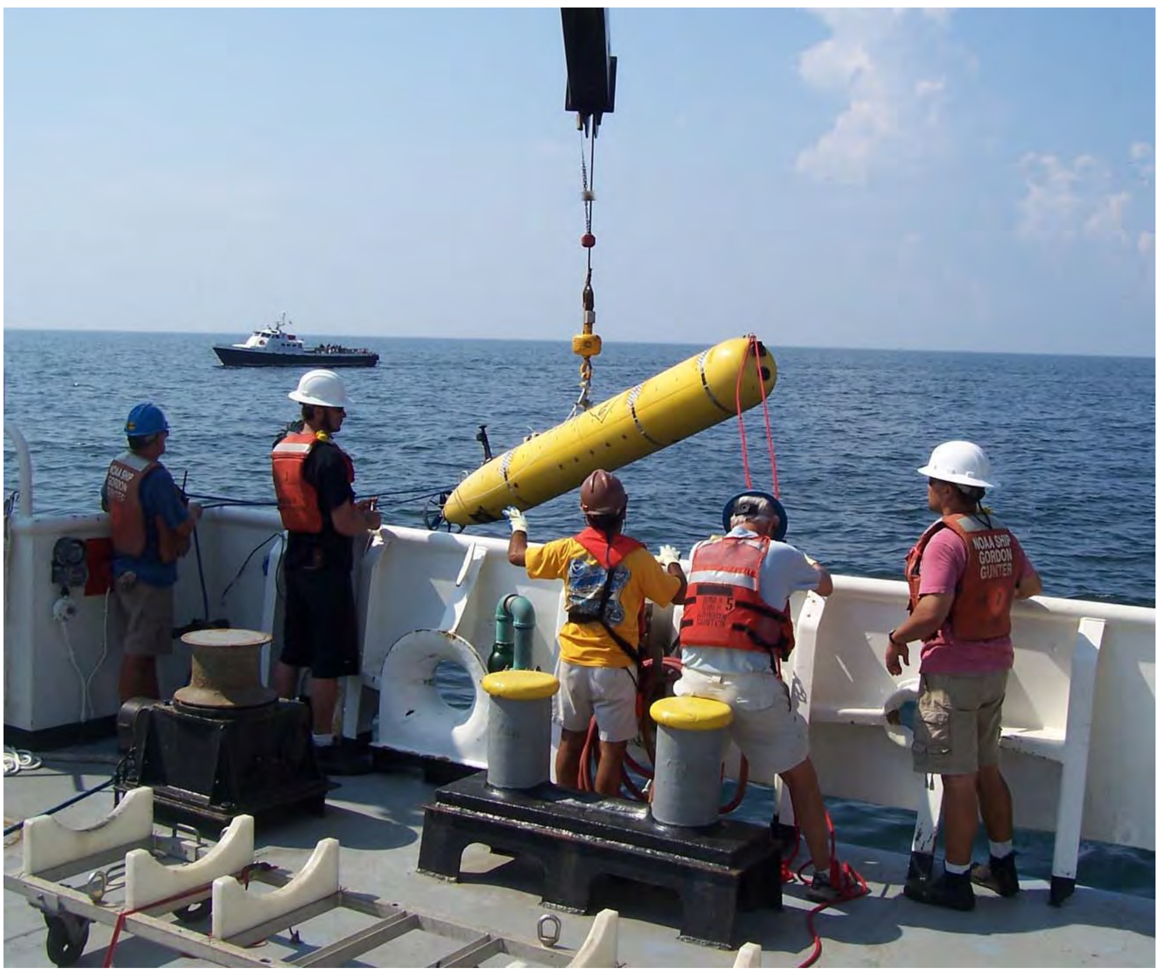
Report

Capabilities and Uses of Sensor-Equipped Ocean Vehicles for Subsea and Surface Detection and Tracking of Oil Spills

OGP-IPIECA Oil Spill Response Joint Industry Project
Surveillance, Modelling & Visualization
Work Package 1: In Water Surveillance

November 2014



MBARI AUV deployed from the NOAA research vessel *Gordon Gunter* near the *Deepwater Horizon* drilling rig accident site on May 28, 2010. Image: Yanwu Zhang © 2010 MBARI

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Acknowledgments

BP supported a Battelle study in 2012 that formed the foundation for this 2014 report. Total supported a Euro Engineering study in 2012 that resulted in a report entitled *Observations of Marine Pollution by Hydrocarbons*. API supported an HDR Ecosystem Management and Associates study in 2012 and 2013 that resulted in a report entitled *Monitoring Hydrocarbon Releases in Deep Water Environments: A Review of New and Emerging Technologies*. These two reports provided information on sensors and sensor technologies for hydrocarbon detection in water that was used to help update and expand Battelle's 2012 study. Finally, the OGP-IPIECA Joint Industry Project on Oil Spill Response (OSR-JIP) provided the funding and guidance to make the present study possible.

Executive Summary

This report evaluates a range of oil detection sensors and oceanographic vehicles and their overall compatibility for detecting and tracking oil in water. Oil detection sensors include *in situ* contact sensors that utilize either direct or indirect sensing methods and surface remote sensors that utilize either passive or active sensing methods. Oceanographic vehicles include autonomous underwater vehicles (AUVs), autonomous surface vehicles (ASVs), and manned surface vessels. Remotely operated vehicles (ROVs) were addressed in a separate OSR-JIP study.

To assess the compatibility of candidate oil detection sensors and oceanographic vehicles, a general qualitative assessment was performed at an overview-level as gaps in both sensor and vehicle payload interface data precluded a detailed quantitative comparison. With these limitations in mind, general observations are made regarding the combination of sensors and vehicles for oil detection at sea.

Several direct oil detection sensors are commercially available that focus on detecting either polyaromatic hydrocarbons (PAH) or refined and crude hydrocarbons (HC); a methane detection sensor is also available. Multiple commercially available indirect oil detection sensors are available to detect the changes between the properties of baseline local environment seawater and modified properties in the presence of oil, such as conductivity, temperature, turbidity, and presence of dissolved gases. The direct and indirect oil detection sensors measure the water at essentially a single local point; mapping the extent of hydrocarbons over a large geographic area and/or water column depth requires a large number of readings to be made.

Multiple viable combinations of direct and indirect oil detection sensors can be hosted on each of the classes of unmanned vehicles evaluated. Autonomous underwater vehicles (AUVs), gliders and autonomous surface vehicles (ASVs) have different strengths and weaknesses for their use as host vehicles for sampling the seawater environment. Principal among these are their launch and recovery (L&R) requirements and endurance which drive manning requirements. Many of the vehicles will likely have some amount of non-recurring engineering (NRE) associated with accommodating novel sensor configuration (one which the manufacturer has not already performed). This is due to the need to maintain and verify that overall vehicle trim and balance and hydrodynamics are maintained within acceptable design tolerances. This is especially true for the smaller AUVs and gliders. Different sizes and configurations of AUVs, gliders and ASVs are available commercially though some have only been produced in limited numbers. Direct and indirect oil sensors can also be deployed from almost any manned surface vessel provided that the vessel has a winch or similar device for raising/lowering or towing the sensor.

Several types of commercially available, passive remote sensors can be used to detect oil on the surface by exploiting phenomenologies that result in a distinct contrast between oil and the seawater background in the sensor image. These types of sensors include ultraviolet (UV), visible, and thermal infrared (IR) imagers, many of which have very common and widespread commercial applications. Active remote sensors include radar and fluorescence LIDAR which rely on post-processed images of returned energy to detect oil on water. Radar is a mature technology that is commonly available on many surface vessels and has been demonstrated to be useful for oil detection on water while fluoresce LIDAR is far less common and remains relatively unproven for oil detection from a surface vessel.

Passive imaging sensors can be either handheld or mounted and impart few if any requirements on the surface vessel. Radars can operate on most surface vessels but require installation and power for several components. However, many surface vessels already have built-in navigation radar and require only an additional back end processor to utilize for oil detection. Fluorescence LIDARs are large, expensive, and require significant power resources to operate and must therefore be used on a relatively large surface vessel.

Following the evaluation of oil detection sensors, oceanographic vehicles, and their overall compatibility for oil detection and tracking, these evaluations were applied to two oil response studies. The first study related these evaluations to guidance provided by the U.S. National Response Team (NRT) on atypical dispersant operation. The second study used these evaluations to determine priority recommendations of sensor and vehicle combinations for five specific oil spill scenarios.

The NRT guidance was developed in response to the *Deepwater Horizon* event, in which dispersants were applied at subsea depths greater than 300 m and for prolonged durations (>96 hours) on the surface. Neither of these scenarios is addressed in pre-existing dispersant application and monitoring guidance documents. For subsea, the 300 m depth requirement is the critical issue, and most direct (fluorometers) and indirect (CTD, particle size, turbidity, dissolved O_2) detection systems can be coupled with larger AUVs (light, heavy, and large displacement) to monitor oil during dispersant operations. For prolonged surface application, passive imaging sensors (visible, infrared, ultraviolet) as well as direct and indirect sensors meet specific NRT monitoring needs and can be integrated onto any surface vessels (manned or unmanned).

Priority recommendations of sensor and vehicle combinations were applied to five oil spill scenarios identified by the OSR-JIP: a release at a coastal terminal, an oil tanker in transit offshore, an offshore oil platform, an offshore pipeline rupture, and a deepwater well blowout. Combinations of oil detection sensors and oceanographic vehicles were assigned a high, medium, or low prioritization for each scenario depending on the operational capabilities and limitations for conducting emergency response operations.

As many viable combinations are plausible, a larger view of the entire concept of operations including host ship interfaces, time-on-station, manning requirements and constraints, and the duration for operation sustainment would need to be developed to determine the optimal number and type of sensors and vehicles required relative to the type of hydrocarbon spilled. The results of this study may be used as a screening tool to narrow the range of possibilities and prioritize combinations worthy of further consideration. In this regard, this study can be used to help identify those criteria that have the best probability of success relative to each specific mission scenario.

The identification of any sensor, specification, system or vehicle in this report is for general comparison purposes only and in no way represents any kind of endorsement or recommendation by Battelle.

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1.0 Introduction

This report provides information on commercially available sensors that can directly or indirectly detect the presence of oil in the ocean as well as remote sensors that can detect the presence of oil in water from a standoff distance. In addition to these sensors, this report identifies a range of commercially available autonomous oceanographic vehicles grouped into their respective classes, and summarizes their capabilities and limitations. Information on these sensors and vehicles, as well as manned surface vessels, was then applied to two oil spill response studies to address how sensor and vehicle technologies might be combined for use in oil spill response operations. The first study assessed the applicability of these sensors and vehicles to guidance provided by the U.S. National Response Team (NRT) on atypical dispersant operation. The second study derived priority recommendations of sensor and vehicle combinations for several oil spill scenarios.

Data used in this report were collected primarily through a general Internet search using targeted keywords to identify commercial companies that offer potentially viable sensor and vehicle solutions. The Autonomous Undersea Vehicle Applications Center (AUVAC) database was utilized to narrow down initial Internet search results. Company websites were reviewed to evaluate the commercial availability and applicability of sensors and vehicles. In addition, technical reports from TOTAL and API were used as sources of recent information on sensors for detection of oil in water.

Technical specifications of potentially viable sensors and vehicles were obtained from company websites, published datasheets and independent communication with company representatives. In general, detailed sensor and vehicle performance data tend to be closely held by their respective manufacturers which regard this information as proprietary and seek to work with prospective clients to generate solutions rather than simply providing a catalog.

The identification of any sensor, specification, system or vehicle in this report is for general comparison purposes only and in no way represents any kind of endorsement or recommendation by Battelle.

2.0 Oceanographic Sensors

Petroleum hydrocarbons (HC) may be present in seawater as a multiphase mix consisting of liquid, dissolved, gaseous or solid phases. The liquid phase contains significant amounts of polyaromatic hydrocarbons (PAH) whereas the gas phase consists of mostly lighter alkanes such as methane. HCs can be detected directly by suitable sensors (e.g., gaseous and dissolved methane, PAH) or indirectly by measuring an associated anomaly in the environmental baseline (e.g., changes in temperature, salinity, other parameters). These direct and indirect sensors, and the use of sensors that can monitor fluid flow underwater, as well as relevant sensor communication protocols are evaluated below.

2.1 Direct Oil Detection

This section identifies a range of sensors that are capable of directly sensing oil in the water column. It summarizes operational parameters, limitations and other data resulting from a survey of vendors and a review of their offerings available on company websites.

Although there are many commercially available sensors that can be used to directly sense oil in the water column, most rely on one of three principal detection methods, as follows:

- Non-dispersive infrared (NDIR) spectrometry measurement of methane (CH_4) – using a high precision optical analyzing NDIR system to perform in-situ measurement of dissolved CH_4. The dissolved CH_4 molecules are diffused through a membrane into the detector chamber, where their number is determined by means of infrared (IR) absorption spectrometry, and concentration dependent IR light intensities are converted into output signals. General uses include in-situ measurement of dissolved CH_4 motivated by climate change studies, methane hydrate studies, limnology, profiling/moorings, offshore risk management, pipeline inspection, and leak detection.
- Fluorometric measurement of polyaromatic hydrocarbons – a fluorometer or fluorimeter measures parameters of fluorescence: the intensity and wavelength distribution of emission spectrum after excitation by a certain spectrum of light. These parameters are used to identify the presence and the amount of specific molecules in a medium which in this instance are detectable PAHs including fluorene, acenaphthene, naphthalene, phenanthrene, and chrysene. Fluorometric methods are widely used in environmental monitoring, analytical chemistry, limnological, and oceanographic biology. Online fluorometers allow continuous measurements and nondestructive sampling in combination with high specificity and low detection limits.
- Fluorometric measurement of refined and crude HC – in this application, a chromophoric dissolved organic matter (CDOM) fluorometer is used to measure the concentration of refined HCs (360nm) or crude HCs (440nm). The presence of both scattering and fluorescence is an excellent indicator of the existence of an oil emulsion. These sensors are effective crude oil fluorometers because crude oil has extremely broad absorption and emission spectra and the emission wavelength of the CDOM fluorometers is centered at the primary crude emission peak. The fluorescence of CDOM is used in many applications such as continuous monitoring of wastewater discharge, natural tracer of specific water bodies, ocean color research and the effect of CDOM on satellite imagery,

and investigations of CDOM concentrations impacting light availability used for primary production.

Many of the sensors can be configured for either pumped or open flow-through deployment, and the sensors are all employed in a similar manner with the sensor's window or pump inlet installed on the host vehicle such that it is exposed to the water column.

The sensor acquires and processes the sample completely before the next sample is acquired. The sensors sample the water column at a specified point and rely on their host to provide the geo-spacing amongst the sampled points. Most of the sensors rely on anti-fouling coatings to prevent contamination from skewing measurement results. Table 2-1 summarizes the principal characteristics for twenty-two representative sensors identified as being able to sense oil directly in the water column. For this and other tables in this document, if no information was available for a particular parameter then the corresponding table cell was left blank.

2.2 Indirect Oil Detection

This section identifies a range of sensors with the capability to sense oil indirectly in the water column and summarizes the sensor operational parameters, limitations, and other data resulting from a survey of vendors and a review of their offerings available on company websites.

Many commercially available sensors can be used to sense oil indirectly in the water column. In general, all of the approaches to indirect oil detection rely on discriminating the properties of the baseline local seawater environment with and without the presence of oil. The following detection methods appear to be the principal techniques used across the identified range of sensors.

- Measurement of seawater physical properties (conductivity, temperature, salinity) – the name CTD is an acronym for conductivity, temperature and depth, the three parameters which this instrument measures. The CTD does this with three different sensors: a thermistor, a conductivity sensor and a pressure sensor. Conductivity, temperature and pressure are converted into other quantities such as salinity and density that reveal the ocean's vertical and horizontal structure and provide precise and comprehensive charting of the distribution and variation of water physical properties. Depth is derived from measurement of hydrostatic pressure, and salinity is obtained from electrical conductivity.
- Optical light scattering measurement for water turbidity – turbidity is the measurement of scattered light that results from the interaction of incident light with suspended and undissolved material in a water sample and it is an important water quality indicator. Turbidity is defined by the International Standards Organization (ISO) as the reduction of transparency of a liquid caused by the presence of undissolved matter. Turbidity can be interpreted as a measure of the relative clarity of water and often indicates the presence of dispersed, suspended solids—particles not in solution such as silt, clay, algae and other microorganisms, and organic matter and other minute particles. Turbidity is measured using the techniques of turbidimetry or nephelometry and is expressed in arbitrary Nephelometric Turbidity Units (NTUs). The direct relationship between turbidity data and suspended solids concentration depends on many factors including particle size distribution, particle shape and surface condition, refractive index of the scattering

particles and wavelength of the light. This measurement is known to have good correlation to the amount of suspended matter in water and can be used to monitor variables such as sediment, algae and other particles. These sensors are used in river and stream gaging, wastewater and effluent measurement, control instrumentation for settling ponds, sediment transport research, and laboratory measurements. There are three basic designs of turbidity meters:

  - Nephelometer: measures directly the intensity of light scattered by the sample. The light intensity is directly proportional to the amount of matter suspended in the light path. The sensor is mounted at an angle (usually 90°) to the traversing beam to record scattered light. Nephelometers usually provide greater precision and sensitivity than turbidimeters and are normally used for samples of low turbidity containing small particles.
  - Turbidimeter (also called absorption meter): measures the intensity of the light beam after it has passed through the sample. Suspended matter in the light path causes scattering and absorption of some light energy. The transmitted light is measured in relation to initial beam intensity. Turbidimeters are more appropriate for relatively turbid samples in which the scattering particles are large in relation to the light wavelength used.
  - Ratio turbidimeter: measures both transmitted and scattered light intensities. For this purpose, transmitted light and 90 deg-scattered light are measured simultaneously with two different light sensors. This design is appropriate for liquids either strongly colored or of variable color concentration and for samples of high turbidity.

- Measurement of dissolved oxygen concentration – these commercially available sensors measure the oxygen concentration in liquids with great accuracy. There are two types of oxygen sensors available: electrodes (electrochemical sensors) and optodes (optical sensors).
  - The Clark-type electrode is the most commonly used sensor for measuring oxygen dissolved in a liquid. The basic principle involves a cathode and an anode submersed in an electrolyte. Oxygen enters the sensor through a permeable membrane by diffusion, and is reduced at the cathode, creating a measurable electrical current. A linear relationship exists between the oxygen concentration and the electrical current. With a two-point calibration (0% and 100% air saturation), it is possible to measure oxygen in the sample. One drawback to this approach is that oxygen is consumed during the measurement with a rate equal to the diffusion in the sensor. This means that the sensor must be stirred in order to get the correct measurement and avoid stagnant water. With an increasing sensor size, the oxygen consumption increases and so does the stirring sensitivity. In large sensors there tends to also be a drift in the signal over time due to consumption of the electrolyte. However, Clark-type sensors can be made very small with a tip size of 10 µm. The oxygen consumption of such a microsensor is so small that it is practically insensitive to stirring and can be used in stagnant media such as sediments or inside plant tissue.
  - The optode relies on optical measurement of the oxygen concentration and is rapidly replacing the Clark-type electrode. A chemical film is glued to the tip of an optical

cable and the fluorescence properties of this film depend on the oxygen concentration. Fluorescence is at a maximum when there is no oxygen present. When an O_2 molecule comes along it collides with the film and this quenches the photoluminescence. For a given oxygen concentration there will be a specific number of O_2 molecules colliding with the film at any given time, and the fluorescence properties will be stable. The signal (fluorescence) to oxygen ratio is not linear, and an optode is most sensitive at low oxygen concentration. That is, the sensitivity decreases as oxygen concentration increases following the Stern–Volmer relationship. The optode sensors can, however, work over the whole region 0% to 100% oxygen saturation in water, and the calibration is done the same way as with the Clark type sensor. No oxygen is consumed and hence the sensor is insensitive to stirring, although the signal will stabilize more quickly if the sensor is stirred after being put in the sample.

- Non-dispersive infrared spectrometry (NDIR) measurement of dissolved CO_2 concentration – this is the use of a high precision optical analyzing NDIR system to perform in-situ measurement of dissolved CO_2. The dissolved CO_2 molecules are diffused through a membrane into the detector chamber, where their number is determined by means of IR absorption spectrometry, and concentration dependent IR light intensities are converted into output signals. Common applications include in-situ measurement of dissolved CO_2 motivated by air-sea gas exchange research, ocean acidification, limnology, climate studies, agriculture/fish farming, fresh water control, and carbon capture and storage (CCS).

These indirect oil detection sensors are employed in a manner similar to the direct oil detection sensors previously discussed. The sensors are configured for either pumped or open flow-through deployment, and the host installation assures that the sensor’s window or pump inlet is exposed to the water column. The sensor takes a sample and processes it before the next sample is taken. Sampling is at a specified point and the sensors rely on their host to locate the sensor at the sampling point. As before, the sensors typically rely on anti-fouling coatings to prevent interference. Table 2-2 summarizes the principal characteristics for fifteen representative indirect oil detection sensors reviewed for this study. These sensors are exemplars for the numerous sensors available in this class.

Table 2-1: Direct Oil Detection Sensors

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Analyte	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
ASD Sensortechnik BackScat I		120 msec	aromatic hydrocarbons		air: 3.1 water 1.7	7-16VDC; 45mA @ 12VDC	1500 3000 6000	Xe-flashlight fluorometer One channel fluorometer	
Bowtech Leak Detection System			HC	camera: 31 x 169 lamp 76 x 125	camera: air: 0.27 water: 0.16 Lamp: air: 0.46 water: 0.24	camera: 12-24VDC, 100mA Lamp: 24VDC, 1000mA	camera: 4000 Lamp: 3000	LED lamp, fluourescent tracer dye, low light camera	
Chelsea Technologies Subsea Pipeline Leak Detection			HC				600 6000	fluorometer	
Chelsea Technologies UviLux Fluorometer			PAH	70 d x 149	air: 0.8 water: 0.15	9 to 36Vdc; <W @ 12 volt	600	fluorometer	
Chelsea Technologies UV AquaTrack Fluorometer			refined HC, crude HC	89.3 d x 406	air: 5.5 water: 3.5		6000	fluorometer	
CONTROS HydroC CH4 Hydrocarbon and Methane sensor	±3% of reading		CH_4	90 d x 376	air: 4.7 water: 3	300mA @ 12V (without external pump)	2000 4000 6000	NDIR	Windows Software DETECT™
CONTROS HydroC PAH Fluorometer sensor			PAH	500m: 68 d x 280 6000m: 75 d x 320	500m: air: 1.8 water: 1.0 6000m: air: 4.8 water: 2.8	12-26 VDC; 240 mA @12V; max 3.0W	500 2000 4000 6000	fluorometer	Windows Software DETECT™
CONTROS Mobile Leak Detection System			CH_4, PAH, CTD	520 x 170 x 200	air: 12.3 water: 9.2	12 / 24 VDC @ 18W (max 35W on start-up)	max 2000	Direct and indirect methods	Windows Software DETECT™
Hach FP 360 SC Oil-in-Water Sensor			PAH	68 x 306	air: 2.8			UV Fluorescence	

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Analyte	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
Neptune Oceanographic SNIFFIT			dissolved and gaseous methane		1.5	24-36VDC; 400 mA @ 24VDC	2000		
Ocean Tools OceanSENSE Leak Detection			HC	105 d x 220 l	air: 1.9 water: 0.97	24 VDC 250 mA	3000	LED lamp, tracer dyes	RS-232, RS-485
Phaze Hydrocarbon Leak Detector			HC				4000		
Sea & Sun Technology UV Fluorometer		500 msec	PAH	88 d x 220	2.7	9-36VDC	500 2000	fluorometer	
Seapoint UV Fluorometer		0.1 sec	crude oil	168 x 64	1	8.5-20 VDC, 15mA, integrate into any system accepting 0 - 5 VDC	6000	fluorometer	pigtail cable and connector
Smart Light Devices LDS3 Laser Leak Detection System	<50 ppb		HC	190 x 470	air: 10 water: 5	24VDC, 30W Optional 90-260VAC	3000	class 1 laser, tracer dyes	RS-232, RS-485
Sonardyne Automatic Leak Detection Sonar (ALDS)			HC					High Bandwidth ultrasonic pulse	Ethernet
Teledyne TSS MELDS System		< 10 sec	CH_4 PAH CTD	170 x 200 x 520	air: 12.3 water: 9.3	12/24 VDC 18W; 35W max start-up	3000	Sniffer, Flowhead, fluorometer, other	
TriOS enviroFlu-DS	0.1 ppb		PAH	80 x 414	air: 4.5	12-26 VDC	6000	fluorometer	
TriOS enviroFlu-HC			PAH	68 x 280	SS body: air: 2.7 Ti body: air: 1.85	12-26 VDC	300 6000	fluorometer	TriBox2 Pocket-MSDA handheld software
Turner Designs C3 Submersible Fluorometer		1 sec	crude oil, fine oil	100 x 230	air: 1.64	8-30 VDC, 5W	600	fluorometer	

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Analyte	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
Turner Designs Cyclops 6K customizable		1 sec	crude oil, refined oil, fluor-oescence	44.5 x 167.6	0.62	3 - 15 VDC; integrate into any system accepting 0-5 VDC input	6000	fluorometer	pigtail cable and connector
Turner Designs Cyclops 7 customizable		1 sec	crude oil, refined oil, turbidity, fluor-oescence	SS or Ti body: 22.3 x 144.8 Delrin body: 31.8 x 144.8	0.126	3 - 15 VDC; integrate into any system accepting 0-5 VDC input	600	fluorometer and optical light scatter	pigtail cable and connector

Table 2-2: Indirect Oil Detection Sensors

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Analyte	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
AADI Conductivity Sensor 4319	±0.005 S/m (A model) ±0.0018 S/m (B model)	2 sec – 255 minutes (interval)	conductivity (salinity)	36 (w) x 39 (d) x 86 (l)	0.24	6 to 14VDC	300 2000 6000	Inductive cell	
AADI Oxygen sensor 3830	<8µM or 5% whichever is greater; <5%	From 1 s to 255 minutes or controlled by data logger	oxygen conc., air saturation	36 x 86	0.21	SR10: -6 to -14Vdc RS-232: +5 to +14Vdc	6000	optode	sensor cable; data logger
AADI Seaguard O2	<8 mM or 5%, whichever is greater	<8 sec with fast-response foil; <25 sec with standard foil	dissolved oxygen	shallow:139 d x 356 intermediate : 140 d x 352 deep: 143 d x 368	shallow: air: 6.0 water: 1.5 intermediate: air: 12.2water: 7.3 deep:air: 13.1water: 8.5	6 to 14Vdc	300 2000 6000	fluorescence	
AADI Turbidity Sensor 4112			turbidity	36 d x 105	air: 0.086	7-20 Vdc	300		
AML Oceanographic Smart CTD	cond.:±0.01 mS/cm temp.:±0.005°C press.:±0.05% FS salin.:±0.01 psu dens.:±0.027 kg/m3	up to 25Hz	conductivity temp, pressure, salinity (calc), density (calc)	cage: 70 body: 46 OAL: 420		8-26 VDC	Delrin:500 Ti: 10,000	conductive cell, thermistor, strain gauge	

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Analyte	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
CONTROS HydroC CO2 Carbon Dioxide Sensor	±1% of reading		CO_2	90 d x 376	air: 4.7 water: 3	300mA @ 12V (without external pump)	2000 4000 6000	NDIR	Windows Software DETECT™
Sea & Sun Technology Conductivity Sensor			conductivity (salinity)	39 d x 270	air: 0.3	9-18 V DC	500		
Sea Bird SBE 19plus V2 SeaCAT	cond.:±0.0005 S/m temp.:0.005°C press.:0.1% FS (strain gauge)0.02% FS (quartz)	4 Hz	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	99 d x 800	Plastic air: 7.3 water: 2.3 Ti air: 13.7 water: 8.6	9 - 28 VDC aux power out up to 500 mA at 10.5 - 11 VDC Voltage sensor A/D resolution 14 bits Voltage sensor input range 0 - 5 VDC	Plastic:600 Ti: 7000	internal platinum electrode, thermistor, precision quartz crystal resonator, strain gauge	
Sea Bird SBE 25 plus Sealogger	cond.:±0.0003 S/m temp.:0.001°C press.:0.1% FS	16 Hz	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	305 x 279 x 965	22.5	14-20 VDC Aux power out 12 VDC, up to 1.2 A across all channel Voltage sensor 0 - 5 VDC, 16-bit resolution	6800	internal platinum electrode, thermistor, strain gauge	SeatermV2

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Analyte	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
Sea Bird SBE 49 FastCAT CTD sensor	cond.:±0.0003 S/m temp.:0.002°C press.:0.1% FS	16 Hz	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	62 d x 620 83 mm at widest part	Plastic:air: 1.8 water: 0.5 Ti:air: 2.7 water: 1.4	9-24 VDC	Plastic:250Ti: 7000	conductivity cell, thermistor, strain gauge	
Sea Bird SBE 911 plus; 917 plus	cond.:±0.0003 S/m temp.:0.001°C press.:0.015% FS	24 Hz	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	132 x 432 x 432	911:air: 10 917 Al:air: 9 917 Ti:air: 12	130 watts @ 115 or 230 VAC 50-400 Hz	10,500	conduct-ivity cell, thermistor, precision quartz crystal resonator	300 baud full-duplex FSK subcarrier modem (2025/2225 Hz down-link; 1070/ 1270 Hz uplink)
SeaPoint Sensors Turbidity Meter	<2% deviation 0-750 FTU	0.1 sec (output time constant)	turbidity	Connector version: 120 x 25 Bulkhead version: 112 x 25	86 g	7-20 VDC, 3.5 mA avg., 6 mA pk.	6000	optical light scatter	pigtail cable and connector, easily interfaced with data acquisition packages
Teledyne RD Instruments Citadel CTD Products	cond.:±0.0009 S/M temp.: ±0.005°C press.: 0.05% FS	1 to 15 Hz	conductivity, temperature, pressure	82.55 x 444.5	shallow: air: 2.03water: 0.71 deep: air: 3.29 water: 2.05	8 to 35 VDC @ 40 mA	500 7000 (optional Ti)	inductive cell, thermistor, silicon	Direct digital output via RS-232, RS-485 or CMOS Windows software

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Analyte	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
Wetlabs WQM	±0.003 mS/cm ±0.002 deg C ±0.1% FS 2% of satur. 0.2% FS ug/l 0.1% FS NTU	1 Hz	conductivity temperature pressure dissolved oxygen fluorescence turbidity	0.654 x 0.185	air: 5.4 water: 1.8	9–16 VDC	200	thermistor fluorometer others	
YSI EXO Series			conductivity temperature dissolved oxygen pH turbidity fDOM	47 d x 648 l 76 d x 711 l	1.42 3.62	9-16.5VDC	250		Bluetooth wireless technology; USB cable,RS-485, RS-232, SDI-12

2.3 Flow Characterization Sensors

This section identifies sensors with the capability to characterize the flow of water. This characterization can be used to support dispersant injection or effectiveness evaluation. The specific parameters that are of interest are the total volume flow, flow composition, and particle size and density. The goal of dispersant injection is to separate the oil into micro droplets to reduce the surface expression and increase the rate of decomposition. To obtain the necessary information related to total flow volume requires both macro and micro area sensors.

The macro area sensors that are required relate to the determination of the size of the flow stream in questions. This information can be obtained through the use of commercially available systems ranging from high resolution forward looking sonars to parallel laser measuring devices. The purpose is to determine the total size of the stream at the point of measurement.

The micro area sensors provide specific details related to the dimensions and quantities of the suspended objects in the water. The two primary sensor technologies are discussed in the following bullets with specific sensors contained in Table 2-3. Both of these sensors can determine the size distribution, quantities, and velocity of the suspended objects.

- Underwater Microscopy – this type of sensor is generally used in the study of underwater microscopic organism. In recent years the technology has advanced to automate the process of image acquisition and analysis. The core technology is based on using a varying focal range microscope to obtain images that detail a specific volume. The volume being sampled is generally very small.
- Optical light diffraction measurement – this technology is very similar to many turbidity meters but instead of using reflected, or scattered, light it uses the property of light diffracting around objects. The instrument measures the diffraction pattern and transmitted light intensity to determine the volume scattering function. This information is then used to mathematically determine the particle size distribution required to obtain this reading.

Table 2-3: Flow Characterization Sensors

Manufacturer/ Sensor	Sensor Parameters								
	Accuracy	Sample Rate	Sensor	Size, mm	Weight, kg	Power	Depth, m	Detection Method	Communications
Sequoia LISST-Deep	1.25-250um 2.5-500um	1 sec	32-ring custom photodiode ring detector	126 d x803 l	air: 17 water: 8	6-24 VDC measuring : 145mA @ 9VDC quiescent: 8mA @ 9VDC	3000	Small- angle forward scattering	RS-232
4DEEP Inwater Imaging Submersible Microscope	1 micron	16-50 Hz	4Mp Imaging Sensor	100 x 300	air: 1.8 water: 1.4	120-240VAC, 5W 12VDC adapter supplied	150 m 6000m option		Gigabit Ethernet

Both of the identified sensors provide the micro flow characterization that would be required to support total flow characterization. The primary data collected form a histogram that relates the quantity of particles with size of particles. These instruments are also capable of determining flow velocity through the instrument and total particulate volume flow. Since both instruments measure only a small volume in a restricted flow area, it would be expected that the measured velocity would have a greater error with increased free flow velocity. This would be the reason to use an external acoustic method to measure true flow velocity. Likewise the microscope method requires the flow velocity to be less than 0.1 m/s to obtain satisfactory images. The benefit of the microscope is that it can provide additional information regarding shape and composition of the particles along with photographic records. A sample screenshot for the 4Deep Inwater Imager is shown in Figure 2-1 and also shows that the software can be configured to only count objects that are round. This would help in locations that have higher turbidity. The light diffraction sensor allows the operator to perform background readings to zero-out local turbidity but counts all particles in the water. The benefit of this sensor is that it has a longer use record and can sample flows that are higher velocity. A sample screenshot of the LISST-Deep is shown in Figure 2-2.

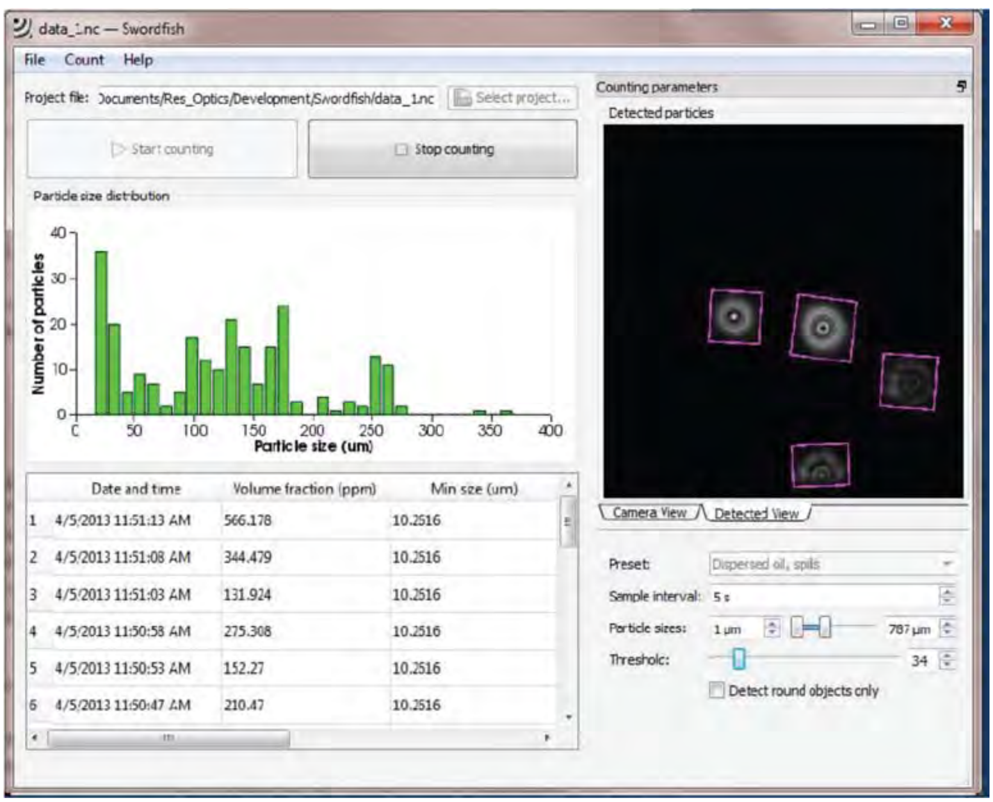

Figure 2-1: 4Deep Inwater Imager Screenshot

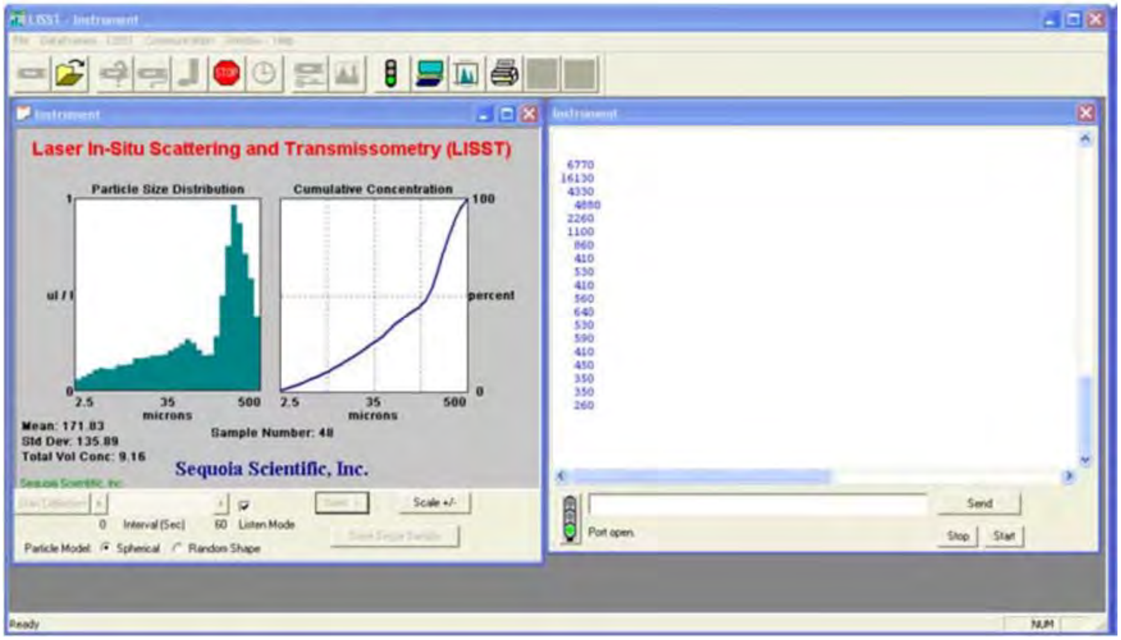

Figure 2-2: LISST Deep Screenshot

2.4 Sensor Technology Combinations

As HCs in seawater are a multiphase mix, in order to detect HC reliably in seawater under a range of environmental conditions, the use of a combination of direct and indirect methods is desirable. Direct detection methods can leverage the fact that the oil phase contains significant amounts of PAH, whereas the gas phase contains mainly methane. Indirect methods would evaluate the range of parameters present in the environmental baseline and seek anomalies. Multiple detection methods provide a broad coverage of the various phases of an oil spill in seawater. Because the sensors are seeking different analytes, individual sensors can be used as opposed to an integrated sensor package that depends on host interfaces.

