1-2023

Comparing Recent Advances in Estimating and Measuring Oil Slick Thickness: An MPRI Technical Report

CRRC

NOAA

MPRI

BSEE

Comparing Recent Advances in Estimating and Measuring Oil Slick Thickness

Multi-Partner Research Initiative (MPRI) Final Report

Acknowledgements

This work was funded by under a Memorandum of Understanding between the National Oceanic Atmospheric Administration (NOAA), a U.S. government agency within the U.S. Department of Commerce, as represented by the National Ocean Service, Office of Response and Restoration (ORR) and Her Majesty the queen in right of Canada, as represented by the Minster of Fisheries and Oceans (MOU No. 2019-044/11739). The project is part of the Multi-Partner Oil Spill Research Initiative to advance oil spill research to support science-based decision making for oil spill preparedness and response.

Significant additional project contribution and support were provided by the Bureau of Safety and Environmental Enforcement (BSEE) and the Ohmsett National Oil Spill Research and Renewable Energy Test Facility in Leonardo New Jersey. We also appreciate and acknowledge the financial support from the Oil Spill Recovery Institute (Cordova, AK).

All phases of this project were supported and administered by the NOAA ORR and the University of New Hampshire's Coastal Response Research Center (CRRC). The project was guided with significant support from the project steering committee members:
Jay Cho, BSEE
Robyn Conmy, USEPA
Lisa DiPinto, NOAA
George Graettinger, NOAA
Alan Guarino, Ohmsett
Nancy Kinner, CRRC
Kristi McKinney, BSEE
W. Scott Pegau, AK OSRI
Philip Ramsey, UNH
Dana Tulis, USCG MER

The project team would like to thank Kathy Mandsager for her invaluable support in managing numerous administrative, logistical, and technical components. We also would like to thank CRRC/UNH staff and students: Kathy Mandsager, Katie Perry, Jess Manning, Wesley Lambert, Quinn Wilkins, Tori Sweet, Wilder Byrne, Chris Keohane, Devon Mexcur, Nate Wunderlich, Sam Williams for their seemingly tireless support for the discussions, experiments, analyses and writing.

Other key partners who assisted in a variety of ways include Dr. Joseph Katz and Subhamoy Gupta (Johns Hopkins University), Jay Coady (NOAA, OR&R, ARD), and Prof. Philip Ramsey (UNH, Mathematics and Statistics).

Contents

Material in this report may be used for the purposes of internal or external communications.

PART A: Project Information

1. **Project Title:** Comparing Recent Advances in Estimating and Measuring Oil Slick Thickness
2. **Project Lead:** Lisa DiPinto
3. **Name of Organization:** NOAA Office of Response and Restoration
4. **Term of the Agreement:** June 2019 – to March 2022
5. **Contribution Period (Final):** From April 2021 – to September 2022
6. **Report Submission Date:** December 7, 2022

PART B: Project Objectives and Results

7. Project Objectives

Characterization of the degree and extent of surface oil during and after an oil spill is a critical part of emergency response and Natural Resource Damage Assessment (NRDA) activities. More specifically, understanding floating oil thickness in real-time can guide response efforts by directing limited assets to priority cleanup areas; aid in 'volume released' estimates; enhance fate, transport and effects modeling capabilities; and support natural resource injury determinations. An international workshop (http://www.cvent.com/events/2018-gulf-of-mexico-oil-spill-and-ecosystem-science-conference/custom-125-6ae61bf76b204d0392d48b8bf15ed1eb.aspx#6) brought researchers from agencies, academia and industry who were advancing *in situ* and remote oil characterization tools and methods together with stake holders and end users who rely on information about floating oil thickness for mission critical assignments (e.g., regulatory, assessment, cleanup, research). In total, over a dozen researchers presented and discussed their findings from tests using various different sensors and sensor platforms. The workshop resulted in discussions and recommendations for better ways to leverage limited resources and opportunities for advancing research and developing tools and methods for oil spill thickness measurements and estimates that could be applied during spill responses. **One of the primary research gaps identified by the workshop participants was the need for side-by-side testing and validation of these different methods, to better understand their respective strengths, weaknesses and technical readiness levels, so that responders would be better able to make decisions about what methods are appropriate to use under what conditions, and to answer the various questions associated with response actions.**

Approach:

1) Convene a more in-depth multi day researcher workshop to discuss and develop specific workplan to conduct side-by-side validation and verification experiments for testing oil thickness measurements.

2) Conduct the validation and verification experiments in controlled environments: the Coastal Response Research Center (CRRC) highbay at the University of New Hampshire (UNH); and the Ohmsett National Oil Spill Response Research & Renewable Energy Test Facility.

8. Expected Results and Deliverables

- Sensor specifications table and report delivering information on detection limits, accuracy and precision, scene footprints available, TRL, strengths, weaknesses, etc.
- Peer review publication (if appropriate) highlighting findings.

PART C: Reporting

9. Results Achieved

9.A. Sensor Specifications and Capabilities

One of the goals of the project was to obtain information on existing oil sensors and their capabilities. These data are located in Appendix A and B in this report. Appendix A is a series of tables (one per sensor) for those sensors evaluated during this project. Appendix B is a spreadsheet that includes all of the sensor packages discussed at the in-depth, multi-day workshop in November 2019. Information in these appendices includes: a description of each sensor, its technical readiness level (TRL), the range of thicknesses detectable, resolution, scene footprints (swath size), time required for various operations, space and power requirements, and the signal to noise ratio. For sensors evaluated at UNH and Ohmsett, information on accuracy and precision, strengths and weaknesses are also included. For other sensors, not evaluated, the estimates could not be independently verified.

9.B. Development of an Oil Thickness Sensor Testing Protocol

After the November 2019 workshop, the Steering Committee (SC) realized that one of the major deficiencies of previous oil spill remote sensing studies was the lack of "blind" slick thickness evaluation of sensors. A "blind" test is one where the sensor/sampler operator is asked to determine the thickness of a slick without knowing the answer beforehand. The problem with doing this stemmed from the lack of a protocol to consistently create slicks of known uniform thickness that were not patchy and variable across the surface. The SC decided to develop a protocol for slicks as thin as 1 μm. The experiments determined that the tanks in which the slicks are contained should be stainless steel because of the inhibition of spreading in the presence of the chemicals that leach from plastic tanks (e.g., fish totes). [N.B., The stainless steel tanks used at UNH for the validation testing were 3 ft x 4 ft maple sap storage tanks.] The tank should contain a black anodized aluminum liner (with attached zinc anodes to prevent corrosion) to avoid confounding some sensors with bright light reflective spots. Water in the tank must not contain organic chemicals (e.g., not surface water treated with polymers during coagulation-flocculation processes) that will inhibit uniform slick formation. Water in the tank must be allowed to "still" so that internal currents do not exist that could cause these slicks to "swirl." Stilling time are longer for thinner slicks (e.g., 12+ hr for 1-10 μm slicks).

Oil must be added to the tanks using a pre-weighed delivery device (e.g., separatory funnel, burette) located just above the tank water's surface that minimizes disturbances. A stainless-steel containment ring (sized based on the volume delivered and tared) is located at the water's surface. The ring holds the oil after it is released from the delivery device. Once the oil has uniformly spread in the containment ring and no bubbles are present, the ring is lifted directly up and out of the water smoothly and quickly using a device that spans the tank. The ring is removed from the device and weighed to determine the amount of oil that adheres to it. The amount of oil retained in the delivery device is also determined. The total amount of oil delivered to the water's surface is calculated as:

(Initial Oil in Delivery Device) - (Oil Remaining in the Delivery Device + Retained on the Ring) = Oil on the Water's Surface

The oil is allowed to spread until it reaches a stable footprint (~5-10 min), usually at or adjacent to the sides of the tank. We consistently noted a relatively uniform distribution of oil across the tanks (Figure 9.B.1. and 9.B.2.) The oil thickness is estimated by knowing the volume of oil delivered and the surface area of the slick in the tank. The surface area is obtained by measuring the area of the slick using a high-resolution UV camera (Andor iXon ultra 888; Oxford Instruments; Concord, MA) suspended ~5 m above the tank. The area of the photograph is determined using ImageJ software (U.S. National Institutes of Health). Thickness = Volume/Area. The thickness is a nominal value (i.e., average estimated), and is not a point- specific measurement.

