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Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

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Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

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16. Abstract (MAXIMUM 200 WORDS) The U.S. Coast Guard (USCG) Research and Development Center (RDC) and the National Oceanic and Atmospheric Administration (NOAA) conducted a series of experiments in the Arctic as part of continued effort to advance detection of surface oil in remote, icy environments using uncrewed aircraft systems (UAS). The project was divided into two phases: Phase I for shore-based experiments at Oliktok Point, AK and Phase II for vessel-based experiments onboard the Canadian Coast Guard Ship (CCGS) Sir Wilfrid Laurier. For Phase I, the project team collected data using thermal and multispectral sensors mounted on UAS platforms that imaged an array of rectangular containers (totes) containing different Alaska North Slope crude oil or marine diesel thicknesses and ice combinations. For Phase II, the team tested capabilities for operationalizing data acquisition and processing onboard the vessel, and data delivery in near real-time from the vessel to NOAA.					
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EXECUTIVE SUMMARY

The U.S. Coast Guard (USCG) Research and Development Center (RDC) and the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration (OR&R), with the support of the University of New Hampshire Coastal Response Research Center (CRRC) conducted a series of experiments in the Arctic as part of continued effort to advance detection of surface oil using uncrewed aircraft systems (UAS) during oil spills in remote icy environments. The project team divided the Arctic work into two phases: Phase I for shore-based experiments at Oliktok Point, AK and Phase II for vessel-based experiments onboard an icebreaker, Canadian Coast Guard Ship (CCGS) Sir Wilfrid Laurier. For Phase I, the project team collected data using thermal and multispectral sensors mounted on UAS platforms that imaged an array of rectangular containers (totes) containing different Alaska North Slope (ANS) crude oil or marine diesel thicknesses and ice combinations over the course of four days under different weather and lighting conditions. The totes contained a range of oil thicknesses from 0 to 5,000 μm . The project team also executed survey missions over the totes and tundra natural features to develop orthomosaic and oil thickness classification maps.

The Phase I experiments showed a relationship between ANS thickness and apparent temperature¹, as measured by the thermal sensor at 0% and 50% ice cover. The range of thicknesses evaluated (50 to 5,000 μm) yielded hyperbolic curves that could be used to estimate ANS thickness for a range of light levels and water temperatures as a function of apparent temperature. The shape and position of the curves changed with the water temperature and to a lesser extent the light level (lux). At higher light levels ($> 34,000$ lux), water temperature seemed to be the major variable impacting the characteristics of the curves. In conditions where water temperatures were similar, the curves were the most similar to one another. Additionally, 50% ice decreased the temperature of the water in the totes and therefore lowered the position of the hyperbola and flattened its shape somewhat. Despite this, it appeared that with sufficient light, the sensors could potentially predict oil thickness with a degree of certainty.

The uncertainty associated with the estimation of ANS oil thickness increases as the standard deviation of the apparent temperature increases. The experiments were not designed with thin enough oil slicks to determine the detection limits of the thermal sensors for ANS, but it may be < 50 μm for the Arctic conditions tested.

The thermal sensors had difficulty monitoring changes in apparent temperature as a function of marine diesel thickness. The hyperbolic shape of the curves was flattened with $r^2 < 0.6$ (as compared to > 0.80 for the ANS). This was true with and without ice and for the range of light levels and water temperatures tested at Oliktok Point. The thermal sensors can detect marine diesel, but there is no marked change in apparent temperature with thickness. This suggested that the thermal sensor may be only able to do presence/absence detection of diesel under Arctic conditions. The minimum detection limit for marine diesel using thermal sensor is a subject of further research.

For Phase II vessel-based experiments, the team embarked on the CCGS Sir Wilfrid Laurier between 30-50 miles offshore of Utqiagvik, AK with the objective of testing UAS operations and remote sensing technology for mapping ice conditions. The project team flew UAS with thermal and multispectral sensors

¹ Calibrated thermal sensors provide a temperature scale of oil features captured on an image. When using these sensors, a nominal level of emissivity is set for the entire image. These temperatures are ‘apparent’ and should only be used as a scale or reference among the features captured on the image. Note that these temperatures may be interpreted as actual [real] temperatures if the exact level of emissivity, Apparent Thermal Inertia, and conductivity of the material are captured on each pixel which rarely happens.



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

from the vessel's deck in moving water with broken ice conditions. The project team collected, processed, and delivered data while onboard, and in operational response timeframes. The team tested capabilities for operationalizing data acquisition and processing onboard the vessel, and data delivery in near real-time from the vessel to NOAA OR&R.

The Phase II vessel field trials successfully demonstrated the operationalization of the UAS platform and sensors effectively in the Arctic environment from a moving vessel platform. The project team developed recommendations for flying from vessels in cold environments. The team successfully executed surveillance and monitoring operations with multispectral, thermal, and visual sensors for mapping survey missions, supporting tactical positioning of the vessel, detecting marine life (e.g., ringed seal) with the thermal sensor, and processing and delivering data in near real-time. This includes development of data products suitable for response, Natural Resource Damage Assessment (NRDA), and fate and transport modeling.

This report includes lessons learned from Phase II that point to future work including the development of training programs for USCG pilots for the operationalization of UAS with the intention not only to teach them how to collect data for mapping purposes over ice, but also for instructing them in the necessary steps to comply with data sharing protocols. Ongoing work should also focus on testing multiple DoD/DHS approved UAS platforms, as this is an evolving technology.

Future research, including work in the Great Lakes ice environments, could be conducted to collect more data to allow for the development of a 'family' of curves that could be better used to determine oil slick thickness. This includes comprehensive monitoring of water temperatures over a complete set of oil in water and ice concentrations at a series of relevant altitudes, with concurrent, accurate ground level temperature measurements. In addition, continuous light levels and air temperatures should be monitored to support evaluations of their influence on detection capabilities. The slicks on the surface of the totes (and the ice) should be captured using a stable overhead mounted camera to resolve the extent of the oil distribution. This will be used to determine the oil thickness using an imaging processing program on a more continuous basis. Also, additional testing with UAS flying over larger totes with a series of progressively thicker slicks (0 up to 50 μm) of crude oil at oblique angles could determine detection limits.



TABLE OF CONTENTS

EXECUTIVE SUMMARY	v
LIST OF FIGURES	ix
LIST OF TABLES	xii
LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS.....	xiii
1 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Scope of Work for Phases I and II.....	3
2 PROCEDURES	5
2.1 Experiment Locations	5
2.1.1 Phase I: Shore-Based Experiments	5
2.1.2 Phase II: Vessel-Based Experiments	5
2.2 Experiment Setup.....	7
2.2.1 Phase I: Shore-Based Experiments	7
3 RESULTS AND ANALYSES	9
3.1 Phase I: Shore-Based Experiments	9
3.1.1 Thermal Analysis on Oil Thicknesses in Totes	9
3.1.2 Mapping Products	38
3.1.3 UAS Observations of Surface Features	44
3.1.4 Image Classifications	50
3.1.5 Near Real-Time Data Processing.....	54
3.1.6 Standard Operating Procedure for Data Delivery into ERMA	57
3.1.7 Use of UAS Mapping and Classification to Monitor Changing Features/Conditions over Time	60
3.1.8 Mapping Broken Ice	61
3.2 Phase II: Vessel-Based Experiments	66
3.2.1 Objective 1. UAS Flight Operations and Maneuvering From a Moving Vessel in Broken Ice.....	66
3.2.2 Objective 2. Data Acquisition and Processing on the Vessel	69
3.2.3 Objective 3. Data Delivery in Near Real-Time from the Vessel to NOAA OR&R	71
3.2.4 Tactical Positioning of the Vessel for Oil Spill Response Operations	75
3.2.5 Tactical Position and Detection of Targets with Thermal and Multispectral Sensors.....	76
3.2.6 Analysis of Thermal Gradient between Ice and Open Water	78
4 CONCLUSIONS	80
4.1 Phase I: Shore-Based Experiments	80
4.1.1 Thermal Detection of ANS	80
4.1.2 Thermal Detection of Marine Diesel	81
4.1.3 Limits of Thickness Detection of Oil with Ice.....	81
4.1.4 Variation of Temperatures with Flight Altitude	81
4.1.5 Operationalization of UAS	82



TABLE OF CONTENTS (Continued)

4.1.6	Classification Maps.....	82
4.1.7	Near Real-Time Data Processing.....	82
4.2	Phase II: Vessel-Based Experiments	82
5	RECOMMENDATIONS.....	83
5.1	Determine Use-Case Scenarios for CG Oil-Spill Responders to Collect and Manage UAS-Based Sensor Data	83
5.2	Conduct Further Experimentation on Spill-Thickness Measurement.....	83
6	REFERENCES.....	84
	APPENDIX A. OIL IN ICE FILE TRANSFER SOP.....	A-1



LIST OF FIGURES

Figure 1. Left: Quadcopter with multispectral and thermal sensors. Right: Skydio X2D.....	3
Figure 2. Left: Aerial imagery of Sandia National Laboratory facility. Right: Map of Oliktok Point, AK.	5
Figure 3. CCGS Sir Wilfrid Laurier.	6
Figure 4. Approximate location of UAS flights offshore near Utqiagvik, AK.....	6
Figure 5. Array of 36 totes with different ANS/marine diesel thicknesses and ice pairings.	7
Figure 6. Totes setup in Oliktok Point, AK with different oil/ice pairings.	8
Figure 7. Thermal (left) and visual (right) nadir imagery from UAS at 58 ft altitude of 36 totes with different ANS/marine diesel and ice pairings.	10
Figure 8. Subset of totes from Figure 7 showing warmer oil (red) and colder water (yellow and blue).....	11
Figure 9. Array of totes captured for different weather conditions.	12
Figure 10. Array of totes captured for different weather conditions on 5/31/22.	13
Figure 11. Images of totes with oil targets of 200 μm at different altitudes.	14
Figure 12. Images of totes with oil targets of 750 μm at different altitudes.	14
Figure 13. Apparent temperature observations of oil, ice, and water under colder conditions at different altitudes for the 2,000 μm totes on 6/2/22.	15
Figure 14. Data from the CRREL UAS experiments in March 2021 showing the apparent temperature change vs. oil thickness under overcast skies.	16
Figure 15. Apparent temperature vs. thickness of ANS crude with 0% ice on 5/31/22.	17
Figure 16. Apparent temperature vs. thickness of ANS crude with 0% ice on 6/2/22.	18
Figure 17. Apparent temperature vs. thickness of ANS crude with 0% ice on 6/2/22 at 1633 hr.	19
Figure 18. Apparent temperature vs. thickness of ANS crude with 0% ice on 5/31/22 and 6/2/22.	20
Figure 19. Apparent temperature vs. target thickness of ANS crude oil with 0% ice on 6/3/33.....	21
Figure 20. Apparent temperature vs. ANS crude oil thickness with 0% ice on 6/2 and 6/3.	22
Figure 21. Relationship developed from the CRREL data of apparent temperature vs. ice cover.	23
Figure 22. Apparent temperature vs. thickness of ANS crude with 50% ice on 6/2/22.	24
Figure 23. Apparent temperature vs. thickness of ANS crude (0% and 50% Ice) on 6/2/22.	25
Figure 24. Apparent temperature vs. target thickness of ANS crude oil in 0% and 50% ice on 6/3/22.....	26
Figure 25. Apparent diesel temperature vs. marine diesel thickness in 0% ice on 5/31/22 at 1001 hr.	27
Figure 26. Apparent diesel temperature vs. marine diesel thickness in 0% ice on 5/31/22 at 1407 hr.	28
Figure 27. Apparent temperature vs. thickness of ANS at 0% ice on 6/2/22 at 16:33 and marine diesel at 0% ice on 5/31/22 at 1001 and 1407 hr.....	29
Figure 28. Apparent temperature vs. thickness of ANS crude and marine diesel at 0% ice on 6/2/22 at 1633 hr.	30
Figure 29. Apparent temperature vs. thickness of marine diesel at 0% ice on 5/31/22 and 6/2/22.....	31
Figure 30. Apparent temperature vs. thickness of marine diesel at 50% ice on 5/31/22 and 6/2/22.....	32
Figure 31. Apparent temperature vs. thickness of ANS crude at 50% ice and marine diesel at 0 and 50% ice on 6/2/22.	33
Figure 32. Apparent temperature vs. thickness of ANS crude oil at 50% ice and marine diesel at 0 and 50% ice on 6/3/22.....	34
Figure 33. Apparent temperature vs. thickness of ANS crude in 50% ice on 6/2/22 at 1633 hr.	35
Figure 34. Standard deviation and percent relative standard deviation at 0746 hr.	36
Figure 35. Standard deviation and percent relative standard deviation at 1633 hr.	37
Figure 36. Ultra-high resolution (sub-centimeter) map of working area around the totes using visual imagery.	39



LIST OF FIGURES (Continued)

Figure 37. Ultra-high-resolution map using visual imagery with less than 5 mm per pixel resolution.....	40
Figure 38. Visual orthomosaic, created at 1 cm resolution flown at 200 ft.	41
Figure 39. Orthomosaic maps of ultra-high resolution visual imagery. (a) Altitude 200 ft; 1 cm resolution / pixel. (b) Altitude 100 ft; 5 mm resolution / pixel.	42
Figure 40. Visual orthomosaic map generated from UAS data collected at 400 ft. Resolution = 2.5 cm/pixel.	43
Figure 41. Orthomosaic of the totes as observed at 400 ft altitude.....	44
Figure 42. Visual orthomosaic map of the totes and ground verification (Altitude = 200 ft).	45
Figure 43. Map of the RGB post-image processing for feature classification.....	46
Figure 44. In-situ verification of tundra (vegetation) with UAS altitude at 200 ft.	47
Figure 45. In-situ verification of snow with UAS altitude at 200 ft.	48
Figure 46. In-situ verification of ice with UAS altitude at 200 ft.	49
Figure 47. In-situ verification of gravel with UAS altitude at 200 ft.	50
Figure 48. Classification map of features observed and verified by the in-situ survey.....	51
Figure 49. RGB and classification maps of selected features. This example shows gravel (road) as well as snow, and tundra vegetation.	52
Figure 50. RGB and classification maps of selected features. This map shows ice, snow, tundra, and soil (or gravel).	53
Figure 51. Map of open water near to shoreline showing a solid sheet of ice.....	54
Figure 52. Near real-time UAS mapping of tundra.	55
Figure 53. Example of UAS mapping of tundra as displayed on ERMA.....	58
Figure 54. Example of UAS classification product derived from the visual sensor as displayed on ERMA.	59
Figure 55. Example of classification product derived from the thermal sensor as displayed on ERMA.	60
Figure 56. Timelapse of ice melting observed from 31 May to 3 June 2022.	61
Figure 57. UAS orthomosaic simulating oil spill monitoring mapping mission of broken ice in open water. Altitude = 400 ft; max resolution = 2.5 cm.....	63
Figure 58. Subset of simulated and spill orthomosaic showing broken ice accumulation on one side of a bridge.	64
Figure 59. Visual orthomosaic and classification of thermal imagery for identification of ice blocks.....	65
Figure 60. Rapid classification of visual orthomosaic for mapping broken ice.	66
Figure 61. Pilot conducts a pre-flight visual inspection of the UAS on a wooden platform.	68
Figure 62. Hand-catch landing of the UAS assisted by the visual observer.....	68
Figure 63. SAR satellite imagery of broken-ice conditions.....	69
Figure 64. Enlarged SAR satellite image showing ice boundary on the north side of the map and the areas surveyed by the UAS.	70
Figure 65. UAS orthomosaic showing CCGS Sir Wilfrid Laurier and broken ice.....	71
Figure 66. ERMA screen capture showing imagery (orthomosaic) and classification data (shapefile) delivered in near real-time from the icebreaker.	72
Figure 67. UAS classification data ingested on oil spill model GNOME.	73
Figure 68. UAS survey flown at an altitude of 150 ft over a thick layer of multiyear ice.	74
Figure 69. UAS survey flown at an altitude of 400 ft over a thick layer of multiyear ice.	75
Figure 70. UAS broken ice mapping.	76
Figure 71. UAS detection of a seal on the ice edge with an 80x optical zoom.	77
Figure 72. Detection of a seal using the thermal sensor at an altitude of 200 ft.....	78



LIST OF FIGURES (Continued)

Figure 73. Visual (left) and thermal (right) UAS images capturing broken ice and the water next to the icebreaker.	79
Figure 74. Comparison of the visual (RGB) (top) and thermal images (bottom) showed that the water in between the floating pieces of broken ice was much colder than the open water.	80



LIST OF TABLES

Table 1. ANS 0% ice experimental conditions.....	21
Table 2. Near real-time steps and durations for the entire cycle from data processing to delivery.....	56



LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

%RSD	Percent relative standard deviation
ACS	Alaska Clean Seas
ANS	Alaska North Slope
BSEE	Bureau of Safety and Environmental Enforcement
cm	Centimeter(s)
cm ²	Square centimeter(s)
CCG	Canadian Coast Guard
CCGS	Canadian Coast Guard Ship
CONOPS	Concept of operations
COP	Common operating picture
CRRC	Coastal Response Research Center
CRREL	Cold Regions Research and Engineering Laboratory
DIVER	Data Integration and Visualization Exploration and Reporting
EPA	Environmental Protection Agency
ERD	Emergency Response Division
ERMA®	Environmental Response Management Application
°F	Degree Fahrenheit
FAA	Federal Aviation Administration
ft	Feet
GB	Gigabyte(s)
GPS	Global positioning system
GRF	Geophysical Research Facility
hr	Hour(s)
HOOPS	Hoover Offshore Oil Pipeline System
IMU	Inertial Measurement Unit
IR	Infrared
ISB	In-situ burn
km	Kilometer(s)
MB	Megabyte(s)
MBps	Megabyte(s) per second
m	Meter(s)
mm	Micrometer(s)
µm	Micron(s)
min	Minute(s)
mph	Mile(s) per hour
NOAA	National Oceanic and Atmospheric Administration
NRDA	Natural Resource Damage Assessment
OR&R	Office of Response and Restoration
OSRO	Oil Spill Removal Organization
PQL	Practical limit of quantification
RGB	Red, Green, Blue



LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

RDC	Research and Development Center
RDL	Reporting detection level
RTK	Real-time kinematic positioning
SAR	Synthetic Aperture Radar
SD	Standard deviation
SOP	Standard operating procedure
TTP	Tactic, technique, and procedure
UAS	Uncrewed aircraft system
USCG	United States Coast Guard



The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce.



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1 INTRODUCTION

The U.S. Coast Guard (USCG) Research and Development Center (RDC) and the National Oceanic and Atmospheric Administration (NOAA) conducted a series of experiments from 29 May-3 June 2022 in Oliktok Point, AK, as part of continued effort to advance detection of surface oil using uncrewed aircraft systems (UAS) during oil spills in remote icy environments, such as the Arctic. These experiments were a follow up to studies conducted in April 2021 at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH. The experiments at CRREL served as initial steps towards operationalizing UAS platforms for oil spill response. Several questions remained after the CRREL experiments that required further research in the Arctic (Garcia et al., 2022). These questions included identifying uncertainty bounds for oil thickness measurements, and how multispectral imaging detects different types of oil (e.g., fresh, weathered, emulsified). The report also included suggestions for requirements so that UAS can withstand operations in Arctic conditions, streamlined calibration protocols, workflow and data processing, and easy-to-interpret work products for responders.

The project team divided the Arctic work into two phases: Phase I for shore-based experiments at Oliktok Point, AK and Phase II for vessel-based experiments onboard the Canadian Coast Guard Ship (CCGS) Sir Wilfrid Laurier. Phase I experiments focused on characterizing surface oil, and mapping oil and tundra surface features. They served to improve the understanding of UAS platforms and sensors to detect different oil (i.e., diesel and Alaska North Slope (ANS) crude oil) thicknesses in ice and non-ice conditions. A project goal was to confirm whether the relationship between apparent oil temperature and oil thickness and associated algorithms was repeatable under Arctic conditions. The project team collected data using multiple sensors (e.g., visual, multispectral, and thermal) over rectangular containers (totes) containing water, ice, and oil to facilitate identification and characterization of oil and ice features.

For Phase II, the main mission was establishing practices of thermal-difference detection and characterization, and data-delivery/data-management methods (“operationalizing”) for a UAS in a broken ice environment. The project team put the lessons learned from the Oliktok Point experiments into practice during Phase II while simulating an oil spill response operation from a moving vessel in broken ice. To accomplish this objective, the USCG coordinated with the CCG to conduct a field campaign onboard the CCGS Sir Wilfrid Laurier from 25-29 July 2022.

1.1 Background

The USCG has supported a series of controlled experiments and field trials that developed and advanced methods for more efficiently and effectively detecting and characterizing surface oil in cold water environments, with particular focus on ice-infested waters. This work was led by NOAA’s Office of Response and Restoration (OR&R) with support from the Coastal Response Research Center (CRRC) and involved extensive collaboration with multiple partners and stakeholders, including the Arctic Domain Awareness Center/University of Alaska Anchorage. The project team conducted the first tests at the Geophysical Research Facility at CRREL to advance understanding of the strengths and limitations of using multispectral and thermal sensors mounted on UAS platforms to detect and characterize oil in ice-infested waters. Findings from these controlled oil in ice tests in freshwater at CRREL demonstrated some of the differences and challenges associated with detection of oil in temperate versus ice-infested waters.



Testing at CRREL determined that a different multispectral channel combination (e.g., Near Infrared, Red Edge, and Red) is needed to differentiate between fresh and emulsified oil in icy waters than has been used in temperate waters without ice. Further, thermal sensors must account for the relationship between ice cover percentage and apparent temperature. This relationship must be included in the oil thickness algorithms for use in icy waters. Also, CRREL testing demonstrated higher detection limits for surface oil (currently identified to be 50 to >100 μm). The relationships based on the controlled testing at the CRREL facility had to be validated for remote sensing technologies for surface oil characterization in cold climates.

While the experiments at CRREL served as a step towards understanding remote detection of oil in ice-infested waters, additional field trials were needed to understand detection and slick characterization in more environmentally realistic field conditions. The additional experiments conducted for this project required testing in the Arctic. The Arctic environment presented opportunities to collect additional data points in the presence of Arctic vegetation, tundra conditions, and snow to validate the relationship between ice cover percentage and apparent temperature. Testing in the Arctic also presented realistic environmental conditions that UAS pilots are expected to operate in, such as extreme cold temperature and high wind speeds.

The objectives of this work were to conduct field trials and drills to: 1) refine detection limits based on actual Arctic field conditions; 2) advance understanding of the relationship between percent ice cover and thermal sensor-based oil thickness characterization; 3) use this information to support predictions of surface oil volume estimates with refined accuracy; 4) develop faster workflows to allow for production of mapping and other data products to support response and assessment activities (e.g., Common Operational Picture (COP); NOAA Environmental Response Management Application (ERMA®); Data Integration Visualization Exploration and Reporting (DIVER) tool); and 5) develop more standardized procedures for using UAS and remote sensing technology for detection of oil in ice-infested waters. While multiple operational missions have taken place in temperate waters, complementary procedures are needed for the Arctic because the imaging conditions and climate present different challenges. These differences impact detection capabilities by sensors and the operations and maneuvering of UAS systems.

Flight operation procedures depend on the type of mission for oil spill response operations. The main two types of spill-response UAS flight missions are:

Reconnaissance/Surveillance Flights

- This flight is intended to identify floating oil, including the extent, direction, type of oil (e.g., thickness, emulsification) and develop situational awareness for oil spill responses. Responders will normally use this type of flight to plan survey flights or assist with response operations (e.g., containment, chemical dispersant use, skimming, or *in situ* burn (ISB)).
- This flight includes high resolution optical cameras and thermal sensors. Real-time video helps decision makers document the state of the spill for planning the next missions.
- This type of flight could be broadcasted in near real-time (e.g., less than 1 hour from landing) to the UAS pilot's website or to the NOAA Office of Response and Restoration (OR&R) Environmental Response Management Application (ERMA) COP website, including oblique imagery (imagery collected at an angle to the target) (with GPS information) for documentation and reporting.

Surveying Flights for Mapping

- This type of flight is intended to produce maps of floating oil identifying location, extent, thickness, emulsification, or weathering.



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

- Flights are conducted in nadir mode (target directly below sensor).
- Depending on illumination conditions, flights may use optical, upward-looking sensors mounted to the top of the UAS to monitor incoming light, multispectral, and/or thermal sensors.
- Surveying flights for mapping could include shoreline or vegetation mapping for injury or oil impact assessment.

The project team executed experiments to understand how the two main types of UAS flight missions for oil spill response operations can be adjusted based on the different conditions (i.e., Arctic vs. temperate). Phase I consisted of onshore UAS experiments (flown from the ground level) where the project team collected data from overflight sensing using totes with various diesel and ANS oil thicknesses with and without ice. The team also flew missions over natural onshore environments (e.g., tundra, shorelines), and solid-continuous and broken ice targets in freshwater environments (i.e., Kuparuk River). Phase II consisted of a cruise expedition in which the project team flew UAS flight missions from a moving vessel in broken sea ice.

For both experiments, the project team flew a quadcopter with real-time kinematic positioning (RTK), dual thermal and visual camera, and multispectral MicaSense RedEdge (

Figure 1, left). Coast Guard District 9 provided a Skydio X2D with a dual thermal and visual camera for characterizing surface oil (

Figure 1, right). The project team calibrated the generated products and constructed orthomosaic maps of the broken ice and Arctic environments (e.g., tundra, shorelines, ice, snow). The team used the products to show how the targets were identified at different altitudes.



Figure 1. Left: Quadcopter with multispectral and thermal sensors. Right: Skydio X2D.

1.2 Scope of Work for Phases I and II

The shore-based work (Phase I) included experiments to:

- A. Refine and expand the ability to use UAS platforms with thermal and multispectral sensors to detect, characterize, and map surface oil thickness in ice infested waters, building upon findings from the CRREL experiments.



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

- The project team observed an array of totes containing a range of oil thicknesses (0 to 5,000 μm) of ANS crude oil and marine diesel, without (0%) and with (50%) ice cover over the course of four days on the North Slope Borough of Alaska. The objectives were to:
 - Refine detection limits (based on thermal and multispectral imaging);
 - Advance understanding of the relationships between percent ice cover and thermal sensor-based oil thickness; and
 - Characterize uncertainty bounds associated with surface oil thickness estimates as a function of environmental conditions (e.g., sun angle and intensity and ambient temperature).
- B. Use new thermal and multispectral data to support predictions of surface oil volume estimates and to refine algorithms developed during the CRREL experiment to estimate oil volumes in the totes.
- C. Develop rapid workflows to allow for production of mapping and other data products that can support response and assessment activities. This includes use in the Environmental Response Management Application (ERMA) common operational picture and the Data Integration Visualization Exploration and Reporting (DIVER) tool. The more specific objectives were to:
 - Optimize workflow to improve delivery time of data and related map classification products.
 - Work in coordination with the USCG and NOAA OR&R emergency response and damage scientists to identify data products that support short-term response (both real-time and near real-time) and longer term (post-collection) assessment needs.
- D. Develop more standardized procedures, including the use of UAS and other remote sensing technology for detection of oil in Arctic waters including shore-based and vessel-based conditions.
- E. Consider UAS specifications and procedures needed to withstand and operate in cold weather environments from USCG vessels and shore-based operations.

The specific objectives of Phase II of the UAS operationalization experiments conducted on the Sir Wilfrid Laurier were:

- A. Conduct UAS flight operations and maneuvering from a moving vessel in broken ice.
- B. Refine data acquisition and processing on board the vessel.
- C. Refine data delivery in near real-time from the vessel to NOAA OR&R.

These UAS operations have been performed by many individuals and organizations in temperate waters, but not in Arctic conditions from a response vessel. This opportunity was designed to discover the limit and possible technical difficulties that the Arctic would impose on UAS operations with paths extending far away from the ice.



2 PROCEDURES

2.1 Experiment Locations

2.1.1 Phase I: Shore-Based Experiments

The project team conducted Phase I experiments in Oliktok Point, AK from 29 May-3 June 2022 at the Sandia National Laboratory facility. This facility offered access, space, and resources to conduct the experiment close to the shoreline and sea ice (Figure 2). Figure 2 also shows an aerial view of the facilities where the experiment was conducted.



Figure 2. Left: Aerial imagery of Sandia National Laboratory facility. Right: Map of Oliktok Point, AK.

For the shore-based experiment, the project team collected data using sensors mounted on UAS platforms that imaged an array of rectangular containers (totes) containing different: ANS crude oil or marine diesel, thicknesses, and ice combinations. A quadcopter was used to execute survey missions over the totes and tundra natural features to develop orthomosaic (large high-resolution map made by combining many smaller images) and classification maps. At the time of testing, there was no access to broken sea ice. Instead, there was pooled meltwater over a layer of ice.

2.1.2 Phase II: Vessel-Based Experiments

From 25-29 July 2022, the project team embarked on the vessel CCGS Sir Wilfrid Laurier (Figure 3) with the objective of testing remote sensing of ice conditions with UAS. Similar to the onshore-based experiment, the project team operated a quadcopter rigged with a dual thermal and visual camera.



Figure 3. CCGS Sir Wilfrid Laurier.

The team conducted UAS flights between approximately 30 to 50 miles from the shore as shown on the map below (Figure 4).

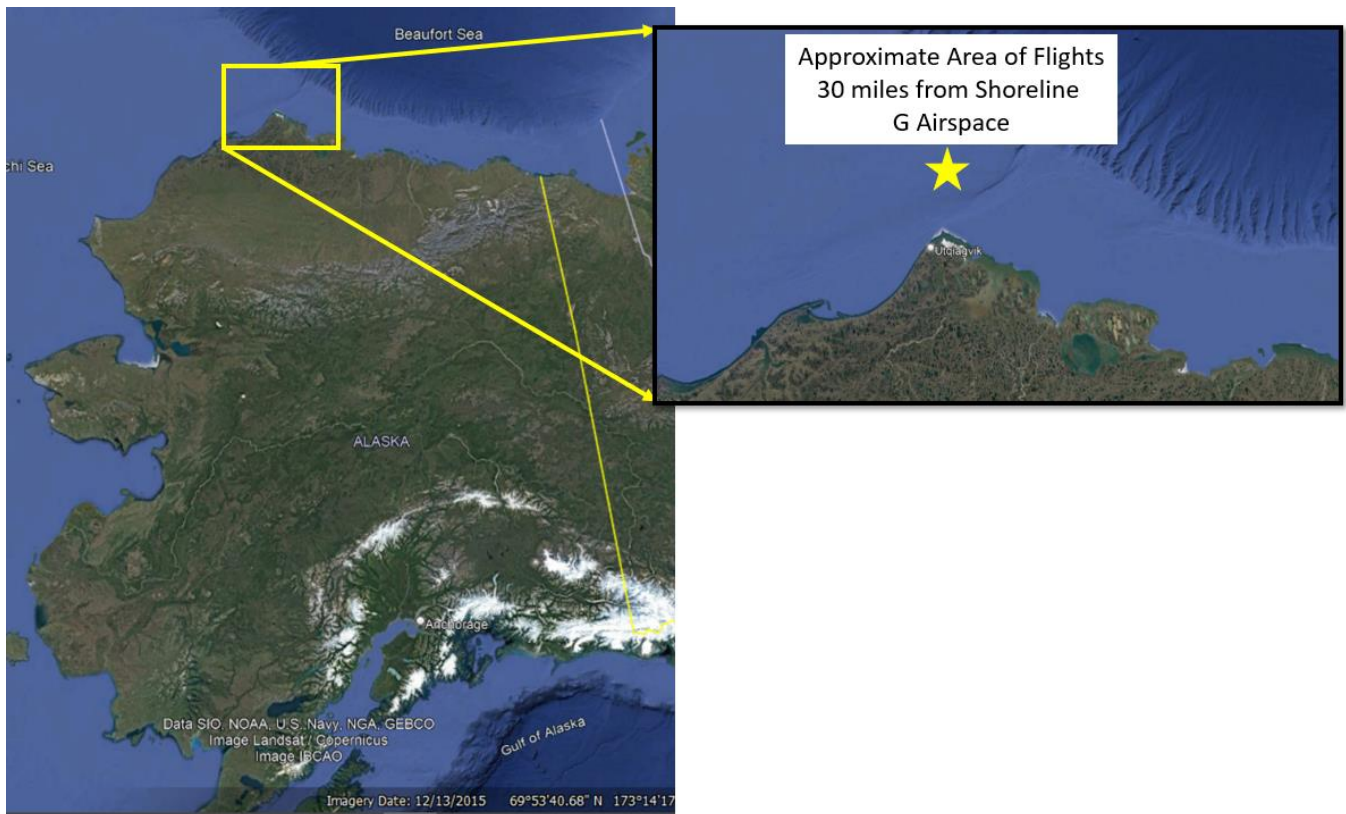


Figure 4. Approximate location of UAS flights offshore near Utqiagvik, AK.



2.2 Experiment Setup

2.2.1 Phase I: Shore-Based Experiments

The tote array was arranged by oil type (ANS and marine diesel) and ice condition (50% ice and no ice (or 100% water)) resulting in a total of 36 totes (Figure 5 and Figure 6). The selected oil thicknesses were based on previous CRREL results, which indicated that there was a major change in apparent oil temperature with oil thickness until $\sim 750 \mu\text{m}$ and thereafter the effect diminished. This suggests that the upper bound thickness for characterizing thickness is at or above $\sim 750 \mu\text{m}$ (Garcia et al., 2022).

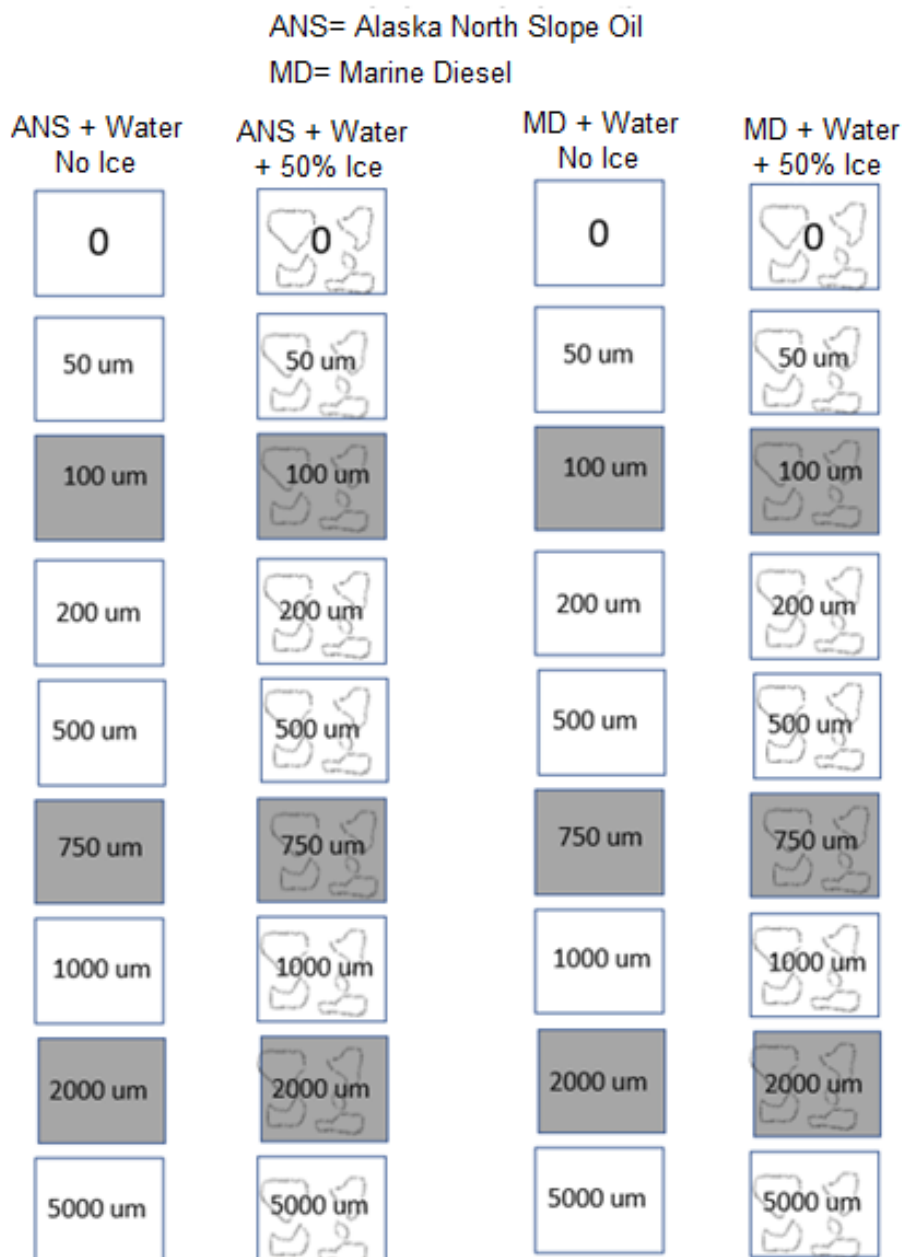


Figure 5. Array of 36 totes with different ANS/marine diesel thicknesses and ice pairings.



Figure 6. Totes setup in Oliktok Point, AK with different oil/ice pairings.

The totes used in the experiments were made of commercial-grade plastic and measured 19 x 15 x 5 inches internally. The team selected the gray color to control the black body effect heating from the sun that occurred at CRREL and in separate outdoor experiments that CRRC and NOAA OR&R conducted in New Hampshire in March 2022². The totes were filled with freshwater. ENI (an oil/energy company) provided a fresh single batch of ANS oil and diesel. Alaska Clean Seas (ACS) staff members harvested the broken sea ice from near offshore.

The project team marked an area measuring ~25 x 50 ft on the ground at the Sandia facility using yellow plastic berm material and snow fence provided by ENI. As shown in Figure 5, the totes were arranged in a uniform grid with ~3 ft between them in each direction. The project team filled each tote with ~3 gallons of water. Once filled, sea ice was added as appropriate until it covered ~50% of the tote's surface area. The project team then pre-weighed glass jars filled with the appropriate volume of ANS oil/diesel fuel. The team slowly poured the contents into the totes without additional mixing energy.

² In this test, the project team explored the impact of air/water temperatures and light levels on the apparent temperature/thickness relationships. The team collected thermal sensor data over two 24-hour cycles in totes similar to those later used at Oliktok Point. The totes contained Hoover Offshore Oil Pipeline System (HOOPS) oil or diesel fuel (thickness = 50, 200, 500, 1,000 and 5,000 μm) and either no ice or 50% freshwater ice. The project team analyzed the 24-hour cycles of air, apparent oil (thermal sensor), and in situ water temperature data using multivariate analysis. Air temperature was found to have no statistically significant relationship with the apparent temperature. The light level and water temperature were strongly correlated to apparent temperature. The team examined the data analysis for the Oliktok Point experiments considering the relationships gleaned from this earlier experiment.

On two days (31 May and 3 June), the ANS did not distribute evenly across the water's surface on the totes but coalesced into thicker circles. This meant that for totes containing 50, 100, 200 and 500 µm of ANS, the oil thicknesses were >1,000 µm in certain spots (Figure 5). The diesel fuel spread uniformly for all days.

The project team determined nominal oil thicknesses using color photos of the totes' surfaces using handheld cameras just before or after the UAS flights. The project team used an imaging processing program (ImageJ, version 2, Free Software Foundation, Inc., Boston, MA) in conjunction with the photos to determine the surface area covered by the ANS or diesel. By measuring the mass of oil poured out of the bottles (initial mass bottle + mass oil – final mass bottle after oil poured) and assuming a uniform thickness of the oil over the surface area cover (as determined by ImageJ), the project team could estimate the average thickness as shown in Equation 1.

Equation 1. Oil thickness in totes.

$$\text{oil thickness } (\mu\text{m}) = \frac{\left(\frac{1}{\text{oil density}}\right) (\text{mass of bottle and oil before pouring} - \text{mass of bottle with oil remaining after pouring})}{(\text{Surface area caused by oil (m}^2\text{), calculated from ImageJ})}$$

The project team used Advanced Visible Light SD Card Datalogger (850005; SPER Scientific; Taiwan), Hobo MX Pendant Temperature Data Loggers (MX2201, ONSET Computer Corporation, Bourne, MA) to collect water column data continuously in the 0, 100, and 1,000 µm totes and integrated air temperature sensors (CSAT3B, Campbell Scientific, Logan, UT) from a Present Weather Detector (CS125, Campbell Scientific, Logan, UT). Immediately after tote setup for the day, the project team took surface temperatures of the water, ice and oil using FLUKE 561 Infrared and Contact Thermometer (505882, Fluke; China).

