Autonomous Surface Vehicle Workshop

PROCEEDINGS

November 18-20, 2015
Solomons, MD

Funded by the National Oceanic and Atmospheric Administration (NOAA) through the U.S. Integrated Ocean Observing System (IOOS). [UMCES] CBL 2016-005

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Acronyms

ACT	Alliance for Coastal Technologies
ASV	Autonomous Surface Vehicle
CBL	Chesapeake Biological Laboratory
COLREGS	International Regulations for Preventing Collisions at Sea 1972
IOOS	Integrated Ocean Observing System
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
UMCES	University of Maryland's Center for Environmental Science

About ACT

The Alliance for Coastal Technologies (ACT) is a partnership of research institutions, resource managers, and private sector companies dedicated to fostering the development and adoption of effective and reliable sensors and platforms for use in coastal, freshwater and ocean environments.

ACT workshops are designed to aid these partners by identifying and discussing the current status, standardization, potential advancements, and obstacles in the development and use of sensors and sensor platforms for studying, monitoring, and predicting the state of coastal, fresh and open ocean waters. The workshop goals are to both build consensus on the steps needed to develop useful tools while also facilitating the critical communications between the various groups of technology developers, manufacturers, and users. Workshop reports provide a status report on current technologies and recommendations for both ACT and the broader community on steps forward (Alliance for Coastal Technologies, 2015).

Author Acknowledgement

The following individuals contributed towards the development of this report: Dr. Guy Meadows, Great Lakes Research Center, Michigan Technological University; Mr. Val Schmidt, University of New Hampshire; Dr. Mark Luther, University of Florida; and Mr. Rob Downs, National Oceanic and Atmospheric Administration. The authors wish to acknowledge the publication development assistance provided by Ms. Elizabeth Hoy (contribution No. 35 of the Great Lakes Research Center), Michigan Technological University.

Executive Summary

The Alliance for Coastal Technologies (ACT) convened a workshop on *Autonomous Surface Vehicles (ASVs) for Shallow Water Mapping and Water Quality Monitoring* at the University of Maryland's Chesapeake Biological Laboratory on November 18-20, 2015. The goal of the workshop was to develop a consensus of future actions that would accelerate the use of unmanned systems, particularly ASVs, to meet shallow water survey requirements established by the National Oceanic and Atmospheric Administration (NOAA) and to aid in the transition of evolving technologies from "research tools" to "operational tools." While the initial scope of the workshop focused on shallow water, the lessons learned through participant exchange will allow for informed decisions regarding broader ocean applications of ASVs. In particular, the workshop focused on opportunities in the user market, performance parameters, usability requirements, cost considerations, and feasibility of use.

To facilitate broad input in the feasibility of unmanned systems use, workshop participants included representatives from the private sector, research and end-user communities. Private sector participants included vendors and manufacturers of ASVs. End-user participants included resource managers responsible for preservation and stewardship of coastal regions. The research community included representatives from academia, state and federal agencies. Participants were asked to assess current state and future applications of ASV use to meet a variety of needs. For example, could ASVs provide improved efficiency of data acquisition, including a reduction in time, personnel, and operating costs; improved quality of data acquired; improved safety of survey operations; and provide data that is beneficial, but otherwise unattainable or typically difficult to obtain?

The workshop included a field demonstration of ASV systems by attending vendors/manufacturers to provide proof of performance in the field and demonstrate real-time autonomous survey capabilities. The vendors/manufacturers were given a hydrographic challenge to provide a demonstration survey of an approach channel to Solomons Island, MD and associated shoals in adverse weather conditions.

Autonomous systems offer advantages over manned systems. Autonomy can be described as independence, or freedom from external control or influence. ASVs represent a field of emerging, integrated, marine observing technologies that includes hardware, software, platforms, sensors, data acquisition, storage, processing and transfer technologies, on a vessel moving across the water surface in an intelligent manner. Presently, ASVs offer extended mission endurance (as great as 20 days), excellent payload capabilities, and large power budgets available for both instrumentation and data storage/analysis. Coupled with relatively shallow drafts and the ability to produce high quality survey products in environments which are repetitive (dull), hazardous to human crews (dangerous) and environmentally unhealthy (dirty) make ASVs a promising tool. Hence, the "three Ds" of dull, dangerous and dirty, define the current suite of missions ideally suited for ASV operations.

At sea, operational requirements must be met, while still pursuing greater functionality in ASV operational modes. Currently, at sea retrieval, maintenance, and repair of existing ASV models have proven to be costly and difficult. At the present state of ASV development, little crew or cost savings have been realized over conventional survey operations. There are notable exceptions to this generalization when ASVs are used as a force multiplier, working in collaboration (within line of sight) of a conventional survey platform.