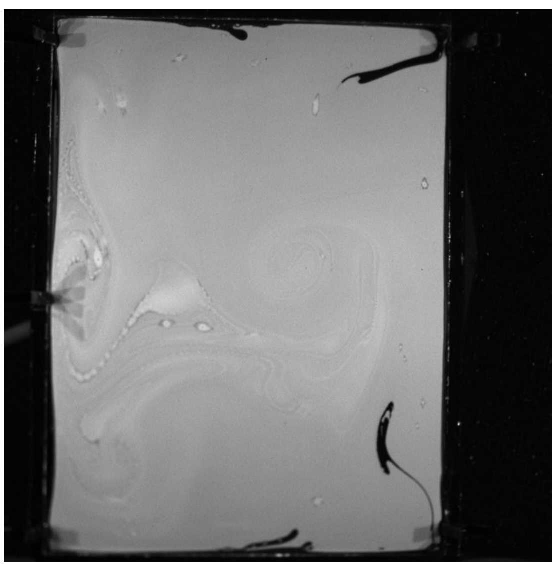

Figure 9.B.1. Target 10 Micrometer Film

Figure 9.B.2. Target 750 Micrometer Film

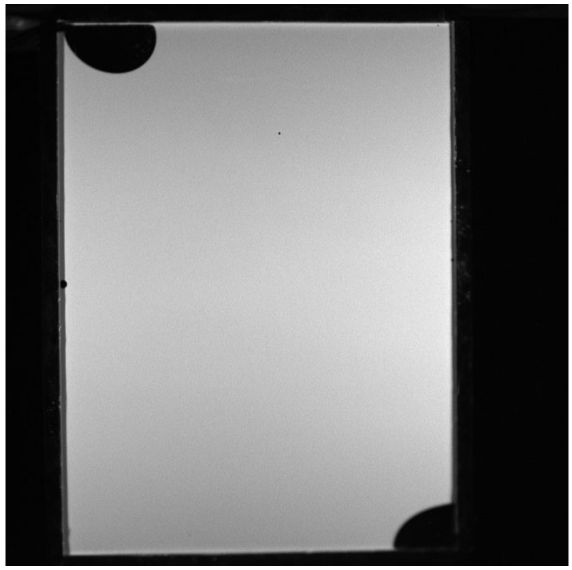

Figure 9.B.1.2. Target 1500 Micrometer Film

The UV camera images are calibrated and optimized based on manufacturer's specifications. The UV camera used for this research was provided by Prof. Joseph Katz (Johns Hopkins University; Baltimore, MD). Prof. Katz and his Ph.D. student Subhamoy Gupta trained UNH team members on the calibration of the camera and provided images of the slicks for subsequent ImageJ analyses. Camera calibrations were performed before each slick was created. [N.B., In subsequent work, a Canon EOS Rebel Digital Camera T8 is equipped with an 18 – 55 mm STM lens was used.]

In most cases, an operator whose sensor was being evaluated was given the opportunity to measure the slick three times for each thickness created. UV images were captured before and after an operator measured the slick. This controlled for any change in slick area over the time of the experiment (~3-6 minutes per slick measurement per operator). The operators then processed their data and reported the measured thicknesses to the SC. The time to process and report was noted and compared to typical operational timeframes during a response.

After testing was completed, PIG oil-only sorbent pads (New Pig; Tipton, MA) and large Kimwipes (Kimberly Clark; Roswell, GA) were used to remove the oil. The tank and all surfaces and glassware in contact with the oil were cleaned three times with isopropyl alcohol, dried with PIG pads and allowed to air dry before the next use.

Eight UV lights (realUV LED Flood Lights 395nm; Waveform Lighting, Vancouver, WA) (four on each side of the tank) were used so the SC could see the slick when it was created and for the high-resolution UV camera could capture its footprint. The oil fluoresced yellow when illuminated by the UV lights. The "sunlight" lighting used for the radiometer and multispectral sensors and ROSV camera consisted of four work lights (HDX 1200-Watt Halogen Work Lights with Tripod, China) (two per side). The "sunlights" were on when the operators were conducting their measurements, except for the acoustic sensor testing where only overhead fluorescent lighting in the highbay was used.

9.C. Test Results for Sensors Using the Thickness Protocol

Eight sensors were evaluated using the Thickness Protocol (2 airborne, 4 surface, 2 subsurface) (Table 9.C.1). Operators were not told the thicknesses nor the oil type. However, they were given a 50 mL sample of the oil (i.e., HOOPS weathered to 10% by volume). Up to two slick thicknesses could be evaluated per day (a thin slick in the morning where the water had a 12+hr stilling time overnight, and a thicker slick in the afternoon with a <3 hr stilling time). The SC determined that the target thicknesses should be 1, 10, 200, 500 and 1,000 µm. The subsurface acoustic sensor had a practical lower detection limit of ~200 µm, so the SC determined the thicknesses for that device should be 200, 500, 750, 1,000, and 1,500 µm. To avoid confusion and ensure each participant was given sufficient time for preparation and analysis, sensors were evaluated on separate weeks instead of simultaneously. The exceptions were the dip plates, sorbent pads and tube samplers which were evaluated after non-disruptive sensor analyses of slicks. The photometric sensor and ROSV are still under development, while the other sensors have been used at oil spills (multispectral and tube sampler) or in large tank testing (acoustic sensor Ohmsett, CRREL).

The testing schedule is shown in Appendix C.

Results for individual sensor testing at UNH are located in Appendix D. For each sensor, the target thickness, estimated average sick thickness, and sensor-reported thickness are listed. In addition, a Factor Difference (FD) is given that shows the relationship between the estimated slick thickness created and the sensor-reported thickness where:

$$Factor\ Difference\ (FD) = \frac{Greater\ Thickness}{Lesser\ Thickness}$$

Hence, if the sensor-reported thickness was greater than the nominal slick thickness:

$$FD = \frac{Sensor\ Thickness}{Nominal\ \ Thickness}$$

Table 9.C.1 Sensors Tested Using Thickness Protocol

Sensor Category	Sensor Type*	Slick Thickness Tested (µm)
Airborne	Multispectral	1, 10, 200, 500, 1,000
	Radiometer	1, 10, 200, 500, 1,000
Surface	Sorbent Pads	1, 10, 200, 500, 1,000
	Dip Plates	1, 10, 200, 500, 1,000
	Camera from Remotely Operated Surface Vehicle (ROSV)	1, 10, 200, 500, 1,000
	Tube Sampler	1, 10, 200, 500, 1,000
Subsurface	Acoustic	200, 500, 750, 1,000, 1,500
	Photometric	1, 20, 200, 500, 1,000

*Descriptions of sensors are located in Appendix B.

Ɨ All slicks were weathered HOOPS (aerated to a loss of 10% by volume).

In cases where the FD was +, the sensor reported a thickness greater than the slick. If the sensor reported a thickness less than the nominal slick created:

$$FD = \frac{Nominal\ Thickness}{Sensor\ Reported\ Thickness}$$

The FD was assigned a - sign to indicate an underestimate.

The best result any sensor could achieve was an FD of the absolute value of 1.00 (i.e., nominal and sensor reported thickness were identical).

Table 9.C.2 and Figure 9.C.1 show summaries of the results obtained for the slick thickness protocols testing. The format of Figure 9.C.1 mimics that of a QA/QC percent recovery chart using factor differences where the deviation was measured from the line where the FD = |1.00| (absolute value of 1.00).