The project team cleaned all totes at the end of each day by wiping them down with PIG Oil-Only Absorbent Mat Pads (New Pig; 47131901; Tipton; PA) to remove residual oil. The totes were then sprayed down with Citra-Solv (Pro Chem, Inc.; Alpharetta; Georgia) and then wiped clean. ENI staff disposed of all residual water, oil waste, ice, and contaminants according to their procedures.

The project team recorded all data in Excel spreadsheets; it prepared graphs using SigmaPlot (Palo Alto, CA) and JMP statistical software (Cary, NC). Final data storage from the experiments were posted to NOAA OR&R's DIVER website.

3 RESULTS AND ANALYSES

3.1 Phase I: Shore-Based Experiments

3.1.1 Thermal Analysis on Oil Thicknesses in Totes

The project team obtained water and oil data synchronously with UAS and ground-based sensors (i.e., temperatures in the totes) as well as air temperature and incoming solar radiation (lux). Figure 7 shows a nadir view of the full array of totes with thermal and multispectral red, green and blue channels (RGB) data as collected by the multispectral imager and the thermal/visual camera.

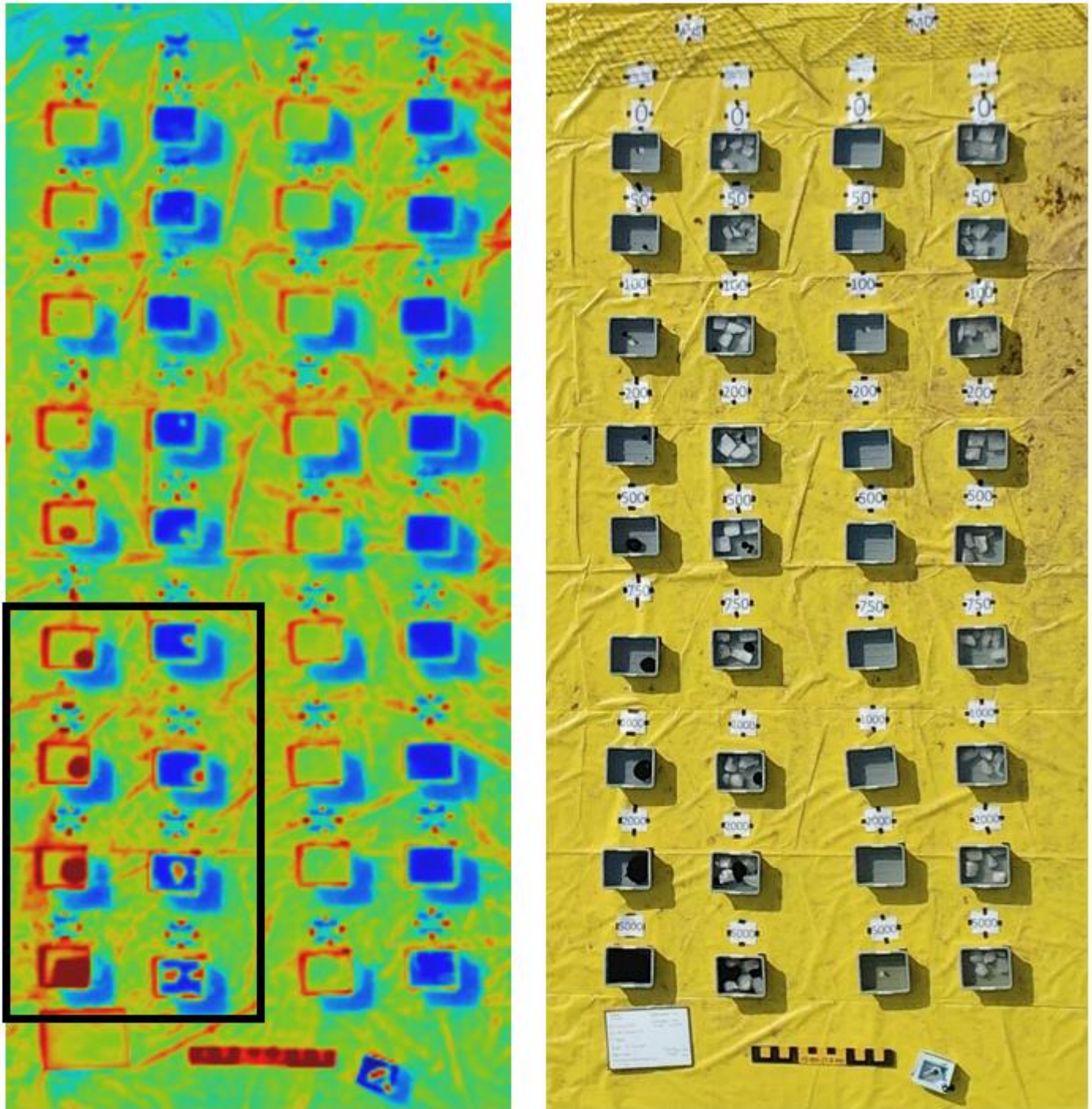


Figure 7. Thermal (left) and visual (right) nadir imagery from UAS at 58 ft altitude of 36 totes with different ANS/marine diesel and ice pairings.

The lowest altitude where the UAS could capture all the totes at once inside the field of view of the sensor was 58 ft. The team aimed to capture all the totes at the same time inside one single image to measure apparent temperatures under the exact illumination and angle conditions. Figure 8 shows a detailed view of the totes inside the black square (from Figure 7) in the thermal panel.

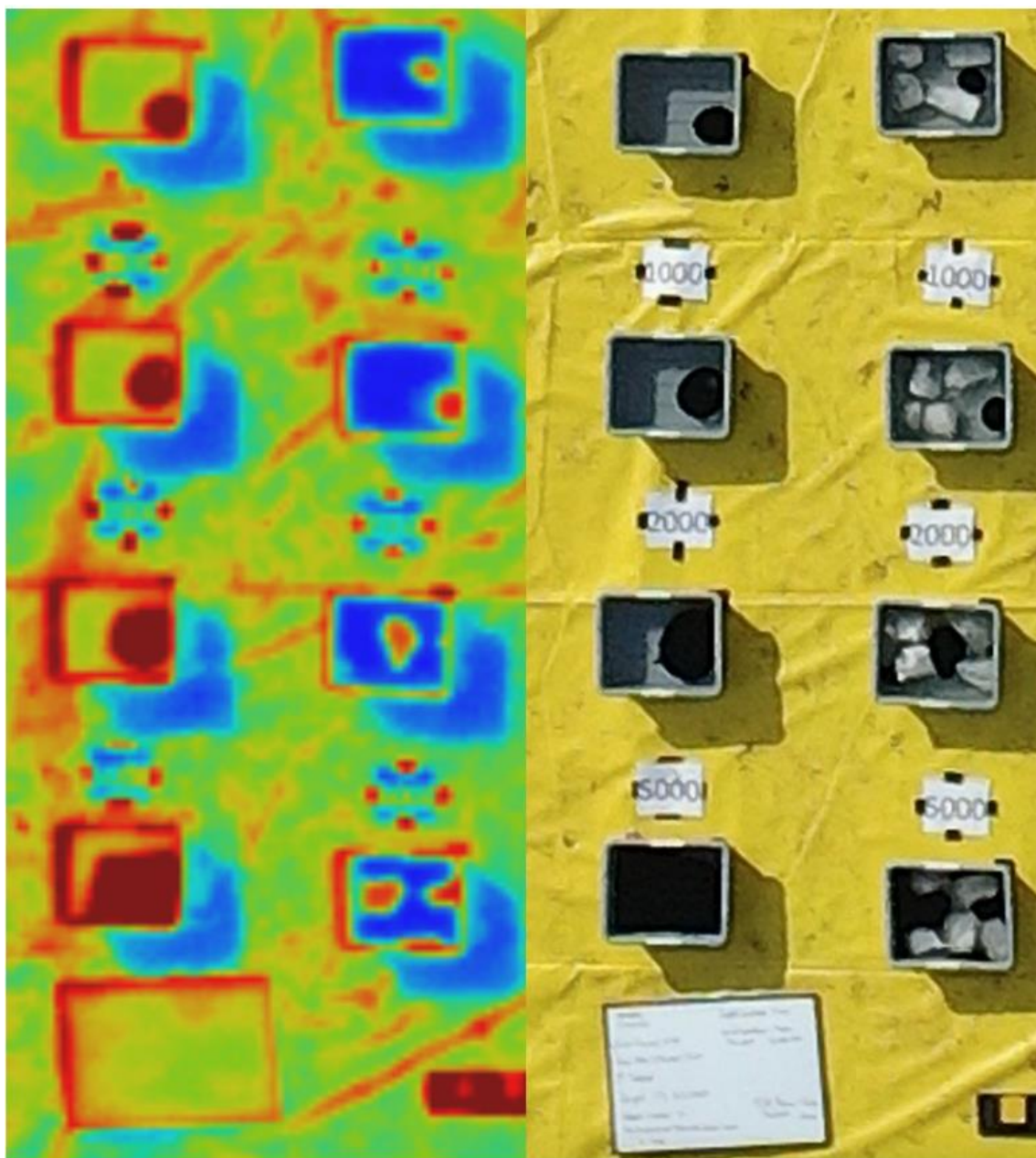


Figure 8. Subset of totes from Figure 7 showing warmer oil (red) and colder water (yellow and blue).

The high definition of the sensor captured imagery with millimeter resolution. Observing these two images (thermal and RGB) together allowed the identification of particular thermal features. The thermal sensor (left) showed the effect of the shadow generated by the totes on the ground cover (light blue). The bright red corresponded to the floating oil. The visualization of these features on the thermal image depended on the settings of the thermal range for the color palette.

UAS infrared sensors use the thermal radiance reflected from objects and can be ‘calibrated radiometrically’ to quantitatively estimate object’s “apparent” (not actual) temperature. The term ‘calibrated radiometrically’ refers to the capacity of the sensor to assign an apparent temperature to each pixel inside the thermal image. Sensors that are not calibrated only provide a thermal contrast, not an actual thermal measurement. A

Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

radiometrically calibrated thermal sensor must be used to derive oil thicknesses. The experiments at CRREL indicated that the data should be interpreted as “apparent” temperatures. The offsets of the apparent temperatures from the actual temperature can be determined by measuring *in situ* temperatures with a sensor making direct contact with the object under observation (in this case the water inside the tote and the air above it). Thermal measurements derived by UAS infrared sensors are only relative measurements of temperature in the imaged objects. The observed temperature of the objects will vary according to the sensor parameters, imaging environment, and other external factors.

The apparent temperatures of all the objects in the field of view are captured; every pixel in the image corresponds to an apparent temperature measurement with a precision of up to 2 decimal Fahrenheit degrees. Figure 9 shows the range of apparent temperatures obtained during four UAS flights conducted 31 May-3 June 2022. The color palette ranges from 19 °F to 58.5 °F. Using this color palette, differences in contrast ratios can be observed (from blue (cool) to red (warm)). The purpose of this comparison is to show the difficulty of detecting some features (e.g., oil) when colder conditions are present because it reduces the contrast or range of temperatures within a given scene.

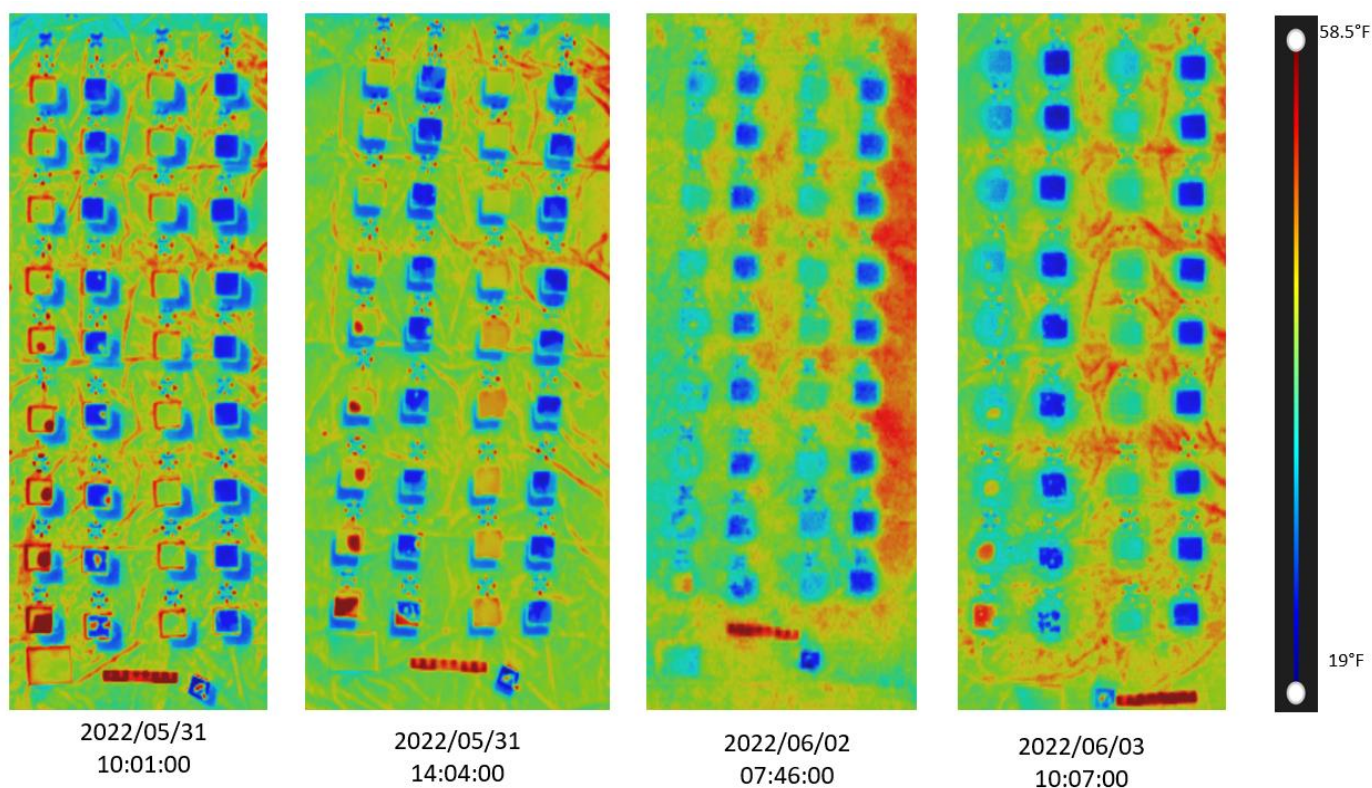


Figure 9. Array of totes captured for different weather conditions.

Warmer conditions during flights on 31 May made the oil more clearly distinguishable in the totes (red spots inside totes), while colder conditions during 2-3 June make the detection of the oil more difficult. The temperature variability of the oil was recorded for every case, and even on colder days (2-3 June), oil can be differentiated from non-oil features, but it was harder to identify thickness. Figure 9 demonstrated that temperature range must be adjusted during flight by the UAS pilot depending on the ambient conditions in order to make the targets (e.g., oil, ice) more evident.



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

One of the objectives of this experiment was to determine the detection limit of oil for thermal sensors as a function of weather conditions and UAS altitude. The team collected temperature data from specific features at different altitudes within a few minutes of each other so that weather and illumination conditions were similar.

Figure 10 shows the observations over the totes on 31 May at ~ 1000 hr with a target oil thickness of 2,000 μm with and without ice at different altitudes. As the UAS descended, apparent temperatures of the features on the infrared images tended to increase.

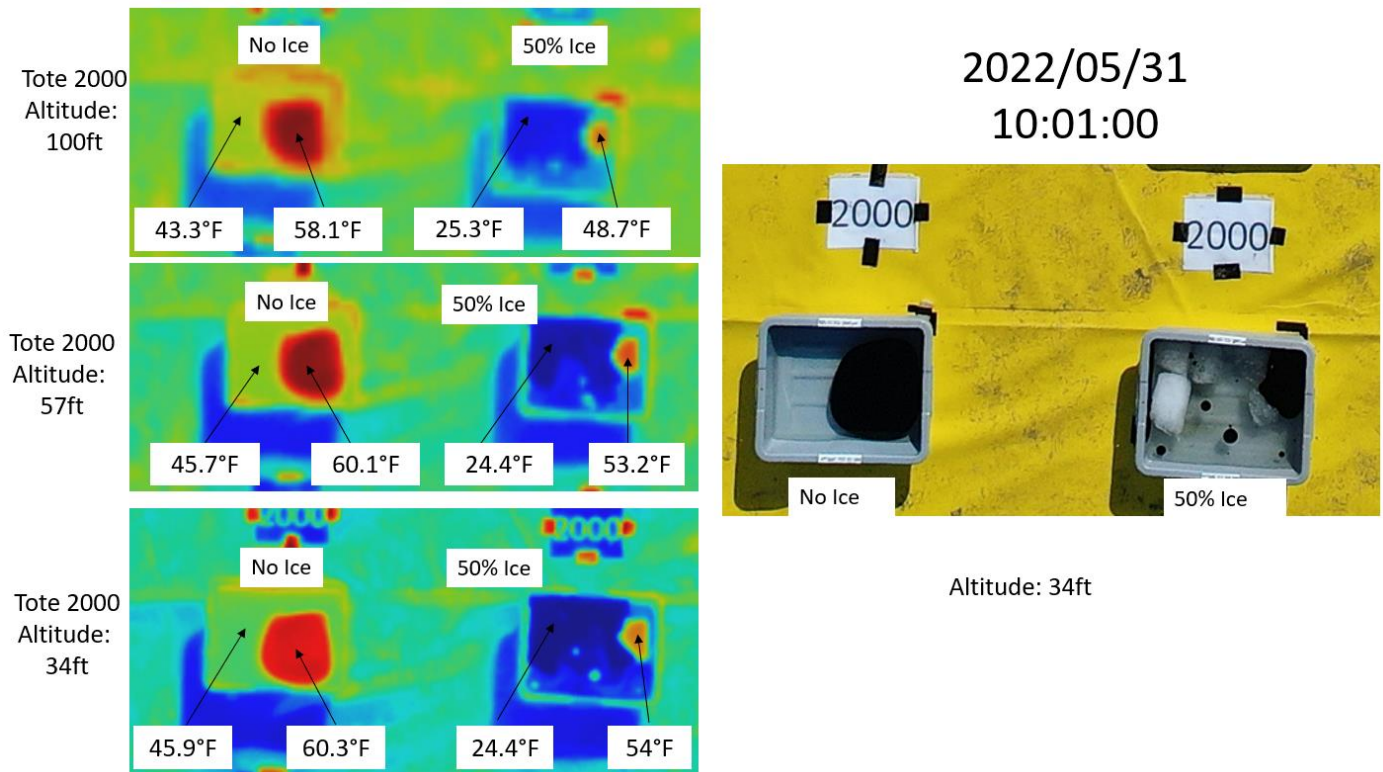


Figure 10. Array of totes captured for different weather conditions on 5/31/22.

The project team took apparent temperature measurements of oil, water, ice, at 34 ft, 57 ft, and 100 ft.

The recorded temperature for oil in the tote with ice increased from 48.7 °F to 54 °F as altitude decreased from 100 ft to 34 ft due to changes in scene acquisition geometry, underscoring that images should be interpreted as relative measurements. This increase in apparent temperature as a function of altitude could be due to spatial resolution.

In Figure 11, an oil target of 200 μm is shown at 34 ft, 57 ft, and 100 ft. The apparent temperature of the oil on the tote with no ice increased from 50.2 °F to 56.5 °F, as the UAS altitude decreased from 100 ft to 34 ft. Figure 12 shows a similar effect for totes with 750 μm of ANS.



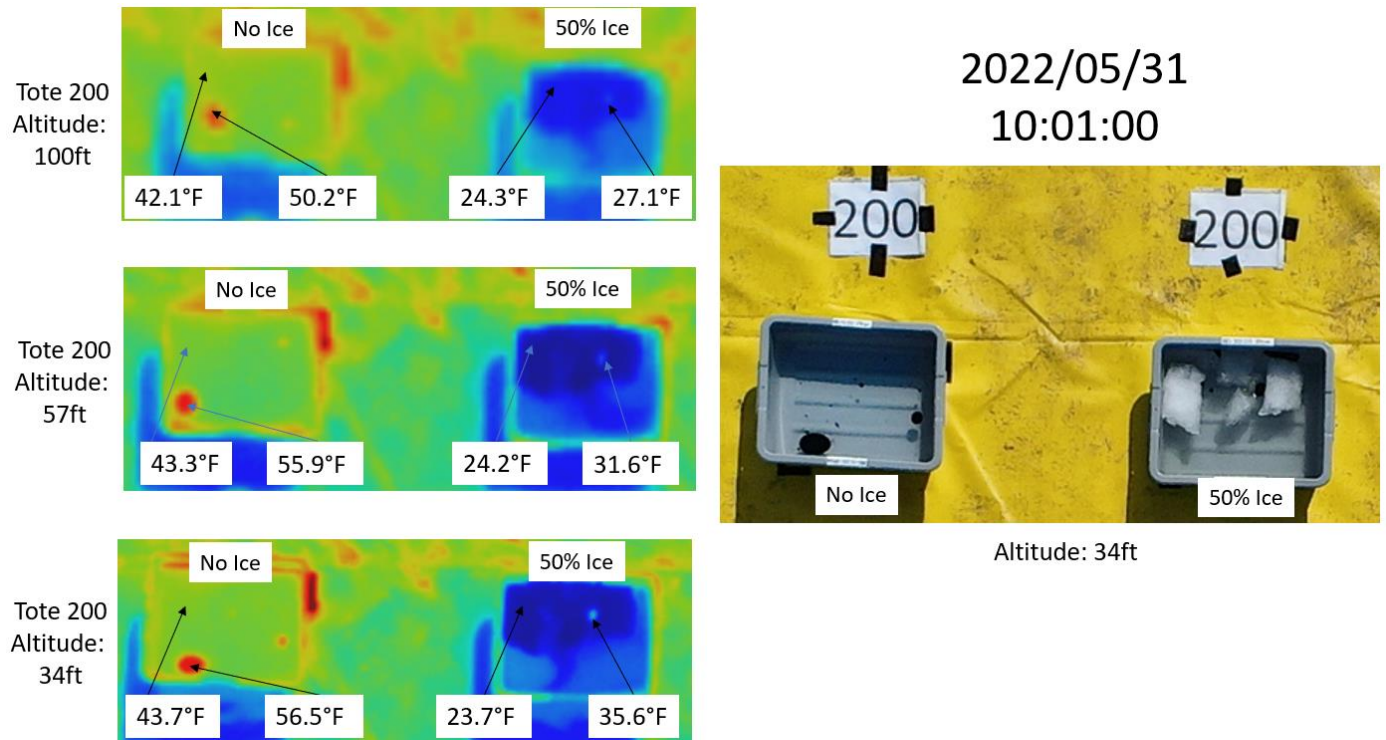


Figure 11. Images of totes with oil targets of 200 μm at different altitudes.

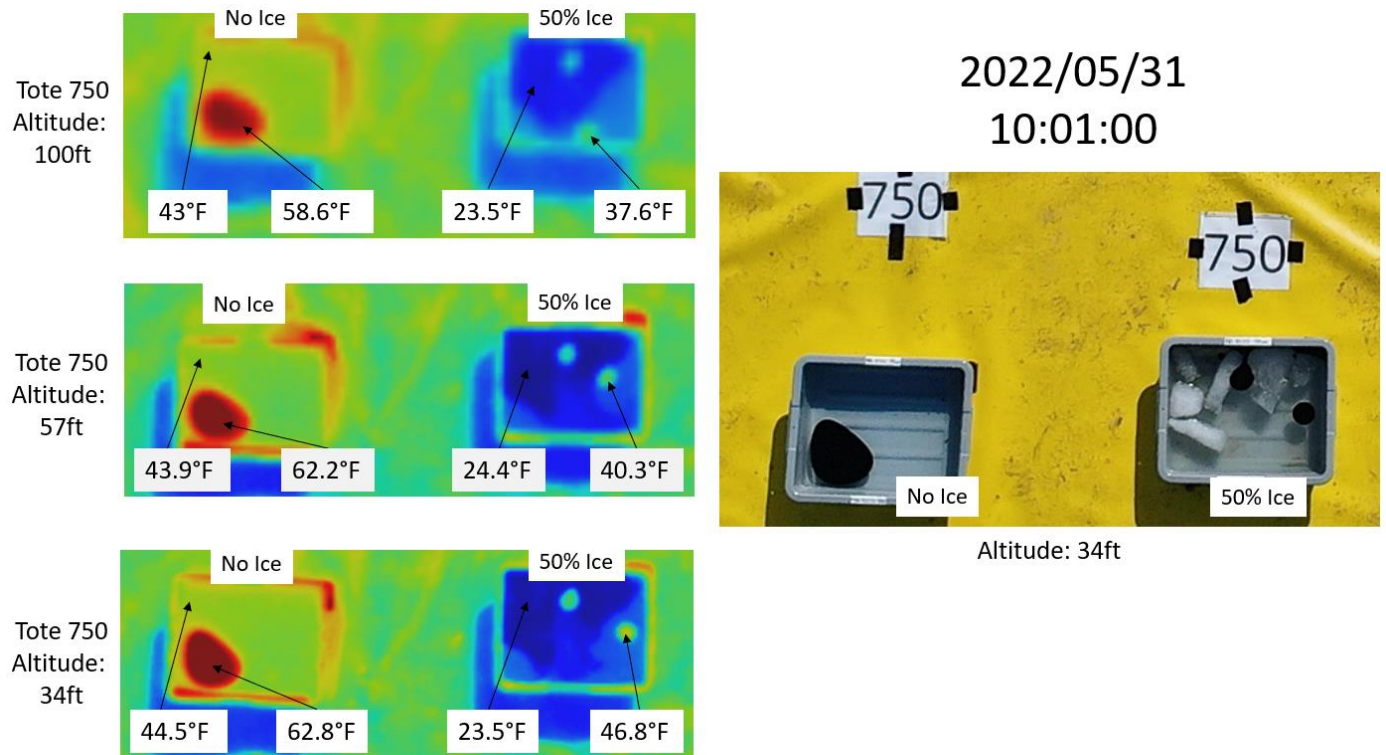


Figure 12. Images of totes with oil targets of 750 μm at different altitudes.

Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

Figure 10 to Figure 12 highlight the importance of staying at the same altitude when making relationship estimates between apparent temperature and oil thickness.

Observations of temperature variability were repeated under colder conditions. Figure 13 (from 2 June) can be compared with Figure 10 (from May 31), showing that the temperature of the oil ranged from 23.3 °F to 23.7 °F (minimum difference of 0.4 °F range) on a cold day (2 June), while the same target in warmer conditions (as shown on Figure 10) had a temperature range from 48.7 °F to 54 °F (5.3 °F range). Therefore, the temperature variability was much lower when colder conditions were present compared to warmer conditions (0.4 °F vs 5.3 °F). Although the range of temperature variability under colder conditions is much smaller, the increasing apparent temperature as the UAS descends is consistent with the previous cases.

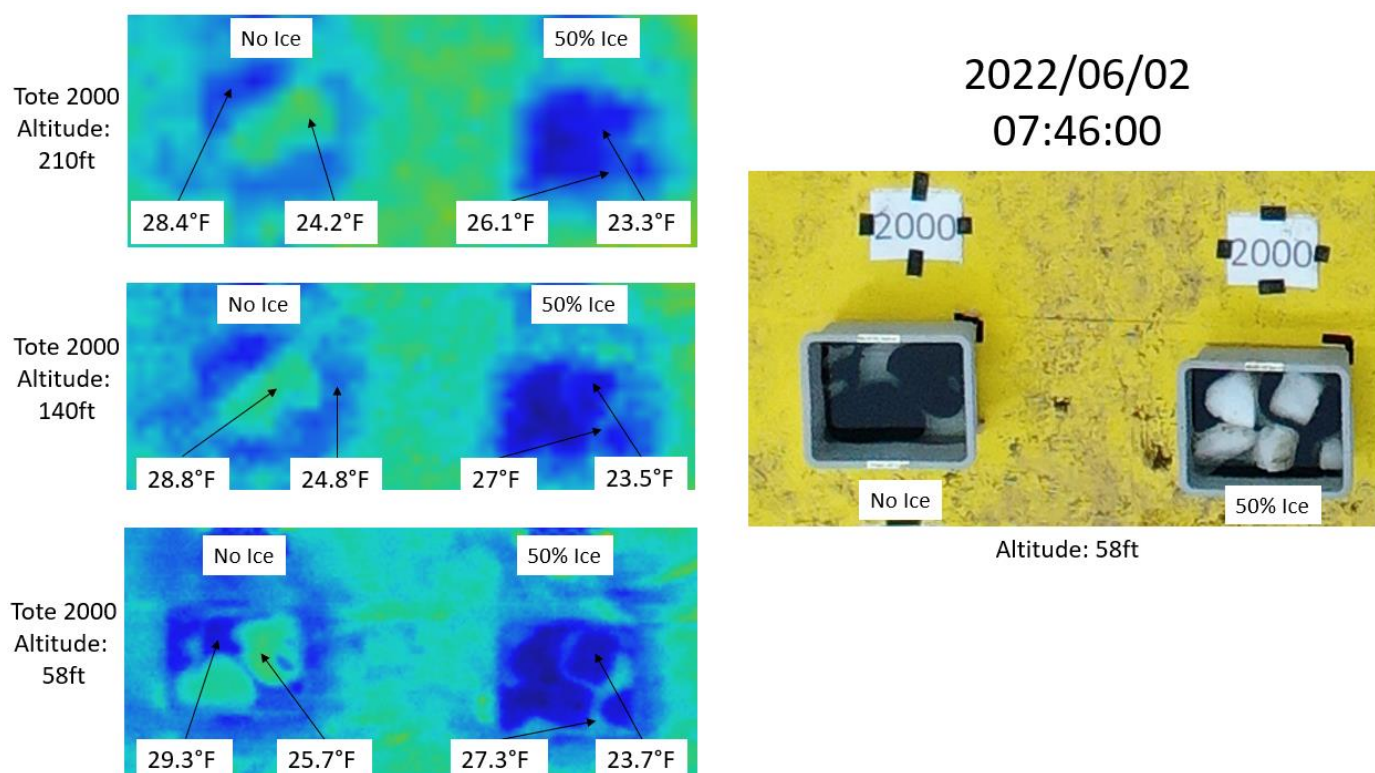


Figure 13. Apparent temperature observations of oil, ice, and water under colder conditions at different altitudes for the 2,000 μm totes on 6/2/22.

The CRREL experiments in 2021 (Garcia et al., 2022) generated graphs and algorithms that showed the relationship between ANS oil thickness, and the apparent temperature of the oil detected by the thermal sensor (Figure 14). The asymptotic relationship indicated that below $\sim 1,000 \mu\text{m}$, the apparent temperature changed noticeably as thickness increased. Above $\sim 1,000 \mu\text{m}$, the apparent temperature change was diminished (reaching an asymptote) making it difficult to distinguish changes in thickness as a function of apparent temperature.



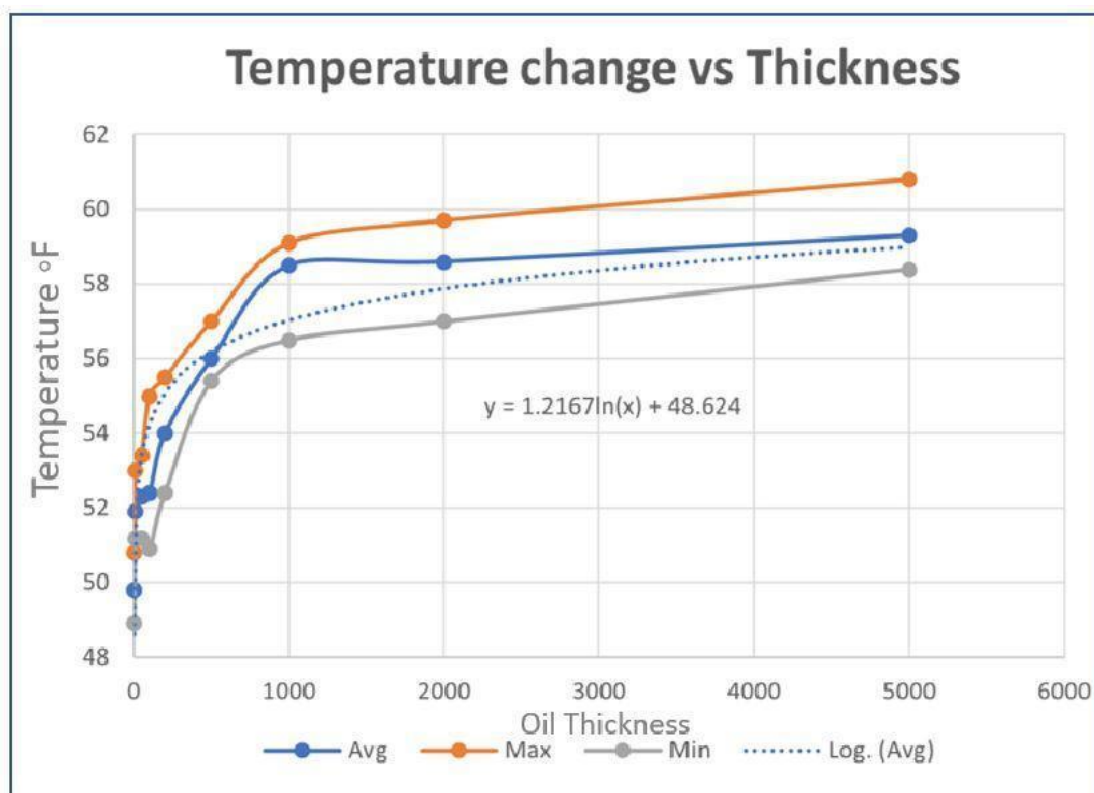


Figure 14. Data from the CRREL UAS experiments in March 2021 showing the apparent temperature change vs. oil thickness under overcast skies.

The Oliktok Point tests occurred on three days when the wind and weather permitted flying (5/31/22, 6/2/22, 6/3/22). Two drone flights per day occurred on 5/31 and 6/2; on 6/3 only one flight was possible. The thicknesses of the diesel and ANS were in the range desired (0, 50, 100, 200, 500, 750, 1,000, 2,000, 5,000 μm) on 6/2 and 6/3. On 5/31, the ANS thickness did not span the range because the oil did not spread properly in the 0% or 50% ice totes. Hence, thicknesses were all $>1,000 \mu\text{m}$ ranging up to $\sim 7,000 \mu\text{m}$ (Figure 15). While lines of best fit could be drawn, they did not follow the distinct hyperbolic shape observed at CRREL ($r^2 < 0.8$). Fortunately, the oil spread was more uniform on 6/2 and 6/3 in all the totes. There were no problems with spreading in the diesel totes on any of the days. In order to get more even measurements of apparent temperatures from the oil inside the totes, the project team attempted to produce evenly distributed thickness layers of oil, however, achieving even spreading of oil under cold conditions is challenging and is also a reflection of how oil would behave on the open water.

Apparent Temperature vs. Thickness of ANS Crude (0% Ice) on 5/31/22 at 10:01 and 14:07

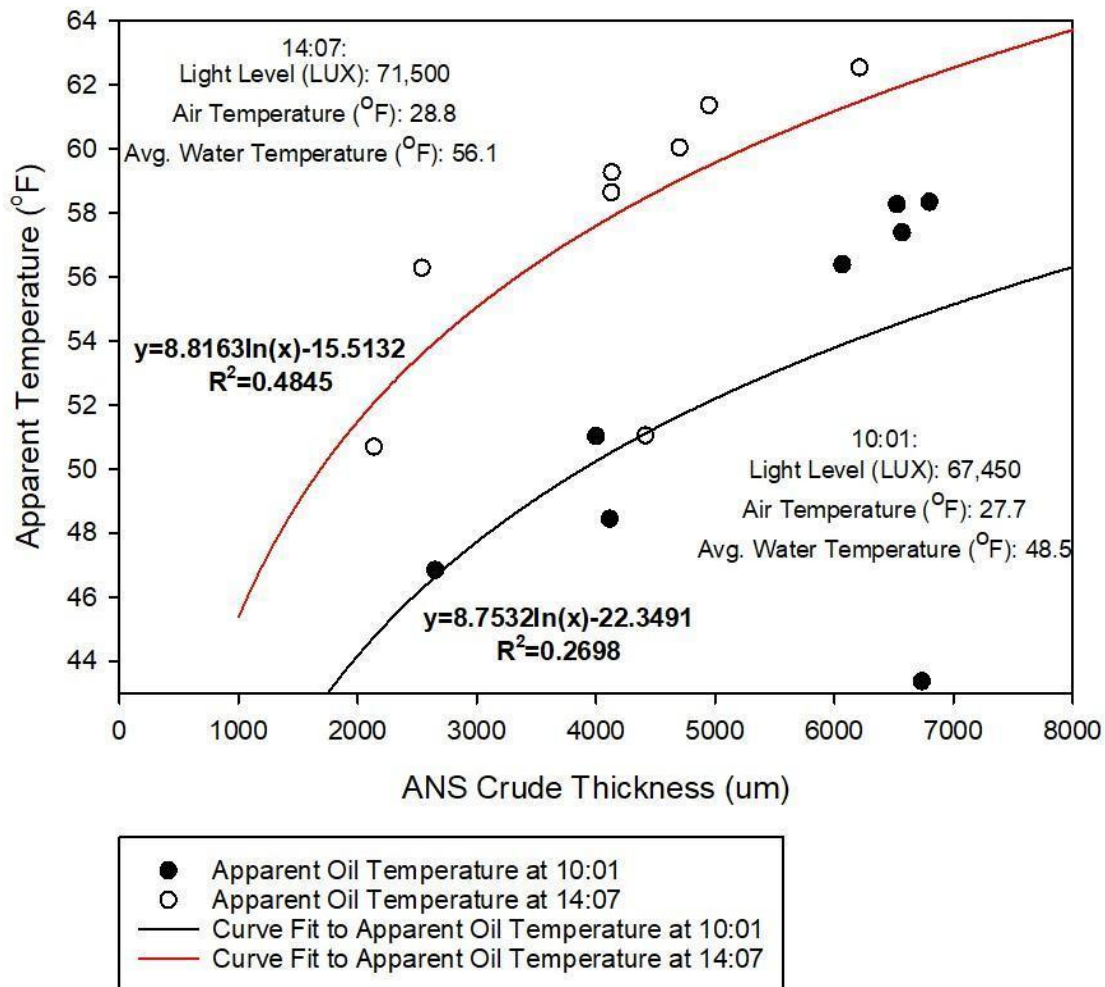


Figure 15. Apparent temperature vs. thickness of ANS crude with 0% ice on 5/31/22.

3.1.1.1 ANS 0% Ice

With the more-uniform spread of ANS on 6/2, the first flight of the day occurred in the morning. Both air and water temperatures were cold (20.1 °F and 36.6 °F, respectively) and light levels were ~23,700 lux. There was little change in apparent temperature with oil thickness and the asymptotic relationship was not observed (Figure 16).