Acknowledging that ASV development has lagged behind underwater autonomous vehicle development, the workshop participants made the following recommendations for continuing the improvement of ASV use and operation and assessing user needs in both the short and long term:

1. Continue development of base, open source systems for broader use and greater adoption.
2. Establish an ASV Technical Committee to advise future development and bring to the ASV environment best practices already established by other domains.
3. Develop and communicate success cases to aid in greater adoption and use of ASV platforms for a wide variety of survey and water quality monitoring applications.
4. For specific applications, identify funding partners for continued research and development.
5. Develop a set of recommended best practices.
6. Create a national/international, repository/database of available platforms and sensor technologies.
7. Develop expectations for responsible conduct of "at sea" operations as a function of survey complexity (environment).
8. Develop a strategy for adoption by: a) looking at levels of autonomy and best practices in other modes - terrestrial, aerial, etc.; and b) incorporating maturing technologies into next generation ASVs.

ACT could help stimulate multiple markets and resource needs to demonstrate capacity. For example, the U.S. Integrated Ocean Observing System (IOOS) Marine Sensor Innovation: Ocean Technology Transition appears ideal to aid in further developing ASV technology for ocean applications (Department of Commerce, 2015).

At the current state of technology, ASVs are better referred to as *Unmanned* Surface Vehicles, given the current level of operator intervention and monitoring that is required for safe and effective operations. Unmanned systems, regardless of level of autonomy, should not be considered as viable one-for-one replacements for manned survey platforms, nor should their adoption be driven by a desire to reduce staffing. It would be beneficial to identify specific operational environments, observation requirements, or concepts of operations for which unmanned systems are well-suited and to fund operational demonstrations to strengthen the case for their transition to operational acceptance.

Introduction

To explore recent advancements of ASV technology, NOAA, through the IOOS Program Office (http://www.ioos.noaa.gov/), funded ACT to organize a workshop on *Autonomous Surface Vehicles (ASVs) for Shallow Water Mapping and Water Quality Monitoring*. The workshop focused on accelerating research, operational readiness and further development of ASV technologies. The workshop was planned and executed with the involvement and cooperation of a broad and diverse group of federal agencies, vendors and manufacturers, resource managers and university researchers with scientific and operational application experience.

ACT convened the workshop at the University of Maryland's Center for Environmental Sciences (UMCES), Chesapeake Biological Laboratory (CBL) to develop a consensus of future actions that would accelerate the feasibility of having unmanned systems, particularly ASVs, to meet shallow water survey requirements established by NOAA and to aid in the transition of evolving technologies from "research tools" to "operational tools." In particular, the workshop focused on opportunities in the user market, performance parameters, usability requirements, cost considerations, and feasibility of use.

NOAA's National Ocean Service (NOS) line office provides services and tools that play a key role in ensuring the safe and efficient movement of ships while protecting our nation's waterways and coastal environments. High quality surveying, mapping and water quality monitoring of coastal waters are essential to NOS's work. The combination of these compelling and collaborative goals provided the framework within which to assess the current state of ASV development and to create an avenue to further advance this developing technology. This national level workshop was conceived to inform and advance the current "state of the art" of autonomous surface vehicles.

The purpose of the workshop was to explore current and soon to be in place technologies to: a) better understand their potential benefits and limitations; b) to understand end-user requirements for ASV applications; and, c) to make strategic recommendations for the future development and application of ASVs for environmental water quality monitoring and surveying in shallow coastal waters. While the initial scope of the workshop and manufacturers' demonstrations were focused on shallow water, the lessons learned inform decisions regarding broader application of ASVs by addressing challenging environments.

The workshop addressed questions, including:

- Could ASVs provide improved efficiency of data acquisition, including a reduction in time, personnel, and operating costs?
- Could ASVs provide improved quality of data acquired?
- Could ASVs provide improved safety of survey operations?
- Could ASVs provide data that is beneficial, but otherwise unattainable or typically difficult to obtain?

Much of the current ASV technology operates at a level of basic autonomy. Autonomy can be described as independence, or freedom from external control or influence. ASVs represent a field of emerging, integrated, marine observing technologies that includes hardware, software, platforms, sensors, data acquisition, storage, processing and transfer technologies, on a vessel moving across the water surface in an intelligent manner. Basic autonomy requires operator involvement to a substantial extent in planning, executing, overseeing and recovery from the mission. By improving the level of ASV autonomy, vehicles capable of performing planned objectives and having increased levels of onboard intelligence may benefit the user community that relies on ASVs for shallow water quality monitoring and mapping. However, many obstacles hinder these advancements. Obstacles include definition of a clear, efficient, and value added, hydrographic survey mission for ASVs; concerted efforts to engage the research community in further ASV development (as has been the case for Underwater Autonomous Vehicles); and, the present existence of a relatively small number of manufacturers engaged in development and servicing ASVs coupled with an equally limited current market demand.