	Table 9.C.2. Ohmsett Final Results					
	Airborne Sensors					
	Multispectral Sensor			**Radiometer**		
Target Thickness (um)	**Reported Thickness (um)**	**Factor Difference**	**% RSD**	**Reported Thickness (um)**	**Factor Difference**	**% RSD**
1	4 3 2	3.6 2.7 1.8	33.3	10 17 10 12 16	10.2 17.5 10.3 12.4 16.8	25.5
10	16 14 15	1.3 1.2 1.3	6.7	36 13 31 21 20	2.8 1.0 2.5 1.7 1.6	38
200	250 228 244	1.4 1.3 1.4	4.7	113 119	-1.8 -1.6	3.7
500	742 745 722	1.6 1.7 1.6	1.7	248 316 303	-1.8 -1.4 -1.4	12.5
750						
1000	1404 1329 1321	1.4 1.4 1.4	3.4	317 336 339	-3.3 -2.9 -2.9	3.6
1500						

*ROSV is "Remotely Operated Surface Vehicle"
*All reported thicknesses are written as they were provided (i.e., to the place value they were reported)
*All factor differences are calculated to the tenths place

Surface Sensors

Target Thickness (um)	Sorbent Pads			Dip Plates		
	Reported Thickness (um)	Factor Difference	% RSD	Reported Thickness (um)	Factor Difference	% RSD
1	1.1 1.7 0.8	1.1 1.8 -1.2	38.2	-9 9 0 13	-9.2 9.3 -1.0 14.0	301.9
10	13.5 14.0 11.2	1.0 1.1 -1.1	11.6	0 0 0 7	-13.1 -12.8 -12.6 -1.5	200
200	232.7 225.5 212.9	1.3 1.2 1.2	4.5	55 46 46 66	-3.4 -3.9 -3.9 -2.8	17.8
500	71.2 58.7 58.7	-6.2 -7.4 -7.4	11.5	101 101 73 83 99	-4.4 -4.3 -6.0 -5.3 -4.9	14
750						
1000	121.5 132.2 105.3	-8.1 -7.3 -9.1	11.3	101 83 73 185	-9.8 -11.7 -13.2 -4.9	46
1500						

	Surface Sensors					
	ROSV			Tube Sampler		
Target Thickness (um)	**Reported Thickness (um)**	**Factor Difference**	**% RSD**	**Reported Thickness (um)**	**Factor Difference**	**% RSD**
1				<5	<4.5	
10	510	49.0		19.61 *This replicate was reported to the hundredths place	1.6	
200	1250 960	6.0 5.1		223	1.3	
500	4750	10.5		715	1.6	
750						
1000	6030	5.9		1476	1.5	
1500						

Target Thickness (um)	Underwater Sensors					
	Acoustic Thickness Sensor			Photometric Sensor		
	Reported Thickness (um)	Factor Difference	% RSD	Reported Thickness (um)	Factor Difference	% RSD
1				2 3 2	1.8 2.7 1.8	24.7
10				13 10.31 11.80 *This replicate was reported to the hundredths place	1.1 -1.2 -1.0	11.5
200	250 190 180	1.3 -1.0 -1.0	18.3	276 232 264	1.6 1.4 1.5	8.8
500	540 500 470	1.1 1.0 -1.0	7	768 774 729	1.7 1.7 1.6	3.2
750	800 740 700	1.0 1.0 -1.0	6.7			
1000	1100 1070 1040	1.0 1.0 1.0	2.8	1332 1308 1293	1.3 1.3 1.3	1.5
1500	1430 1400 1380	1.0 1.0 1.0	1.8			

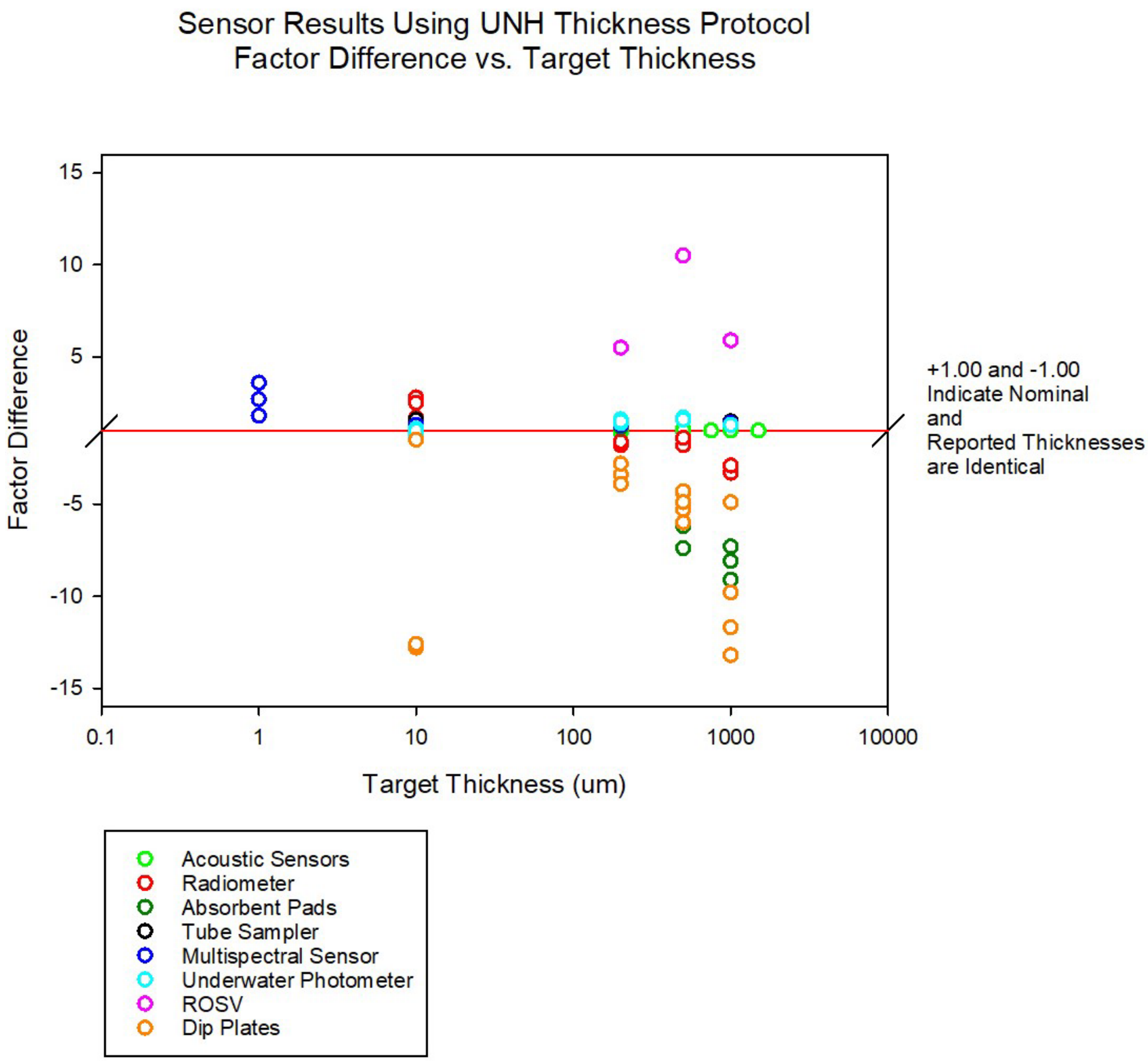

Figure 9.C.1. All sensor results using UNH thickness protocol.

N.B., The desired result is FD= 1 indicating the correct thickness was measured. Positive FD>1 indicated overestimates of thickness. FD values that were more negative than -1 were underestimates of thickness. ROSV FD= 49 for 10 µm not shown.

Two sensors, the dip plates and ROSV camera, consistently gave slick thicknesses that were up to 4.0x different than the thickness delivered over the range evaluated. At thicknesses of 500 and 1,000 µm, the sorbent pads also had a large negative FD, underestimating the thickness. This suggests that these sensors may be less useful in predicting oil thickness in their present form over these ranges.

It is very important to note that the ROSV camera had to be adapted to the tank testing conditions by enclosing the camera window within an outer casing (Figure 9.C.2). The ROSV camera required manual manipulation and was moved back and forth through the slick. Therefore, the results are not representative of the sensor's true potential to measure slick thickness. In addition, the ROSV may benefit by adding a calibration SOP with the oil being observed as is done with other devices (e.g., tube sampler).