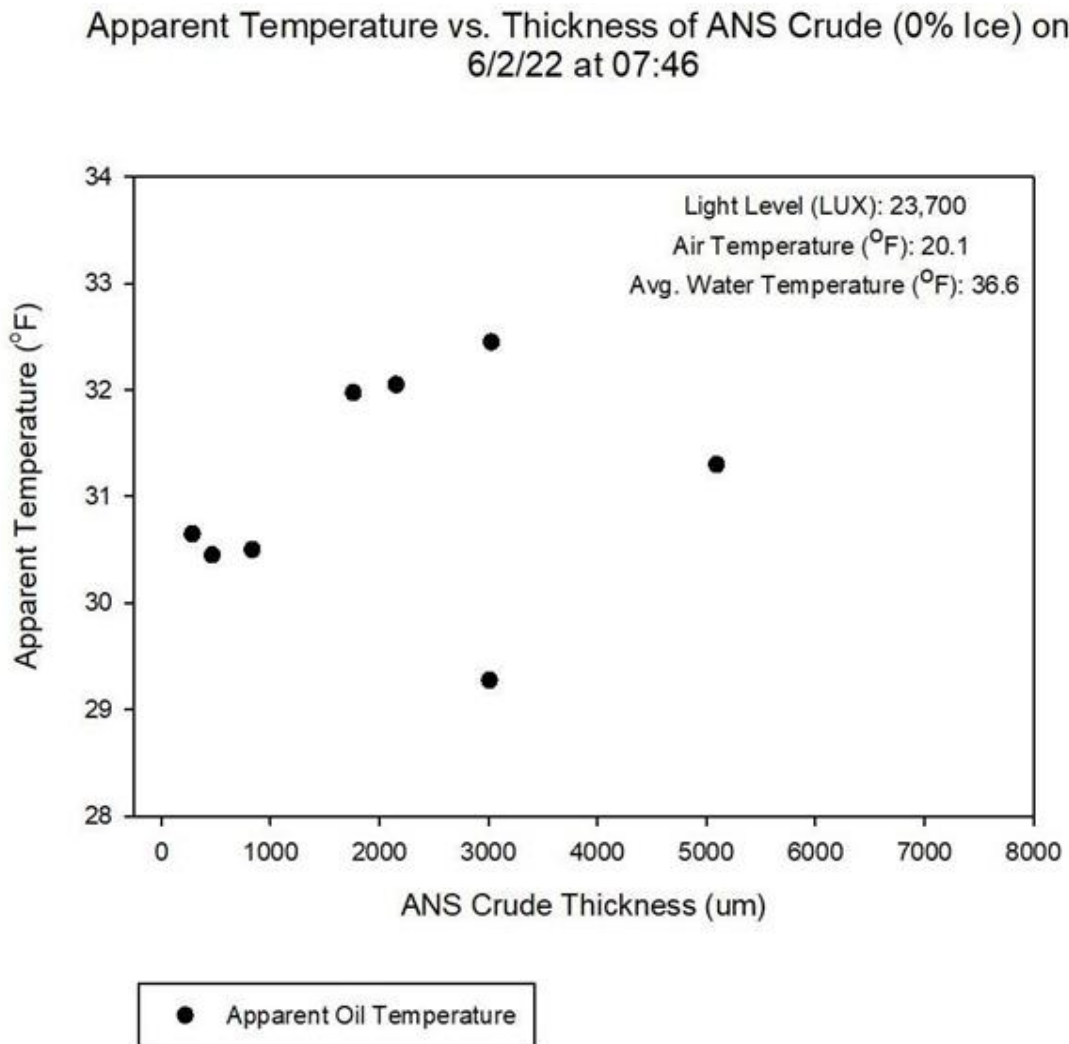


Figure 16. Apparent temperature vs. thickness of ANS crude with 0% ice on 6/2/22.

By the time of the second flight (1633 hr), the air temperature was still ~20 °F, but the light levels (37,050 lux) and the water temperature (54.3 °F) were considerably higher (Figure 17). An asymptotic relationship was observed ($r^2 = 0.8531$) that was similar to the one obtained at CRREL (Equation 2):

Equation 2. Lines of best fit for apparent temperature vs. ANS thickness at Oliktok and CRREL.

$$y = 1.2424 \ln(x) + 49.0286 \text{ (Oliktok Point)}$$

$$y = 1.2167 \ln(x) + 48.624 \text{ (CRREL)}$$

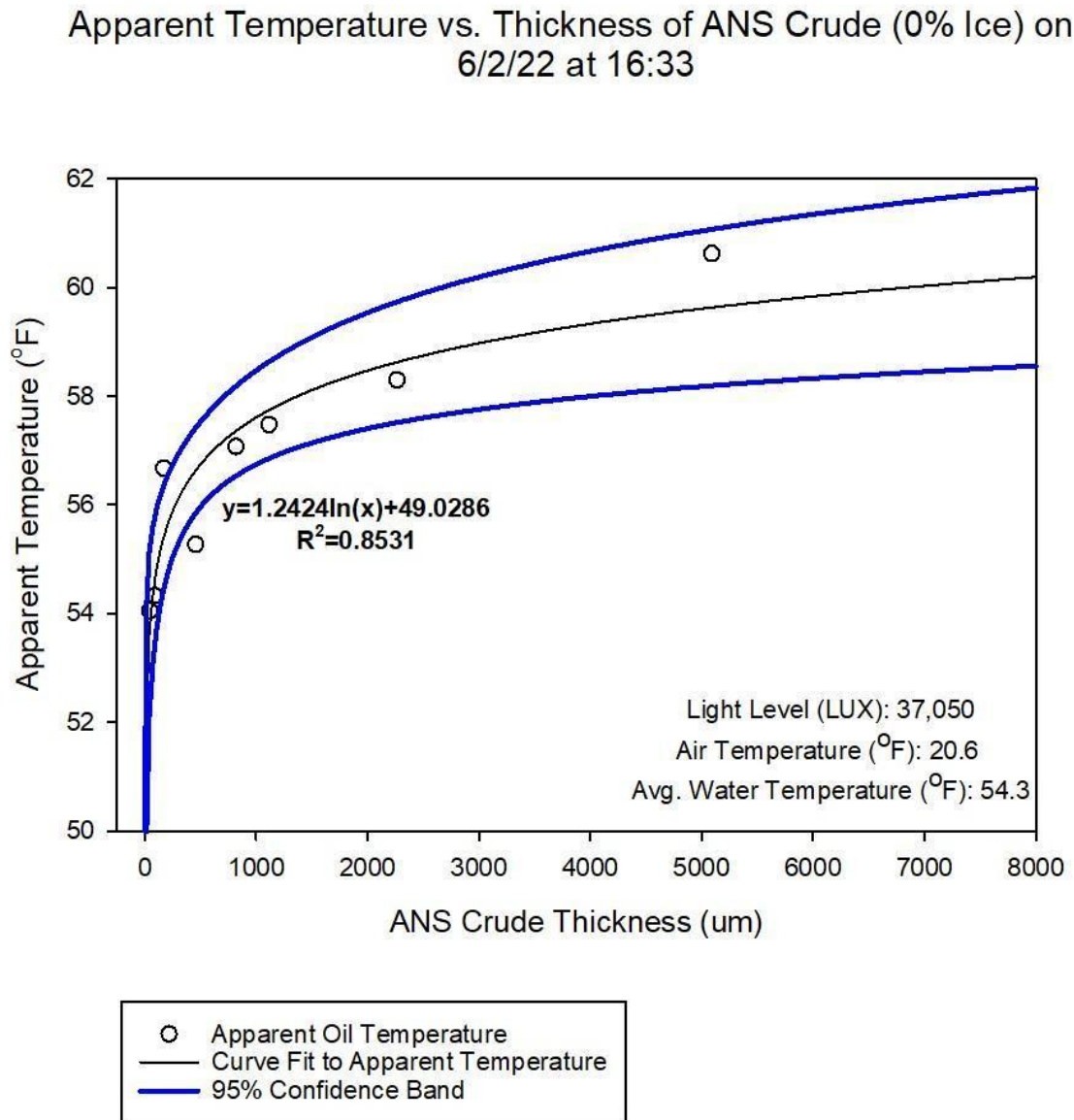


Figure 17. Apparent temperature vs. thickness of ANS crude with 0% ice on 6/2/22 at 1633 hr.

The similar apparent temperatures of the ANS and of the equations for Oliktok and CRREL were very encouraging. However, the team knew from the New Hampshire experiments that water temperature and lux levels play a major role in the apparent temperature and thickness relationship. Unfortunately, lux measurements and water temperature were not continuously monitored at CRREL, so the conditions causing the similarity of the equations could not be determined.

While the 5/31 thicknesses of the ANS in the 0% ice totes were not across the desired range, the data were still valid and those from 1407 hr were plotted with those generated on 6/2 at 1633 hr to determine if they were within the 95% confidence bands (Figure 18). Some of the points were within the bands, but three were markedly lower. The conditions for the two flights were different: 71,500 vs 37,050 lux and air temperature 28.8 °F vs 20.6 °F, but based on the NH tote results, air temperature does not have a marked influence on the apparent temperature results. The water temperatures on 5/31 and 6/2 were similar (56.1 °F vs 54.3 °F,

respectively). The difference in lux or the variation in the oil distribution in the 5/31 totes may have accounted for the differences observed.

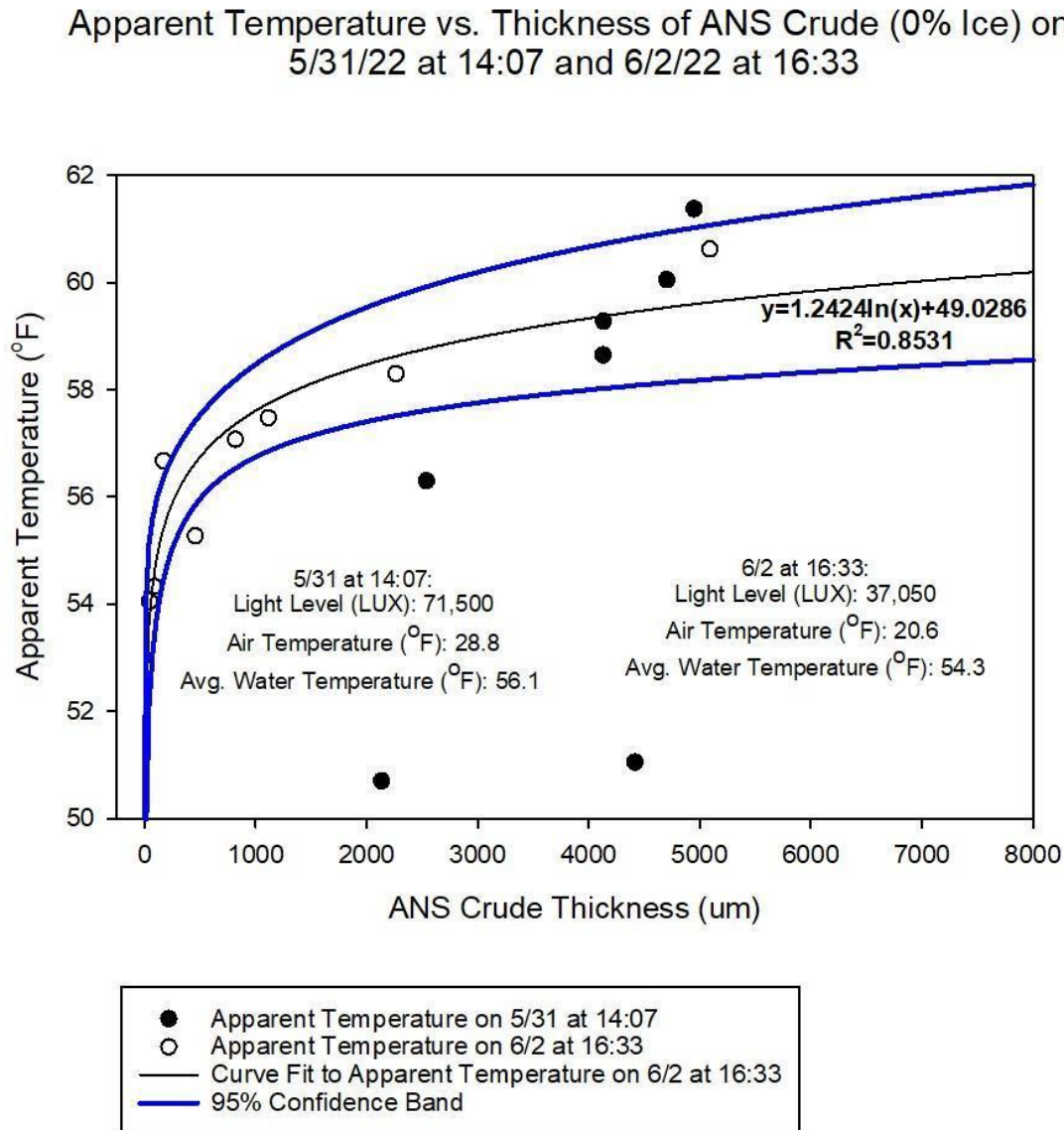


Figure 18. Apparent temperature vs. thickness of ANS crude with 0% ice on 5/31/22 and 6/2/22.

Water temperature played an important role in determining the exact shape and position of the curve as demonstrated by the difference in the equations. For example, the flight on 6/3 occurred at 1007 hr. The lux (32,900) was lower than for the 6/2 afternoon flight (37,050) and the water temperature was much lower (39.2 °F vs 54.3 °F, respectively). While the relationship was hyperbolic (Figure 19), the curve was shifted downward with the apparent temperatures in the range of ~29 °F to 36 °F (vs. ~54 °F to 59 °F for 6/2).

$$y = 1.8049 \ln(x) + 21.4985 \text{ [6/3 at 10:07]}$$

$$y = 1.2424 \ln(x) + 49.0286 \text{ [6/2 at 16:33]}$$



Apparent Temperature vs. Target Thickness of ANS Crude Oil (0% Ice)
on 6/3/22 at 10:07

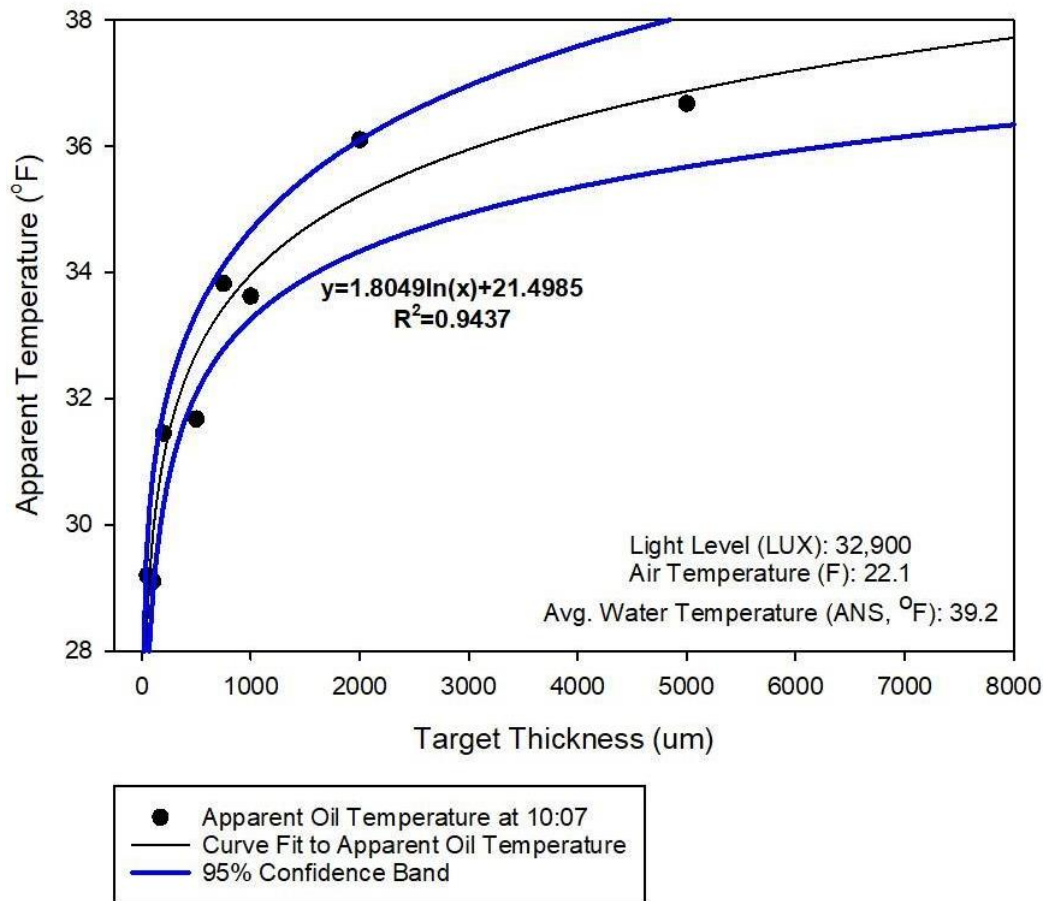


Figure 19. Apparent temperature vs. target thickness of ANS crude oil with 0% ice on 6/3/33.

Table 1 summarizes the impact of light levels, and water and air temperatures on the relationships.

Table 1. ANS 0% ice experimental conditions.

Date	Times (h)	Air Temp (°F)	Water Temp (°F)	LUX	App Temp Range (°F)	Equation
6/2	0746	20.1	36.6	23,700	29-32	y = not significant
6/2	1633	20.6	54.3	37,050	54-60	
6/3	1007	22.1	39.2	32,900	29-36	

These data indicated that water temperature and, to a lesser extent light levels, were controlling. At low light in the early morning thermal relationships with oil thickness were not distinct even when <1,000 µm. Once light levels were higher, in the range ≥30,000 lux, the water temperature appeared to influence hyperbolic relationships impacting the coefficients of the equation (i.e., the vertical position and shape of the curves) (Figure 20).

Apparent Temperature vs. ANS Crude Oil Thickness (0% Ice) on 6/2/22 at 16:33 and Target Thickness on 6/3/22 at 10:07

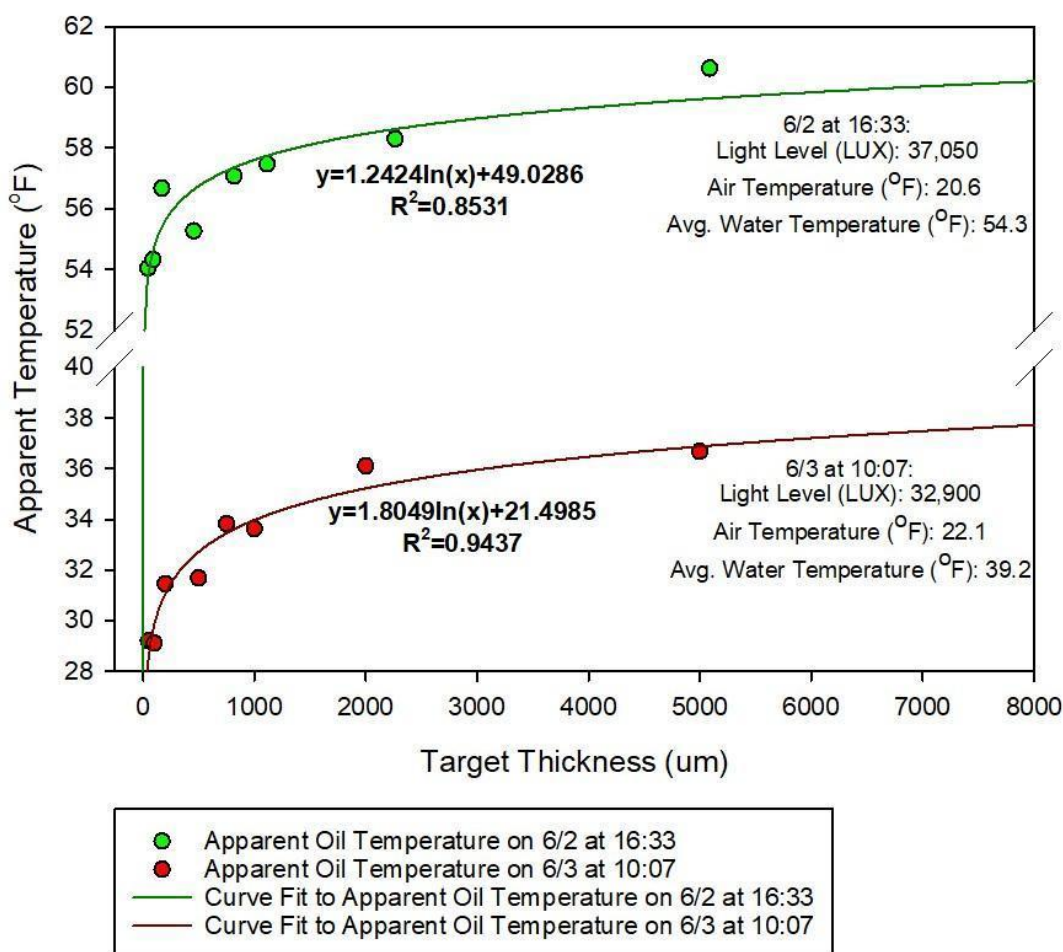


Figure 20. Apparent temperature vs. ANS crude oil thickness with 0% ice on 6/2 and 6/3.

Typical water temperature in the near-coastal Arctic will change with warming climate and melting ice. “Warm” water temperatures (~50° F) can also occur in coastal environments during low tide when shallow water may warm significantly. This is consistent with previous findings, as noted in the CRREL report (Garcia et al., 2022):

“...each time a mission is conducted in the Arctic, the thermal imagery (i.e., apparent temperature) must be calibrated on-site to obtain reliable oil thicknesses.”

It may be possible to generate a “family” of curves relating the water temperature to the apparent temperature observed for specific oil thicknesses which could be used to help estimate oil thicknesses, not only for Arctic conditions, but also for temperate waters and operations under low visibility conditions (e.g., under dense fog or at night).

3.1.1.2 ANS 50% Ice

At CRREL, the ice ranged from 0% to 75%, and the oil thicknesses were increased for each percent ice condition over time. The team generated a graph that related percent ice cover to apparent oil temperature using the 1,000 μm data (Figure 21). The flight occurred at 1409 hr local time under overcast skies (water temperature and light level not measured). For the non-emulsified (fresh) ANS, the apparent oil temperature decreased as the percent ice increased with the most dramatic effects from 0% to 25% cover. Using this relationship, the 50% ice cover at Oliktok Point was expected have temperature of $\sim 40^\circ\text{F}$ for 1,000 μm . For the 50% ice totes, the apparent temperature for 1,000 μm was not always 30°F (Figure 22 and Figure 23). This was not surprising as the 0% ice results indicated that water temperature and, to a lesser extent light levels, impact apparent temperatures.

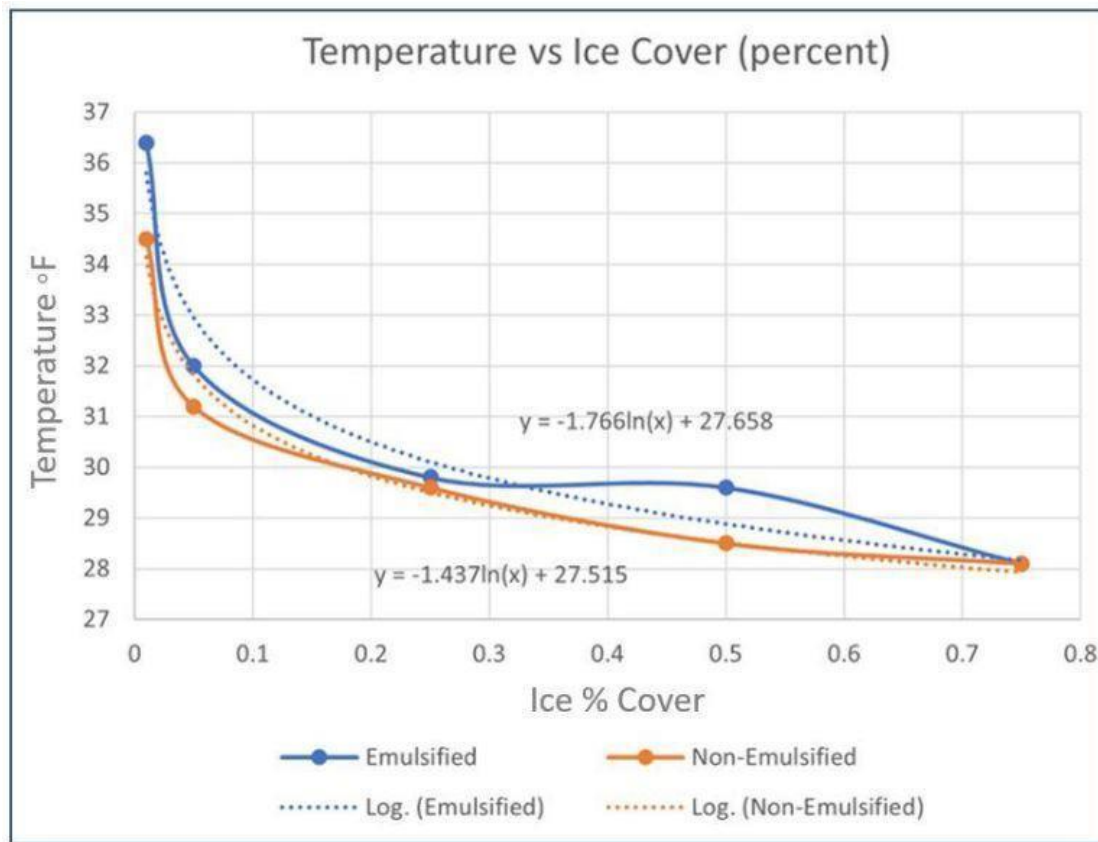


Figure 21. Relationship developed from the CRREL data of apparent temperature vs. ice cover.

Apparent Temperature vs. Thickness of ANS Crude (50% Ice) on
6/2/22 at 07:46 and 16:33

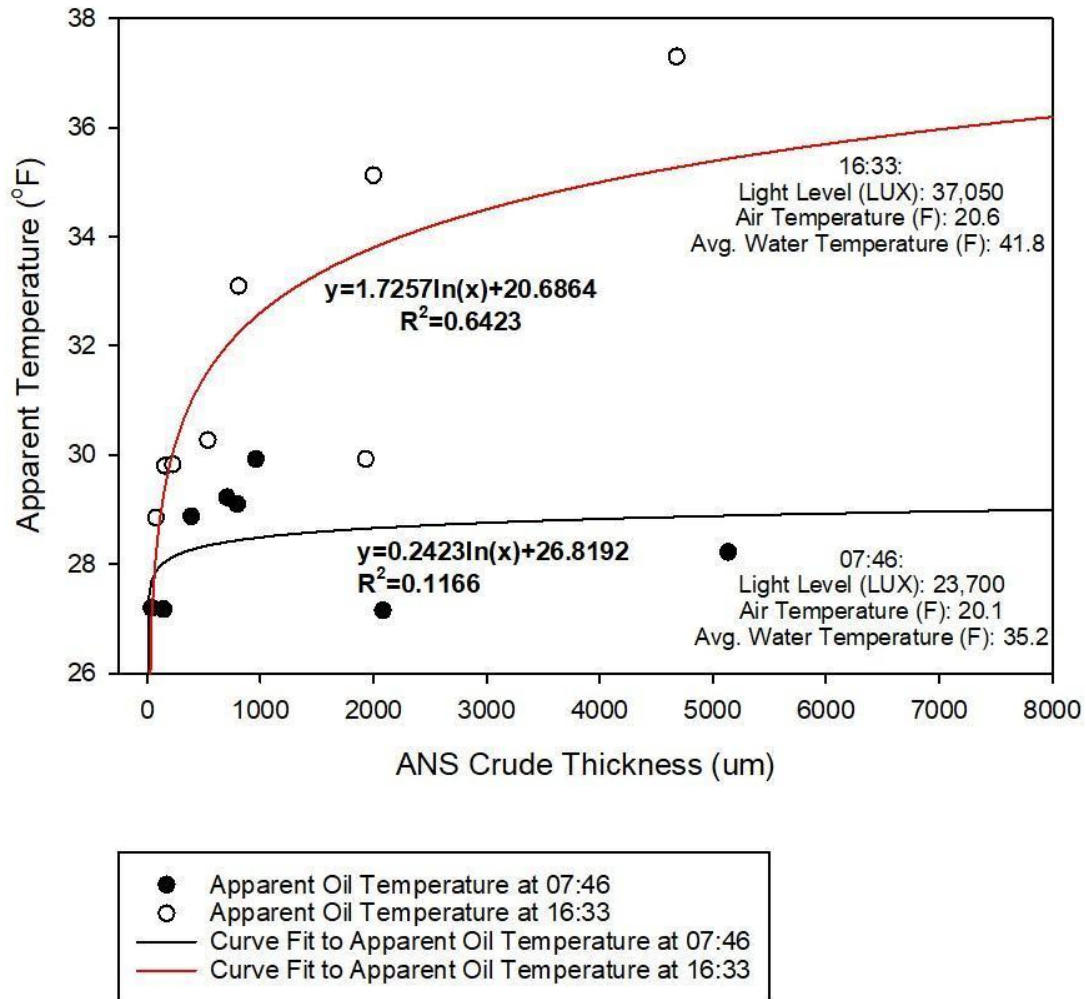


Figure 22. Apparent temperature vs. thickness of ANS crude with 50% ice on 6/2/22.

Apparent Temperature vs. Thickness of ANS Crude (0% and 50% Ice) on 6/2/22 16:33

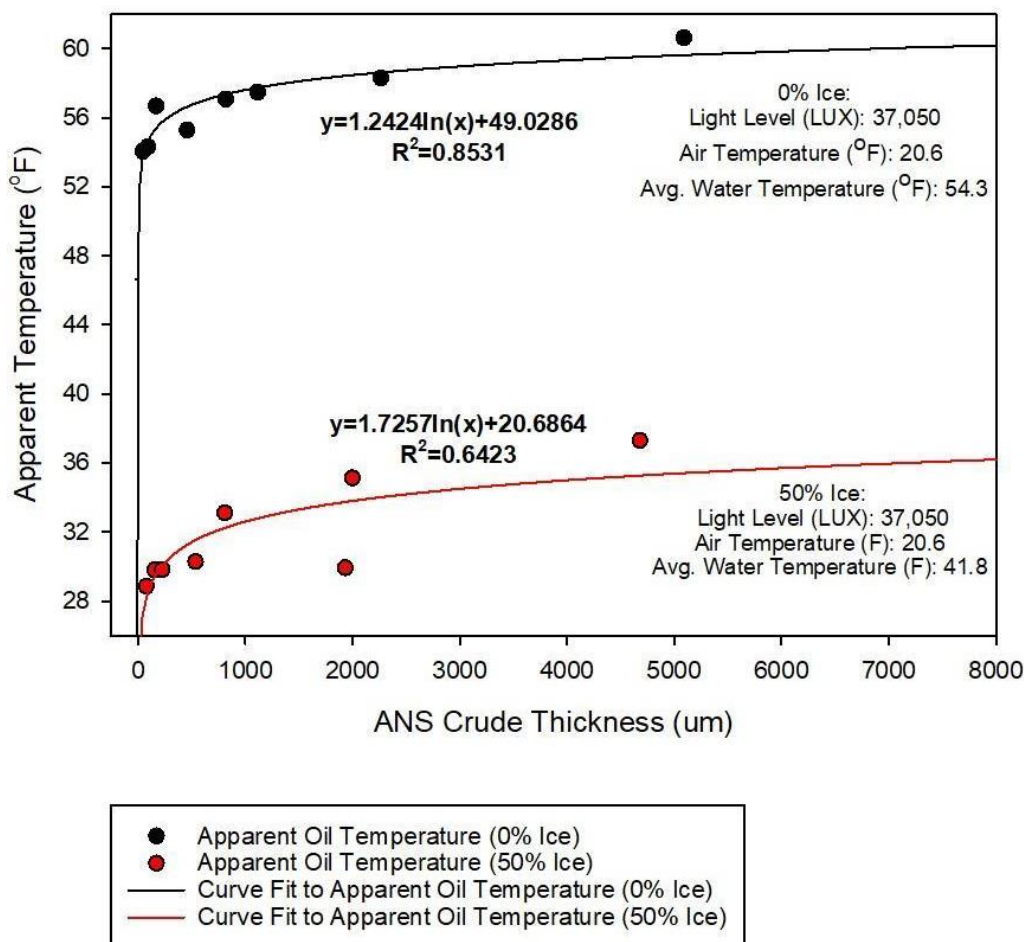


Figure 23. Apparent temperature vs. thickness of ANS crude (0% and 50% Ice) on 6/2/22.

The relationship for 50% ice on 6/2 at the different times of day (Figure 22), again showed that at low light, the ability to detect changes in apparent temperature with thickness is difficult. By the afternoon, with more light and greater water temperature (41.8 °F), the hyperbolic relationship was stronger, though it was at a somewhat lower apparent temperature range (27 °F to 37 °F) for the corresponding condition with 0% in the same day (Figure 23). The 50% ice depressed the water and apparent temperatures vs. the 0% ice (apparent temperature ~54 °F to 60 °F; 54.3 °F). There is also one point in the data (thickness ~2,000 μm, apparent temperature ~29.5 °F in Figure 22) that affects the shape of the curve and appears to be “atypical”. It is possible that this apparent temperature was influenced by the proximity of the ice to the point of measurement or that the oil was not uniformly distributed in the tote (i.e., the thickness <2,000 μm at that location).

The 50% ice curve for ANS on 6/3 also showed a lower curve as compared with the 0% ice data for the same day and time (Figure 24). Similar to the 6/2 data, the overall water temperature and apparent temperature were depressed in the 50% ice totes.



Apparent Temperature vs. Target Thickness of ANS Crude Oil (0% Ice) and Thickness of ANS Crude (50% Ice) on 6/3/22 at 10:07

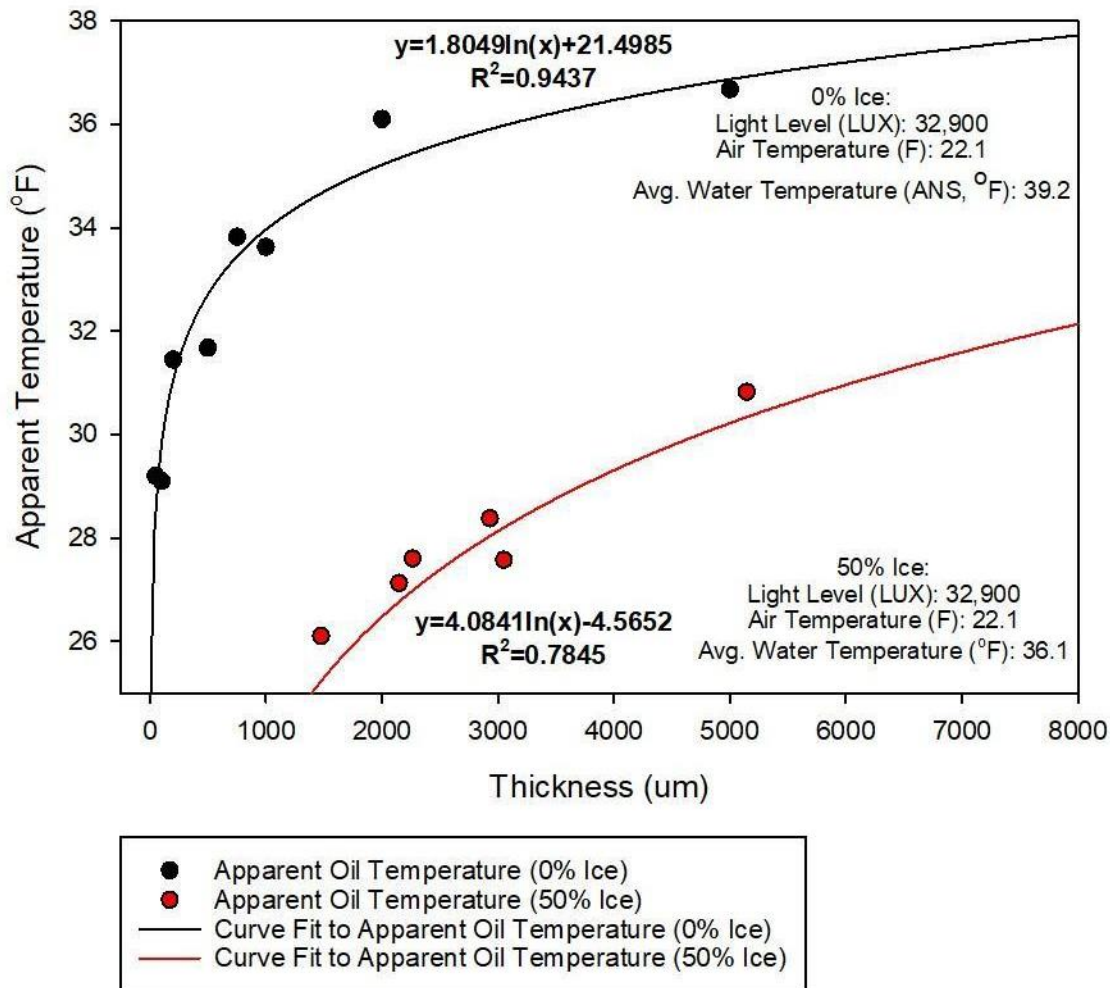


Figure 24. Apparent temperature vs. target thickness of ANS crude oil in 0% and 50% ice on 6/3/22.

Overall, it appeared that at 50% ice cover, the thermal sensors could detect changes in oil thickness given sufficient light, but the strength of this relationship needs to be confirmed in future experiments.

3.1.1.3 Marine Diesel 0% Ice

The diesel spread uniformly in all totes and at both ice conditions. The totes on 5/31 at 1001 hr and 1407 hr, at very high light levels (67,450 and 71,500 lux, respectively), had different water temperatures (51.3 °F vs 64.5 °F) and apparent temperature ranges (38 – 39 °F vs. 46 – 49 °F) (Figure 25 and Figure 26). The curves, however, were not the hyperbolic relationships observed for the ANS (Figure 27). This was probably because the diesel did not warm as much because it was clear/yellow, not black like ANS. The results from 6/2 were similar (Figure 28) even though the light levels were higher on 5/31. The water temperatures, as with the ANS, appeared to be the strongest indicator of the apparent temperature of the diesel (Figure 29).

Apparent Diesel Temperature vs. Marine Diesel Thickness (0% Ice) on
5/31/22 at 10:01

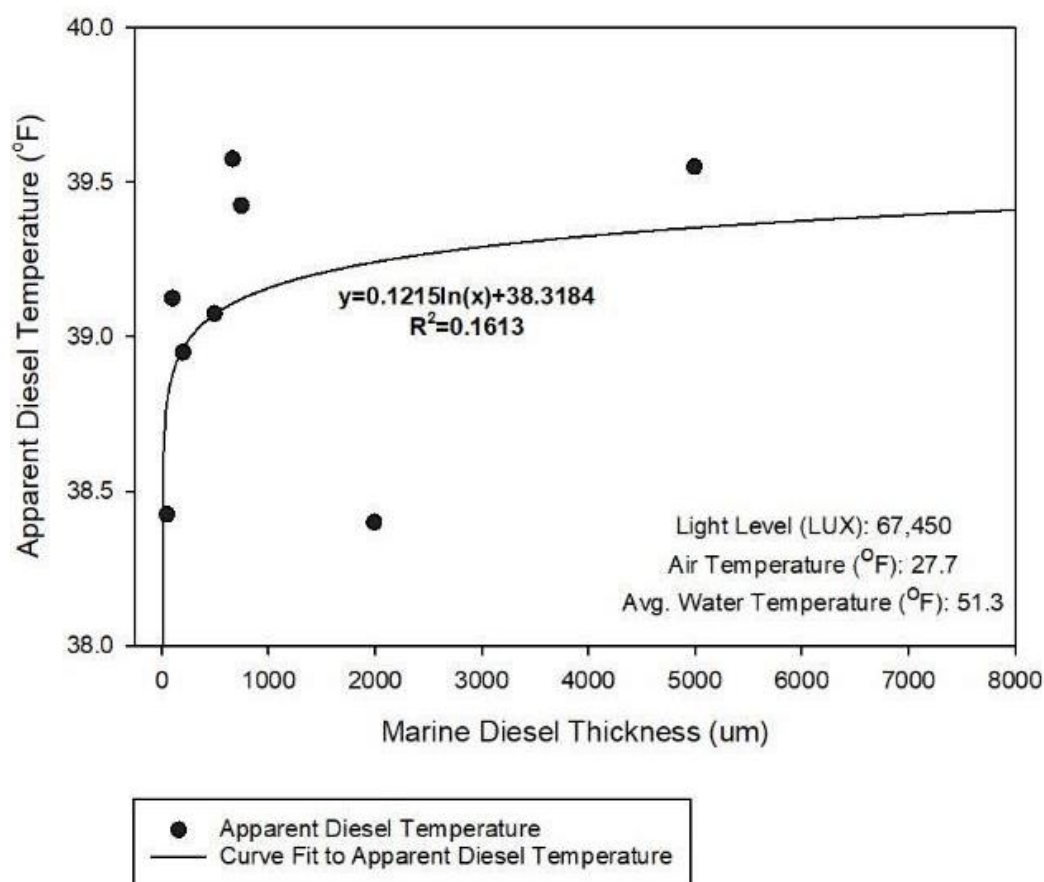


Figure 25. Apparent diesel temperature vs. marine diesel thickness in 0% ice on 5/31/22 at 1001 hr.

