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In Situ Monitoring of Dispersion in the Water Column, Final Product for the Detection and Mitigation of Oil within the Water Column Project

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N O T I C E

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ADAC	Arctic Domain Awareness Center
ADDS Pack	Airborne Dispersant Delivery Systems
AIS	Automatic Information System
AOR	Area of responsibility
ARGOS	Advanced Research and Global Observation Satellite
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
CG	Coast Guard
COTS	Commerical off-the-shelf
D11	Coast Guard District 11
D17	Coast Guard District 17
DOI	Department of the Interior
EEZ	Economic Exclusive Zone
EPA	Environmental Protection Agency
ERT	Environmental Response Team
GPS	Global Position System
HC	Hydrocarbon
KPP	Key performance parameter
L&R	Launch and recovery
LRAUV	Long range AUV
MANET	Mobile Ad hoc Network
MPU5	Man Pack Unit 5
MOTT	Maritime Object Tracking Technology
NICS	Next Generation Incident Command System
nm	Nautical mile
NOAA	National Oceanic and Atmospheric Administration
NRT	National Response Team
NSF	National Strike Force
OSRL	Oil Spill Response Limited
PAH	Polyaromatic hydrocarbons
POPEIE	Probe for Oil Pollution Evidence in the Environment
RDC	Coast Guard Research and Development Center
RRT	Regional Response Team
SLDMB	Self Locating Datum Marker Buoy
SMART	Special Monitoring of Applied Response Technologies
SSC	Scientific Support Coordinator
USCG	U.S. Coast Guard
UUV	Unmanned underwater vehicle
WHOI	Woods Hole Oceanographic Institution

EXECUTIVE SUMMARY

The U.S. Coast Guard (CG) Research and Development Center (RDC) drafted this report in response to an ideation submitted by CG District 17 (D17). It described a need to more quickly transmit data about the efficacy of dispersants applied to an oil spill in remote locations (defined here in this report as 50 to 150 nautical miles (nm) away from the nearest shoreline) to the Unified Command through the use of aircraft. This would significantly reduce CG and industry resources and manpower when executing the Special Monitoring of Applied Response Technologies (SMART) protocol in remote locations.

RDC started with market research of commercially available monitoring technologies that can provide SMART teams with the necessary data to determine the dispersants' efficacy. Results gave RDC an idea of the types of monitoring technologies that exist, from fluorometers to sonars, and what different sizes and shapes they come in. The next step was to determine what type of platform that will allow the monitoring instrument to be safely deployed from an aircraft and delivered to the spill site for data collection at specific depths in accordance to the requirements described in the SMART protocol. For this, RDC considered two main approaches: one-time-use sensor platforms and unmanned vehicles.

One-time-use sensor platforms have been used in previous RDC work. An example is the Self Locating Datum Marker Buoy (SLDMB), which can begin collecting data immediately after impact with the water surface. It transmits data to users via satellite communication. These sensor platforms may be modified to include fluorometers. There are still many unknowns associated with this approach, such as buoyancy maintenance, ability to stay within the boundaries of an oil spill, ability to quickly transmit data, and costs.

Unmanned vehicles are widely available and frequently used as a platform to detect submerged oil. RDC performed a market research of commercially available unmanned vehicles. They come in different types, from autonomous underwater vehicles (AUVs) to gliders and autonomous surface vehicles (ASVs). RDC also looked into which type of monitoring technology was compatible with specific unmanned vehicles. Based on the market research conducted, one major limitation is that unmanned vehicles are generally not designed for air launch from fixed wing aircraft. There are questions about unmanned vehicle survivability and the associated onboard monitoring technologies after aerial deployment.

In moving forward, RDC recommends the first priority for any future work be development and defining key performance parameters (KPPs) to dictate how future prototypes should be constructed to withstand impact with the water surface, protect the monitoring technologies onboard the platform, execute the SMART protocol, and transmit data to Unified Command quickly.

RDC recommends further research of one-time-use sensor platforms as they are already designed for aerial deployment. RDC also recommends looking into previous work and building off of those efforts. Designing unmanned vehicles for aerial deployment is a large undertaking and RDC recommends partnering with external Federal agencies, academia, or industry if this approach is pursued.

On the communications side, RDC recommends continuing internal, existing research in improving communication capabilities in remote locations, especially in areas of higher latitude.

1 INTRODUCTION

After the use of dispersants is authorized and they are applied to an oil slick as an option to mitigate the impacts of an oil spill, the U.S. Coast Guard (USCG) National Strike Force (NSF), the U.S. Environmental Protection Agency (EPA) Environmental Response Team (ERT), and/or commercial vendors carry out the Special Monitoring of Applied Response Technologies (SMART) protocol to determine the dispersant's effectiveness in breaking down the slick into smaller droplets. There are several tiers within the SMART protocol; the Federal On-Scene Coordinator (FOSC) determines the most appropriate tier to carry out for a given spill scenario. Tier I provides visual observations by a trained observer. Tier II confirms Tier I observations through real-time monitoring and water sampling. Tier III provides additional sampling to evaluate movement of the dispersed plume. Tier II and III include deploying a fluorometer at varying depths in the water column from a vessel and taking measurements as well as collecting water samples. The data may be sent electronically to the Unified Command in near real time, or the data logger itself is returned to the Dispersant Monitoring Technical Specialist (who is typically the National Oceanic and Atmospheric Administration's (NOAA) Scientific Support Coordinator (SSC)) at the end of the day. The data is further analyzed and processed into usable formats for the FOSC so he/she can assess the dispersant efficacy and make decisions about the next steps in the spill response effort.

Once the decision is made to authorize dispersants, the FOSC requires rapid feedback about their efficacy on the spilled oil in order to make sound decisions on strategic and tactical oil spill response mitigation efforts. The current practice is to execute Tier I of the SMART protocol (visual observations) as a minimum, but the preference is to execute Tier II, which is to deploy a vessel to the scene of the spill where the dispersant is applied and coordinate with visual observers in aircraft; to take measurements at specific locations and at 1-meter depth. However, in a remote area, the vessel trip may take hours, which increases logistics complexity and may hamper the response. Data may not be available until the end of the day. Significant Coast Guard and industry resources and manpower are engaged in carrying out this mission. These challenges are difficult to overcome in the Gulf of Mexico and would be even more so off Alaska.

1.1 Objective and Assumptions

USCG District 17 expressed a need to deploy in-situ monitoring technologies from the air, capable of taking measurements at specific locations and depths within a remote spill location, transmitting data to the Unified Command, and in a variety of environmental conditions. Receiving data would enable the FOSC to closely track dispersant response operations and make more informed decisions earlier in the response effort.

The focus of this work is on how the FOSC may receive feedback on the efficacy of dispersant use more rapidly during SMART operations. The following assumptions are made:

- Spilled crude oil is within the Seventeenth Coast Guard District's (D17) area of responsibility (AOR) and is 50 to 150 nautical miles (nm) away from the nearest shoreline.
- Fresh crude oil spill is not continuous and use of dispersants is authorized.
- Mixing energy for the dispersants is provided.
- Water is ice free.

1.2 Background

D17 is located in the Alaskan maritime region with an AOR of approximately 3.9 million square miles. It includes the Arctic waters of the Bering, Chukchi, and Beaufort Seas where there is increasing vessel traffic due to diminishing sea ice. Further, adding to the risk of oil spills in this region is a strong likelihood of drilling for oil in Arctic waters in the future. With limited infrastructure, few resources, and challenging working conditions, mounting and supporting an oil spill response in the Arctic region is a daunting task.