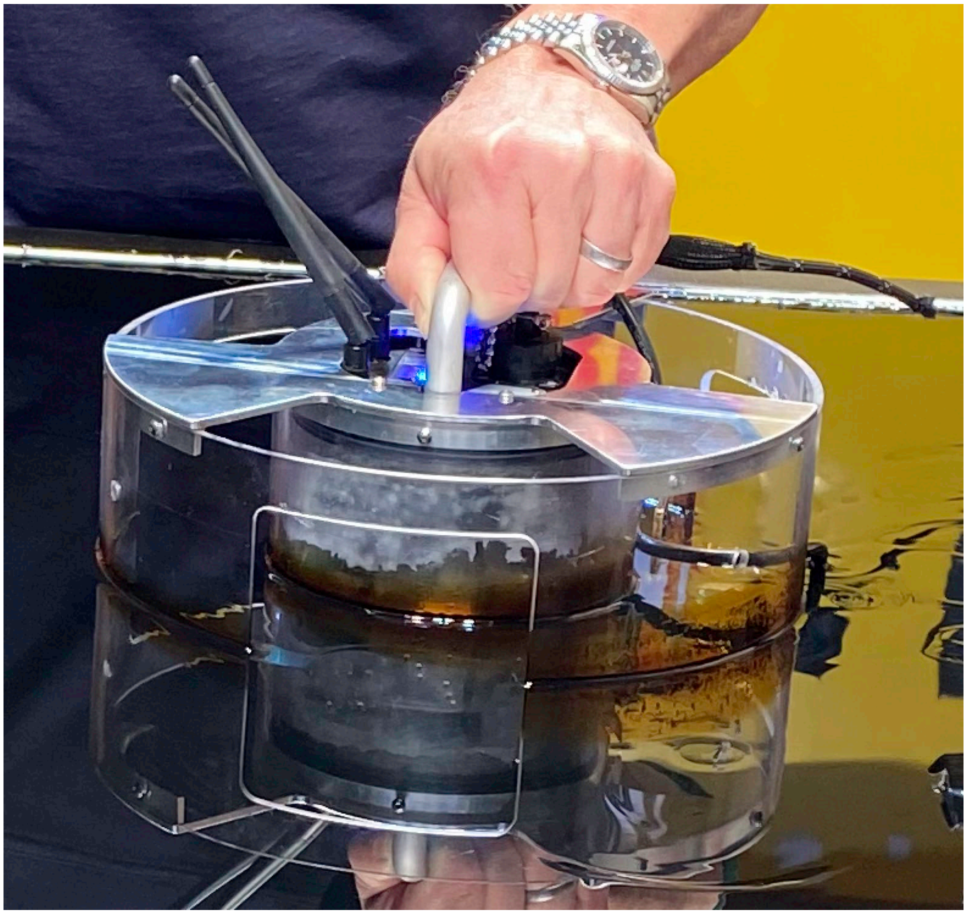

Figure 9.C.2. Photo of ROSV Camera

The remaining sensors (acoustic, multispectral, tube sampler, radiometer, photometer) all estimated the slick thickness with FDs of |>1.0 to 3.0|, either under- or overestimating the nominal value (Figure 9.C.3).

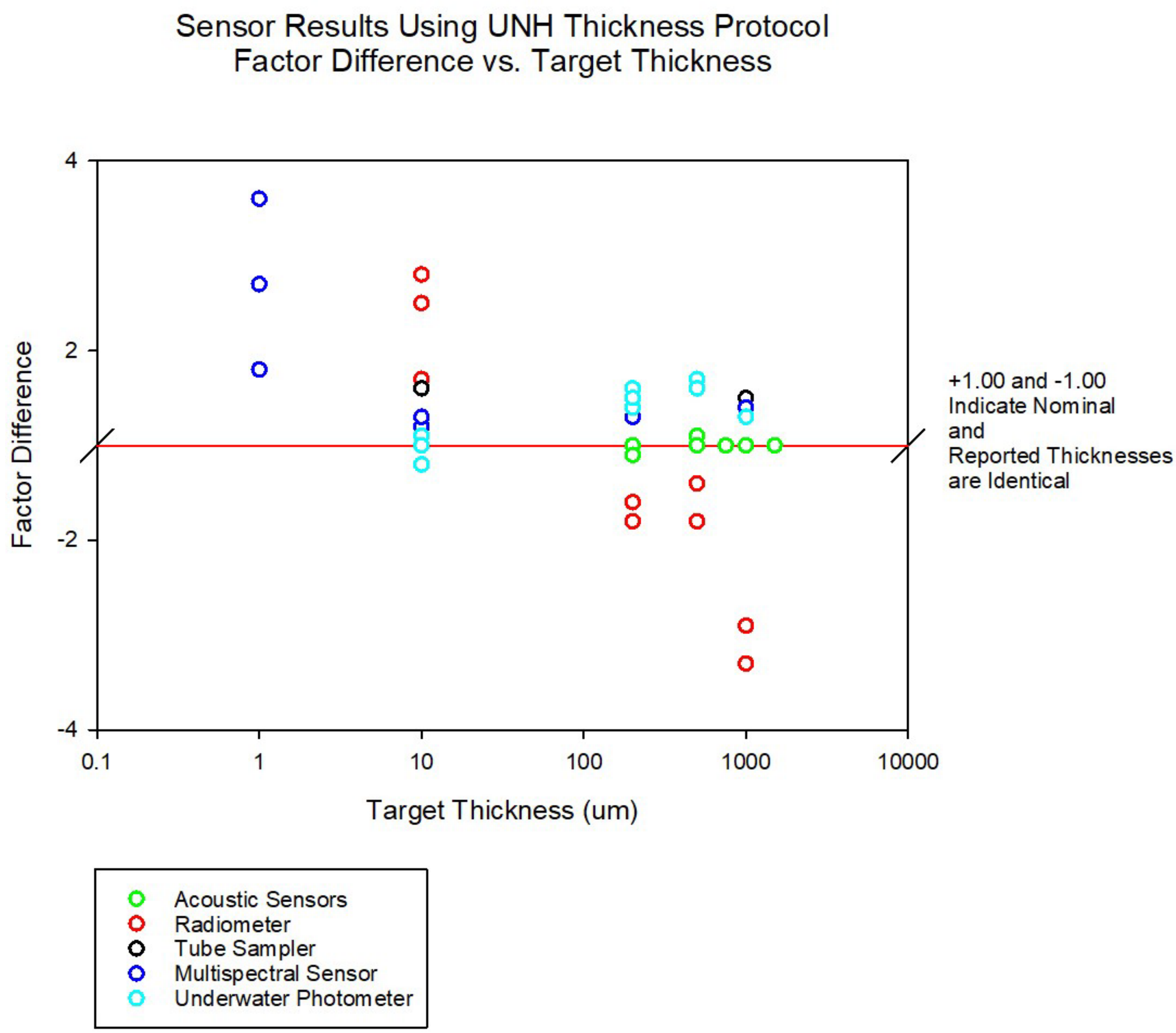

Figure 9.C.3. Sensor results using UNH thickness protocol, excluding dip plates, sorbent pads and ROSV. [Note scale change (4 to -4) compared with Fig 9.C.1. (15 to -15)]

The underwater acoustic sensor was calibrated with the HOOPS sample provided to determine the acoustic signal of the oil. Eight sensors were placed across the bottom of the stainless steel tank to measure the slick thickness and the data were interpreted by the operator using proprietary software. The acoustic sensor package came the closest to predicting the nominal slick thicknesses that were created for each test across its entire range (200 – 1,500 µm). The accuracy of the acoustic sensor is indicated by its FD, ranged from -1.06 to +1.28. At its practical detection limit of 200 µm, the percent relative standard deviation for the reported thickness was 18.3% (%RSD = std dev/x · 100). In all other cases, the %RSD ranged from 2% to 7%, which is very good precision.

For the 1 µm thickness, the sorbent pads came remarkably close (FD = +1.8 to -1.2), followed by the photometric, multispectral, and tube samplers that predicted thicknesses <5 µm. The radiometer reported thicknesses between 10 and 17 µm for the 1 µm slick. These results are particularly good considering that the 1 μm thickness was below the reported detection limit for the radiometer, tube sampler, and sorbent pads. The multispectral sensor was the only one that has a detection limit reported to be in the 1 μm range. The dip plates did not do well (FD = -9.2 to 14.0). The ROSV camera was not evaluated at the 1 μm thickness because it was below its detection limit.

For the 10 μm slicks, the sorbent pads, photometer, and multispectral sensors came the closest to the nominal value, ranging from FD = – 1.2 to 1.3, with the tube sampler slightly greater at 1.7. The radiometer generally overestimated the thickness with an FD ranging from 1.0 to 2.8. The %RSDs for these sensors ranged from 6.7 to 38.0%. Precision is typically not as good when instruments are evaluated near their detection capabilities. The dip plates continued to perform poorly, as did the ROSV camera (FD = 49%).