When using sensors to detect oil indirectly in the water column it is advantageous to use more than one sensor technology to reduce the number of false positives that are experienced. An example would be to use a DO sensor and a CTD sensor to provide independent methods to indirectly detect the presence of oil in the water column. As oil ages in the water, aerobic bacteria reduce the available oxygen, and at the same time the conductivity of the oil changes. Temperature is used along with depth in order to identify if the conductivity change is related to the environment or the presence of HCs.

Tables 2-1 and 2-2 identify representative commercially available combination sensor packages that were identified in the course of this study. The CONTROS™ Leak Detection System is a fully integrated sensor suite for the detection, localization, verification and quantification of subsea oil and gas leaks. This sensor uses a combination of direct and indirect methods to detect PAH, methane and anomalies in seawater temperature, salinity, and density. The WQM incorporates WET Labs' fluorometer-turbidity and Seabird's CTD sensors, providing temperature, salinity, depth, dissolved oxygen, chlorophyll fluorescence, turbidity, and backscattering data.

2.5 Open Geospatial Consortium

Open Geospatial Consortium (OGC) Standards can be used to support sensor web enablement (SWE). OGC/SWE is a system of systems designed to enable the user to have common communication protocols across interconnections. This OGC standard allows multiple users with dissimilar interests and interfaces to easily access data in a timely manner. The portion of the OGC/SWE standard that is related to sensors is:

- Observations & Measurements (O&M) – General models and XML encodings for observations and measurements.
- PUCK Protocol Standard – Protocol to retrieve a SensorML description, sensor “driver” code, and other information from the device itself, thus enabling automatic sensor installation, configuration and operation.
- Sensor Model Language (SensorML) – Standard models and XML Schema for describing the processes within sensor and observation processing systems.

A survey of direct oil detection sensor manufacturers resulted in seven of the eleven companies responding. As a result of the survey, no direct oil detection sensor manufacturers that are OGC compliant were identified. However, one company is planning on implementing OGC PUCK protocol and another has sensor communications that are similar. Feedback from manufacturers indicates that in order to have better acceptance and execution of the OGC compliance at the sensor level, clear benefits of having the sensor manufacturers provide OGC compliant interfaces should be communicated, and simpler information that is easily understood needs to be made available.

3.0 Autonomous Oceanographic Vehicles (AOVs)

This section summarizes the range of autonomous oceanographic vehicles (AOVs) available for use as hosts for subsea oil detection sensors, including autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASV), and their potential suitability for various mission applications. Provided in this section are tables summarizing relevant vehicle operational parameters and limitations with respect to their potential suitability for various mission applications. Data were collected from a survey of vehicle manufacturers and information available on company websites.

The vehicles considered in this section fall into a range of availability and years of operational use. While all of the vehicles are considered mature technology, the number of each type built and the degree of field usage vary considerably. To reflect this, each vehicle has been classified into one of three categories ranked by how readily available they are for purchase in numbers or short lead time. The definitions listed below were used to classify vehicle availability.

- Limited – vehicles that have been around for several years and either have multiple prototypes or a single unit that is from a commercial company rather than academic source. This group of vehicles may be listed as available for sale but have not been widely deployed.
- Available – either an academic vehicle that is being produced in some numbers (e.g., SAUV II) or a single vehicle that is being produced by a reputable company with manufacturing capabilities (e.g., Talisman).
- Commercial – produced for sale on a commercial scale and many vehicles are already in use.

Surface communications for AOVs can utilize several methods. These include satellite, line of sight radio, and beacon transmissions. Satellite communication is usually through either the Advanced Research and Global Observation Satellite (ARGOS) or the Iridium Communications Inc., constellations. Larger AUVs often incorporate several communications methods.

3.1 Autonomous Underwater Vehicles

An AUV is a robot that travels underwater without requiring input from an operator. AUVs constitute part of a larger group of undersea systems known as unmanned undersea vehicles (UUVs), a classification that includes non-autonomous remotely operated underwater vehicles (ROVs) controlled and powered from the surface by an operator/pilot via an umbilical or using remote control. In military applications AUVs are more often referred to simply as UUVs.

The AUV market is effectively split into three areas: scientific (including universities and research agencies), commercial offshore (oil and gas etc.), and military application (mine countermeasures, battle space preparation). The majority of these roles use a similar design and operate in a cruise (torpedo-type) mode. They collect data while following a preplanned route at speeds typically between 1 and 4 knots. Most AUVs follow the traditional torpedo shape as this is seen as the best compromise among size, usable volume, hydrodynamic efficiency, and ease of handling. Some vehicles use a modular design, enabling components to be changed by the operators.

Hundreds of different AUVs have been designed over the past 50 or so years but only a few companies sell vehicles in significant numbers. Several companies sell AUVs on the international market, including Bluefin Robotics, Hydroid (now owned by Kongsberg), International Submarine Engineering (ISE) Ltd., Kongsberg Maritime, and Teledyne Gavia (previously known as Hafmynd).

Vehicles range in size from lightweight man-portable AUVs to large diameter vehicles of over 10 meters in length. Large vehicles have advantages in terms of endurance and sensor payload capacity; smaller vehicles benefit significantly from lower logistical burden (e.g., support vessel footprint; launch and recovery systems).

Primarily oceanographic tools, AUVs carry sensors to navigate autonomously and map features of the ocean. Typical sensor payloads include compasses, depth sensors, sidescan and other sonars, magnetometers, thermistors, and conductivity probes. AUVs can be monitored from a distance, from a small vessel, or they can in many cases operate completely autonomously. In general, the following modes of operation can be defined:

- Autonomous – the AUV executes its mission without any interaction during mission execution. This typically requires some prior knowledge about the area of operation, such as a general idea of the bathymetry, currents, and threats (e.g., trawling nets and complex obstacles). When operating completely autonomously, the AUV will surface and obtain its own GPS fix. Between position fixes and for precise maneuvering, an inertial navigation system on board the AUV measures the acceleration of the vehicle, and Doppler velocity technology is used to measure rate of travel. A pressure sensor measures the vertical position. These observations are filtered to determine a final navigation solution. In case of a serious malfunction, the AUV will rise to the surface if at all possible, and transmit its location.
- Semi-autonomous – the AUV is in intermittent contact with its support ship, through satellite, radio frequency (RF) or acoustic links. The support ship is free to perform other tasks during the AUV mission.
- Supervised – the AUV is in near-continuous contact with the support ship through acoustic links. In this mode, the operator can change nearly any aspect of the mission execution and monitor data recorded by the payload sensors. The support ship needs to stay within a few hundred meters to a few kilometers to the AUV, depending on the conditions.
- Long Baseline (LBL) – the AUV navigates using an underwater acoustic positioning system. When operating within a net of sea floor deployed baseline transponders, this is known as LBL navigation. When a surface reference such as a support ship is available, ultra-short baseline (USBL) or short-baseline (SBL) positioning is used to calculate where the subsea vehicle is relative to the known (GPS) position of the surface craft by means of acoustic range and bearing measurements.

Transitions between different modes of operation can occur; the AUV may start and end its mission in supervised mode and switch to autonomous mode later (pre-planned, or when receiving a command from the support vessel).

Weather limits for AUV launch and recovery (L&R) operations depend on many factors. The size of the AUV, the use of a dedicated launch and recovery system (LARS), and the type of dedicated ship or ship of opportunity are all factors in determining the sea state that AUVs can be launched and recovered. Many recovery operations require small boats to connect a lifting line to the AUV. Dedicated LARS allow the AUV to be recovered without launching small boats into the water, thereby extending the sea state conditions in which operations can take place.

3.1.1 Man-Portable AUVs

Figure 3-1 illustrates the man-portable class of AUVs. Man-portable AUVs are appropriately named due to their small sizes and weight. The vehicles can be deployed from most vehicles or shore sites, but are typically deployed by a few personnel in inflatable boats. The displacement of these vehicles is generally up to approximately 80 kilograms (two-person lift) though a few configurations can be heavier. This class of vehicle exhibits the following characteristics:

- Endurance ranges from <10 hours to 20 hours depending on speed and hotel (including sensors) power load
- Payload volume is modest <0.25 ft^3 (0.007 m^3)

Figure 3-2 shows examples of typical small boat operations for a REMUS-100 or Teledyne Gavia type of man-portable AUV as well as examples of the stowage containers for this class of AUV. Vehicle handling is performed using bails mounted to the vehicle with one usually located mid-body and the other on the vehicle’s nose. Alternately, slings can be used to assist the operators in handling the vehicles.

Packaging to support field operations typically consists of ruggedized cases and includes operation and support items (e.g., ruggedized laptop computer, removable media, power/data interface cables, spares/maintenance kit).

Table 3-1 lists representative man-portable AUVs reviewed for this study. As indicated in the table there are several manufacturers producing this class of vehicles on a commercial scale with a considerable number of vehicles already in service.

Figure 3-1: Man-Portable AUVs

Figure 3-2: Man-Portable AUV Launch and Recovery and Stowage

Table 3-1: Man-Portable Class Autonomous Underwater Vehicles (AUV)

	Vehicle Parameters													
Manufacturer/ Platform	**Length m**	**Width m**	**Height m**	**Dia. m**	**Weight dry, kg**	**Depth Rating m**	**Max. Mission Duration hrs**	**Available payload power**	**Payload volume cu. m**	**Payload weight kg**	**Mission Turnaround Time**	**Typical cruise speed knots**	**Communications**	**Vehicle Availability**
Atlas Elektronik SeaCAT	2.3	0.3	0.3	0.3	130	300	6 to 10		variable			3-4	Ethernet	C - Commercial
BAE Systems Talisman L	1.4	2.5	1.1		50	300						up to 5		A - Limited
Bluefin Robotics Bluefin-9	1.75	0.24	0.24	0.24	60.5	200	12	15 W	0.0025	variable free-flooded system	<15 min (field swap); 6 hrs battery charge from empty to full	3	RF acoustic modem Ethernet via shore power cable	C - Commercial
Bluefin Robotics Bluefin-9M	2.5	0.24	0.24	0.24	70	300	10					3	RF acoustic modem Ethernet via shore power cable	C - Commercial
ECA Robotics ALISTER 9	1.7-2.5				50-90	100 200	24					2-3	WiFi or Ethernet Acoustic modem Radio (VHF) Satellite link on request	C - Commercial
Graal Tech Folaga	2	0.15	0.15	0.15	31	80	6	12VDC			12VDC 45Ah	2	2.4 GHz radio link	B - Available
Kongsberg Maritime REMUS 100/100-S AUV	1.6	0.19	0.19	0.19	38.5	100	8 to 10				Battery recharge time 8-10 hours empty to full	4.5	Acoustic modem Iridium satellite WiFi Gateway buoy	C - Commercial
Ocean Server Iver2-580-EP (Expandable payload)	1.4	0.1	0.1	0.15	21+	100	14		22 inches forward		4 to 8 hours to fully charge from empty to full	2-Jan	WiFi 802.11G Ethernet	C - Commercial
Ocean Server Iver2-580-S	1.27	0.1	0.1	0.15	19	100	14-24	15 W	10 inches forward	10	4 to 8 hours to fully charge from empty to full	2.5	WiFi Iridium satellite Acoustic modem	C - Commercial

	Vehicle Parameters													
Manufacturer/ Platform	**Length m**	**Width m**	**Height m**	**Dia. m**	**Weight dry, kg**	**Depth Rating m**	**Max. Mission Duration hrs**	**Available payload power**	**Payload volume cu. m**	**Payload weight kg**	**Mission Turnaround Time**	**Typical cruise speed knots**	**Communications**	**Vehicle Availability**
Ocean Server Iver3-450 Nano	1.6	0.1	0.1	0.1	18	60	10-Jun	24VDC			356 WHrs of li-Ion	2.5	WiFi 802.11n Ethernet	C - Commercial
Ocean Server Iver3-580-S	1.5-2.2	0.15	0.15	0.15	39	100	14	18-24VDC			800-1200 WHrs of Li-Ion	2.5	WiFi Iridium satellite Acoustic modem	C - Commercial
QinetiQ Sea Scout	0.9			0.12		200		14VDC				0-15	Radio (VHF) Iridium satellite	B - Available
Teledyne Gavia Defense AUV	1.8	0.2	0.3	0.2	49	500 1000	7				Batteries can be field swapped; 5-6 hours to charge empty to full	3	WLAN 802.11G Iridium satellite Acoustic modem	A - Limited
Teledyne Gavia Offshore Surveyor AUV	2.7	0.2	0.2	0.2	70-80	500 1000	4 – 5				Batteries can be field swapped; 5-6 hours to charge empty to full	3-Jan	WLAN 802.11G Iridium satellite Acoustic modem	C - Commercial
Teledyne Gavia Scientific AUV	1.8	0.2	0.3	0.2	49	500 1000	6				Batteries can be field swapped; 5-6 hours to charge empty to full	3	WLAN 802.11G Iridium satellite Acoustic modem	C - Commercial
YSI EcoMapper	1.5	0.1	0.1	0.15	20	100	8	12-18 VDC	10 inches forward		4 to 8 hours to fully charge from empty to full	2.5	WLAN 802.11G	C - Commercial

3.1.2 Lightweight Vehicle (LWV) and Heavyweight Vehicle (HWV) AUVs

Figure 3-3 identifies representative AUVs in the lightweight vehicle (LWV) and heavyweight vehicle (HWV) classes that were reviewed as part of this study. LWVs are larger in terms of size and weight compared to man-portable AUVs. This vehicle size is defined as nominally 12.75-inches in diameter and typically includes cylindrically-shaped vehicles. This size fills the need for a vehicle with extended endurance and ease of handling. HWVs are nominally 21 inches in diameter and are also typically cylindrical shaped.

These classes of vehicle exhibit the following characteristics:

- LWV:
  - typically 12.75 inches in diameter and approximately 500 lbs in weight though heavier configurations exist
  - endurance ranges from 10 hours to 40 hours depending on speed and hotel (including sensor) power load
  - payload volume is on the order of 1-3 ft^3 (0.03-0.08 m^3).
- HWV:
  - are typically 21 inches in diameter and weighing up to 3,000 lbs
  - endurance ranges from 20 hours to 80 hours depending on speed and hotel (including sensor) power load
  - payload volume is on the order of 4-6 ft^3 (0.11-0.17 m^3).

Other than select vehicles with discrete payload compartments or bays, these vehicles are generally constructed as cylindrical modular vehicles broken into sections that are joined together to comprise the entire vehicle. As such, payload sections can be of variable length largely constrained by overall weight, balance and control limits of the vehicle design and the handling and storage limits of the on-deck cradle, launch and recovery equipment. Most manufacturers have a catalog of “standard” payload sections for their vehicles, though most can be customized for specific sensor integrations.

As illustrated in Figure 3-4, these classes of AUVs are typically launched using an A-frame or boom type of crane system, a launch and recovery ramp, or specialized launch and recovery system equipment developed specifically for AUV L&R. Launch and recovery consists of a free-floating vehicle actively swimming off the surface and being recovered while drifting on the surface. The AUVs are configured with recovery straps (lifting points) and nose recovery bails that are installed on the AUV. This equipment is kept on during operations and used for hook-based (e.g., crane or davit) L&R. This method requires dexterity with equipment and manpower. The use of people very close to (touching) the vehicle, small boats and cantilevered hoists require relatively calm sea-states for safe and controlled L&R. Alternately, the recovery bail and main lifting point on the AUV can be attached at sea by shipboard operators using a long (~30-foot) carbon fiber pole.

Most of these AUVs can also use a LARS that eliminates the close proximity “pole hooking” approach. In this case the recovery consists of the crew securing the AUV recovery line from a distance, manipulating the ship into a towing position, and a winch operation that retrieves and lifts the AUV onto a cradle by the nose.

Figure 3-3: LWV and HWV Class AUVs

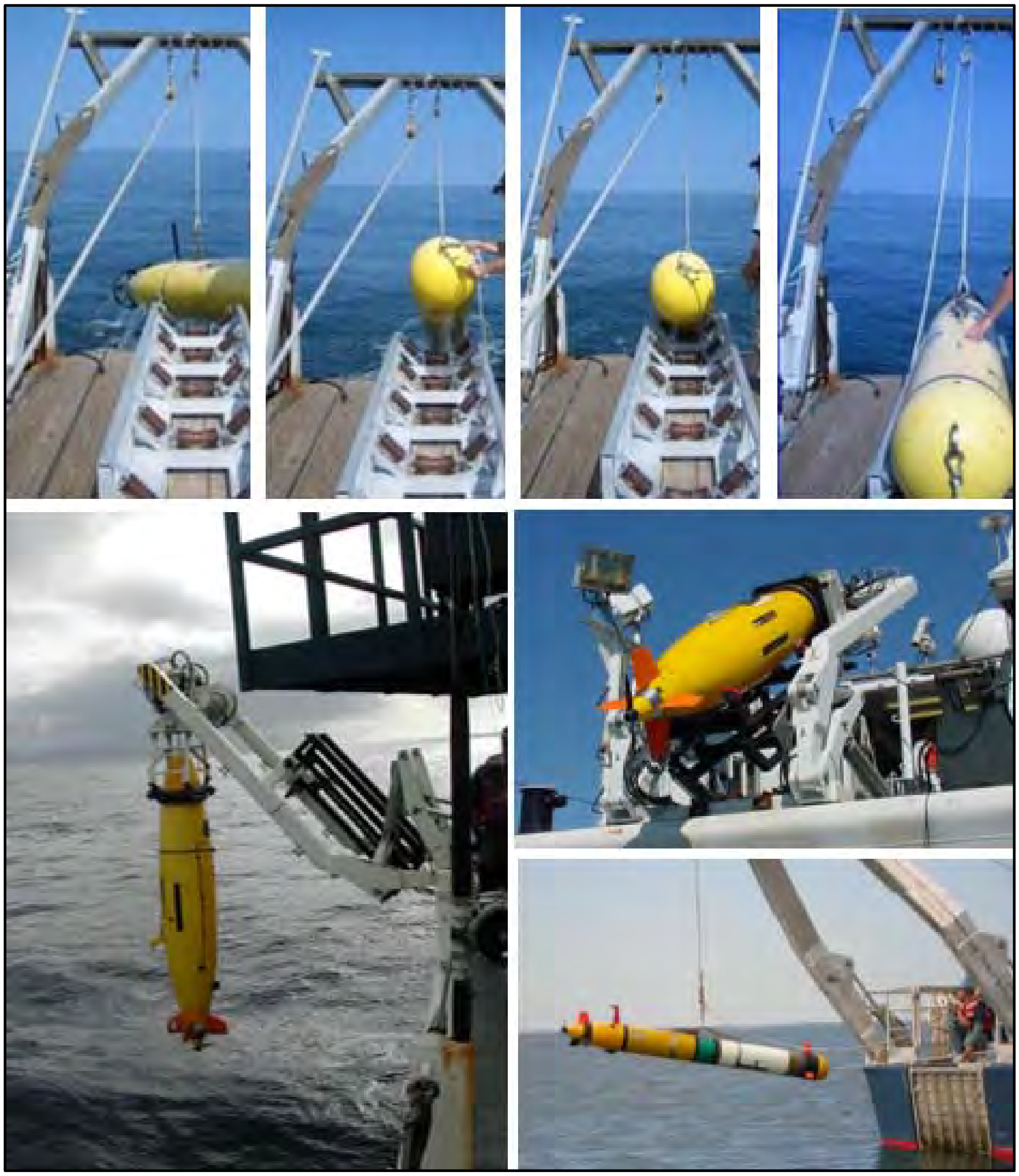

Figure 3-4: Typical L&R Mechanisms for LWV and HWV Class AUVs

For launch, the AUV is released and slides down (tail first) from the recovery cradle. The AUV would release the recovery line and float (from the nose) on command, which is captured with a grapple fired from a pneumatic gun as part of this process. Figure 3-5 shows this L&R sequence for a HUGIN AUV from its support ship. The technique is proven in open-ocean operations and the stern ramp has been shown (both by Kongsberg and Hydroid) to fit multiple ship configurations using "typical" power and hydraulics.

Table 3-2 lists the representative LWV and HWV AUVs that were reviewed for this study. Two companies account for most of the vehicles manufactured in this size class: Bluefin Robotics and Kongsberg Maritime.

Figure 3-5: Typical UAV Launch and Release

Table 3-2: LWV and HWV Class Autonomous Underwater Vehicles (AUV)

Manufacturer/ Platform	Vehicle Parameters													
	Length m	Width m	Height m	Diameter m	Weight dry, kg	Depth Rating m	Max. Mission Duration hrs	Available payload power	Payload volume cu. m	Payload weight kg	Mission Turnaround Time	Typical cruise speed knots	Communi-cations	Vehicle Availability
Bluefin Robotics Bluefin-12S	3.77	0.32	0.7	0.32	213	200	26	400 W	0.0066	variable free-flooded system	6 hrs battery charge from empty to full	3	RF Iridium satellite acoustic modem Ethernet via shore power cable	C - Commercial
Bluefin Robotics Bluefin-12D	4.32	0.32	0.65	0.32	260	1500	30	400 W	0.0066	variable free-flooded system	6 hrs battery charge from empty to full	3-4	RF Iridium satellite acoustic modem Ethernet via shore power cable	C - Commercial
Bluefin Robotics Bluefin-21	4.93	0.53	0.8	0.53	750	4500	30	800 W	0.197	variable free-flooded system	30 min (field swap); 6 hrs battery charge from empty to full	2-3	RF Iridium satellite acoustic modem Ethernet via shore power cable	C - Commercial
CIRS Girona 500	1.5	1	1	0.3	200	500								A - Limited
ECA Robotics ALISTER 18 (high resolution and high coverage)	3.5-4.6			0.47	290-440	600	24					1-2	WiFi or Ethernet Acoustic modem Satellite link on request	B - Available
ECA Robotics ALISTER 27 (multi-mission, long endurance)	5				800-1000	300	30					3	WiFi or Ethernet Acoustic modem Radio (VHF) Satellite link on request	B - Available
ECA Robotics ALISTER 18 TWIN	2.6-3.3				490-620	300 600	15					5 max	WiFi or Ethernet Acoustic modem Satellite link on request	B - Available

Manufacturer/ Platform	Vehicle Parameters													
	Length m	Width m	Height m	Diameter m	Weight dry, kg	Depth Rating m	Max. Mission Duration hrs	Available payload power	Payload volume cu. m	Payload weight kg	Mission Turnaround Time	Typical cruise speed knots	Communi-cations	Vehicle Availability
Falmouth Scientific SAUV II	2.3	1.1	0.5	0.2	200	500		10 W stand-by energy use thruster energy use 58-140 W max full charge solar panels provides 1900 Wh of available energy 10W hotel load is typical			Battery Charge Rate: 400 to 700 Whr/day (uses 2 batteries)	1-2	Iridium satellite RF Acoustic modem	B - Available
Kongsberg Maritime REMUS 600/600-S AUV	4.27	0.32	0.32	0.32	240	600 1500 3000	up to 70	150 W		87 typical	Battery recharge time 6-8 hours empty to full	3	Acoustic modem Iridium satellite WiFi 100 base-T Ethernet	C - Commercial
Kongsberg Maritime REMUS 6000	3.99	0.71	0.71	0.71	862	4000 6000	16-22				2 hours if field swapped; 8 hours if charged	4.5	Acoustic modem Iridium satellite 802.11G WiFi	C - Commercial
Lockheed Martin Marlin	3.05		1.22	1.52	954	300	419 97			114		0-4	Acoustic modem WiFi RF	B - Available
Saab Seaeye Eagle SAROV	2.9	1.3	1		540	500 1500 3000	10+	600+ W		250		4-8	Gigabit Ethernet WiFi Radio Acoustic	C - Commercial

3.1.3 Large Displacement AUVs

Figure 3-6 identifies the representative large displacement class AUVs that were reviewed as part of this study. This vehicle class is the largest size in operation. The driving factor for the large size is endurance and payload capacity. In order to travel long distances (>100 miles), and to have long times on station (>1 week), their energy capacity must be significant. This class of vehicle exhibits the following characteristics:

- Typically greater than 36 inches in diameter and weighing up to 20,000 lbs
- Endurance greater than 100 hours depending on speed and hotel (including sensor) power load
- Payload volume on the order of 15-30 ft^3 (0.4-0.8 m^3)

Payload is carried in discrete payload bays designed into the overall vehicle arrangement. L&R is similar to that indicated for the LWV and HWV AUV classes, but scaled-up to reflect the size and weight of these vehicles. Table 3-3 lists the large AUVs reviewed for this study. Due to their size and cost, these vehicles have not been produced in great numbers, though the vehicle manufacturers are reputable companies that have been in the maritime industry for a considerable period of time.

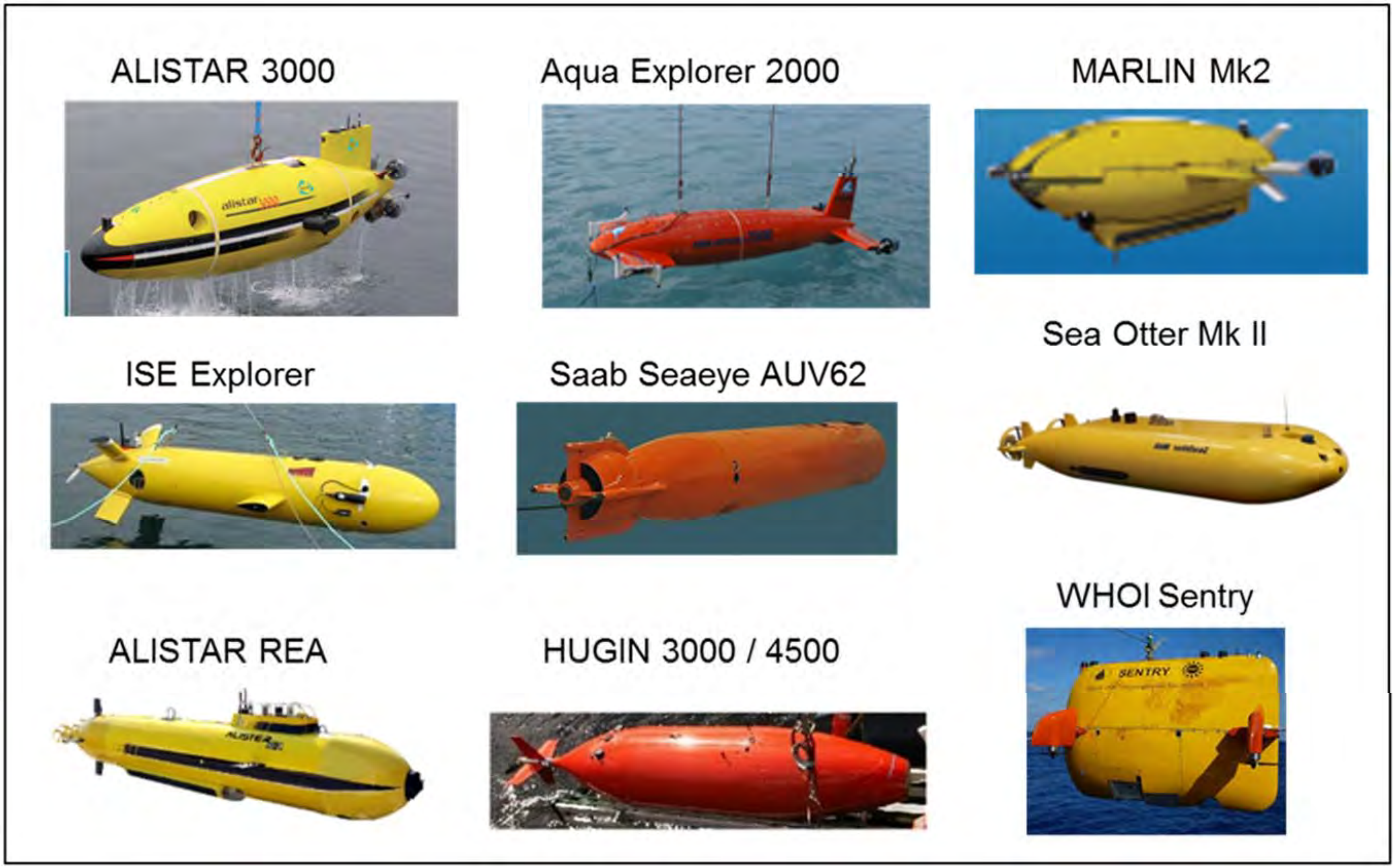

Figure 3-6: Large Displacement AUVs

Table 3-3: Large Displacement Class Autonomous Underwater Vehicles (AUVs)

Manufacturer/ Platform	Vehicle Parameters													
	Length, m	Width, m	Height, m	Dia., m	Weight dry, kg	Depth Rating, m	Max. Mission Duration, hrs	Available payload power	Payload volume cu. m	Payload weight kg	Mission Turnaround Time	Typical cruise speed knots	Communi-cations	Vehicle Availability
Atlas Elektronik Sea Otter Mk II	3.65	1.1	0.48		1000	600 1500	24		modular	160	4 hours for 2 Li batteries (18 kWh capacity each)	4	LAN (on deck) WiFi Radio Iridium satellite Fiber Optic Acoustic modem ARGOS	B - Available
C&C Technologies C-Surveyor IV (HUGIN 3000 platform with integrated payload packages)	4.57	1	1	1	1400	3000		UltraSparc 650 mHz cPCI with 1 gigabyte ram			2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive		Acoustic modem	A - Limited
C&C Technologies C-Surveyor V (HUGIN 3000 platform with integrated payload packages)	6.2	1	1	1	1400	3000		UltraSparc 650 mHz cPCI with 1 gigabyte ram			2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive		Acoustic modem	A - Limited
C&C Technologies C-Surveyor VI (HUGIN 3000 platform with integrated payload packages)	6.35	1	1	1		3000						4	Acoustic modem	A - Limited
C&C Technologies C-Surveyor II (HUGIN 3000 platform with integrated payload packages)	6.2	1	1	1	1400	3000	50	UltraSparc 650 mHz cPCI with 1 gigabyte ram			2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive		Acoustic modem	A - Limited

Manufacturer/ Platform	Vehicle Parameters: Length , m	Width, m	Height , m	Dia., m	Weight dry, kg	Depth Rating, m	Max. Mission Duration , hrs	Available payload power	Payload volume cu. m	Payload weight kg	Mission Turnaround Time	Typical cruise speed knots	Communi-cations	Vehicle Availability
C&C Technologies C-Surveyor III (HUGIN 4500 platform with integrated camera and side sonar system)	6.4	1	1	1	1500	4500	50	UltraSparc 650 mHz cPCI with 1 gigabyte ram			2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive		Acoustic modem	A - Limited
ECA Robotics ALISTAR 3000	5	1.68	1.45	1.68	2300 incl. pay-load	3000	20			150		2	RF GPS/DGPS Acoustic modem Acoustic localization transponder	C - Commercial
ECA Robotics ALISTER REA (rapid enviro. assessment)	4.4-5.0	0.7	1.2	0.7	800-960	300	12 to 20					4		C - Commercial
ISE Explorer	4.5 - 6.0	0.69	1.79	3000 m: 0.69 5000 m: 0.74	750-1250	300 1000 3000 5000 6000	24-85	75 W	Variable -- forward free-flooding section allows for installation of 19-inch rack mounted equip.	1000m: 275 3000m: 200 5000m: 125	5-10 hours depending on number of batteries used	3	Acoustic modem Iridium satellite RF	B - Available
Kongsberg Maritime HUGIN 1000; HUGIN 1000 for 3000 m	4.5 4.7	0.75	0.75	0.75	650-850	1000 3000	24	200 W	variable		6 hours to recharge from empty to full	3-4	Ethernet Acoustic modem Iridium satellite RF WLAN	C - Commercial

Manufacturer/ Platform	Vehicle Parameters													
	Length , m	Width, m	Height , m	Dia., m	Weight dry, kg	Depth Rating, m	Max. Mission Duration , hrs	Available payload power	Payload volume cu. m	Payload weight kg	Mission Turnaround Time	Typical cruise speed knots	Communi-cations	Vehicle Availability
Kongsberg Maritime HUGIN 3000	5.5	1	1	1	1400	3000	60		variable		2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive	4	Ethernet Acoustic modem RF Iridium WLAN	C - Commercial
Kongsberg Maritime HUGIN 4500	6	1	1	1	1900	4500	60		variable		2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive	4	Ethernet Acoustic modem RF Iridium WLAN	C - Commercial
Lockheed Martin Marlin MK2	3	1.5	1.3		954	304-4000	18-24	200+ W	0.1416	113		0-6	Acoustic modem Ethernet Iridium satellite WiFi RF Optional fiber optic tether	B - Available
Mitsui Engineering and Shipbuilding Aqua Explorer 2000	3	1.3	0.9	0.9	3000	2000	16					3	Acoustic low-level command link	A - Limited
Saab Seaeye AUV62-MR	4-7 10 opt.			0.53	600-1500	500						0-20	WLAN UHF/VHF SatLink	B - Available
Woods Hole Sentry	2.9	2.2	1.8		1250	6000	20-40	48-52VDC			10 hrs	0-2	Acoustic modem	A - Limited

3.2 Gliders

An underwater glider is a type of AUV that uses small changes in its buoyancy in conjunction with wings to convert vertical motion to horizontal, thereby propelling itself forward with very low power consumption. Figure 3-7 illustrates representative gliders that were reviewed as part of this study. Gliders operate under extremely tight power constraints—they travel thousands of kilometers in the ocean consuming about 1 W for propulsion and about the same for hotel. Minimizing drag, and maximizing lift/drag of lifting surfaces, is essential to achieving range and endurance, which are typically considered the most important glider characteristics. This class of vehicle exhibits the following characteristics:

- Slower than conventional AUVs (0.4-0.7 kts vs. 3-5 kts)
- Significantly increased endurance and range (from hours to weeks or months, and to thousands of kilometers)
- Following an up-and-down profile through the water (often referred to as a sawtooth), typical glide slopes, on of the order 1:4, are much steeper than the slope of oceanic distributions, so each leg of a glider sawtooth produces the equivalent of an ocean profile.
- The shallowest points on the sawtooth are at the surface where satellite navigation and communication are carried out, eliminating the need for in-situ tracking networks (Figure 3-8).

Four basic sampling modes for gliders have presented themselves:

- Forward motion can be used to counter ambient currents and maintain position, allowing gliders to sample virtually as a vertical array of moored instruments
- Moving from place to place yields a highly resolved section, although the slowness of advance mixes time and spatial variability
- Multiple gliders controlled remotely from a research vessel can form an array to describe a spatial and temporal context for intensive measurements
- The long operating lives and ability to sample densely suit gliders to missions where unusual events are sought and then studied intensely when found.