Apparent Diesel Temperature vs. Marine Diesel Thickness (0% Ice) on
5/31/22 at 14:07

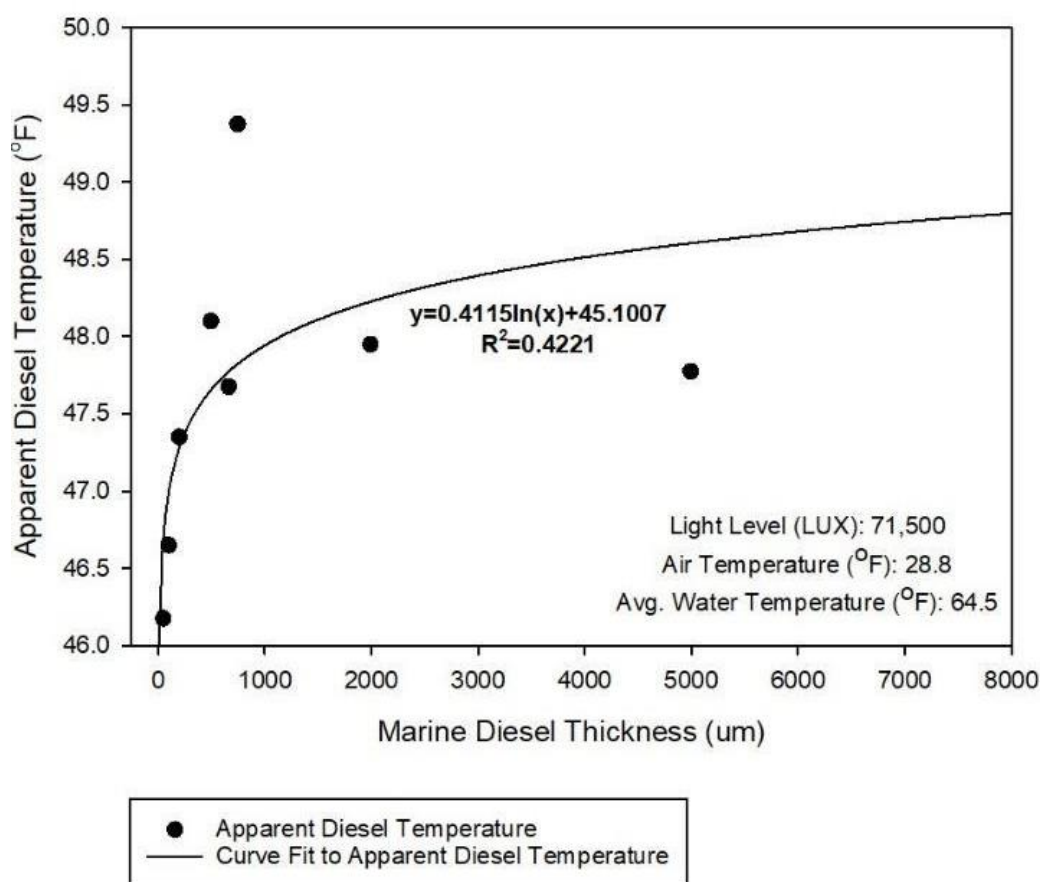


Figure 26. Apparent diesel temperature vs. marine diesel thickness in 0% ice on 5/31/22 at 1407 hr.

Apparent Temperature vs. Thickness of ANS and Marine Diesel (0% Ice) on 5/31/22 at 10:01 and 14:07 and 6/2/22 at 16:33

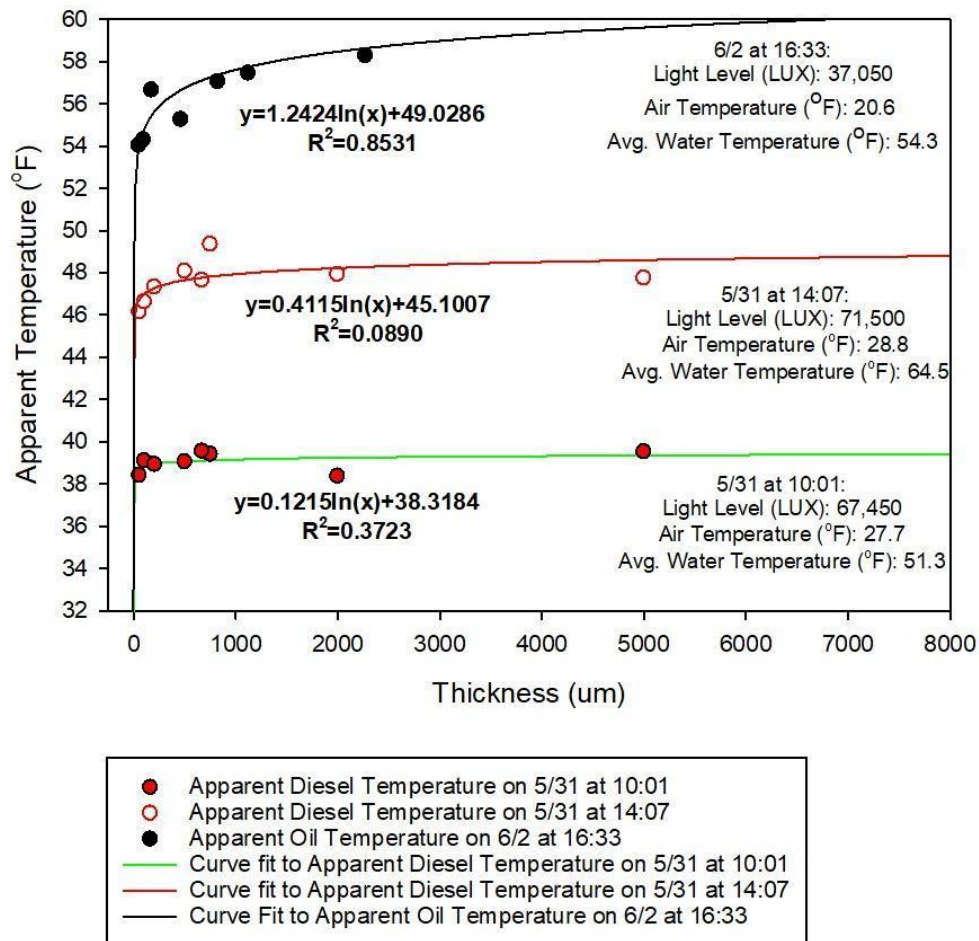


Figure 27. Apparent temperature vs. thickness of ANS at 0% ice on 6/2/22 at 16:33 and marine diesel at 0% ice on 5/31/22 at 1001 and 1407 hr.

Apparent Temperature vs. Thickness of ANS Crude (0% Ice) and Target Thickness of Marine Diesel (0% Ice) on 6/2/22 at 16:33

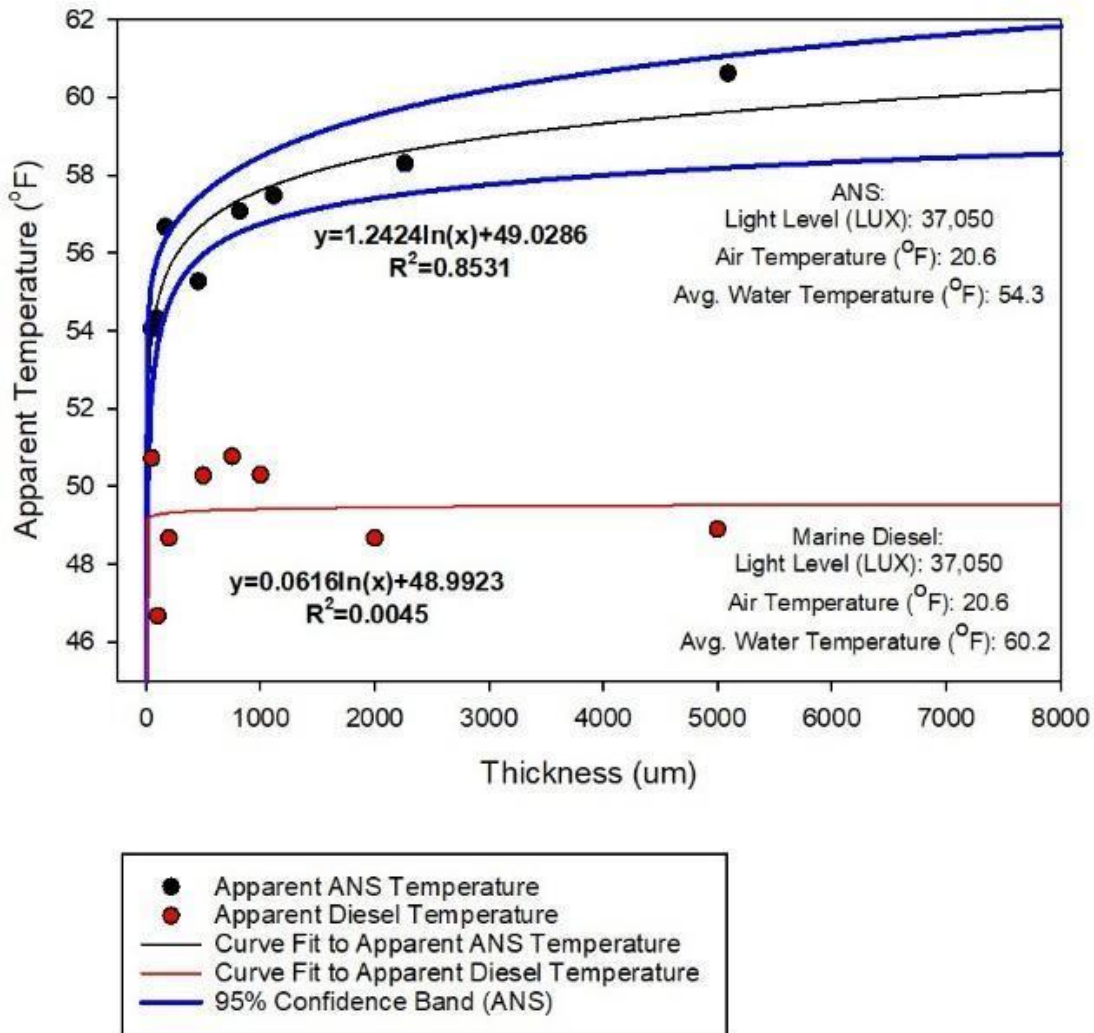


Figure 28. Apparent temperature vs. thickness of ANS crude and marine diesel at 0% ice on 6/2/22 at 1633 hr.

Apparent Temperature vs. Thickness of Marine Diesel (0% Ice) on
5/31/22 at 10:01 and 14:07 and 6/2/22 at 07:46 and 16:33

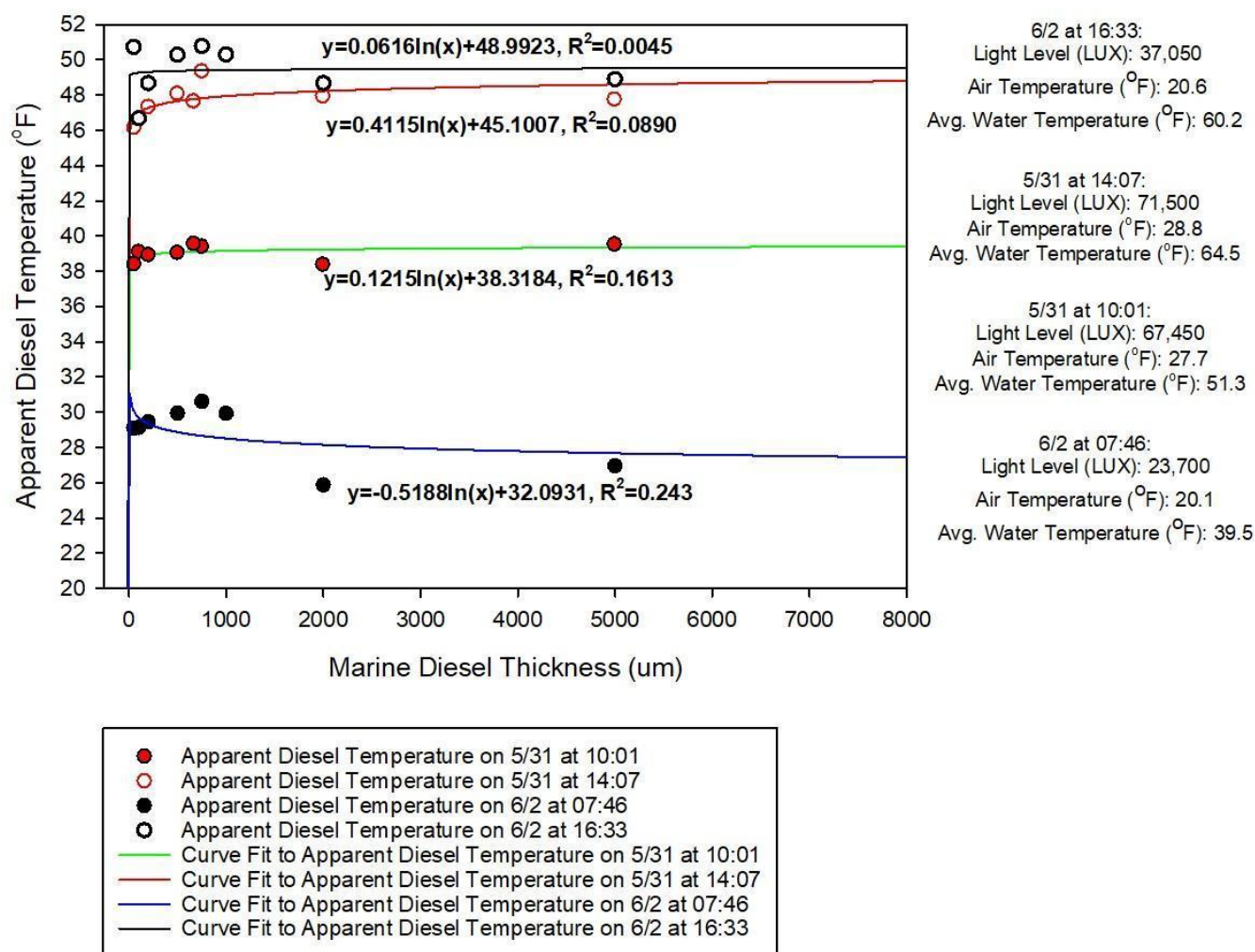


Figure 29. Apparent temperature vs. thickness of marine diesel at 0% ice on 5/31/22 and 6/2/22.

3.1.1.4 Marine Diesel 50% Ice

As with ANS, the presence of ice decreased the apparent temperatures for the same dates and times (i.e., same lux) (Figure 30, Figure 31, and Figure 32). The hyperbolic relationship was also not significant ($r^2 < 0.6$) indicating that the change in apparent temperature is not positively unrelated with thickness over the entire range tested.

These data indicated that detection of marine diesel thickness may be difficult in Arctic conditions regardless of the presence of ice. Further controlled testing is needed to validate these results.



Apparent Temperature vs. Thickness of Marine Diesel (50% Ice) on
5/31/22 at 10:01 and 14:07 and 6/2/22 at 16:33

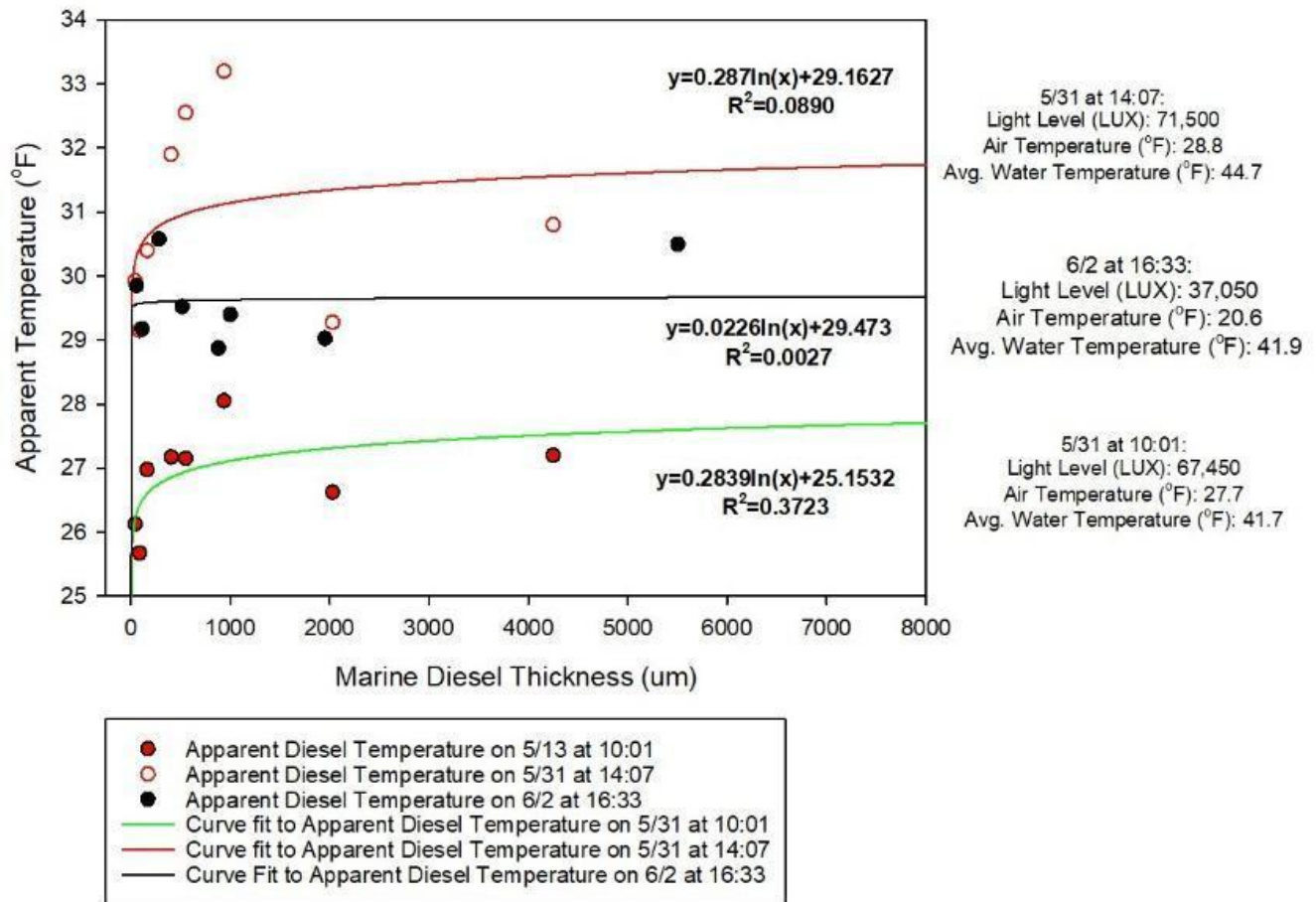


Figure 30. Apparent temperature vs. thickness of marine diesel at 50% ice on 5/31/22 and 6/2/22.

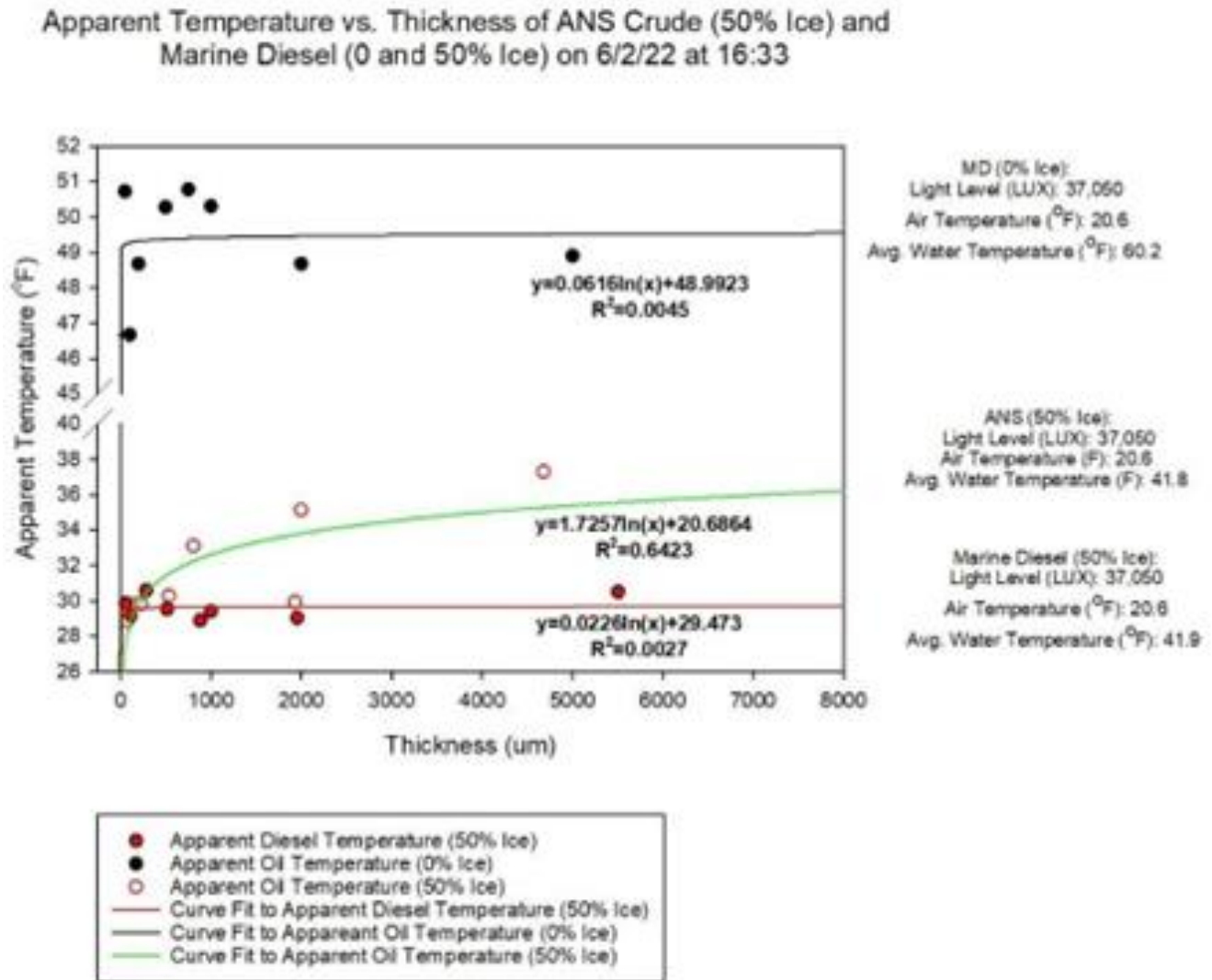


Figure 31. Apparent temperature vs. thickness of ANS crude at 50% ice and marine diesel at 0 and 50% ice on 6/2/22.

Apparent Temperature vs. Thickness of ANS Crude Oil and Marine Diesel (0 and 50% Ice) on 6/3/22 at 10:07

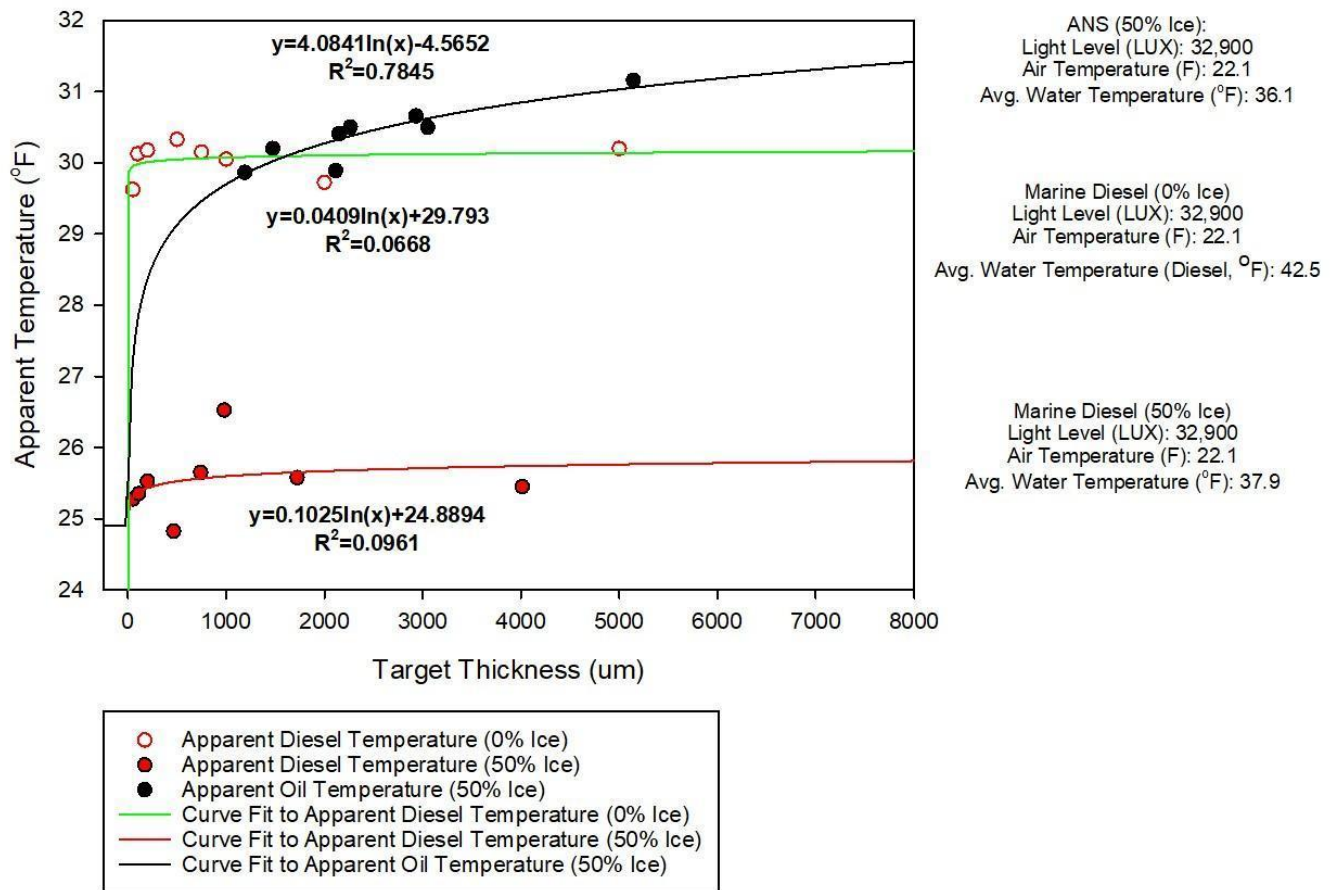


Figure 32. Apparent temperature vs. thickness of ANS crude oil at 50% ice and marine diesel at 0 and 50% ice on 6/3/22.

3.1.1.5 Uncertainty

One of the objectives of the research was to characterize the uncertainty bounds associated with surface oil thickness estimates as a function of sun angle (not measured at Oliktok Point) and intensity (lux) and ambient temperature. The data from the March 2022 New Hampshire experiments indicated that air temperature was not a factor in determining the sensor's ability to determine thickness of ANS. [Note: The sensor's ability to determine the thickness of diesel was limited and will not be discussed in this section.] The uncertainty bounds are plotted on Figure 17, Figure 18, and Figure 19. While these bounds suggested that there is noise within the data, they and the relatively high r^2 values indicated that thermal measurements, especially at 0% ice will allow responders to have a general sense of the thickness of the ANS. This is also observed at 50% ice (e.g., Figure 33), albeit with a wider confidence interval.

Apparent Temperature vs. Thickness of ANS Crude (50% Ice) on 6/2/22 at 16:33

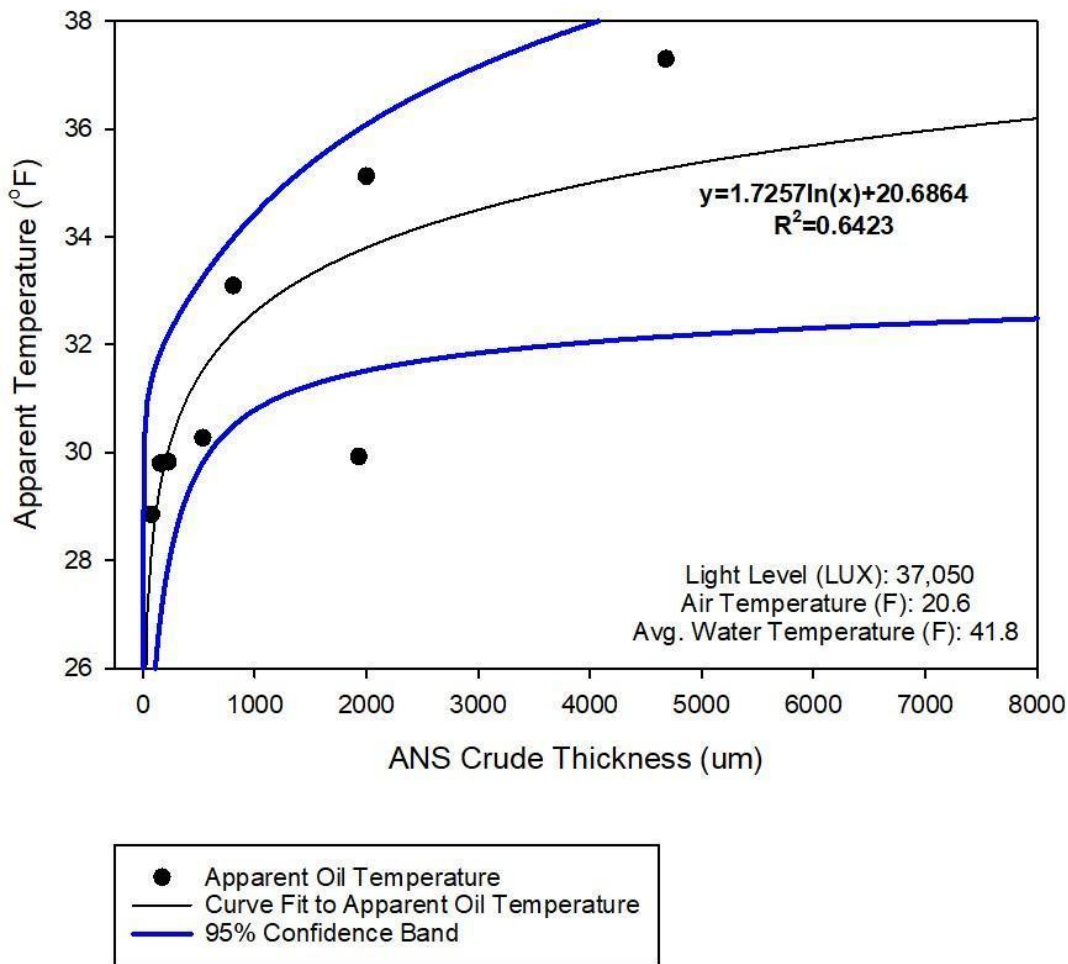


Figure 33. Apparent temperature vs. thickness of ANS crude in 50% ice on 6/2/22 at 1633 hr.

In addition, the project team examined the standard deviation and percent relative standard deviation (%RSD) over the ANS thickness range for 6/2. At 0746 hr when there was little light (Figure 34), there was no trend between thickness and the standard deviation or %RSD the apparent temperature. At 1633 hr, when there was a strong hyperbolic relationship between thickness and apparent temperature, the standard deviation increased with thickness, while the %RSD was relatively flat (Figure 35). This supports the conclusion that the uncertainty in the data increases as the thickness increases where the signal is dampened.

Standard Deviation and Percent Relative Standard Deviation (%RSD) of Reported Apparent ANS Crude Temperatures vs. Thickness on 6/2/22 at 07:46

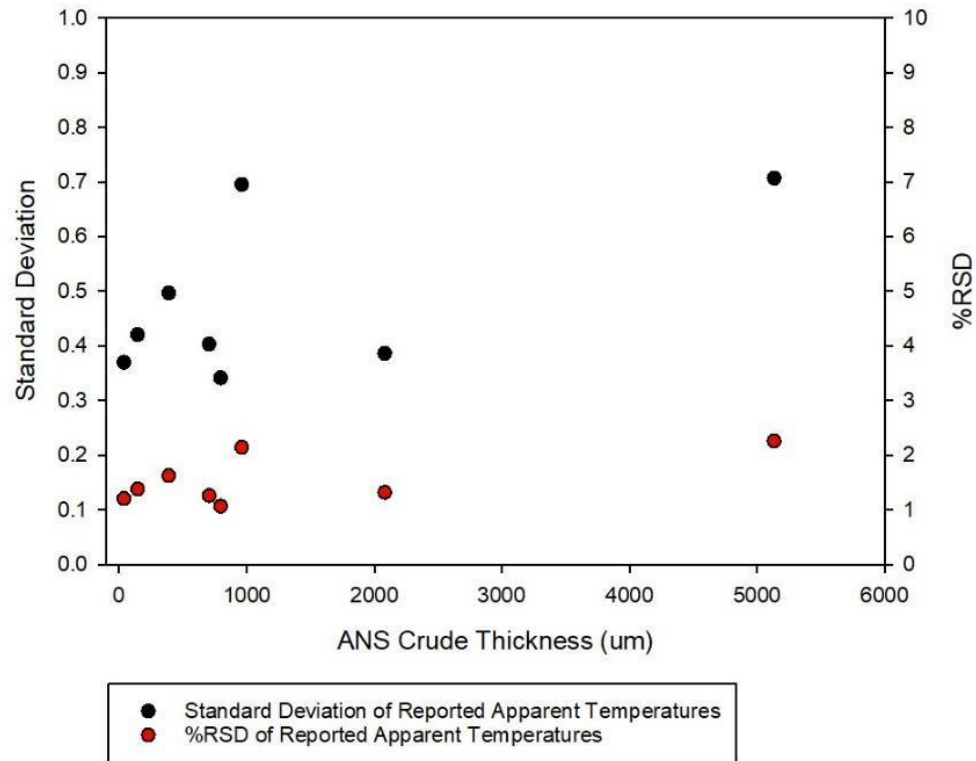


Figure 34. Standard deviation and percent relative standard deviation at 0746 hr.

Standard Deviation and Percent Relative Standard Deviation (%RSD) of Reported Apparent ANS Crude Temperatures vs. Thickness on 6/2/22 at 16:33

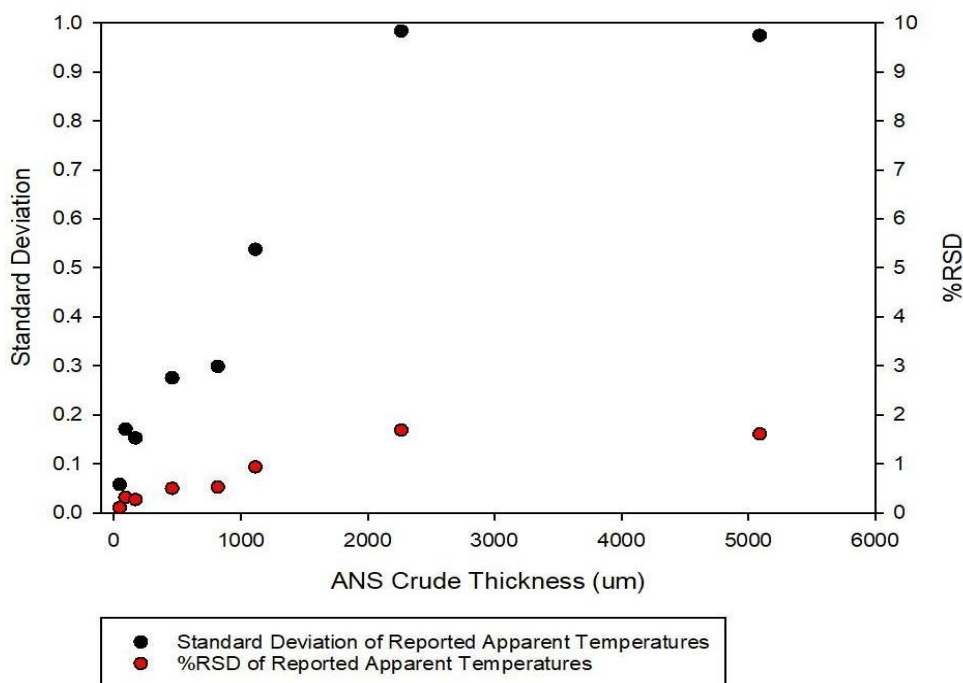


Figure 35. Standard deviation and percent relative standard deviation at 1633 hr.

3.1.1.6 Detection Limits

The project team did not design the tote experiments with a great enough set of thicknesses of ANS in the low range to be able to define lower bound detection limits. This was due to a combination of factors including ability to create thin sheens in outdoor totes, time, and space limitations. However, theoretically, the data suggest that thicknesses $<50 \mu\text{m}$ can be detected quantitatively. The practical limit of quantification (PQL) can be predicted in numerous ways, for one of which the Oliktok Point tote data could be used. In this method, the noise (standard deviation) of the blank (SD_b) (clean water) apparent temperature is determined.

This value is $10 \times (SD_b)$ to obtain the PQL. The presence/absence reporting detection level (RDL) is typically $3 \times (SD_b)$. A few values of PQL were $<5 \mu\text{m}$. However, there was no consistent pattern in the calculations, due to the (SD_b) on the different days for the different lux and water temperatures. It is necessary to determine the detection limits in controlled experiments where more thicknesses near the actual PQL or RDL are monitored under different conditions (lux, water temperature). That allows the PQL and RDL to be calculated as a function of the standard deviation of those thicknesses near the detection limits where SD_b is the y intercept of the line of best fit of the apparent temperatures of the thin slicks vs. their respective SD. This value of SD_b is used in the PQL and RDL calculations.

Oil thicknesses thinner than $50 \mu\text{m}$ are below the threshold considered as ‘actionable oil’ for spill responders. During oil spill response operations, this term refers to floating layers of oil that could be contained, treated, dispersed, or burned. The project team has seen that the magnitude or the cut-off for the oil thickness to be considered as ‘actionable oil’ varies among Oil Spill Removal Organizations (OSROs),



regulatory/enforcement agencies (e.g., BSEE, USCG), or environmental agencies (e.g., EPA, NOAA). While OSROs would assign a threshold of actionable oil depending on their containment capacity from 100 μm to 200 μm (e.g., depending on the use of skimmers, or booming), environmental organizations tend to use 50 μm to define actionable due to the impact of such a large volume of oil on the environment.

In practice, the project team has seen that oil below what is consider ‘actionable oil’ (or 50 μm in this case) is more detectable with multispectral or visual sensors than with thermal sensors. The thin layers of oil are mostly in thermal balance with the water underneath and its harder to see a thermal contrast until oil reaches thicknesses above 50 μm . For thicknesses of oil below 50 μm , oil produces different appearances (or aspect) due to its interaction with the incoming light. Those aspects are commonly known as silver, rainbow, or metallic sheens with thickness ranges up to 1, 5 and 50 μm . For detection limits below actionable oil (in this case interpreted as 50 μm), the team prefers to rely on multispectral or visual sensors able to detect the different aspects of sheens as discussed in Garcia et al. (2019). Hence, detection of thin sheens should be carried out using the visual sensor instead of thermal.

3.1.2 Mapping Products

Besides the thermal analysis of oil in totes, the project team used thermal and visual data from the UAS to generate ultra-high resolution maps. Normally, UAS imagery in the range of centimeter resolution is considered high. When the resolution is less than a centimeter, it is ultra-high. The team created Figure 36 as an orthomosaic of visual images collected over the totes at low altitudes. This map has a spatial resolution of 5 mm per pixel for the UAS images flown at an altitude of ~50 ft. This orthomosaic was created by compiling multiple single images projected on a map using a Web Mercator coordinate system. The grid on the map shows the latitude and longitudes, orientation, and scale.



Figure 36. Ultra-high resolution (sub-centimeter) map of working area around the totes using visual imagery.

The purpose of this orthomosaic is to show the capacity of the UAS-mounted multispectral sensor to capture features in extremely high detail and show them on a map that could be helpful for oil spill practitioners. Figure 37 shows details at the millimeter scale. In case of an oil spill, such detail can be used to identify vegetation or wildlife, preserving their attributes (e.g., location, orientation, scale).