On the ocean surface, the ever present (or nearly so) availability of global positioning systems provides significant navigational advantages over underwater autonomous operations. However, these advantages are quickly overcome by difficulties of operations at the air/sea interface. The presence of harsh conditions at this interface, including wind, waves, structural icing, floating ice and other vessel traffic, compound the problems of ASV operation and development.

Presently, ASV's offer extended mission endurance (as great as 20 days), excellent payload capabilities, and large power budgets available for both instrumentation and data storage/analysis. Coupled with relatively shallow drafts and the ability to produce high quality survey products in environments which are repetitive (dull), hazardous to human crews (dangerous) and environmentally unhealthy (dirty) make ASVs a promising tool. Hence, the "three Ds" of dull, dangerous and dirty, define the current suite of missions ideally suited for ASV operations.

Furthermore, at sea operational requirements must be met, while still pursuing greater functionality in ASV operational modes. Currently, at sea retrieval, maintenance, and repair of existing ASV models have proven to be costly and difficult. At the present state of ASV development, little crew or cost savings have been realized over conventional survey operations. There are notable exceptions to this generalization when ASVs are used as a force multiplier, working in collaboration (within line of sight) of a conventional survey platform.

Workshop Overview

The ACT workshop on *Autonomous Surface Vehicles (ASVs) for Shallow Water Mapping and Water Quality Monitoring* was held November 18 - 20, 2015, in Solomons, Maryland, at UMCES CBL. NOAA's ocean observation and mapping requirements include the critical, nearshore, shallow water (less than 10 meters) regions of the coastal ocean and Great Lakes, which is reflected in the shoreline near CBL. Within these coastal waters, rapidly changing bathymetry and water quality is common, making frequent mapping and monitoring critical. Furthermore, traditional shipboard observations may not be possible or effective in these regions and in many cases, small boat survey operations may be laborious and/or unsafe. CBL offered an ideal, tidally dominated, location to bring these constraints to the forefront.

To investigate and discuss the feasibility of using unmanned systems, particularly ASVs, to meet NOAA's shallow water requirements, the workshop included participants (see Appendix A) from the following sectors:

- Private sector vendors and manufacturers of ASVs
- End-users, including resource managers responsible for preservation and stewardship
- Researchers from academia, state, and federal agencies

The workshop agenda (see Appendix B) began with a series of background presentations that summarized the role of ACT, NOAA and its partner programs in further developing ASV technology to meet current and future nearshore survey needs. In addition, brief presentations from each vendor/manufacturer were delivered to demonstrate the current "state of the art" of commercially available ASV systems, sensors and onboard processing systems (see Appendix C for vendor/manufacturer slides).

A series of workshop charge questions were posed to facilitate dialogue across the broad spectrum of participants. In response, the workshop participants provided input on various aspects of desired operational, physical and technical characteristics of ASVs, characteristics of any required shipboard or shore-side equipment, as well as ASV launch and recovery requirements, desired ASV payload capabilities, ASV operating environment capabilities, ASV specific systems, and response behaviors for navigational safety, command and control systems, and vehicle fault tolerances.

The workshop also included a field demonstration of ASV systems by attending vendors/manufacturers to provide proof of performance in the field and demonstrate real-time autonomous survey capabilities. Prior to the workshop the vendors/manufacturers were given a hydrographic challenge to provide a demonstration survey of the approach channel and associated shoals to Solomons, MD. The red-hashed area shown in Figure 1 designates the ASV Workshop demonstration survey area. This allowed each vendor an opportunity to demonstrate how their ASV platform operated in the field including data collection and their analysis process. During the ASV field demonstration, winds were strong from the southeast with wave heights running approximately 2 ft. Vehicle demonstrations included a Z-Boat profile platform from Teledyne Oceansciences, a kayak profile platform developed by Woods Hole Oceanographic Institution, and a catamaran profile platform from SeaRobotics. ASVs manufactured by other participants, ASV Global, LLC and Sea Machines Robotics, were too large to bring to the workshop demonstration.