Scientific payloads for gliders are limited by size, flow disturbance, and power requirement considerations. Gliders achieve their low overall power consumption by using low-power electronics and sampling schemes that limit the duty cycle of sensors. The relatively slow glider speeds allow sampling intervals of 8-10 seconds to achieve a vertical resolution of 1 meter. Sensor systems must fit within the payload fraction of the vehicle and, because gliding involves modest buoyancy forces, ballast and trim are paramount considerations. In general, sensors must be hydrodynamically unobtrusive, lest they spoil gliding performance by adding drag. Streamlining can be achieved by using sensors that are small or mounted flush to the vehicle hull. Outward-looking acoustic and optical sensors conveniently fit this requirement and have been used on the gliders described here. Figure 3-9 illustrates some examples of glider payload installation.

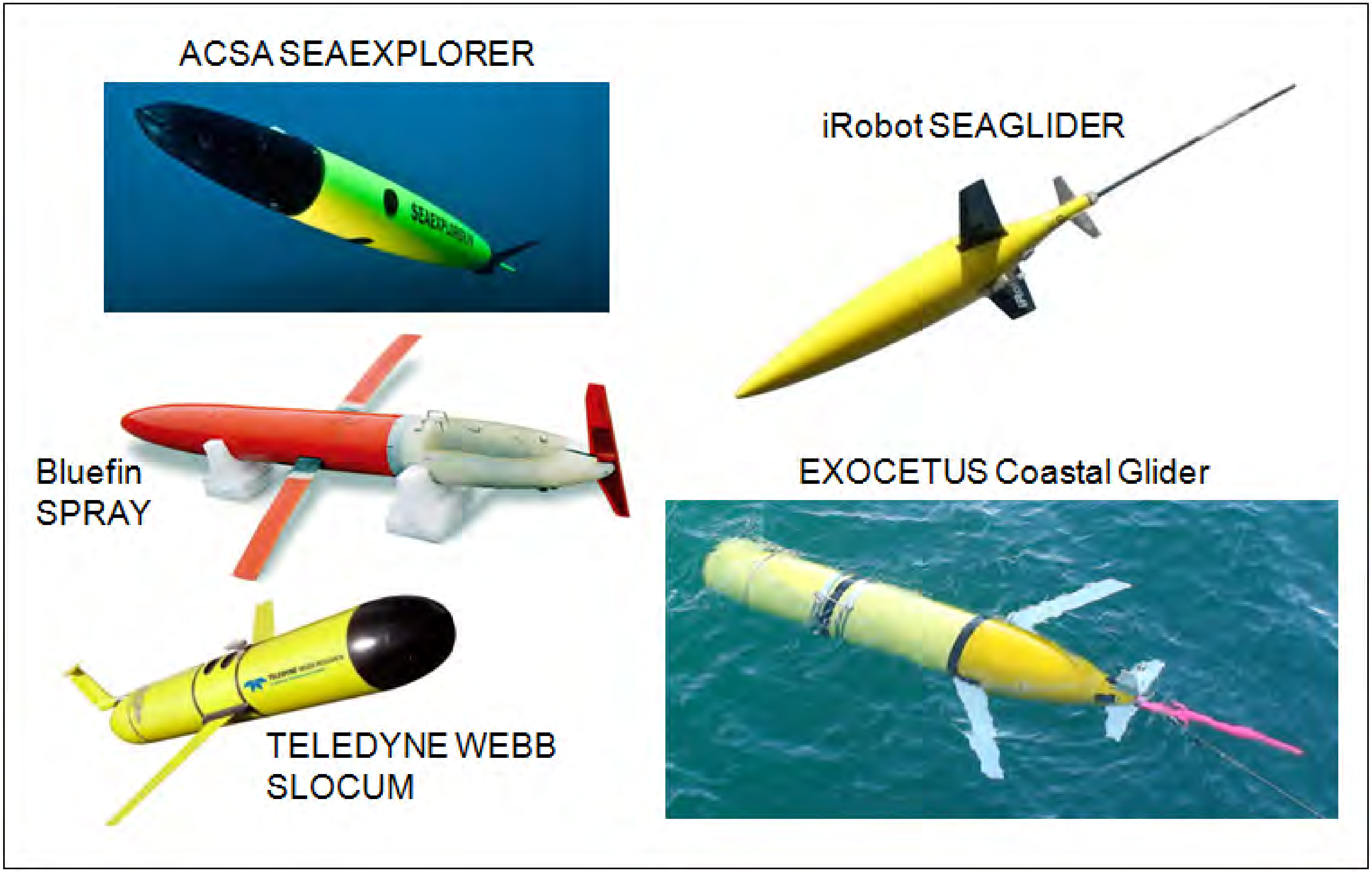

Figure 3-7: Gliders

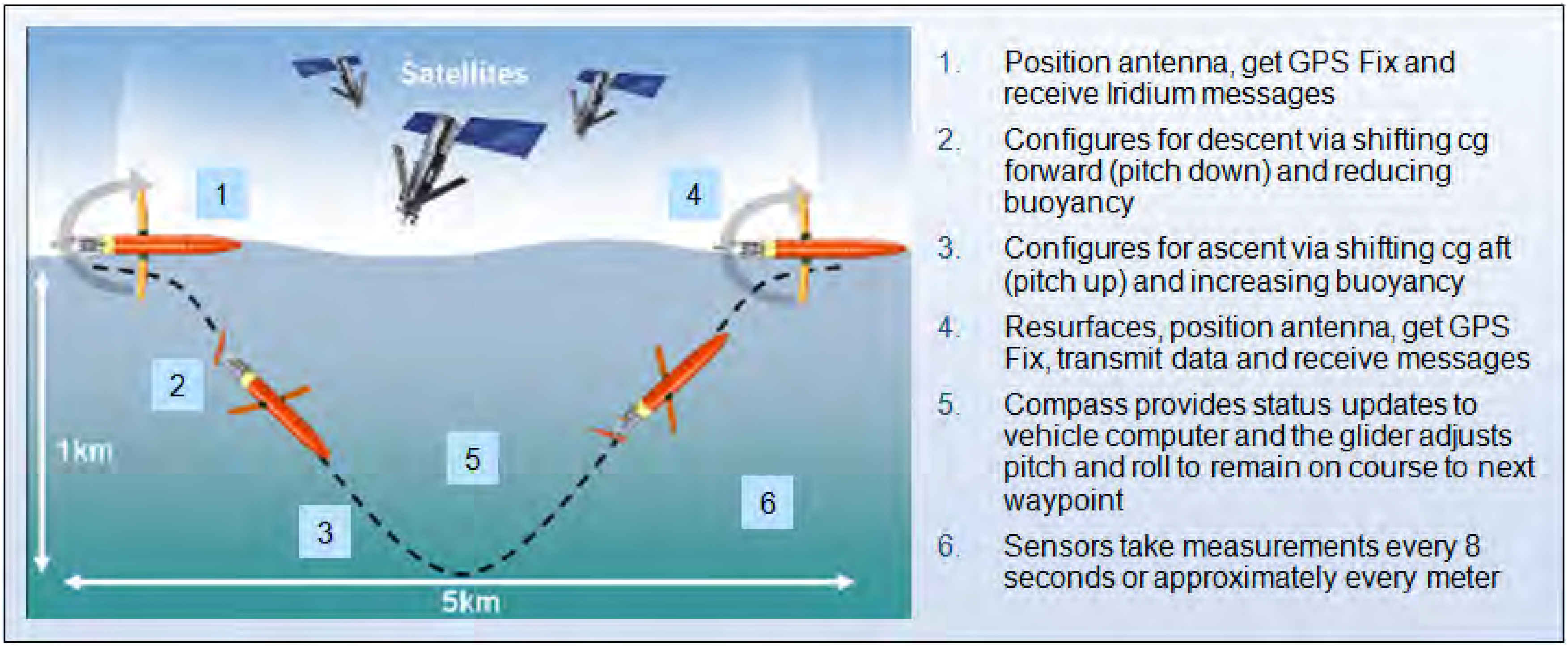

Figure 3-8: Representative Glider Mission Profile

Figure 3-9: Representative Glider Payload Installation

Glider L&R is similar to that of other AUVs. Most gliders are capable of being launched by 1-2 personnel and a small boat similar to the man-portable class of AUVs. The Exocetus Coastal Glider would be handled in a manner similar to a LWV-class of AUV. Table 3-4 summarizes the principal characteristics of the seven representative gliders identified in this study.

Table 3-4: Gliders

	Sensor Parameters													
Manufacturer/ Platform	**Length m**	**Width m**	**Height m**	**Dia. m**	**Weight dry, kg**	**Buoyancy Swing kg**	**Depth Rating m**	**Max. Mission Duration hrs**	**Available payload power**	**Payload volume cu. m**	**Payload weight kg**	**Typical cruise speed knots**	**Communications**	**Vehicle Availability**
ASCA SeaExplorer	2.9	0.25	0.25	0.25	59		700				5	3-4	Iridium satellite RF modem	A - Limited
Bluefin Robotics Spray Glider	2.13	1.01	0.3	0.3	52	0.4 net pos.	1500	4320 (180 days)			3.5	0.4	Iridium satellite GPS	B - Available
Konsberg 1KA Seaglider	1.8-2	1 wing	0.4	0.3	52		up to 1,000	7200 (10 months)	5 payload ports	0.344	4	0.5	Iridium satellite ARGOS	C - Commercial
Teledyne Webb Research G2 Slocum Glider	1.5			0.22	54			alkaline batt.: 360-1200 (15-50 days) Li batt: 2922-5844 (122-244 days)		0.098		2-3	RF modem Iridium satellite ARGOS Acoustic modem	C - Commercial
Teledyne Webb Research Slocum Electric Glider (aka Battery Glider)	1.79	1 wing	0.49	0.21	52		4-200 1000	720 (30 days)	9–14 kHz transducer for active sonar use or for an acoustic modem 200-kHz transducer for altimeter use		4-Mar	1-2	RF modem Iridium satellite ARGOS Telesonar modem	C - Commercial
Teledyne Webb Research Slocum Thermal Glider	1.79	1.01	0.49	0.21	60		1200	26,297 to 43,829 (3-5 years)				0.7	RF modem Iridium satellite ARGOS	C - Commercial
Exocetus Coastal Glider	2.87	0.32	2	2	109-120	2.5	200	alkaline batt.: 336 hrs (14 days) Li batt: 1440 hrs (60 days)	GPIO switch: 12 VDC (3 amp max) power available Expansion board: 5 VDC, and 3.5 VDC power available Raw battery: 18-33 VDC power available	0.113	5		Iridium satellite ARGOS Freewave (UHF) WiFi GPS	B - Available

3.3 Wave and Wind Powered ASVs

The Liquid Robotics Inc. (LRI) Wave Glider and MOST (Autonomous Vessels) Ltd AutoNaut (Figure 3-10) fall into a new class of wave-propelled, persistent ocean vehicles. The key innovation of these vehicles is the ability to harvest the abundant energy in ocean waves to provide essentially limitless propulsion. A wave powered vehicle can be regarded as a small, self-propelled (albeit slow) buoy capable of an average forward speed of about 1 m/s (1.5 knots) in seas with 0.5 m – 1 m wave height.

The Wave Glider is a hybrid sea-surface and underwater vehicle comprised of a submerged "glider" attached via a tether to a surface float. The AutoNaut is a more conventional sea-surface vehicle that has similar planes on the bow and stern. The vehicles are propelled by the conversion of ocean wave energy into forward thrust, independent of wave direction. The wave energy propulsion system is purely mechanical; electrical power is neither generated nor consumed by the propulsion mechanism.

As a surface vehicle the Wave Glider can maintain continuous GPS and Iridium communication, allowing it to be controlled in real-time. The current graphical interface provides the operator with two distinct modes of operation: mission planning and direct control. Mission planning is waypoint navigation based on geographical references provided by GPS; direct control allows the operator to effectively "drive" the vehicle (within the operator's line-of-sight) to aid in L&R operations or to navigate harbors and other confined waterways. Wave Glider L&R is similar to that of a LWV-class AUV, being typically deployed using a small crane. Deck stowage would be in the form of a cradle. The Wave Glider has two dry payload bays on the float and payload mounts on the glider body as illustrated in Figure 3-11. The payload mounts are suspended ~23 feet below the float and can be used for sampling. Payload power is provided by the batteries which are recharged by solar panels. It is also conceivable for a payload to be suspended or towed from the glider body.

The Saildrone is an autonomous rigid foil sailboat (Figure 3-10) that uses the wind for propulsion and solar panels to provide additional electrical power for steering and sensors. Saildrone is constructed from high-strength carbon fiber to create a strong and durable structure. While delicate in appearance, Saildrone is engineered to be fully submerged and rolled in extreme waves. The Saildrone's hydrodynamic design is a hybrid, combining the features of mono- and multi-hulls. The result is a fully self-righting platform that also benefits from high righting moments for speed and wave piercing capabilities to reduce pitching and energy absorption from waves. Saildrone has two payload bays and external payload attachments, configurable to serve varied mission requirements. Total payload weight capacity is currently 100 kg, and can be expanded with larger craft as required. Various power options and sampling solutions are offered depending on the mission specific tasks.

Table 3-5 summarizes the principal characteristics of these wave and wind powered ASVs.

Figure 3-10: Wave and Wind Powered ASVs

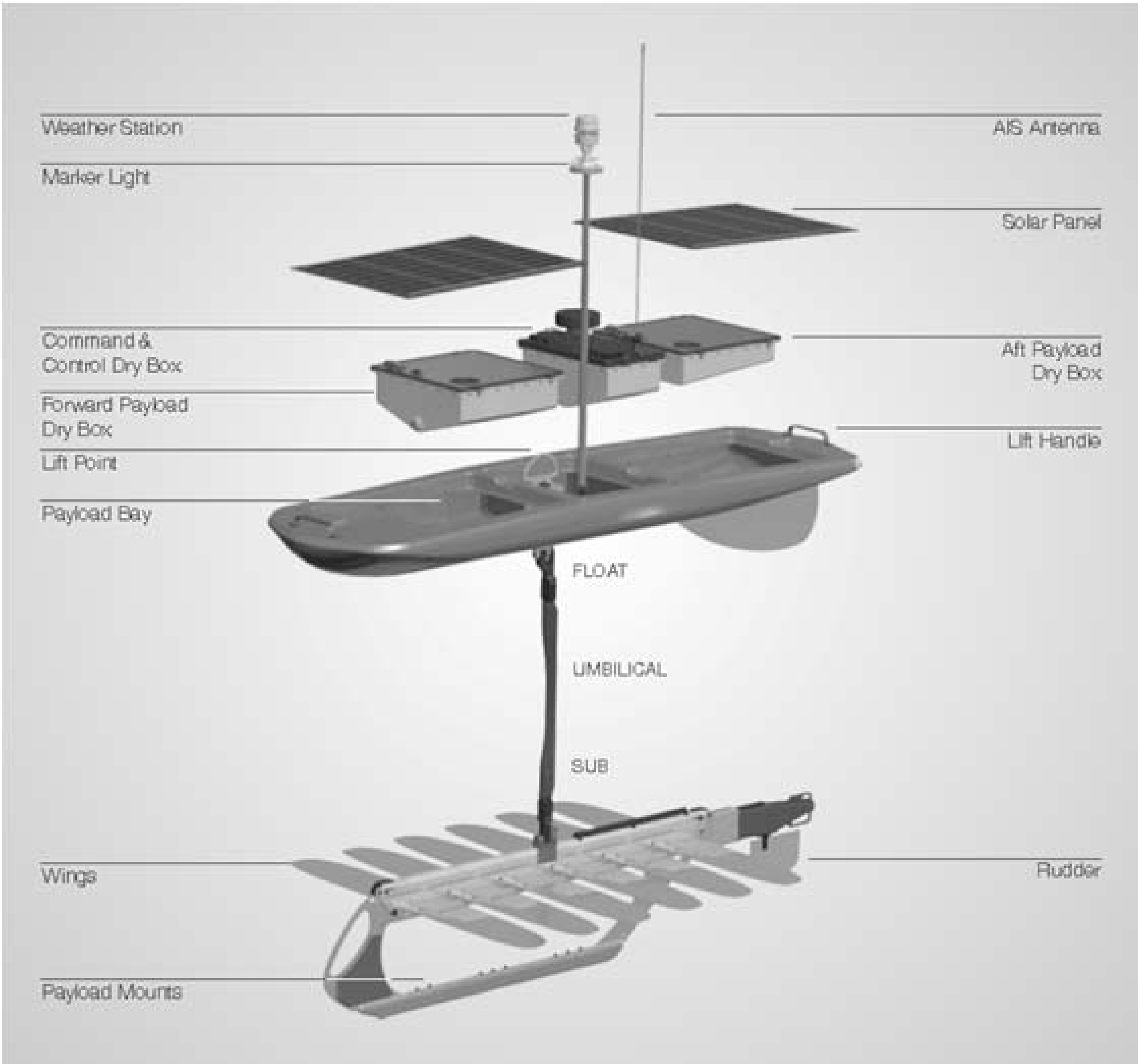

Figure 3-11: Liquid Robotics, Inc. (LRI) Wave Glider Components

Table 3-5: Wave and Wind Powered

	Vehicle Parameters										
Manufacturer/ Platform	**Length m**	**Width m**	**Weight dry, kg**	**Reserve buoyancy**	**Max. Mission Duration hrs**	**Available payload power**	**Payload volume cu. m**	**Payload weight kg**	**Typical cruise speed knots**	**Communications**	**Vehicle Availability**
Liquid Robotics Wave Glider SV2	Float: 2.1 Glider: 1.9	1.07 (wing)	90	Displacement: 150 kg	Up to 1 year	10 W Payload ports (3): 3A/13.2V PEP port: 5A/13.2V Glider port: 1A/13.2V System maximum: 10A/13.2V	0.04	18	0.5-1.6	Iridium Satellite RF modem Wifi	C - Commercial
Liquid Robotics Wave Glider SV3	Float: 2.9 Glider: 1.9	1.4 (wing)	90	Displacement: 150 kg	Up to 1 year	10 W Payload ports (3): 3A/13.2V PEP port: 5A/13.2V Glider port: 1A/13.2V System maximum: 10A/13.2V	0.09	45	1-2 w/o thruster 1.5-2.3 w/ thruster	Iridium Satellite RF modem Wifi	C - Commercial
MOST AutoNaut	3.5			3 months (@2-3 kts)	20W @ 50% duty cycle for 90 days			Battery: 720Wh lead gel Solar PV: 125Wp Generator: 45 watt methanol fuel cell, 20 liters fuel (22kWh of power)		UHF XBEE PRO Iridium	B - Available
Saildrone Saildrone	5.8	2.1			5000 hrs	5-10 W		100	5	Satellite	A - Limited

3.4 Autonomous Surface Vehicles (ASVs)

The term ASV or unmanned surface vehicle (USV) refers to a vehicle that operates on the surface of the water without a crew. ASVs have been tested since World War II but have been largely overshadowed by other AOVs. Navies around the world are developing, testing, and using autonomous surface vehicles today. They are reliable, fast, and highly maneuverable, allowing the conduct of a wide range of missions, including patrols of the coast, without endangering personnel. ASVs are also used in oceanography as they are more capable than moored or drifting weather buoys, far cheaper than the equivalent weather ships and research vessels, and more flexible than commercial-ship contributions. Figure 3-12 and Figure 3-13 identify representative ASVs reviewed for this study

ASV payload integration for subsea operations is either hull-mounted, uses a mechanical boom extension, or uses a dipper or a tow-fish on a winch. The term “dipper” refers to a sensor suspended on the winch line without great regard for stabilization. Of these approaches, only the dipper and tow-fish can achieve significant water depth. Arguably, any method of sensor employment suitable for small boat operations and capable of being automated is useable from an ASV, though it may not be considered standard equipment from the ASV manufacturers.

As a surface vehicle, an ASV can maintain continuous communication with the operator allowing the ASV to be controlled in real-time via either satellite GPS and Iridium communication or line-of-sight radio communication. The operator possesses two distinct modes of ASV operation: mission planning and direct control. Mission planning is waypoint navigation based on geographical references provided by GPS; direct control allows the operator to effectively pilot the vehicle (within the operator’s line-of-sight) to aid L&R operations or to navigate harbors and other confined waterways. Research is ongoing to develop ASVs that will operate under minimal supervisory command and control for long durations, with shore bases intermittently monitoring performance and providing high-level mission objectives through beyond line-of-sight communications links. These vessels will be provided with advanced autonomous navigation and anti-collision features to keep them within maritime law and the International Regulations for Preventing Collisions at Sea.

ASV L&R is similar to that of a HWV-class or larger AUV since an ASV would typically be deployed using a small crane or boat ramp. Deck stowage would be in a cradle.

Figure 3-12: Small ASVs

Figure 3-13: Large ASVs

Table 3-6 lists the small ASVs that were reviewed for this study. This group represents vehicles identified that were less than 100 kg and could be considered capable of being launched and recovered manually. As noted there is one manufacturer, Sea Robotics, which has a range of vehicles intended for different purposes. Payload integration is largely hull-mounted on a strut to submerge the payload a modest distance below the hull (1-2 feet seems typical) though two vehicles, the USV-2600 and USV-5000, are available with an optional winch system to allow for lowering an instrument cage. The manufacturer's data gathered for this report provides limited insight into the overall seaworthiness of this set of vehicles.

Table 3-7 lists the large ASVs that were reviewed for this study. This group represents vehicles identified that were several hundred to several thousands of kilograms in size. These vehicles would need to be launched from a host ship using a davit or crane. Those configurations that appear to have been manufactured in larger numbers are generally based on a rigid-hulled inflatable boat (RHIB) design or similar. The RHIB is a light-weight but high-performance and high-capacity vessel constructed with a solid, shaped hull and flexible tubes at the gunwale. The design is stable and seaworthy; the inflatable collar allows the vessel to maintain buoyancy even if a large quantity of water is taken aboard during unfavorable sea conditions. Typical uses include work boats in trades that operate on the water supporting shore facilities or larger ships, as well as lifeboats and military craft where they are used in patrol roles and to transport troops between vessels or shore. Submerged payload integration is typically towed or suspended from these types of designs.

Table 3-6: Small Autonomous Surface Vehicles (ASV)

	Vehicle Parameters										
Manufacturer/Platform	Length m	Width m	Weight dry, kg	Max. Mission Duration hrs	Available payload power	Payload volume cu. m	Payload weight kg	Power source	Mission turnaround time	Communications	Vehicle Availability
CMR Instrumentation Sailbuoy	2		60	1 yr		0.06	10			Iridium	B - Available
EvoLogics Sonobot	0.45	0.92	30	10 (@2 kts)						WiFi	B - Available
Robotic Marine Systems Scout	3			8						RF WiFi	B - Available
Sea Robotics USV-1000 High Speed Trimaran	3	1.2	40	12 (@2.4 kts) 6 (@4.37 kts)			80	Ni-MH batteries; Li-polymer batteries optional	Battery fields swap	2402 MHz Ethernet	C - Commercial
Sea Robotics USV-2600 Mission Reconfigurable USV (catamaran)	3.25	1	75-100	8 (@2.4 kts) 3 (@4.37 kts)				Ni-MH batteries; Li-polymer batteries optional	Battery fields swap	2403 MHz Ethernet	C - Commercial
Sea Robotics USV-450 Heavy Payload Catamaran	1.9	1.2	40	8 (@2.4 kts) 2 (@4.37 kts)			80	Ni-MH batteries; Li-polymer batteries optional	Battery fields swap	2400 MHz Ethernet	C - Commercial
Sea Robotics USV-5000 Self Righting Mono-Hull	4.25	0.5	60	12 (@2.4 kts) 6 (@4.37 kts)			50	Ni-MH batteries; Li-polymer batteries optional	Battery fields swap	2404 MHz Ethernet	C - Commercial
Sea Robotics USV-600 Mission Reconfigurable USV	1.25	0.66	15	8 (@2.4 kts) 3 (@4.37 kts)			8	Ni-MH batteries; Li-polymer batteries optional	Battery fields swap	2401 MHz Ethernet	C - Commercial

Table 3-7: Large Autonomous Surface Vehicles (ASV)

	Vehicle Parameters										
Manufacturer/Platform	Length m	Width m	Weight dry, kg	Max. Mission Duration hrs	Available payload power	Payload volume cu. m	Payload weight kg	Power source	Mission turnaround time	Communications	Vehicle Availability
ASV C-Enduro	4.2		350-500	3 months				Solar and Wind		LOS Radio Satellite	B - Available
SIEL Advanced Sea Systems UAPS 20: RHIB 500	5.05		320	12 continuous			810	4 strokes outboard engine, 60 to 110 Hp			C - Commercial
ASV C-Cat 5	5		650-1000	diesel genset: 48 Battery alone: 8			500	2 x DC Electric Motors (3.6 kW each), Diesel Genset or Direct Drive Diesel options		UHF S-Band L-Band Xbee Option	C - Commercial
ASV C-Hunter	6.3		2,000	50+ (@6 kts) 96+ (@4 kts)			300	1 x Yanmar 3YM30 Diesel Engine (30 Hp)		UHF up to 8 km or Satellite/GSM communication options	B - Available
ASV C-Worker	5.85		3500-5000	720 @ 4knts 240 @ 6 kts				2x diesel generator sets 13kW each		LOS Radio Satellite	B - Available
C&C Technologies ASV 6300 Hydrographic Survey Vehicle (semi-submersible)	6.3		2000	96 (@4 kts) 50+ (@6 kts)			300	30 HP Yanmar Diesel Engine			A - Limited
C&C Technologies ASV 9500Multi Role (semi-submersible)	9.5			720				diesel engine			A - Limited
C&C Technologies SASS-Q (semi-submersible)	6						200				A - Limited
ECA Robotics INSPECTOR MK2 Imagery and Bathymetric Survey	8.4		4,700	20 (@6 kts)			1000	2 diesel hydro jets (2 x 170 to 215 kW)			B - Available
ISE Dorado (semi-submersible)	8.23	2.28	6,600	28		0.6	210	marine diesel engine	1-2 hours (refuel)	RF Ethernet	B - Available

	Vehicle Parameters										
Manufacturer/Platform	**Length m**	**Width m**	**Weight dry, kg**	**Max. Mission Duration hrs**	**Available payload power**	**Payload volume cu. m**	**Payload weight kg**	**Power source**	**Mission turnaround time**	**Communications**	**Vehicle Availability**
Maritime Robotics USV Mariner	5.8	2	1700	50 (@5 kts)		1		Volvo Penta D3 Engine		VHF/UHF GPRS/Iridium opt.	B - Available
QinetiQ Blackfish	3.2		470	1			150			VHF/UHF WiFi Iridium	A - Limited
SIEL Advanced Sea Systems UAPS 20: RHIB 750	7.5		850				2160	4 strokes outboard engine, 110 to 250 Hp			C - Commercial
SIEL Advanced Sea Systems UAPS 20: RHIB 900	8.8		1500				2160	4 strokes twin outboard engine, 500 Hp			C - Commercial
ZyCraft Vigilant	16.5		6000-13000	720		18	2700				A - Limited

3.5 Autonomous Oceanographic Vehicle Cost Comparisons

Table 3-8 provides representative relative cost information on AOVs.

Table 3-8: Autonomous Oceanographic Vehicles Base Costs

Type	Manufacturer	Vehicle	Base Price (Primary)	Estimated Cost (Third party)
AUV	Bluefin Robotics	Bluefin-9	–	$700,000 - $850,000
	Bluefin Robotics	Bluefin-12	–	$1.6 million - $2 million
	Bluefin Robotics	Bluefin-21	–	$3.5 million - $4 million
	Kongsberg Maritime/Hydroid	REMUS 100/100-S AUV	–	$325,000+
	Kongsberg Maritime/Hydroid	REMUS 600/600-S AUV	–	$250,000 - $1 million
	Teledyne Gavia	Gavia Scientific AUV	–	$600,000 - $850,000
	OceanServer	Iver2-580-S	$50,000	–
Gliders	Bluefin Robotics	Spray Glider	–	$100,000 with CTD sensors
	Teledyne Web Research	Slocum Electric Glider	–	$100,000
	iRobot	1KA Seaglider	–	$100,000
Wave Glider	Liquid Robotics	Wave Glider	$250,000	Fully loaded $500,000+
ASV	Sea Robotics	USV-450 Heavy Payload Catamaran	$50,000	–
	Sea Robotics	USV-600 Mission Reconfigurable USV	$90,000	–
	Sea Robotics	USV-1000 High Speed Trimaran	$110,000	–

4.0 AOV and Sensor Compatibility Assessment

This section assesses the sensors that can be accommodated aboard the various AOVs based on payload volume, weight and power capacities.

4.1 Description and Use of Matrix

This section provides matrices that can be used to help gauge compatibility of various sensor types (i.e. direct or indirect) with vehicle types (i.e. AUV, glider, ASV). Of the three principal payload metrics considered for this evaluation (size, weight and power), payload volume emerged as the primary criterion to rate overall compatibility for the propelled subsurface AUVs (i.e., those vehicles other than gliders or ASV). Power was not a driver for payload compatibility within this set of vehicles and sensors, as most of these vehicles were designed to be capable of hosting one or more kinds of SONAR, resulting in sufficient power available for environmental sensors. Other than select vehicles with discrete payload compartments or bays, these vehicles are constructed such that they have a variable length payload section which is attached to other vehicle sections (energy and navigation) to form the complete vehicle. As such, the payload section length can be extended and can even be traded with the size of the energy section within the overall weight, balance and control limits of the vehicle design, and the handling and storage limits of the on-deck cradle and L&R apparatus. Most manufacturers have “standard” payload sections for each of their vehicles, although they can be tailored for custom sensor integrations. To assess the influence of power beyond this level is difficult as it is heavily dependent upon required mission duration and profile and the duty cycle of the sensors within the mission. These variables, along with the ability to trade payload space for additional power sources, would require a detailed investigation that considers all aspects of specific missions.

The metric of available payload weight is a driver specific to either AUVs with variable ballast or ASVs. The remaining AUVs and gliders typically require that the payload be neutrally buoyant. This requirement then turns into a volume and packaging density trade on using foam to achieve neutral buoyancy instead of actually being based on weight.

The tables in this section provide a single score that is assigned based on payload volume. This metric has been chosen since it has the most available data and is frequently traded for additional power or buoyancy. The tables show a rating of 1, 2 or 3 depending on the compatibility of the vehicle to host the specific sensor, as follows:

1: Sensor not expected to be compatible with that specific vehicle.

2: Sensor is compatible with the vehicle but may require external mounting due to the nature of the sensor. This rating is also assigned if the sensor is expected to consume almost all of the available payload volume within the AUV.

3: Sensor readily fits within the vehicle and allows for additional payloads to be carried.

NR (not rated) was used where there was insufficient sensor data available to assign a rating.

4.2 Compatibility of Man-Portable Class AUVs with Direct and Indirect Sensors

Table 4-1 and Table 4-2 assess the compatibility of the man-portable AUVs identified in Section 3.1.1 with the direct and indirect oil detection sensors. As indicated in the tables, most of the direct and indirect detection sensors investigated are compatible as payloads for the man-portable class of AUVs. Of the man-portable AUVs, three appear to provide the most payload selection flexibility: the Bluefin-9, Ocean Server Iver2-580-EP and the REMUS-100. These vehicles generally integrate payload either by adding length or mounting sensors externally. Of these vehicles, the Bluefin-9 has the largest cross section to accommodate larger sensors. The smallest is the Ocean Server which does not allow one of the sensors that the other two are capable of carrying.

In general this class of vehicle does not have the degree of payload modularity that is present in the larger AUVs. Because of this, it is likely that more non-recurring engineering (NRE) is required to custom fit the sensors into the standard vehicle by using a custom length addition and locating ballast and foam to retain neutral buoyancy.

Integration of more than one detection sensor is possible for the smaller and lighter sensors across most of these vehicles. Many of the sensors in this report are fairly small in size and weight. Several of the sensors are small enough to fit within the vehicle or as a small attachment external to the standard vehicle without major drag considerations. If it is desired to carry more sensors then it may be possible to substitute multiple small, light sensors for the standard sonar system equipment normally included while maintaining the external profile. Again, this would require NRE to tailor the installation to the vehicle.

Four of the larger sensors investigated are incompatible with the man-portable class of AUVs due to their overall size and weight. These sensors seem to be developed for use by an ROV or suspended from a surface vessel and employed as a vertical profiler. These sensors include the CONTROS Mobile Leak Detection System, the Chelsea Technologies Subsea Pipeline Leak Detection sensor, the Sea Bird SBE 911 plus / 917 plus, and the Sea Bird SBE 25 plus Sealogger.

Table 4-1: Man-Portable AUV to Direct Detection Sensor Matrix

	Direct Detection																						
Vehicle	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak Detection	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and Methane	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection System	Sonardyne Automatic Leak Detection Sonar (ALDS)	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak Detection
Atlas Elektronik SeaCAT	NR	2	1	3	2	2	2	1	2	NR	2	NR	2	3	1	NR	1	2	2	2	3	3	NR
BAE Systems Talisman L	NR	3	1	3	3	3	3	1	3	NR	3	NR	3	3	2	NR	1	3	3	3	3	3	NR
Bluefin Robotics Bluefin-9	NR	2	1	3	2	2	3	1	3	NR	3	NR	3	3	2	NR	1	2	2	3	3	3	NR
Bluefin Robotics Bluefin-9M	NR	2	1	3	2	2	3	1	3	NR	3	NR	3	3	2	NR	1	2	2	3	3	3	NR
ECA Robotics ALISTER 9	NR	2	1	3	2	2	3	1	3	NR	3	NR	3	3	2	NR	1	2	2	3	3	3	NR
Graal Tech Folaga	NR	2	1	3	2	2	3	1	3	NR	3	NR	3	3	2	NR	1	2	2	3	3	3	NR
Kongsberg Maritime REMUS 100/100-S AUV	NR	2	1	3	2	2	3	1	3	NR	3	NR	3	3	2	NR	1	2	2	3	3	3	NR
Ocean Server Iver2-580-EP (Expandable payload)	NR	2	1	3	2	2	2	1	3	NR	3	NR	2	3	2	NR	1	2	2	3	3	3	NR
Ocean Server Iver2-580-S	NR	2	1	3	2	2	2	1	3	NR	3	NR	2	3	2	NR	1	2	2	3	3	3	NR
Ocean Server Iver3-450 Nano	NR	2	1	3	2	2	2	1	3	NR	3	NR	2	3	2	NR	1	2	2	3	3	3	NR
Ocean Server Iver3-580-S	NR	2	1	3	2	2	2	1	3	NR	3	NR	2	3	2	NR	1	2	2	3	3	3	NR
QinetiQ Sea Scout	NR	2	1	3	1	1	2	1	2	NR	1	NR	1	2	1	NR	1	1	1	1	3	3	NR
Teledyne Gavia Defense AUV	NR	2	1	3	2	2	2	1	3	NR	2	NR	2	3	2	NR	1	2	2	2	3	3	NR
Teledyne Gavia Offshore Surveyor AUV	NR	2	1	3	2	2	2	1	3	NR	2	NR	2	3	2	NR	1	2	2	2	3	3	NR

Vehicle	Direct Detection																						
	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak Detection	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and Methane	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection System	Sonardyne Automatic Leak Detection Sonar (ALDS)	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak Detection
Teledyne Gavia Scientific AUV	NR	2	1	3	2	2	2	1	3	NR	2	NR	2	3	2	NR	1	2	2	2	3	3	NR
YSI EcoMapper	NR	2	1	3	1	1	2	1	3	NR	2	NR	2	3	1	NR	1	2	1	2	3	3	NR

Table 4-2: Man-portable AUV to Indirect Detection and Flow Sensor Matrix

	Indirect Detection															Flow Characterization	
Vehicle	**AADI Conductivity Sensor 4319**	**AADI Oxygen sensor 3830**	**AADI Seaguard O2**	**AADI Turbidity Sensor 4112**	**AML Oceanographic Smart CTD**	**CONTROS HydroC CO2 Carbon Dioxide Sensor**	**Sea & Sun Technology Conductivity Sensor**	**Sea Bird SBE 19plus V2 SeaCAT**	**Sea Bird SBE 25 plus Sealogger**	**Sea Bird SBE 49 FastCAT CTD sensor**	**Sea Bird SBE 911 plus; 917 plus**	**SeaPoint Sensors Turbidity Meter**	**Teledyne RD Instruments Citadel CTD CT-EK**	**Wetlabs WQM**	**YSI EXO Series**	**Sequoia LISST-Deep**	**4DEEP Inwater Imaging Submersible Microscope**
Atlas Elektronik SeaCAT	3	3	2	3	2	2	2	1	1	2	1	3	2	1	2	1	2
BAE Systems Talisman L	3	3	2	3	2	2	3	2	1	2	1	3	2	2	2	2	3
Bluefin Robotics Bluefin-9	3	3	2	3	2	2	3	1	1	2	1	3	2	1	2	1	3
Bluefin Robotics Bluefin-9M	3	3	2	3	2	2	3	1	1	2	1	3	2	1	2	1	3
ECA Robotics ALISTER 9	3	3	2	3	2	2	3	1	1	2	1	3	2	1	1	1	3
Graal Tech Folaga	3	3	2	3	2	2	3	1	1	2	1	3	2	1	2	1	3
Kongsberg Maritime REMUS 100/100-S AUV	3	3	3	3	2	2	3	1	1	2	1	3	2	1	2	1	3
Ocean Server Iver2-580-EP (Expandable payload)	3	3	2	3	2	2	3	1	1	2	1	3	2	1	1	1	2
Ocean Server Iver2-580-S	3	3	2	3	2	2	3	1	1	2	1	3	2	1	1	1	2
Ocean Server Iver3-450 Nano	3	3	2	3	2	2	2	1	1	2	1	3	2	1	1	1	2
Ocean Server Iver3-580-S	3	3	2	3	2	2	2	1	1	2	1	3	2	1	1	1	2
QinetiQ Sea Scout	3	3	1	3	1	1	2	1	1	1	1	3	1	1	1	1	1
Teledyne Gavia Defense AUV	3	3	2	3	2	2	2	1	1	2	1	3	2	1	2	1	2

	Indirect Detection															Flow Characterization	
Vehicle	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel CTD CT-EK	Wetlabs WQM	YSI EXO Series	Sequoia LISST-Deep	4DEEP Inwater Imaging Submersible Microscope
Teledyne Gavia Offshore Surveyor AUV	3	3	2	3	2	2	2	1	1	2	1	3	2	1	2	1	2
Teledyne Gavia Scientific AUV	3	3	2	3	2	2	2	1	1	2	1	3	2	1	2	1	2
YSI EcoMapper	3	3	2	3	2	2	2	1	1	1	1	3	2	1	1	1	2

4.3 Compatibility of LWV and HWV Class AUVs with Direct and Indirect Sensors

Table 4-3 and Table 4-4 assess the compatibility of the LWV and HWV Class AUVs identified previously in Section 3.1.2 with the direct and indirect oil detection sensors. As indicated in the tables, most of the direct and indirect detection sensors investigated are compatible as payloads for the LWV and HWV class of AUVs, with the HWV class vehicles exhibiting a greater ease of payload integration and capacity over the LWV class vehicles.