Applying dispersants to a surface oil slick is one option to mitigate the impacts of an oil spill in the offshore waters. They break crude oils into tiny droplets that entrain and diffuse into the water column using wave, wind, and/or tidal energy. If dispersants are applied to waters in ice-infested regions, mixing energy usually needs to be supplied in order to promote dispersion. The presence of ice floes generally dampens wave motions, which takes away a natural source of mixing energy.

Dispersants are generally the most effective when applied to fresh crude oil. Over time, crude oil naturally weathers and becomes more viscous, which can render dispersants less effective or not at all (NRC, 2005). However, the oil weathering process in Arctic conditions is slower when compared to that in moderate climates. This gives the FOSC a greater window of opportunity to exercise the dispersant option.

The oil droplets formed by the dispersants have increased surface-to-volume ratios and can be dissolved, digested, or broken down by natural processes such as biodegradation, photodegradation, and reduction/oxidation to form less stable compounds (ADEC, 2016). Depending on the time of the year, the offshore waters within D17's AOR may be ice-infested. With or without ice in the water, the use of chemical dispersants may be pre-authorized by the Alaska Regional Response Team (RRT) if it is spilled within the preauthorization area (see Figure 1). It extends from 24 nm offshore to the outer boundary of the Exclusive Economic Zone (EEZ), 200 nm offshore south of Alaska's mainland and islands in the Prince William Sound, Cook Inlet, Kodiak, Bristol Bay, and Aleutian subareas; and from 24 nm to 100 nm offshore north of the Aleutian Islands. Certain restrictions within the preauthorization areas apply. For instance, dispersant application cannot impede mechanical recovery efforts and small test applications of dispersants are required before large scale dispersant use (Alaska RRT, 2016).

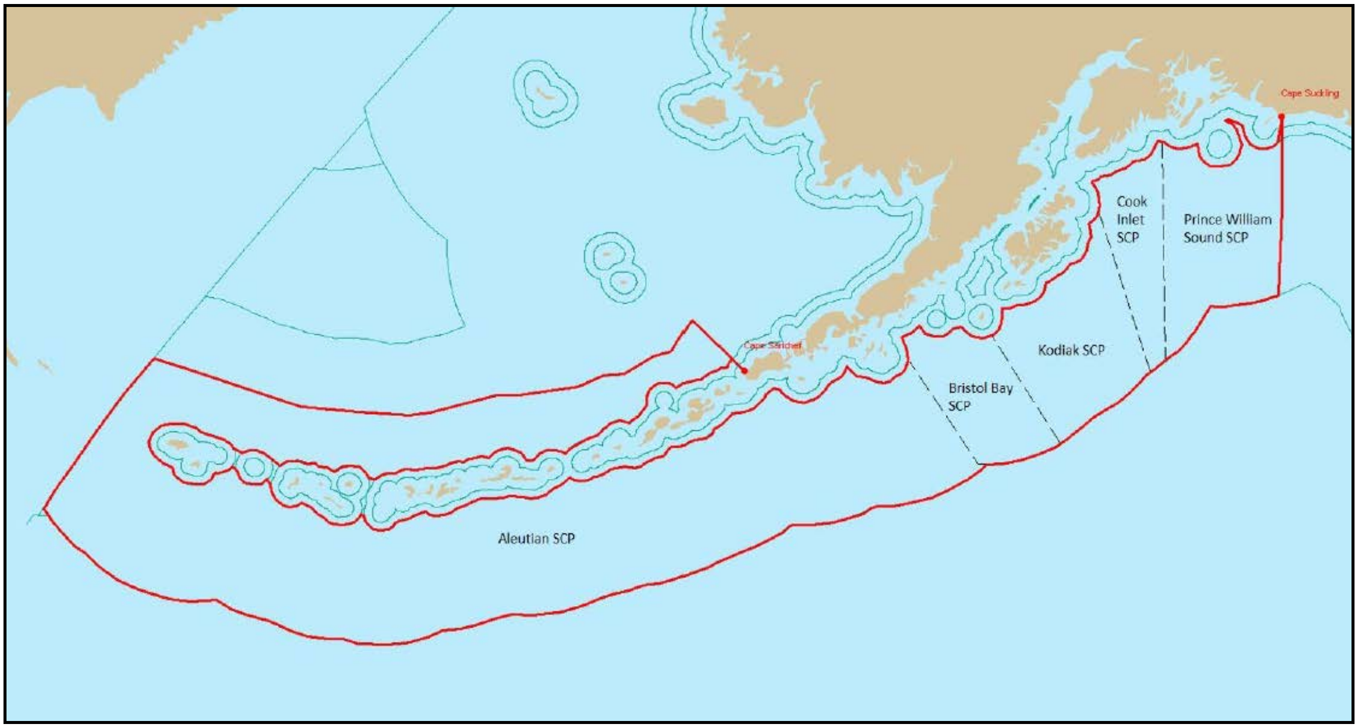

Figure 1. Alaska RRT's preauthorization area (outlined in red) (Alaska RRT, 2016).

For oil spills that occur outside of the preauthorization area (undesignated areas), the use of dispersant is considered on a case-by-case basis and requires consultation with USCG, the Environmental Protection Agency (EPA), the state of Alaska, the U.S. Department of the Interior (DOI), and the U.S. Department of Commerce. Local and tribal governments and other stakeholders are also engaged through subarea committees and Alaska RRT meetings (Alaska RRT, 2016).

1.2.1 SMART Protocol

The SMART protocol is a widely accepted procedure used to determine the dispersant's efficacy in the specific circumstances of the spill. SMART teams are typically small, mobile, and involve the NSF and/or others trained to use the monitoring equipment. The equipment they use is related to the SMART option or tier chosen for the oil spill in question. Each option is activated at the FOSC's judgment and discretion and is largely dependent on the spill location and complexity of response operations. Raw data gathered from the SMART teams are passed on to the Dispersant Monitoring Technical Specialist (NOAA's SSC). The SSC processes and interprets the data, and provides the FOSC with usable results that can influence response decisions. This research is focused on technologies suited for Tier II operations being carried out in remote locations.

1.2.1.1 *Tier I: Visual Observations*

Tier I involves visual observation by a trained observer. The observer uses visual aids (NOAA, 2009) to provide a consistent, general, and qualitative assessment of dispersant effectiveness. In addition, the aerial monitors ensure compliance with all application restrictions. Observations are photographed and videotaped to help the observers communicate results to the Unified Command and to better document the data for future use. When available, infrared thermal imaging and other devices provide a higher degree of sensitivity in determining dispersant effectiveness (USCG et al., 2006).

1.2.1.2 *Tier II: On-Water Monitoring for Efficacy*

To confirm visual observations, a monitoring team may be deployed to the dispersant application area to confirm the visual observations by using real-time monitoring and water sampling. The monitoring consists of taking measurements with a fluorometer at a 1-meter depth into the water column. Rough conditions may force it to 2 meters. Water sampling may be performed simultaneously with in-situ monitoring. The data logged by the monitoring technology are used for scientific evaluation by NOAA's SSC while the water samples are taken for later analysis at a laboratory (USCG et al., 2006). The SMART team also records Global Position System (GPS) data to mark specific locations where the measurements are taken.

1.2.1.3 *Tier III: Additional Monitoring*

If dispersants are effective and more information is needed on the movement of the dispersed oil plume, Tier III may be activated. It follows Tier II procedures but teams collect information on the transport and dispersion of the oil in the water column. Tier III work verifies that dispersed oil is being made more bio-available for microbes to consume. SMART teams use two separate fluorometers at multiple water depths (typically at 1 and 5 meters, and up to 10 meters) deployed from a single vessel. The measurements are taken at time intervals of 2 to 5 minutes, or as otherwise specified. The vessel transects the dispersed plume like it does for Tier II operations except that multiple monitoring technologies are used. During Tier III work, SMART teams also use a portable water quality laboratory to measure water temperature, pH, conductivity, dissolved oxygen, and turbidity (USCG et al., 2006). Additionally, water samples are collected for potential future analyses.