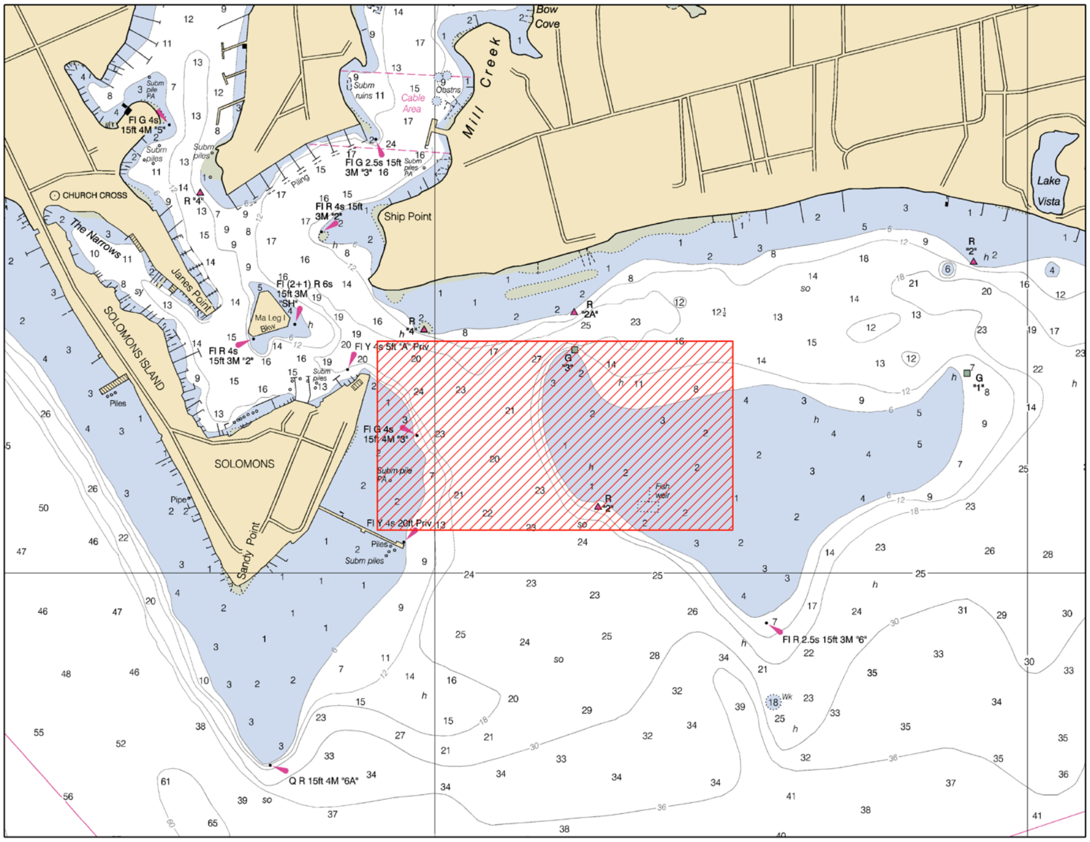

Figure 1. Approach Channel and associated shoals to Solomons, MD. The red zone designates the ASV Workshop demonstration survey area.

As an example, the ASV demonstrated by Woods Hole Oceanographic Institution provided the vehicle tracks and multi-beam sonar coverage swaths shown in Figure 2 and the gridded and interpolated bathymetry shown in Figure 3 respectively.

For comparison NOAA provided images shown in Figure 4 of the 1944 survey H6876 (top), and the current navigation chart (bottom). As one can see, virtually all the soundings in the test area come from this WWII era sounding-pole survey. In most shoal areas the charted depths drop to as little as 1 ft., making survey by conventional manned launches and autonomous surveys difficult to plan as the uncertainty in depth would not allow even most shallow draft autonomous vessels to operate in this region. The new measurements reveal most of these areas were 1 m or deeper, allowing operation of survey vessels. This is not to say that this chart has not been periodically updated producing a useable and safe product, albeit based on very old data.