Table 4-3 rates one sensor for which there was limited information (the Chelsea Sub-Sea Pipeline Leak Detection System) as a “2” absorbing most of the payload volume. This sensor appears to be a combination of multiple sensors that are capable of directly detecting the presence of various HCs along with fluorescent dyes typically used in the industry. There were no readily available specific technical data related to size or weight but the literature discusses the ability of the system to detect multiple forms of HCs. The literature supplied with the Chelsea UV AQUAtracka states that this unit can detect either refined or crude HCs. It was assumed that the Leak Detection System would require two of these units to provide full range of HCs. These sensors do not mention an ability to detect the fluorescent dyes so it was then assumed the system would include at least one Chelsea UniLux sensor for this ability. This sensor also does not specifically state if it can sense a wide range or only a narrow range of frequencies, though the literature states that a range of wavelengths are available. Therefore, it was assumed that the system would require two specifically tuned sensors for each of the most common fluorescent dyes used in the industry. This would bring the total system weight to 13 kg and a size of 4 in x 8 in x 16 in. This would make this system about half the size but twice the weight of the WetLabs comparable sensor suite.

Most of the lightweight and heavyweight AUVs are built as modular, cylindrical or torpedo-like vehicles with a variable length payload section, and as such can accommodate significant payload customization. It is not uncommon for these vehicles to have sensor heads that protrude out of the payload section in order to better expose the sensor to the water flow around the vehicle. Also it is common practice for long, small diameter (<3 – 6″) sensors to be mounted directly onto the vehicle hull and to use foam and ballast as a method to trim the vehicle.

As an example, the larger of the direct and indirect oil detection sensors (listed below) can be made to fit within the diameter of the LWV class (12.75 in. diameter) with little or no protuberances or as an oversized section (e.g., 15 in. diameter) even in their cage type of packaging for use as a suspended profiling sensor. If the sensor is repackaged, greater clearance can be made:

- Contros Mobile Leak Detection System at 520 mm x 170 mm x 200 mm (20.5 in x 6.7 in x 7.9 in) and weight of 12.3 kg (27.1 lbs) in air / 9.2 kg (20.3 lbs) in seawater
- Sea Bird SBE 25 plus Sealogger at 305 mm x 279 mm x 965 mm (12 in x 11 in x 38 in) and a weight of 22.5 kg (50 lbs) in air
- Sea Bird SBE 911 plus/917 plus at 330 mm x 305 mm x 950 mm (13 in x 12 in x 37.4 in) and a weight of 12kg (26 lbs) in air / 7.3 kg (16 lbs) in water

It is likely in accommodating these large sensors that additional vehicle length inserts for foam and ballast may be needed to maintain neutral buoyancy and trim. As such for these vehicles, sensor integration becomes a trade-off of vehicle endurance due to increased drag from sensor protuberances or from trading potential battery storage volume for sensor payload volume.

While this class of AUV can accommodate these sensors, unless the AUV manufacturer has already developed the particular sensor-AUV combination of interest or something very similar as one of their catalog models, there will likely be some degree of NRE to be performed. This would be to optimize the AUV’s trim and balance and hydrodynamics to maximize endurance. The Lockheed Martin Marlin may be somewhat of an exception to this generality as it was developed with a discrete payload bay and does not rely on modular vehicle inserts for payload integration as it is not a torpedo-shaped vehicle.

Table 4-3: Light and Heavy Weight AUV to Direct Detection Sensor Matrix

Vehicle	Direct Detection																						
	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection	Sonardyne Automatic Leak Detection Sonar	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak
Bluefin Robotics Bluefin-12S	NR	3	2	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Bluefin Robotics Bluefin-12D	NR	3	2	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Bluefin Robotics Bluefin-21	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
CIRS Girona 500	NR	3	2	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ECA Robotics ALISTER 18 (high resolution and high coverage)	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ECA Robotics ALISTER 27 (multi-mission, long endurance)	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ECA Robotics ALISTER 18 TWIN	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Falmouth Scientific SAUV II	NR	2	1	3	2	2	2	1	2	NR	3	NR	2	2	3	NR	NR	3	2	3	3	3	NR
Kongsberg Maritime REMUS 600/600-S AUV	NR	3	2	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Kongsberg Maritime REMUS 6000	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Lockheed Martin Marlin MK1	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Saab Seaeye Eagle SAROV	**NR**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**NR**	**3**	**NR**	**3**	**3**	**3**	**NR**	**NR**	**3**	**3**	**3**	**3**	**3**	**NR**

Table 4-4: Light/Heavy Weight AUV and Indirect Detection/Flow Sensor Matrix

	Indirect Detection															Flow Characterization	
Vehicle	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel CTD CT-EK	Wetlabs WQM	YSI EXO Series	Sequoia LISST-Deep	4DEEP Inwater Imaging Submersible Microscope
Bluefin Robotics Bluefin-12S	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3
Bluefin Robotics Bluefin-12D	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3
Bluefin Robotics Bluefin-21	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
CIRS Girona 500	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3
ECA Robotics ALISTER 18 (high resolution and high coverage)	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3
ECA Robotics ALISTER 27 (multi-mission, long endurance)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ECA Robotics ALISTER 18 TWIN	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Falmouth Scientific SAUV II	3	3	2	3	2	2	2	1	1	2	1	3	3	1	2	1	2
Kongsberg Maritime REMUS 600/600-S AUV	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3
Kongsberg Maritime REMUS 6000	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Lockheed Martin Marlin MK1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Saab Seaeye Eagle SAROV	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

4.4 Compatibility of Large Displacement AUVs with Direct and Indirect Sensors

Table 4-5 and Table 4-6 assess the compatibility of the LWV and HWV Class AUVs identified previously in Section 3.1.3 with the direct and indirect oil detection sensors.

As indicated in the tables, the direct and indirect detection sensors evaluated are compatible as payloads for the large class of AUVs and do not pose significant challenges to the vehicle's cargo capacity. As this class of AUV's payload capacity greatly exceeds the sensor interface requirements it would be anticipated that the amount of NRE needed to accommodate these sensors would be minimal.

Table 4-5: Large Displacement AUV to Direct Detection Sensor Matrix

	Direct Detection																						
Vehicle	**ASD Sensortechnik BackScat I**	**Bowtech Leak Detection System**	**Chelsea Technologies Subsea Pipeline Leak Detection**	**Chelsea Technologies UniLux Fluorometer**	**Chelsea Technologies UV AquaTrack Fluorometer**	**CONTROS HydroC CH4 Hydrocarbon and Methane**	**CONTROS HydroC PAH Fluorometer sensor**	**CONTROS Mobile Leak Detection System**	**Hach FP 360 SC Oil-in-Water Sensor**	**Neptune Oceanographic SNIFFIT**	**Ocean Tools OceanSENSE Leak Detection**	**Phaze Hydrocarbon Leak Detector**	**Sea & Sun Technology UV Fluorometer**	**Seapoint UV Fluorometer**	**Smart Light Devices LDS3 Laser Leak Detection System**	**Sonardyne Automatic Leak Detection Sonar (ALDS)**	**Teledyne TSS MELDS System**	**TriOS enviroFlu-DS**	**TriOS enviroFlu-HC**	**Turner Designs C3 Submersible Fluorometer**	**Turner Designs Cyclops 6K customizable**	**Turner Designs Cyclops 7 customizable**	**Weatherford BigEars Passive Acoustic Leak Detection System**
Atlas Elektronik Sea Otter Mk II	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor IV (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor V (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor VI (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor II (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor III (HUGIN 4500 platform with integrated camera & side sonar)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ECA Robotics ALISTAR 3000	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ECA Robotics ALISTER REA (rapid enviro. assessment)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ISE Explorer	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Vehicle	Direct Detection																						
	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak Detection	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and Methane	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection System	Sonardyne Automatic Leak Detection Sonar (ALDS)	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak Detection System
Kongsberg Maritime HUGIN 1000; HUGIN 1000 for 3000 m	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Kongsberg Maritime HUGIN 3000	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Kongsberg Maritime HUGIN 4500	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Lockheed Martin Marlin MK2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Mitsui Engineering and Shipbuilding Aqua Explorer 2000	3	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Saab Seaeye AUV62-MR	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Woods Hole Sentry	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Table 4-6: Large Displacement AUV to Indirect Detection Sensor Matrix

	Indirect Detection															Flow Characterization	
Vehicle	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel CTD CT-EK	Wetlabs WQM	YSI EXO Series	Sequoia LISST-Deep	4DEEP Inwater Imaging Submersible Microscope
Atlas Elektronik Sea Otter Mk II	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor IV (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor V (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor VI (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor II (HUGIN 3000 platform with integrated payload packages)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies C-Surveyor III (HUGIN 4500 platform with integrated camera and side sonar system)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ECA Robotics ALISTAR 3000	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ECA Robotics ALISTER REA (rapid enviro. assessment)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ISE Explorer	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Kongsberg Maritime HUGIN 1000; HUGIN 1000 for 3000 m	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

	Indirect Detection															Flow Characterization	
Vehicle	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel CTD CT-EK	Wetlabs WQM	YSI EXO Series	Sequoia LISST-Deep	4DEEP Inwater Imaging Submersible Microscope
Kongsberg Maritime HUGIN 3000	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Kongsberg Maritime HUGIN 4500	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Lockheed Martin Marlin MK2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Mitsui Engineering and Shipbuilding Aqua Explorer 2000	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
Saab Seaeye AUV62-MR	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Woods Hole Sentry	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

4.5 Compatibility of Gliders with Direct and Indirect Sensors

Table 4-7 and Table 4-8 assess the compatibility of the glider class vehicles identified previously in Section 3.2 with the direct and indirect oil detection sensors. As indicated in the tables, there are several incompatibilities between the direct and indirect detection sensors evaluated and gliders.

The glider class of vehicles is generally very payload restrictive. The vehicles not only require neutral buoyancy but also an appropriate location for the buoyancy change that drives the vehicle. This arrangement along with the profile and the location of the fins makes the vehicle attain a certain nose angle when diving or surfacing. These relationships cause these vehicles to be very sensitive to external drag and major changes to overall vehicle dimensions. This being said, the two vehicles that appear to have the greatest flexibility are the two largest gliders: Bluefin Spray Glider and Exocetus Coastal Glider. However, even these two vehicles are unable to carry all of the sensors identified within this report. The first major factor that eliminates many sensors is the weight. The largest vehicle can still only manage to accommodate a payload weight of 5 kg. Several of these sensors exceed this limit and the vehicles do not have sufficient excess payload volume to compensate with foam as is typically done with the powered vehicles. The next limiting factor is the sheer size of some of the sensors. Again many of the powered vehicles can accommodate extended sections but gliders do not tend to permit this type of modification. This limits the maximum length of sensor unless it is externally mounted. These externally mounted sensors tend to stay fairly small, less than 5 cm diameter, so this combination rules out several more sensors for many of the smaller vehicles.

Table 4-7: Glider AUV to Direct Detection Sensor Matrix

	Direct Detection																						
Vehicle	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak Detection	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and Methane	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection System	Sonardyne Automatic Leak Detection Sonar (ALDS)	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak Detection System
ASCA SeaExplorer	NR	1	1	3	1	1	2	1	2	NR	1	NR	2	2	1	NR	NR	1	2	1	2	2	NR
Bluefin Robotics Spray Glider	NR	2	1	3	2	2	2	1	2	NR	2	NR	2	2	2	NR	NR	2	2	2	3	3	NR
Exocetus Coastal Glider	NR	3	2	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Konsberg 1KA Seaglider	NR	1	1	3	1	1	2	1	2	NR	1	NR	2	2	1	NR	NR	1	2	1	2	2	NR
Teledyne Webb Research Slocum Thermal Glider	NR	1	1	3	1	1	2	1	2	NR	1	NR	2	2	1	NR	NR	1	2	1	2	2	NR
Teledyne Webb Research G2 Slocum Glider	NR	1	1	3	1	1	2	1	2	NR	1	NR	2	2	1	NR	NR	1	2	1	2	2	NR
Teledyne Webb Research Slocum Electric Glider (aka Battery Glider)	NR	1	1	3	1	1	2	1	2	NR	1	NR	2	2	1	NR	NR	1	2	1	2	2	NR

Table 4-8: Glider AUV to Indirect Detection and Flow Sensor Matrix

	Indirect Detection															Flow Characterization	
Vehicle	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel CTD CT-EK	Wetlabs WQM	YSI EXO Series	Sequoia LISST-Deep	4DEEP Inwater Imaging Submersible Microscope
ASCA SeaExplorer	3	3	1	3	1	1	2	1	1	2	1	3	3	1	1	1	1
Bluefin Robotics Spray Glider	3	3	2	3	2	2	2	1	1	2	1	3	3	2	2	2	2
Exocetus Coastal Glider	3	3	3	3	3	3	3	2	1	3	1	3	3	2	2	2	3
Konsberg 1KA Seaglider	3	3	1	3	1	1	2	1	1	2	1	3	3	1	1	1	1
Teledyne Webb Research Slocum Thermal Glider	3	3	1	3	1	1	2	1	1	2	1	3	3	1	1	1	1
Teledyne Webb Research G2 Slocum Glider	3	3	1	3	1	1	2	1	1	2	1	3	3	1	1	1	1
Teledyne Webb Research Slocum Electric Glider (aka Battery Glider)	3	3	1	3	1	1	2	1	1	2	1	3	3	1	1	1	1

4.6 Compatibility of the Wave and Wind Powered ASVs with Direct and Indirect Sensors

Table 4-9 and Table 4-10 assess the compatibility of the Wave and Wind Powered vehicles identified previously in Section 3.3 with the direct and indirect oil detection sensors. As indicated in the tables, all of the direct and indirect detection sensors investigated are compatible as payloads for the Wave Glider and AutoNaut. Only the largest sensors are not compatible with the Saildrone restriction on surface mounted sensors.

The LRI Wave Glider mounts payloads to either the float or the submerged body. Float mounted sensors sample water near the surface while the submerged body location allows sampling at a depth of approximately 20 feet. The LRI website states that the following are the typical sensors and their locations:

- Float mounted sensors: ADCP, flourometer, wave sensor, acoustic modem
- Tether mounted sensors: temperature
- Submerged body mounted sensors: conductivity, dissolved O_2, hydrophone, fish tracker

Certain sensors rated as a “2” in Table 4-10 indicating that while they fit they are expected to occupy most of the available payload volume due to the overall sensor length and the fixed length of the sensor mounting points. It is possible that the sensor could be mounted in a configuration below the bottom and have unlimited length allocation with marginal impact to vehicle performance. Two of these sensors, SBE 911 and SBE 25, are of significant enough width to have some concern about disrupting the flow of water through the wings. It may be possible to repackage these sensors for higher packaging density and thus alleviating this concern. Additionally, as this vehicle is essentially a wave propelled version of a small ASV, it is conceivable to have payloads at a greater depth by suspending them from the submerged body. The additional water depth achieved would likely be modest due to limitations on overall vehicle power and buoyancy.

Table 4-9: Wave and Wind Powered ASVs to Direct Detection Sensor Matrix

	Direct Detection																						
Vehicle	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak Detection	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and Methane	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection System	Sonardyne Automatic Leak Detection Sonar (ALDS)	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak Detection System
Liquid Robotics Wave Glider SV2	NR	3	2	3	3	3	3	2	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Liquid Robotics Wave Glider SV3	NR	3	2	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
MOST AutoNaut	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Saildrone Saildrone	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR

Table 4-10: Wave/Wind Powered ASVs to Indirect Detection/Flow Sensor Matrix

Vehicle	Indirect Detection															Flow Characterization	
	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel CTD CT-EK	Wetlabs WQM	YSI EXO Series	Sequoia LISST-Deep	4DEEP Inwater Imaging Submersible Microscope
Liquid Robotics Wave Glider SV2	3	3	3	3	3	3	3	2	2	2	2	3	3	2	2	3	3
Liquid Robotics Wave Glider SV3	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
MOST AutoNaut	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
Saildrone Saildrone	3	3	2	3	3	3	3	3	1	3	1	3	3	2	3	3	3

4.7 Compatibility of Small and Large Class ASVs with Direct and Indirect Sensors

Table 4-11 and Table 4-12 assess the compatibility of the small ASVs identified in Section 3.4 with the direct and indirect oil detection sensors. As indicated in the tables, all of the direct and indirect sensors evaluated are capable of being used on most of the vehicles. The two most restrictive vehicles in this class are the USV-600 and USV-5000. The USV-600 has a very stable platform but has a low payload capacity which is unable to support several of the sensors. Conversely, the USV-5000 has sufficient payload capacity but with only a 0.5 meter beam and a self-righting design approach, there are potential stability concerns.

The majority of sensors are easily within the range for these vehicles. The two largest sensors mounted in a cage frame would occupy most of the payload for these vehicles. They would also contribute to monohull ASV instability. These vehicles can mount their payload to the float body which would allow water sampling at the surface (~1 to 2 foot depth). Two vehicles (USV-2600 and USV-5000) have optional sensor winch systems to allow for profiling at increased water depth, though the exact relationship between depth and allowable sensor weight is not readily discernible from the general information reviewed in this study.

Table 4-11: Small ASV to Direct Detection Sensor Matrix

	Direct Detection																						
Vehicle	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak Detection	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and Methane sensor	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection System	Sonardyne Automatic Leak Detection Sonar (ALDS)	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak Detection System
CMR Instrumentation Sailbuoy	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
EvoLogics Sonobot	NR	3	3	3	3	3	3	2	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Robotic Marine Systems Scout	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Sea Robotics USV-1000 High Speed Trimaran	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Sea Robotics USV-2600 Mission Reconfigurable USV (catamaran)	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Sea Robotics USV-450 Heavy Payload Catamaran	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Sea Robotics USV-5000 Self Righting Mono-Hull	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Sea Robotics USV-600 Mission Reconfigurable USV	NR	3	2	3	2	2	2	1	3	NR	3	NR	3	3	3	NR	NR	2	3	3	3	3	NR

Table 4-12: Small ASV to Indirect Detection Sensor Matrix

	Indirect Detection															Flow Characterization	
Vehicle	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel CTD CT-EK	Wetlabs WQM	YSI EXO Series	Sequoia LISST-Deep	4DEEP Inwater Imaging Submersible Microscope
CMR Instrumentation Sailbuoy	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
EvoLogics Sonobot	3	3	3	3	3	3	3	2	1	2	1	3	3	2	2	2	3
Robotic Marine Systems Scout	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
Sea Robotics USV-1000 High Speed Trimaran	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
Sea Robotics USV-2600 Mission Reconfigurable USV (catamaran)	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
Sea RoboticsUSV-450 Heavy Payload Catamaran	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3	3
Sea Robotics USV-5000 Self Righting Mono-Hull	3	3	2	3	3	3	3	3	1	3	1	3	3	2	3	3	3
Sea Robotics USV-600 Mission Reconfigurable USV	3	3	1	3	2	2	3	1	1	3	1	3	2	2	2	3	3

Table 4-13 and Table 4-14 assess the compatibility of the large ASVs identified in Section 3.4 with the direct and indirect oil detection sensors. As indicated in the tables, all of the direct and indirect detection sensors investigated are compatible as payloads for the large class of ASVs and do not generally pose challenges to the vehicle's cargo capacity.

These vehicles are large enough to carry a winch and tow-body or sensor cage to allow for profiling at different water depths. As this class of ASV's payload capacity greatly exceeds the sensor interface requirements it would be anticipated that the amount of NRE needed to accommodate these sensors will be minimal unless a specific adaptation needs to be made to support a tow-fish type of sensor deployment.

There are two sensors that heavily burden the smallest of vehicles in this class. The sensors are the largest sensors in the trade, Seabird SBE-911 and SBE-25, and would consume more than half of the available payload space. Unlike the smaller ASV class these sensors would not be expected to cause stability problems but would likely limit the number of additional sensors or the incorporation of a winch system to perform profiling.

Table 4-13: Large ASV to Direct Detection Sensor Matrix

	Direct Detection																						
Vehicle	ASD Sensortechnik BackScat I	Bowtech Leak Detection System	Chelsea Technologies Subsea Pipeline Leak Detection	Chelsea Technologies UniLux Fluorometer	Chelsea Technologies UV AquaTrack Fluorometer	CONTROS HydroC CH4 Hydrocarbon and Methane sensor	CONTROS HydroC PAH Fluorometer sensor	CONTROS Mobile Leak Detection System	Hach FP 360 SC Oil-in-Water Sensor	Neptune Oceanographic SNIFFIT	Ocean Tools OceanSENSE Leak Detection	Phaze Hydrocarbon Leak Detector	Sea & Sun Technology UV Fluorometer	Seapoint UV Fluorometer	Smart Light Devices LDS3 Laser Leak Detection System	Sonardyne Automatic Leak Detection Sonar (ALDS)	Teledyne TSS MELDS System	TriOS enviroFlu-DS	TriOS enviroFlu-HC	Turner Designs C3 Submersible Fluorometer	Turner Designs Cyclops 6K customizable	Turner Designs Cyclops 7 customizable	Weatherford BigEars Passive Acoustic Leak Detection System
ASV C-Enduro	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ASV C-Cat 5	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ASV C-Hunter	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ASV C-Worker	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
C&C Technologies ASV 6300 Hydrographic Survey Vehicle	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
C&C Technologies ASV 9500 Multi Role (semi-submersible)	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
C&C Technologies SASS-Q (semi-submersible)	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ECA Robotics INSPECTOR MK2 Imagery and Bathymetric Survey	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ISE Dorado (semi-submersible)	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
Maritime Robotics USV Mariner	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
QinetiQ Blackfish	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
SIEL Advanced Sea Systems UAPS 20: RHIB 750	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR

	Direct Detection																						
Vehicle	**ASD Sensortechnik BackScat I**	**Bowtech Leak Detection System**	**Chelsea Technologies Subsea Pipeline Leak Detection**	**Chelsea Technologies UniLux Fluorometer**	**Chelsea Technologies UV AquaTrack Fluorometer**	**CONTROS HydroC CH4 Hydrocarbon and Methane sensor**	**CONTROS HydroC PAH Fluorometer sensor**	**CONTROS Mobile Leak Detection System**	**Hach FP 360 SC Oil-in-Water Sensor**	**Neptune Oceanographic SNIFFIT**	**Ocean Tools OceanSENSE Leak Detection**	**Phaze Hydrocarbon Leak Detector**	**Sea & Sun Technology UV Fluorometer**	**Seapoint UV Fluorometer**	**Smart Light Devices LDS3 Laser Leak Detection System**	**Sonardyne Automatic Leak Detection Sonar (ALDS)**	**Teledyne TSS MELDS System**	**TriOS enviroFlu-DS**	**TriOS enviroFlu-HC**	**Turner Designs C3 Submersible Fluorometer**	**Turner Designs Cyclops 6K customizable**	**Turner Designs Cyclops 7 customizable**	**Weatherford BigEars Passive Acoustic Leak Detection System**
SIEL Advanced Sea Systems UAPS 20: RHIB 900	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR
ZyCraft Vigilant	NR	3	3	3	3	3	3	3	3	NR	3	NR	3	3	3	NR	NR	3	3	3	3	3	NR

Table 4-14: Large ASV to Indirect Detection Sensor Matrix

	Indirect Detection														Flow	
Vehicle	AADI Conductivity Sensor 4319	AADI Oxygen sensor 3830	AADI Seaguard O2	AADI Turbidity Sensor 4112	AML Oceanographic Smart CTD	CONTROS HydroC CO2 Carbon Dioxide Sensor	Sea & Sun Technology Conductivity Sensor	Sea Bird SBE 19plus V2 SeaCAT	Sea Bird SBE 25 plus Sealogger	Sea Bird SBE 49 FastCAT CTD sensor	Sea Bird SBE 911 plus; 917 plus	SeaPoint Sensors Turbidity Meter	Teledyne RD Instruments Citadel	Wetlabs WQM	YSI EXO Series	4DEEP Inwater Imaging Submersible
ASV C-Enduro	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3
ASV C-Cat 5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ASV C-Hunter	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ASV C-Worker	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies ASV 6300 Hydrographic Survey Vehicle (semi-submersible)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies ASV 9500 Multi Role (semi-submersible)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
C&C Technologies SASS-Q (semi-submersible)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ECA Robotics INSPECTOR MK2 Imagery and Bathymetric Survey	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ISE Dorado (semi-submersible)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Maritime Robotics USV Mariner	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
QinetiQ Blackfish	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3
SIEL Advanced Sea Systems UAPS 20: RHIB 500	3	3	3	3	3	3	3	3	2	3	2	3	3	3	3	3
SIEL Advanced Sea Systems UAPS 20: RHIB 750	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
SIEL Advanced Sea Systems UAPS 20: RHIB 900	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ZyCraft Vigilant	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

5.0 Remote Sensors and Surface Vessels

This section assesses surface oil sensors that are relevant and specific to generic manned surface vessels (boats, ships, etc.). This work builds upon Sections 2.0-4.0, which document a variety of direct and indirect detection technologies that can be used by autonomous underwater and surface vehicles. Such direct and indirect sensors are immersed and rely upon direct contact with the oil in the water. In this section, a variety of non-contact remote sensing technologies were investigated that detect the presence of oil on or near the surface of the water. These sensors must be mounted on surface vessels and therefore cannot be used in underwater vehicles. Other types of contact sensors (for direct and indirect detection) can also be used on manned or unmanned surface vessels, but these sensors have already been addressed in previous sections therefore this section does not include further discussion of contact sensors.

5.1 Remote Oil Detection Technologies

This section identifies a range of sensors with the capability to detect oil on or near the surface of the water from a surface vessel. These types of sensors generally use electromagnetic radiation to detect oil at a distance, thus not requiring direct contact with the oil in the water. Such remote sensors ideally would be able to detect, locate, and track oil on the surface of water under a wide range of operational conditions (e.g., sea state, weather, day/night).

In many cases, remote sensing technologies may be better suited for airborne platforms that allow downward or sideways view angles and sufficient altitude to observe a broad field of view. However, several remote sensing technologies can still provide value on surface vessels despite the restricted view angle and overall field of view. Therefore, this assessment is restricted to sensors that can operate within these constrained field of view parameters. Sensor technologies are considered that are currently available commercially and that are known to have been used on surface vessels for previous oil spill detection operations. These sensor systems are summarized in the following sections.

5.1.1 Ultraviolet Systems

Ultraviolet (UV) imagers are passive systems that can discriminate a layer of surface oil from the surrounding water. These sensors detect solar radiation at UV wavelengths (100-400 nm) that are reflected from the surface of the water, similar to visible cameras. Because oil is more reflective than seawater at these wavelengths, the sensor will detect an oil spill as a “bright” area in the field of regard, as shown in Figure 5-1. UV sensors can be used to map the extent of an oil spill under sufficient daylight and visibility conditions.

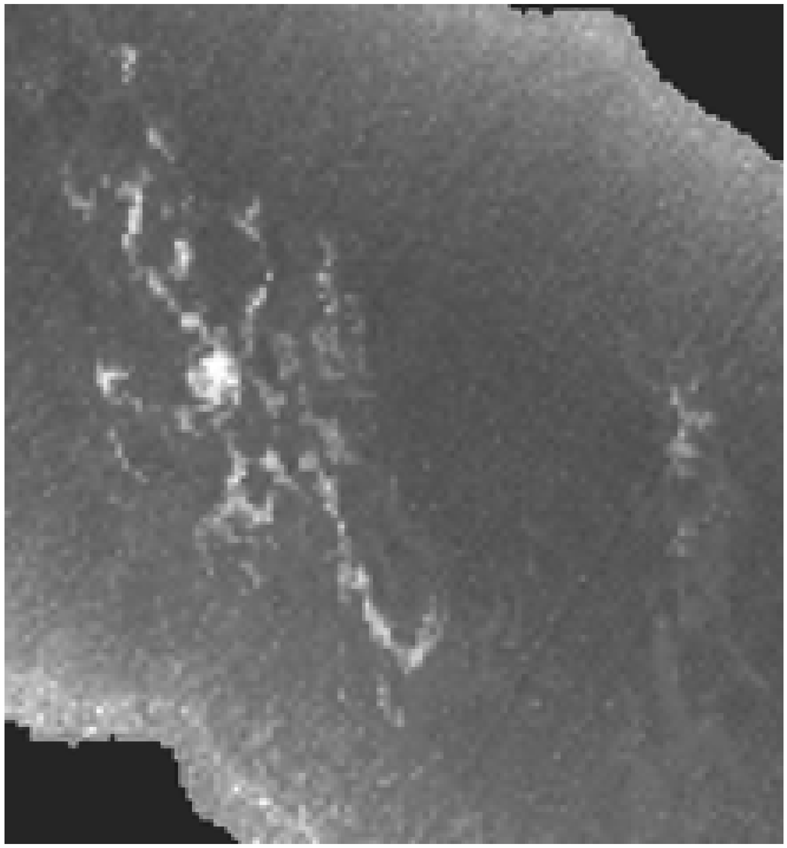

Figure 5-1: UV Image of Crude Oil on Water[1]

Commercial UV systems have been used to detect oil from a variety of operational platforms, including surface vessels. UV sensors are particularly advantageous because they can detect, in real time, thin oil sheen thicknesses (~ 0.01 µm) and therefore have very high sensitivity for detecting oil on water. In addition, the relative brightness of the imaged oil slick can provide information on the relative thickness. Emulsions are known to produce particularly strong UV scattering signatures. UV sensor technology is mature, commercially available, and relatively inexpensive.[2]

However, UV sensors have some limitations for remote sensing of oil on water. Because they require solar illumination, these sensors can operate only under daytime conditions. In addition, UV wavelengths are highly susceptible to scattering due to mist, fog, clouds, and rainfall, thus requiring good visibility conditions. Furthermore, numerous interferences, such as wind effects,

[1] SEOS; Marine Pollution, http://lms.seos-project.eu/learning_modules/marinepollution/marinepollution-c02-s18-p01.html (date accessed: 5 September 2014).

[2] Huang, L., Marini, L., Cazalas, R., Guillou, A., "Observation of marine pollution by hydrocarbons," Final Report from Euro Engineering to Total, File: EP1-11-90, February 2012.

sun glints, and biogenic materials, can produce false positive detections.[3] Therefore, confirmatory measurements are often required to ensure that the UV sensor has in fact positively detected oil.

UV cameras are typically used on aircraft platforms to detect surface oil spills; however they can be mounted on a surface vessel if installed on a mast or other structure at sufficient height above surface. The lateral detection range can be as much as 250-2000 m, depending on the associated optics and observational height, with a spatial resolution on the order of meters.

Individual UV cameras can range in price from a few hundred to tens of thousands of dollars, depending on the quality and complexity of the optics needed. In general, UV charge coupled device (CCD) cameras, such as those listed in Table 5-1 and shown in Figure 5-2, are readily available commercially, but remote sensing systems, which may require complicated quartz optics, are not. Researchers have previously integrated off-the-shelf UV cameras with remote viewing optical systems on a customized basis.

Figure 5-2: UV cameras from Sony (left), JAI (center), and Hamamatsu (right).

[3] Fingas, M. F., Brown, C. E., Review of Oil Spill Remote Sensing, *Proceedings of the Fifth International Conference on Remote Sensing for Marine and Coastal Environments,* Environmental Research Institute of Michigan, Ann Arbor, Michigan, 2000, pp. 211-218

Table 5-1: Representative Examples of UV Systems

Manufacturer / Sensor	Sensor Parameters									
	Technology	Size (mm)	Weight (kg)	Power	Resolution	User Interface	Data Output Interfaces	Cost ($)	Mounting	Integrated GPS
Sony XC-EU50 Monochrome CCD camera	UV camera	29x29x32	0.05	12 VDC	768x494 pixels	PC, monitor	Analog video output	$895	Hand held, tripod	No
JAI RM-6740GE	UV camera	51x51x85	0.194	12 VDC, 440 mA	640 x 480 pixels	PC	Gigabit Ethernet, analog		Hand held, tripod	No
Hamamatsu High Performance UV Digital camera C8484-16C	UV camera	47x47x50 (head), 65x65x 135 (control unit)	0.16 (head) 0.61 (control)	12 VDC, 8 VA	1344x1024 pixels	PC (RS-232C)	cameraLink digital output	>$1000	Benchtop	No

Note: table does not include dimensions or cost related to external optics that facilitate remote detection operation.

5.1.2 Visible Systems

The visible spectrum ranges from approximately 400 to 750 nm. Visible sensors, especially the human eye, are by far the most common sensors used to detect oil on water. Like UV sensors, visible sensors detect oil on water due to differences in absorption and reflection of solar radiation from objects, thereby creating visible contrasts that can be used to detect the oil. The appearance of oil on water is affected by many factors such as weather conditions, viewing angle, altitude, color of seawater, sun glint and cloud cover. As a result, a visual estimation of oil thickness is usually highly subjective. Despite these challenges, an oil appearance code was established through the Bonn Agreement for estimating oil layer thickness and volume per area that is widely accepted throughout the oil spill response community. The Bonn Agreement is a cooperation agreement of European North Sea states established to combat pollution in the North Sea from maritime disasters and pollution from ships and offshore installations. Table 5-2 lists the oil appearance code established by the Bonn Agreement.

Table 5-2: Bonn Agreement Oil Appearance Code4

Code	Description – Appearance	Layer Thickness Interval (µm)	Liters per km^2
1	Sheen (silvery/gray)	0.04 to 0.30	40 – 300
2	Rainbow	0.30 to 0.50	300 – 5000
3	Metallic	5.0 to 50	5,000 – 50,000
4	Discontinuous True Oil Color	50 to 200	50,000 – 200,000
5	Continuous True Oil Color	More than 200	More than 200,000

Limitations of visible sensors include daytime operation only, significantly degraded performance in bad weather conditions such as fog and rain, and susceptibility to false positives. False positives include cloud cover, algae blooms, wind shadows from landforms, surface wind patterns on the sea, surface dampening by submerged objects or weed beds, and biogenic oils.[5] It is helpful to have a trained operator when trying to identify oil slicks visually or estimate thicknesses although very little training is actually required to use the visible devices themselves.

There are several types of commercially available visible sensors that are useful for maritime oil detection and monitoring. These include binoculars, still cameras, and video cameras. A brief description of these devices is provided below along with some of their key features and limitations in regards to maritime oil spill detection and monitoring.

- Binoculars are small, cheap, and portable devices that are commonly used and highly effective for locating oil spills on water. Binoculars can significantly increase the viewing distance of the human eye, as can the zoom features in many digital still and video cameras. They are useful for any type of manned, above-surface oil detection and

[4] Bonn Agreement Aerial Operations Handbook Part 3, Annex A: Guidelines for Oil Pollution Detection, Investigation and Post Flight Analysis/ Evaluation for Volume Estimation, p. 11, 12 June 2009
[5] Fingas, M. F., Oil Spill Remote Sensing – Summary of the Series, ISCO Newsletter, Issue 320, February 2012, p. 7

monitoring mission whether by shore, surface vessel, or aircraft and are generally included in any response plan or response equipment. A wide range of magnifications and fields of view are available and some models are specifically designed for maritime applications. Sony offers digital recording binoculars that have many of the same features found on high end video cameras, although they currently cost around $2,000.