The ability of the multispectral, radiometer, and photometric sensors, tube sampler and sorbent pads to detect these thin slicks in the highbay with FD <|2.0| was encouraging and unexpected, though the lower precision means that the data must be used with caution. [Note: %RSD could not be calculated for the tube sampler as only one value was reported.] While this does not mean that the field performance will be as good, it suggested that the sensors can detect the thickness when it is uniform, unlike the patchiness in the field.

The 200 μm thicknesses were detected with FD < | 1.8| and RSDs of 3.7 to 8.8% by the multispectral and photometric sensors, sorbent pads, radiometer, and tube sampler (tube sampler did not have %RSD). For the 500 μm slicks, the multispectral and photometric sensors, radiometer, and the tube sampler had FDs <|2.0| and RSDs of 1.5 to 3.4%. The radiometer performed slightly less well at 500 and 1,000 μm for precision and accuracy, respectively (%RSD = 12.5% at 500 μm and FD = ~3 at 1,000 μm). At the 500 and 1,000 μm thicknesses, the sorbent pads joined the dip plates and ROSV in performing less well.

The satisfactory performance of the acoustic, multispectral, and photometric sensors, radiometer, and tube sampler suggested that fundamentally these systems can detect slick thicknesses accurately (FD< |2.0|) over the range evaluated with good precision (10% RSD). While field conditions introduce many sources of variability, the ability of these sensors to perform well in the highbay instills confidence that they are sound. Excellent performance of sensors in laboratory conditions is always a prerequisite if they are to be useful in field conditions (Statistics and Chemometrics for Analytical Chemistry; J.N. Miller and J.C. Miller. 2005 (5th ed.) ISBN 0-13-129192-0; Statistics for experimenters; G.E.P. Box, J.S. Hunter, and W.G. Hunter. 2005 (2nd ed.) ISBN 0-471-71813-0).

9.D Test Results for Sensors at Ohmsett Tank

Results were obtained for four oil thickness sensors at Ohmsett: airborne = multispectral sensor and radiometer, surface = tube sampler, sorbent pads and dip plates. [N.B., The operators of the ROSV camera, and photometric and acoustic sensors decided not to evaluate them at Ohmsett.]

The HOOPS oil was prepared in two states by Ohmsett staff for the tank-scale validation experiments. The HOOPS was weathered to reduce its mass by 10%. [N.B., The UNH testing used HOOPS weathered to reduce its volume by 10%. Both the UNH and Ohmsett weathering methods involved aeration in gas blowdown apparati.] The Ohmsett staff also used the Stone and Guarino (2017, IOSC Proceedings 2017-071) protocol to prepare water-in-oil emulsions. The emulsion status was checked by observing an oil sample under a microscope. The emulsion was prepared daily immediately before the Ohmsett tank testing.

As with the UNH protocol, aliquots of the oil (weathered or emulsified) were weighed into tared jars and the data recorded. The bottles were then taken tank-side to four stations. Different sensors were evaluated at each station: A = Multispectral Sensor, B = Tube Sampler, C = Radiometer and Dip Plates, and D = Sorbent Pads. Nine 1.5 m diameter rings were placed at each station. The rings were made of 8-inch aluminum flashing and supported around the outside by diameter black polypropylene tubing. A random number generator was used to determine which type and volume of oil was added to each ring at each station. The testing was performed on three consecutive days in May 2022. Each day, the ring contents were randomized separately for each station. The operators did not know the oil type, state (weathered or emulsified) nor the thicknesses. Four target thicknesses were prepared for each oil type for each station: 50, 200, 500, and 1,000 µm. One randomly designated ring at each station received no oil.

Oil was added to the rings using a pouring device that allowed its addition to the center of the ring (Figure 9.D.1). The bottles containing the prescribed amount of oil were attached to the pouring devices. Once emptied, the bottles were removed from the pouring device and re-weighed to determine the amount discharged into each ring. Photographs were taken of each ring before and after sensor measurements to determine the position of the oil. The change in oil in the bottles was used to estimate the average thickness of oil in the ring as if it were uniformly distributed. Uniform distribution did not always occur as shown in Figure 9.D.2 and by the photographs in the spreadsheet in Appendix E.

Figure 9.D.1. Oil pouring device used at Ohmsett.

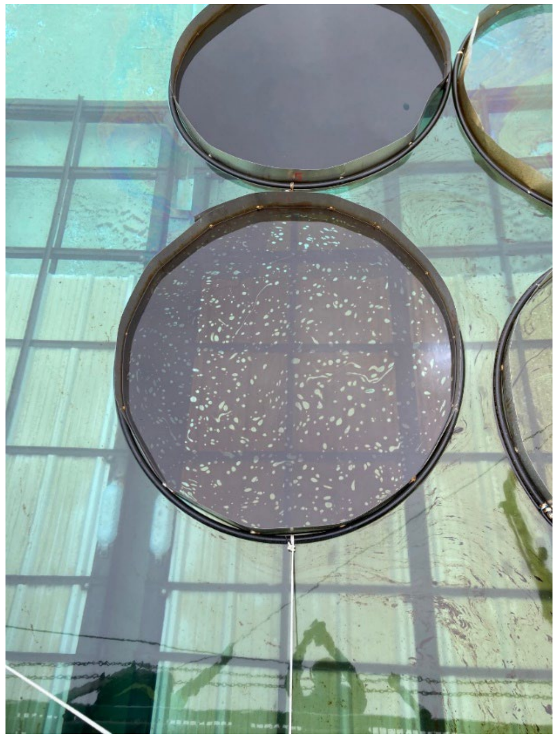

Figure 9.D.2. Examples of oil slicks in the rings at Ohmsett.

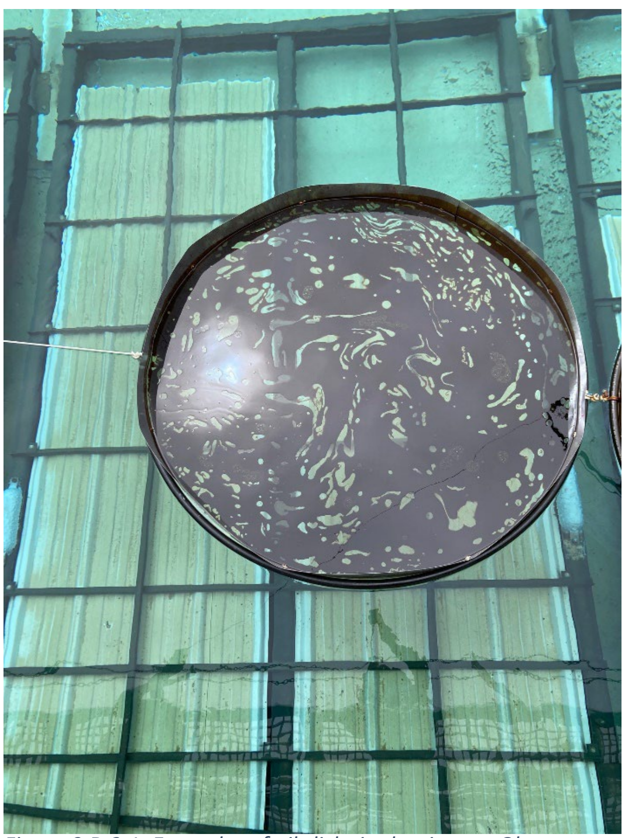

Figure 9.D.2.1. Examples of oil slicks in the rings at Ohmsett.

Figure 9.D.2.2. Examples of oil slicks in the rings at Ohmsett

Results for the individual sensors evaluated at Ohmsett are contained in Appendix E. Table 9.D.1 and Figure 9.D.3 are the summary of the results obtained. Results for the radiometer were not delivered by the operator as specific numerical thicknesses, but in descriptive terms (e.g., relatively thin oil). Hence, they could not be graphically displayed in Figure 9.D.3. On the third day, the operator of the multispectral sensor and tube sampler requested to perform both measurements on the oil slicks in one set of rings (instead of using two stations of rings), as this is the way it would be conducted in the field during an actual event. The SC granted this request, and those data are shown separately. Each operator was given a sample of the HOOPS (emulsified) and HOOPS (weathered), but they were not told the type of oil or its weathering state. Results for the sorbent pads are reported assuming the contents of the rings were either oil type A or B (i.e., weathered HOOPS and emulsified HOOPS, respectively).