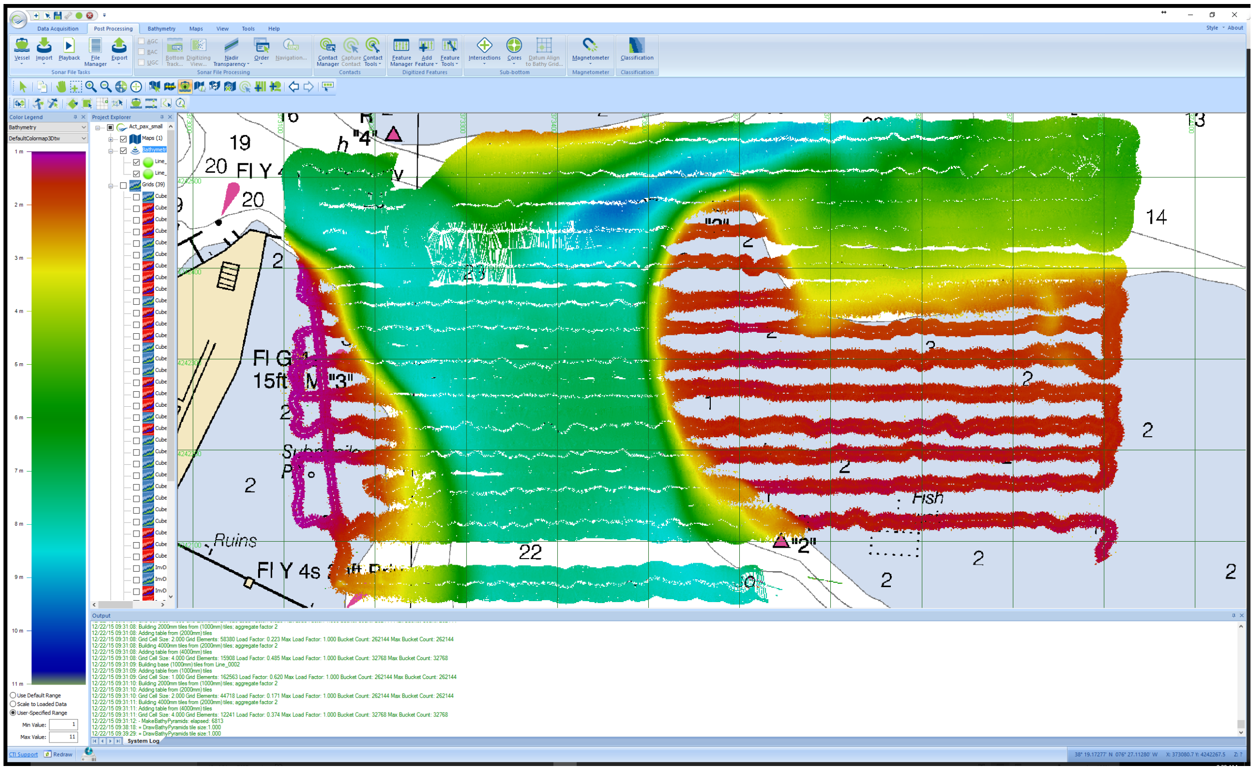

Figure 2. ASV vehicle tracks and multi-beam sonar coverage swaths through the demonstration area. *Woods Hole Oceanographic Institution – Peter Traykovski* ptraykovski@whoi.edu