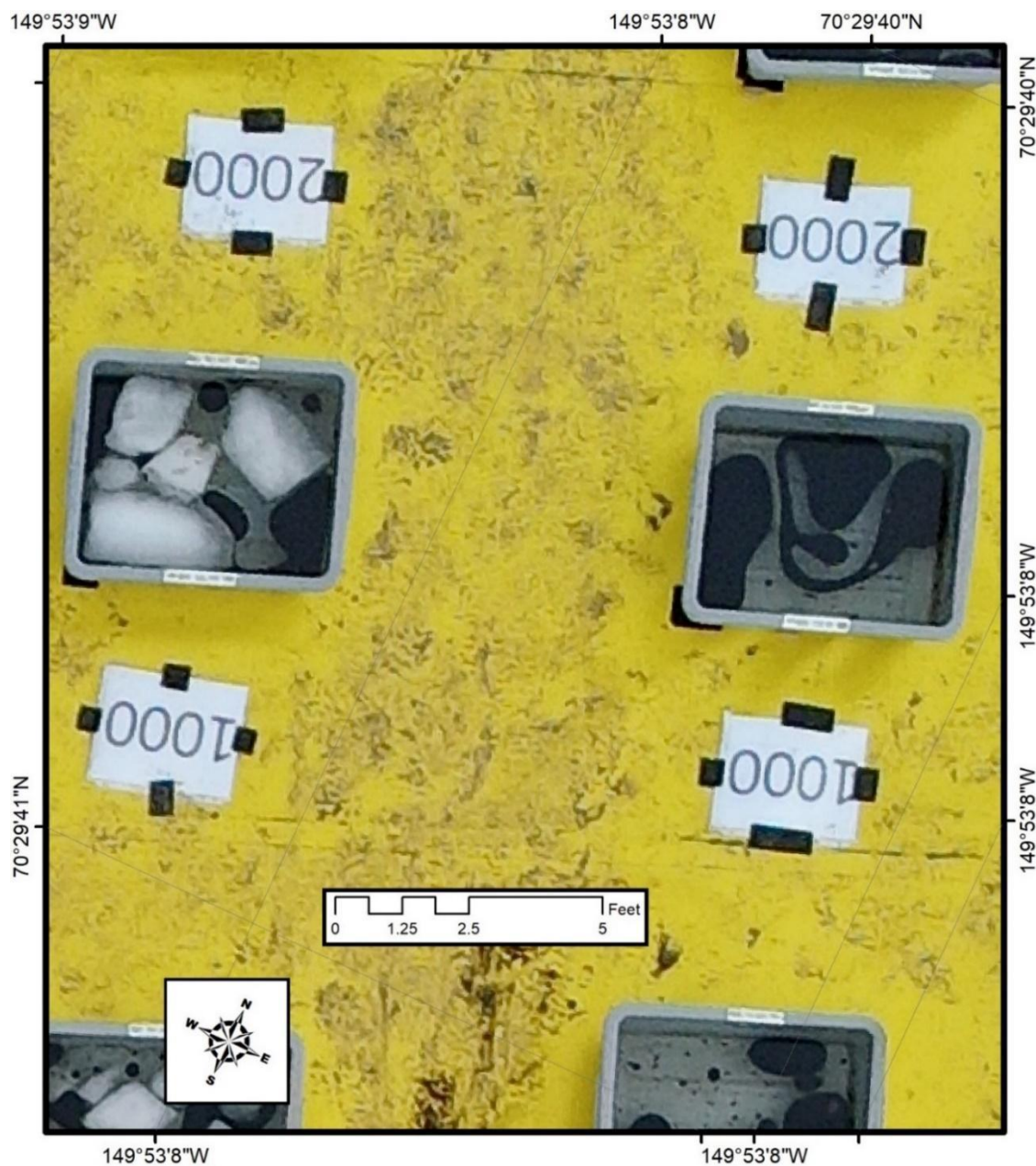


Figure 37. Ultra-high-resolution map using visual imagery with less than 5 mm per pixel resolution.

The project team also executed flights at altitudes of 200 ft and 400 ft. Figure 38 shows a subset of an orthomosaic from a flight at an altitude of 200 ft in which spatial resolution was 1 cm. This altitude seems optimal as a tradeoff of coverage and resolution that may be helpful for detection of wildlife. The UAS covered an area of 0.75 km x 1 km flying at 200 ft. The level of detail on this map shows features that could be identified with thermal and visual imagery.



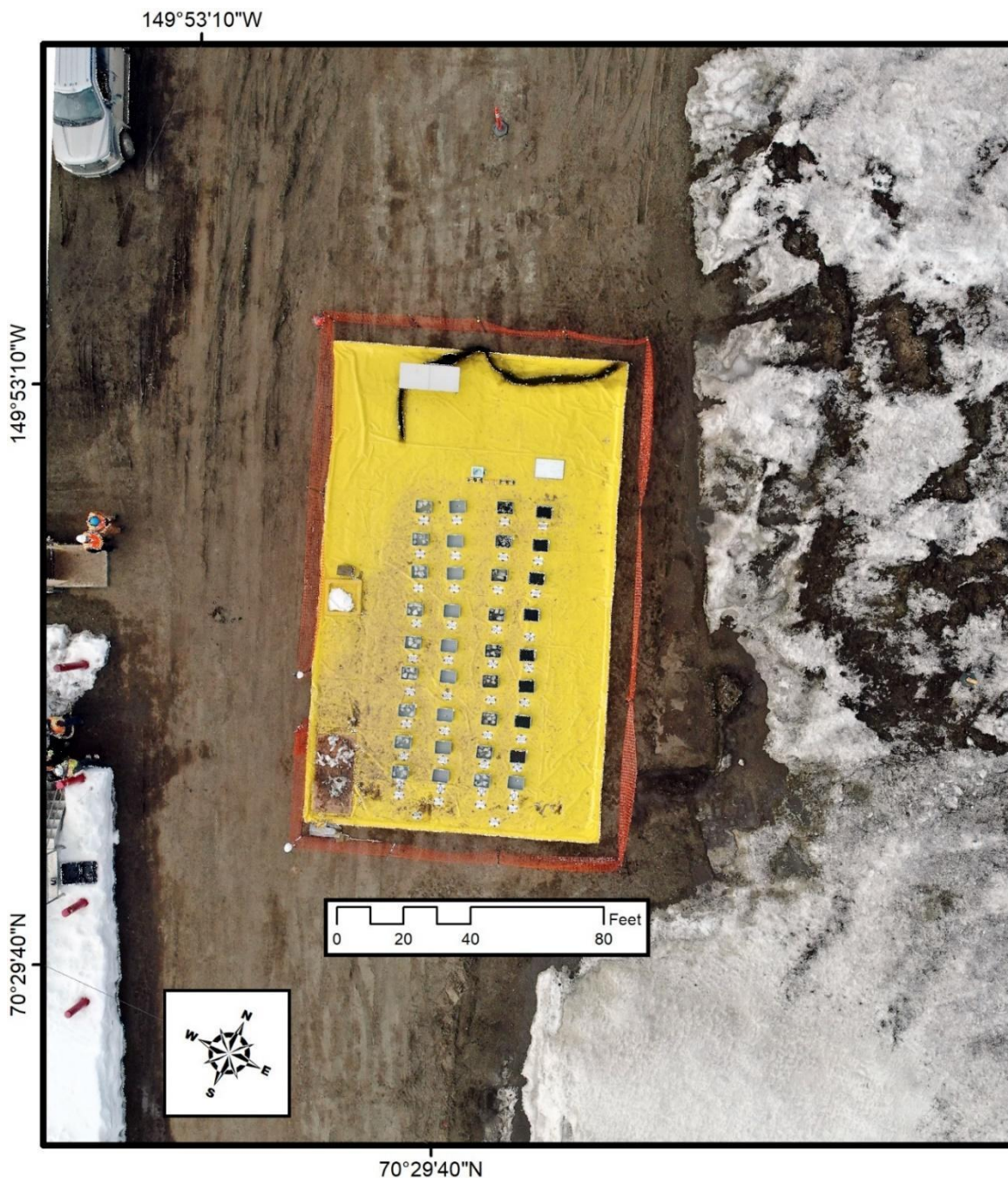


Figure 38. Visual orthomosaic, created at 1 cm resolution flown at 200 ft.

The capacity to capture high resolution imagery could be crucial for Natural Resource Damage Assessment (NRDA) tasks. Figure 39 shows a comparison of 5 mm resolution and 1 cm resolution achieved at 100 ft (right) and 200 ft (left) altitudes, respectively. Numbers on the ground could be read from both altitudes, proving that 200 ft is useful for reconnaissance operations that require high definition (e.g., NRDA applications).



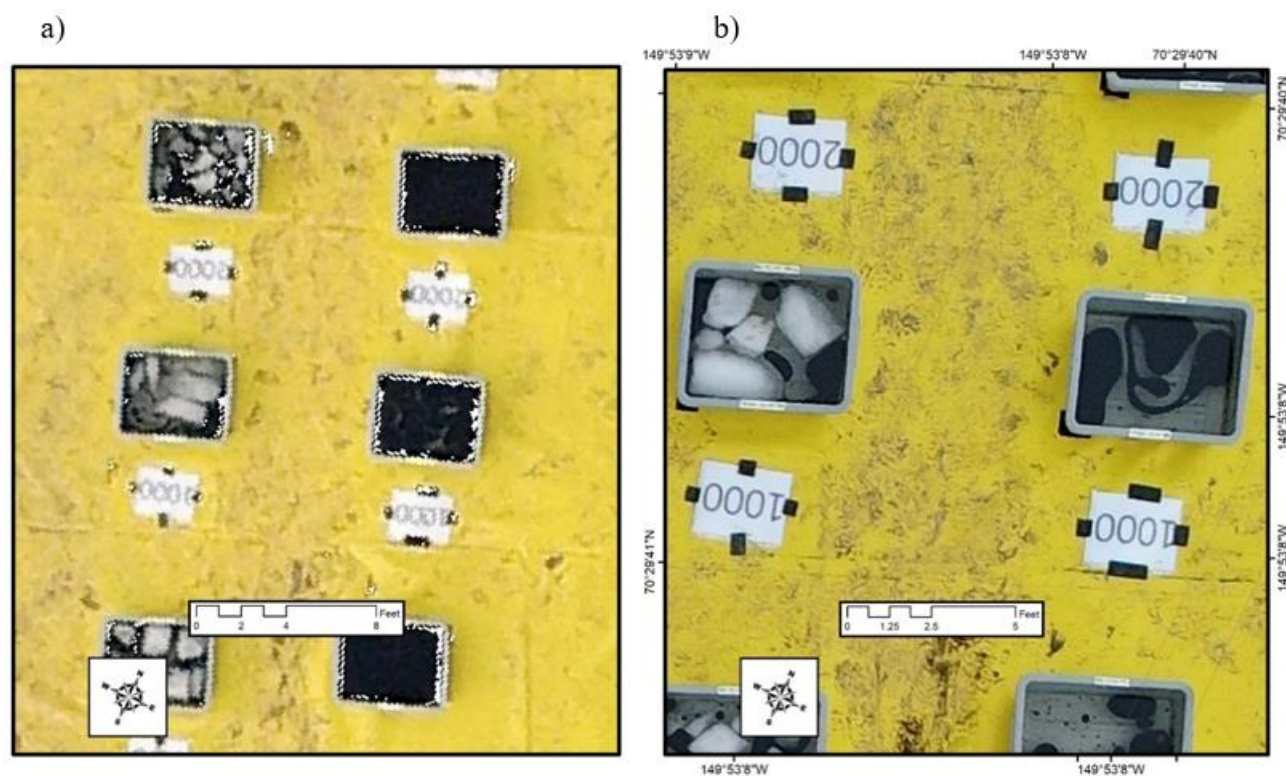


Figure 39. Orthomosaic maps of ultra-high resolution visual imagery. (a) Altitude 200 ft; 1 cm resolution / pixel. (b) Altitude 100 ft; 5 mm resolution / pixel.

400 ft was the maximum altitude for the flight surveys because it is the normal altitude above which UAS operation is restricted by the Federal Aviation Administration (FAA). Figure 40 shows an orthomosaic with a ground spatial resolution of 2.5 cm per pixel at 400 ft. This altitude is preferable for covering large areas, although the spatial resolution is reduced. It may not capture the needed details for NRDA applications (e.g., identification of wildlife).

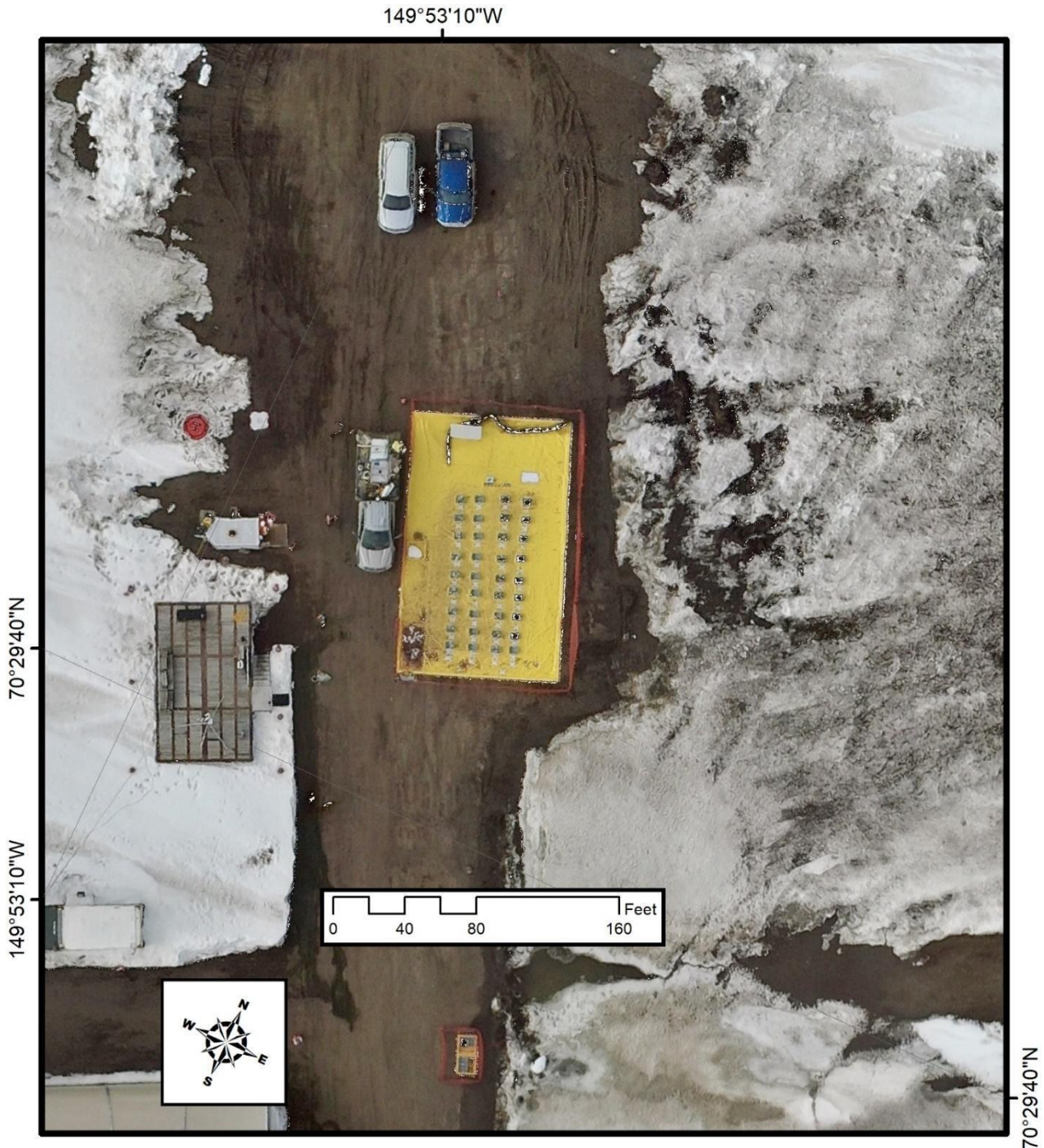


Figure 40. Visual orthomosaic map generated from UAS data collected at 400 ft. Resolution = 2.5 cm/pixel.

When flying at 400 ft, there was limited spatial resolution when the visual sensor focused on a small area (Figure 41).

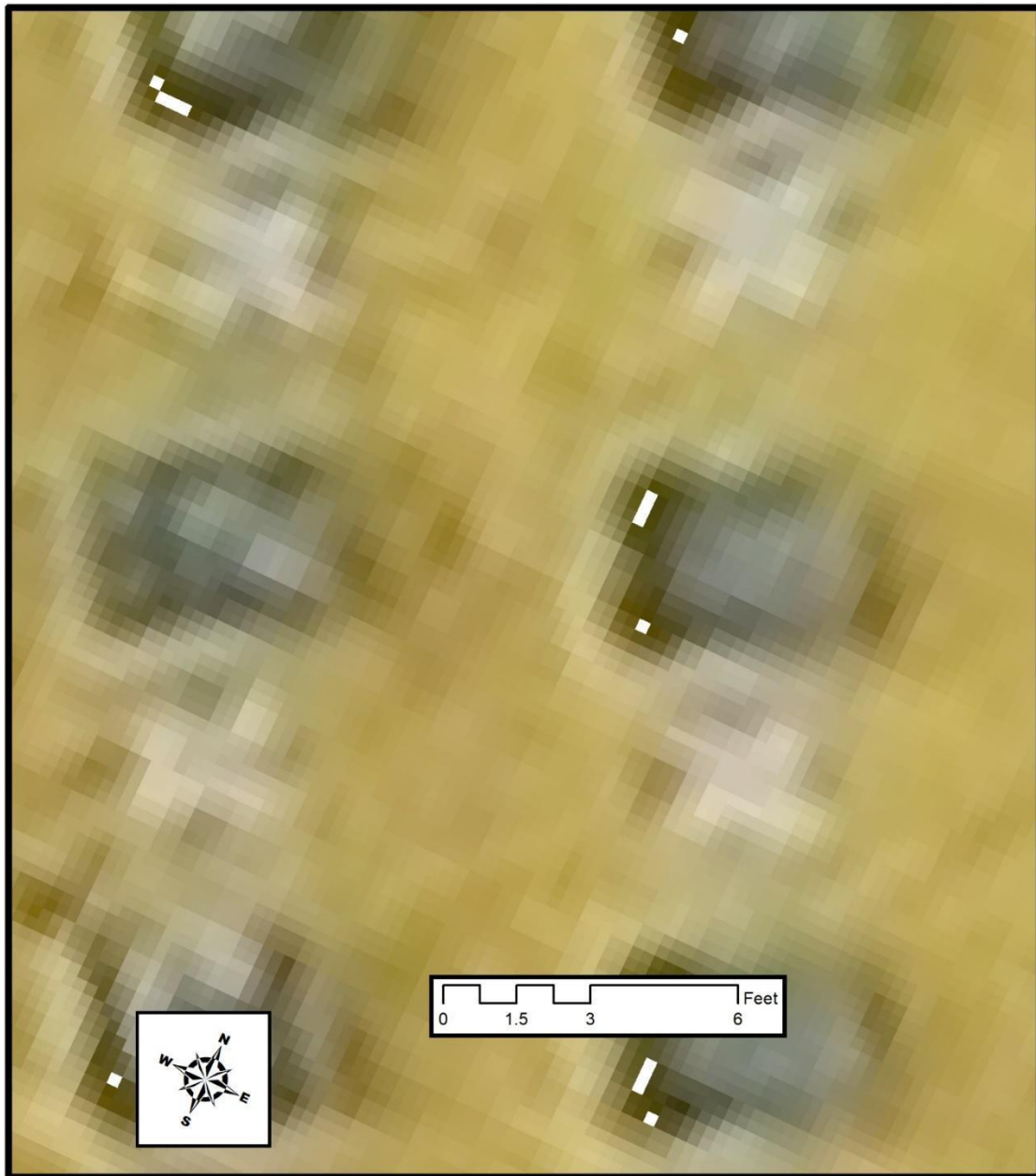


Figure 41. Orthomosaic of the totes as observed at 400 ft altitude.

This maximum altitude was optimal for covering larger areas, however, the identification of features in small areas on the ground was compromised due to lower resolution.

3.1.3 UAS Observations of Surface Features

The project team made observations of specific ground targets (features) in the area near the totes with the objective of producing classification maps. These targets included: snow, ice, ground (e.g., gravel, dirt, soil), and vegetation (tundra). The project team documented observations with thermal measurements taken

Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

at ground level with corresponding GPS information. The photos collected with a handheld camera were used to validate the classification of UAS/sensor orthomosaics.

Figure 42 shows the area of the totes (on the west side in yellow, on the left of the figure) and the points where the team conducted ground verification (green dots on the east). The area shown on the map was approximately 1 km x 1 km, with the quadcopter flown at 200 ft.

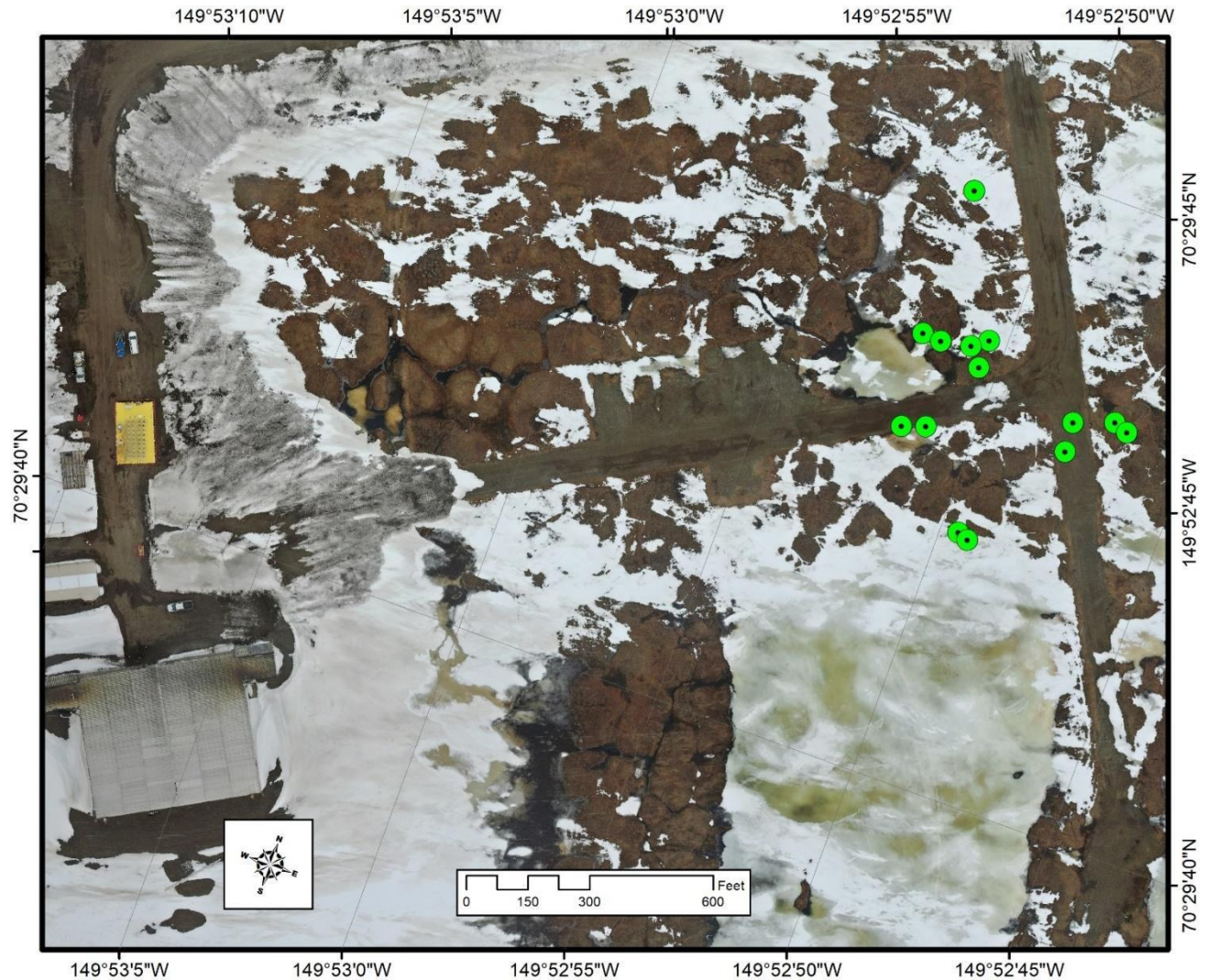


Figure 42. Visual orthomosaic map of the totes and ground verification (Altitude = 200 ft).

Figure 43 shows a close-up of the area where the ground verification was conducted. The RGB image on this map has been post-processed enhancing the color of the imagery. Imagery enhancement is a secondary step that is performed before the image classification. Features on this map are more distinguishable than on the map in Figure 42.



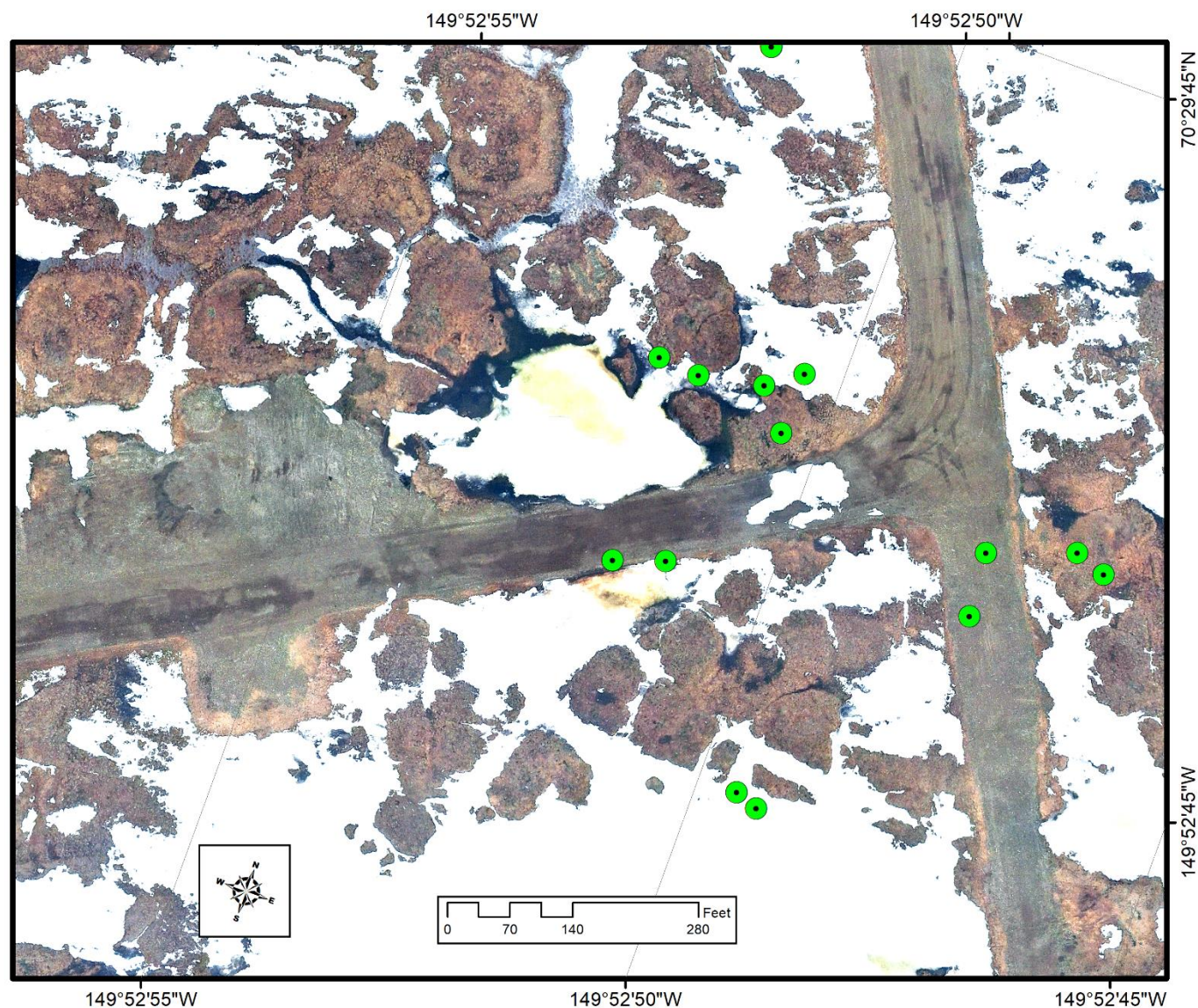


Figure 43. Map of the RGB post-image processing for feature classification.

Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

Figure 44 to Figure 47 show imagery of surface features on the ground and from the UAS at 200 ft. The lower panel shows the mapped location (green dots) where each photo was taken.

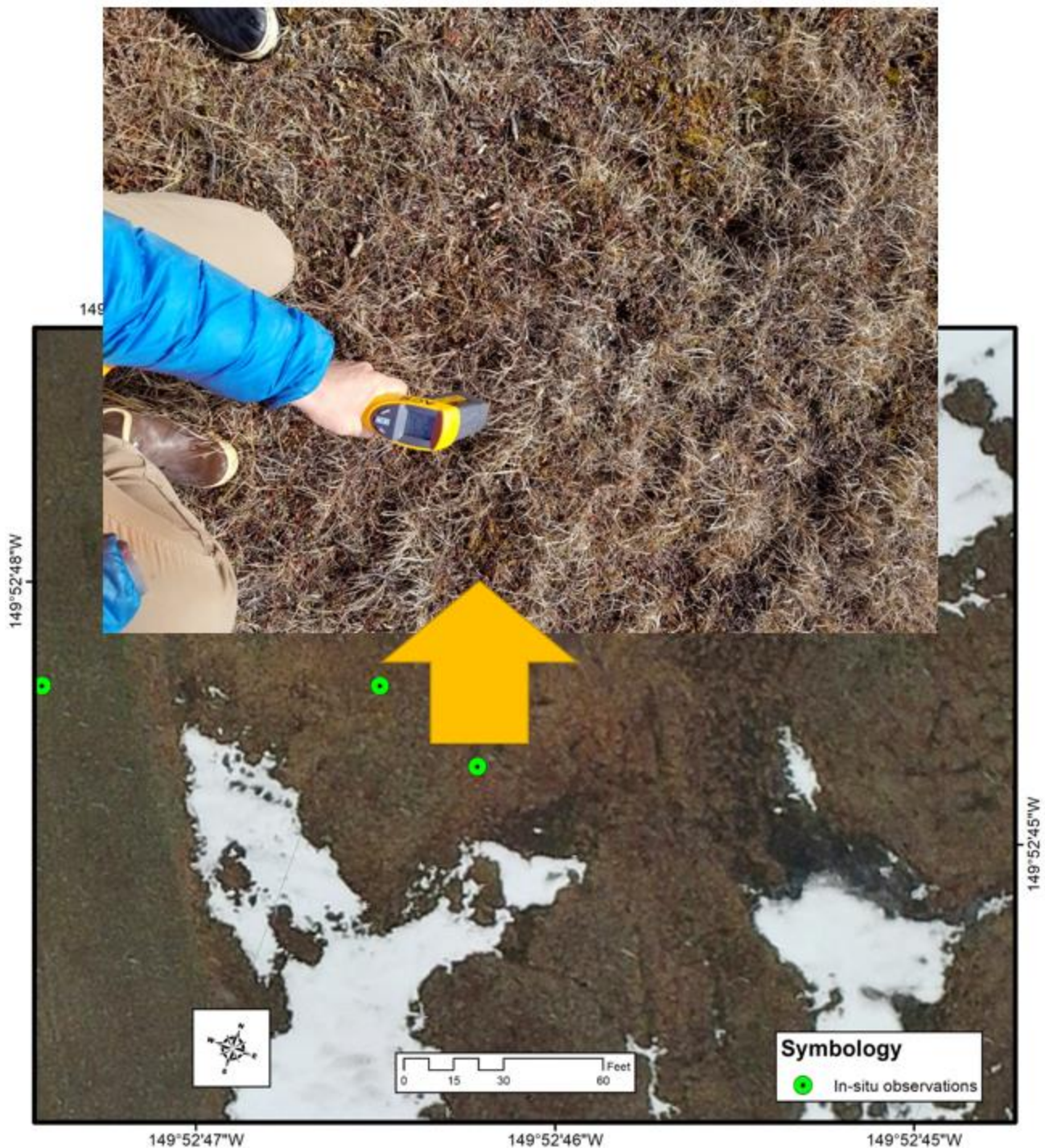


Figure 44. In-situ verification of tundra (vegetation) with UAS altitude at 200 ft.





Figure 45. In-situ verification of snow with UAS altitude at 200 ft.



Figure 46. In-situ verification of ice with UAS altitude at 200 ft.

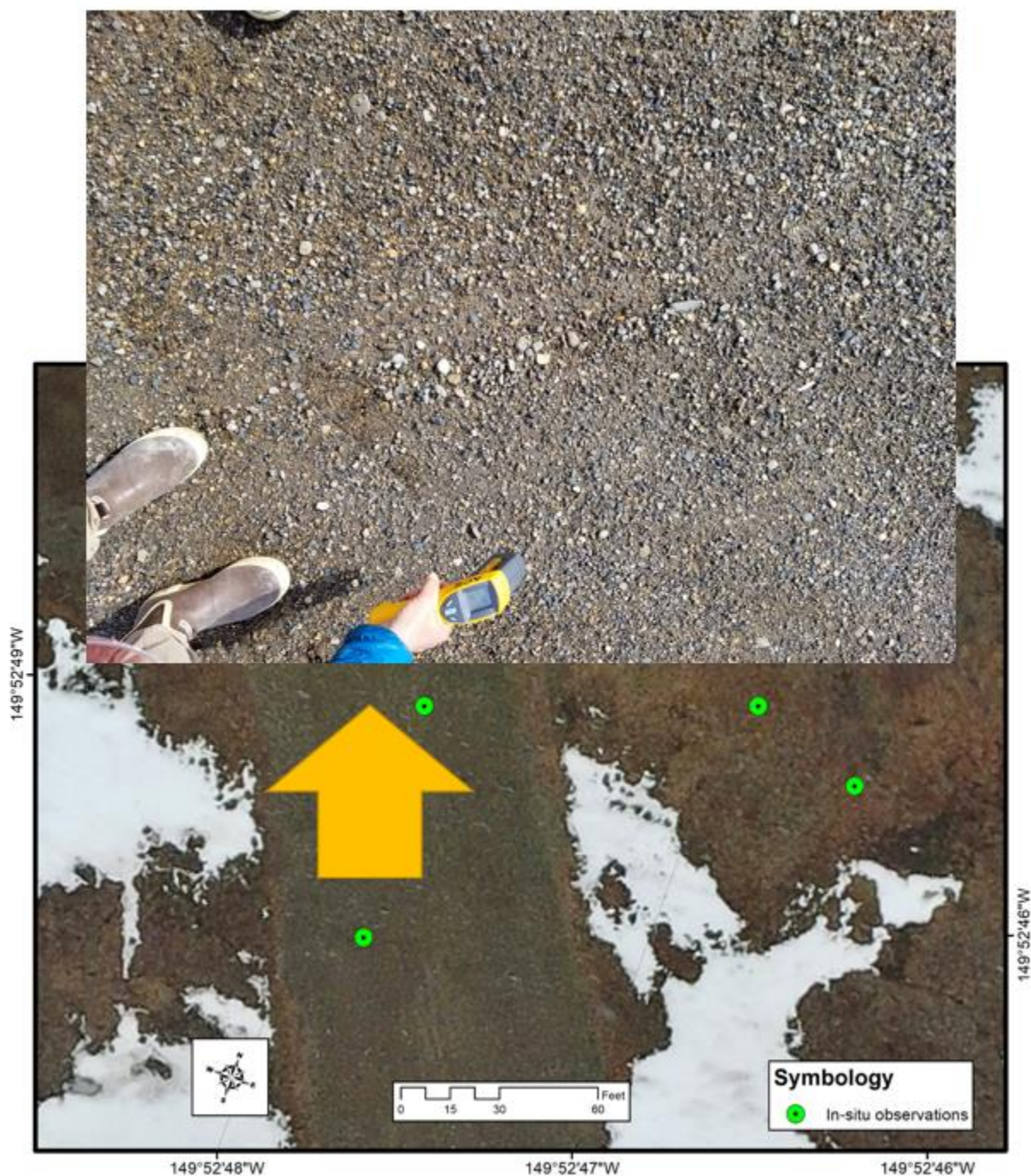


Figure 47. In-situ verification of gravel with UAS altitude at 200 ft.

3.1.4 Image Classifications

The team used the UAS orthomosaic generated from the post-processed RGB imagery as an input for classification of the features. Water Mapping, LLC (contractor) developed software for the image processing. The “RGB” orthomosaic file is used as an input for the classification process. This file is inspected by an analyst who creates training sets of the different features observed on the image. Training

sets are created by selecting pixels representative of each class. The training set is a database that contains pixel information (reflectance values) that are then processed by a 'Maximum Likelihood' function that assigns a class to each pixel on the RGB orthomosaic based on the statistical correlation with the training samples. The result of this process is a new map (GeoTIFF) in which each pixel on the RGB can be assigned a new class. The end product of this process is a classification map (Figure 48). Readers can compare this map to the visual map (Figure 42).

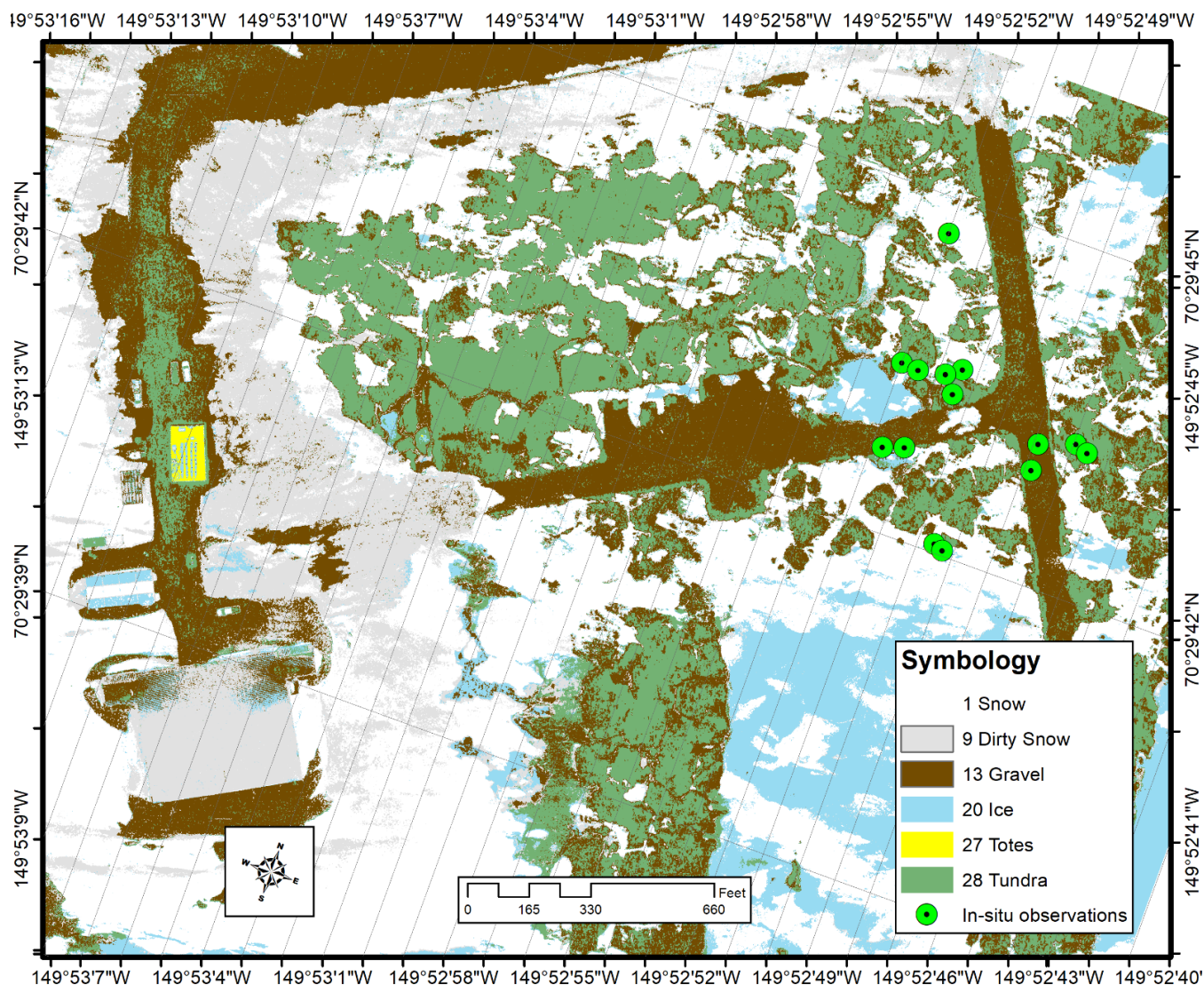


Figure 48. Classification map of features observed and verified by the in-situ survey.

