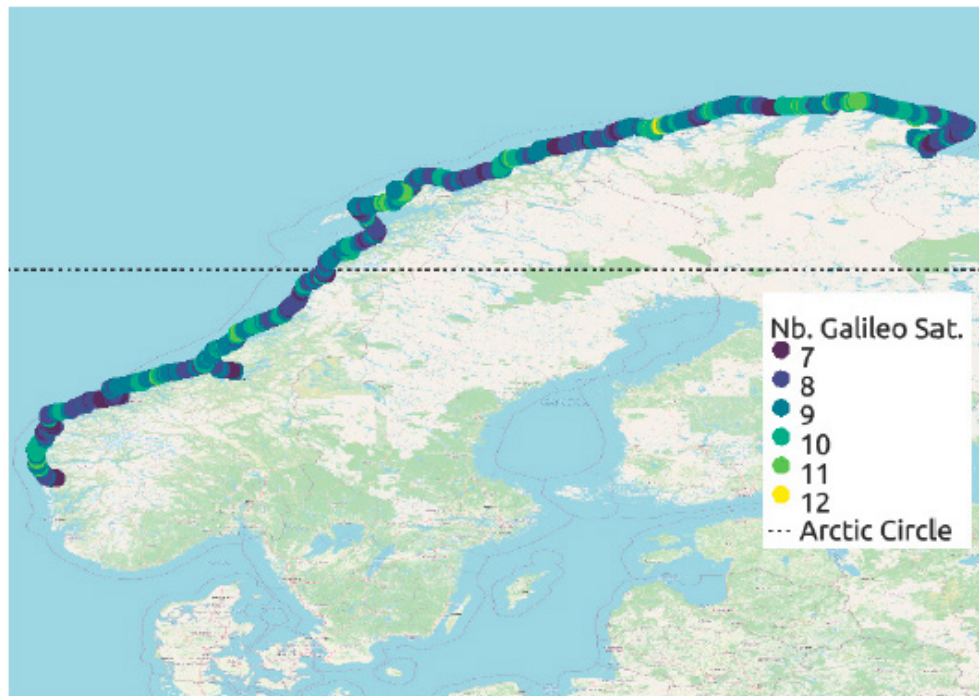


Figure 60. Vessel trajectory color coded as a function of number of satellites based on Galileo constellation. Source: Susi et al. (2021).

Additionally, there have also been tests conducted at a land-based station in the high north to test this HAS capability in a heavily scintillated environment. “High latitudes can represent a harsh environment for high-accuracy applications due to the reduced visibility of satellites at a high elevation and the occurrence of ionospheric scintillation that can affect the signal quality” (Susi et al. 2023). The details of these two reports are very technical and provide specifics that go beyond the scope of this report. However, they are included to support the facts presented in this paper on the difficulties the arctic presents to navigation at higher latitudes. However, these articles are valuable references to gain insight on future developments in satellite navigation in the Arctic, which will enable accurate positioning for USCG ships and the UAS conducting the necessary missions in the arctic. Figure 61 shows one of the Arctic test facilities and Figure 62 highlights its location.



Figure 61. The Polish Polar Station with HAS antenna. Source: Susi et al. (2023).



Figure 62. Map view of location of the Polish Polar Station on Spitsbergen in the Norwegian Svalbard archipelago. Source: Susi et al. (2023).

b. VHF/UHF Communications

The LoS technology analysis is largely centered around the range constraints that preclude broad implementation of LoS systems in the prescribed CONOP. The explored CONOP involves the ability to communicate across ranges north of 100 miles, which goes beyond the capabilities of most LoS systems. DOD and a host of commercial companies have tackled this problem and have developed range expansion systems. Below are a few proposals that could satisfy future stakeholders' requirements in support of operations in the northern regions:

1. The tethered Combat SkySat has been in use for over a decade (PICRYL 2013). Since then, many newer, more modernized, and capable systems have been developed to support both military and civil operations across the globe. The unique SkySat system, which has a tethered and a free-floating version, has served as a repeater for hand-held military communications equipment. This equipment has a typical range of 2 – 35

miles and SkySat expands that range to nearly 500 miles, Figure 63 (PICRYL 2013).



Figure 63. Marines with 26th Marine Expeditionary Unit's command element prepare to launch a lofted communications balloon. Source: 26th MEU (2010).

2. Recently industry and DOD have been experimenting with smaller UASs, outfitted with radio transmission relay systems in the effort to enable LoS systems' deployment across extended distances, Figure 64 (NPSTC 2018). These UAS, when used as a relay, allow BLoS flight operations in challenging environments; mountainous, high-density urban regions, as well as maritime – allowing radio communications across geographically separated nodes (NPSTC 2018).



Figure 64. Drone deployment, outfitted with Wi-Fi and UHF radio communication payload. Source: NPSTC (2018)

5. “Arctic UAS Selector Tool”

The “Arctic UAS Selector Tool” is the culmination of two separate research efforts and capstone projects (Eilertsen et al. 2023). That said, there is still much room to expand upon its utility. The team suggests increasing the classification level of the tool to at least Controlled Unclassified Information to have the ability to input more specific data from military sources. With higher fidelity data feeding the tool, the user may have higher confidence in the output for critical mission planning.

The tool may also be updated with information regarding sea states and, as individual ship-board procedures are developed for each UAS type, more specific wind limits may be used. It is suspected that different launch and recovery types may impact these metrics.

The team also suspects that the weighting within the tool may not be appropriate in all situations and suggests performing a requirements analysis to determine more accurate weighting for the model.

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