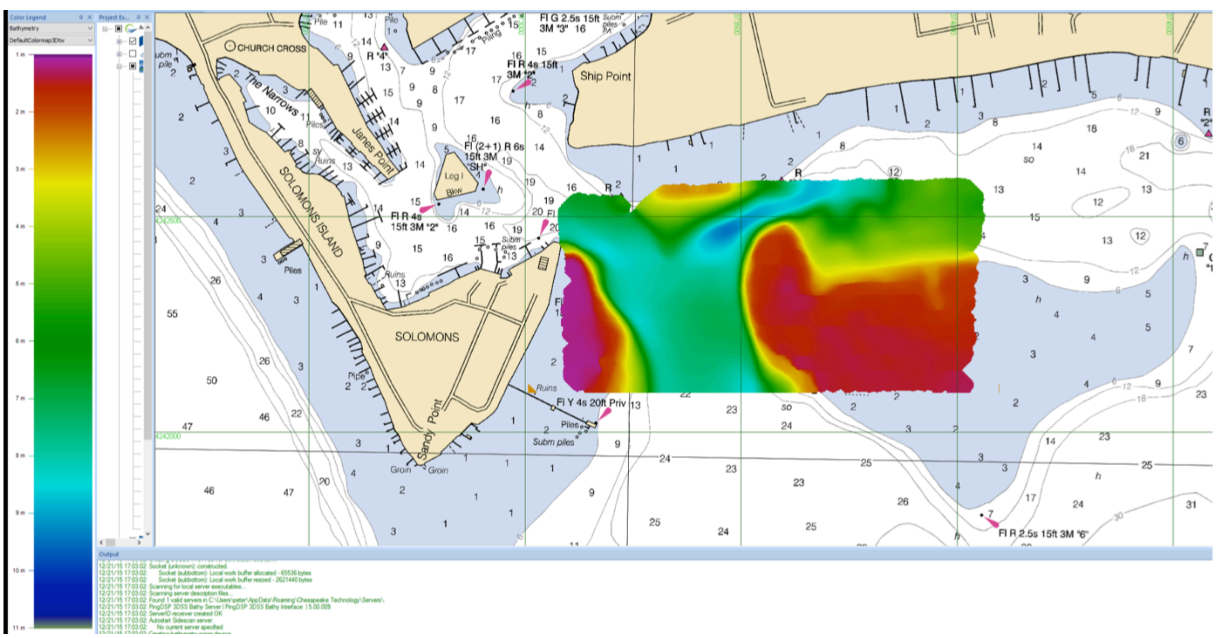

Figure 3. Resulting gridded and interpolated bathymetry from ASV demonstration. *Woods Hole Oceanographic Institution – Peter Traykovski* ptraykovski@whoi.edu

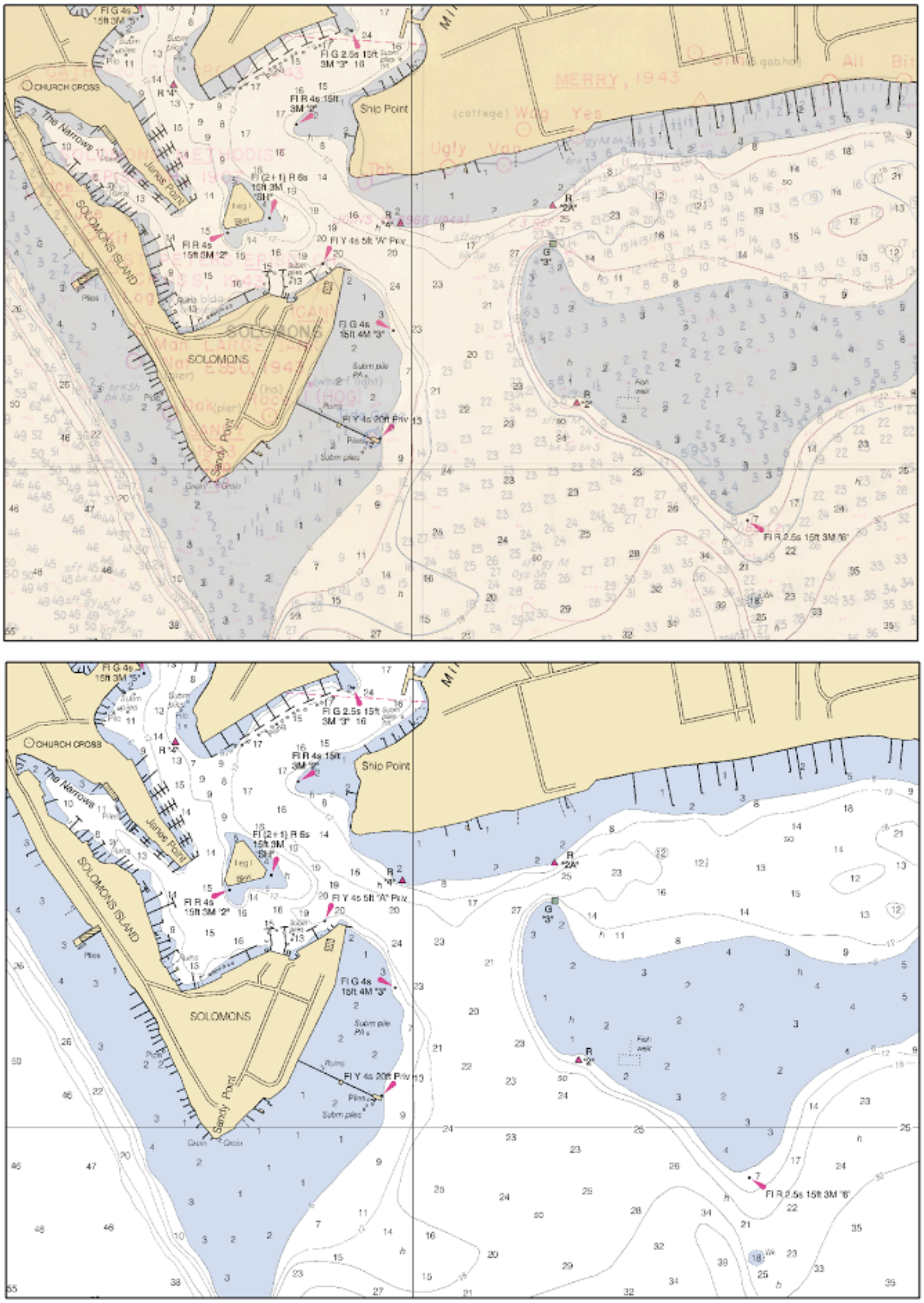

Figure 4. NOAA provided images attached of the 1944 survey H6876 (top), and the current (bottom) navigation chart. *Samuel Greenaway - NOAA National Ocean Service* samuel.greenaway@noaa.gov