Figure 49 and Figure 50 show subset maps of the different areas in visual (RGB on top) and classification (color coded on bottom). These maps and the ground control points (green dots) were used to validate the classification result.

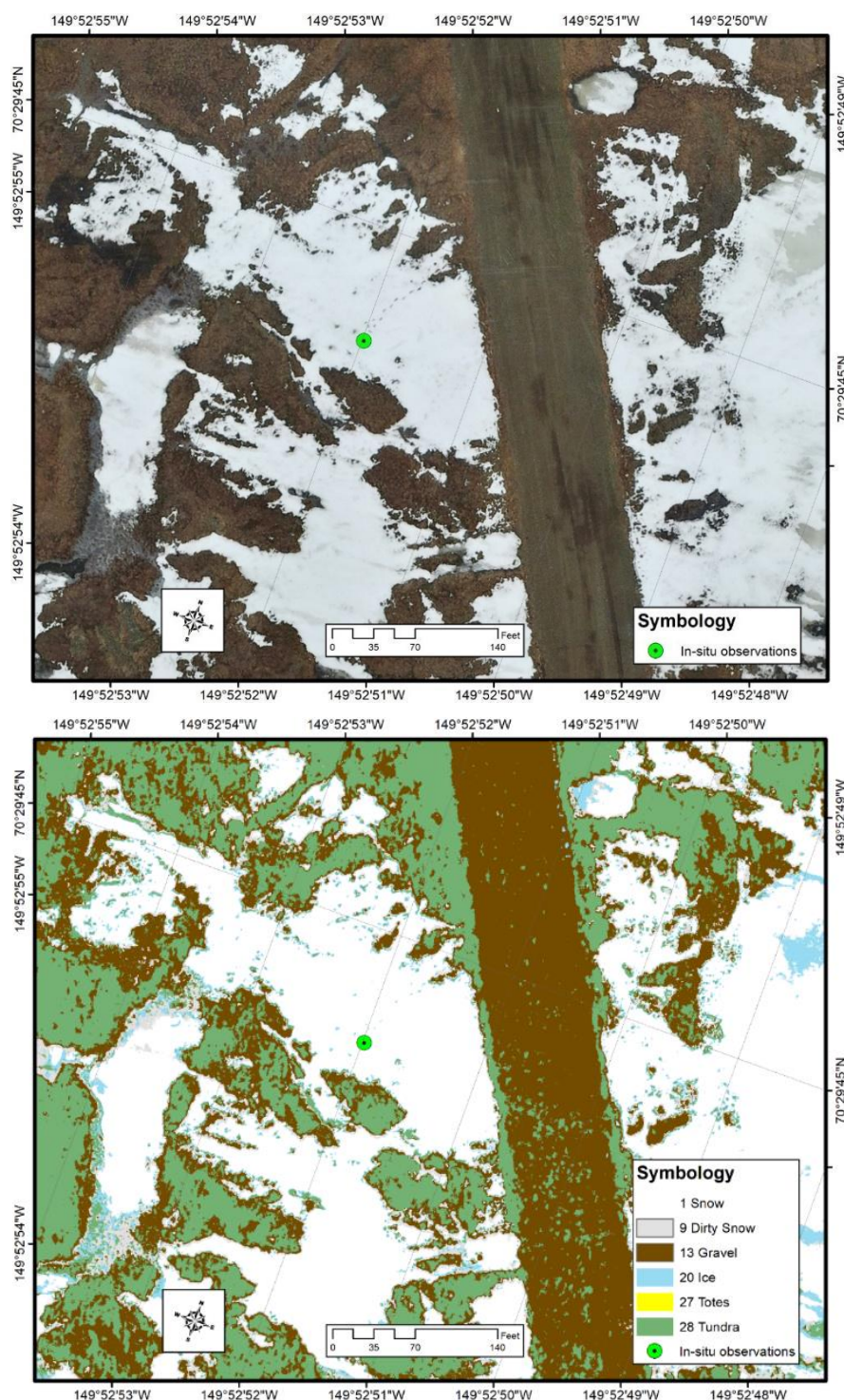


Figure 49. RGB and classification maps of selected features. This example shows gravel (road) as well as snow, and tundra vegetation.

Figure 50 shows where ice, tundra, and vegetation were detected and classified. The high resolution imagery detected even small features such as the footprints left on the snow. The pixel-based segmentation achieved by the software created a classification map with the same spatial pixel resolution as the original orthomosaic.

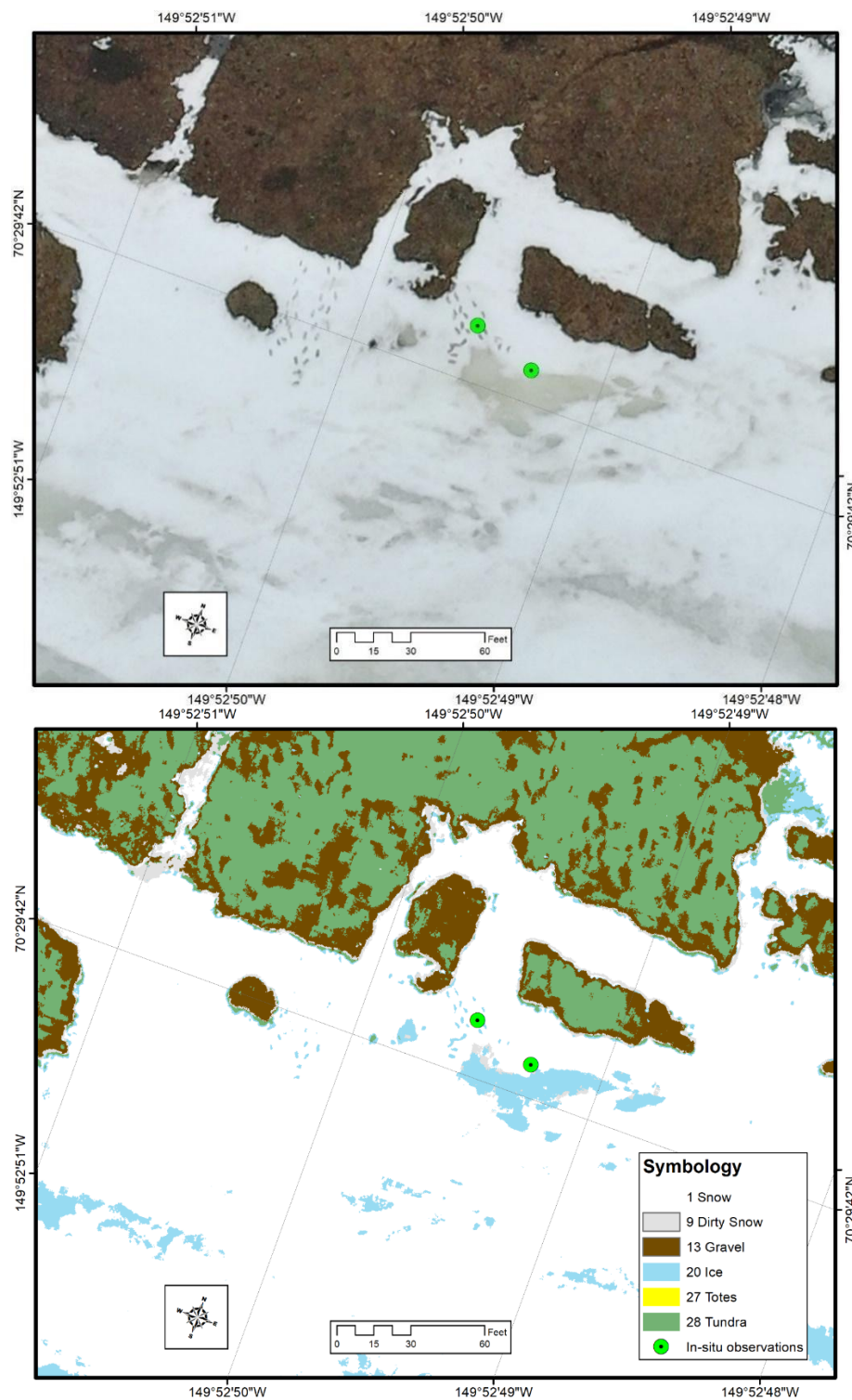


Figure 50. RGB and classification maps of selected features. This map shows ice, snow, tundra, and soil (or gravel).

3.1.5 Near Real-Time Data Processing

One of the main objectives of the project was to develop rapid workflows to create mapping products in support of response and assessment activities. During a spill, time is of the essence, and effectiveness of UAS platforms/sensors will depend on how rapidly data collected is converted into useful products. For example, the information produced must be in a form that can be used by responders to direct activities associated with monitoring, containment, or treatment of oil spills (e.g., deployment of boom barriers, dispersants, in-situ burning).

The project team conducted UAS surveys at maximum altitude of 400 ft in the shoreline area of the study site. These surveys covered the “open water” areas and tundra. There was a solid sheet of ice with scattered thin pockets of melted water on top (Figure 51).

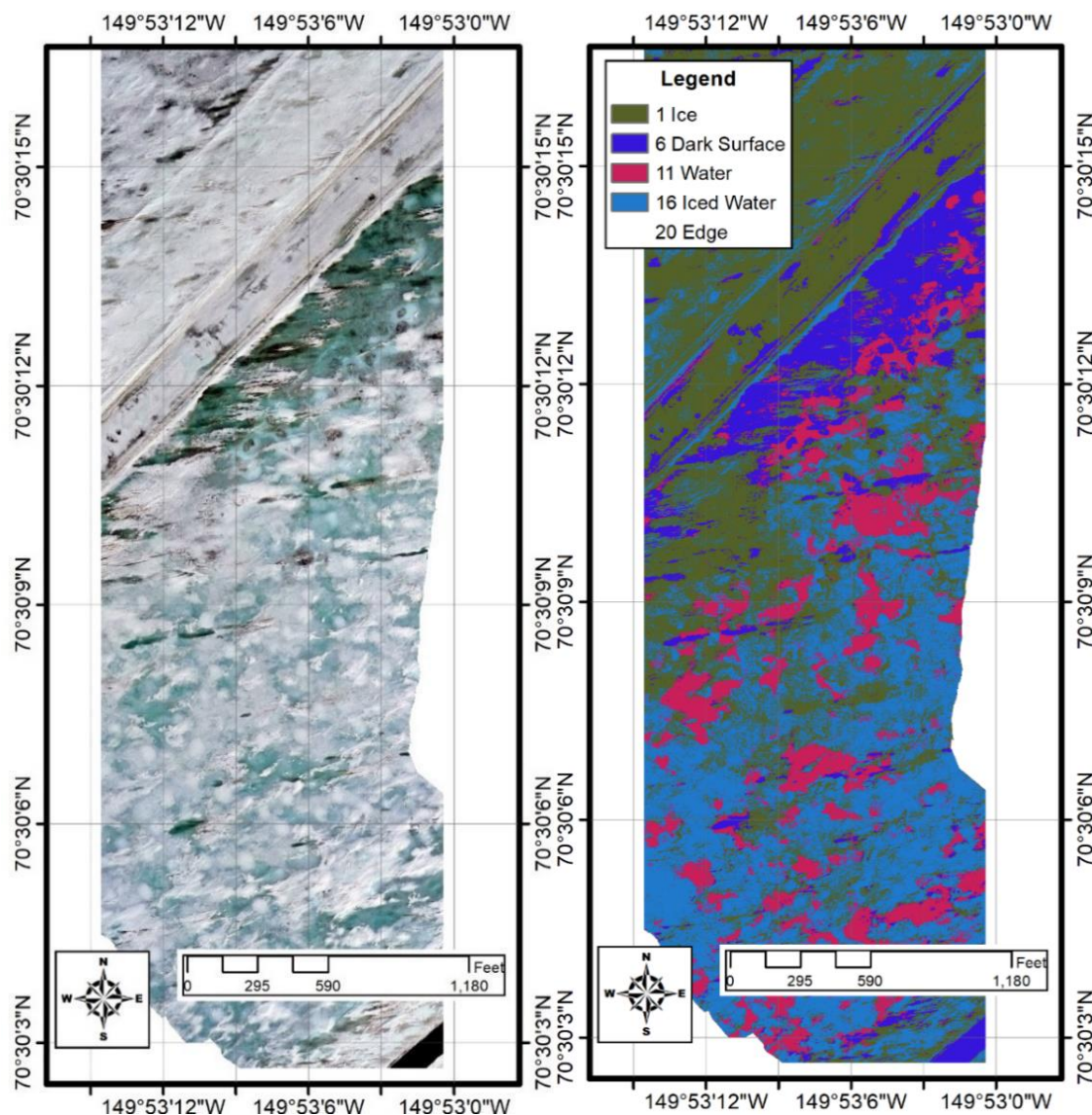


Figure 51. Map of open water near to shoreline showing a solid sheet of ice.

Figure 50 (tundra) and Figure 51 (ice on open water area) include the visual map (top/left) and its classification (bottom/right), respectively. The UAS survey over the tundra captured features such as snow, ice, vegetation, rocks, and gravel. The examples shown in Figure 51 and Figure 52 were produced using the processing software in near real-time in 41 minutes; this time includes the moment data was copied on the laptop computer in the field to the time that data was uploaded on DIVER.

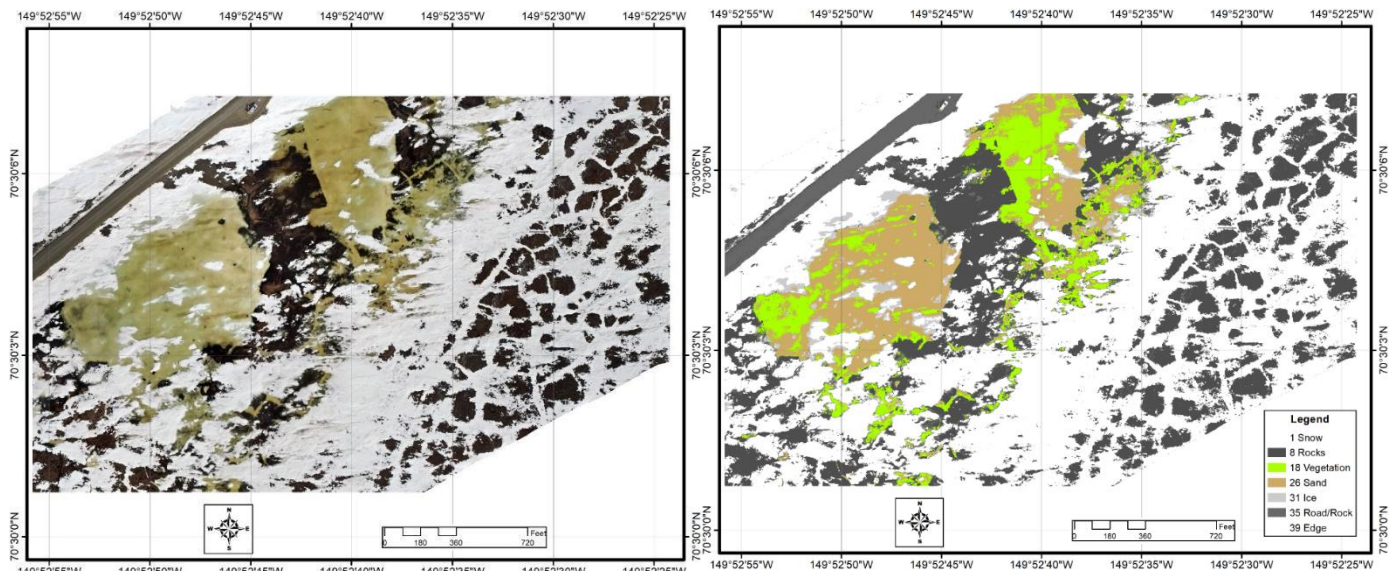


Figure 52. Near real-time UAS mapping of tundra.

The team used the NOAA OR&R DIVER data warehouse to transfer the UAS data and products to the NOAA server, so the maps produced could be displayed on the NOAA ERMA COP. The team recorded the time required to process this data from extraction of the imagery files off the UAS memory card to the point where data were uploaded onto DIVER – shown in Table 2. The team transferred data from the Oliktok Point site to the contractor lab in Florida, and then uploaded to DIVER after being fully processed remotely.

Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

Table 2. Near real-time steps and durations for the entire cycle from data processing to delivery.

Step	Process	Duration (minutes)	Description
1	Extraction of data from the UAS (after the survey had been completed) for backup (copy) of the data in the mobile workstation	5	The full UAS survey of approximately 20-minute flight took approximately 1,200 snapshots of thermal, visual, and zoom imagery.
2	Transfer of data collected to remote location (contractor office in Florida) for image processing	5-10 (depending on survey size)	With the bandwidth available from ENI's base camp Wi-Fi, 6 GB of data were transferred from the field (Oliktok Point) to contractor lab in approximately 5-10 minutes.
3	Data inspection and folder organization of data	5	In order to process the imagery rapidly, data was stored and separated by sensor type and organized in separate folders.
4	Projection and ortho-registration of imagery for orthomosaic production	10	The first processing step on the UAS imagery was conducted by assigning the projection to each still collected by the UAS individually. Contractor software performed this operation generating a projected orthomosaic using Web Mercator projection in GeoTIFF format preserving the maximum pixel resolution of each image.
5	Visual (or thermal) imagery inspection for classification	5	This was a supervised process conducted by a trained analyst using contractor software and consisted of the sampling of pixels on the orthomosaic for classification.
6	Image processing for classification	5	After the training set was generated, the computer ran the image classification process which took ≤ 10 minutes at maximum pixel resolution.
7	Inspection of visual and classification maps	5	Final products were inspected for quality assurance and compliance of format requirements for the ERMA system.
8	Data transfer to ERMA	5	With broad bandwidth, the data transfer of the final products from the contractor's office to DIVER was almost instantaneous. Transfer time for files ranging from 250 MB to 2 GB varied from 2-5 minutes.
	Total Time	45	



A relatively good bandwidth (approximately 1-5 MBps upload) connection was available, therefore, the time used for the data transfer of the files was just a few minutes (included in the total of 45 minutes for the whole process). Times shown were specific to the surveys shown in Figure 51 and Figure 52. Shorter surveys would take less time, while larger surveys could take longer to be fully processed. Overall, near real-time processing was achieved within 30 to 60 minutes when the processing of the data was performed remotely and UAS map products were needed with the maximum resolution. This processing time could be improved in the future if the processing was conducted onsite.

The project team performed mapping classification on UAS imagery to preserve its maximum native resolution. The objective of processing imagery at maximum resolution was to generate products that could be used for multiple oil spill response applications (e.g., NRDA, containment operations, modeling). However, the processing time could be expedited in oil spill response operations by processing the images at lower resolution, saving computing capacity and transfer time. For example, an oil spill responder might not need the full detail of features exposed to oil, but only the images that show areas where it was detected. Processing imagery at 5 m resolution, instead of 2.5 cm resolution shown in Figure 51 and Figure 52, could be achieved in less than 25 minutes (including the data transfer, processing, and uploading time). Maps with full UAS resolution could be large (>250 MB); a reduced resolution map could be small (5 MB to 10 MB).

3.1.6 Standard Operating Procedure for Data Delivery into ERMA

The project team produced a standard operating procedure (SOP) for data transfer into DIVER and ERMA (APPENDIX A) that can serve as a basis for future UAS missions. The SOP facilitates rapid review of the data after it was verified by the UAS operators to make it available for the response community through the ERMA system.

The data formatting of UAS products for ERMA began during the Deepwater Horizon oil spill. The Oliktok Point research was another milestone in the development of UAS products because it standardized the processing procedure for future responses. The SOP can also serve as a basis for similar remote sensing technology derived from other aerial or spaceborne platforms.

Examples of the ERMA interface, displaying the UAS maps generated during this project, are shown from Figure 53 to Figure 55. A table with links where this and more data can be accessed on ERMA is provided in Appendix A.



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

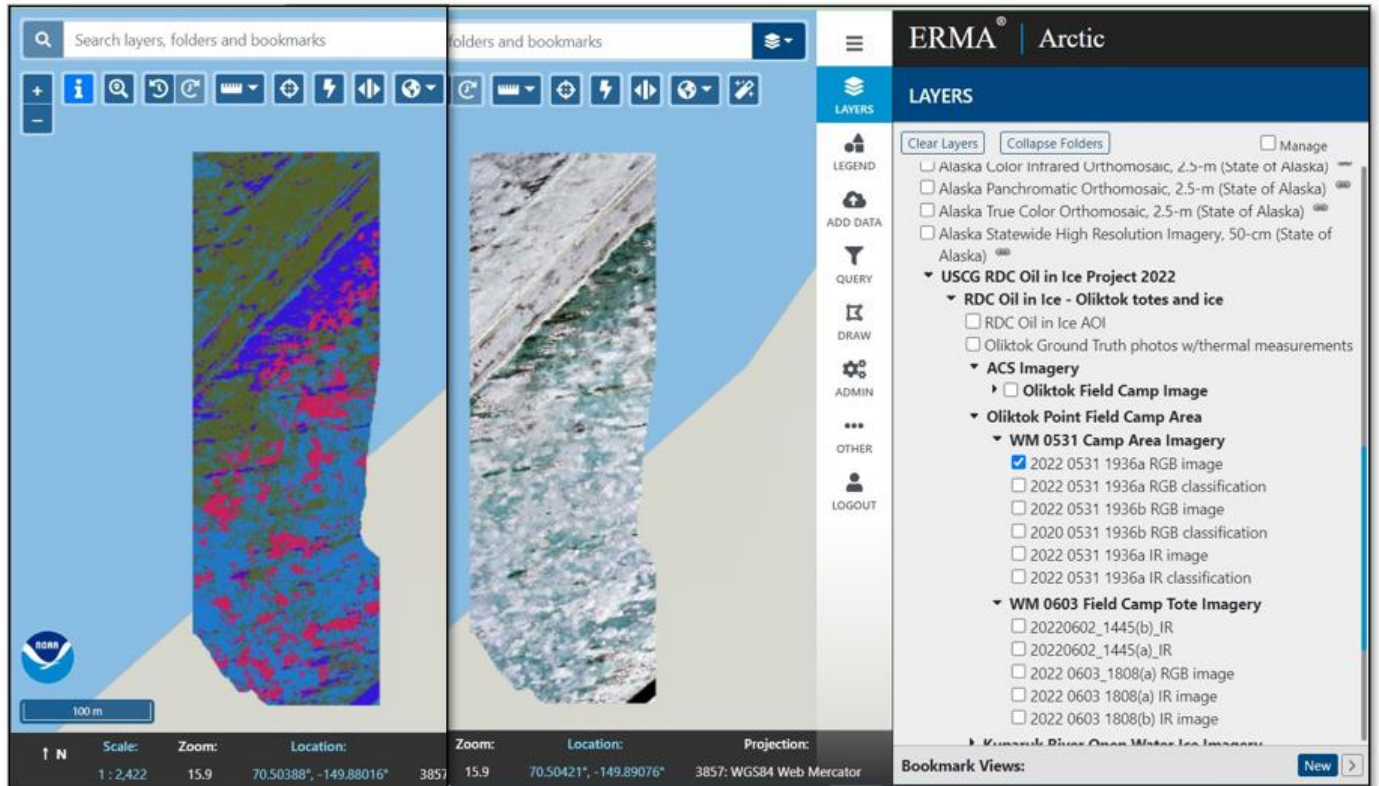


Figure 53. Example of UAS mapping of tundra as displayed on ERMA.



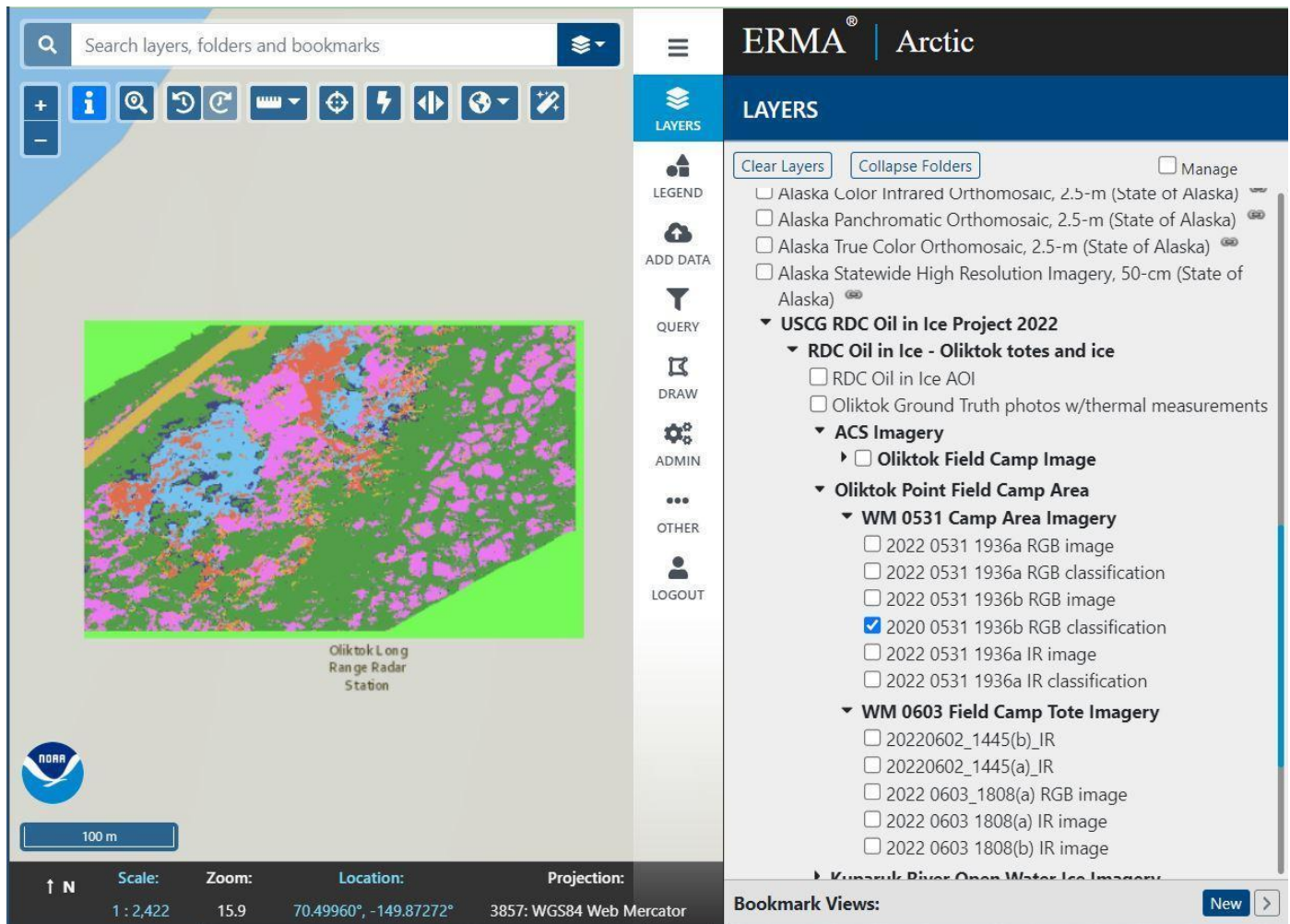


Figure 54. Example of UAS classification product derived from the visual sensor as displayed on ERMA.

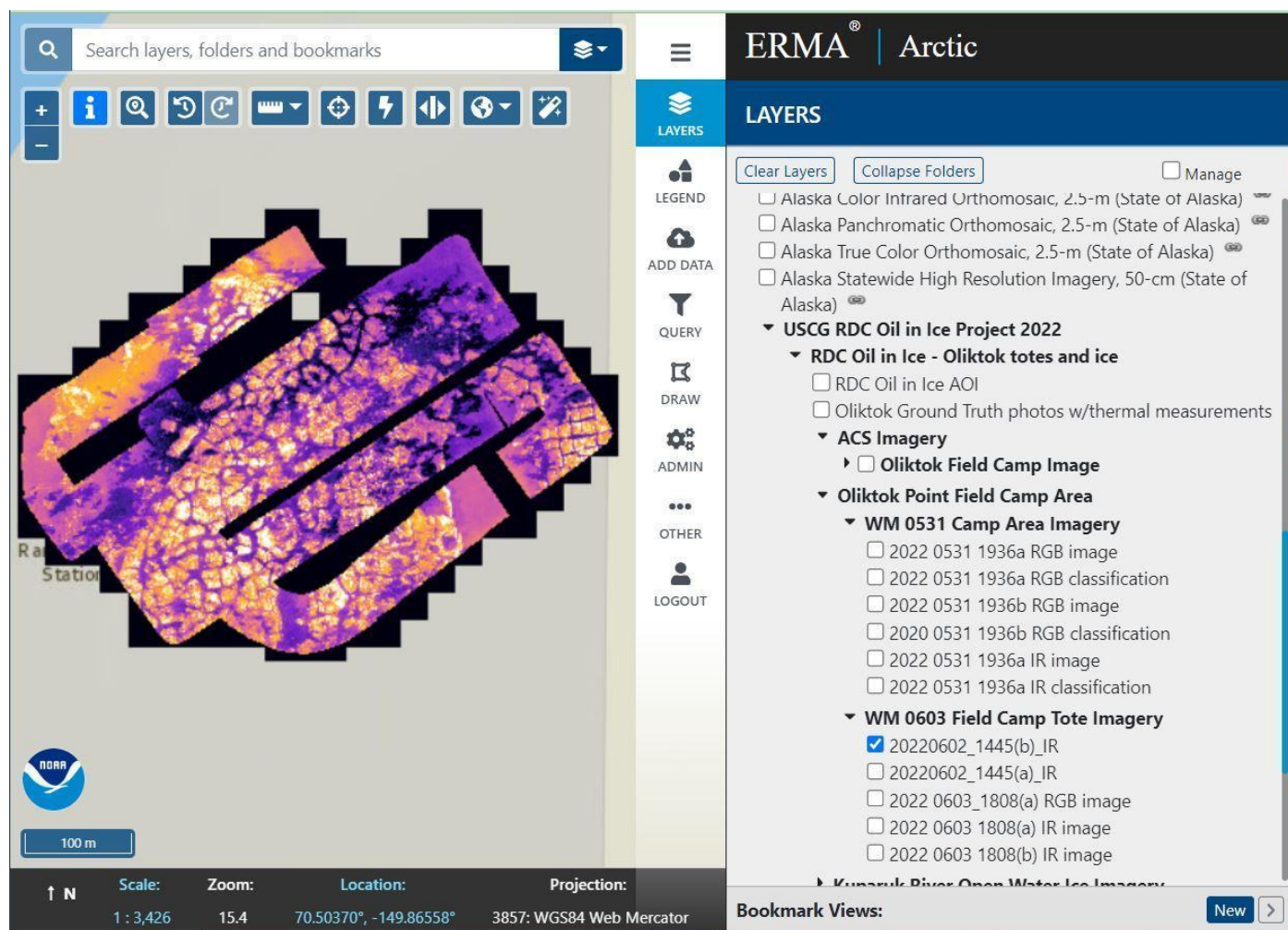


Figure 55. Example of classification product derived from the thermal sensor as displayed on ERMA.

3.1.7 Use of UAS Mapping and Classification to Monitor Changing Features/Conditions over Time

The project team used data from UAS surveys to develop mapping products that showed the changing of conditions over time. It is important during a spill to continuously monitor sensitive areas that could be impacted by the presence of oil. This had not been done using UAS in the Arctic. To demonstrate how this could be accomplished, the project team executed UAS surveys on large areas of ice cover on 31 May 2022. The surveys were repeated four days later on 3 June over the same area to monitor the process of ice melting. Figure 56 shows an orthomosaic generated from the visual sensor (left) and its classification (right) from 31 May and 3 June.

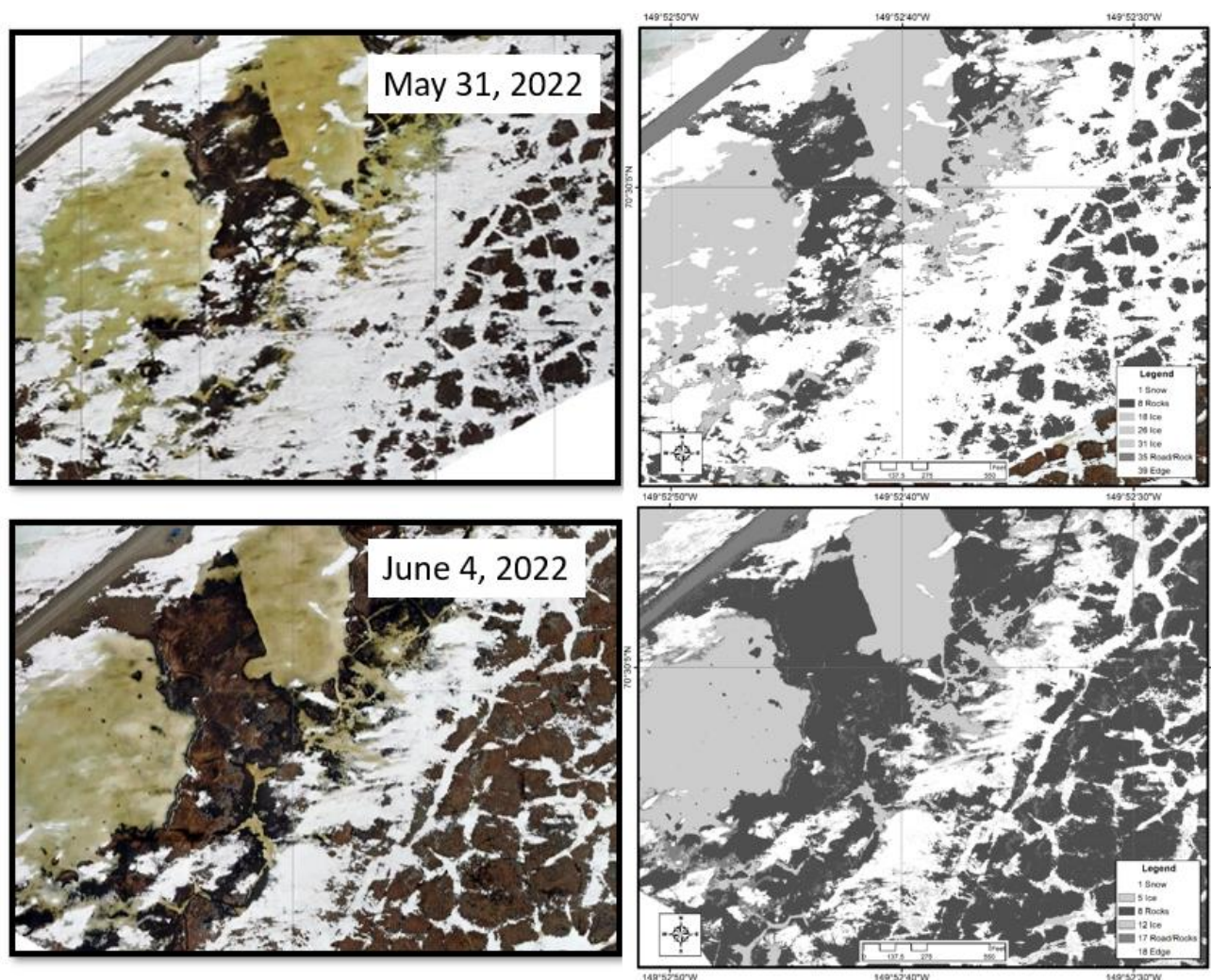


Figure 56. Timelapse of ice melting observed from 31 May to 3 June 2022.

3.1.8 Mapping Broken Ice

As part of the research at Oliktok Point, the project team collected data and produced maps of broken ice. The team conducted UAS surveys over the Kuparik River, a freshwater river, separately from the work done adjacent to the totes. Previous UAS surveys over floating broken ice had not been collected for image classification. The main challenge of mapping features over water is its continuous motion from wind and waves, which creates constant reflections in aerial imagery. When UAS surveys are performed over water, images are collected looking straight down (nadir) along the flight path. These reflections create image artifacts that make it impossible for commercially available software to produce orthomosaics.

Commercially available software matches the location of pixels with the same characteristics. This process works only on land where features are static and their aspect (color) does not change. Moving water represents a challenge. The contractor software and algorithms create orthomosaics by projecting each individual image over a map, compiling all of them as they are projected over the surface on their corresponding location. This process involves a geometric computation for the positioning of every pixel on

each of the images based on the altitude, look angle, and field of view of the sensor as it progressively collects imagery during a survey.

The software projection routines are based on a parallel processing algorithm that is capable of assigning projection attributes to hundreds of individual images concurrently. The software reads the GPS coordinates in which each image was taken from the flight log, and the altitude and viewing angles to assign projection attributes. When a flight log is unavailable, proprietary algorithms are used to estimate the required projection parameters. The algorithms for open water had to be evaluated to determine if they were applicable for floating broken ice visual orthomosaic classification. Kuparik River served as an example for this validation.

Figure 57 is a map corresponding to multiple flight paths in which a UAS survey was performed. The team collected data in mapping mode (nadir angle) to produce an orthomosaic map. It performed the UAS flight following the procedures of conventional monitoring UAS missions on oil spills in open water in temperate conditions. Generally, these procedures entail flying transects as far as possible (with the visual observer maintaining a line of sight with the UAS) in multiple directions in order to monitor or detect possible features associated with floating oil. The flight path shown in Figure 57 has the shape of two deltas intersecting. The pilot tried to optimize the direction of flights (and battery life) to cover as large an area as possible while the sensor was constantly collecting imagery in nadir mode within line of sight.



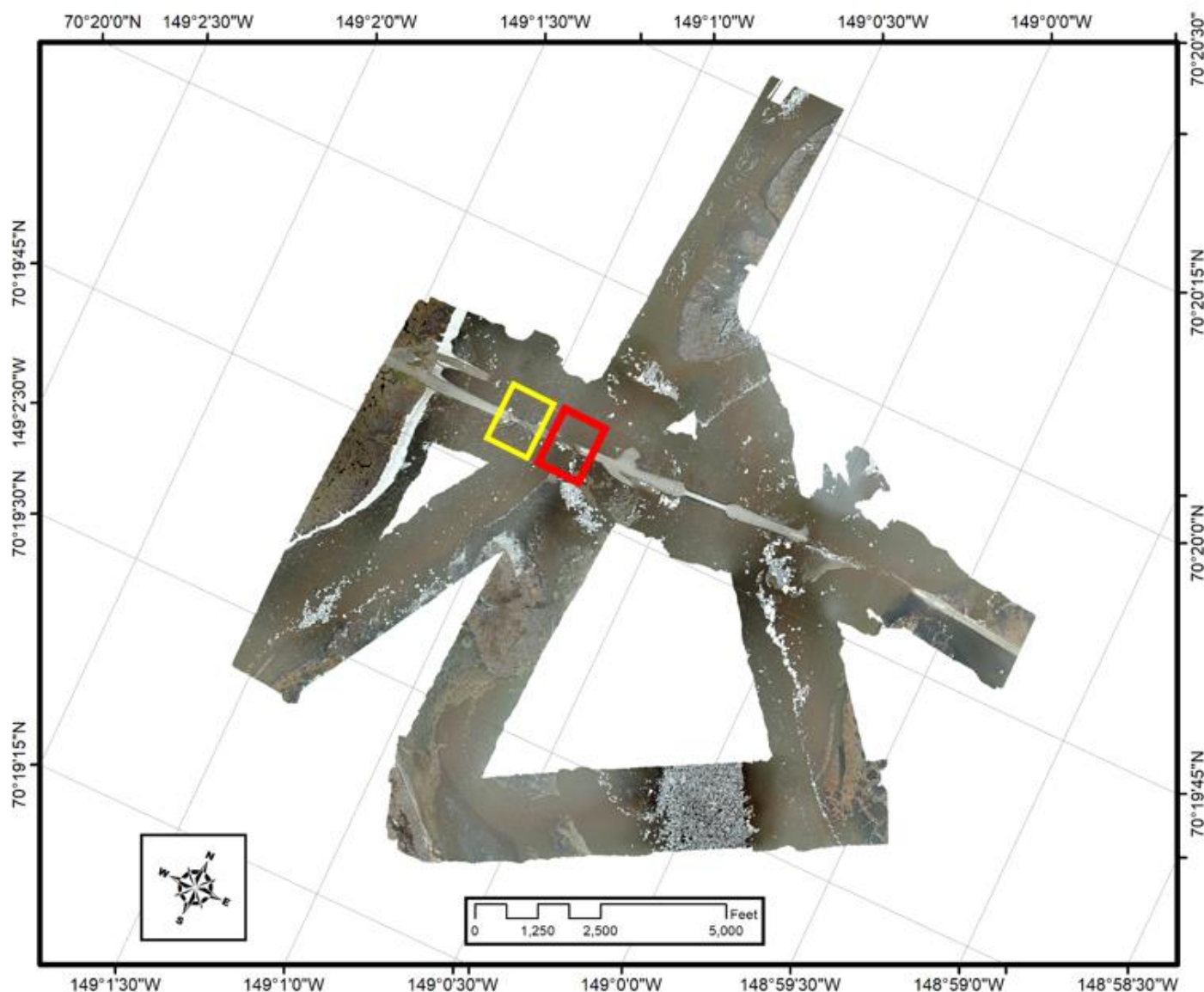


Figure 57. UAS orthomosaic simulating oil spill monitoring mapping mission of broken ice in open water. Altitude = 400 ft; max resolution = 2.5 cm.