1.2.1.4 *Tier III+: Supplemental Monitoring*

During the Deepwater Horizon oil spill, several SMART teams performed what they informally called "Tier III+". It essentially follows normal Tier III work except more advanced technologies were used such as a laser particle size analyzer and increased water sampling for laboratory analysis (Levine et al., 2011).

2 SUBSEA MONITORING TECHNOLOGIES AND PLATFORMS

RDC performed a market research of commercial off-the-shelf (COTS) monitoring technologies that are capable of direct or indirect measurements and unmanned vehicles. A wide range of unmanned vehicles was considered, from small man-portable autonomous underwater vehicles (AUVs) to large surface autonomous vehicles (ASVs). Much of the analysis is drawn from a 2014 Battelle report titled "Capabilities and Uses of Sensor-Equipped Ocean Vehicles for Subsea and Surface Detection and Tracking of Oil Spills". The report reviewed oil spill detectors and oceanographic vehicles available at the time in 2012 and their overall compatibility with each other. Any new monitoring technologies developed after 2012 will need to be carefully reviewed on a case-by-case basis to determine its compatibility for a given unmanned vehicle.

2.1 Submerged Oil Detection

Direct measurements are taken by sensors that focus on detecting either polyaromatic hydrocarbons (PAH) or refined and crude hydrocarbons (HC). Indirect sensors detect the changes between the properties of baseline local environment seawater and modified properties in the presence of oil, such as conductivity, temperature, and turbidity (Battelle, 2014).

The National Response Team (NRT) divides subsea monitoring into four categories: site characterization, source oil sampling, water sampling and monitoring, and sediment sampling and monitoring (2013). This report's scope of work is limited to the water sampling and monitoring category, which characterizes the fate and transport of dispersed oil into the water column. This includes oceanographic data, microbial oxidation (dissolved O_2 and CO_2), oil droplet size distribution, continuous monitoring of oil and conditions (conductivity, temperature, salinity) in the water column, and discrete sampling and analysis (Battelle, 2014).

Sensors capable of taking direct and indirect measurements while mounted on an unmanned underwater vehicle (UUV) include:

- Fluorometry (provides direct in situ detection of refined or crude HCs and PAHs);
- Underwater microscopy (determines the size distribution of suspended oil in small sampled volume);
- Optical diffraction sensor (determines the size distribution of the suspended oil);
- Conductivity, temperature, and depth sensor (provides density characterization, salinity, and other relevant oceanographic data);
- Optical light scattering for water turbidity (characterizes the presence of suspended and undissolved material in the water column);
- Dissolved oxygen sensor (determines the concentration of dissolved O_2 in water to indicate microbial oxidation); and
- Dissolved CO_2 sensor (determines the concentration of dissolved CO_2 in water to indicate microbial oxidation) (Battelle, 2014).

2D and 3D sonar technologies are capable of subsea monitoring, but were not fully explored in the Battelle report. They are easily adapted to a variety of UUVs and capable of detecting oil. RDC previously studied the use of this technology for submerged oil detection and determined that it would be difficult for sonar to positively identify and characterize oil, especially if the oil disperses as individual droplets. Acoustic profiling at multiple frequencies also generates a large amount of data, which must be stored and processed. This may limit real-time availability of data and imagery to support rapid decision making (Fitzpatrick et al., 2014).

The listed sensors in Battelle's paper do not grab water samples for further tests in ship- or land-based laboratories (Battelle, 2014). If the goal is to provide rapid feedback to the FOSC regarding the efficacy of the dispersant use, then the collecting of water samples to be taken for laboratory analyses is not practical. Water samples do assist responders with correlation and calibration after the spill incident for quality assurance/quality check purposes. In this research, a sensor's ability to grab discrete water samples for further analyses was not explored. Battelle collected COTS subsea monitoring technologies, determined their target measurement and type of monitoring, and organized them into a table, reproduced in Appendix A (Battelle, 2014).

The Turner Designs C3 fluorometer is frequently used by the NSF during current SMART missions and is currently the most likely instrument to be used for assessing the efficacy of dispersant operations in remote locations. Other similar fluorometers may be used. RDC does not anticipate any difficulties with transitioning this particular technology onto most UUVs to collect data. If the SMART protocol evolves to include other instruments, such as a particle size analyzer, further investigation would be needed to ensure compatibility with the chosen platform. The sensor payload volume and weight can affect the UUV's power consumption and performance.

2.2 Unmanned Vehicles for Subsea Monitoring

There are a number of unmanned vehicles that can serve as a platform for the suite of sensors needed to detect dispersed oil in the water column up to 10 meters in depth. Most UUVs and Autonomous Surface Vehicles (ASVs) are designed to maneuver in depths greater than 10 meters so depth would not be a limiting factor in the selection of an appropriate vehicle. Payload capacity and launch logistics need to be carefully considered. Launch and recovery (L&R) of UUVs are typically carried out with the greatest care from vessel decks, shorelines, and in some cases, helicopters using cranes or tethers.

2.2.1 Autonomous Underwater Vehicles (AUVs)

AUVs are commonly used as a sensor platform in the oil spill community and come in many different shapes and sizes. They can be designed for specific purposes, such as staying in the water as long as possible while collecting data or housing as many sensors as it possibly can without interference to it's mobility. Others are designed to be submerged into deep waters at depths greater than 300 meters. Battelle defines an AUV as a robot that travels underwater without requiring input from an operator (Battelle, 2014). AUVs can be monitored from a large distance, from a small vessel, or they can be operated completely autonomously. A semi-autonomous AUV means it is in intermittent contact with its support ship through satellite, radio frequency, or acoustic links. Transitions between different modes of operations can occur, such as starting its mission while in supervised mode and ending in autonomous mode (Battelle, 2014).

AUVs can be broken down into four different categories: man-portable, lightweight, heavyweight, and large displacement AUVs.

2.2.1.1 *Man-Portable AUVs*

Man-portable AUVs weigh approximately 175 pounds and can be deployed by a few people in inflatable boats or shore sites. Endurance ranges from <10 to 20 hours depending on speed and power load. The payload volume is defined as modest (approximately 0.25 cubic feet (ft^3) or less). RDC has two man-portable AUVs in house. One is the Bluefin SandShark model and the other is the Riptide Micro-UUV model, as seen in Figure 2. The Riptide was deployed from a small boat in the Arctic during a RDC exercise in 2017.

Figure 2. Riptide Micro-UUV, representative of man-portable AUV.

2.2.1.2 *Lightweight, Heavyweight, and Large Displacement AUVs*

Lightweight AUVs are slightly larger in terms of size and weight than man-portable AUVs. They are approximately 1 foot in diameter and weigh roughly 500 pounds. They usually have longer endurance (10 to 40 hours) and are generally easy to handle. Payload volume is larger at approximately 1-3 ft^3. Heavyweight AUVs are approximately 21 inches in diameter and weigh up to 3,000 pounds. Their endurance can range from 20 to 80 hours and payload volume is approximately 4-6 ft^3. Both lightweight and heavyweight AUVs are generally constructed of separated sections that can be joined together to form the entire vehicle (Battelle, 2014). They are usually launched by an A-frame or boom type of crane system, or a launch and recovery ramp. Figure 3 shows a Jaguar AUV, one of the SeaBed class of vehicles developed at Woods Hole Oceanographic Institution (WHOI) that is representative of a lightweight AUV. RDC tested this platform for an oil spill project in the Great Lakes in 2013.