Table 9.D.1. Ohmsett Final Results

	Airborne Sensors					
	Multispectral Sensor			Radiometer		
Target Thickness (um)	Reported Thickness (um)	Factor Difference	% RSD	Reported Thickness (um)	Factor Difference	% RSD
0	5	5.0	0	Almost the same as oil-free water	N/A	N/A
	5	5.0		Oil sheen	N/A	
	5	5.0		Negligible oil	N/A	
50 W	290	5.9	58.4	Thin oil. Strong patchiness	N/A	N/A
	68	1.4		Thin oil. Strong patchiness	N/A	
	250	5.2		Relatively thick oil. Strong patchiness	N/A	
50 E	380	7.0	91.7	Relatively thin oil. Strong patchiness	N/A	N/A
	39	-1.4		Intermediate thickness	N/A	
	150	2.8		Thin oil	N/A	
200 W	550	2.8	38.2	Relatively thick oil. Strong patchiness	N/A	N/A
	250	1.3		Relatively thick oil. Strong patchiness	N/A	
	380	1.9		Relatively thick oil	N/A	
200 E	471	2.2	21.7	Relatively thick oil (thinner than ring 1), Strong Patchiness	N/A	N/A
	460	2.1		Relatively thick oil. Strong patchiness	N/A	
	310	1.4		Relatively thick oil. Strong patchiness	N/A	
500 W	430	-1.2	10	Relatively thick oil. Strong patchiness	N/A	N/A
	523	1.1		Relatively thick oil. Strong patchiness	N/A	
	500	1.0		Thick oil. Possible patchiness	N/A	

500 E	670	1.2	7.7	Relatively thick oil. Strong patchiness	N/A	N/A
	580	1.1		Relatively thick oil (thinner than ring 1)	N/A	
	600	1.1		Relatively thick oil	N/A	
1000 W	840	-1.2	11.5	Thick oil, possible thicker than ring 1	N/A	N/A
	840	-1.2		Very thick oil, possible beyond detection limit	N/A	
	1020	1.0		Very thick oil, possible beyond detection limit	N/A	
1000 E	750	-1.5	20.3	Thick oil	N/A	N/A
	1080	-1.0		Very thick oil, possible beyond detection limit	N/A	
	800	-1.4		Very thick oil, possible beyond detection limit	N/A	

Target Thickness (um)	Surface Sensors								
	Dip Plates			Sorbent Pads					
	Reported Thickness (um)	Factor Difference	% RSD	Reported Thickness If Oil Type A (um)	Factor Difference	% RSD	Reported Thickness If Oil Type B (um)	Factor Difference	% RSD
0	6	6.0	48	1.7	1.7	28	1.3	1.3	25.8
	15	15.0		1.6	1.6		1.2	1.2	
	18	18.0		2.6	2.6		1.9	1.9	
50 W	17	-2.9	17.7	32	-1.5	119.7	24	-2.0	119.0
	23	-2.1		270	5.5		201	4.1	
	24	-2.1		38	-1.3		29	-1.6	
50 E	19	-2.8	16.2	111	2.1	55.7	82	1.5	54.9
	25	-2.2		29	-1.9		22	-2.4	
	26	-2.1		88	1.6		65	1.2	
200 W	36	-5.5	17.4	445	2.3	20.3	331	1.7	20.4
	47	-4.2		490	2.5		364	1.8	
	51	-3.9		325	1.7		241	1.2	
200 E	34	-6.4	18.0	173	-1.3	65.3	128	-1.7	65.6
	49	-4.5		569	2.6		423	2.0	
	42	-5.2		236	1.1		175	-1.2	
500 W	90	-5.5	8.1	597	1.2	25.1	443	-1.1	25.5
	102	-4.9		963	2.0		715	1.4	
	88	-5.6		963	2.0		715	1.5	
500 E	67	-8.1	20.4	220	-2.5	60.4	163	-3.3	60.5

	97	-5.6		536	-1.0		398	-1.4	
	99	-5.5		878	1.6		652	1.2	
	126	-7.9		2078	2.4		1543	1.8	
1000 W	135	-7.4	18.6	1928	1.9	22.6	1431	1.4	22.7
	177	-5.6		1319	1.3		979	-1.0	
	158	-6.9		2481	2.4		1842	1.8	
1000 E	166	-6.6	8.5	2106	1.9	33.3	1563	1.4	33.3
	186	-5.9		1225	1.1		910	-1.2	

	Surface Sensors		
	Tube Sampler		
Target Thickness (um)	**Reported Thickness (um)**	**Factor Difference**	**% RSD**
0	3	3.0	66.2
	17	17.0	
	18	18.0	
50 W	44	-1.1	72.8
	139	2.9	
	257	5.3	
50 E	249	4.6	45.4
	92	1.7	
	179	3.3	
200 W	62	-3.2	85.9
	88	-2.2	
	294	1.5	
200 E	68	-3.2	71.0
	91	-2.4	
	243	1.1	
500 W	1011	2.0	45.8
	734	1.5	
	368	-1.3	
500 E	1230	2.2	56.9
	574	1.0	
	435	-1.3	
1000 W	567	-1.8	54.3
	1258	1.3	
	498	-2.0	
1000 E	1089	-1.0	42.7
	511	-2.1	
	595	-1.8	

	Combined Sensors		
	Tube Sampler + Multispectral Sensor		
Target Thickness (um)	**Reported Thickness (um)**	**Factor Difference**	**% RSD**
0	5	5.0	N/A
50 W	180	3.7	N/A
50 E	105	1.9	N/A
200 W	245	1.2	N/A
200 E	217	-1.0	N/A
500 W	545	1.1	N/A
500 E	485	-1.1	N/A
1000 W	600	-1.7	N/A
1000 E	700	-1.6	N/A