- Still cameras provide a quick, efficient method for documenting spills and providing situational awareness to response control centers and other decision makers. Key features can include a wide range of easily adjustable and swappable lenses to provide an optimal combination of magnification and field of view using high resolution optical zoom, image stabilization, and GPS with automatic geo-tagging. Their main limitation is that they are not very useful for detecting or locating spills compared to a pair of binoculars. In addition, automatic geo-tagging is usually only offered on higher end models that are priced in the thousands rather than the hundreds of dollars.
- Video cameras are useful for both oil spill detection and documentation. They can be used as either handheld devices and viewed on their liquid crystal display (LCD) screens or mounted to a pan and tilt system in a high location and viewed remotely. Key features can include both optical and digital zoom for enhanced viewing, image stabilization, and the ability to take still images for conveying information quickly. Limitations include a limited selection with automatic geo-tagging. In addition, mounted cameras require a ruggedized housing unless they are stowed away during bad weather and not in use.
- Action cameras are rapidly becoming more popular with the recent success of the GoPro cameras as well other models such as the Sony POV Action Cam. These video cameras are small, cheap, rugged, and wearable/mountable and are designed to be used in unusual or extreme conditions. Key features can include miniature size, rugged waterproof housings, numerous mounting accessories (tripods, grips, extension arms, head straps, suction cups, jaws clamps, etc.), image stabilization, Wi-Fi remote/smartphone control, and high definition video. Video can be viewed live using USB or HDMI connections. Limitations include limited GPS options and fixed optics designed for relatively short distances. Despite these limitations, action cameras can easily be included in a response go-kit and quickly mounted to the highest location on a vessel to provide a high up view when other cameras are unavailable or difficult to mount up high. Figure 5-3 shows an example of a GoPro image taken from the top of a 15-foot mast on a surface vessel.

Figure 5-3: Image taken from Go-Pro Video mounted on a 15 ft mast

Table 5-3 lists representative examples of visible sensors. Nikon offers a line of binoculars specifically designed for marine applications. Each model is waterproof and is filled with nitrogen gas and sealed with o-rings to minimize the effects of temperature changes such as fog and condensation. Additional features (depending on the model) include coated lenses to enhance image brightness, built-in compass to provide viewing direction, built-in scale allowing the observer to measure either object dimensions or object distance, polarizing filters to filter out light reflections from water, and horn-shaped rubber eyecup to shield eyes from peripheral light and provide a soft interface to face. The Canon EOS series of cameras has been one of the most popular series on the commercial market for several decades and offers a wide range of performance and features at prices ranging from $500 to $7,000.

None of these cameras have built-in GPS but several of them are compatible with Canon GPS receivers through either USB or hot shoe connections. The Canon GPS receivers provide GPS coordinates, direction, and time in EXIF data format. Automatic geo-tagging is supported by a few higher end, later models while manual geo-tagging after shooting is supported by all EOS digital cameras. The EOS series also offers a wide range of compatible lenses that include standard, wide angle, ultra-wide, telephoto, and super telephoto zoom. The EOS 5D Mark III listed in Table 5-3 is a high end camera that costs $3,400 without a lens but is one of the select few that supports automatic geo-tagging.

The GoPro Hero 3+ action camera comes with a waterproof housing and numerous mounting accessories. Although GoPro does not yet seem to offer integrated GPS or geo-tagging, these features are available on the Sony POV Action Cam. The Sony HDR-PJ540/B is a commercial quality digital video camera that is compact and portable. Useful features include high definition (HD) quality video, image stabilization, and a 30x optical zoom. FLIR offers an extensive line of hard mounted and hand held imagers designed specifically for maritime applications. The FLIR M-618CS is a hard mounted, high end system that features both a visible and IR camera along with a 2-axis, gyro-stabilized pan and tilt system.

Table 5-3: Representative Examples of Visible Sensors

Manufacturer/ Sensor	Sensor Parameters									
	Technology	Size (mm)	Weight (kg)	Power	Optics	User Interface	Data Output Interfaces	Cost ($)	Mounting	GPS
Canon EOS 5D Mark III	Still camera	152x116x 76	0.95	Rechargeable battery pack	63° to 107° diagonal (10-22 mm lens)	3.2 in. LCD Display	Memory card, USB, HDMI	3,400	Hand held or tripod mount	Automatic Geo-tagging with external GPS Receiver
FLIR M-618CS	Visible and Thermal IR*	178 (diameter) x291	5.2	12 – 24 V DC, 25 W nominal	18° x 14° FOV, 2x and 4x digital zoom	PC	Ethernet	40,000	2-axis, gyro-stabilized, 360° pan, +/- 90° tilt	No
GoPro Hero3+ Black	Video camera	216x180x 81	0.136 (with waterproof housing)	Rechargeable Li- Ion battery pack, USB power	37.2° x 125.3° FOV	PC (USB), TV (USB, HDMI), Wi-Fi, Attachable LCD screen (accessory)	Memory card, USB, HDMI	400	Tripod, Grip Mount, Extension Arm, Suction Cup, Head Strap, Jaws Mount	No
Nikon 7x50IF WP Compass	Binoculars	178x203	1.2	NA	7° FOV	Binoculars	NA	700	Hand held or tripod mount	No but has built-in compass
Sony HDR-PJ540/B	Video camera	62x67x12 1	325	Rechargeable battery pack	30x optical zoom	3 in. LCD touch screen	Memory card, USB, HDMI	700	Hand held or tripod mount	No

5.1.3 Infrared Systems

IR imaging technology is highly mature and used in a wide range of applications. As a result, a very large variety of IR imagers are commercially available. IR imagers can be categorized in many different ways and, as with visible sensors, there are far too many IR sensors available to discuss in detail. However, several discriminators can be considered to help in the selection for detecting oil on the water from a surface vessel:

- A long wave infrared (LWIR – 7 to 14 µm) imager should be selected rather than a short wave infrared (SWIR – 1 to 3 µm) or mid-wave infrared (MWIR – 3 to 5 µm) imager because peak thermal radiation intensity occurs in the LWIR.
- An uncooled imager should be selected rather than a cooled imager due to lower cost, less maintenance, and higher reliability. Cooled imagers can provide higher thermal resolution but uncooled imagers typically provide sufficient thermal resolution to detect oil on water.
- A staring imager should be selected rather than a scanning imager due to smaller size, less power consumption, lower cost, and higher reliability. Scanning imagers were developed in large part to increase the image field of view due to limitations with fabricating image arrays of sufficient size. Modern focal plane array (FPA) technology has eliminated this issue and FPAs can be fabricated in a wide range of sizes.

Two physical properties that thermal IR imagers exploit to reveal contrast between oil and water are emissivity and temperature. Emissivity is the ratio of energy radiated from a surface by an object to the energy radiated by a blackbody at the same temperature. Oil has a slightly lower emissivity than seawater, and therefore, it radiates less thermal energy than seawater at the same temperature. In conditions such as nighttime where the oil and water are at the same temperature, the oil will therefore appear cooler than water in an IR image. This difference in apparent temperature will depend largely on the difference in emissivity between the oil and water and also on the oil thickness. In the daytime under sunlight conditions, oil will typically retain more heat than seawater, thereby raising its temperature relative to the surrounding seawater and appearing warmer in an IR image. This difference in true temperature will depend on several variables such as the oil thickness and the relative differences in properties between the oil and seawater such as emissivity, thermal conductivity, and specific heat. Light oil sheens do not have enough thermal mass to retain additional heat while thick layers can reach temperatures up to 8 ºC above the surrounding water.[6] Most thermal IR imagers have sensitivities of 0.1 ºC or greater, and therefore a temperature difference of a few tenths of a degree or greater can be sufficient to detect oil in water.

Advantages of IR sensors include mature technology, a wide variety of commercially available products, daytime and nighttime operation, and a limited ability to measure relative oil thicknesses. IR sensors have moderate sensitivity for detecting oil on water, with an ability to detect oil thicknesses of 10 µm or greater. Disadvantages of IR sensors include degraded performance for oil-in-water emulsions, susceptibility to false positives, and degraded performance in low visibility conditions such as rain and fog. Emulsions typically contain 50 to

[6] Fingas, M. F., Oil Spill Remote Sensing – Summary of the Series, ISCO Newsletter, Issue 317, January 2012, p. 9

70% water and thus there is usually little temperature difference between the oil and water while the difference in emissivity is greatly reduced.[7] Sources of false positives include biogenic oils (kelp beds), upwellings, boat wakes, and river outflows that show up as thermal contrasts in the IR image.[8]

Figure 5-4 shows a thermal IR image of a clean-up ship in the Gulf of Mexico during the *Deepwater Horizon* spill response effort. This image was taken from an aerial video using a FLIR IR camera and shown on the May 28, 2010 CBS Evening News broadcast. In this image, the temperature range of the IR camera is configured to maximize the contrast between the warmer oil, which appears as an orange color temperature, and the cooler water, which appears as a pink color temperature. The ship appears as a glowing white object because it is hotter than the upper temperature range that is configured on the camera and is therefore saturated. The orange streaks indicate that the oil moving due to wind currents.

Figure 5-4: Aerial Image of Clean-Up Ship in the Deepwater Horizon Spill[9]

Table 5-4 lists several representative examples of thermal IR imagers. As mentioned for the visible sensors above, the FLIR M-618CS is a hard mounted, high end system that features both a visible and IR camera along with a 2-axis, gyro-stabilized pan and tilt system. The FLIR BHM-6XR+ is a hand held, thermal IR bi-ocular imager (Figure 5-5) and is offered with three different lenses for wide, standard, or telephoto view. The cost for this bi-ocular is $7,200 plus an

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[7] Fingas, M. F., Oil Spill Remote Sensing – Infrared, ISCO Newsletter, Issue 321, February 2012, p. 6
[8] Hover, G. L., Plourde, J. V., Evaluation of Infrared Sensors for Oil Spill Response Operation, June 1995, p. xv.
[9] https://archive.org/details/WJZ_20100528_230000_CBS_Evening_News_With_Katie_Couric#start/480/end/540

additional $2,000 to $5,500 depending on the lens selection. The InfraTec VariCAM HD Research 900 is a hand held, high end thermal IR camera that operates very similarly to a commercial video camera, including a 5.6 in. color LCD display for both viewing and playback and a 32x digital zoom. In addition, this camera has an integrated GPS receiver. The Jenoptik IR-TCM 640 is a hard mounted, high end thermal IR camera. This camera would need to be mounted on a pan and tilt system and would likely require an environmental enclosure to protect it from the elements. This camera was included because it has been tested for oil detection in water through aerial surveillance by Ocean Imaging Corporation and was used extensively as part of an oil detection and thickness measurement system during the *Deepwater Horizon* response operations in 2010.

Figure 5-5: FLIR BHM-6XR+ IR Bi-Ocular with Highlighted Features

Table 5-4: Representative Examples of Thermal IR Imagers

Manufacturer / Sensor	Sensor Parameters										
	Technology	Size (mm)	Weight (kg)	Power	FOV (°H x °V)	Temperature Resolution	User Interface	Data Output Interfaces	Cost ($)	Mounting	Integrated GPS
FLIR M-618CS	Visible and Thermal IR*	178 (diameter)x 291	5.2	12 – 24 V DC, 25 W nominal	18° x 14° FOV, 2x and 4x digital zoom	0.1 °C	PC	Ethernet	40,000	2-axis, gyro-stabilized, 360° pan, +/- 90° tilt	No
FLIR BHM-6XR+	Thermal IR	280x165x67 (w/o lens)	1.0 (w/o lens)	4-AA batteries (4-6 hours life)	18° x 13° FOV (35 mm lens), 2x and 4x digital zoom	0.1 °C	Color LCD display	Memory card, USB	9,200 – 12,700	Hand held	No
InfraTec VariCAM HD Research 900	Thermal IR	210x125x155	1.7	Rechargeable Li-Ion batteries (up to 3-hour life)	32.4° x25.6° FOV (30 mm lens), 32x digital zoom	0.05 °C	5.6 in. color LCD display, view finder	GIgE, DVI-D, C-video, RS-232, WLAN, USB 2.0, Bluetooth		Hand held	Yes
Jenoptik IR-TCM 640	Thermal IR	109 x 100 x 100 (w/o lens)	0.65 (w/o lens)	(9-24 V DC)	30° x 23° FOV (standard lens)	0.07 °C	PC	FireWire, S-/C-Video, VGA or RS-232 (Gig-E optional)	28,000	Pan and tilt	No

5.1.4 Radar Systems

Radar systems offer the potential of very long range, very wide field of view, and real-time detection of oil. Radars generate and detect pulses of radio frequency radiation, thereby classifying them as active sensors. Radars can discriminate oil from water based on the way the oil "absorbs" localized movement of waves at the surface. Normally, waves generate a radar return known as "sea clutter", which is suppressed in the presence of oil. Therefore, oil will appear as a "dark" region of the radar return because the cross section is smaller than for normal surface waves. Radar enables day/night operation due to its active nature and can operate under adverse weather conditions. Figure 5-6 shows a display of a typical radar output that has been analyzed for the presence of oil. Here, the radar signature of the oil is discriminated from the background clutter as highlighted in the area outlined in the NW quadrant.

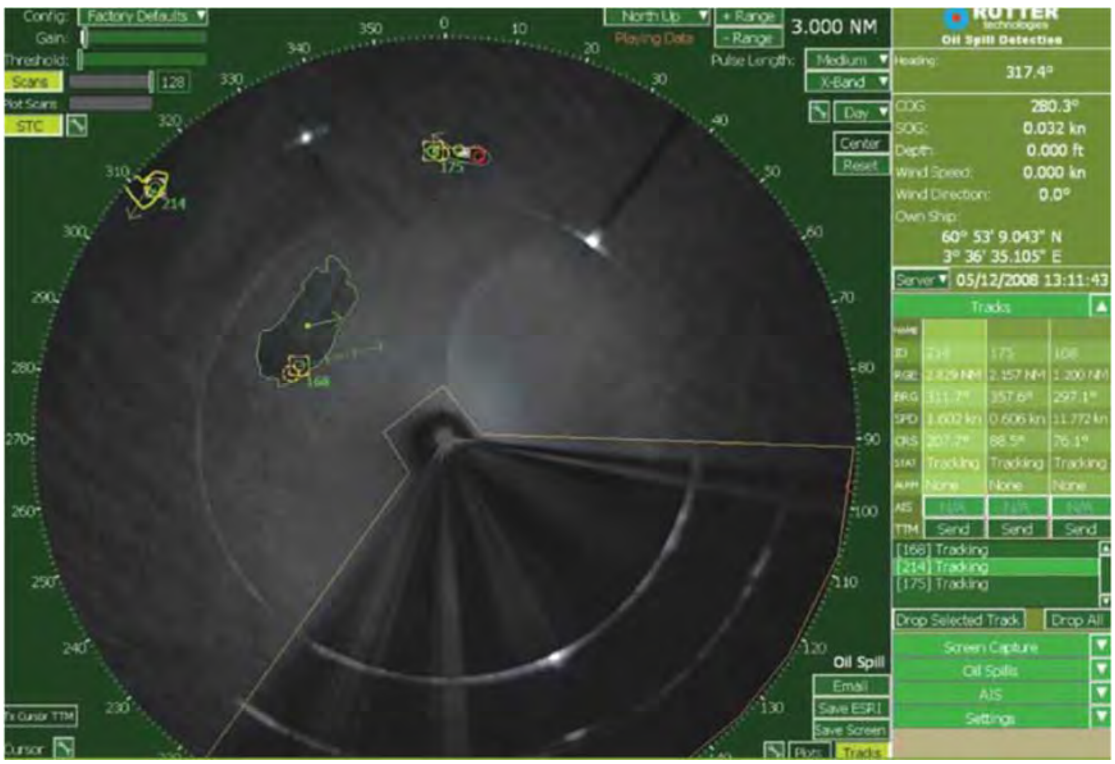


Figure 5-6: Radar Signature of Oil on Water[10]

Ship-board oil detection radar systems typically use X-band navigation radars already in place on many ships. These commodity radars are available from many companies and are commonly found on many larger surface vessels. A specialized backend data processing unit is required to analyze normal navigation radar signals for oil detection and mapping. The Miros OSTDR Radar System, shown in Figure 5-7, is an example of this type of unit. Processing units are available from a limited number of vendors, as listed in Table 5-5.

[10] "Detecting oil on water using microwave radar," from Port Technology International (www.porttechnology.org), Rutter Inc., St. Johns, Canada.

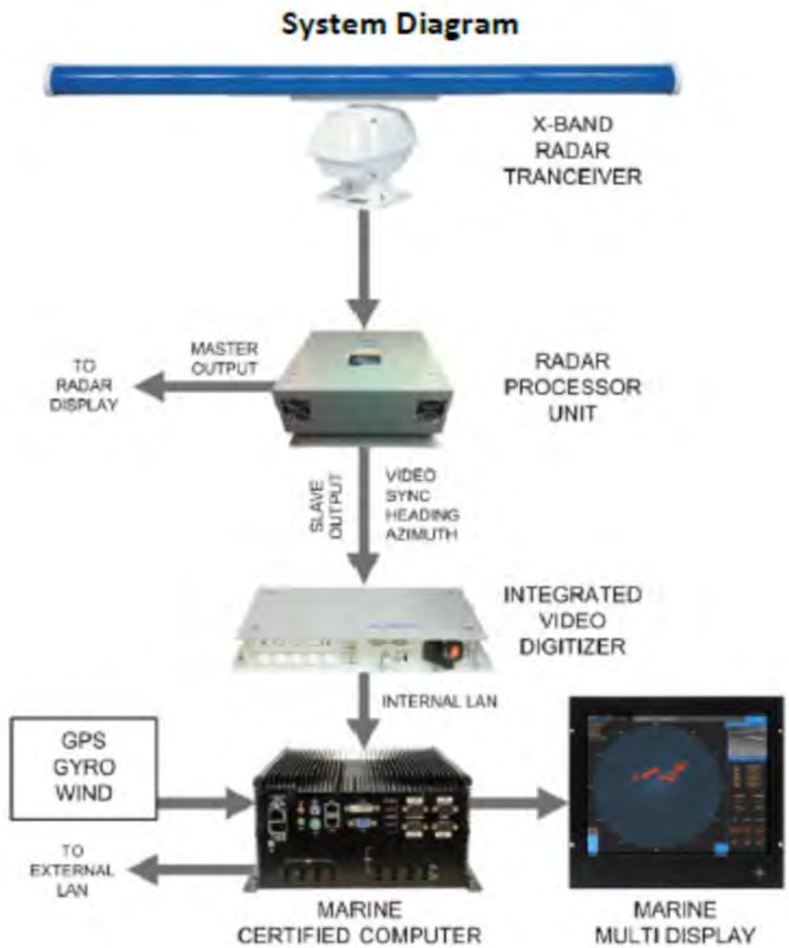


Figure 5-7: Component Diagram of Miros OSDTM Radar System[11]

While radars are generally unaffected by operational conditions such as clouds, rainfall, poor visibility, or day/night lighting, they do require the presence of a measurable "sea clutter", which is usually associated with wind speeds ranging from 1.5 m/s to 6 m/s. Below the lower end of this range, the "sea clutter" is too weak to discriminate many oil spills, and above this range the waves can become too large, dispersing the radar signal and blocking oil from detection. Radar systems also are subject to false positives because they cannot discriminate oil signatures from other naturally occurring phenomena (e.g., calm seas, biomaterials, etc.). Range is limited by radar height above the water surface as well as incidence angle and available horizon.

[11] MIROS OSDTM, Data Sheet, Miros AS, Asker, Norway.

Table 5-5: Representative Examples of Radar Systems

Manufacturer / Sensor	Sensor Parameters									
	Technology	Size	Weight (kg)	Power	FOV (°H x °V)	User Interface	Data Output Interfaces	Cost ($)	Mounting	Integrated GPS
Miros OSD™	X-band radar (with thermal IR)	6-8' X-band antenna		100-240 VAC	360 degree FOV, 2-7 km range	Maritime system computer, can operate unattended	Flat screen monitor, data export to 3rd party systems		X-band radar antenna mounted 15-80 m above sea level	Interface to external GPS
Rutter S6 OSD	X-band radar	8' X-band antenna	55 (antenna)			Maritime system computer, can operate unattended	ESRI shape file, AIS target and chart overlay		Rutter Radar-100S6 or other existing X-band radar	Interface to external GPS

5.1.5 Fluorescent LIDAR Systems

Oil can be detected in real time by LIDAR systems using UV lasers operating around 300-355 nm. The intense UV light from the laser induces a fluorescence signature from the oil but not water as shown in Figure 5-8. In general, the fluorescent return for oil is in the 420-480 nm range while many biological materials fluoresce at longer wavelengths (685 nm).[12] Therefore, fluorescent LIDAR enables better discrimination of oil from biomaterials than other sensing techniques. In addition, the sensitivity can be quite high (~1 ppm)[13] and thickness of the oil can be measured in a limited capacity (< 20 μm).[14] Because it is an active system, fluorescent LIDARs can operate during day or night and are not affected by cloud cover. However, these LIDAR systems are very complex and large (~1 m^3, 100-400 kg), consume relatively large amounts of power (1-5 kW), and are less mature and more expensive (~$1M) than passive imagers or radars. Only two companies are known to manufacture suitable LIDAR systems for fluorescent monitoring of oil on water.[15,16] In addition, efficacy of these systems on a surface vessel platform is not as well-established as those operating on an aircraft platform. Weather (rain, fog, mist) and water surface roughness can diminish performance, particularly in the measurement of the weak fluorescent return signature. Figure 5-9 shows an example of these types of systems, the FLS®-SUV ship-mounted LIDAR made by Laser Diagnostic Instruments.

[12] Hengstermann, T. and Reuter, R., Lidar fluorosensing of mineral oil spills on the sea surface. *Applied Optics* 29, 3218-3227 (1990).
[13] Babichenko, S., Dudelzak, A., Poryvkina, L., Laser remote sensing of coastal and terrestrial pollution by FLS-LIDAR, EARSeL eProceedings 3, 1-7 (2004)
[14] Lennon, M., Babichenko, S., Thomas, N., Mariette, V., Mercier, G., Lisin, A., Detection and mapping of oil slicks in the sea by combined hyperspectral imagery and laser-induced fluorescence. EARSeL eProceedings 5, 120-129 (2006).
[15] Laser Diagnostic Instruments. Product Data: FLS™-A (Airborne) LiDARs. Tallinn, Estonia; Product Data: Compact FLS®-SUV LiDAR.
[16] OPTIMARE Sensorsysteme AG. *Product: LFS Light*. Bremerhaven, Germany.

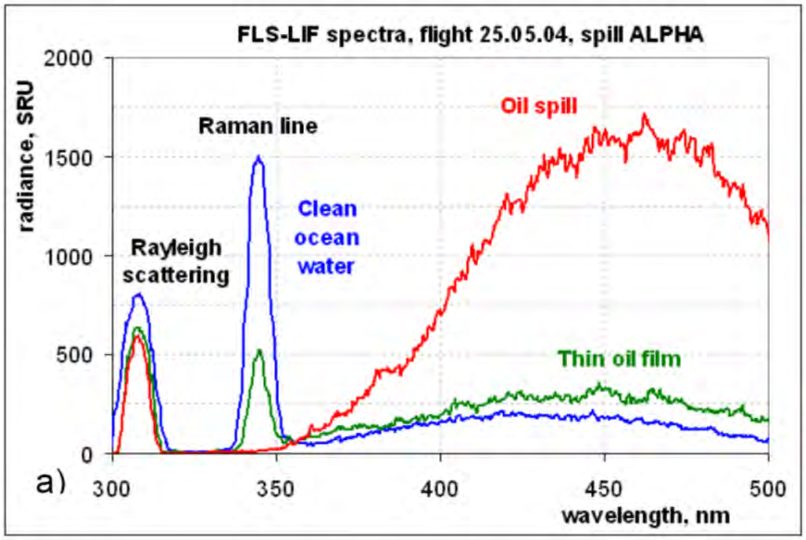


Figure 5-8: Example Spectra from LIF-based LIDAR System at 308 nm[17]

Figure 5-9: Ship-Mounted UV LIDAR System.

Table 5-6 provides examples of commercial fluorescent LIDAR systems. Given the custom nature of these systems, sufficient time must be devoted to the acquisition (6-12 month lead time) and integration of the system onto a surface vessel platform. Integrated GPS enables real time mapping of oil spills, and pre-set alarm thresholds enable real time decision-making or trigger of supplemental sensors, as needed.

[17] Lennon, M., Babichenko, S., Thomas, N., Mariette, V., Mercier, G., Lisin, A., Detection and mapping of oil slicks in the sea by combined hyperspectral imagery and laser-induced fluorescence. EARSeL eProceedings 5, 120-129 (2006).

Table 5-6: Representative Examples of Fluorescent LIDAR Systems

Manufacturer / Sensor	Sensor Parameters									
	Technology	Size	Weight (kg)	Power	FOV (°H x °V)	User Interface	Data Output Interfaces	Cost ($)	Mounting	Integrated GPS
AS Laser Diagnostic Instruments - Compact FLS®-SUV LiDAR	UV LIDAR	60x40x40 cm	40	300 VA	25m range	Unattended operation, PC GUI	Internal database, alarm system, external triggering, LAN		Mounting frame allows integration on open deck	Yes
Optimare Laser Fluorosensor Light	UV LIDAR	136x781x52 cm	120	28 VDC, 70 A	0.5 mrad beam divergence	Separate mission computer	Customizable, optical Ethernet		Originally developed for air platform, custom installation required for surface vessel	

5.1.6 Sensor Combinations

Combinations of sensor technologies are commonly used in oil detection missions to increase probability and reliability of detecting and mapping oil spills.[18] Often, sensor combinations take advantage of mutually exclusive benefits while mitigating mutually exclusive limitations. Several examples include:

- UV and IR: UV and IR systems used often in combination take advantage of optimal daytime (UV) and nighttime (IR) measurement conditions. In addition, each sensor type has different interferences,[19] and UV allows for detection of emulsions (which IR cannot do). Images obtained by both sensors can be produce maps of the spill that provide more reliable estimates of oil thickness. Figure 5-10 is an example of UV and IR images shown separately and overlaid.[20] The overlaid image provides more detailed information than the separate UV and IR images and enables the characterization of relative oil thickness.
- Radar and IR: These two sensor types are combined to reduce the false positives inherent in the long range radar measurements, providing preliminary confirmation of the presence of oil. The combination of the two data types also enables greater characterization of the oil, such as better estimates of extent or depth.[21]

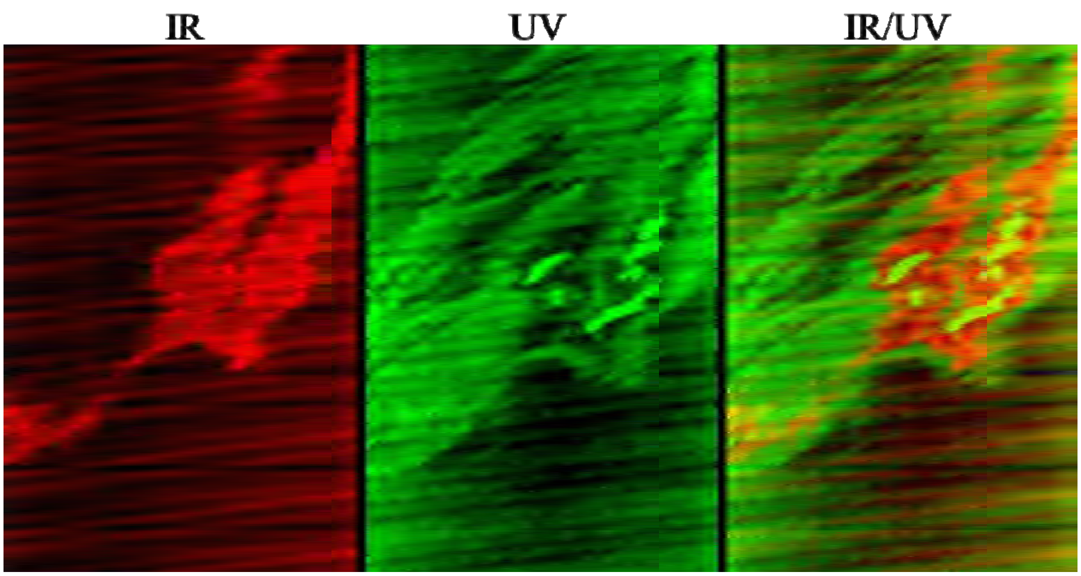


Figure 5-10: UV and IR Images Separate (left, center) and Overlaid (right)[22]

[18] "Remote Sensing in Support of Oil Spill Response: Planning Guidance," API Technical Report 1144 (Sept. 2013).
[19] M. Fingas, "Oil Spill Remote Sensing: A Review," Chevron Oil Spill Workshop, San Francisco, CA (Sept 1991).
[20] Huang, L., Marini, L., Cazalas, R., Guillou, A., "Observation of marine pollution by hydrocarbons," Final Report from Euro Engineering to Total, File: EP1-11-90, February 2012.
[21] Miros AS. Application Note DB-124_01: "Oil Spill Recovery using Miros OSD and Thermal Imager," Asker, Norway.
[22] OPTIMARE GMBH

5.2 Other Remote Sensors

Several other types of remote sensing technologies that are known to detect oil on the surface of water were not considered based on a variety of factors. In some cases, these sensors may have proven performance on an air platform but are inappropriate for shipboard operation. In other cases the technologies were either too immature or have not shown sufficient performance at this time. These systems, described below, are evaluated within the Total report.[23]

- Acoustic systems: Sonar sensors can be mounted on the hull of most surface vessels and can provide potential to detect oil remotely in the water column. Several sonar systems are commercially available and may be in use on many ships. However, acoustic systems frequently produce false positive detections and have not been recognized as reliable methods for oil detection.
- Hyperspectral imaging systems: These passive, multi-wavelength optical systems operate at visible through IR wavelengths and provide an additional spectral dimension to enable better discrimination or identification capabilities. To date, these systems have been deployed only on aircraft for oil detection, as they typically require optimal, stable imaging conditions available in a downward looking configuration. In addition, these sensors are expensive, complex, and available from only a few commercial providers.
- Microwave radiometers: While these passive microwave sensors provide day/night and all-weather operation, they have only been deployed on aircraft for oil detection missions. In addition, they are large, expensive systems that are available only from a small number of vendors.
- Backscatter LIDAR systems: These sensors typically are deployed on air platforms for bathymetry or surface terrain mapping. They can detect the presence of oil but have a high incidence of false positives and negatives. In addition, they are large, expensive, and available from few commercial providers.
- Laser ultrasonic systems: This experimental LIDAR technique offers potential for accurate oil thickness measurements. However, the systems are immature, very large and costly, not available commercially, and have been demonstrated only on air platforms.

5.3 Manned Surface Vessels

Numerous types of manned surface vessels may be available for oil detection operations, ranging from small boats to large ships and oil platforms. In general, the selection of an appropriate surface vessel platform to support oil detection activity depends on whether the vessel type can support the desired sensor(s) to be used. Therefore, the critical details of interest include whether the vessel can support the size, weight, and power requirements of the sensor as well as provide adequate elevation above the water surface (i.e., mast, A-frame, boom crane). In addition, and perhaps of highest priority, the range and duration that a vessel can be deployed for a given mission is critical. In many cases, long term monitoring or tracking may require larger vessels that can remain at sea for longer durations than smaller boats.

[23] Huang, L., Marini, L., Cazalas, R., Guillou, A., "Observation of marine pollution by hydrocarbons," Final Report from Euro Engineering to Total, File: EP1-11-90, February 2012.

For the purposes of the present assessment, we limited the assessment to vessels of opportunity that may be available in an area of operation. The U.S. Code of Federal Regulations (33 CFR 155.1020) defines a vessel of opportunity (VOO), also referred to as a ship of opportunity (SOO), as a "vessel engaged in spill response activities that is normally and substantially involved in activities other than spill response and not a vessel carrying oil as a primary cargo."[24] This is not to be confused with dedicated response vessels, for which "the service is limited exclusively to oil and hazardous substance spill response-related activities, including spill recovery and transport, tanker escorting, deployment of spill response equipment, supplies, and personnel, and spill response-related training, testing, exercises, and research."[25]

The types, numbers, and size of VOO/SOOs will vary with geographic area. In this study, discussions, descriptions, and examples focus on surface vessels available in the Gulf of Mexico (GOM) as representative of many different types of vessels. Assessments of remote oil detection sensors from VOO/SOO must consider whether they can fulfill certain requirements such as cruise/operational range, deck space, weight capacity, stability, height available for installation of sensor or observers, power available for the sensors, towing capacity, dynamic positioning and crane/winch capacities. When visual observers, radar, or optical based sensors are employed, vertical height improves the range and the incidence angle, allowing a larger area to be covered by a fewer number of VOO/SOOs. Bridge height and vessel length tend to correspond with longer vessels having higher bridges, suggesting that operators might select larger vessels for all applications. However, many commercial and recreational fishing/shrimping vessels tend to provide access to higher elevations to mount sensors and or employ observers disproportionate to their length. Workboats of similar length tend to lack the extended height observation platforms used in the fishing community. Table 5-7 lists illustrative examples of some of the VOO/SOO that are available in the GOM. Figure 5-11 shows several examples of commercial fishing and work boats, illustrating relative height above the water surface. In cases where additional power is needed, often an auxiliary generator can be temporary installed on deck. Similarly on boats with available deck space, temporary cranes and winches typically can be installed.

[24] http://www.gpo.gov/fdsys/granule/CFR-2012-title33-vol2/CFR-2012-title33-vol2-sec155-1020
[25] http://www.gpo.gov/fdsys/granule/CFR-2012-title33-vol2/CFR-2012-title33-vol2-sec155-1020

Table 5-7: Representative Ships of Opportunity in the Gulf of Mexico

Gulf of Mexico Ships of Opportunity						
Coast Guard Ship class	Subclass	Length (m)		Tonnage (GRT)	Approximate number of vessels	Description
		min	max			
Tank Vessels		226	458		4420 worldwide	Transport of crude oil
Passenger Vessels	Ferry		up to 75m			
	Cruise Ships	30	360	up to 225282	797 worldwide	Human transport
Oil rig service Cargo and Miscellaneous Vessels	Mini Supply	27	46	~100	Edison Chouest has over 200	Designed to move personal and supplies to and from oil rigs. Also used for towing and construction operations.
	Utility	30	38			
	Fast Supply	46	56			
	Platform Supply vessels	52	110	Up to 5000		
	Crew Boats	46	56			
	Geophysical surveys and seafloor mapping vessels	37	75	97 - 2065		Perform geophysical surveys
Uninspected Vessels	Recreational	no min	70+			Recreational privately owned to superyachts
	Fishing –Shrimp offshore	avg.	20	~100	1,578	
	Towing-Ocean		45	<1600	5200 (as of 2005)	
Oceanographic Vessels	None	27	91	100-2300		Research vessels designed to measure ocean science parameters

Figure 5-11: Shrimp Boat (left), Fishing Boat (center), and Work Boat (right)

When the sensor to be used is either to be towed or cast, the necessity of a high observation tower or sensor placement is negated while available deck space and appropriate crane or winch accessibility becomes more important. While some oil detection sensors are small enough to be supported through manual handling even a simple manual pulley lifting frame reduces risk. A-frame and boom cranes can be found on some work boats as small as 10 meters in length. This allows for a broader selection of boats that can be utilized for sensor operations.

5.4 Compatibility of Surface Vessels with Remote Sensors

Compatibility matrices, similar to those presented in Section 4.0, were not generated for remote sensors and surface vessels for two main reasons. First, it is difficult to define a straightforward and concise way to classify surface vessels due to the very broad range. Second, most surface vessel sensors have fairly simple vessel requirements (modest size, weight, and power) if any at all, and therefore, a matrix is not likely to convey much useful information. As an alternative approach, surface vessel attributes that would facilitate the available remote sensors were highlighted. This approach attempts to convey important surface vessel features to look for rather than trying to convey what type of surface vessels to use. Desirable surface vessel attributes for remote sensing include the following:

- Vessel size for crew safety – inflatable boats or boats with decks that sit right on the water (such as pontoon boats) are not suitable for oil spill response efforts due to the potential of exposure to crewmembers to hazardous HC constituents such as volatile organic compounds (VOCs) in the breathing zone.
- Integrated maritime cameras – maritime cameras (both visible and IR) are useful for a wide range of applications including law enforcement, search and rescue operations, anti-piracy, ice detection, and day/night collision avoidance for navigation. These cameras can be either handheld or mounted to the vessel. If mounted, it is desirable for them to have an integrated pan and tilt system for optimal viewing and extended coverage and an environmental housing for protection against the elements.
- Integrated ship radar – radars are common on many types of ships for navigation and collision avoidance. Some radar video processors may be suitable for oil detection while others may require a complementary processing system to be useful for oil detection.
- Available shipboard power – onboard power that can supply up to 100 W at 12 to 24 V DC is sufficient for most imaging systems that utilize a pan and tilt system and external display while handheld (battery charging) and fixed mounted imaging systems require less power. Active sensors, such as radars or LIDARs, may require additional power (if a radar is not already integrated).
- Sensor height – higher operating elevations are better for all above-surface sensors in terms of increased operating range, increased projected area, and improved sensor performance. Range and projected area both increase with height due to the increased sensor viewing angle. Sensor performance improves with increased viewing angles because the contrast between oil and water increases with imaging sensors and the amplitude of the return signal (and therefore the signal-to-noise) increases for active sensors such as radars and LIDARs.
- Internet connectivity – spill images and other critical sensor data should be provided expeditiously to the operational control center so that important response decisions can be made quickly. A satellite phone/data connection is therefore desirable for any ship traveling out of range of onshore cell towers or operating in remote locations. Alternatively, many satellite phone/data systems are highly portable and can be easily be set up on a ship if available and service is enabled. Onboard cellular equipment such as

signal amplifiers and cellular antennas that are mounted high are also desirable for operations that may remain within range of a cell tower.