Figure 3. Jaguar AUV, representative of a lightweight AUV.

Large displacement AUVs are the largest AUVs in operation and they are designed for both endurance and payload capacity. They are able to travel greater than 100 miles and can stay in the field longer than 100 hours. They are typically greater than 36 inches in diameter and may weigh up to 20,000 pounds. Payload volume is between 15 to 30 ft^3.

2.2.2 Gliders

Gliders are UUVs that use small changes in buoyancy and center of gravity combined with rigid wings to convert vertical motion into horizontal, propelling itself forward with minimal power consumption (Battelle, 2014). Compared to AUVs, gliders have significantly increased endurance and range (from hours to weeks/months and hundreds of miles) and follow an up-and-down profile through the water. However, they travel at slower speeds (0.4 to 0.7 knots compared to 3 to 5 knots for AUVs) and sensors that can be added to gliders are limited by size, flow disturbance, and power requirements. Gliders are sensitive to buoyancy forces, ballast, and trim so the sensors themselves need to be unobtrusive to the platform's movement in water to reduce drag forces (Battelle, 2014). They would need to be small or mounted flush to the vehicle hull, which could limit some technologies needed for monitoring the dispersants' efficacy. Figure 4 shows a typical glider, manufactured by Teledyne Webb.

Figure 4. Slocum Glider (Available at: https://www.sequoiasci.com/about/news/lisst-glider-development/).

2.2.3 AUV/Glider Hybrid

Currently, the Arctic Domain Awareness Center (ADAC), a Department of Homeland Security Center of Excellence at the University of Alaska, is working with Woods Hole Oceanographic Institution (WHOI) on a project to allow a long range AUV (LRAUV) to operate in buoyancy glider mode and to be deployed from a helicopter. A previous version of the LRAUV completed a mission of almost 1,000 nm at a speed of 2 knots. The LRAUV's concept of operations would have it survey the underside of an ice field and map any oil detected. Communications may be through acoustic bouys installed in the ice field. The LRAUV's size, 7.5 feet long, 12 inches in diameter, and weight of approximately 256 pounds, will make helicopter delivery a challenge. Currently, the mechanism of delivery into the water has not yet been designed. RDC plans to monitor this project closely as it holds promise for both oil detection and as a platform for other sensors.

2.2.4 Autonomous Surface Vehicles (ASVs)

ASVs refer to vehicles that operate on the water surface without a crew. Since they are continuously on the water surface, unbroken communication between ASVs and operators is possible. Communication methods include satellite GPS, Iridium, or line-of-sight radio. ASVs can be operated under minimal supervisory command and control for long durations but require beyond line-of-sight communication links, which may inhibit its use for monitoring oil spills in remote locations, especially in the Arctic regions. For subsea monitoring, ASV payloads can be hull-mounted or suspended on a winch line to the surface platform without consideration for stabilization. The launch and recovery (L&R) for ASVs are typically performed using a small crane or boat ramp (Battelle, 2014).

2.2.4.1 *Wave and Wind Powered ASVs*

A wave powered vehicle can be regarded as a small, self-propelled (very slow) buoy capable of an average forward speed of approximately 1.5 knots in seas with 3 feet wave height (Battelle, 2014). It does not require any external power for propulsion; most power is consumed by the monitoring equipment. Payload power is provided by batteries that can be recharged by solar panels. The monitoring technologies can be suspended or towed from the glider body. Because it is a surface vessel, it can maintain continuous GPS and Iridium communication, which allows it to be controlled in real time (Battelle, 2014).

Wind powered ASVs use wind for propulsion and solar panels to provide power for steering and the monitoring technologies. They can be used in strong waves and the total payload weight capacity for one specific model (Saildrone) is approximately 220 pounds. Figure 5 shows the Wave Glider (a common wave powered ASV) ready to be deployed from USCGC HEALY during a RDC exercise in the Arctic in 2014. The Science and Technology Innovation Center at the RDC plans to test Saildrone with various communication sensors in the upcoming year.

Figure 5. Wave Glider ready to be deployed off of USCGC HEALY during Arctic Shield 2014.

2.2.4.2 *Small and Large ASVs*

Small ASVs are typically less than 220 pounds and can be launched and recovered manually. Payload integration is largely hull-mounted on a strut to be submerged 1 to 2 feet below the water surface. Certain types of small ASVs provide a winch system that can lower a cage filled with sensors. Large ASVs range from hundreds to thousands of pounds and they are typically deployed by using a large crane or davit. Submerged payload integration is typically towed or suspended from large ASVs (Battelle, 2014).

2.3 Compatibility between Unmanned Vehicles and Monitoring Technologies

Battelle performed an assessment to determine whether specific monitoring technologies were compatible with specific unmanned vehicle models. In that evaluation, Battelle gave special consideration to payload volume as most vehicles provide sufficient power required by monitoring technologies. The grid in Table 1, extracted from the Battelle report, shows how compatible the unmanned vehicle models are for a given monitoring technology. The number of models for each vehicle is given. If the monitoring equipment is not expected to be compatible with the vehicle, it is marked as red. If the equipment is compatible with the vehicle but requires external mounting due to the nature of the equipment, or if the equipment is expected to use almost all the available payload volume within the vehicle, it is marked as yellow. If the equipment fits within the vehicle and allows for additional payloads to be carried, it is marked as green (Battelle, 2014). The numbers represent how many vehicle models out of the total number of models for that class are rated for the highlighted color. For instance the Turner Designs C3 submersible fluorometer is classified as green for man-portable AUVs and marked as “10/16”. This means that the fluorometer can fit on 10 out of 16 man-portable AUV models that Battelle explored and still have enough space for more monitoring equipment. Another example is the Chelsea Aquatrack fluorometer; this particular instrument is marked as “5/7” and is colored red under the Gliders column. This means that the instrument is **not** compatible on 5 out of 7 different glider models.

Table 1. Compatibility between unmanned vehicles and monitoring technologies.[1]

Sensor	Unmanned Vehicles						
	Man-portable AUVs (16 models)	Light/Heavyweight AUVs (12 models)	Large Displacement AUVs (16 models)	Gliders (7 models)	Wave/Wind Powered ASVs (4 models)	Small ASVs (8 models)	Large ASVs (14 models)
4DEEP Inwater Imaging Submersible Microscope	9/16	11/12	16/16	5/7	4/4	8/8	14/14
AADI Conductivity Sensor 4319	16/16	12/12	16/16	7/7	4/4	8/8	14/14
AADI Oxygen Sensor 3830	16/16	12/12	16/16	7/7	4/4	8/8	14/14
AADI Seaguard O_2	14/16	11/12	16/16	5/7	3/4	6/8	14/14
AADI Turbidity Sensor 4112	16/16	12/12	16/16	7/7	4/4	8/8	14/14
AML Oceanographic Smart CTD	15/16	11/12	16/16	5/7	4/4	7/8	14/14
ASD Sensortechnik	N/A	N/A	16/16	N/A	N/A	N/A	N/A
Bowtech Leak Detection System	15/16	11/12	16/16	5/7	4/4	8/8	14/14
Chelsea Technologies Subsea Pipeline Leak Detection	16/16	7/12	16/16	6/7	2/4	7/8	14/14
Chelsea Technologies UV AquaTrack Fluorometer	13/16	11/12	16/16	5/7	4/4	7/8	14/14
Chelsea Technologies UviLux Fluorometer	16/16	12/12	16/16	7/7	4/4	8/8	14/14
CONTROS HydroC CO2 Carbon Dioxide Sensor	15/16	11/12	16/16	5/7	4/4	7/8	14/14

[1] Battelle, 2014

Table 1. Compatibility between unmanned vehicles and monitoring technologies (Cont'd).