The orthomosaic map (Figure 57) was produced by flying the survey mission at maximum altitude (400 ft). The longest transect mapped covered 5.1 km. Figure 58 and Figure 59 show a close-up detail of the ice being trapped by a bridge as a crane conducted operations to remove it so as to prevent obstruction of water flow (red and yellow rectangles in Figure 57). This map is an example of the usefulness of preserving the maximum resolution when generating the orthomosaics to capture as much details as possible.

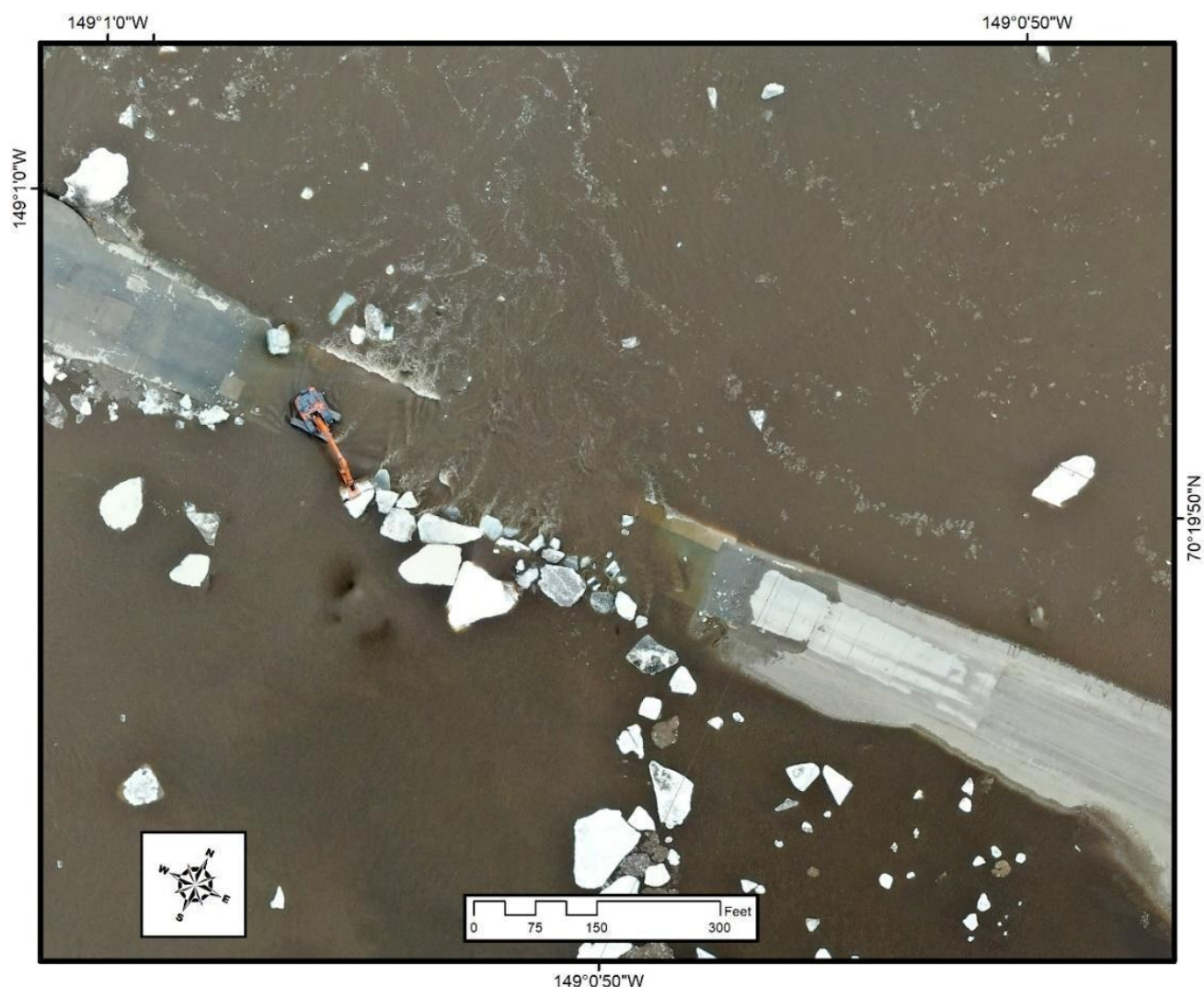


Figure 58. Subset of simulated and spill orthomosaic showing broken ice accumulation on one side of a bridge.

By using maximum resolution on the orthomosaic, the project team can identify features with a high level of detail. This subset of the orthomosaic on Figure 58 only shows a portion of the bridge where the crane is working to remove the ice obstruction. It is important to note that this map extends for almost 5 km, preserving this level of resolution throughout. The digital version of this orthomosaic can be explored on a visualization software (i.e., ArcMap) including the various areas of the map at maximum resolution (i.e., reviewing the imagery north-south and east-west by using the panning and zoom in-out tools).

In parallel to the visual orthomosaic, a thermal orthomosaic map shows a clear distinction among the features captured by the infrared sensor. Figure 59 is another subsection of the orthomosaic where the visual and thermal images can be observed at the same time. The thermal sensor covers a much narrower swath (or field of view) than the visual. The thermal sensor identified features such as rocks, dust and dirt, the road, water, and ice, with their different temperature values. Similarly, the thermal sensor would detect a different gradient of temperature for floating oil, if it were present.



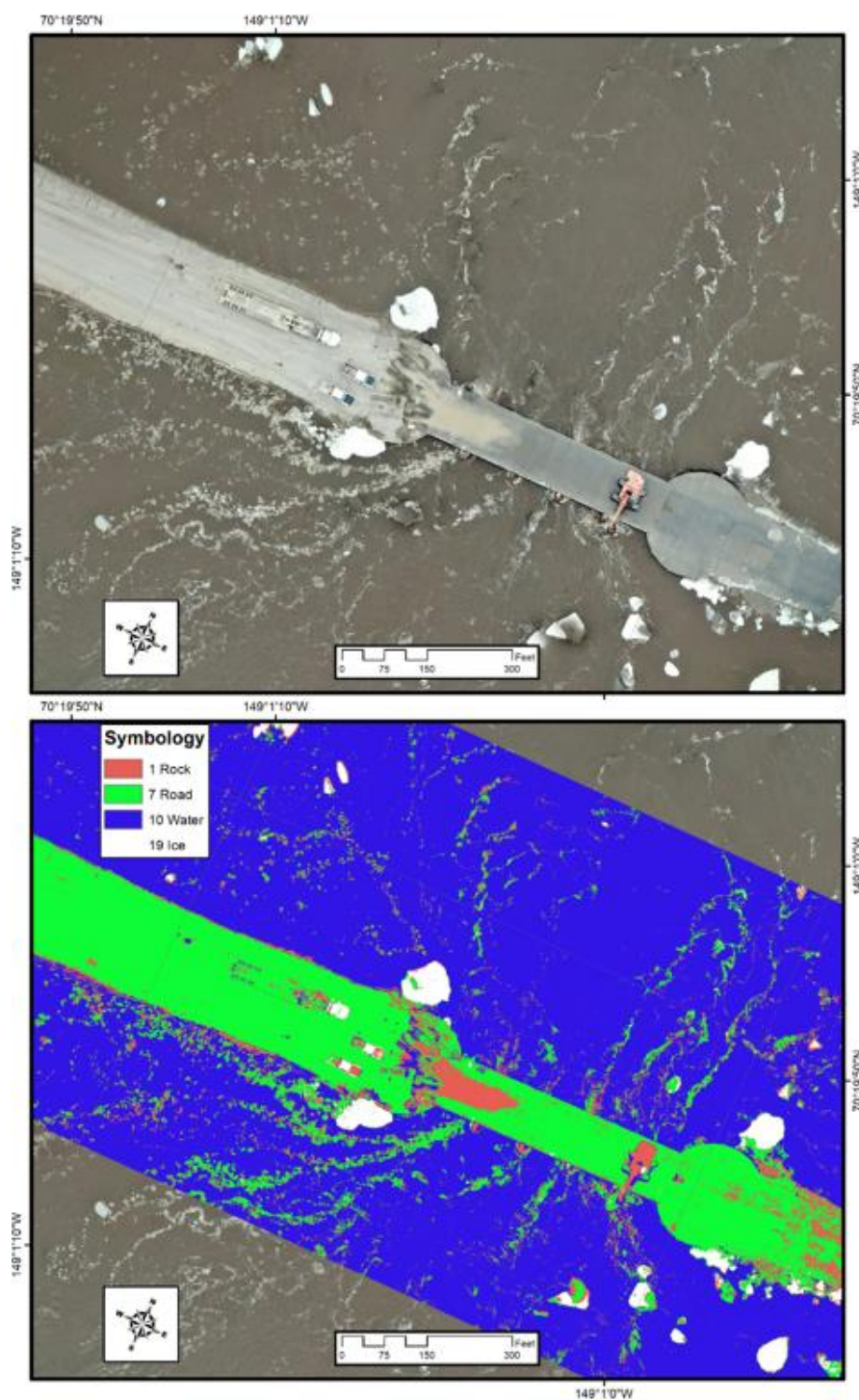


Figure 59. Visual orthomosaic and classification of thermal imagery for identification of ice blocks.

UAS data collected during the broken ice survey included visual, thermal, and multispectral imagery. The example in Figure 60 shows a visual map of broken ice (left), and its classification map from the thermal imagery (right).

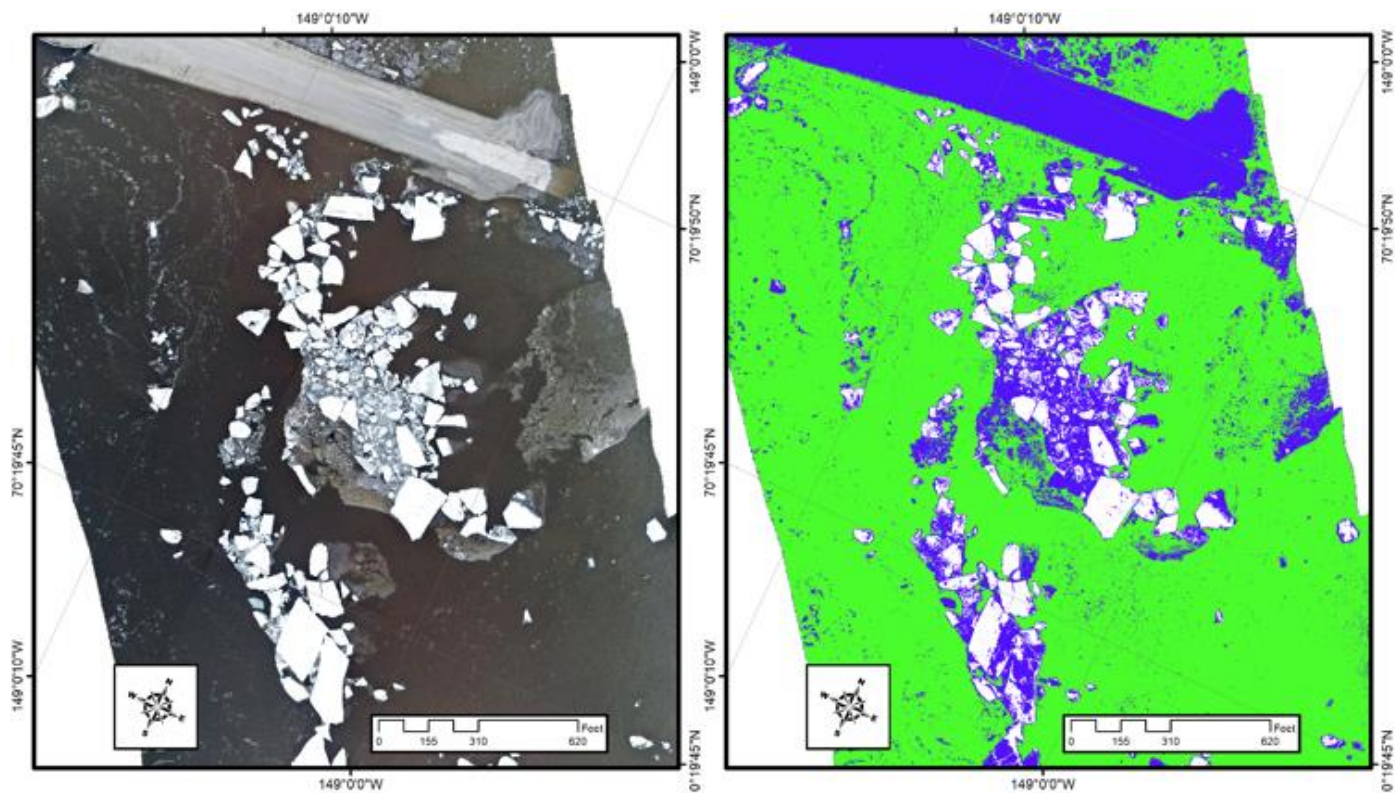


Figure 60. Rapid classification of visual orthomosaic for mapping broken ice.

3.2 Phase II: Vessel-Based Experiments

The project team conducted Phase II operations aboard the Canadian icebreaker and buoy tender Sir Wilfrid Laurier (Figure 3). This ship is 83 m long and is a high endurance, multi-tasked vessel. It is equipped with a flight deck, laboratory space, and has Wi-Fi internet.

3.2.1 Objective 1. UAS Flight Operations and Maneuvering From a Moving Vessel in Broken Ice

3.2.1.1 UAS platform

The project team used the same UAS for the Oliktok Point experiments for Phase II, the quadcopter outfitted with multispectral and thermal sensors.

3.2.1.2 Pilot protection

For extreme cold conditions, the pilot must wear special gloves (not only for the touch screen, but also for sensitivity of the joystick controller) and use handwarmers so the joysticks, switches, and touch screen on the controller can be operated properly.

3.2.1.3 Battery safety in extreme cold

In freezing conditions, the Lithium-polymer battery (LiPo) 12 cell (12S) batteries that power the quadcopter require charging temperatures to be at least 41 °F for optimal charging and preventing damage to the battery. The team charged LiPo batteries inside the vessel to prevent the LiPo cells from experiencing strain due to the extreme cold. Charging batteries outside should be avoided, as freezing temperatures interfere



with the charge readings and can produce critical errors during charging and use of the batteries during flight. Setup and operation of the UAS equipment is performed mostly on the vessel's deck.

3.2.1.4 *Sensor transition from mild to low temperature*

The pilot must ensure that there is no condensation on the lenses of the multispectral camera. Getting the sensor from inside the vessel to the deck exposes it to drastic temperature changes that can cause condensation or freezing of the optics and/or of the mechanism of the gimbal and the lenses on the sensors. The equipment must be inspected quickly, but thoroughly every time it is brought outside. Though the multispectral sensor in particular is waterproof, exposure to moisture or water under freezing conditions can produce icing on moving parts that could result in critical malfunctions of the equipment. Therefore, it is imperative to constantly inspect the equipment for water, condensation, and ice.

3.2.1.5 *UAS safety in high wind conditions*

The Arctic conditions experienced during the voyage (i.e., dense fog, strong winds, rain) were challenging for the operation of the UAS. When operating a UAS from a moving vessel, the pilot has to be aware of the orientation and motion of the vessel, possible obstacles, and limited room for landing and takeoff. The sea was calm since floating ice dampened the effect of the wind on the ocean surface. However, conditions were often above the quadcopter's wind limits. Although the UAS had flown in >30 mph winds over land, the strong and frequent gusts above the limit would have compromised safety. During the summer months in the Arctic, daylight occurs 24 hours a day, but the team had visibility issues with dense fog.

The project team monitored the weather forecast constantly. As part of pre-flight check procedures, UAS operation was evaluated based on wind, visibility, rain, fog, and temperature. Fortunately, a narrow window of opportunity for testing the equipment occurred on the evening of July 27 when winds dropped to ~20 mph and the team initiated a short flight at 200 ft. It evaluated the UAS' flight performance, navigation systems and sensors, and collected nadir imagery to simulate a survey mapping mission.

3.2.1.6 *Navigation UAS safety*

The metal hull and electronic components of the vessel create a magnetic interference that can interfere with the UAS's compass, Global Positioning System (GPS), and Inertial Measurement Unit (IMU). An IMU measures the UAS specific force, angular rate, and orientation. The compass, GPS, and IMU showed signs of interference when the UAS was within 20 ft of the vessel (including during landing and takeoff). NOAA OR&R has used UAS for offshore operations for a decade. Over the years it saw an improvement on the technology related to the aircraft systems, software, controllers, sensors, etc. However, there is always the need for testing the drone's navigational system to ensure that it can be operated safely. Some of the risks of having magnetic interference with the navigational system of the drone can cause loss of control of the aircraft which could end in significant risk while approaching the vessel during takeoff or landing. Since the team knew about previous incidents related to magnetic and compass interference on other UAS equipment, as a safety practice, it minimized UAS operations in proximity of the vessel. The compass and IMU were calibrated before each flight to help minimize risk. There were no issues with the aircraft navigation systems during Phase II testing.

To minimize the interference from the metal deck, the project team used a wooden platform as a launching pad (Figure 61) and performed hand-landing with the assistance of the visual observer (Figure 62), which prevented contact with the metal deck. During flights, there were always >10 GPS satellites available, which is well above the minimum required for the navigation system of the UAS. It is also possible to fly in



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

manual mode with fewer/no satellites. The RTK system was activated, which added more satellites to enhance the precision of the positioning of the aircraft.



Figure 61. Pilot conducts a pre-flight visual inspection of the UAS on a wooden platform.



Figure 62. Hand-catch landing of the UAS assisted by the visual observer.



3.2.2 Objective 2. Data Acquisition and Processing on the Vessel

The voyage was planned and scheduled on one of the most favorable seasons in the Arctic, which is the middle of summer. The project team acquired near real-time Synthetic Aperture Radar (SAR) satellite imagery and analyzed them on the vessel to locate broken ice (e.g., Figure 63 and Figure 64).

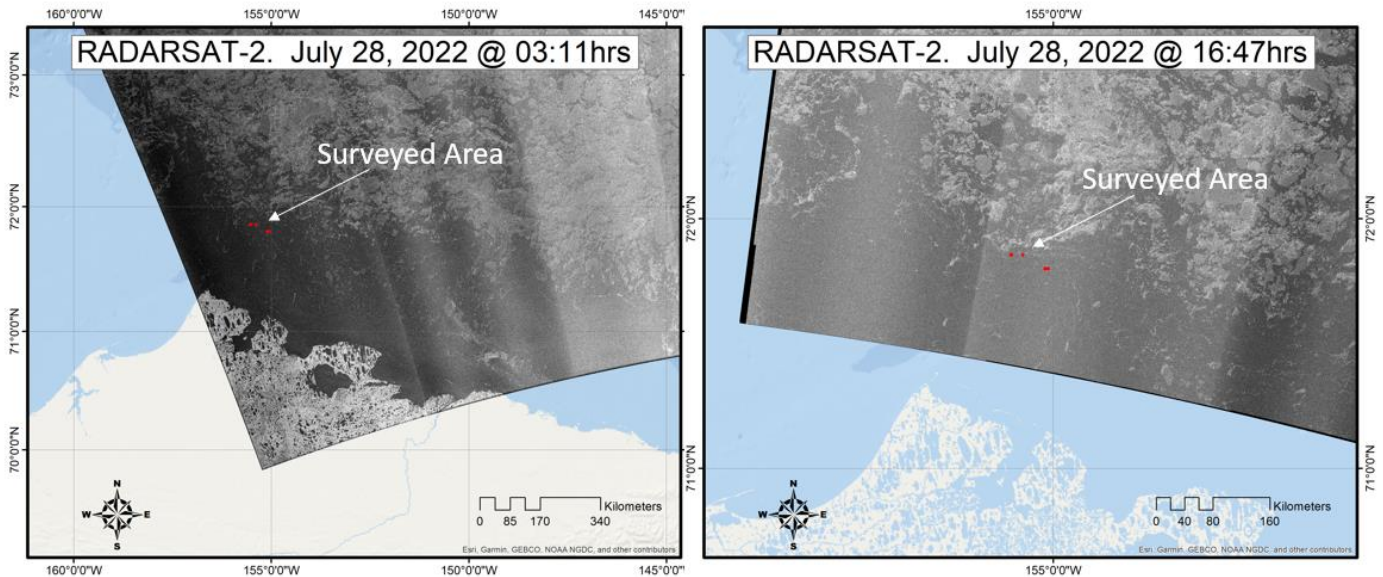


Figure 63. SAR satellite imagery of broken-ice conditions.

Satellite images were helpful with planning the missions and the navigation trajectory of the icebreaker. Figure 64 shows satellite images collected on July 28 showing the ice boundary on the open sea. The brighter feature on the north side of the satellite image shows the ice, the dark area on the image is open water, and the white feature on the south part of the map is the North Slope, AK. The surveyed areas were approximately 30 – 50 miles from shore. The project team used these images to plan the vessel's trajectory to encounter the broken ice north of Utqiagvik, AK.



Figure 64. Enlarged SAR satellite image showing ice boundary on the north side of the map and the areas surveyed by the UAS.

On July 26, the project team executed a short flight to test the UAS equipment, software, and data transmission. The majority of the flights (seven in total) occurred on July 27 when environmental conditions improved (<20 mph winds). The team also executed UAS maneuvers used during conventional oil spill response operations including: tactical positioning of the vessel, detection of targets with thermal imagery, surveillance missions, and multiple surveys for mapping. The team successfully collected survey mission data from the first flight on July 27 using the multispectral sensor following the procedure that would be used during an oil spill. Once the maximum altitude (200 ft due to heavy fog) during flight was reached, the pilot used real-time video on the UAS controller to fix a flight path and started collecting imagery in nadir mode.

The first UAS survey collected 260 images using the multispectral sensor. For this and all of the subsequent flights, the procedures for UAS operations were the same as used in temperate waters. The dataset was processed using the image processing software to produce an orthomosaic (Figure 65) with the true color (RGB) map on the left and its classification on the right.

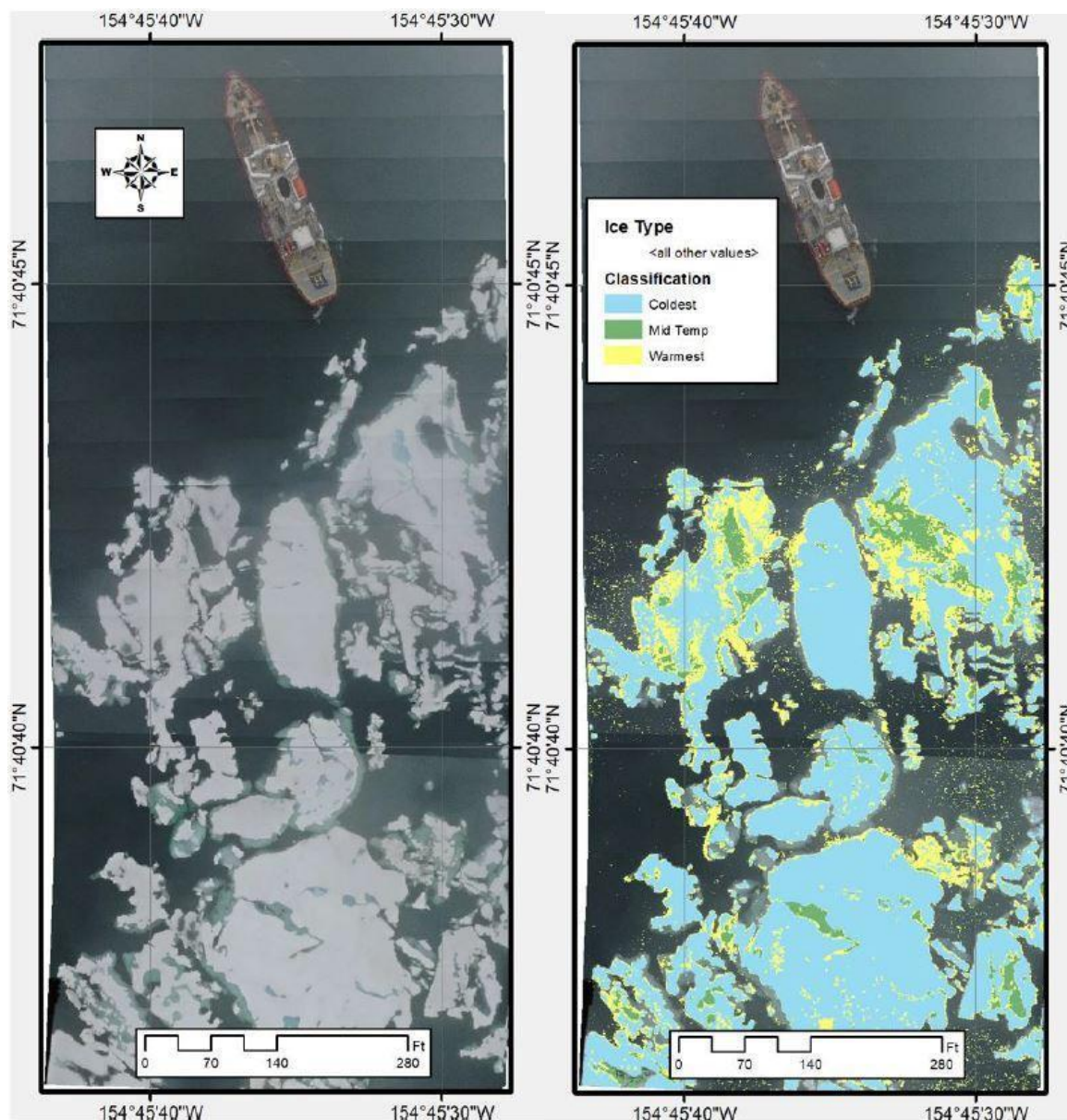


Figure 65. UAS orthomosaic showing CCGS Sir Wilfrid Laurier and broken ice.

While operating from the ground, the pilot can walk around and plan for landing, takeoff, and maneuvering with a lot more room to adjust the flight of the UAS. However, from a moving vessel, the pilot has to be aware of the orientation and motion of the vessel, possible obstacles, and limited room for landing and takeoff. Acquiring the datasets of broken ice on the Kuparik River was crucial to prepare, plan, and practice for the processing of the data while onboard the icebreaker.

3.2.3 Objective 3. Data Delivery in Near Real-Time from the Vessel to NOAA OR&R

The Sir Wilfrid Laurier was outfitted with internet and Wi-Fi. However, the bandwidth was limited. The data handling procedures had to be modified to manage the transmission of the data to a NOAA server by uploading files of less than 5 MB into DIVER. To accomplish this, processing routines were modified, and spatial resolution was reduced to 1 m x 1 m per pixel outputs. Some data outputs were at different levels of

Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

resolution to preserve features of interest. Outputs were produced as shapefile polygons (ArcGIS datatype) as required by ERMA.

Data from the first flight was processed, uploaded to DIVER, and posted on ERMA <1 hr after the UAS landed (Figure 66). Once the process was fully integrated, the processing time was reduced to <30 min. Future missions may be able to perform this process more rapidly.

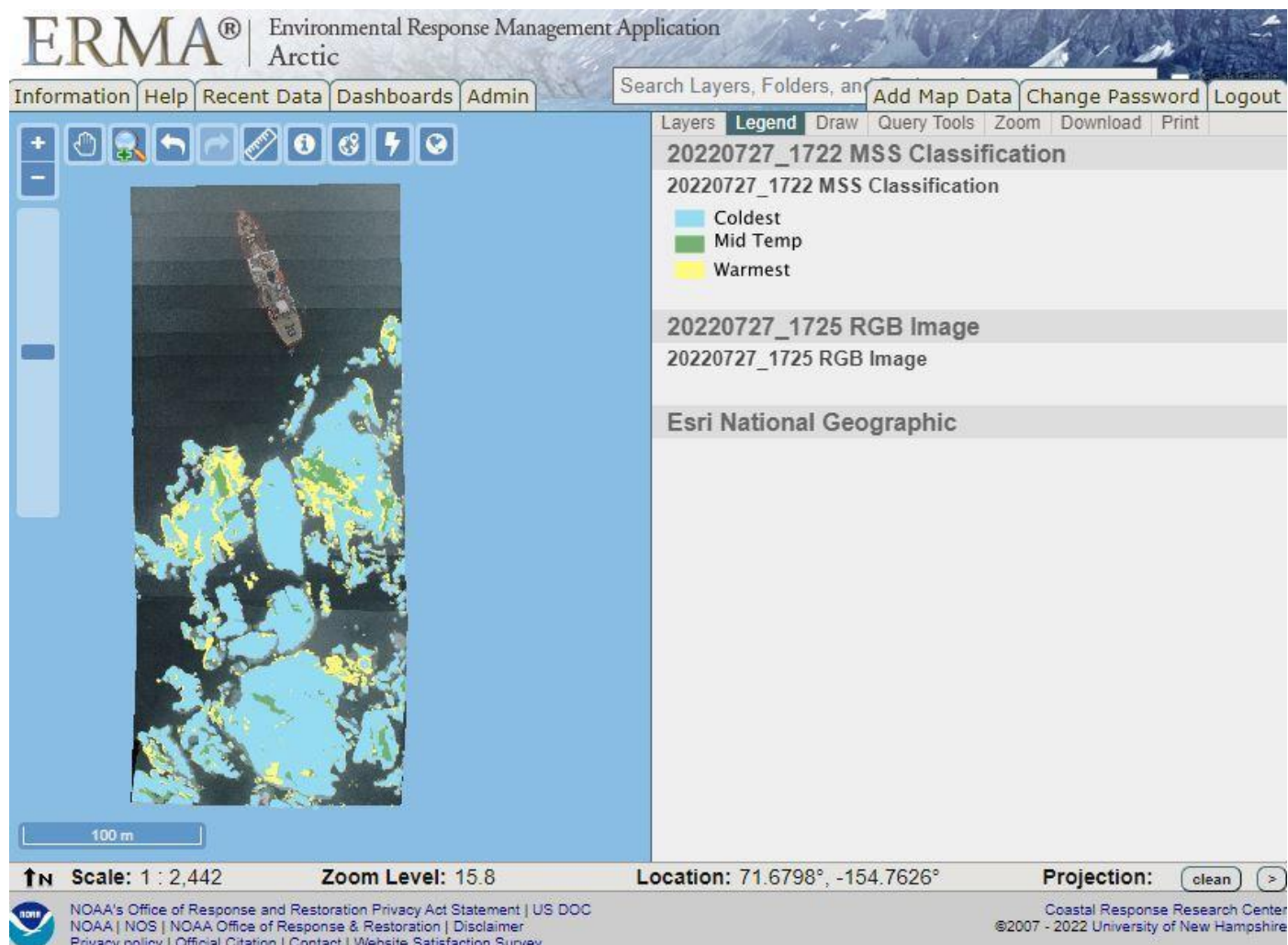


Figure 66. ERMA screen capture showing imagery (orthomosaic) and classification data (shapefile) delivered in near real-time from the icebreaker.

The UAS data shown in Figure 65 and Figure 66 were also sent to the NOAA OR&R Emergency Response Division (ERD) modeling team. The data generated from multiple flights was used in conjunction with the OR&R modeling software WebGNOME, a publicly available Web-based application that provides a user-friendly interface for modeling oil spill scenarios. WebGNOME allows users to easily set up a custom spill scenario, run the model, and visualize the results. Figure 67 shows a screenshot of the UAS data ingestion into WebGNOME.



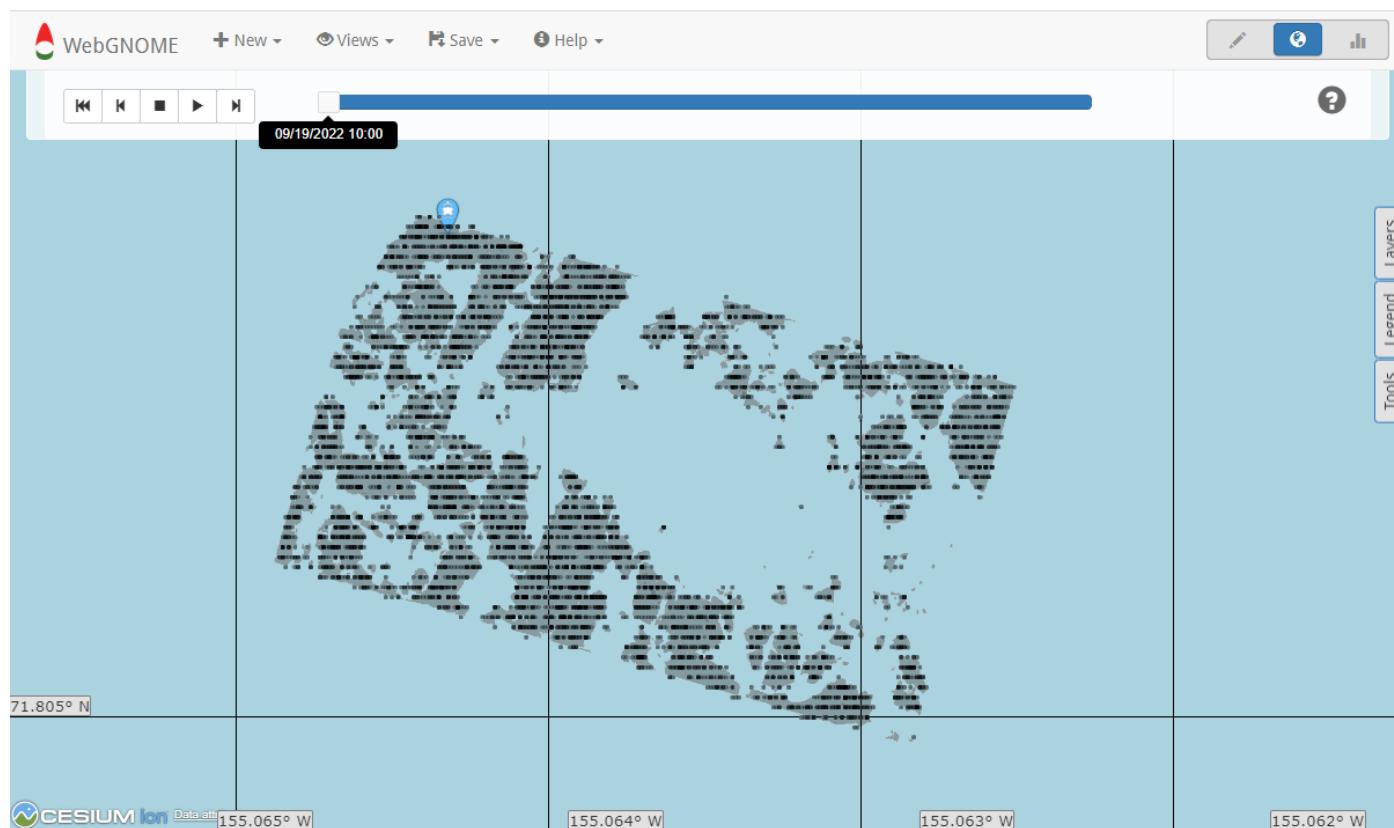


Figure 67. UAS classification data ingested on oil spill model GNOME.

On July 29, the project team conducted mapping survey missions at different altitudes and multiple patterns of flights including grids and linear transects. It detected different types of ice features with the multispectral and thermal sensors. For example, Figure 68 shows a UAS survey flown at an altitude of 150 ft over an area where a thick layer of multiyear ice was detected. Figure 69 shows a UAS survey at a maximum altitude of 400 ft in which the field of view of the sensor allowed wider coverage of the mapping mission on a single pass. The image resolution of a map flown at 150 ft is approximately 1 cm² per pixel, while the resolution at 400 ft is approximately 2.5 cm² (i.e., note the difference in the size of the icebreaker in Figure 68 and Figure 69). The ultra-high resolution of the UAS sensor is more than adequate for the detection of ice or oil features even at a maximum altitude of 400 ft. The blue line used on the maps shows the delineation of the ice/water boundaries. The legend on the classification map: 20220728_1346a_MSScls follows a format defined by NOAA for ERMA which includes YearMonthDay_Time_series_Sensor.

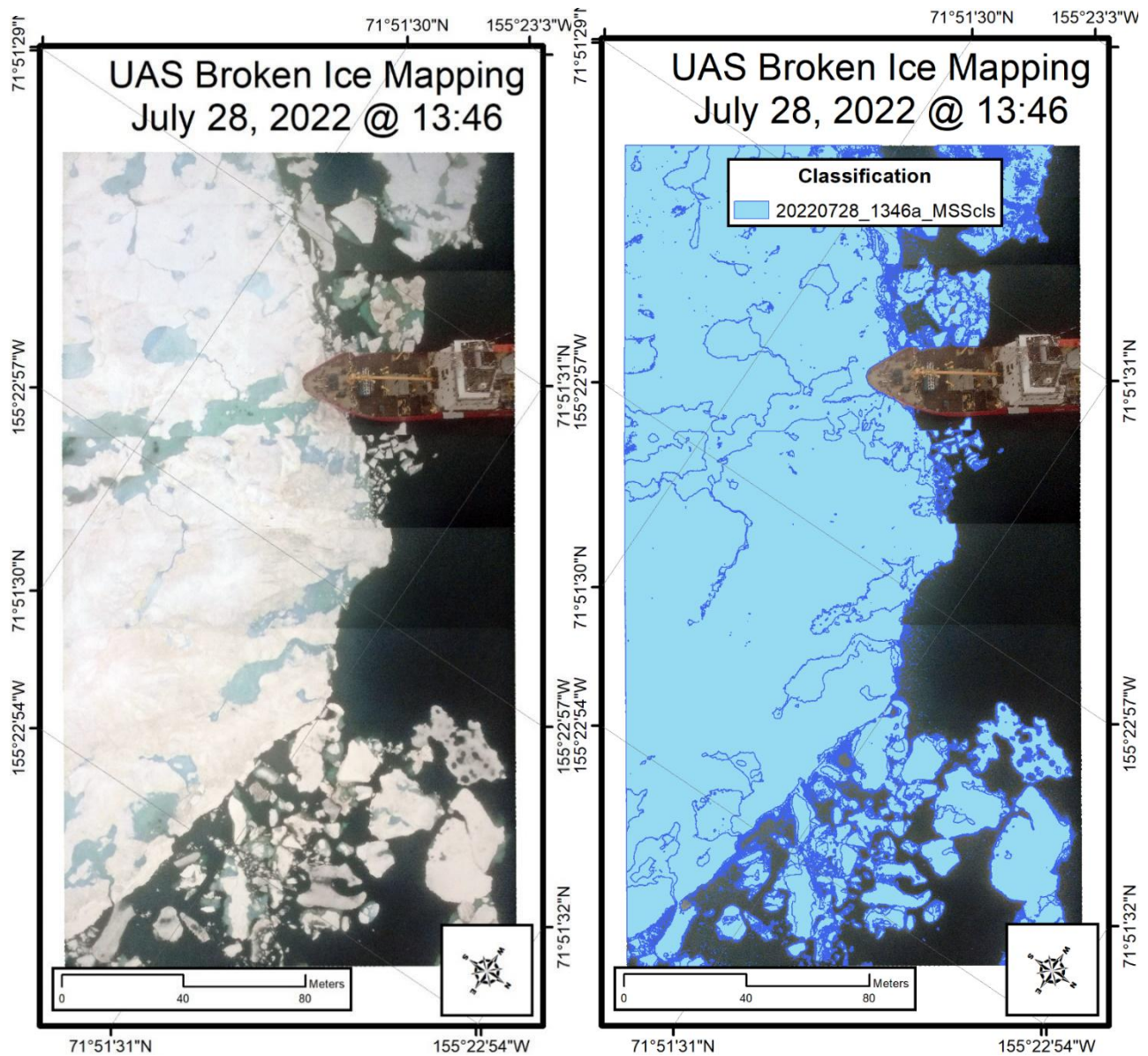


Figure 68. UAS survey flown at an altitude of 150 ft over a thick layer of multiyear ice.