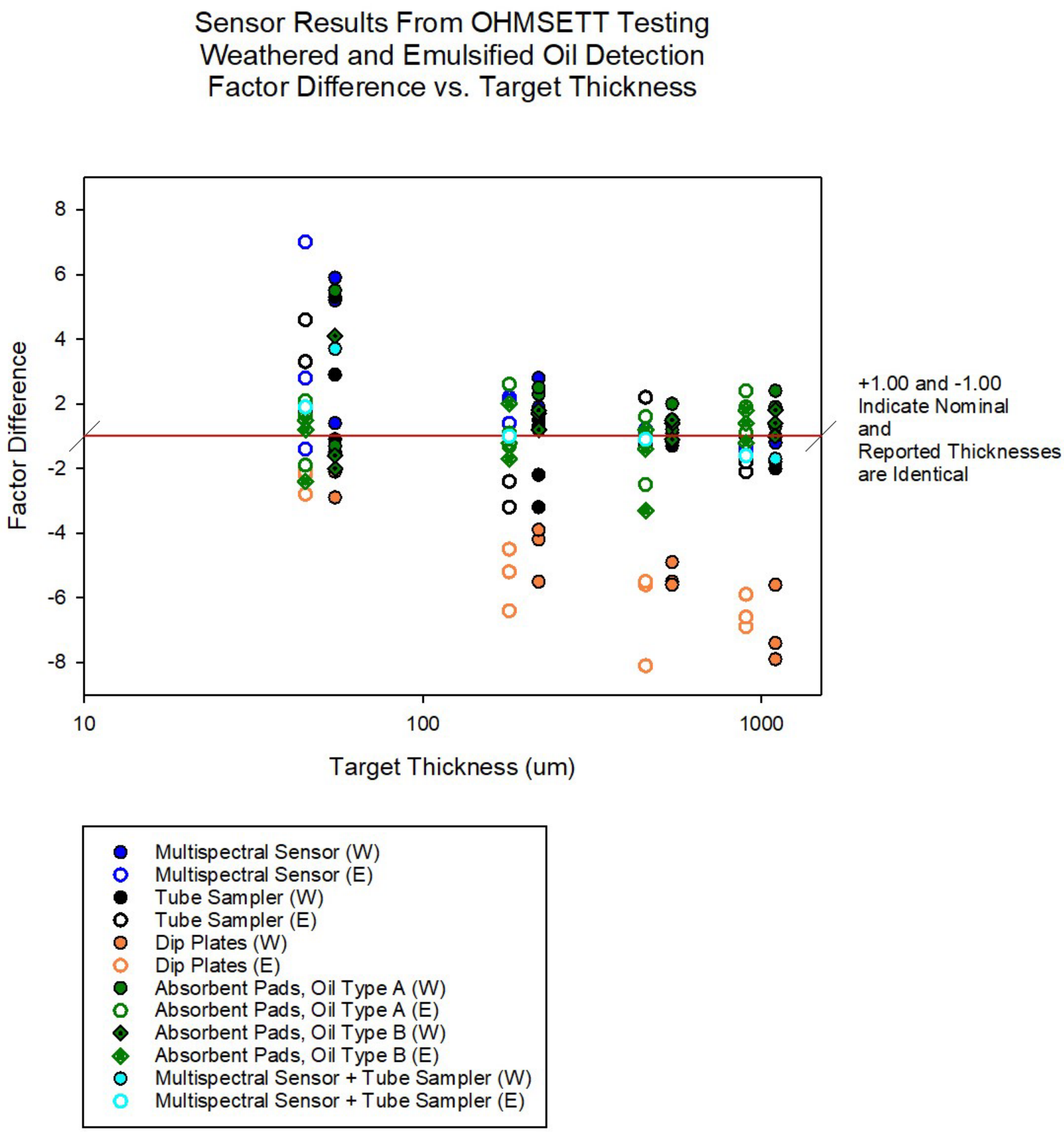

Figure 9.D.3. All sensor results from Ohmsett testing weathered and emulsified oil detection – average factor difference vs. target thickness.

The sorbent pads, as at UNH, provided the closest estimate for the no oil control rings (FD = 1.2 to 2.6). It is likely that there was some residual oil in the control rings because the Ohmsett tank is never completely oil-free. The other methods reported thicknesses <20 µm for the no oil controls, some as low as 5 µm (FD = 3.0 to 18.0). It is also important to note that the negligible oil thickness in these control rings is below the reported detection limits for all of the sensors. The RSDs were high (> 25%) except for the multispectral sensor with an RSD of 0%.

The radiometer reported negligible amounts of oil for the rings to which no oil was added. The other relative thickness reports for the radiometer ranged from relatively thin (50 µm), to relatively thick to thick 200 – 500 µm, and thick to very thick (1,000 µm), regardless of the type of oil (emulsified, weathered).

The dip plates, as at UNH, were less accurate than the other sensors or samplers, always underestimating the oil thickness by an FD of -2.8 to -2.1 (50 µm) to -3.9 to -8.1 for (200 – 1,000 µm) with RSDs of 8.1 to 20.4 %. The plates are point measurements and therefore, hard to extrapolate to overall thickness.

The sorbent pads usually had FDs < |2.6| regardless of whether it was assumed the oil was emulsified or weathered HOOPS. The RSDs were poor ranging from 20 to >60%. As with the dip plates, the pads make point measurements that are hard to extrapolate to overall thickness in the field.

The multispectral sensor produced a range of estimates for the 50 µm oil thickness (FD = -1.4 to 7.0), but for 200 – 1,000 µm was usually within an FD of <|2.0|, especially for slicks of 500 and 1,000 µm where it was usually within an FD of ≤|1.2|. RSDs ranged from 91.7 to 10%, the better RSDs were obtained for the 500 and 1,000 µm slicks, likely because they were more uniformly distributed. For the 50 µm slick, the FD of the tube sampler ranged from -2.4 to 5.3, but slightly better (-3.2 to 2.0) for 200 µm. The tube sampler had an FD of |1.0| to |3.3| for 500 and 1,000 µm. SDs for the tube sampler were high ranging from 45 to 86%, which was the highest of all the methods. The combination of the multispectral and tube samplers produced results within a FD of |1.0 to 1.7| for slicks of 200 – 1,000 µm, and -2.4 to 5.3 for the 50 µm slick.

The multispectral sampler usually predicted that the oil was emulsified, even when it was only weathered. The radiometer did not detect that any of the oil in the rings was emulsified, even when it was. Results were collected within 1 – 1.5 hr of pouring onto the tank surface and the emulsions created at Ohmsett in the morning of each test day were stable more than 3 hr which exceeded the measuring period for the radiometer.

As expected, the results at Ohmsett were not as close to the estimated thicknesses as at UNH. This was because the slicks were not as uniformly distributed as under the highly controlled conditions and pouring regime at UNH. Despite the best attempts to create a uniform surface slick at Ohmsett, the oil was unevenly distributed in the rings, influenced by the wind and associated natural small waves in the large tank, and potentially by the variable light and temperature regimes. In spite of these conditions, the multispectral sensor, sorbent pads and tube sampler did well with an FD consistently ≤|2.0| for slicks of 200 to 1,000 µm. The dip plates performed more poorly. The radiometer was able to detect thickness differences, though only in relative terms which may not be as desirable during a spill. The RSDs were highest for the point sampling methods (i.e., pads, tube sampler, and to a lesser extent the dip plates) and the multispectral sensor at the low thicknesses. The multispectral was better with the 500 and 1,000 µm slicks. No sensor was consistently able to determine the difference between emulsified and weathered oil.

Each operator was given the same instructions about reporting their results for the UNH and Ohmsett testing (Appendix F and G, respectively). Samples of these reports are located in Appendix H. These reports vary in their application for a response. The multispectral and tube sampler results are in a report format that has been used for spill response previously. The speed with which these results were uploaded for viewing by the SC was also rapid (typically <24 hr). Dip plate results were reported in a straightforward and easily readable table within a few hours to 2 days of collection, but without details on the calculations methods used or variability associated with results.

Results from the sorbent pads cannot be reported until the chemistry is run by an analytical laboratory. This took ~1 month. Once those data were provided, the report was submitted. The results from the ROSV camera were submitted within a week of the testing with photos from the camera and a conversion of the pixels to thickness. The radiometer data was submitted within nine days of the testing in a format more suited for research than response, but this could be easily modified for future application. The radiometer data from Ohmsett was not reported quantitatively.

NOAA ORR has recently developed recommendations for remote sensing data submissions to its DIVER database and the Common Operating Picture ERMA®. These guidelines will help remote sensing operators report their data and findings in a format more useful to responders during a spill and with the appropriate metadata and resolution to be used in a trajectory model validation. These recommendations/guidelines were not available for use by the remote sensing operators at UNH or Ohmsett.

Near-real time data collection and thickness estimation are desirable in a report and with mapping products that give responders oil thickness, volume, and oil condition information to help them access clean-up options.

10. Significance of Results

The protocols developed during this project will allow remote sensing methods to be validated for thickness and volume estimates for the first time. While the protocols are developed for a small stainless steel tank (e.g., 3 ft x 4 ft), they can be scaled to larger tanks, especially if an acoustic sensor array is located below the water's surface and a high-resolution camera and UV lights are located above. The primary protocol used at Ohmsett can also potentially be improved with placement of a subsurface acoustic array below and a high-resolution camera above (perhaps mounted on a UAS).

The testing protocols that were developed as part of the project are reproducible and can be used for future testing and sensor/sampler validation, to evaluate different oils or other products, and to help train other operators with sensor packages to characterize oil.

The issues with adequate lighting (i.e., appropriate wavelengths for some sensor in a high bay/laboratory setting) and wind and wavelets at Ohmsett present challenges. However, for emergency oil spill response, that level of precision and accuracy may not be required. Responders often want information on whether oil is "recoverable" or present in sufficient volume to deploy resources. Both of these criteria may not require thickness estimates to the nearest micron or even millimeter. Therefore, confirming that there are a number of sensors and samplers that can characterize surface oil to within a 1-2-fold factor difference, within response operational timeframes is a significant development.

One key finding that was surprising was the inability of either the radiometer or multispectral sensor to consistently determine whether the oil was emulsified. This warrants further investigation as responders want to know the state of the spilled oil to determine the appropriate clean-up options.

Of the sensors evaluated at UNH, the acoustic and multispectral sensors, photometer, tube sampler, and sorbent pads all gave results with an FD of <|2 | over their operating range and the test conditions (10 – 1,000 µm; 200 – 1,500 µm for the acoustic sensor). Only the multispectral sensor had a stated detection limit <1 µm thickness. At 1 µm, it gave thickness estimates within a factor of <4. Over its detection range (~200 µm and greater), the acoustic sensor was within a factor of |1.1| of the thickness, better than the other methods. The variability (RSD) of the slick estimates was typically within 10% and improved to <4% for 500 and 1,000 µm.