Workshop Outcome

Workshop discussions revealed significant advancements and potential applications, but also recommendations related to a critical need for a common framework to address issues of environment, supervision and risk in current and future ASV use and operation. Based on input provided by workshop attendees, Mr. Val Schmidt of the University of New Hampshire (a workshop participant) provided the following discussion of standardizing terminology to mitigate risk in autonomous marine vessel operations.

Environment, Autonomy and Supervision: Standardizing Terminology to Mitigate Risk in Autonomous Marine Vessel Operations

Autonomous surface and underwater vessels provide unique capabilities to scientific research, the offshore oil and gas industry, fisheries management, hydrographic survey, habitat mapping and many others. Autonomous vessels can be small, highly portable and quickly deployed. Or they can be large, with long endurance, and have large electrical and mechanical payloads. Regardless of the size, operating environment or mission goals, autonomous surface and underwater vessels must be operated within tolerable levels of risk for the safety of the vessel, other vessels and human life.

The level of tolerable risk is defined, in part, by the operating organization and by governmental regulations regarding safe operations of vessels at sea. Military operations in a war-time environment may tolerate a higher level of risk. Research organizations may have higher tolerances for risk for the vehicle itself when testing new algorithms and systems. Oil and gas exploration may have very low tolerances for risk due to the great danger to human life and the environment involved. In any event, efforts by organizations to meet a tolerable level of risk result from three primary considerations: 1) the operational environment, 2) the level of autonomy of the vessel, and 3) the level of supervision of the vessel during autonomous operations.

When designing systems, purchasing systems for a particular mission type, preparing for operations of autonomous vessels and conducting those operations at sea, it is helpful to have in mind standard definitions for levels of autonomy of the vessel, as well as standard definitions for the level of supervision under which a vessel is to be operated. Doing so allows a customer to specify a desired level of autonomy in a request for proposals and allows a manufacturer to build a vessel using a standard level of autonomy as a design goal. In this way, communications between customers and manufacturers are made clear. Defining standard levels of autonomy also allows classification of a vehicle at a particular level such that operators can formalize and even quantify the risk posed by operations in various environments and under various circumstances. For example, a malfunction of a critical object avoidance subsystem might not prevent mission operation, but might place the vehicle in a lower autonomy level requiring a higher level of supervision to meet the same risk tolerance. When standard levels of autonomy and supervision are defined categorically the precise actions to take to meet this risk tolerance become more clear.

Therefore, in the following sections, after first illustrating several kinds of operational environments to provide context for future discussion, five levels of autonomy and three levels of supervision are proposed. In defining these levels, a standard is set that may be adopted by vessel manufacturers, operators and the public to clarify their communications and thinking about operation of autonomous marine vessels.

Operational Environment

Operational environments vary greatly in the level of risk presented to unmanned vehicles. Ports and harbors present a very complex, high risk environment in which an unmanned system would have to contend with a high density of other vessel traffic, complex vessel traffic routing schemes, fishing gear, and other navigational hazards. Polar areas are unlikely to present similar hazards and the unmanned system may not encounter any other vessels or obstacles at all, but can present other risks, such as ice and remote operations, that may require very robust systems. At the other end of the range, unmanned systems may be operated in controlled environments, such as lakes or reservoirs, where the obstacles are known and can be managed in advance.

Additionally, areas with high currents require different considerations from those without, particularly when the currents are a large fraction of the vessel's maximum speed. Weather and sea state further complicate any environment. Therefore, it is important to recognize the interaction between environment, level of autonomy, and level of supervision desired when assessing risk and determining the suitability of an unmanned system for the desired task. The high level of autonomy necessary for unsupervised operations in a high risk environment, such as a busy harbor, may not be achievable. However, a system with basic autonomy may be suitable for such an environment if a high level of supervision is practical. Conversely, basic autonomy may be all that is necessary to successfully operate a system with very little supervision in a controlled environment.

Levels of Vessel Autonomy

Because the levels of vessel autonomy can vary so greatly between vessels, environment and mission it is useful to define them categorically. Well defined levels of autonomy help to clarify requirements between manufacturers and their customers. Moreover, they imply a level of the relative risk of operations and therefore ancillary systems to put in place to mitigate those risks. Thus five levels of autonomy are defined and described in detail below with examples for illustration. They are: Remote Piloting ("manual"), Basic Autonomy ("do as you're told"), Intermediate Autonomy ("do as your told and react to what's known"), Advanced Autonomy ("do as your told, sense and react to what's not known") and Planning ("think").