Left panel is the true color (RGB) and the right panel is its classification showing the delineation of the ice. The blue line on the classification delineates the boundary of the ice and water pockets on top of the ice or separated fragments of floating ice.

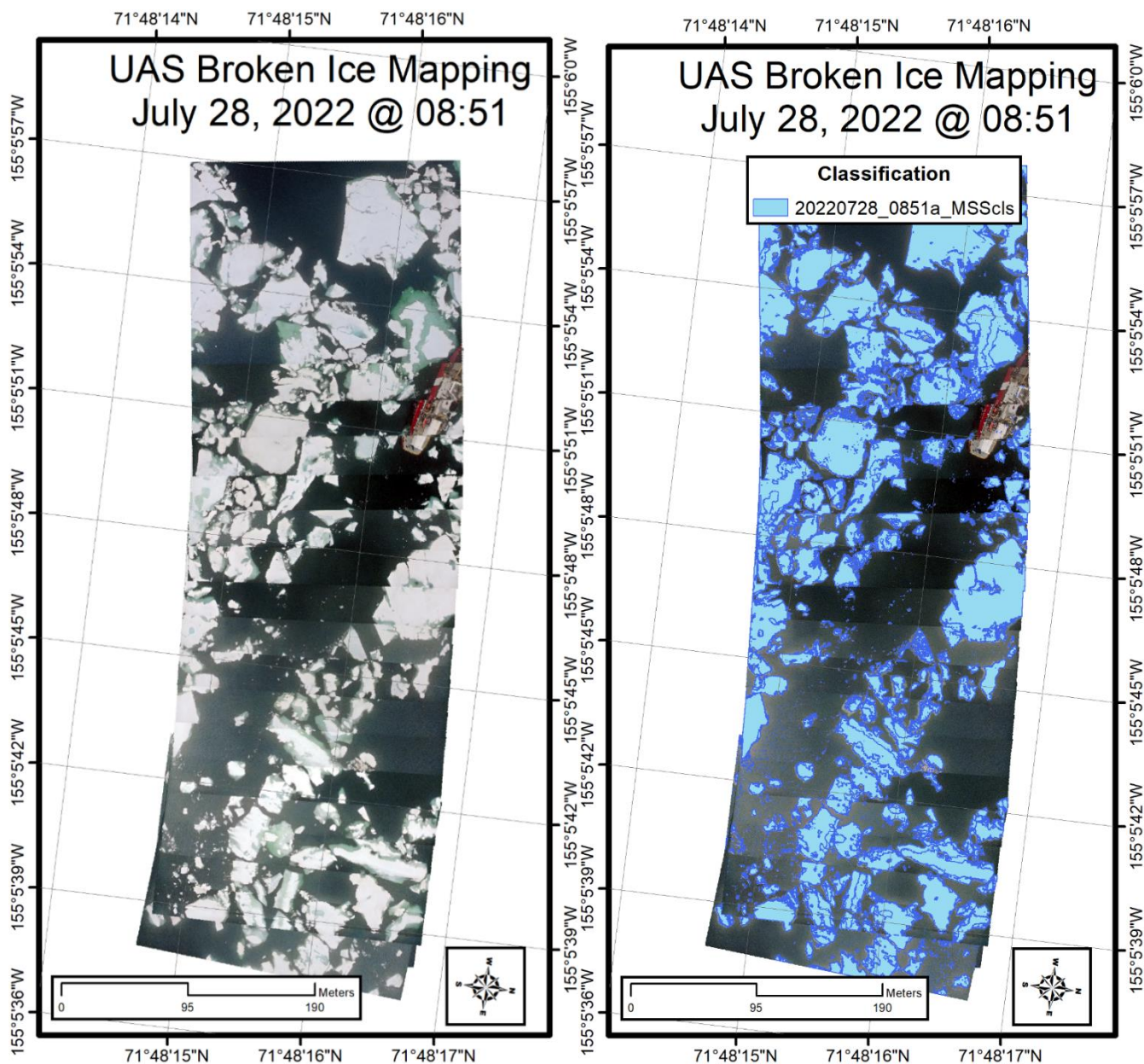


Figure 69. UAS survey flown at an altitude of 400 ft over a thick layer of multiyear ice.

Left panel is the true color (RGB) and the right panel is its classification showing the delineation of the ice over ~1 km long track. The blue line on the classification delineates the boundary of the ice from water pockets on top of the ice or separated fragments of floating ice.

3.2.4 Tactical Positioning of the Vessel for Oil Spill Response Operations

During temperate waters oil spills, UAS real-time video feedback can be used to direct response vessels towards targets of interest. The project team successfully performed a similar operation during test flights on July 28. When the icebreaker was moving (breaking ice), the visual observer used a radio to communicate with the captain of the vessel regarding navigation of the vessel by on the real-time video feed from the UAS (Figure 70).

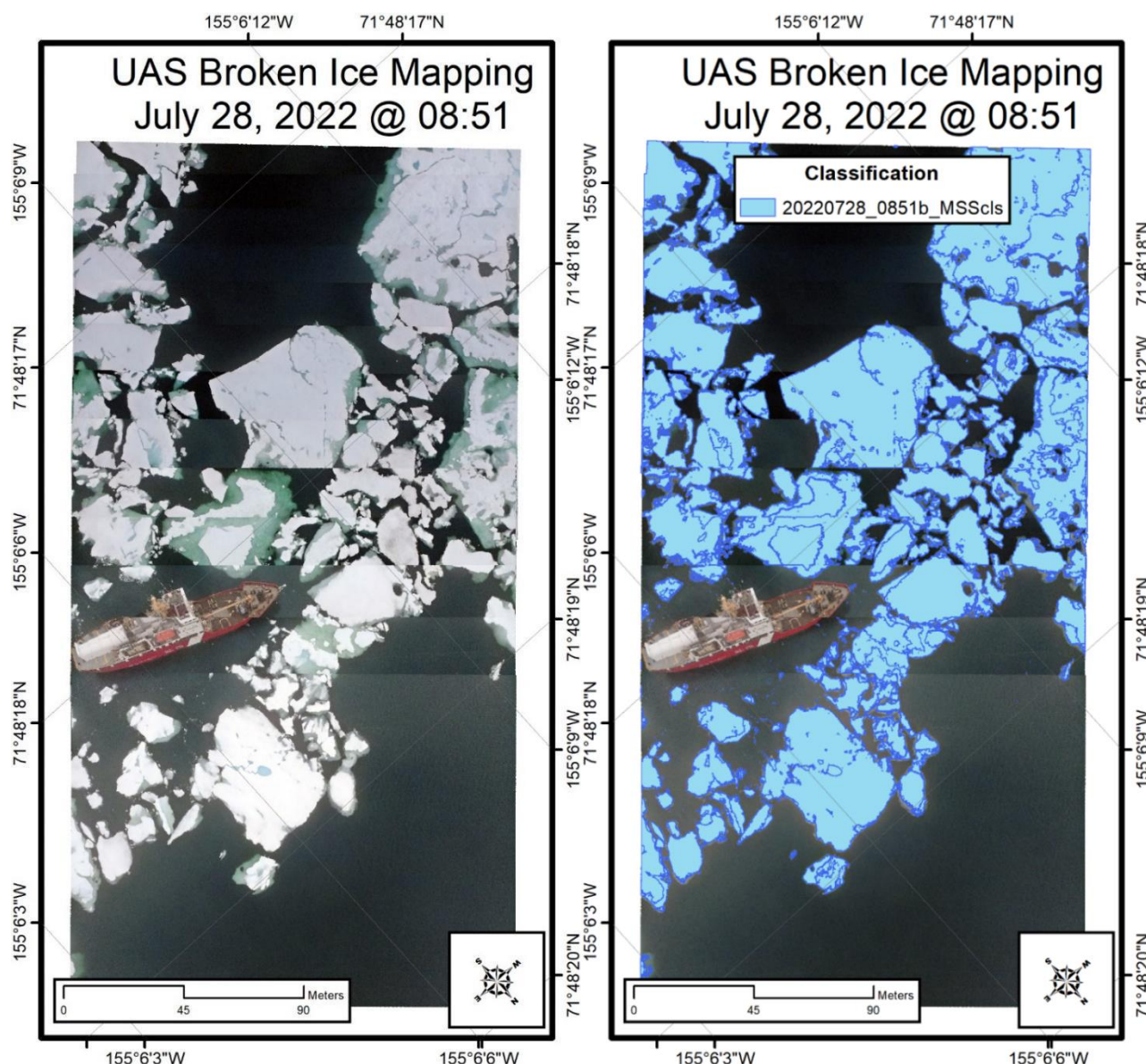


Figure 70. UAS broken ice mapping.

Based on the protocols established by NOAA to generate and label data products, it has been specified that 'DATE_TIME_SensorType' should be used as a file naming convention. For this case, the label 20220728_0851b_MSScls corresponds to the date and time of this orthomosaic which was generated from a multispectral sensor (see Appendix A).

3.2.5 Tactical Position and Detection of Targets with Thermal and Multispectral Sensors

UAS can be equipped with sensors other than the ones with which they were purchased (i.e., thermal sensor) to detect oil spill thickness. The thermal sensor can also be useful in detecting targets not easily seen using visual channels, such as warm blooded biota (e.g., marine mammals) that may be exposed to oil. For example, during one of the flights, the thermal imager rapidly detected a seal resting on the edge of the ice. To avoid disturbing the seal, the team used an 80x optical zoom from a distance greater than 200 ft. The seal

Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

photography was allowed because the team was operating under the auspice of the NOAA MMHSRP permit (18786-06).

The potential for UAS equipment for the detection and monitoring of natural resources with multispectral, thermal, and visual imagery can prevent exposure of sensitive species to oil by informing the deployment of response assets. It can also support assessments by providing time-critical data showing marine mammals with potential for exposure before, during or following an incident. The signature created by marine life is distinctive on the thermal imagery (Figure 71 and Figure 72). A contrasted thermal image is much better than a visual one to quickly distinguish marine life from their surroundings, in this case the seal from the ice and surrounding waters. The seal's apparent temperature was 37.6 °F not easily seen using visual channels, while the ice and surrounding waters were ~13.6 °F.

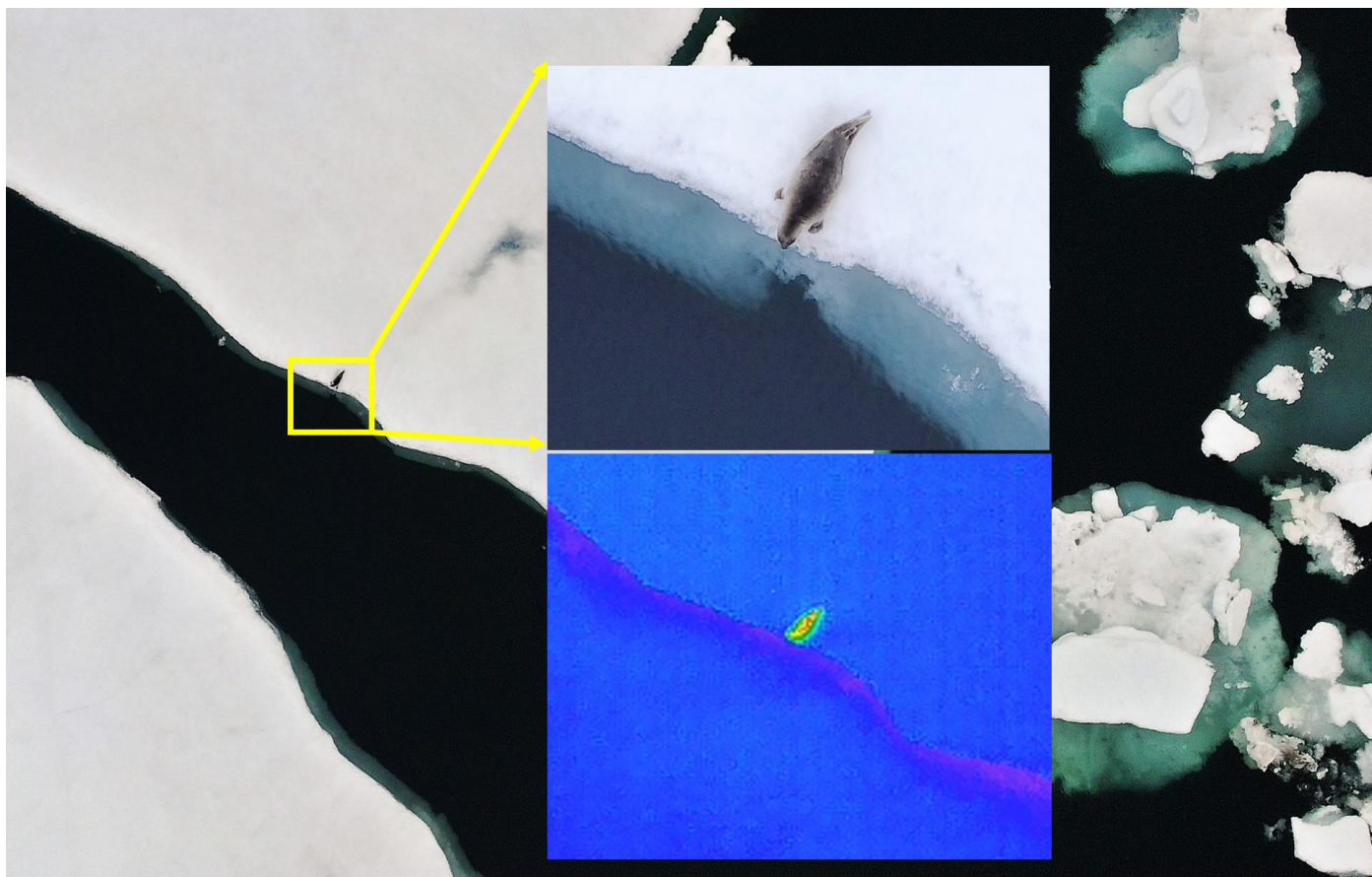


Figure 71. UAS detection of a seal on the ice edge with an 80x optical zoom.



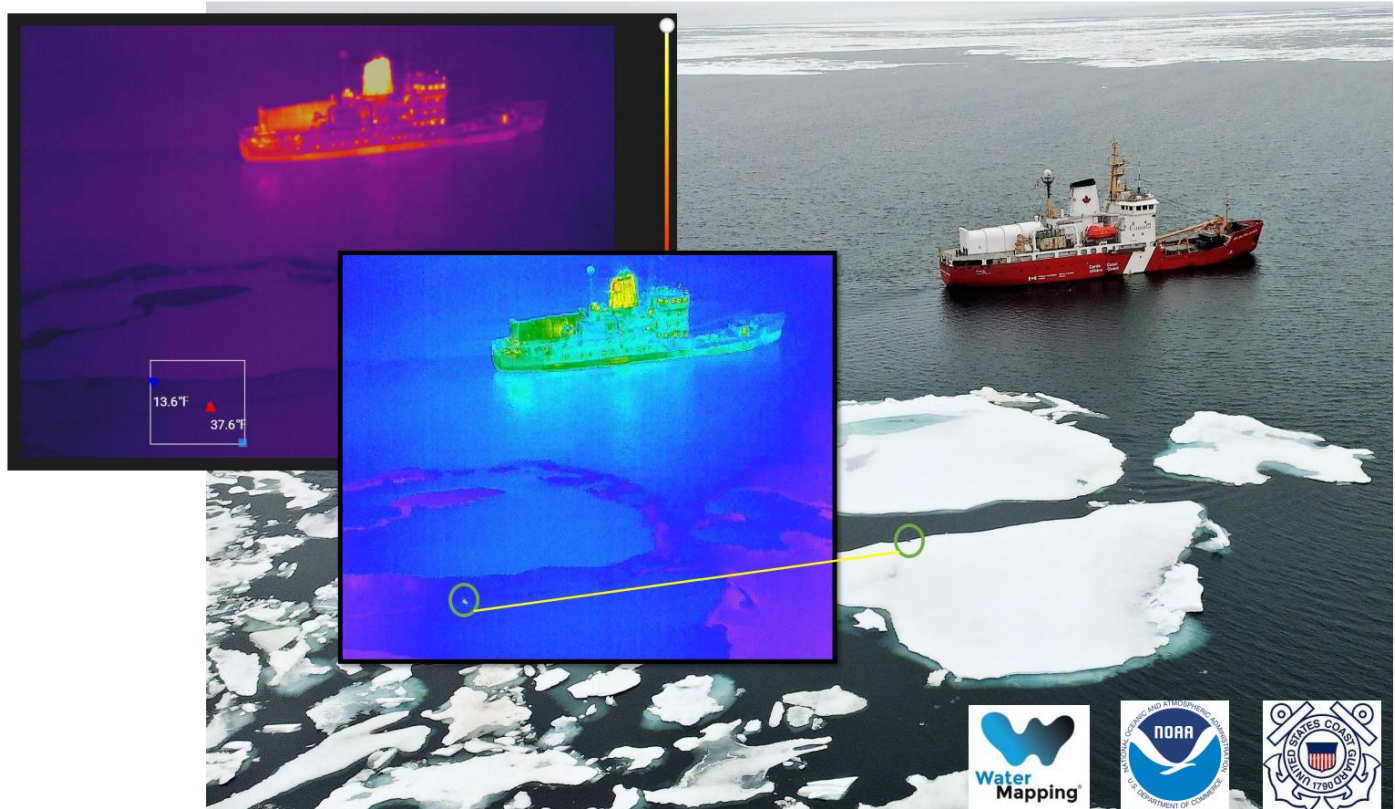


Figure 72. Detection of a seal using the thermal sensor at an altitude of 200 ft.

3.2.6 Analysis of Thermal Gradient between Ice and Open Water

Determination of oil thickness using a thermal sensor depends on the “background” apparent temperature of the clean open water compared to the oil’s apparent temperature. The broken ice in the open water can affect the temperature readings of the floating oil. Figure 73 shows an example of the thermal imagery of ice and open water. A color palette can be used to highlight key features. The rear of the vessel shows yellow and orange colors depicting the warmest temperatures, while the dark purple is the coldest (ice).

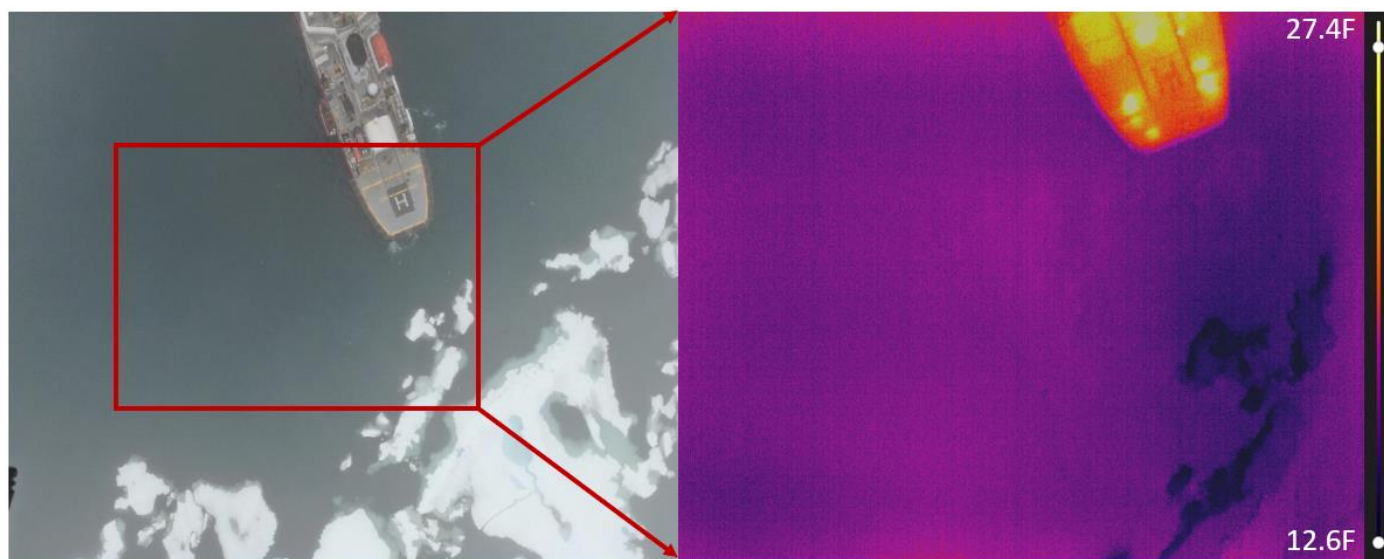


Figure 73. Visual (left) and thermal (right) UAS images capturing broken ice and the water next to the icebreaker.

Because the propulsion of the vessel created turbulence that mixed water from deeper to upper layers (lighter purple behind the vessel on thermal image), temperature relationships between the ice and water had to be determined when the vessel was not nearby (Figure 74). To analyze the gradient of temperatures as the distance from the ice increases, the project team used a linear (gray scale) color palette to analyze the temperatures gradient. The infrared imagery detects thermal boundaries invisible to the naked eye. For example, by comparing the visual against the thermal, the cooling effect of the ice underneath the water can be seen with the light changes of tones (linked to slight changes on temperatures). The colder the temperature, the darker the color. Figure 74 also shows a snapshot of the complex thermodynamic process of warmer and colder water circulating among the ice features. There are convective (vertical and horizontal) patterns depending on the proximity of the water to the ice. The reflection of the infrared light from the ice makes it appear warmer than the water. It is important to point out that the thermal readings from the infrared sensor are only for the surface waters. These thermal patterns require further investigation. For future missions, thermal imagery should be collected at low altitudes (and ground truth).

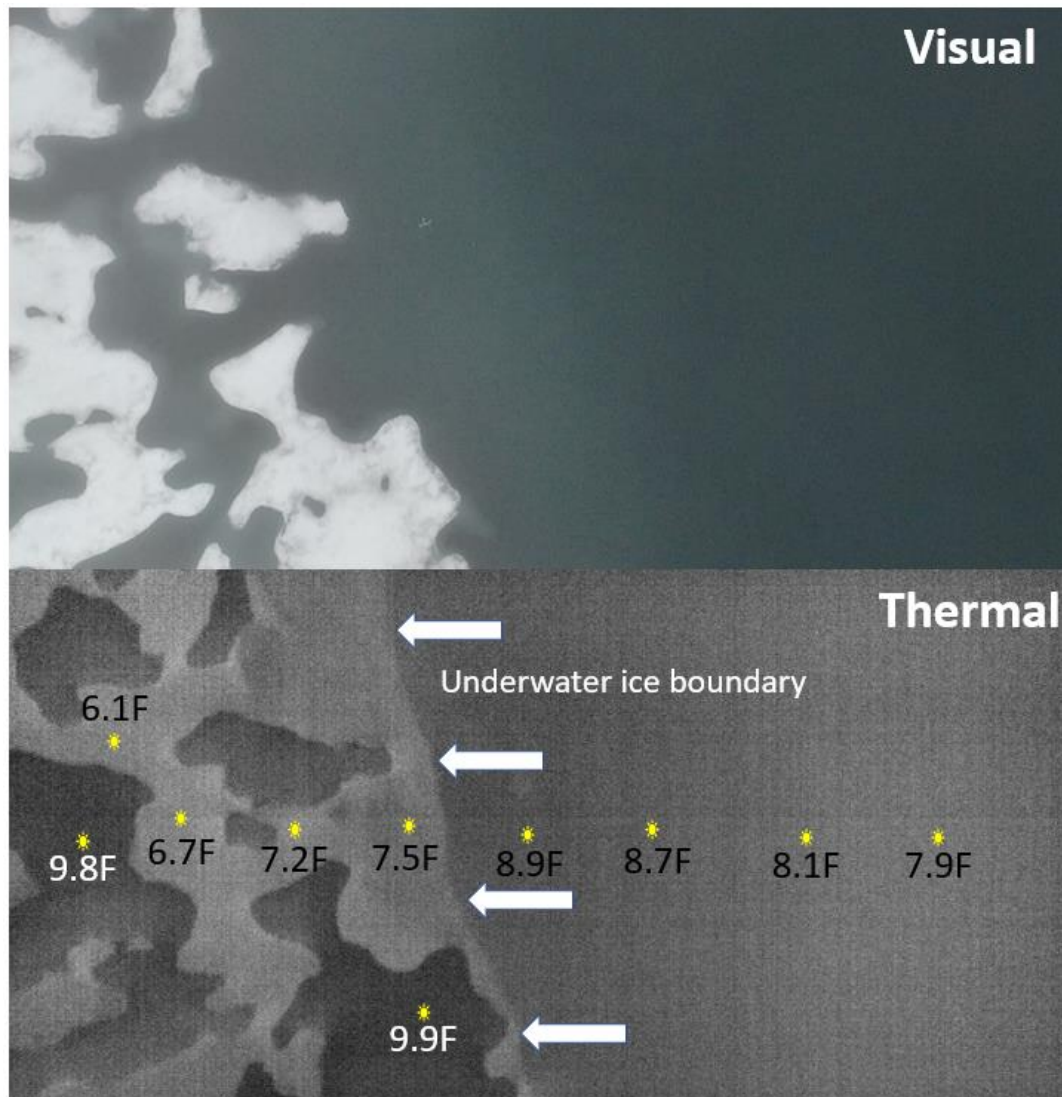


Figure 74. Comparison of the visual (RGB) (top) and thermal images (bottom) showed that the water in between the floating pieces of broken ice was much colder than the open water.

4 CONCLUSIONS

4.1 Phase I: Shore-Based Experiments

4.1.1 Thermal Detection of ANS

There is a hyperbolic relationship between ANS thickness and apparent temperature, as measured by the thermal sensor at 0% and 50% ice cover. The shape and position of the curves changed with the water temperature and to a lesser extent the light level (lux). At Oliktok Point in the morning at ~ 0700 (~23,000 lux) there was not enough light for the sensor to measure significant changes on apparent temperature. At higher light levels (> 34,000 lux), water temperature seemed to be the major variable impacting the characteristics of the curves. In conditions where the water temperatures were similar, the curves were the most similar to one another.



50% ice decreased the temperature of the water in the totes and therefore lowered the position of the hyperbole and flattened its shape somewhat. In spite of this, it appeared that with sufficient light, the sensors could potentially predict oil thickness with degree of certainty.

The project team designed the Oliktok Point tote experiments based on conclusions/future research suggested by the CRREL research. While the range of thicknesses evaluated (50 to 5,000 μm) yielded hyperbolic curves that could be used to estimate ANS thickness for a range of light levels and water temperature as a function of apparent temperature, there was not enough data to generate a family of curves. This is because there were only two flights per day. In addition, on 5/31 there was uneven distribution of the ANS. Thus, all thicknesses were $\geq 1,000 \mu\text{m}$. The other concern was the lack of continuous water temperature data in all of the totes (only 100 and 5,000 μm totes had data loggers). There was also a calibration problem with the ground level temperature device used to monitor surface water temperatures.

The sensitivity of the thermal sensors (ability to evaluate two thicknesses that are close to each other) is unknown.

The uncertainty associated with the estimation of oil thickness increases, as the standard deviation of the apparent temperature increases. The experiments were not designed with thin enough oil slicks to determine the detection limits of the thermal sensors for ANS, but it may be $\leq 50 \mu\text{m}$ for the Arctic conditions tested.

4.1.2 Thermal Detection of Marine Diesel

The thermal sensors had difficulty monitoring changes in apparent temperature as a function of the thickness in marine diesel. The hyperbolic shape of the curves was flattened with $r^2 < 0.6$ (as compared to > 0.80 for the ANS). This was true with and without ice and for the range of light levels and water temperatures tested at Oliktok Point. The thermal sensors can detect diesel, but there is no marked change in apparent temperature with thickness. This suggested that the thermal sensor may be only able to do presence/absence detection of diesel under Arctic conditions. The minimum detection limit for marine diesel using thermal sensor is a subject of further research.

4.1.3 Limits of Thickness Detection of Oil with Ice

Experiments with totes demonstrated the complexity of attempting to derive oil thicknesses with thermal imagery on Arctic freezing conditions. The main challenges faced were the cold temperature causing low contrast between oil features, ice, and water (compared to temperate conditions). While temperature changes progressively increased as oil concentration increased, this could only be observed during the warmer days.

Operationally, thermal and visual sensors on UAS should be used for detection (presence/absence) and for relative (qualitative) identification of oil thicknesses.

4.1.4 Variation of Temperatures with Flight Altitude

The experiments demonstrated that regardless of the ambient conditions (warmer or colder days), UAS thermal sensors register higher apparent temperature for the oil as the flight altitude decreases. This could be due to spatial resolution and localized atmospheric effects.

4.1.5 Operationalization of UAS

Although the Skydio X2D UAS presented some sensor and operating limitations, newer generations of small drones should provide greater capability. A larger, utility-style UAS would provide higher payload capacity that could include both thermal and multispectral sensors for detection and precision mapping.

4.1.5.1 Skydio X2D

The Skydio X2D is a small, quick-response UAS, not a scientific research tool. There are limitations in the hardware and software, such as not being able to calibrate the thermal sensor. This prevents detailed imagery analysis. Understanding the limitations of the Skydio X2D will allow responders to obtain the best field results. Further testing would increase understanding of how effectively the Skydio X2D can identify oil in open waters, specifically:

- Range that the Skydio X2D can detect oil;
- Minimal surface oil thickness for detection;
- Optimal environmental conditions for oil detection; and
- Additional software for Skydio X2D that can aid in detection.

The Skydio's battery did not experience significant degradation in battery life during cold conditions; it flew for approximately 20 to 25 minutes. The flight time was within expectations for this model. More frequent use, standardized training, and operating familiarity, particularly at high-latitude and in cold weather, would enhance user confidence and better-identify potential control issues.

4.1.6 Classification Maps

In-situ, direct-observation of features verified UAS detection, classification, and mapping of gravel, ice, snow, and tundra vegetation. High and ultra-high-resolution imagery made possible the identification of centimetric details that could be confirmed in ground level and mid-altitude mapping. For this work, the optimal trade-off of spatial coverage and resolution for a UAS survey that required high detail was obtained with the UAS at 200 ft.

4.1.7 Near Real-Time Data Processing

One of the most important outcomes of this research was data production and distribution in near real-time. A SOP was created that describes the details of the technical parameters for all the data formatting. The SOP can serve as a foundation for future remote sensing data management processes (APPENDIX A).

The dataset produced from the broken ice experiment demonstrated the capacity of the mapping methods to produce classification maps identifying features such as broken ice, roads, and open water.

4.2 Phase II: Vessel-Based Experiments

The experiments aboard the CCGS Sir Wilfried Laurier allowed the team to demonstrate the potential of a UAS with a multispectral sensor as an operational tool for Arctic oil spill response, including providing a template for data delivery/management and UAS operation in cold weather. While freezing Arctic conditions present challenges for UAS operations, the team generated data products that could serve many aspects of an oil spill response. These data products can be used for tactical operations, NRDA, and modeling.



The vessel-based UAS operations executed included:

1. Surveillance and monitoring with multispectral, thermal, and visual sensor.
2. Survey missions for mapping.
3. Tactical positioning of the vessel.
4. Detection of marine life with thermal sensor.
5. Mapping and classification maps of detected features.
6. Processing and delivery of data in near real-time.
7. Data products suitable for NRDA, tactic response, and modeling.

5 RECOMMENDATIONS

5.1 Determine Use-Case Scenarios for CG Oil-Spill Responders to Collect and Manage UAS-Based Sensor Data

Current CG policy allows purchase of small UAS on a local basis subject to the provisions of the Short-Range Uncrewed Aviation Systems program manager. Guidance or functional requirements for the type(s) of UAS/sensor combination best-suited for field-unit oil-spill detection and mapping in open water and broken ice conditions must be developed. For future UAS program integration, detailed sensor or sensor payload requirements must be documented to meet oil-spill response mission needs including detection, characterization, thickness determination, mapping, and data delivery/management. The requirements should be platform-agnostic, allowing for scaling to align with UAS payload capacity.

Though a significant amount of oil-spill response UAS activity will be shore-based, strategies with boat and cutter facility managers to ensure oil-spill responders gain familiarity with operating a UAS from a moving vessel while acquiring data in a mapping mode must be developed, including cold-weather operations and data collection/delivery, where possible.

UAS operators should be trained and familiarized in oil-spill response protocols for data collection and delivery. This includes methods and standard operating procedures to assure that data are collected in a consistent manner throughout the CG. Operators should be introduced to using DIVER and ERMA platforms for uploading and sharing data.

5.2 Conduct Further Experimentation on Spill-Thickness Measurement

This project developed relationships (characterized by hyperbolic curves) between sensor-detected apparent oil temperature and actual oil thickness as a function of water temperature. Researchers should conduct additional experimentation to determine whether certain thresholds of illuminance need factoring into the calibration. Additionally, a comprehensive monitoring regime, including water temperature, ground-level thermal measurements, and light levels coupled with larger containment systems, more-evenly spread oil thickness (at progressively thicker slicks), and using sensors at oblique angles might assess detection limits.

Future research, including work in the Great Lakes ice environments, could be conducted to collect more data to allow for the development of a ‘family’ of curves that could be better used to determine oil slick thickness. This includes comprehensive monitoring of water temperatures over a complete set of oil in water and ice concentrations at a series of relevant altitudes, with concurrent, accurate ground level temperature measurements.



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APPENDIX A. OIL IN ICE FILE TRANSFER SOP

This appendix is intended for the UAS operating teams to support recommendations and procedures for delivering the data in a manner compatible with the USCG-NOAA Common Operating Picture (COP). This documentation ensures that files are formatted and delivered to DIVER for subsequent upload into ERMA.

Document Naming, Content and Formatting Requirements:

Please use the following file naming, file content and formatting conventions for all files to be posted/transferred to DIVER or AWS S3. These conventions will aid in the management of all of the data collected under a particular project.

File Naming Conventions:

General Naming Structure:

YYYYMMDD_description.zip

- Zip files for complete package per imagery set
- Underscores instead of spaces in .zip name and files within .zip
- Description: less than 75 character brief data guide

YYYYMMDD_HHMM

HHMM : 24-hr local time

_Imagery.zip : raw imagery, mosaic imagery, video, frames

_Trackline.zip : GPS trackline: gpx or other GIS file

_Classification.zip : raster and/or vector classification results

Example Format Standards:

- *(note: do not include “()” or “#” in file name)*

Date_TimeLegAltitude_Type

- *(Leg and Altitude are optional)*

Multiple features, same flight increment with a letter

- *(e.g. a,b,c...etc.)*

Multiple Altitudes should be noted

- **# = Altitude** (e.g. 50, 100, 400... etc.)

Imagery:

20211017_1430a#_RGB.zip

20211017_1430a#_TIR.zip

20211017_1430a#_MSS.zip

- raw imagery, mosaic imagery, video, frames. Data Manager/PI will decide if raw/unprocessed imagery should be included with processed imagery

Tracklines:

20211017_1430a#_tk.zip

- GPS trackline: gpx or other GIS file. Can contain planned path and actual flight information

Classification/Product:

20211017_1430a#_TYPEcls.zip

- classification/processing result

20211017_1430a#_RGBcls.zip

20211017_1430a#_TIRcls.zip

20211017_1430a#_MSScls.zip



Image Resolution

Full-resolution images may have a “_full” name

Medium and low-resolution versions of the imagery, (for data transfer efficiency and quick looks), should have a “_medium” and “_low” designation

Example: 20211017_1430(a)_RGB_full.zip

File Contents:

Zip file within project folder will contain:

metadata about the camera platform (manufacturer, spectral collection characteristics (e.g. RGB and NIR spectral range))

One .zip file/activity (e.g. flight) which contains all information required for future work:

Raw imagery

See note above about Full Resolution Imagery. Imagery may be down-sampled for quicker uploading/reviewing. Naming of files needs to reflect the resolution.

- Full resolution images do not need to specify “_full” - that will be used for just the name of the .zip
- images/mosaics that are a medium or low resolution version should be named to that note:

20211017_1430a_RGB_low.zip

File Format:

Format: GeoTIFF (preferred). Can also be Imagine, png/jpg with world file

File Projections:

Preference: either Geographic wgs84/wgs84 (EPSG:4326) or Web Mercator (Auxiliary Sphere) (EPSG:3857).

Projection should be stabilized as early in the processing chain as possible. Use only one projection across a project activity

File Size Limitations (NEEDS MORE DETAIL and TESTING):

Field data reporting packages should be limited to approximately 1 - 1.5 GB or less if possible. Images and image mosaics should be compiled so that the file packages do not exceed reasonable download speeds, particularly when internet conditions are slow or inconsistent.

Images may be split in ArcGIS/ArcPro (data management, split raster) or by reducing image resolution. Full resolution data should always be retained for damage assessment requirements.

ERMA Image Processing:

It is highly recommended that imagery and image products use standard projections (geographic, Web Mercator, etc.) as early in processing as possible. ERMA cannot honor ArcGIS Image stretch parameters so the ArcGIS stretch must be forced into the image for ERMA imagery to “look” like your image in ArcGIS.

When preparing to export RGB imagery to prepare for ERMA (all steps happen at once)

- Apply appropriate stretch in ArcGIS/ArcPro (e.g., percent clip)
- Export from ArcGIS (retain source projection, do not project into new system)
- Specify 8-bit tiff with a no data value of 0 (may need to be modified)
 - Data values should never include 0
- Rendering settings



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

- Use Render
- Force RGB
- Output format is tiff with LZW compression
- Ensure pyramid/overviews are created with the final tiff

Once complete remove the ArcGIS stretch (***set stretch to none***) and zip the image and component files together and the image will be ready to import directly into ERMA. A quick check in an image viewer such as Windows built in viewer, IrfanView, XnView should show an image that looks like it was seen in Arc - no additional stretch required.

Data Storage/Transfer Requirements:

DIVER File Collections:

Oliktok Point:

<https://portal.diver.orr.noaa.gov/group/uscg-noaa-rdc-oil-in-ice-project-oliktok>

Canadian Cruise:

<https://portal.diver.orr.noaa.gov/group/rdc-oil-in-ice/filecollection/19920>

Data, imagery, in situ

Example File Collection Structure:

Northeast > RDC Oil in Ice - CRREL > Collected Data File Collection > Oliktok - Water Mapping-collected data

Northwest & Arctic > RDC Oil in Ice > Collected Data File Collection

Canadian Cruise:

Northwest & Arctic > RDC Oil in Ice > Data Files > Canadian Vessel Cruise - Water Mapping Collected Data

Adding UAS imagery (mosaics, video)

File Type: GIS Files (zip)

Review Status: New

Sharing Status: All Workspace Members (unless otherwise noted by data managers)

Supporting documents, field notes

Northwest & Arctic > RDC Oil in Ice - Oliktok > Document File Collection > Field documents

Adding field documents: photos, weather/ice reports

File Type: Other Document or Upload Notes

Review Status: New

Sharing Status: All Workspace Members (unless otherwise noted by data managers)

AWS S3:

Bucket: noaa-diver-rdc

Folder: Oliktok/
Oliktok/WaterMapping

Transfer Methods:

FileZilla Pro - local computer file transfer application (requires software license)



Advancing Detection Capabilities for Monitoring Oil Spills in Ice Environments

AWS CLI - command-line version

Amazon S3 Explorer - browser-based transfer (may have issues with large (> 2gb) files)

<https://noaa-diver-s3-explorer.s3.amazonaws.com/index.html>

Data Collection and Processing Workflow (simplified):

- Fly drone capturing imagery with sensor(s)
- Download data from drone SD cards to field computer
- Select necessary data from downloaded data required to produce products (mosaics, classifications and drone tracks)
- Selected data zipped on field computer and posted to Google Drive for remote processing
- Data retrieved from Google Drive to remote computer
- Data processed on remote computer using proprietary code
 - Geoprocessing individual image frames
 - Individual image frames are mosaiced
 - Mosaiced imagery is then classified (RGB, IR/Thermal, MSS follow unique methods)
- Imagery track lines are created (polyline)
- Metadata is (will be) generated for each sensor classification
- Processed data renamed using the standard file naming conventions and posted to DIVER