Sensor	Unmanned Vehicles						
	Man-portable AUVs (16 models)	Light/Heavyweight AUVs (12 models)	Large Displacement AUVs (16 models)	Gliders (7 models)	Wave/Wind Powered ASVs (4 models)	Small ASVs (8 models)	Large ASVs (14 models)
CONTROS HydroC PAH Fluorometer Sensor	10/16	11/12	16/16	6/7	4/4	7/8	14/14
CONTROS Mobile Leak Detection System	16/16	11/12	15/16	6/7	3/4	6/8	14/14
Hach FP 360 SC Oil-in-Water Sensor	14/16	11/12	16/16	6/7	4/4	8/8	14/14
Ocean Tools OceanSENSE Leak Detection	10/16	12/12	16/16	5/7	4/4	8/8	14/14
Phaze Hydrocarbon Leak Detector	N/A	N/A	16/16	N/A	N/A	N/A	N/A
Sea & Sun Technology Conductivity Sensor	8/16	11/12	16/16	6/7	4/4	8/8	14/14
Sea & Sun Technology UV Fluorometer	9/16	11/12	16/16	6/7	4/4	8/8	14/14
Sea Bird SBE 19plus V2 SeaCAT	15/16	11/12	16/16	6/7	3/4	6/8	14/14
Sea Bird SBE 25 plus Sealogger	16/16	11/12	15/16	7/7	3/4	5/8	12/14
Sea Bird SBE 49 FastCAT CTD Sensor	14/16	11/12	16/16	6/7	3/4	7/8	14/14
Sea Bird SBE 911 plus; 917 plus	16/16	6/12	15/16	7/7	3/4	5/8	12/14
SeaPoint Sensors Turbidity Meter	16/16	12/12	16/16	7/7	4/4	8/8	14/14

Table 1. Compatibility between unmanned vehicles and monitoring technologies (Cont'd).

Sensor	Unmanned Vehicles						
	Man-portable AUVs (16 models)	Light/Heavyweight AUVs (12 models)	Large Displacement AUVs (16 models)	Gliders (7 models)	Wave/Wind Powered ASVs (4 models)	Small ASVs (8 models)	Large ASVs (14 models)
Seapoint UV Fluorometer	15/16	11/12	16/16	6/7	4/4	8/8	14/14
Sequoia LISST-Deep	15/16	11/12	16/16	5/7	4/4	7/8	N/A
Smart Light Devices LDS3 Laser Leak Detection System	13/16	12/12	16/16	5/7	4/4	8/8	14/14
Sonardyne Automatic Leak Detection Sonar	N/A	N/A	16/16	N/A	N/A	N/A	N/A
Teledyne RD Instruments Citadel CTD Products	15/16	12/12	16/16	7/7	4/4	7/8	14/14
Teledyne TSS MELDS System	16/16	N/A	16/16	N/A	N/A	N/A	N/A
TriOS enviroFlu-DS	14/16	12/12	16/16	5/7	4/4	7/8	14/14
TriOS enviroFlu-HC	13/16	11/12	16/16	6/7	4/4	8/8	14/14
Turner Designs C3 Submersible Fluorometer	10/16	12/12	16/16	5/7	4/4	8/8	14/14
Turner Designs Cyclops 6K customizable	16/16	12/12	16/16	5/7	4/4	8/8	14/14
Turner Designs Cyclops 7 customizable	16/16	12/12	16/16	5/7	4/4	8/8	14/14
Wetlabs WQM	15/16	11/12	16/16	5/7	2/4	5/8	14/14
YSI EXO Series	9/16	11/12	16/16	5/7	3/4	6/8	14/14

From Table 1, it appears that gliders are generally poor vehicles for the monitoring technologies that RDC is interested in. However, new monitoring instruments have been developed since the Battelle study that are specifically designed for the glider platform or other unmanned vehicles, such as the Sea Bird Scientific SeaOWL UV-A SLC. Generally, most of the glider models do not have enough space or the necessary requirements for easily mounting the monitoring technologies. In addition, gliders typically operate at depths deeper than what is required for the SMART protocol and lack full time communication equipment.

Man-portable AUVs may or may not be good UUVs for RDC's purposes. The particular UUV employed largely depends on the sensor one chooses to use to monitor the dispersants' efficacy. If monitoring is to be performed with the Turner Designs C3 fluorometer that SMART teams regularly use, then man-portable AUVs can be utilized (10 out of 16 man-portable AUV models can easily accommodate this specific fluorometer type).

Most monitoring technologies are capable of being fitted into lightweight/heavyweight AUVs, large displacement AUVs, wind and wave powered ASVs, and small/large ASVs.

3 ONE-TIME-USE SENSOR PLATFORMS

One-time-use sensor platforms are a potential solution for the challenge of assessing dispersants' effectiveness in remote locations. The monitoring instruments can be deployed at a spill site, take measurements, and then biodegrade or sink to the ocean's floor after mission execution. Some aspects of this concept have been previously tested. One such example is the Self Locating Datum Marker Buoy (SLDMB) that RDC was involved with in the past. Considered a "throwaway sensor", it can be deployed from an aircraft and begin collecting data after impact to the water surface. It transmits data to users via satellite communication. After a given amount of time, the sensor ceases to function and sinks to the ocean floor. However, some may be modified to keep from sinking and recovered at a later time.

More recently, RDC performed tests of a prototype Maritime Object Tracking Technology (MOTT) that can be deployed from as high as 200 feet without the aid of parachutes. MOTT is approximately 21 inches in length and remains afloat after impact. It is capable of transmitting Automatic Information System (AIS). Due to its low cost (targeted to be $500 each), MOTT is seen as a one-time use technology that can transmit data for a period of time before it ceases to function.

Fluidion, Inc. is a company that manufactures monitoring instruments that can be submerged into the water column and collect data on dispersants' efficacy. Fluidion representatives indicate that the current sensor platform could be modified to include fluorometry. Some products in the company's offering can be attached to UUVs but some can also function without a vehicle as long as they are dropped in correct locations. After taking measurements, these sensors from Fluidion are able to surface and transmit data before they are recovered by a vessel. Further market research is needed to determine if other manufacturers produce sensors that biodegrade and sink to the ocean floor after use.

There are many unknowns associated with this approach, including buoyancy maintenance, ability to stay within the boundaries of the spill and dispersant application sites, ability to transmit data, and costs.

4 TRANSPORT OF MONITORING TECHNOLOGIES TO REMOTE LOCATIONS

4.1 Fixed Wing Aircrafts

Should an oil spill occur in a remote location (defined in this report as 50 to 150 nm away from the nearest shoreline) within D17's AOR and dispersant use is authorized, a commercial C-130 or other equivalent aircraft available may be deployed with the necessary monitoring equipment and vehicle. A single fixed wing aircraft is envisioned to serve as both the dispersant sprayer and spotter but in reality, this may not be possible. The size of the oil spill, complexity of the response operation, and number of available resources need to be taken into consideration.

C-130s offer good range in the shortest amount of time and have the capacity for carrying the necessary cargo for the monitoring effort. In 2016, Oil Spill Response Limited (OSRL) announced the addition of two new 727s for its dispersant spraying operations. Drawing from lessons learned during Deepwater Horizon, a joint industry program started a project to secure aircraft that could travel further and faster than what was used during the Macondo oil spill (OSRL, 2016). The modified 727s in OSRL's fleet have 7 tanks each that can hold up to 15,000 liters of dispersants and can be sprayed from a height of 150 feet (OSRL, 2016). Though 727s are capable of deploying UUVs, RDC is focused on C-130s for this report as they have been used in the past for dispersant spraying operations, and may potentially accommodate monitoring equipment for deployment.