Of the sensors evaluated at Ohmsett, the multispectral sensor, tube sampler and sorbent pads all yielded results within an FD = |2| for the slicks applied for 200, 500 and 1,000 µm. This is remarkable considering that the oil was often patchy due to the winds. The results for the 50 µm slicks were higher FD<|3-5|. The thickness estimates were more variable for each sensor when evaluated at Ohmsett (RSDs of > 8% and often > 20% or 50%). The issues with wind and evaporation and other short term weathering processes likely contributed to this variability.

Results can be produced within 24 hr by the multispectral and acoustic sensors and tube sampler. With practice, it is likely the <24 hr turnaround could be obtained for the radiometer. The sorbent pads require chemical analysis which delays the data processing. More effort will need to be made to ensure data are available in a format usable by responders with appropriate metadata and visualization products. Reports for the multispectral sensor and tube sampler were in a response compatible format because they have been used at spills.

Having the continuous input and engagement of our multi-agency SC was also a significant contribution. Bringing in expertise from key stakeholders (BSEE, NOAA, USEPA, USCG, OSRI) not only enhanced the quality of the testing, but served as an important communication mechanism, raising the awareness and overall profile of the work.

11. Challenges Encountered and Mitigation

The first phase of the project was a workshop held in November 2019 to understand the remote sensing systems available, their TRLs and capabilities as stated by the operators. As a result of the workshop, the SC realized that there was no method to judge the accuracy and precision of the sensors. Synoptic sampling in the field (e.g., simultaneous airborne and surface measurements of slicks) allows comparison of the methods, but because the actual slick thickness is unknown and constantly changing, accuracy and precision cannot be determined.

The SC decided to develop a method to create controlled and repeatable slicks across a range of thicknesses. This phase of the research, not in the original proposal, was conducted at UNH. Shortly after this decision was made, the COVID pandemic shut down all testing and travel for many weeks. Testing was resumed in May 2020, but COVID restrictions on proximity of personnel and supply chain delays made progress slower than anticipated. Operators, Johns Hopkins University (JHU) and federal personnel (USCG, NOAA, USEPA) were able to travel to UNH for experiments in June and Fall 2020. Costs for the UNH high bay experiments were covered by rebudgeting approved by the funding agency, MPRI.

The pandemic delays and travel restrictions made it necessary to eliminate the offshore field testing originally proposed. Pandemic-related logistics for this would have been very difficult and more expensive than budgeted. The time delays due to COVID, and the time needed for the high bay accuracy and precision experiments also changed the schedule for the project, so that the field work could not be conducted before the funding ended.

The proposed work in the Ohmsett tank was also delayed because of the renovations to the facility. The original Ohmsett testing was scheduled for October 2021 and was delayed ultimately until the second week of May 2022. Our tests were the first conducted at the newly renovated Ohmsett facility.

Two very positive contributions greatly helped the project: BSEE agreed during the initial proposal development to provide access to the Ohmsett tank free of charge and covered the cost of the personnel at the facility. In addition, OSRI provided funding for the operators to travel to UNH for accuracy and precision testing, which was not in the original proposal.

When the decision was made to focus on the accuracy and precision testing, the SC was expanded to include Prof. Joseph Katz (JHU) and his laboratory personnel (Subhamoy Gupta, Ph.D. candidate, Diego Muriel Delgado, Postdoctoral Scientist). They provided expertise and equipment on UV sensing to determine slick area (coverage). That information, along with the volume dispersed, allowed us to calculate slick thickness; Volume/Area = Thickness). Funds from OSRI and money originally designated for the field testing were used (the latter with permission from MPRI) to cover the costs of involving JHU.

Another set of challenges was the lack of participation in the experiments by some of the operators who attended the initial workshop or actively use oil sensors during spill response. Their concerns about the high bay testing included: (1) the wavelengths of electromagnetic radiation available, (2) safety (LiDAR use indoors), and (3) inability of their sensors to measure actual thickness vs. presence/absence. [N.B., The SC determined that sensors that only measured presence/absence should not be included.] Some operators did not respond to multiple invitations to participate.

At Ohmsett, the number of participating operators decreased further. Some felt that their sensors needed more development or had scheduling conflicts. The operator for the acoustic sensor changed affiliations and is no longer doing oil detection work. USEPA's ASPECT sensor package was scheduled to be evaluated, but their team could not come at the time designated.

The final constraint was that the satellite testing could not be accommodated in either the high bay or at Ohmsett. In the case of Ohmsett, the issue was the size of the rings (1.5 m) which was too small to detect. Due in part to the extended time for renovations on the tank and the associated backlog, the SC did not have access to the tank for a second week, so filling the entire tank with the oil needed for satellite testing was not possible.

Finally, it is important to note that the results obtained are a function of the sensor's capabilities and each operator's approach to using them. This suggests that standard protocols and calibration are a necessity when using these sensors at a spill and that operators must have field experience.

12. Data Dissemination / Technology Transfer

The data and documentation for the project for the UNH and the Ohmsett Facility experiments will be made publicly available via the Projects page of the NOAA DIVER website at www.diver.orr.noaa.gov. The data collected include Acoustic, Multispectral, Photometer, Tube Sampler, Sorbent Pads, Dip Plates, Radiometer, RMSV camera collections.

13. Contributions towards HQP (Highly Qualified Personnel)

The project made several contributions towards the training of Highly Qualified Personnel (HQP). At UNH, one M.S. graduate student, two undergraduates (who recently transitioned to M.S. students) and eight other undergraduates worked on the project. A large team was needed because of the preparation and clean-up required to produce a slick for sensor testing. These students interacted with all of the sensor operators and three of the SC members who came to UNH during the experiments. Participation in these experiments caused two of the undergraduates to pursue an M.S. degree in Environmental Engineering (thesis option). One, who conducted the experiments that validated in the protocol, will be doing remote sensing work with oil for his thesis research. The undergraduates who graduated in May 2022 are all working in consulting engineering, particularly pollution control. Two underrepresented STEM students worked on this project. One from the University of Puerto Rico will apply to UNH for Fall 2022 in environmental engineering and wants to do oil spill related research. He is eager to get the M.S. so he can return to Puerto Rico to work on disaster response.

In addition, Ohmsett now has all of the oil rings (~40) and the four pouring devices to conduct future experiments.

The results of this project were discussed at the USCG's kick off meeting for its new Great Lakes National Center of Expertise (GLCOE) the week of September 19, 2022. As a result of that discussion, a NOAA HABs scientist who flies UAS missions with hyperspectral and UV sensors will be coming to UNH to evaluate these sensors with oil. We hope to be able to offer validation opportunities to a range of sensor operators on a full spectrum of oils and conditions using the equipment purchased and constructed for the CAMPRI project.

14. Recommendations

1. Remote sensing validation testing should be conducted on sensors that operators use for oil spill response.
2. A "library" of calibration responses for standard sensors (e.g., multispectral) could be created for a range of oils, including those that are new/emerging and at different temperatures, lighting conditions and oil weathering/emulsification. Products could include diesel, No 6 fuel. FR-3 (used in wind turbines), diluted bitumen, and other commonly used/shipped fuels.
3. Methods should be developed/enhanced that allow operators to calibrate their sensors immediately prior to and after an operation. This QA/QC technique will allow responders to have more confidence in the results. For example, the tube sampler method relied on a calibration using the test oil.
4. Research should be conducted to determine if and how thickness sensors can determine the difference between fresh, weathered, and emulsified oils.
5. Standard protocols for operating the sensors should be developed along with recommendations for operator training to ensure that the optimal performance is achieved.
6. The UNH protocol should be vetted by other laboratories to determine its veracity as a "standard" method. Lighting should be optimized for a wider range of sensors and an acoustic sensor array should be added to measure thickness, in addition to a high-resolution camera and ImageJ calculations.
7. Standard report formats should be developed/circulated so that remote sensing data results can be rapidly understood and used by responders to determine the suitability of clean-up methods and for model validation/reinitialization. This will be especially helpful for those operators who have little experience at spills.
8. Further work on the ROSV camera, radiometer, and photometer, as well as other remote sensing devices, are suggested to improve the results obtained.
9. Systems for remote sensing in ice infested waters and for subsurface platforms should also be investigated more thoroughly, especially coupled with validation methods.
10. The methods should be published in peer reviewed literature.