5.5 Summary

A variety of remote sensing systems are available to detect and monitor oil remotely from surface vessels. These sensors include passive optical imagers operating at UV, visible, and IR wavelengths as well as active radar and UV LIDAR systems. Each type of sensor has distinct advantages and disadvantages with respect to oil detection and characterization. While each sensor may be integrated onto a variety of manned surface vessels, there are certain characteristics such as available power and mounting height that will impact the sensor's performance and operability. Individual combinations of sensors and surface vessels must be evaluated on a case-by-case basis for specific sensing requirements.

6.0 U.S. National Response Team Dispersant Guidance

In the response to the Deepwater Horizon event, dispersants were applied at unprecedented amounts and depths. Such atypical usage of dispersant was not included in previous planning documents, including the Special Monitoring of Applied Response Technologies (SMART) monitoring program.[26] Consequently, the U.S. National Response Team (NRT) developed a guidance document to address challenges associated with atypical dispersant operations.[27] The scope of this document includes guidance for monitoring subsea application (depths below 300 m and below the average pycnocline) and prolonged surface application (supplement to SMART program for operations beyond 96 hours from the first dispersant application).

While the NRT document does not impose regulatory requirements on oil development and production companies or impose Oil Spill Response Plan (OSRP) requirements, it can be used as a planning tool by each Regional Response Team (RRT), and as such is considered to be a "living document" subject to revision as new technologies or practices are identified. In this spirit, this section seeks to identify specific types of sensing technologies and vehicles that can help users to assess their options for atypical dispersant operations.

The objective of this section is to relate findings from the research on oil detection sensors and appropriate surface or underwater vehicles presented in Sections 2.0-5.0 to guidance provided by the NRT on atypical dispersant operation. The goal is to provide potential users with more detailed information on sensor and vehicle options as they relate to specific sensing requirements or practices described in the NRT report. The following two sections provide sensor and vehicle guidance for subsea and surface missions, respectively.

6.1 Subsea Monitoring Guidance

The NRT document outlines guidance for monitoring subsea dispersant operations, which were not addressed in the original SMART program. This guidance applies to subsea discharges at depths greater than 300 m and below the average pycnocline (i.e., deep ocean water in which vertical currents are effectively prevented). Subsea monitoring operations are broken down into four categories:

- Site characterization: includes estimates of discharge flow rates for the source oil and associated hydrocarbons (which determine dispersant type, delivery methods and equipment, injection rate, and duration).
- Source oil sampling: provides specific chemical data on the source oil and related materials, including collection and analysis of source oil, detection of dissolved methane, and estimation of rise rate of non-dispersed oil through the water column.
- Water sampling and monitoring: characterizes the fate and transport of the dispersed oil in the water column, incorporating oceanographic data, microbial oxidation (dissolved O_2 and CO_2), oil droplet size distribution, continuous monitoring of oil and conditions

[26] U.S. Coast Guard, National Oceanic and Atmospheric Administration, U.S. Environmental Protection Agency, Centers for Disease Control and Prevention, Minerals Management Service; "Special Monitoring of Applied Response Technologies," (August 2006).
[27] U.S. National Response Team; "Environmental Monitoring for Atypical Dispersant Operations," (May 30, 2013).

(conductivity, temperature, salinity) in the water column, and discrete sampling and analysis (GC-FID, GC-MS, UV/visible fluorescence, turbidity).

- Sediment sampling and monitoring: provides additional information on oil transport via sediment collection and laboratory analysis, as needed. Sediment sampling and monitoring is outside the scope of this report and is therefore not addressed further.

Based on these guidelines, the types of sensors investigated in this study that are relevant to subsea dispersant monitoring include the following:

- Non-dispersive infrared spectrometry for dissolved methane (CH_4): monitor CH_4 content in source oil (source oil sampling) and characterize biodegradation of CH_4 (water sampling and monitoring).
- Fluorometry: direct *in situ* detection of refined or crude hydrocarbons and polyaromatic hydrocarbons (source oil sampling, water sampling and monitoring).
- Underwater microscopy: determine the size distribution (water sampling and monitoring), quantities (source oil sampling), and velocity (site characterization) of the suspended oil in a very small sampled volume.
- Optical diffraction measurement: determine the size distribution (water sampling and monitoring), quantities (source oil sampling), and velocity (site characterization) of the suspended oil.
- Conductivity, temperature, and depth sensor: provides density characterization (site characterization, water sampling and monitoring), salinity (water sampling and monitoring), and other relevant oceanographic data (water sampling and monitoring).
- Optical light scattering for water turbidity: characterizes presence of suspended and undissolved material in water (water sampling and monitoring).
- Dissolved oxygen sensors (Clark-type electrode or optical): determines concentration of dissolved O_2 in water to indicate microbial oxidation (source oil sampling, water sampling and monitoring).
- Dissolved carbon dioxide NDIR sensors: determine concentration of dissolved CO_2 in water to indicate microbial oxidation (water sampling and monitoring).

Table 6-1 illustrates the correlation between specific sensors that fall within the sensor types listed above and the subsea dispersant sensing requirements. While these *in situ* sensors meet many of the dispersant monitoring requirements, some requirements, particularly those involving sample analysis in ship- or land-based laboratories, are not addressed by the listed technologies. In general, most of the sensors (or certain variants of these sensors) can be used at depths required for subsea monitoring (>300 m). Only the Wetlabs WQM and YSI EXO Series products are rated for less than 300 m depth, and therefore cannot be used for subsea dispersant monitoring.

The sensors described above may be used on a variety of autonomous underwater vehicles to meet the sensing needs described in the NRT guidance document. Two key criteria primarily define the applicability of these vehicles for subsea monitoring. First, the vehicle must be rated to operate at depths greater than 300 m, and second, the vehicle must have sufficient payload capacity and power to support the sensors' operation. Section 4.0 of this report assesses the applicability of multiple vehicle types with the various sensor types in question. Coupling these results with maximum depth capability yields the following guidance:

- Man-Portable AUVs: of the 11 vehicles assessed, only four are rated to operate at depths exceeding 300 m (Falmouth Scientific and three Teledyne vehicles). These four vehicles are capable of supporting most of the direct and indirect oil sensors, as shown in Table 4-1 and Table 4-2. Specific sensor selection would occur on a case-by-case basis to ensure that the compatible sensors meet performance requirements for specific missions.
- Light and Heavy Weight AUVs: of the eight vehicles assessed, five are rated to operate at depths exceeding 300 m (Bluefin-12D and Bluefin-21, ECA Robotics ALISTER 18, Kongsberg REMUS 600 and REMUS 6000). These vehicles are compatible with nearly all of the direct and indirect oil sensors shown in Table 4-3 and Table 4-4.
- Large Displacement AUVs: of the 15 vehicles assessed, all but two are rated (or have variants that are rated) to operate at depths exceeding 300 m. Both of these, the BAE Talisman M and ECA Robotics ALISTER 3000, are rated for exactly 300 m. All of the Large Displacement vehicles have sufficient capacity to support all sensors evaluated.
- Glider AUVs: of the seven gliders assessed, only one (Exocetus Coastal Glider) is not rated for operation below 300 m. However, as shown in Table 4-7 and Table 4-8, these vehicles can support approximately half (on average) of the sensors evaluated. If glider operation is needed, sensors will need to be selected on a case-by-case basis to meet specific performance requirements for the mission at hand.

Table 6-1: Sensors and Subsea Dispersant Monitoring Requirements

Sensor	Sensing Method	Target Measurement	Depth Rating (meters)	Site Characterization		Source Oil Sampling				Water Sampling and Monitoring						
				Discharge flow rate - source oil	Discharge flow rate – associated hydrocarbons	Source oil detection	Associated hydrocarbon detection	Dissolved methane detection	Rise rate of non-dispersed oil in. column	Oceanographic data	Dissolved O2	Dissolved CO2	Oil droplet size distribution	Continuous oil monitoring	Discrete oil sampling and analysis	Turbidity
4DEEP Inwater Imaging Submersible Microscope	underwater microscopy	flow rate, particle size	150, 6000 (option)	●	●								●			●
AADI Conductivity Sensor 4319	inductive cell	conductivity (salinity)	300, 2000, 6000							●						
AADI Oxygen sensor 3830	optode	oxygen conc., air saturation	6000								●					
AADI Seaguard O2	fluorescence	dissolved oxygen	300, 2000, 6000								●					
AADI Turbidity Sensor 4112		turbidity	300													●
AML Oceanographic Smart CTD	conductive cell, thermistor, strain gauge	conductivity temp, pressure, salinity (calc), density (calc)	500, 10000 (option)							●						
ASD Sensortechnik BackScat I	fluorometer	aromatic hydrocarbons	1500, 3000, 6000			●	●							●		
Bowtech Leak Detection System	fluorometer	hydrocarbons	3000			●	●							●		
Chelsea Technologies Subsea Pipeline Leak Detection	fluorometer	hydrocarbons	600, 6000			●	●							●		

Sensor	Sensing Method	Target Measurement	Depth Rating (meters)	Site Characterization		Source Oil Sampling				Water Sampling and Monitoring						
				Discharge flow rate - source oil	Discharge flow rate – associated hydrocarbons	Source oil detection	Associated hydrocarbon detection	Dissolved methane detection	Rise rate of non-dispersed oil in. column	Oceanographic data	Dissolved O2	Dissolved CO2	Oil droplet size distribution	Continuous oil monitoring	Discrete oil sampling and analysis	Turbidity
Chelsea Technologies UV AquaTrack Fluorometer	fluorometer	refined, crude hydrocarbons	600			●	●							●		
Chelsea Technologies UviLux Fluorometer	fluorometer	polyaromatic hydrocarbons	6000			●	●							●		
CONTROS HydroC CH4 Hydrocarbon and Methane sensor	NDIR	CH4	2000, 4000, 6000					●								
CONTROS HydroC CO2 Carbon Dioxide Sensor	NDIR	CO2	2000, 4000, 6000									●				
CONTROS HydroC PAH Fluorometer sensor	fluorometer	polyaromatic hydrocarbons	500, 2000, 4000, 6000			●	●							●		
CONTROS Mobile Leak Detection System	direct and indirect methods	CH4, polyaromatic hydrocarbons, CTD	2000			●	●	●		●				●		
Hach FP 360 SC Oil-in-Water Sensor	fluorometer	polyaromatic hydrocarbons				●	●							●		
Neptune Oceanographic SNIFFIT		CH4	2000					●								

Sensor	Sensing Method	Target Measurement	Depth Rating (meters)	Site Characterization		Source Oil Sampling				Water Sampling and Monitoring						
				Discharge flow rate - source oil	Discharge flow rate – associated hydrocarbons	Source oil detection	Associated hydrocarbon detection	Dissolved methane detection	Rise rate of non-dispersed oil in. column	Oceanographic data	Dissolved O2	Dissolved CO2	Oil droplet size distribution	Continuous oil monitoring	Discrete oil sampling and analysis	Turbidity
Ocean Tools OceanSENSE Leak Detection	fluorometer	hydrocarbons	3000			●	●							●		
Phaze Hydrocarbon Leak Detector		hydrocarbons	4000			●	●							●		
Sea & Sun Technology Conductivity Sensor		conductivity (salinity)	500							●						
Sea & Sun Technology UV Fluorometer	fluorometer	polyaromatic hydrocarbons	500, 2000			●	●							●		
Sea Bird SBE 19plus V2 SeaCAT	internal platinum electrode, thermistor, precision quartz crystal resonator, strain gauge	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	600, 7000 (option)							●						
Sea Bird SBE 25 plus Sealogger	internal platinum electrode, thermistor, strain gauge	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	6800							●						
Sea Bird SBE 49 FastCAT CTD sensor	conductivity cell, thermistor, strain gauge	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	250, 7000 (option)							●						

Sensor	Sensing Method	Target Measurement	Depth Rating (meters)	Site Characterization		Source Oil Sampling				Water Sampling and Monitoring						
				Discharge flow rate - source oil	Discharge flow rate – associated hydrocarbons	Source oil detection	Associated hydrocarbon detection	Dissolved methane detection	Rise rate of non-dispersed oil in. column	Oceanographic data	Dissolved O2	Dissolved CO2	Oil droplet size distribution	Continuous oil monitoring	Discrete oil sampling and analysis	Turbidity
Sea Bird SBE 911 plus; 917 plus	conductivity cell, thermistor, precision quartz crystal resonator	conductivity, temp, pressure, salinity (calc), density (calc), sound velocity (calc)	10500							●						
SeaPoint Sensors Turbidity Meter	optical light scatter	turbidity	6000													●
Seapoint UV Fluorometer	fluorometer	crude oil	6000			●								●		
Sequoia LISST-Deep	optical diffraction	flow rate, particle size	3000	●	●								●			●
Smart Light Devices LDS3 Laser Leak Detection System	fluorometer	hydrocarbons	3000			●	●							●		
Sonardyne Automatic Leak Detection Sonar (ALDS)	ultrasonic	hydrocarbons				●	●							●		
Teledyne RD Instruments Citadel CTD Products	inductive cell, thermistor, silicon	conductivity, temperature, pressure	500, 7000 (option)							●						
Teledyne TSS MELDS System	fluorometer	CH4, polyaromatic hydrocarbons, CTD	3000			●	●	●		●				●		
TriOS enviroFlu-DS	fluorometer	polyaromatic hydrocarbons	6000			●	●							●		

Sensor	Sensing Method	Target Measurement	Depth Rating (meters)	Site Characterization		Source Oil Sampling				Water Sampling and Monitoring						
				Discharge flow rate - source oil	Discharge flow rate – associated hydrocarbons	Source oil detection	Associated hydrocarbon detection	Dissolved methane detection	Rise rate of non-dispersed oil in. column	Oceanographic data	Dissolved O2	Dissolved CO2	Oil droplet size distribution	Continuous oil monitoring	Discrete oil sampling and analysis	Turbidity
TriOS enviroFlu-HC	fluorometer	polyaromatic hydrocarbons	300, 6000			●	●							●		
Turner Designs C3 Submersible Fluorometer	fluorometer	crude, fine oil	600			●								●		
Turner Designs Cyclops 6K customizable	fluorometer	crude, fine oil; turbidity	6000			●								●		●
Turner Designs Cyclops 7 customizable	fluorometer, optical scatter	crude, fine oil; turbidity	600			●								●		●
Weatherford BigEars Passive Acoustic Leak Detection System	acoustic			●	●											
Wetlabs WQM	thermistor, fluorometer, others	conductivity, temperature, pressure, dissolved O2, turbidity	200							●	●					●
YSI EXO Series		conductivity, temperature, pressure, dissolved O2, turbidity	250							●	●					●

6.2 Surface Monitoring Guidance

The NRT document outlines guidance for monitoring prolonged application of dispersant on the surface of the water. In this case, “prolonged” is defined as exceeding 96 hours from first application of dispersant. In general, surface operations are addressed by the original SMART document, however operations with extended duration, such as the *Deepwater Horizon* event, are not. The NRT document defines three key recommendations for surface monitoring:

- SMART protocols: assumes that SMART protocols are followed from the beginning of dispersant operations. Additional guidance related to extended duration is meant to supplement these protocols, which are classified into three tiers:
  - Tier I: Visual Observations – trained observer provides qualitative assessment of dispersant effectiveness, with assistance from still or video cameras and in some cases infrared imagers (as needed).
  - Tier II: On-Water Monitoring for Efficacy – real-time monitoring and water sampling is conducted near the surface (1-2 m). Monitoring must include background water (no oil), surface oil prior to dispersant application, and surface oil after treatment. Methods may include direct, in situ monitoring and continuous sample acquisition for on-board analysis.
  - Tier III: Additional Monitoring – a broader set of monitoring is conducted within the water column, as needed, to verify oil is diluting toward background levels. Specific activities include monitoring at multiple depths (down to 10 m), transecting the slick while monitoring at two depths (usually 1 and 5 m), and measuring additional water parameters (temperature, conductivity, dissolved O_2, pH, and turbidity).
- Assessment of potential dispersibility of oil: addresses weathering effects of oil, which can affect viscosity and degrade performance of dispersants. The objective is to identify and target only areas of the spill that would be susceptible to dispersants, saving resources and reducing dispersant applications by not targeting areas that are not susceptible due to weathering. Evaluations are based primarily on visual characteristics (visible and IR) as learned through laboratory weathering studies and field experience.
- Water column loading and assessment: provides additional information on how the oil is dispersing through the water column. Monitoring is expected to occur 24 hours after dispersant application to understand how the water column is impacted. Methods follow those described in SMART Tier III, with specific emphasis placed on fluorometric and particle size data for *in situ* monitoring and GC-FID or GC-MS for on-board or laboratory sample analysis.

Based on these guidelines, surface, direct, and indirect oil detection systems are relevant to prolonged surface dispersant monitoring. For surface sensing, the following sensors should be considered:

- Visible systems: both still and video cameras operating at visible wavelengths are specifically mentioned in the Tier I SMART protocols and in the assessment of potential dispersibility of oil as an aid to human observers and as a means to document their conclusions. These types of sensors are readily available and sufficiently small such that they can be integrated and used on any surface vessel platform.

- Infrared systems: also specifically mentioned in the Tier I SMART protocols and in the assessment of potential dispersibility of oil, these sensors serve as an adjunct to human observation and to provide expanded capability. IR imagers are also readily available and can be used on any surface vessel platform.
- Ultraviolet (UV) systems: while not mentioned specifically in the NRT surface monitoring guidance, passive UV cameras may provide value through their ability to detect thin sheens of surface oil and emulsions. In addition, their ability (generally in concert with IR systems) to map the extent and relative thickness of surface oil can be beneficial to dispersant application targeting. Like the other passive optical systems, UV cameras are sufficiently small for integration onto any surface vessel platform.
- Radar systems: although they provide the best detection range and all-weather operability, radar systems are not as useful as other systems for identifying and characterizing oil as recommended in the aforementioned guidance. Radars are beneficial for locating and tracking a spill, but often require another sensing modality to confirm or characterize the spill. Systems that are used for oil detection typically leverage ubiquitous X-band navigation radars, which can be integrated onto all but the smallest unmanned surface vessels.
- Fluorescent LIDAR systems: despite their potential for excellent detection and characterization performance, fluorescent LIDAR systems typically are too large, complex, and costly for use on most surface vessels. Most require special integration and resources that may not be readily available in the short time scales required of immediate response to a spill.

In addition to these surface detection systems, a variety of direct and indirect contact sensors that are discussed in the subsea monitoring section above are relevant to prolonged surface monitoring. These sensors can be used on surface vessels, either affixed to the hull or tethered, to monitor and characterize the oil near the surface and at a variety of depths. Specifically:

- Fluorometry: provides direct *in situ* detection to address SMART Tier II and III as well as assessments of potential dispersibility and water column loading of treated and non-treated oil. Fluorometers are specifically mentioned in the prolonged surface monitoring guidance and can be used on all types of surface vessels.
- Underwater microscopy: can determine oil droplet size distribution, as specifically mentioned in the water column loading and assessment guidance.
- Optical diffraction measurement: can determine oil droplet size distribution, as specifically mentioned in the water column loading and assessment guidance.
- CTD sensor: characterizes necessary water properties, as mentioned specifically in SMART Tier III guidance, particularly if tethered to access a variety of depths.
- Optical light scattering for water turbidity: characterizes presence of suspended and undissolved material in water, as required by SMART Tier III guidance.

- Dissolved oxygen sensors (Clark-type electrode or optical): determines concentration of dissolved O_2 in water as required by SMART Tier III guidance.

6.3 Summary

Based on the subsea and prolonged surface monitoring guidance provided in the NRT document and in the SMART protocols, numerous combinations of sensors and vehicles can be exploited to meet dispersant monitoring mission requirements. General conclusions of this assessment include the following:

- Subsea monitoring
  - Many of the evaluated sensors can address key elements of the NRT subsea guidance.
  - Operation at depths greater than 300 m is the critical issue that defines applicability of sensors and underwater vessels.
  - Most direct and indirect detection systems can be coupled with larger AUVs (Light and Heavy Weight AUVs, Large Displacement AUVs) that are rated for operation below 300 m depth.
  - Smaller AUVs (Man-Portable, Glider) do not provide as much flexibility as larger AUVs with respect to depth and payload capacity; sensor/vessel combinations should be evaluated on a case-by-case basis in the context of specific mission requirements.
- Prolonged surface monitoring
  - Passive optical imagers (ultraviolet, visible, infrared) meet specific NRT and SMART monitoring guidelines and can be integrated onto any surface vehicle.
  - Certain types of direct (fluorometer) and indirect (CTD, particle size, turbidity, dissolved O_2) sensors meet specific NRT and SMART monitoring needs and can be integrated on the hull or tethered to any surface vessels (manned or unmanned).

7.0 Spill Scenario Priority Recommendations

Having evaluated a range of contact and remote sensors as well as underwater and surface vessels, the following section applies this knowledge to five credible oil spill scenarios in which these assets might be deployed. Combinations of sensors and vehicles were prioritized according to their compatibility as well as their relevance to the scenario under consideration. Prioritization also considered operational limitations of conducting emergency response operations and the availability of the proposed sensors and deployment of vehicles within relevant timeframes.

7.1 Spill Scenarios

Battelle evaluated combinations of vehicles and sensors to predict relative probability of success in detecting and monitoring oil according to the following five OSR-JIP spill scenarios:

- Release at a coastal terminal (Scenario 2)
- Oil tanker in transit offshore (Scenario 3)
- Offshore oil platform – both surface and subsurface accidental releases of finite amount (Scenario 4)
- Offshore pipeline rupture (Scenario 5)
- Deepwater well blowout – Macondo-type continuous release (Scenario 6)

The parameters associated with each credible spill scenario are summarized in Table 7-1. In establishing each scenario, parameters were generalized based on spill data reported by organizations and agencies such as ITOPF[28], CEDRE[29], UNEP[30], BOEM[31], USCG[32] and other Internet resources, and included factors such as spill location, depth, size and duration. General considerations used to help define these parameters included the following:

- Tanker spills tend to occur either when a tanker grounds (shallow water near the coast) or because of another vessel or platform collision.

[28] Case Studies, The International Tanker Owners Pollution Federation Limited (ITOPF), http://www.itopf.com/in-action/case-studies/

[29] Centre of Documentation, Research and Experimentation on Accidental Water Pollution (CEDRE), http://www.cedre.fr/en/spill/spill-area.php.

[30] Accidental Discharges of Oil, Global Marine Oil Pollution Information Gateway, United Nations Environment Programme, http://oils.gpa.unep.org/facts/oilspills.htm.

[31] *Update of Occurrence Rates for Offshore Oil Spills*, Bureau Ocean Energy Management, OCS Report BOEM 2012-069, June 2012, http://www.boem.gov/uploadedFiles/BOEM/Environmental_Stewardship/Environmental_Assessment/Oil_Spill_Modeling/AndersonMayesLabelle2012.pdf

[32] Polluting Incidents In and Around U.S. Waters, A Spill/Release Compendium: 1969 – 2011, United States Coast Guard (USCG), December 2012, https://homeport.uscg.mil/mycg/portal/ep/contentView.do?contentTypeId=2&channelId=-18374&contentId=120051&programId=91343&programPage=%2Fep%2Fprogram%2Feditorial.jsp&pageTypeId=13489

- Most oil platforms are less than 200 km from an operating base, with fewer in the 200-400 km range, and almost none beyond that.
- Pipelines most likely to fail are the older ones and these are located in relatively shallow water.
- The depth of the deepwater Macondo-type well blowout was selected at 2,000 m to capture the ultra-deepwater combination of vehicles and sensors.

Table 7-1: Spill Scenario Parameters

Scenario	Distance From Shoreline (km)	Spill Depth Below Ocean Surface (m)	Total Oil Spilled (kt)	Spill Area (km^2)	Potentially Affected Shoreline (km)	Oil Spill Release Duration (days)
Release at a Coastal Terminal (Scenario 2)	1	0	1	1	5	1
Oil Tanker in Transit Offshore (Scenario 3)	25	10	10	10,000	1,000	10
Offshore Platform Release (Scenario 4)	50	0 & 300	2	10	0	1
Offshore Pipeline Rupture (Scenario 5)	50	50	1	10	0	5
Deep Water Well Blowout (Scenario 6)	100	2,000	1,000	200,000	2,000	100

Priority ratings would vary according to the type of HC spilled. For example, due to different physical, chemical and weathering characteristics, the prioritizations in each scenario would be different for gaseous HC compared with liquid HC, crude oil compared with refined products, waxy crude compared with asphaltene crude, and so on.

In the scenarios considered below, the HC spilled is postulated to be a light sweet crude. This grade of oil is described as light because of its relatively low density, and sweet because of its low sulfur content. Because it is lighter than seawater, a spill is more likely to rise to the surface than sink to lower depths. Therefore, it is assumed for these illustrative spill scenario priority ratings that the oil would be present somewhere between the spill depths listed in Table 7-1 and the water surface. This has significant consequences for vehicle prioritization since the use of AUVs is considered unnecessary below the spill depth while surface vessels are considered to be important in each scenario. It should also be noted that for surface spills in this case, subsea sensors are assumed to be useful for monitoring at only shallow depths below the seawater surface.

7.2 General Considerations for Sensors, Vehicles, and Spill Scenarios

This section contains general considerations for sensors and vehicles that were used to help guide the priority recommendations for the five light sweet crude OSR-JIP spill scenarios.

7.2.1 Sensor Considerations

Sensor compatibility considerations for different vehicles and scenarios included the following:

- Leak detection sensors relying on the use of tracer dyes were not rated because they are primarily used for inspections on new or recently repaired pipelines and require the tracer dye to be introduced into a pipeline or riser flow path. This includes leak detection systems made by Bowtech, Ocean Tools and Smart Light Devices.
- Acoustic sensors designed for operation from a fixed location were not rated. This includes the Sonardyne Automatic Leak Detection Sonar (ALDS).
- NDIR and electro-chemical sensors utilizing permeable membranes to detect dissolved gases can be used for hydrocarbon detection but were poorly rated due to the susceptibility of the membranes to fouling in the presence of oil. Other types of oceanographic sensors are also vulnerable to degradation from exposure to oil but likely not to the same extent. In addition, while all sensors exposed to hydrocarbons would eventually need to be cleaned, sensors with permeable membranes would also have to be disassembled to the point where the membrane could be removed, replaced, and reassembled.
- Direct oceanographic sensors are compatible with AOVs. However, they are not presently integrated into many AOVs because oil detection is not a common application for these vehicles. Indirect oceanographic sensors such as CTDs are both compatible with AOVs and commonly integrated into many AOVs due to various applications associated with meteorological ocean (METOC) scientific research.
- Scientific research often involves the use of METOC sensors. Several METOC sensors are useful for indirect oil detection and METOC sensors that operate on AOVs are plentiful in the scientific community.
- METOC sensor data are important for predicting oil slick movements.
- Fluorometers, CTDs, dissolved oxygen sensors, and turbidity meters are compatible with many vehicles and useful in most response scenarios.
- Radar is useful for medium to long range detection of oil on water; passive imaging sensors are likely to be more effective at shorter ranges (< 2 km).
- UV passive imagers are rated lower than visible and thermal IR imagers due to limited use as stand-alone sensors.
- The use of passive imaging sensors on small ASVs were rated low due to low viewing angles that reduce both coverage area and contrast between oil and water.
- The use of LIDAR on surface vessels is not a well-established technology application for oil detection on water.

7.2.2 Vehicle Considerations

Vehicle compatibility considerations for different sensors and scenarios included the following:

- Most AOVs are developed for either military or scientific purposes.
- Larger AOVs become more desirable for extended missions as spill duration increases and spills get deeper and farther from shore.
- Man-portable AOVs become less useful in deeper waters due to limited operational duration, depth, and maneuverability.
- AOVs are generally preferred over manned vessels for the purposes of reducing costs and reducing risks of personnel exposure to hazards during spill response.
- It is generally desirable to engage a mix of surface and subsea vehicles for spill detection and tracking.
- Gliders have limited on-board power and might have to operate direct sensors (which typically consume more power than indirect sensors) intermittently rather than continuously using a power management system.
- Gliders are release-and-forget type vehicles that are likely to be useful for monitoring spill perimeters and extents.
- Wave/wind powered ASVs were designed as open water vehicles and are likely to be less effective close to shore.
- In most locations, manned surface vessels are likely to be readily available while any type of autonomous vehicle would likely require a day or longer to deploy in the spill area.
- The appropriate selection of surface vessels must be made on a case by case basis and should consider range (in relation to transit distance), cruising speed (in terms of how long it will take to reach the location), how long the ship can remain on station, and sea worthiness with regards to the spill location sea conditions.
- Some vessels of opportunity are very capable at long distances from shore (100 km and beyond) while others are not. For these prioritizations, it is assumed that 50 km is approaching the useful limit of many vessels of opportunity and 100 km is exceeding the useful limit of most vessels of opportunity. It is also assumed that large vessels are useful at these long distances from shore provided that they have been appropriately vetted for range, cruising speed, endurance, sea worthiness and other important considerations.
- Small ASVs can operate in protected bodies of water such as ports and harbors but are not designed for open seas.
- Wave gliders and ASVs are more useful than AUVs when the majority of the spill is at or near the water surface.
- AUVs are not practical or economical close to shore where the water is shallow and a range of surface vessels are likely to be readily available.

7.3 Priority Recommendations for Spill Scenarios

Table 7-2 through Table 7-7 list priority recommendations of sensor and vehicle combinations for the five light sweet crude OSR-JIP spill scenarios listed above. For each scenario, the available sensors and vehicles were evaluated based on the spill parameters listed in Table 7-1 as well as the sensor and vehicle considerations listed above. Each combination was rated according to the multi-level scale listed below:

3 = High priority combination of vehicle and sensor for this scenario.

2 = Medium priority combination of vehicle and sensor for this scenario.

1 = Low priority combination of vehicle and sensor for this scenario.

– = Vehicle and sensor combination incompatible.

Ratings containing an asterisk (*) indicates that the sensors and vehicles are compatible but are likely not available without upfront investment for integration and software/algorithm development.

7.3.1 Release at a Coastal Terminal

Table 7-2 contains priority recommendations for a relatively small spill occurring at the water surface at a coastal terminal (Table 7-1). Since the spill occurs at the surface of the water, AUVs are unnecessary for this scenario and are therefore rated as low. Wave/wind powered ASVs are rated as a “1” because they are designed for the open sea and would have trouble maneuvering against coastal currents. The most useful combination of sensors and vehicles for this scenario is passive imaging sensors from a surface vessel because they are readily available and ideal for surface spills. In addition, a spill this small could be relatively easily attended by a small number of surface vessels. Small and large ASVs can also be useful for scenarios close to shore where line-of-sight control and wireless video links are well within range. A potentially useful application for ASVs might be for oil sensing just below the water surface using direct and indirect sensors.

7.3.2 Oil Tanker in Transit Offshore

Table 7-3 contains priority recommendations for an oil spill from an oil tanker in transit offshore. This scenario considers a relatively large spill that occurs 25 km offshore at a depth of 10 m. It covers a large area, potentially affecting a long coastline, and lasts for a duration of 10 days. The man-portable AUVs are rated low due to their short mission durations while the large displacement AUVs and gliders are rated low due to the shallow spill depth. Small ASVs are rated low due to problems maneuvering in the open sea while wave and wind powered ASVs are rated high for intended operation in the open sea. Large ASVs and manned vessels are rated high with most sensors since the oil is expected to remain at or near the sea surface.

7.3.3 Offshore Platform

Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

Table 7-4 and Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

Table 7-5 contain priority recommendations for an oil spill from an offshore platform at depths of 0 m and 300 m, respectively. In these scenarios, the spill occurs 50 km from shore and does not jeopardize any coastline. It is a small spill over a short duration and confined to a small area around the platform. As a result, wave and wind powered ASVs are rated medium since they are useful in the open sea but the size and duration of the spill are small. Small ASVs are rated low due to problems maneuvering in the open sea. Large ASVs and large surface vessels are rated high with most sensors due to their extended durations and ability to monitor both above and below the surface. Vessels of opportunity are rated medium because the 50 km distance from shore exceeds the useful range of many types of these vessels.

As might be expected, the difference in prioritization between the 0 m and 300 m depth cases lies in the applicability of subsurface vehicles. For the 0 m depth case, all of the subsurface vehicles rated low since the spill occurred at the surface. For the 300 m depth case, the man-portable AUVs, large displacement AUVs, and gliders all rated medium. The man-portable AUVs are useful largely because they can be deployed and retrieved from the offshore platform itself and operate in a relatively small spill area. Otherwise, they would rate low compared to other AUVs that can perform the same tasks for longer durations at deeper depths since a 300 m depth barely meets or exceeds the depth rating of many man-portable AUVs. Large displacement AUVs and gliders are useful for this scenario but the Light Weight and Heavy Weight AUVs are better suited for depths between 0 and 300 m.

7.3.4 Offshore Pipeline Rupture

Table 7-6 contains priority recommendations for an oil spill due to an offshore pipeline rupture. This spill is assumed to occur 50 km from shore and does not jeopardize any coastline. It is a small spill confined to a small area and occurs at a depth of 50 m over a duration of 5 days. This scenario is similar to the offshore platform scenario at a spill depth of 300 m except for the shallower spill depth and longer spill duration. The main differences between these scenarios lie in the subsea vehicle applications. For the offshore pipeline rupture, the man-portable AUVs rate low because there is no offshore platform to operate from, and therefore their short duration becomes more of an issue since they would require frequent tending from a vessel. In addition, the large displacement AUVs and the gliders rate low because Light Weight and Heavy Weight AUVs are much better suited for shallow depths between 0 and 50 m.

7.3.5 Deepwater Well Blowout (Macondo-Type)

Table 7-7 contains priority recommendations for an oil spill from a deep well blowout that is comparable in scale to the 2010 Macondo well blowout. In this case, the spill occurs 100 km offshore at a depth of 2,000 m and is extensive in terms of spill volume, spill area, duration, and potentially impacted shoreline. For this scenario, most sensor and vehicle combinations rate highly due to the need to locate the oil at all depths so that as much of it can be detected, tracked and cleaned up as possible. The man-portable AUVs are rated low due to their short mission durations, the small ASVs are rated low due to problems maneuvering in the open sea, and vessels of opportunity are rated low because the 100 km distance from shore exceeds the useful range of most types of these vessels. For the remaining vehicles, the sensors (except LIDAR) rate high due to the need for missions at all depths between 2,000 m and the surface.