In an email exchange with a SMART protocol subject matter expert, RDC learned that during Deepwater Horizon, USCG and NOAA quickly concluded that C-130s were not ideal platforms for observing dispersant operations. Thus, they are not recommended for future visual observations of dispersant operations so other aircraft types will need to be explored.

D17 has two air stations that can be used as mobilizing areas: USCG Air Station Kodiak and USCG Air Station Sitka. Air Station Kodiak is home to C-130s as well as USCG helicopters (H-60s and H-65s) while Air Station Sitka houses only H-60s. However, other airports or airstrips throughout the state of Alaska can be used when dispersant operations are approved although runway lengths to accommodate C-130s will need to be considered. Figure 6 shows the locations of the two air stations in D17's AOR (labeled with blue stars).

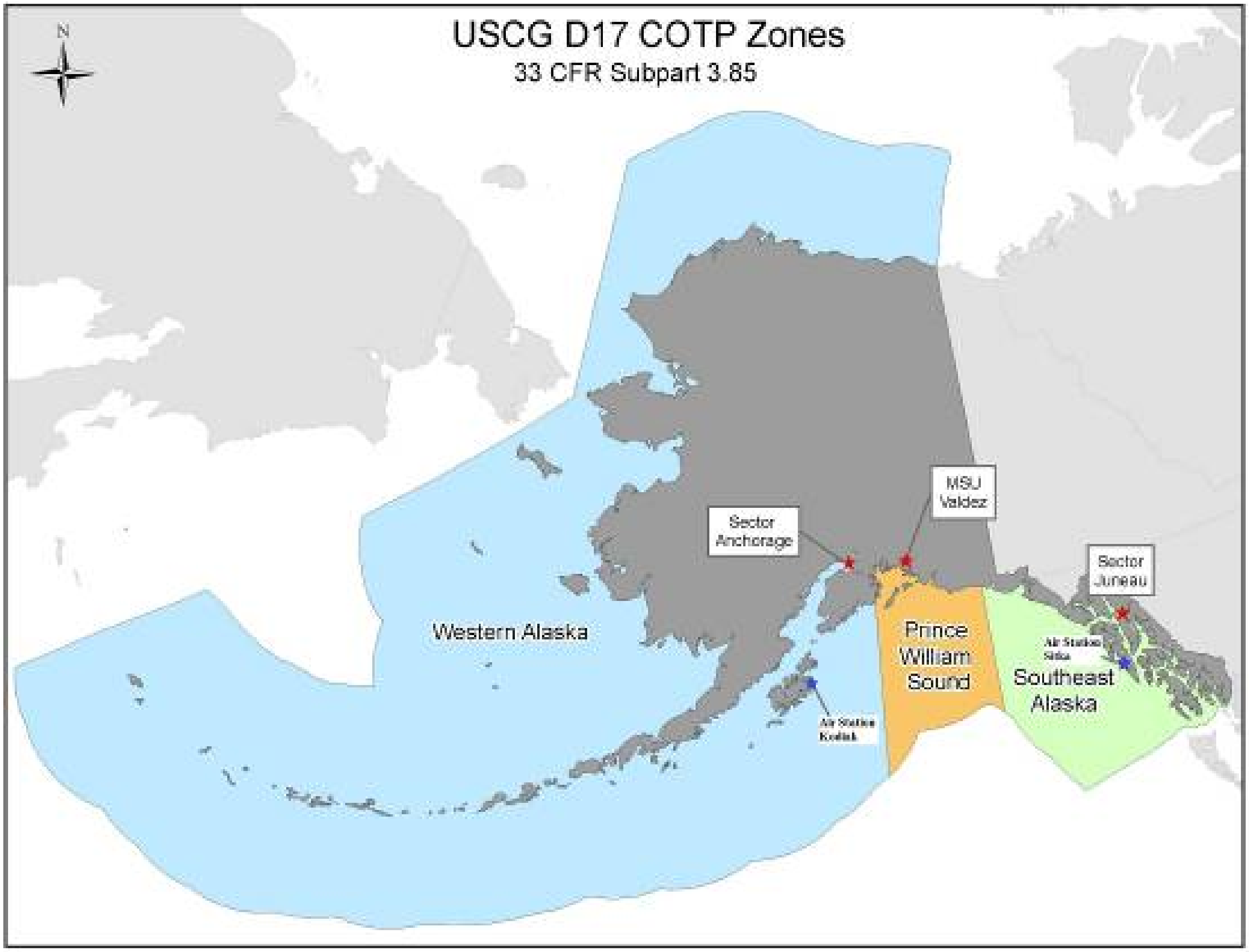

Figure 6. D17's Area of Responsibility and locations of Air Stations Kodiak and Sitka.

The range for a C-130 is approximately 4,500 nm and its endurance is 14 hours, which allows it to cover most of D17's vast AOR. One must consider the amount of dispersants required to treat the oil slick as the weight affects the aircraft's operating distance (NRC, 2005, 33 C.F.R. §155).

Commercial C-130s are the primary aerial platforms and are envisioned to deliver dispersants and also deploy the unmanned vehicle for data collection. In Anchorage, AK, Alyeska-SERVS owns two Airborne Dispersant Delivery Systems (ADDS Packs). Alyeska has a contract with a private airline company with a fleet of C-130s that the ADDS Packs can fit on for dispersant operations in D17's AOR. Alyeska also has a Memorandum of Understanding with USCG for use of its aircraft in case commercial aircraft cannot be secured.

4.2 Deployment Challenges with Fixed Wing Aircrafts

No unmanned vehicle is currently designed for air launches from an aircraft; there are major uncertainties about the UUV's and the associated onboard monitoring technologies' survivability after deployment.

RDC's previous experiences and literature research show that most launches of UUVs are performed from vessels or shoreline areas. Cranes or davits are typically used to deploy UUVs from vessels, if available. For smaller boats, man-portable AUVs can be easily placed into the water by one or two people. In each case of deployment, the goal is to carefully allow entry of the UUV into the water without damaging the onboard sensors, communication and propulsion equipment, and the UUV body itself.

If a parachute is used to assist with the launch, it will need to be disconnected from the UUV body after impact. The size of a parachute is anticipated to be very large for the associated weight of the unmanned vehicle. Using a parachute calculator from www.rocketreviews.com, a 175-pound "rocket" (average weight for a man-portable AUV) would be 50 feet in diameter if the descent rate is desired to be 10 feet per second and 25 feet in diameter if the descent rate is 20 feet per second. For heavier unmanned vehicles, the size of parachutes only gets larger. The disconnected parachute will become marine debris in the spill recovery area, which may be unacceptable, especially if they are very large.

Another challenge is the logistics behind a UUV starting up and performing a system check through radio communication from an operator after deployment. In many RDC projects involving the use of AUVs, they were carefully placed into the water and their buoyancy frequently tested before the operators were confident they could be released. Smaller UUVs are particularly sensitive to water density and likely need additional time for buoyancy adjustments. Most recently, RDC tested an AUV during Arctic Shield 2017 off the Coast Guard Cutter HEALY and experienced difficulty with vehicle buoyancy.

RDC has experience with the Wave Glider, a wind and wave powered ASV, and anticipates it would be difficult to deploy from an aircraft. This particular ASV was used during Arctic Shield 2014 and was deployed from the deck of the Coast Guard Cutter HEALY using an A-frame. Because there are two parts attached to each other by a tether cord, only the top portion was lifted by the crane while the bottom body was handled by hand. With strong winds, the bottom body was difficult to control because the tether cord allowed it to freely swing as it was being deployed into the water. A careful crane evolution carried out by competent crewmembers was needed for a successful launch. However, the National Data Buoy Center previously launched the Wave Glider with the two bodies belted together. The belt was then released after the vehicle entered the water. Overall, aerial deployment presents challenges to a successful launch of this particular vehicle.