Table 7-2: Priority Recommendations for Release at a Coastal Terminal

Scenario 2: Release at a Coastal Terminal										
Sensor Group	Sensor	Subsurface Vehicles				Surface Vehicles				
		AUV Classes			Glider	ASV Classes			Manned Vessels	
		Man-portable AUV	LW/HW AUV	Large Displacement AUV		Wave/ Wind Powered ASV	Small ASV	Large ASV	Vessel of Opportunity	Large Vessel
Subsea Direct Sensors	Fluorometer	1*	1*	1*	1*	1*	2	2	2	2
	NDIR (CH_4)	1*	1*	1*	1*	1*	1	1	1	1
Subsea Indirect Sensors	CTD	1	1	1	1	1	2	2	2	2
	DO (electro-chemical)	1	1	1	1	1	1	1	1	1
	DO (optical)	1	1	1	1	1	2	2	2	2
	NDIR (CO_2)	1	1	1	1	1	1	1	1	1
	Turbidity Meter	1	1	1	1	1	2	2	2	2
Surface Vessel Sensors	Fluorescence LIDAR	–	–	–	–	–	–	–	–	1*
	Radar	–	–	–	–	–	–	1	2	2
	Thermal IR Imagers	–	–	–	–	–	2	2	3	3
	UV Imagers	–	–	–	–	–	1	1	2	2
	Visible Light Imagers	–	–	–	–	–	2	2	3	3

Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

Table 7-3: Priority Recommendations for Oil Tanker in Transit Offshore

Scenario 3: Oil Tanker in Transit Offshore										
Sensor Group	Sensor	Subsurface Vehicles				Surface Vehicles				
		AUV Classes			Glider	ASV Classes			Manned Vessels	
		Man-portable AUV	LW/HW AUV	Large Displacement AUV		Wave/ Wind Powered ASV	Small ASV	Large ASV	Vessel of Opportunity	Large Vessel
Subsea Direct Sensors	Fluorometer	1*	3*	1*	1*	3*	1	3	3	3
	NDIR (CH_4)	1*	1*	1*	1*	1*	1	1	1	1
Subsea Indirect Sensors	CTD	1	3	1	1	3	1	3	3	3
	DO (electro-chemical)	1	1	1	1	1	1	1	1	1
	DO (optical)	1	3	1	1	3	1	3	3	3
	NDIR (CO_2)	1	1	1	1	1	1	1	1	1
	Turbidity Meter	1	3	1	1	3	1	3	3	3
Surface Vessel Sensors	Fluorescence LIDAR	–	–	–	–	–	–	–	–	2*
	Radar	–	–	–	–	–	–	3	3	3
	Thermal IR Imagers	–	–	–	–	–	1	3	3	3
	UV Imagers	–	–	–	–	–	1	2	2	2
	Visible Light Imagers	–	–	–	–	–	1	3	3	3

Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

Table 7-4: Priority Recommendations for Offshore Platform at 0 m Depth

Scenario 4A: Offshore Platform (0 m Depth)										
Sensor Group	Sensor	Subsurface Vehicles				Surface Vehicles				
		AUV Classes			Glider	ASV Classes			Manned Vessels	
		Man-portable AUV	LW/HW AUV	Large Displacement AUV		Wave/ Wind Powered ASV	Small ASV	Large ASV	Vessel of Opportunity	Large Vessel
Subsea Direct Sensors	Fluorometer	1*	1*	1*	1*	2*	1	3	2	3
	NDIR (CH_4)	1*	1*	1*	1*	1*	1	1	1	1
Subsea Indirect Sensors	CTD	1	1	1	1	2	1	3	2	3
	DO (electro-chemical)	1	1	1	1	1	1	1	1	1
	DO (optical)	1	1	1	1	2	1	3	2	3
	NDIR (CO_2)	1	1	1	1	1	1	1	1	1
	Turbidity Meter	1	1	1	1	2	1	3	2	3
Surface Vessel Sensors	Fluorescence LIDAR	–	–	–	–	–	–	–	–	1*
	Radar	–	–	–	–	–	–	3	2	3
	Thermal IR Imagers	–	–	–	–	–	1	3	2	3
	UV Imagers	–	–	–	–	–	1	2	2	3
	Visible Light Imagers	–	–	–	–	–	1	3	2	3

Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

Table 7-5: Priority Recommendations for Offshore Platform at 300 m Depth

Scenario 4B: Offshore Platform (300 m Depth)										
Sensor Group	Sensor	Subsurface Vehicles				Surface Vehicles				
		AUV Classes			Glider	ASV Classes			Manned Vessels	
		Man-portable AUV	LW/HW AUV	Large Displacement AUV		Wave/ Wind Powered ASV	Small ASV	Large ASV	Vessel of Opportunity	Large Vessel
Subsea Direct Sensors	Fluorometer	2*	3*	2*	2*	2*	1	3	2	3
	NDIR (CH_4)	1*	1*	1*	1*	1*	1	1	1	1
Subsea Indirect Sensors	CTD	2	3	2	2	2	1	3	2	3
	DO (electro-chemical)	1	1	1	1	1	1	1	1	1
	DO (optical)	2	3	2	2	2	1	3	2	3
	NDIR (CO_2)	1	1	1	1	1	1	1	1	1
	Turbidity Meter	2	3	2	2	2	1	3	2	3
Surface Vessel Sensors	Fluorescence LIDAR	–	–	–	–	–	–	–	–	1*
	Radar	–	–	–	–	–	–	3	2	3
	Thermal IR Imagers	–	–	–	–	–	1	3	2	3
	UV Imagers	–	–	–	–	–	1	2	2	3
	Visible Light Imagers	–	–	–	–	–	1	3	2	3

Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

Table 7-6: Priority Recommendations for Offshore Pipeline Rupture

Scenario 5: Offshore Pipeline Rupture										
Sensor Group	Sensor	Subsurface Vehicles				Surface Vehicles				
		AUV Classes			Glider	ASV Classes			Manned Vessels	
		Man-portable AUV	LW/HW AUV	Large Displacement AUV		Wave/ Wind Powered ASV	Small ASV	Large ASV	Vessel of Opportunity	Large Vessel
Subsea Direct Sensors	Fluorometer	1*	3*	1*	1*	2*	1	3	2	3
	NDIR (CH_4)	1*	1*	1	1*	1*	1	1	1	1
Subsea Indirect Sensors	CTD	1	3	1	1	2	1	3	2	3
	DO (electro-chemical)	1	1	1	1	1	1	1	1	1
	DO (optical)	1	3	1	1	2	1	3	2	3
	NDIR (CO_2)	1	1	1	1	1	1	1	1	1
	Turbidity Meter	1	3	1	1	2	1	3	2	3
Surface Vessel Sensors	Fluorescence LIDAR	–	–	–	–	–	–	–	–	1*
	Radar	–	–	–	–	–	–	3	2	3
	Thermal IR Imagers	–	–	–	–	–	1	3	2	3
	UV Imagers	–	–	–	–	–	1	2	2	3
	Visible Light Imagers	–	–	–	–	–	1	3	2	3

Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

Table 7-7: Priority Recommendations for Deepwater Well Blowout

Scenario 6: Deepwater Well Blowout (Macondo-Type)										
Sensor Group	Sensor	Subsurface Vehicles				Surface Vehicles				
		AUV Classes			Glider	ASV Classes			Manned Vessels	
		Man-portable AUV	LW/HW AUV	Large Displacement AUV		Wave/ Wind Powered ASV	Small ASV	Large ASV	Vessel of Opportunity	Large Vessel
Subsea Direct Sensors	Fluorometer	1*	3*	3*	3*	3*	1	3*	1	3
	NDIR (CH_4)	1*	1*	1*	1*	1*	1	1*	1	1
Subsea Indirect Sensors	CTD	1	3	3	3	3	1	3	1	3
	DO (electro-chemical)	1	1	1	1	1	1	1	1	1
	DO (optical)	1	3	3	3	3	1	3	1	3
	NDIR (CO_2)	1	1	1	1	1	1	1	1	1
	Turbidity Meter	1	3	3	3	3	1	3	1	3
Surface Vessel Sensors	Fluorescence LIDAR	–	–	–	–	–	–	–	–	2*
	Radar	–	–	–	–	–	–	3	1	3
	Thermal IR Imagers	–	–	–	–	–	1	3	1	3
	UV Imagers	–	–	–	–	–	1	3	1	3
	Visible Light Imagers	–	–	–	–	–	1	3	1	3

Spill = Light sweet crude; Priority 3 = High, 2 = Medium, 1 = Low; – = Incompatible; * = Technology exists but resources are required for integration and software/algorithm development.

8.0 Summary

This study has evaluated a range of oil detection sensors and oceanographic vehicles and their overall compatibility for detecting and tracking oil in water. Oil detection sensors include *in situ* contact sensors that utilize either direct or indirect sensing methods and surface remote sensors that utilize either passive or active sensing methods. Oceanographic vehicles include autonomous underwater vehicles (AUVs), autonomous surface vehicles (ASVs), and manned surface vessels. Remotely operated vehicles (ROVs) were addressed in a separate OSR-JIP study. General observations regarding these sensors and vehicles for oil detection at sea include the following:

- There are several commercially available direct oil detection sensors. These are largely fluorometer based systems focused on detecting either PAHs or refined and crude HCs. At least one vendor provides a methane detection sensor which is based on non-destructive infrared imaging.
- Several indirect oil detection sensors are commercially available. All of the approaches rely on detecting the change between the properties of the baseline local seawater environment and the properties where the presence of oil exists. CTD, fluorometers, and optical light scatter sensors are the ones used most prominently to measure dissolved O_2, conductivity, temperature and pressure, with salinity and density being calculated.
- A couple of manufacturers make an integrated set of detection sensors which may be of interest. The oil detection sensors operate independently of each other (i.e., the measurement of one sensor is not used in taking the measurement of the next sensor). As such, sensors do not necessarily need to be physically integrated unless the packaging is dictated for another purpose. Data integration should be viewed more critically as the motivation for using an integrated sensor suite or a set of individual sensors.
- The direct and indirect oil detection sensors take a reading at essentially a single point in space. To map the extent of oil over a large geographic area and/or water depth would require a large number of readings to be acquired.
- There are multiple viable combinations of direct and indirect oil detection sensors that can be hosted on each of the classes of unmanned vehicles evaluated.
- AUVs can sample at depth along a prescribed path and are largely unrestricted in their movement through the water column although they have limited endurance and are generally only capable of sampling for hours up to a couple of days. AUVs can be programmed to surface to initiate satellite or radio communications, but in doing so temporarily interrupt their normal course of operation.
- Gliders operate according to a sawtooth profile, rising and falling to generate forward speed. They offer long endurance and can survey a region unattended for weeks or even months. Gliders can maintain periodic satellite or radio communications as part of their normal approach to operations. Most gliders are relatively small and fairly payload restrictive. It would likely require multiple vehicles to employ the range of available sensors. One larger glider is available, though it too has more payload restrictions than an equivalently sized AUV.

- ASVs are largely restricted to monitoring at the surface or to a limited depth if configured to suspend the sensor instrument cage. ASVs can maintain nearly continuous radio communication in their normal course of operations allowing data to be transferred quickly after sampling. ASVs can operate hours to days away from manned host ships depending on their configuration and the intended mission.
- The L&R requirements for the various unmanned vehicles range from manual operation from a small boat to large dedicated equipment that restricts the types of ship that can be selected as the host vessel.
- The smaller unmanned vehicles which are compatible with small boat operations are the most restrictive in payload capacity and one may need to employ multiple vehicles to accommodate all sensors.
- While vehicle manufacturers have some standard sensor configurations, all of the manufacturers contacted indicated an ability to customize vehicles for user-specified sensor configurations.
- All of the AUVs will likely have some amount of NRE associated with a novel sensor configuration (one which the manufacturer has not already performed). This is due to the need for AUVs to maintain and verify overall vehicle trim and balance and that hydrodynamics are maintained within acceptable design tolerances. This is especially true for the smaller AUVs and gliders.
- Different sizes and configurations of AUVs, gliders and ASVs are available commercially though some have only been produced in limited numbers.
- In many cases, remote sensing technologies may be better suited for airborne platforms that allow downward or sideways view angles and sufficient altitude to observe a broad field of view. However, several remote sensing technologies can provide value on a surface vessel despite the restricted view angle and overall field of view.
- A variety of remote sensing systems are available to detect and monitor oil remotely from surface vessels. These sensors include passive optical imagers operating at UV, visible, and IR wavelengths as well as active radar and UV LIDAR systems.
- Combinations of sensor technologies are commonly used in oil detection missions to increase probability and reliability of detecting and mapping oil spills. Often, sensor combinations take advantage of mutually exclusive benefits while mitigating mutually exclusive limitations.
- For surface vessels, the critical details of interest include whether the vessel can support the size, weight, and power requirements of the sensor as well as provide adequate elevation above the water surface (i.e., mast, A-frame, boom crane). In addition, and perhaps of highest priority, the range and duration that a vessel can be deployed for a given mission is critical.
- Desirable surface vessel attributes for remote sensing include ample vehicle size for crew safety, integrated maritime cameras, integrated navigational radar, sufficient shipboard power, high sensor mounting locations, and Internet connectivity.

- Most sensors identified in this study are not OGC compliant. While most of the sensor hardware is capable of compliance, there is currently little incentive for manufacturers to comply.
- For subsea dispersant monitoring, operation at depths greater than 300 m is the critical issue that defines applicability of sensors and underwater vessels. Most direct and indirect detection systems can be coupled with larger AUVs (Light and Heavy Weight AUVs, Large Displacement AUVs) that are rated for operation at depths below 300 m.
- For prolonged surface dispersant monitoring, passive optical imagers (ultraviolet, visible, infrared) meet specific NRT and SMART monitoring guidelines and can be integrated onto any surface platform. Certain types of direct (fluorometer) and indirect (CTD, particle size, turbidity, dissolved O_2) sensors also meet specific NRT and SMART monitoring needs and can be integrated on the hull or tethered to any surface vessels (manned or unmanned).

As many viable combinations are plausible, a larger view of the entire concept of operations including host ship interfaces, time-on-station, manning requirements and constraints, and the duration for operational sustainment would need to be developed to determine the optimal number and type of sensors and vehicles required. The results of this study may be used as a screening tool to narrow the range of possibilities and prioritize combinations worthy of further consideration. In this regard, this study can be used to identify those criteria to focus on that have the best probability of success for each specific mission scenario.

Appendix A
List of Acronyms

ADCP	Acoustic Doppler Current Profiler
AKA	Also Known As
AOV	Autonomous Oceanographic Vehicle
API	American Petroleum Institute
ARGOS	Advanced Research and Global Observation Satellite
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
AUVAC	Autonomous Undersea Vehicle Applications Center
CCD	Charge Coupled Device
CCS	Carbon Capture and Storage
CDOM	Chromophoric Dissolved Organic Matter
CH_4	Methane
CO_2	Carbon Dioxide
CTD	Conductivity, Temperature and Depth
DO	Dissolved Oxygen
FPA	Focal Plane Array
GOM	Gulf of Mexico
GPS	Global Positioning System
HC	Hydrocarbon
HD	High Definition
HWV	Heavyweight Vehicle
IPIECA	International Petroleum Industry Environmental Conservation Association
IR	Infrared
ISE	International Submarine Engineering, Ltd.
ISO	International Standards Organization
L&R	Launch and Recovery
LARS	Launch and Recovery System
LBL	Long Baseline
LCD	Liquid Crystal Display
LIDAR	Light Detection and Ranging
LRI	Liquid Robotics Inc.

LWIR	Long Wave Infrared
LWV	Lightweight Vehicle
METOC	Meteorological Ocean
MP	Man-portable
MWIR	Mid-Wave Infrared
NDIR	Non-Destructive Infrared Spectrometry
NRE	Non-Recurring Engineering
NRT	National Response Team
NTU	Nephelometric Turbidity Unit
O_2	Oxygen
OGC	Open Geospatial Consortium
OGP	The International Association of Oil & Gas Producers
OSRP	Oil Spill Response Plan
PAH	Polyaromatic Hydrocarbons
RF	Radio Frequency
RHIB	Rigid-Hulled Inflatable Boat
ROV	Remotely Operated Vehicle
RRT	Regional Response Team
SBL	Short Baseline
SMART	Special Monitoring of Applied Response Technologies
SOOP	Ship of Opportunity
SWE	Sensor Web Enablement
SWIR	Short Wave Infrared
USBL	Ultra-Short Baseline
USV	Unmanned Surface Vehicle
UUV	Unmanned Undersea Vehicle
UV	Ultraviolet
VOC	Volatile Organic Compounds
VOP	Vessel of Opportunity
WQM	Water Quality Monitor
WTI	West Texas Intermediate

Appendix B
Glossary

″	inch
$	US dollar
<	less-than sign
>	greater than
°	degree
°C	degree Celsius/centigrade
Acoustic Doppler Current Profiler	A hydroacoustic current meter that measures water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles within the water column.
active sensors	Sensors that propagate electromagnetic radiation toward a target and then detect a return signature to observe properties of the target.
Autonomous Oceanographic Vehicle	Any surface or underwater vessel that can operate without input from an operator.
Autonomous Surface Vehicle	Any vehicle that operates on the surface of the water without requiring input from an operator.
Autonomous Underwater Vehicle	Any vehicle that operates underwater without requiring input from an operator.
Chromophoric Dissolved Organic Matter fluorometer	Optically measurable component of the dissolved organic matter in water, also known as colored dissolved organic matter.
Clark-type electrode sensor	Sensor composed of a cathode and an anode submersed in an electrolyte. Oxygen enters the sensor through a permeable membrane by diffusion, and is reduced at the cathode, creating a measurable electrical current.
dissolved gas	Gases in solution with liquid (i.e., water). For direct or indirect oil sensing, dissolved CO_2, O_2, and CH_4 are of particular importance.
emissivity	The emissivity of a material (usually written ε or e) is the relative ability of its surface to emit energy by radiation.

false positives	A false positive error, commonly called a "false alarm" is a result that indicates a given condition has been fulfilled, when it actually has not been fulfilled.
fluorescence	Fluorescence is the emission of light by a substance that has absorbed light or other electromagnetic radiation. It is a form of luminescence. In most cases, emitted light has a longer wavelength, and therefore lower energy, than the absorbed radiation
fluorometer	Sensor that measures fluorescence properties such as intensity or wavelength distribution following excitation by a suitable light source.
frequency	The number of cycles or completed alternations per unit time of a wave or oscillation.
glider	Autonomous underwater vehicle that uses small changes in its buoyancy in conjunction with wings to convert vertical motion to horizontal, thereby propelling itself forward with very little power consumption.
Heavyweight Vehicle AUV	AUV that is typically 21 inches in diameter, weighing up to 3,000 lbs., and with payload volume of 4-6 ft^3. Typical endurance ranges are 20-80 hours.
Hotel (load)	Power consumption other than propulsion
hr.	hour
hydrocarbon	Organic compounds consisting entirely of hydrogen and carbon. Hydrocarbons occur naturally in crude oil as well as in refined oil products.
hyperspectral	Hyperspectral imaging, like other spectral imaging, collects and processes information from across the electromagnetic spectrum. Much as the human eye sees visible light in three bands (red, green, and blue), spectral imaging divides the spectrum into many more bands. This technique of dividing images into bands can be extended beyond the visible.
Hz	hertz
in	inch
International Standards Organization	An international standard-setting body composed of representatives from various national standards organizations.
km	kilometer
kW	kilowatt

Large Displacement AUV	AUV that is typically 36 inches in diameter, weighing up to 20,000 lbs., and with payload volume of 15-30 ft^3. Typical endurance range is greater than 100 hours.
latency	Latency is the amount of time between when a remote sensing observation is made and when the data are available to users. The time lag is due to retrieval and processing of the data by the responsible agencies or companies.
Lightweight Vehicle AUV	AUV that is typically 12.75 inches in diameter, weighing up to 500 lbs., and with payload volume of 1-3 ft^3. Typical endurance ranges are 10-40 hours.
Launch and Recovery System	A system typically involving a crane and ramp in which a free-floating vehicle drifting on the water surface is recovered by a ship and crew.
LIDAR	Lidar (also written LIDAR or LiDAR) is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light.
Long Baseline Navigation	An underwater acoustic positioning system used to track underwater vehicles using a network of sea-floor mounted baseline transponders as reference points for navigation.
Man-Portable AUV	Small AUV with displacement less than 80 kg and with payload volume of less than 0.25 ft^3. Typical endurance ranges are 10-20 hours.
MHz	megahertz
microwave radiometer	Passive sensor that measures the emitted spectral radiance from a surface in the microwave region. Radiometer can discriminate water and oil based on differences in microwave emissivities, approximately 0.4 and 0.8, respectively.
min	minute
mm	millimeter
National Response Team	Multifaceted group of U.S. Government agencies that supports emergencies involving hazardous substances, pollutants, oil, and weapons of mass destruction in natural and technological disasters. Member agencies include U.S. Environmental Protection Agency, U.S. Coast Guard, National Oceanic and Atmospheric Administration, and U.S. Department of the Interior.

nephelometer	Sensor that measures intensity of light scattered by the sample, which is directly proportional to the amount of matter suspended in the light path. The sensor is mounted at an angle (usually 90°) to the traversing beam to record scattered light.
non-dispersive infrared spectrometry	Gas sensor in which broadbanded, undispersed infrared light is passed through a gas sample and then detected after an appropriately selected filter.
non-recurring engineering	One time, fixed cost to research, develop, design, and test a new technology
Open Geospatial Consortium	Industry consortium focused on developing publicly available interface standards for geospatial data.
optode sensor	Dissolved oxygen sensor that detects fluorescence signature that depends on amount of oxygen present.
passive sensors	Sensors that detect naturally occurring electromagnetic radiation, such as ultraviolet, visible, or infrared light; they do not generate their own light source.
photoluminescence	Light emission from any form of matter after absorption of electromagnetic radiation.
polycyclic aromatic hydrocarbon	A group of semi-volatile organic compounds that are present in crude oil that has spent time in the ocean. PAHs can also be formed when oil is burned. At elevated concentration they can potentially cause health problems.
PUCK Protocol Standard	Standard that defines a protocol for RS232 and Ethernet connected instruments. It defines a standard instrument protocol to store and automatically retrieve metadata and other information from the instrument.
ppm	parts per million
Radar	Acronym for Radio Detection and Ranging, an active sensor technology that uses reflected radio waves to determine range and direction of a target object.
ratio turbidimeter	Sensor that measures both transmitted and scattered light intensities associated with a liquid sample. Transmitted light and 90 deg-scattered light are measured simultaneously with two different light sensors.
reflection	Reflection is the change in direction of a wave front at an interface between two different media so that the wave front returns into the medium from which it originated.

Remotely Operated Underwater Vehicle	Any vehicle that operates underwater without a human occupant, but that is controlled by a remote human operator.
Rigid-hulled Inflatable Boat	A light-weight but high-performance and high-capacity boat constructed with a solid, shaped hull and flexible tubes at the gunwale.
Sensor Model Language	Provides a robust and semantically-tied means of defining processes and processing components associated with the measurement and post-measurement transformation of sensor observations.
Short Baseline Navigation	An underwater acoustic positioning system used to track underwater vehicles, which does not require seafloor mounted transponders or equipment.
spectrum	A condition that is not limited to a specific set of values but can vary infinitely within a continuum.
thermal infrared	A band of electromagnetic radiation wavelengths that generated by objects at near ambient temperatures, typically ranging from 8 to 12 μm.
turbidimeter	Also called an absorption meter, this sensor measures the intensity of the light beam after it has passed through suspended matter in a liquid sample, causing scattering and absorption of some light energy.
turbidity	Cloudiness or haziness of a fluid caused by large numbers of individual particles that are generally invisible to the naked eye, similar to smoke in air.
Ultra-short Baseline Navigation:	An underwater acoustic positioning system used to track underwater vehicles, which consists of a transceiver mounted on a pole under a ship and a transponder/responder on the seafloor, a two-fish, or on a remotely operated vehicle.
ultraviolet	A band of electromagnetic radiation wavelengths that are shorter than visible light, typically ranging from 400 to 10 nm.
Vessel of Opportunity	A vessel engaged in spill response activities that is normally and substantially involved in activities other than spill response and not a vessel carrying oil as a primary cargo.
visible light	A band of electromagnetic radiation wavelengths that are observable to the human eye, typically ranging from 800 to 400 nm.

water column	Conceptual column of water from surface to bottom sediments, used chiefly for environmental studies evaluating the stratification or mixing of the thermal or chemically stratified layers.
Wave Powered ASV	Wave propelled, persistent ocean vehicle that harvests abundant energy in ocean waves to provide essentially limitless propulsion.
Wind Powered ASV	ASV that uses wind for propulsion and solar panels for additional power for steering and sensors.
XML	Extensible Markup Language (XML) defines a set of rules for encoding documents in a format that is both human-readable and machine-readable based on free open standards.

Appendix C
Sensor and AUV Reference Material

The following are the Internet sources for the sensor and vehicle materials referenced in this report.

ACSA	http://acsa-alcen.com
AADI	http://www.aadi.no
AML Oceanographic	http://www.amloceanographic.com/
ASV	http://www.asvglobal.com
Atlas Elektronik	http://www.atlas-elektronik.com/en/
Atlas Maridan	http://www.maridan.atlas-elektronik.com/
Autonomous Underwater Vehicle Applications Center	http://auvac.org
Bluefin Robotics	http://www.bluefinrobotics.com/
Canon U.S.A. Inc.	http://canon.com
C&C Technologies	http://www.cctechnol.com and contact September 20, 2012.
Chelsea Technologies Group	http://www.chelsea.co.uk
CONTROS	http://www.contros.eu/
ECA Robotics	http://www.eca-robotics.com
Exocetus	http://exocetus.com
Falmouth Scientific, Inc. (FSI	http://www.falmouth.com
FLIR Systems, Inc.	http://www.flir.com
GoPro, Inc.	http://gopro.com
Hamamatsu Photonics K.K.	http://hamamatsu.com
INFRATEC GmbH	http://infratec.com
International Submarine Engineering	http://www.ise.bc.ca & and contact September 13, 2012.
iRobot	http://www.irobot.com/
JAI	http://jai.com
JENOPTIK AG	http://jenoptik.com
Kongsberg Maritime	http://www.km.kongsberg.com
Laser Diagnostic Instruments	http://www.ldi.ee
Liquid Robotics	http://liquidr.com/

Lockheed Martin	http://www.lockheedmartin.com/us/products/marlin.html
Miros	http://miros.no
Mitsui Engineering & Shipbuilding Co., Ltd.	https://www.mes.co.jp/english
Nikon Corporation	http://nikon.com
OceanServer Iver2	http://iver-auv.com/
OPTIMARE Systems GmbH	http://optimare.de
RD Instruments	http://www.rdinstruments.com
Rutter	http://rutter.ca
Sea & Sun Technology	http://www.sea-sun-tech.com
Sea Robotics	http://searobotics.com
Sea-Bird Electronics	http://www.seabird.com
Seapoint Sensors, Inc.	http://www.seapoint.com
SIEL Advanced Sea Systems	http://www.sielnet.com
Sony Corporation of America	http://sony.com
Teledyne Gavia	http://www.gavia.is
Teledyne Webb Research	http://www.webbresearch.com
TriOS Optical Sensors	http://www.trios.de/
Turner Designs	http://www.turnerdesigns.com/
WetLabs	http://www.wetlabs.com/

Appendix D
AOV Quad Charts

Appendix D: AOV Quad Charts

Capabilities and Uses of Sensor-Equipped Ocean Vehicles for Subsea and Surface Detection and Tracking of Oil Spills

OGP Work Package 1: In Water Surveillance Oil Spill Response Joint Industry Project

November 2014

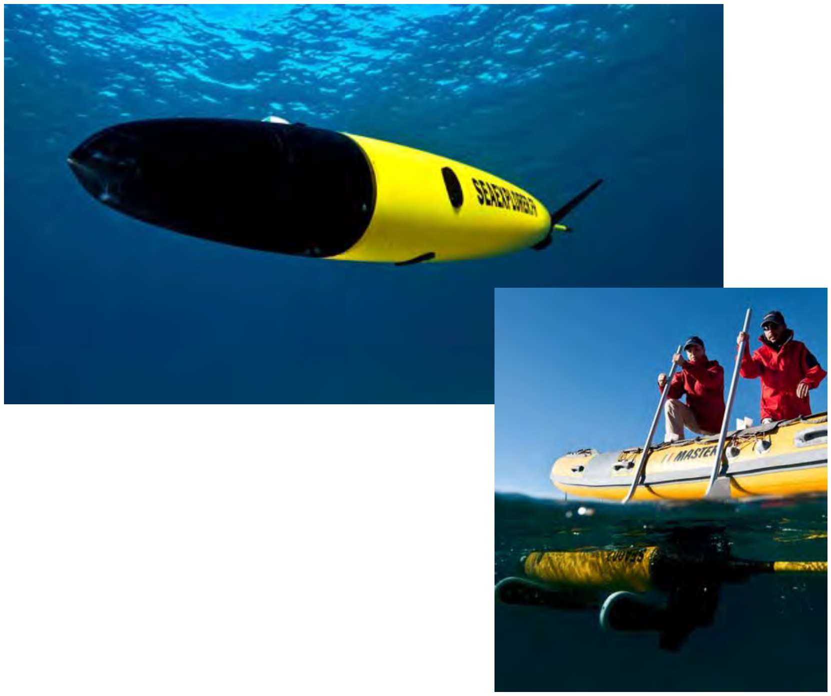
Battelle
The Business of Innovation

Appendix D
AOV Quad Charts

Following is a collection of quad charts that provides readily available high level information about AOVs identified in the main report. The vehicles considered in this section fall into a range of availability and years of operational use. While all of the vehicles are considered mature technology, the number of each type built and the degree of field usage vary considerably. To reflect this, each vehicle has been classified into one of three categories ranked by how readily available they are for purchase in numbers or short lead time. The definitions listed below were used to classify vehicle availability.

- Limited – vehicles that have been around for several years and either have multiple prototypes or a single unit that is from a commercial company rather than academic source. This group of vehicles may be listed as available for sale but have not been widely deployed.
- Available – either an academic vehicle that is being produced in some numbers (e.g., SAUV II) or a single vehicle that is being produced by a reputable company with manufacturing capabilities (e.g., Talisman).
- Commercial – produced for sale on a commercial scale and many vehicles are already in use.

ASCA SeaExplorer



Length **m**	2.9
Width **m**	0.25
Height **m**	0.25
Dia. **m**	0.25
Weight dry, kg	59
Depth Rating **m**	
Max. Mission Duration **hrs**	700
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	5
Typical cruise speed **knots**	3-4
Communications	Iridium satellite, RF modem
Vehicle Availability	A - Limited

ASV C-Enduro

Length **m**	4.2
Width **m**	
Weight dry, kg	350-500
Reserve buoyancy	3 months
Max. Mission Duration **hrs**	
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	Solar and Wind
Typical cruise speed **knots**	
Communications	LOS Radio Satellite
Vehicle Availability	B - Available

ASV C-Cat 5

Length m	5
Width m	
Weight dry, kg	650-1000
Reserve buoyancy	diesel genset: 48, Battery alone: 8
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	500
Payload weight kg	2 x DC Electric Motors (3.6 kW each), Diesel Genset or Direct Drive Diesel options
Typical cruise speed knots	
Communications	UHF, S-Band, L-Band, Xbee Option
Vehicle Availability	C - Commercial

ASV C-Hunter

Length m	6.3
Width m	
Weight dry, kg	2,000
Reserve buoyancy	50+ (@6 kts) 96+ (@4 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	300
Payload weight kg	1 x Yanmar 3YM30 Diesel Engine (30 Hp)
Typical cruise speed knots	
Communications	UHF up to 8 km or Satellite/GSM communication options
Vehicle Availability	B - Available

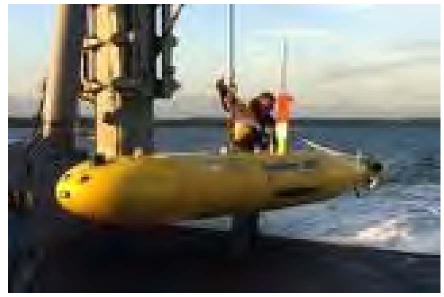
ASV C-Worker

Length m	5.85
Width m	
Weight dry, kg	3500-5000
Reserve buoyancy	720 @ 4knts, 240 @ 6 knts
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	
Payload weight kg	2x diesel generator sets 13kW each
Typical cruise speed knots	
Communications	LOS Radio, Satellite
Vehicle Availability	B - Available

Atlas Elektronik SeaCat

Length **m**	2.3
Width **m**	0.3
Height **m**	0.3
Dia. **m**	0.3
Weight dry, kg	130
Depth Rating **m**	300
Max. Mission Duration **hrs**	6 to 10
Available payload power	
Payload volume **cu. m**	variable
Payload weight **kg**	
Mission Turnaround Time	
Typical cruise speed **knots**	3-4
Communications	Ethernet
Vehicle Availability	C - Commercial

Atlas Elektronik Sea Otter MK II

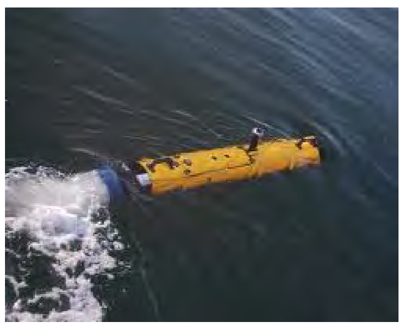


Length m	3.65
Width m	1.1
Height m	0.48
Dia. m	
Weight dry, kg	1000
Depth Rating m	600, 1500
Max. Mission Duration hrs	24
Available payload power	
Payload volume cu. m	modular
Payload weight kg	160
Mission Turnaround Time	4 hours for 2 Li batteries (18 kWh capacity each)
Typical cruise speed knots	4
Communications	LAN (on deck), WiFi, Radio, Iridium satellite, Fiber Optic, Acoustic modem, ARGOS
Vehicle Availability	B - Available

BAE Systems Talisman L

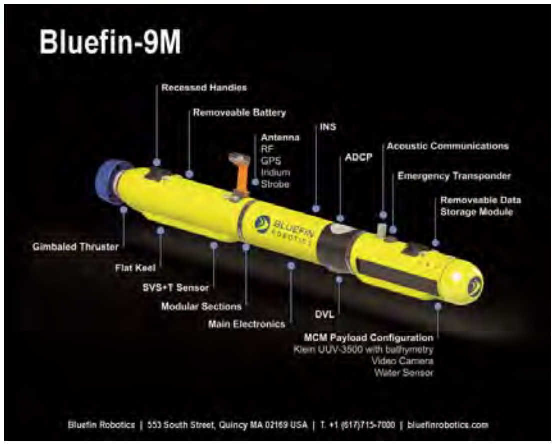
Length **m**	1.4
Width **m**	2.5
Height **m**	1.1
Dia. **m**	
Weight dry, kg	50
Depth Rating **m**	300
Max. Mission Duration **hrs**	
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	
Typical cruise speed **knots**	up to 5
Communications	
Vehicle Availability	A - Limited

Bluefin Robotics Bluefin-9



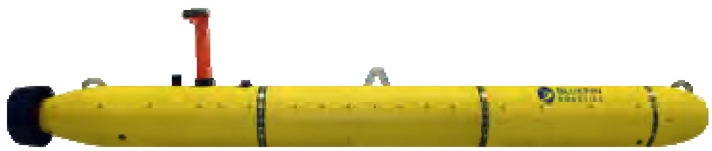
Length m	1.75
Width m	0.24
Height m	0.24
Dia. m	0.24
Weight dry, kg	60.5
Depth Rating m	200
Max. Mission Duration hrs	12
Available payload power	15 W
Payload volume cu. m	0.0025
Payload weight kg	variable free-flooded system
Mission Turnaround Time	<15 min (field swap); 6 hrs battery charge from empty to full
Typical cruise speed knots	3
Communications	RF, acoustic modem, Ethernet via shore power cable
Vehicle Availability	C - Commercial

Bluefin Robotics Bluefin-9M



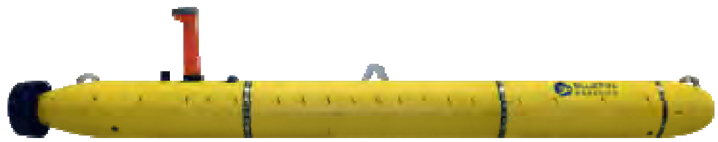
Length m	2.5
Width m	0.24
Height m	0.24
Dia. m	0.24
Weight dry, kg	70
Depth Rating m	300
Max. Mission Duration hrs	10
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	3
Communications	RF, acoustic modem, Ethernet via shore power cable
Vehicle Availability	C - Commercial

Bluefin Robotics Bluefin-12S



Length m	3.77
Width m	0.32
Height m	0.7
Dia. m	0.32
Weight dry, kg	213
Depth Rating m	200
Max. Mission Duration hrs	26
Available payload power	400 W
Payload volume cu. m	0.0066
Payload weight kg	variable free-flooded system
Mission Turnaround Time	6 hrs battery charge from empty to full
Typical cruise speed knots	3
Communications	RF, Iridium satellite, acoustic modem, Ethernet via shore power cable
Vehicle Availability	C - Commercial

Bluefin Robotics Bluefin-12D



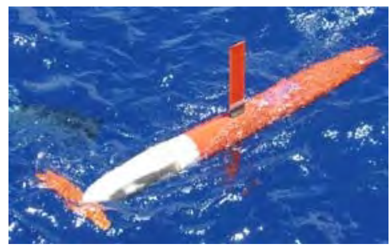
Length m	4.32
Width m	0.32
Height m	0.65
Dia. m	0.32
Weight dry, kg	260
Depth Rating m	1500
Max. Mission Duration hrs	30
Available payload power	400 W
Payload volume cu. m	0.0066
Payload weight kg	variable free-flooded system
Mission Turnaround Time	6 hrs battery charge from empty to full
Typical cruise speed knots	3-4
Communications	RF, Iridium satellite, acoustic modem, Ethernet via shore power cable
Vehicle Availability	C - Commercial

Bluefin Robotics Bluefin-21

Length m	4.93
Width m	0.53
Height m	0.8
Dia. m	0.53
Weight dry, kg	750
Depth Rating m	4500
Max. Mission Duration hrs	30
Available payload power	800 W
Payload volume cu. m	0.197
Payload weight kg	variable free-flooded system
Mission Turnaround Time	30 min (field swap); 6 hrs battery charge from empty to full
Typical cruise speed knots	2-3
Communications	RF, Iridium satellite, acoustic modem, Ethernet via shore power cable
Vehicle Availability	C - Commercial

Bluefin Robotics Spray Glider



Length m	2.13
Width m	1.01
Height m	0.3
Dia. m	0.3
Weight dry, kg	52
Depth Rating m	0.4 net pos.
Max. Mission Duration hrs	1500
Available payload power	4320 (180 days)
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	3.5
Typical cruise speed knots	0.4
Communications	Iridium satellite, GPS
Vehicle Availability	B - Available

C&C Technologies C-Surveyor IV (Modified HUGIN 3000)

Length **m**	4.57
Width **m**	1
Height **m**	1
Dia. **m**	1
Weight dry, kg	1400
Depth Rating **m**	3000
Max. Mission Duration **hrs**	
Available payload power	UltraSparc 650 mHz cPCI with 1 gigabyte ram
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive
Typical cruise speed **knots**	
Communications	Acoustic modem
Vehicle Availability	A - Limited

C&C Technologies C-Surveyor V (Modified HUGIN 3000)

Length m	6.2
Width m	1
Height m	1
Dia. m	1
Weight dry, kg	1400
Depth Rating m	3000
Max. Mission Duration hrs	
Available payload power	UltraSparc 650 mHz cPCI with 1 gigabyte ram
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive
Typical cruise speed knots	
Communications	Acoustic modem
Vehicle Availability	A - Limited

C&C Technologies C-Surveyor VI (Modified HUGIN 3000)

Length m	6.35
Width m	1
Height m	1
Dia. m	1
Weight dry, kg	
Depth Rating m	3000
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	4
Communications	Acoustic modem
Vehicle Availability	A - Limited

C&C Technologies C-Surveyor II (Modified HUGIN 3000)

Length m	6.2
Width m	1
Height m	1
Dia. m	1
Weight dry, kg	1400
Depth Rating m	3000
Max. Mission Duration hrs	50
Available payload power	UltraSparc 650 mHz cPCI with 1 gigabyte ram
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive
Typical cruise speed knots	
Communications	Acoustic modem
Vehicle Availability	A - Limited

C&C Technologies C-Surveyor III (Modified HUGIN 3000)

Length m	6.4
Width m	1
Height m	1
Dia. m	1
Weight dry, kg	1500
Depth Rating m	4500
Max. Mission Duration hrs	50
Available payload power	UltraSparc 650 mHz cPCI with 1 gigabyte ram
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive
Typical cruise speed knots	
Communications	Acoustic modem
Vehicle Availability	A - Limited

C&C Technologies ASV 6300

Length m	6.3
Width m	
Weight dry, kg	2000
Reserve buoyancy	96 (@4 kts), 50+ (@6 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	300
Payload weight kg	30 HP Yanmar Diesel Engine
Typical cruise speed knots	
Communications	
Vehicle Availability	A - Limited

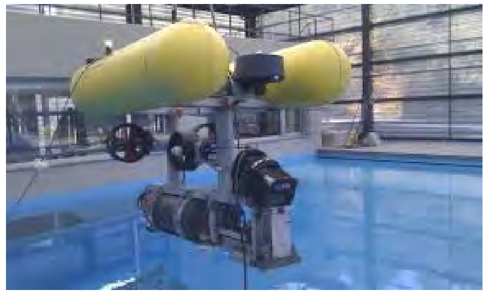
C&C Technologies ASV 9500

Length **m**	9.5
Width **m**	
Weight dry, kg	
Reserve buoyancy	720
Max. Mission Duration **hrs**	
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	diesel engine
Typical cruise speed **knots**	
Communications	
Vehicle Availability	A - Limited

C&C Technologies SASS-Q

Length m	6
Width m	
Weight dry, kg	
Reserve buoyancy	
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	200
Payload weight kg	
Typical cruise speed knots	
Communications	
Vehicle Availability	A - Limited

CIRS Girona 500



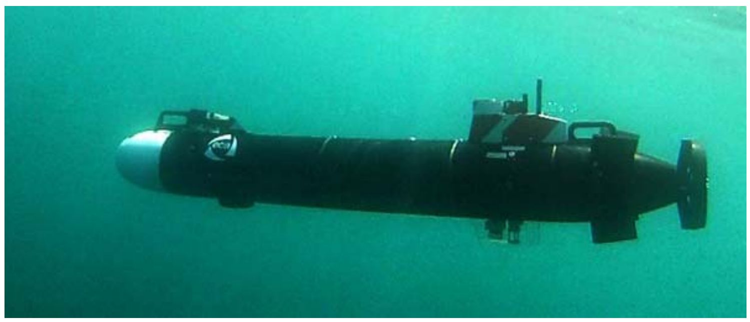
Length m	1.5
Width m	1
Height m	1
Dia. m	0.3
Weight dry, kg	200
Depth Rating m	500
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	
Communications	
Vehicle Availability	A - Limited

CMR Instrumentation Sailbuoy

Length m	2
Width m	
Weight dry, kg	60
Reserve buoyancy	1 yr
Max. Mission Duration hrs	
Available payload power	0.06
Payload volume cu. m	10
Payload weight kg	
Typical cruise speed knots	
Communications	Iridium
Vehicle Availability	B - Available

ECA Robotics Alister 9





Length **m**	1.7-2.5
Width **m**	
Height **m**	
Dia. **m**	
Weight dry, kg	50-90
Depth Rating **m**	100 200
Max. Mission Duration **hrs**	24
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	
Typical cruise speed **knots**	2-3
Communications	WiFi or Ethernet, Acoustic modem, Radio (VHF), Satellite link on request
Vehicle Availability	C - Commercial

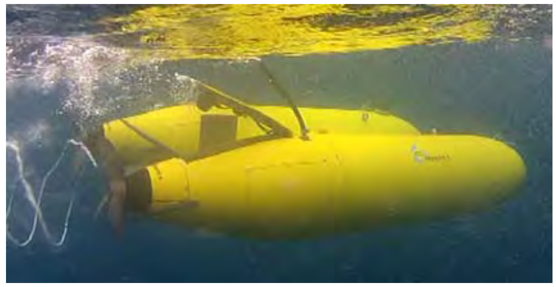
ECA Robotics ALISTER 18

Length m	3.5-4.6
Width m	
Height m	
Dia. m	0.47
Weight dry, kg	290-440
Depth Rating m	600
Max. Mission Duration hrs	24
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	1-2
Communications	WiFi or Ethernet, Acoustic modem, Satellite link on request
Vehicle Availability	B - Available

ECA Robotics ALISTER 27

Length m	5
Width m	
Height m	
Dia. m	
Weight dry, kg	800-1000
Depth Rating m	300
Max. Mission Duration hrs	30
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	3
Communications	WiFi or Ethernet, Acoustic modem, Radio (VHF), Satellite link on request
Vehicle Availability	B - Available

ECA Robotics ALISTER 18 TWIN



Length **m**	2.6-3.3
Width **m**	
Height **m**	
Dia. **m**	
Weight dry, kg	490-620
Depth Rating **m**	300, 600
Max. Mission Duration **hrs**	15
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	
Typical cruise speed **knots**	5 max
Communications	WiFi or Ethernet, Acoustic modem, Satellite link on request
Vehicle Availability	B - Available

ECA Robotics ALISTAR 3000

Length m	5
Width m	1.68
Height m	1.45
Dia. m	1.68
Weight dry, kg	2300 incl. pay-load
Depth Rating m	3000
Max. Mission Duration hrs	20
Available payload power	
Payload volume cu. m	
Payload weight kg	150
Mission Turnaround Time	
Typical cruise speed knots	2
Communications	RF, GPS/DGPS, Acoustic modem, Acoustic localization transponder
Vehicle Availability	C - Commercial

ECA Robotics ALISTER REA

Length **m**	4.4-5.0
Width **m**	0.7
Height **m**	1.2
Dia. **m**	0.7
Weight dry, kg	800-960
Depth Rating **m**	300
Max. Mission Duration **hrs**	12 to 20
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	
Typical cruise speed **knots**	4
Communications	
Vehicle Availability	C - Commercial

ECA Robotics Inspector MK2

Length m	8.4
Width m	
Weight dry, kg	4,700
Reserve buoyancy	20 (@6 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	1000
Payload weight kg	2 diesel hydro jets (2 x 170 to 215 kW)
Typical cruise speed knots	
Communications	
Vehicle Availability	B - Available

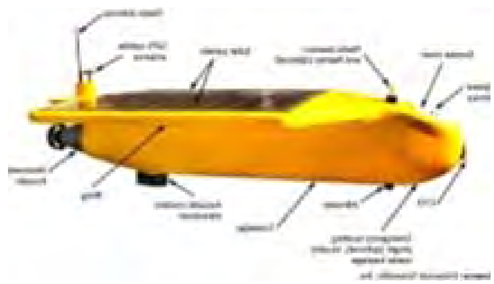
EvoLogics Sonobot

Length m	0.45
Width m	0.92
Weight dry, kg	30
Reserve buoyancy	10 (@2 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	
Payload weight kg	
Typical cruise speed knots	
Communications	WiFi
Vehicle Availability	B - Available

Exocetus Coastal Glider

Length **m**	2.87
Width **m**	0.32
Height **m**	2
Dia. **m**	2
Weight dry, kg	109-120
Depth Rating **m**	2.5
Max. Mission Duration **hrs**	200
Available payload power	alkaline batt.: 336 hrs (14 days), Li batt: 1440 hrs (60 days)
Payload volume **cu. m**	GPIO switch: 12 VDC (3 amp max) power available Expansion board: 5 VDC, and 3.5 VDC power available Raw battery: 18-33 VDC power available
Payload weight **kg**	0.113
Mission Turnaround Time	5
Typical cruise speed **knots**	
Communications	Iridium satellite, ARGOS, Freewave (UHF), WiFi, GPS
Vehicle Availability	B - Available

Falmouth Scientific SAUV II

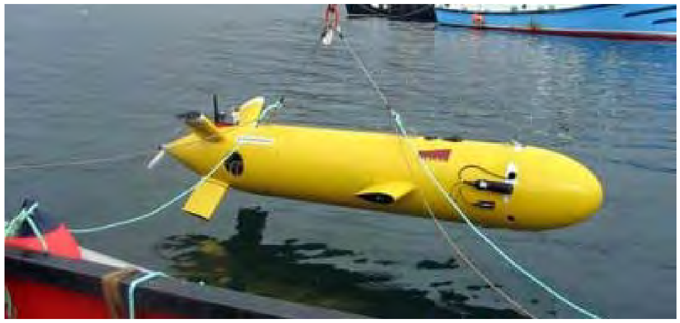


Length **m**	2.3
Width **m**	1.1
Height **m**	0.5
Dia. **m**	0.2
Weight dry, kg	200
Depth Rating **m**	500
Max. Mission Duration **hrs**	
Available payload power	10 W stand-by energy use thruster energy use 58-140 W max full charge solar panels provides 1900 Wh of available energy 10W hotel load is typical
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	Battery Charge Rate: 400 to 700 Whr/day (uses 2 batteries)
Typical cruise speed **knots**	1-2
Communications	Iridium satellite, RF, Acoustic modem
Vehicle Availability	B - Available

Graal Tech Folaga

Length m	2
Width m	0.15
Height m	0.15
Dia. m	0.15
Weight dry, kg	31
Depth Rating m	80
Max. Mission Duration hrs	6
Available payload power	12VDC
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	12VDC 45Ah
Typical cruise speed knots	2
Communications	2.4 GHz radio link
Vehicle Availability	B - Available

ISE Explorer



Length m	4.5 - 6.0
Width m	0.69
Height m	1.79
Dia. m	3000m: 0.69, 5000m: 0.74
Weight dry, kg	750-1250
Depth Rating m	300, 1000, 3000, 5000, 6000
Max. Mission Duration hrs	24-85
Available payload power	75 W
Payload volume cu. m	Variable -- forward free-flooding section allows for installation of 19-inch rack mounted equip.
Payload weight kg	1000m: 275, 3000m: 200, 5000m: 125
Mission Turnaround Time	5-10 hours depending on number of batteries used
Typical cruise speed knots	3
Communications	Acoustic modem, Iridium satellite, RF
Vehicle Availability	B - Available

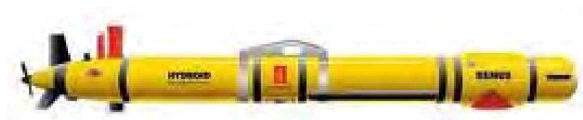
ISE Dorado

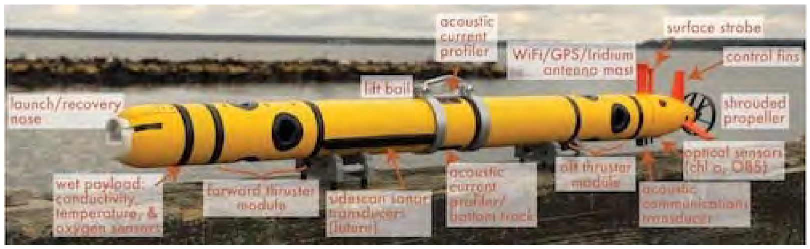
Length m	8.23
Width m	2.28
Weight dry, kg	6,600
Reserve buoyancy	28
Max. Mission Duration hrs	
Available payload power	0.6
Payload volume cu. m	210
Payload weight kg	marine diesel engine
Typical cruise speed knots	1-2 hours (refuel)
Communications	RF, Ethernet
Vehicle Availability	B - Available

Kongsberg REMUS 100/100-S

Length m	1.6
Width m	0.19
Height m	0.19
Dia. m	0.19
Weight dry, kg	38.5
Depth Rating m	100
Max. Mission Duration hrs	8 to 10
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	Battery recharge time 8-10 hours empty to full
Typical cruise speed knots	4.5
Communications	Acoustic modem, Iridium satellite, WiFi, Gateway buoy
Vehicle Availability	C - Commercial

Kongsberg REMUS 600/600-S





Length **m**	4.27
Width **m**	0.32
Height **m**	0.32
Dia. **m**	0.32
Weight dry, kg	240
Depth Rating **m**	600, 1500, 3000
Max. Mission Duration **hrs**	up to 70
Available payload power	150 W
Payload volume **cu. m**	
Payload weight **kg**	87 typical
Mission Turnaround Time	Battery recharge time 6-8 hours empty to full
Typical cruise speed **knots**	3
Communications	Acoustic modem, Iridium satellite, WiFi, 100 base-T Ethernet
Vehicle Availability	C - Commercial

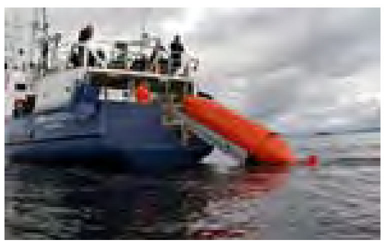
Kongsberg REMUS 6000

Length m	3.99
Width m	0.71
Height m	0.71
Dia. m	0.71
Weight dry, kg	862
Depth Rating m	4000, 6000
Max. Mission Duration hrs	16-22
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	2 hours if field swapped; 8 hours if charged
Typical cruise speed knots	4.5
Communications	Acoustic modem, Iridium satellite, 802.11G WiFi
Vehicle Availability	C - Commercial

Kongsberg HUGIN 1000

Length m	4.5 4.7
Width m	0.75
Height m	0.75
Dia. m	0.75
Weight dry, kg	650-850
Depth Rating m	1000, 3000
Max. Mission Duration hrs	24
Available payload power	200 W
Payload volume cu. m	variable
Payload weight kg	
Mission Turnaround Time	6 hours to recharge from empty to full
Typical cruise speed knots	3-4
Communications	Ethernet, Acoustic modem, Iridium satellite, RF, WLAN
Vehicle Availability	C - Commercial

Kongsberg HUGIN 3000

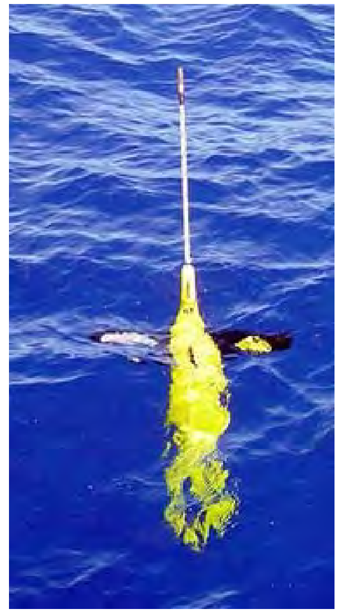


Length **m**	5.5
Width **m**	1
Height **m**	1
Dia. **m**	1
Weight dry, kg	1400
Depth Rating **m**	3000
Max. Mission Duration **hrs**	60
Available payload power	
Payload volume **cu. m**	variable
Payload weight **kg**	
Mission Turnaround Time	2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive
Typical cruise speed **knots**	4
Communications	Ethernet, Acoustic modem, RF, Iridium, WLAN
Vehicle Availability	C - Commercial

Kongsberg HUGIN 4500

Length **m**	6
Width **m**	1
Height **m**	1
Dia. **m**	1
Weight dry, kg	1900
Depth Rating **m**	4500
Max. Mission Duration **hrs**	60
Available payload power	
Payload volume **cu. m**	variable
Payload weight **kg**	
Mission Turnaround Time	2-3 hours for refill of battery chemicals; 3-4 hours for refill of battery chemicals and exchange of anode bars every second dive
Typical cruise speed **knots**	4
Communications	Ethernet, Acoustic modem, RF, Iridium, WLAN
Vehicle Availability	C - Commercial

Kongsberg 1KA Seaglider

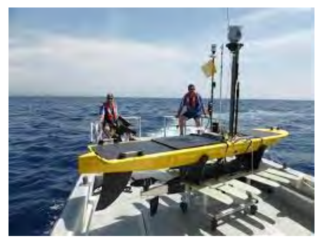


Length m	1.8-2
Width m	1 wing
Height m	0.4
Dia. m	0.3
Weight dry, kg	52
Depth Rating m	
Max. Mission Duration hrs	up to 1,000
Available payload power	7200 (10 months)
Payload volume cu. m	9 payload ports
Payload weight kg	0.344
Mission Turnaround Time	4
Typical cruise speed knots	0.5
Communications	Iridium satellite, ARGOS
Vehicle Availability	C - Commercial

Liquid Robotics Wave Glider SV2

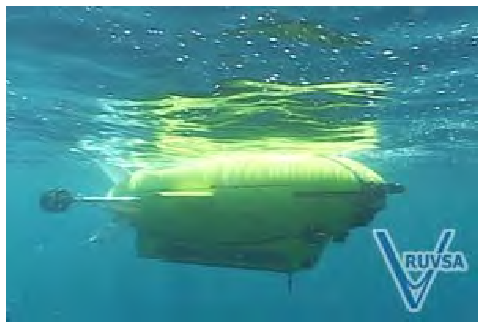
Length **m**	Float: 2.1 Glider: 1.9
Width **m**	1.07 (wing)
Weight dry, kg	90
Reserve buoyancy	Displacement: 150 kg
Max. Mission Duration **hrs**	Up to 1 year
Available payload power	10 W Payload ports (3): 3A/13.2V PEP port: 5A/13.2V Glider port: 1A/13.2V System maximum: 10A/13.2V
Payload volume **cu. m**	0.04
Payload weight **kg**	18
Typical cruise speed **knots**	0.5-1.6
Communications	Iridium Satellite RF modem Wifi
Vehicle Availability	C - Commercial

Liquid Robotics Wave Glider SV3



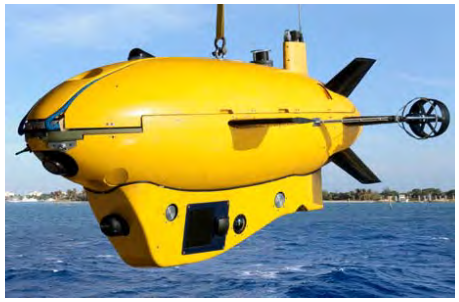
Length m	Float: 2.9 Glider: 1.9
Width m	1.4 (wing)
Weight dry, kg	90
Reserve buoyancy	Displacement: 150 kg
Max. Mission Duration hrs	Up to 1 year
Available payload power	10 W Payload ports (3): 3A/13.2V PEP port: 5A/13.2V Glider port: 1A/13.2V System maximum: 10A/13.2V
Payload volume cu. m	0.09
Payload weight kg	45
Typical cruise speed knots	1-2 w/o thruster 1.5-2.3 w/ thruster
Communications	Iridium Satellite RF modem Wifi
Vehicle Availability	C - Commercial

Lockheed Martin Marlin



Length m	3.05
Width m	
Height m	1.22
Dia. m	1.52
Weight dry, kg	954
Depth Rating m	300
Max. Mission Duration hrs	41997
Available payload power	
Payload volume cu. m	
Payload weight kg	114
Mission Turnaround Time	
Typical cruise speed knots	0-4
Communications	Acoustic modem, WiFi, RF
Vehicle Availability	B - Available

Lockheed Martin Marlin MK2



Length m	3
Width m	1.5
Height m	1.3
Dia. m	
Weight dry, kg	954
Depth Rating m	304-4000
Max. Mission Duration hrs	18-24
Available payload power	200+ W
Payload volume cu. m	0.1416
Payload weight kg	113
Mission Turnaround Time	
Typical cruise speed knots	0-6
Communications	Acoustic modem, Ethernet, Iridium satellite, WiFi, RF, Optional fiber optic tether
Vehicle Availability	B - Available

Maritime Robotics USV Mariner

Length m	5.8
Width m	2
Weight dry, kg	1700
Reserve buoyancy	50 (@5 kts)
Max. Mission Duration hrs	
Available payload power	1
Payload volume cu. m	
Payload weight kg	Volvo Penta D3 Engine
Typical cruise speed knots	
Communications	VHF/UHF/GPRS/Iridium opt.
Vehicle Availability	B - Available

Mitsui Eng. Aqua Explorer 2000

Length m	3
Width m	1.3
Height m	0.9
Dia. m	0.9
Weight dry, kg	3000
Depth Rating m	2000
Max. Mission Duration hrs	16
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	3
Communications	Acoustic low-level command link
Vehicle Availability	A - Limited

MOST AutoNaut

Length m	3.5
Width m	
Weight dry, kg	
Reserve buoyancy	3 months (@2-3 kts)
Max. Mission Duration hrs	20W @ 50% duty cycle for 90 days
Available payload power	
Payload volume cu. m	
Payload weight kg	Battery: 720Wh lead gel, Solar PV: 125Wp Generator: 45 watt methanol fuel cell, 20 litres fuel (22kWh of power)
Typical cruise speed knots	
Communications	UHF, XBEE PRO, Iridium
Vehicle Availability	B - Available

Ocean Server Iver2-580-EP

Length m	1.4
Width m	0.1
Height m	0.1
Dia. m	0.15
Weight dry, kg	21+
Depth Rating m	100
Max. Mission Duration hrs	14
Available payload power	
Payload volume cu. m	22 inches forward
Payload weight kg	
Mission Turnaround Time	4 to 8 hours to fully charge from empty to full
Typical cruise speed knots	2-Jan
Communications	WiFi 802.11G Ethernet
Vehicle Availability	C - Commercial

Ocean Server Iver2-580-S

Length m	1.27
Width m	0.1
Height m	0.1
Dia. m	0.15
Weight dry, kg	19
Depth Rating m	100
Max. Mission Duration hrs	14-24
Available payload power	15 W
Payload volume cu. m	10 inches forward
Payload weight kg	10
Mission Turnaround Time	4 to 8 hours to fully charge from empty to full
Typical cruise speed knots	2.5
Communications	WiFi, Iridium satellite, Acoustic modem
Vehicle Availability	C - Commercial

Ocean Server Iver3-450 Nano

Length m	1.6
Width m	0.1
Height m	0.1
Dia. m	0.1
Weight dry, kg	18
Depth Rating m	60
Max. Mission Duration hrs	10-Jun
Available payload power	24VDC
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	356 WHrs of li-Ion
Typical cruise speed knots	2.5
Communications	WiFi 802.11n Ethernet
Vehicle Availability	C - Commercial

Ocean Server Iver3-580-S

Length **m**	1.5-2.2
Width **m**	0.15
Height **m**	0.15
Dia. **m**	0.15
Weight dry, kg	39
Depth Rating **m**	100
Max. Mission Duration **hrs**	14
Available payload power	18-24VDC
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	800-1200 WHrs of Li-Ion
Typical cruise speed **knots**	2.5
Communications	WiFi, Iridium satellite, Acoustic modem
Vehicle Availability	C - Commercial

QinetiQ Sea Scout

Length m	0.9
Width m	
Height m	
Dia. m	0.12
Weight dry, kg	
Depth Rating m	200
Max. Mission Duration hrs	
Available payload power	14VDC
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	0-15
Communications	Radio (VHF), Iridium satellite
Vehicle Availability	B - Available

QinetiQ Blackfish

Length m	3.2
Width m	
Weight dry, kg	470
Reserve buoyancy	1
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	150
Payload weight kg	
Typical cruise speed knots	
Communications	VHF/UHF, WiFi, Iridium
Vehicle Availability	A - Limited

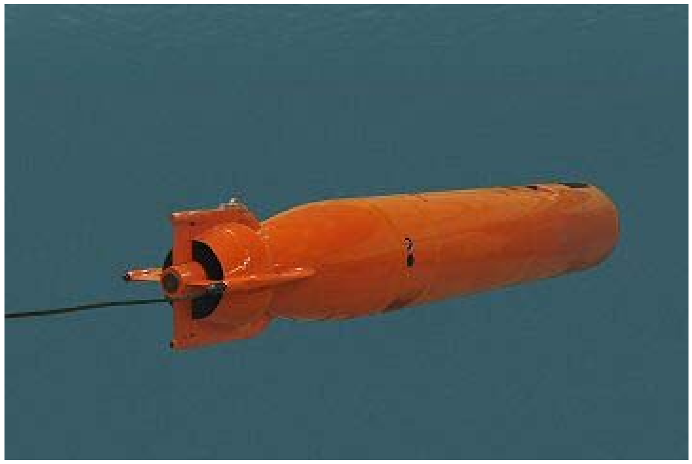
Robotic Marine Systems Scout

Length m	3
Width m	
Weight dry, kg	
Reserve buoyancy	8
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	
Payload weight kg	
Typical cruise speed knots	
Communications	RF WiFi
Vehicle Availability	B - Available

Saab Seaeye Eagle SAROV

Length m	2.9
Width m	1.3
Height m	1
Dia. m	
Weight dry, kg	540
Depth Rating m	500, 1500, 3000
Max. Mission Duration hrs	10+
Available payload power	600+ W
Payload volume cu. m	
Payload weight kg	250
Mission Turnaround Time	
Typical cruise speed knots	4-8
Communications	Gigabit Ethernet, WiFi, Radio, Acoustic
Vehicle Availability	C - Commercial

Saab Seaeye AUV62-MR



Length m	4-7 10 opt.
Width m	
Height m	
Dia. m	0.53
Weight dry, kg	600-1500
Depth Rating m	500
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	
Typical cruise speed knots	0-20
Communications	WLAN , UHF/VHF, SatLink,
Vehicle Availability	B - Available

Saildrone Saildrone

Length m	5.8
Width m	2.1
Weight dry, kg	
Reserve buoyancy	5000 hrs
Max. Mission Duration hrs	5-10 W
Available payload power	
Payload volume cu. m	90
Payload weight kg	Wind and Solar
Typical cruise speed knots	
Communications	
Vehicle Availability	A - Limited

Sea Robotics USV-1000

Length m	3
Width m	1.2
Weight dry, kg	40
Reserve buoyancy	12 (@2.4 kts), 6 (@4.37 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	80
Payload weight kg	Ni-MH batteries; Li-polymer batteries optional
Typical cruise speed knots	Battery fields swap
Communications	2402 MHz Ethernet
Vehicle Availability	C - Commercial

Sea Robotics USV-2600

Length m	3.25
Width m	1
Weight dry, kg	75-100
Reserve buoyancy	8 (@2.4 kts), 3 (@4.37 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	
Payload weight kg	Ni-MH batteries; Li-polymer batteries optional
Typical cruise speed knots	Battery fields swap
Communications	2403 MHz Ethernet
Vehicle Availability	C - Commercial

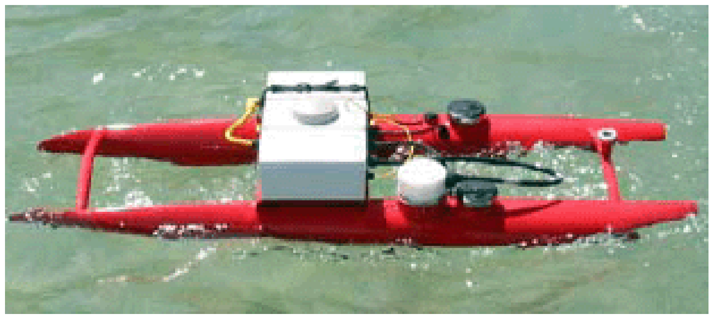
Sea Robotics USV-450

Length m	1.9
Width m	1.2
Weight dry, kg	40
Reserve buoyancy	8 (@2.4 kts) 2 (@4.37 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	80
Payload weight kg	Ni-MH batteries; Li-polymer batteries optional
Typical cruise speed knots	Battery fields swap
Communications	2400 MHz Ethernet
Vehicle Availability	C - Commercial

Sea Robotics USV-5000

Length m	4.25
Width m	0.5
Weight dry, kg	60
Reserve buoyancy	12 (@2.4 kts), 6 (@4.37 kts)
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	50
Payload weight kg	Ni-MH batteries; Li-polymer batteries optional
Typical cruise speed knots	Battery fields swap
Communications	2404 MHz Ethernet
Vehicle Availability	C - Commercial

Sea Robotics USV-600



Length **m**	1.25
Width **m**	0.66
Weight dry, kg	15
Reserve buoyancy	8 (@2.4 kts), 3 (@4.37 kts)
Max. Mission Duration **hrs**	
Available payload power	
Payload volume **cu. m**	8
Payload weight **kg**	Ni-MH batteries; Li-polymer batteries optional
Typical cruise speed **knots**	Battery fields swap
Communications	2401 MHz Ethernet
Vehicle Availability	C - Commercial

SIEL UAPS 20: RHIB 500

Length m	5.05
Width m	
Weight dry, kg	320
Reserve buoyancy	12 continuous
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	810
Payload weight kg	4 strokes outboard engine, 60 to 110 Hp
Typical cruise speed knots	
Communications	
Vehicle Availability	C - Commercial

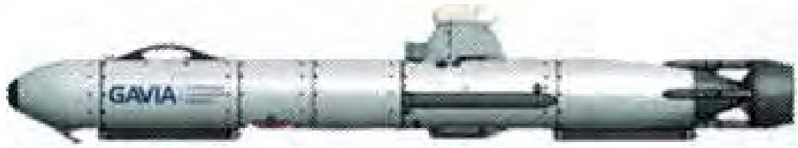
SIEL UAPS 20: RHIB 750

Length **m**	7.5
Width **m**	
Weight dry, kg	850
Reserve buoyancy	
Max. Mission Duration **hrs**	
Available payload power	
Payload volume **cu. m**	2160
Payload weight **kg**	4 strokes outboard engine, 110 to 250 Hp
Typical cruise speed **knots**	
Communications	
Vehicle Availability	C - Commercial

SIEL UAPS 20: RHIB 900

Length m	8.8
Width m	
Weight dry, kg	1500
Reserve buoyancy	
Max. Mission Duration hrs	
Available payload power	
Payload volume cu. m	2160
Payload weight kg	4 strokes twin outboard engine, 500 Hp
Typical cruise speed knots	
Communications	
Vehicle Availability	C - Commercial

Teledyne Gavia Defense

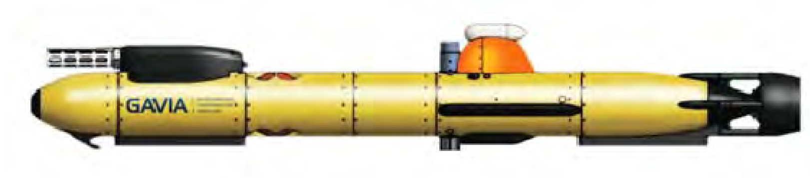


Length m	1.8
Width m	0.2
Height m	0.3
Dia. m	0.2
Weight dry, kg	49
Depth Rating m	500 1000
Max. Mission Duration hrs	7
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	Batteries can be field swapped; 5-6 hours to charge empty to full
Typical cruise speed knots	3
Communications	WLAN 802.11G, Iridium satellite, Acoustic modem
Vehicle Availability	A - Limited

Teledyne Gavia Offshore Surveyor

Length m	2.7
Width m	0.2
Height m	0.2
Dia. m	0.2
Weight dry, kg	70-80
Depth Rating m	500 1000
Max. Mission Duration hrs	4 – 5
Available payload power	
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	Batteries can be field swapped; 5-6 hours to charge empty to full
Typical cruise speed knots	3-Jan
Communications	WLAN 802.11G, Iridium satellite, Acoustic modem
Vehicle Availability	C - Commercial

Teledyne Gavia Scientific



Length **m**	1.8
Width **m**	0.2
Height **m**	0.3
Dia. **m**	0.2
Weight dry, kg	49
Depth Rating **m**	500 1000
Max. Mission Duration **hrs**	6
Available payload power	
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	Batteries can be field swapped; 5-6 hours to charge empty to full
Typical cruise speed **knots**	3
Communications	WLAN 802.11G, Iridium satellite, Acoustic modem
Vehicle Availability	C - Commercial

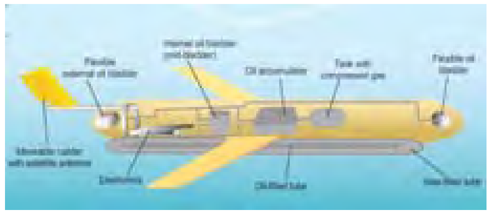
Teledyne Webb G2 Slocum Glider

Length m	1.5
Width m	
Height m	
Dia. m	0.22
Weight dry, kg	54
Depth Rating m	
Max. Mission Duration hrs	
Available payload power	alkaline batt.: 360-1200 (15-50 days), Li batt: 2922-5844 (122-244 days)
Payload volume cu. m	
Payload weight kg	0.098
Mission Turnaround Time	
Typical cruise speed knots	2-3
Communications	RF modem, Iridium satellite, ARGOS, Acoustic modem
Vehicle Availability	C - Commercial

Teledyne Webb Slocum Electric Glider

Length m	1.79
Width m	1 wing
Height m	0.49
Dia. m	0.21
Weight dry, kg	52
Depth Rating m	
Max. Mission Duration hrs	4-200, 1000
Available payload power	720, (30 days)
Payload volume cu. m	9–14 kHz transducer for active sonar use or for an acoustic modem 200-kHz transducer for altimeter use
Payload weight kg	
Mission Turnaround Time	4-Mar
Typical cruise speed knots	1-2
Communications	RF modem, Iridium satellite, ARGOS, Telesonar modem
Vehicle Availability	C - Commercial

Teledyne Webb Slocum Thermal Glider

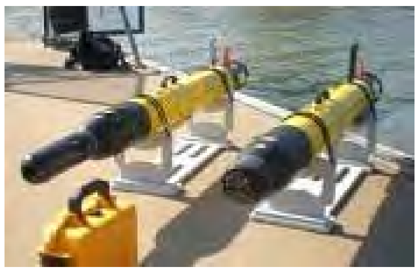


Length **m**	1.79
Width **m**	1.01
Height **m**	0.49
Dia. **m**	0.21
Weight dry, kg	60
Depth Rating **m**	
Max. Mission Duration **hrs**	1200
Available payload power	26,297 to 43,829 (3-5 years)
Payload volume **cu. m**	
Payload weight **kg**	
Mission Turnaround Time	
Typical cruise speed **knots**	0.7
Communications	RF modem, Iridium satellite, ARGOS
Vehicle Availability	C - Commercial

Woods Hole Sentry

Length m	2.9
Width m	2.2
Height m	1.8
Dia. m	
Weight dry, kg	1250
Depth Rating m	6000
Max. Mission Duration hrs	20-40
Available payload power	48-52VDC
Payload volume cu. m	
Payload weight kg	
Mission Turnaround Time	10 hrs
Typical cruise speed knots	0-2
Communications	Acoustic modem
Vehicle Availability	A - Limited

YSI EcoMapper



Length m	1.5
Width m	0.1
Height m	0.1
Dia. m	0.147
Weight dry, kg	20
Depth Rating m	100
Max. Mission Duration hrs	8
Available payload power	12-18 VDC
Payload volume cu. m	10 inches forward
Payload weight kg	
Mission Turnaround Time	4 to 8 hours to fully charge from empty to full
Typical cruise speed knots	2.5
Communications	WLAN 802.11G
Vehicle Availability	C - Commercial

ZyCraft Vigilant

Length m	16.5
Width m	
Weight dry, kg	6000-13000
Reserve buoyancy	720
Max. Mission Duration hrs	
Available payload power	18
Payload volume cu. m	2700
Payload weight kg	
Typical cruise speed knots	
Communications	
Vehicle Availability	A - Limited