A previous RDC project studied the deployment of SLDMBs from fixed wing aircraft. Although the cylindrical unit was roughly 36 inches long, 5 inches in diameter, and weighed approximately 20 pounds, a lengthy approval process was required for a number of them to be deployed from the rear ramp of a Coast Guard aircraft. The project manager noted some success using parachutes to deploy them at a height of at least 200 feet. Even though the lightest class of UUVs (man-portable AUVs) is heavier than 20 pounds and there are some logistical differences, the SLDMB deployment approach is still closely related to an air launch approach. Also, in 2004, the USCG Eleventh District (D11) performed the deployment of the Probe for Oil Pollution Evidence in the Environment (POPEIE) from a C-130 (Sanders, 2005). The POPEIE used the same air deployment package for deploying SLDMBs and the equipment itself is portable (Sanders, 2005).

The issue of availability of USCG aircraft may be encountered as they are in high demand with typical Coast Guard Search and Rescue and Medevac missions. For these reasons and more, commercial aircraft are preferred for dispersant operations and UUV deployments, but USCG aircraft can serve as a backup in case commercial aircraft cannot be secured during an incident. If a USCG aircraft is used, any equipment to be launched from a USCG aircraft requires advance approval from the USCG Office of Aviation Forces, USCG Aviation Logistics Center (CG-711), and/or the Aviation Training Center/Aviation Technical Training Center, which would be a lengthy process. If a commercial aircraft is used, it is more likely that responders will experience quicker approvals for UUV deployments. There is also the logistics challenge of deploying the monitoring equipment from the same platform used for dispersant operations.

4.3 Helicopters

RDC considered helicopters as possible alternatives to fixed wing aircraft for conducting SMART operations in remote locations. Compared to fixed wing aircraft, helicopters have less range (355 nm for MH-65C and 700 nm for HH-60J), which limits their endurance. However, they offer a gentler launch for UUVs when compared to fixed wing aircraft. It is possible that helicopters may be limited to only the transport of the UUV to the spill site. Like commercial fixed wing aircraft, commercial helicopters are expected to be pursued before USCG helicopters are considered. If for any reason USCG helicopters are needed, it may be expensive for them to be mobilized to a spill site because D17's two air stations are located in Kodiak and Sitka. They would likely need to refuel at certain locations on their way to the staging area.

Helicopters have limited cargo space and weight restrictions. For an H-60 helicopter, the floor tiedown rings in the cargo area are rated at 2,500 pounds and the deck area cannot exceed 300 pounds per square foot. The weight restriction would limit most larger sized UUVs, which can weigh up to several thousand pounds. If deployment of an UUV requires the helicopters' hoist system, the UUV may not weigh more than 600 pounds. An alternative is to utilize the helicopters' fixed cargo hook beneath their bodies, which can carry up to 2,000 pounds outside of the cabin during transport. However, the UUV on the cargo hook will limit the helicopter's speed and increase its fuel consumption, which reduces its overall range. Once the helicopter arrives on scene, the hook can be released and the UUV dropped into the ocean. If the UUV is attached to a tether cord, a diver may need to enter the water to manually remove the cord from the UUV so it does not interfere with the UUV's operation.

The cabin door opening of a H-60 helicopter is 54 inches high and 44 inches wide. The transverse distance between the forward cabin door edge and the aircrew seats is approximately 40 inches. Most larger sized UUVs have outsized lengths so even if the weight is acceptable, the little space in the cargo area can make them difficult for the crewmembers to maneuver, thus endangering the overall deployment operation. Additionally, there is inherent risk to the helicopter hovering over the water during deployment of an UUV, especially in unforgiving climates such as the Arctic region.

4.4 Other Possible Deployments

Vessels are often used to deploy UUVs for mission executions but as described in the Introduction section, they are not adequate for oil spills in remote locations because the transit is time consuming and expends a large amount of resources, and the Unified Command will not receive actionable information in a timely manner to target response operations. Another option is to deploy UUVs from the closest shoreline and navigate them directly to the oil spill site. Again, this approach is time consuming. While some AUVs are capable of moving at 5 knots, they would take 30 hours to reach a spill site that is 150 nm away. Other UUV types travel even slower and there are also power consumption and data communication issues to consider. If dispersant use is authorized, the Unified Command needs to know its efficacy as soon as possible. The use of vessels or deploying UUVs from shoreline to a remote site is not a practical option to meet the needs of the Unified Command.

5 DATA TELEMETRY

5.1 Current Capabilities

Several methods for unmanned vehicle surface communications include satellite communication, line-of-sight radio, and beacon transmissions (Battelle, 2014). In the Arctic (some of which D17's AOR lies in) or other higher latitude regions, communication is often hindered by spurious satellite connectivity. New communication technologies are continuously being researched to improve on this. Current satellite communication devices include Advanced Research and Global Observation Satellite (ARGOS), INMARSAT or Iridium Communications, Inc. but they are limited by low bandwidth speeds, in the range from 9 to 256 kilobytes per second. Satellite communication is the primary means of transmitting data from USCG fixed wing aircrafts. An RDC project in 2015 studied this capability and found that no USCG platforms were able to successfully send imagery in real time due to system limitations (e.g., poor bandwidth or connectivity) and/or classifications constraints. RDC is also looking into tethered/free release balloon systems, zeppelins (rigid airships), and CubeSats (a type of miniaturized satellite) that can carry payloads to enhance communications. Every summer, new technologies are tested in the higher latitude regions under the RDC's Arctic Shield program.

Another method to overcome the low bandwidth speed and connectivity interruptions in the Arctic is the use of the Mobile Ad hoc Network (MANET) radios. These are a self-configuring and self-healing wireless communication network that operates independently from satellites. This network contains two or more radios or nodes, each equipped with intelligence to dynamically select the best route for network traffic. The Man Pack Unit 5 (MPU5) is a specific model of MANET technology that RDC recently tested with some success. During an RDC exercise, the MPU5s provided field personnel with a connection to a satellite link. The field connection to the internet included successful transmission of the Next Generation Incident Command System (NICS)-mobile information, as well as a high definition video feed. It is capable of transmitting at least 20 megabytes of data from one node to the other. Depending on the configurations and the best environmental conditions, line-of-sight limitations can be overcome with a node hopping configuration. It is estimated that two MPU5 relay modules between an aircraft and an unmanned vehicle floating on the water surface can be as far as 20 to 25 miles apart.

After data is transferred to the MPU5 relay module on the aircraft, it can be transmitted using other satellite links with higher bandwidths, depending on what the aircraft is authorized to use. Another option is to physically transport the data directly back to command once upload from the unmanned vehicle is completed. RDC continues to investigate different solutions for overcoming high latitude communication challenges but MPU5 appears to be a promising method for data transfers in remote locations. Factors to overcome in this scenario are the approval and installation of a MANET system on USCG aircraft and radio spectrum permissions.

5.2 Communications Challenges

It is anticipated that most monitoring technologies will not be able to process the raw data they collect during transits through the oil slick. The amount of data they send back to a receiver can be as large as 20 megabytes after a 12-hour monitoring period, which would need large bandwidth speeds to transmit data quickly. Satellite communication as a data link is possible but may not be a viable solution when transmitting large data quickly enough on the dispersants' efficacy in a remote location. Additionally, there are challenges associated with sending data from a UUV directly to Unified Command by radio due to long distances between the two endpoints.

Since ASVs operate on the water surface, it is capable of maintaining continuous communication with the operator, which means it can be controlled in real time via satellite GPS and Iridium communication or line-of-sight radio communication (Battelle, 2014). However, the operator would likely need to be in close range with the ASV if it is to be used in remote locations, such as riding on a roving aircraft.

6 RECOMMENDATIONS

RDC recommends the first priority for any future work to begin with the development and defining of key performance parameters (KPPs). They will dictate how future prototypes should be constructed to withstand impact of the water surface, protect the monitoring technologies onboard the platform, execute the SMART protocol, and transmit data to Unified Command quickly.

RDC recommends further research of one-time-use sensor platforms as they are already designed for aerial deployment. They appear to be a more feasible approach and likely will not require as much resource-intensive research and development effort as would be needed for redesigning unmanned vehicles for aerial deployment. However, this would have to be verified with a capabilities-based assessment. More specifically, RDC recommends researching impact survivability of monitoring technologies, the available payload weight/volume on different platforms, and logistical support/communication requirements and limitations. RDC recommends building off previous efforts with SLDMBs, MOTTs, and POPEIEs; further work is needed to incorporate monitoring technologies such as fluorometers into existing platforms.

Designing unmanned vehicles for aerial deployment is a large undertaking and RDC recommends partnering with external Federal agencies, academia, or industry if this approach is pursued. The mechanical infrastructure of unmanned vehicles is generally not designed for such impact; a complete mechanical redesign followed by stress tests are needed. Sensors and associated electronics will also have to be tested for impact protection. Also, one would need to consider the available payload volume on the unmanned vehicle, logistical support/communication/equipment requirements and limitations, and how likely the unmanned vehicle will be approved by CG-711, USCG Office of Aviation Forces, for launch from the rear ramp of an USCG C-130. This would also require an investigation into the types of approval required for unmanned vehicle launch from a commercial aircraft. Ongoing work with ADAC and WHOI will further research in this area.

On the communications side, RDC recommends continuing internal, existing research into improving communication capabilities in remote locations, especially in areas of higher latitude. Coast Guard aviation is beginning to leverage MANET radios for "tactical" long-haul data transmission. The Man Pack Unit 5 (MPU5) is a specific model of MANET technology that RDC recently tested with some success. It appears to be a promising method for data transfers in remote locations and further work with it is strongly recommended.

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APPENDIX A. SUBSEA DISPERSANT MONITORING TECHNOLOGIES AND CAPABILITIES

Table A-1. Subsea dispersant monitoring technologies and capabilities.[2]

Sensor	Sensing Method	Target Measurement	Type of Monitoring					
			Oceanographic Data	Dissolved O_2	Dissolved CO_2	Oil Droplet Size Distribution	Continuous Oil Monitoring	Turbidity
4DEEP Inwater Imaging Submersible Microscope	Underwater microscopy	Flow rate, particle size					X	X
AADI Conductivity Sensor 4319	Inductive cell	Conductivity (salinity)	X					
AADI Oxygen Sensor 3830	Optode	Oxygen concentration, air saturation		X				
AADI Seaguard O_2	Fluorescence	Dissolved Oxygen		X				
AADI Turbidity Sensor 4112		Turbidity						X
AML Oceanographic Smart CTD	Conductive cell, thermistor, strain gauge	Conductivity, temperature, pressure, salinity, density	X					
ASD Sensortechnik	Fluorescence	Aromatic hydrocarbons					X	
Bowtech Leak Detection System	Fluorescence	Hydrocarbons					X	
Chelsea Technologies Subsea Pipeline Leak Detection	Fluorescence	Hydrocarbons					X	

[2] Battelle, 2014.

Table A-1. Subsea dispersant monitoring technologies and capabilities (Cont'd).

Sensor	Sensing Method	Target Measurement	Type of Monitoring					
			Oceanographic Data	Dissolved O_2	Dissolved CO_2	Oil Droplet Size Distribution	Continuous Oil Monitoring	Turbidity
Chelsea Technologies UV AquaTrack Fluorometer	Fluorescence	Refined, crude hydrocarbons					X	
Chelsea Technologies UviLux Fluorometer	Fluorescence	Polyaromatic hydrocarbons					X	
CONTROS HydroC CO_2 Carbon Dioxide Sensor					X			
CONTROS HydroC PAH Fluorometer Sensor	Fluorescence	Polyaromatic hydrocarbons					X	
CONTROS Mobile Leak Detection System	Direct and indirect methods	Methane, polyaromatic hydrocarbons, CTD	X				X	
Hach FP 360 SC Oil-in-Water Sensor	Fluorescence	Polyaromatic hydrocarbons					X	
Ocean Tools OceanSENSE Leak Detection	Fluorescence	Hydrocarbons					X	
Phaze Hydrocarbon Leak Detector		Hydrocarbons					X	
Sea & Sun Technology Conductivity Sensor		Conductivity (salinity)	X					
Sea & Sun Technology UV Fluorometer	Fluorescence	Polyaromatic hydrocarbons					X	

Table A-1. Subsea dispersant monitoring technologies and capabilities (Cont'd).

Sensor	Sensing Method	Target Measurement	Type of Monitoring					
			Oceanographic Data	Dissolved O_2	Dissolved CO_2	Oil Droplet Size Distribution	Continuous Oil Monitoring	Turbidity
Sea Bird SBE 19plus V2 SeaCAT	Internal platinum electrode, thermistor, precision quartz crystal resonator, strain gauge	Conductivity, temperature, pressure, salinity, density, sound velocity	X					
Sea Bird SBE 25 plus Sealogger	Internal platinum electrode, thermistor, strain gauge	Conductivity, temperature, pressure, salinity, density, sound velocity	X					
Sea Bird SBE 49 FastCAT CTD Sensor	Conductivity cell, thermistor, strain gauge	Conductivity, temperature, pressure, salinity, density, sound velocity	X					
Sea Bird SBE 911 plus; 917 plus	Conductivity cell, thermistor, precision quartz crystal resonator	Conductivity, temperature, pressure, salinity, density, sound velocity	X					
SeaPoint Sensors Turbidity Meter	Optical light scatter	Turbidity						X
Seapoint UV Fluorometer	Fluorescence	Crude oil					X	
Sequoia LISST-Deep	Optical diffraction	Flow rate, particle size				X		X
Smart Light Devices LDS3 Laser Leak Detection System	Fluorescence	Hydrocarbons					X	

Table A-1. Subsea dispersant monitoring technologies and capabilities (Cont'd).

Sensor	Sensing Method	Target Measurement	Type of Monitoring					
			Oceanographic Data	Dissolved O_2	Dissolved CO_2	Oil Droplet Size Distribution	Continuous Oil Monitoring	Turbidity
Sonardyne Automatic Leak Detection Sonar	Ultrasonic	Hydrocarbons					X	
Teledyne RD Instruments Citadel CTD Products	Inductive cell, thermistor, silicon	Conductivity, temperature, pressure	X					
Teledyne TSS MELDS System	Fluorescence	Methane, polyaromatic hydrocarbons, CTD	X				X	
TriOS enviroFlu-DS	Fluorescence	Polyaromatic hydrocarbons					X	
TriOS enviroFlu-HC	Fluorescence	Polyaromatic hydrocarbons					X	
Turner Designs C3 Submersible Fluorometer	Fluorescence	Crude, fine oil					X	
Turner Designs Cyclops 6K customizable	Fluorescence	Crude, fine oil, turbidity					X	X
Turner Designs Cyclops 7 customizable	Fluorescence, optical scatter	Crude, fine oil, turbidity					X	X
Wetlabs WQM	Thermistor, fluorescence, others	Conductivity, temperature, pressure, dissolved O_2, turbidity	X	X				X
YSI EXO Series		Conductivity, temperature, pressure, dissolved O_2, turbidity	X	X				X