In addition, when defining the five levels of autonomy it becomes useful to separate the levels of autonomy into three categories within each level. The three categories are

“Self-awareness”, “Operations” and “Sensor” autonomy. The Self-awareness category involves levels of autonomy dealing with the vessel’s ability to monitor and possibly react to its own physical state (position, orientation, speed, and temperature), fuel (or battery) levels and control systems. The Operations category involves the vessel’s ability to be piloted remotely or conduct a mission without operator interaction, whether as a sequential list of objectives or as behavioral routines that are followed under various circumstances. The Operations category at the highest levels of autonomy involves long-term planning, perhaps solving “Traveling Salesman” type problems in which many competing objectives are considered. Finally, the Sensor category involves the ability to operate and manage payload sensors, turning them on and off, logging their data, configuring them from fixed mission plans or within a mission in response to changing circumstances or environments.

Level 1: Remote piloting (manual)
Self-awareness: Position, orientation, speed and possibly rudimentary knowledge of subsystem states (battery voltage/fuel level, rudder position, and thrust level) is telemetered to the operator in real time for display and immediate situational awareness only, with no requirement for logging of data.

Operations: Remote piloting of a vessel is the act of manually controlling thrust and rudder movements through a telemetry link to the vessel. It involves no autonomous behavior.

Sensor: Remote piloting of a sensor is operating the sensor manually for both configuration and logging of data, either prior to mission execution or interactively via remote telemetry link. It involves no autonomous behavior.

Level 2: Basic Autonomy (do as you’re told)
Self-awareness: Basic Autonomy involves the ability to sense, time stamp and log internally the basic vessel condition including position, orientation, speed, fuel status (whether battery voltage, watt-hours consumed or fuel tank level) and may include internal temperatures, humidity level, leak detection and power consumed by various payloads. Basic Autonomy is distinguished from Remote Piloting in that parameters are time stamped and logged to provide a history of operations that may be scrutinized for forensic and engineering analysis to improve operations and understand casualties. Basic Autonomy also involves the ability to generate faults and alarms to the operator based on sensed parameters and fixed alarm set points. These may include leak detections, over-heating, low fuel levels or over speed warnings.

Operations: Basic Autonomy involves the ability to follow a pre-planned fixed mission consisting of a sequential list of waypoints, lines, loiter points and combinations of these without operator interaction. With some exceptions the only inputs are the vessel’s position and heading (from onboard sensors) and the desired point to reach. Generally, the only outputs are thrust and control surface (rudder) angles.

Sensor: Basic Autonomy involves the ability to turn a sensor on or off at specified times during a mission to manage power, acoustic bandwidth etc. and to start and stop logging of data at prescribed points within a sequential mission plan. For example, a sonar might be triggered to log data at the start of each survey line and to stop logging when the line is completed, or to power off systems completely, as prescribed in a mission plan, for example to actively manage power consumption. At the Basic Autonomy level these actions are programmed by the operator as part of the mission plan rather than undertaken by the vehicle itself, except perhaps when load shedding in emergency circumstances. Basic autonomy may also include the ability to time-stamp and log data from sensors that do not have their own native logging capability (i.e. they simply produce data when activated), and managing those log files along with other mission logs (e.g. rotating logs when appropriate, organizing logs by mission, etc.) Basic Autonomy is distinguished from Intermediate Autonomy in that sensors must be manually configured and reconfigured as necessary.

Level 3: Intermediate Autonomy (do as you're told and react to what's known)
Self-awareness: Intermediate Autonomy involves the implementation of models of vehicle performance that are informed by sensor inputs in real-time to provide a more complete estimate of the vehicle's state. The obvious example, is that of an Extended Kalman Filter operating on various (and possibly multiple) measures of position, velocity, acceleration and orientation, to estimate the complete pose of the vehicle. However other simpler models are possible, for example knowledge of the vehicle's turn radius such that Williamson turns can be executed when waypoints fall within it, or fuel consumption models for various speeds that allow the vehicle to predict its ability to complete a mission.

Operations: Intermediate Autonomy involves the ability to adjust a pre-planned mission in a reactionary way to fixed (i.e. not dynamically sensed) input according to fixed rules, for example, to avoid shallow water, charted hazards to navigation, a polygon of prohibited operational area. Intermediate Autonomy is distinguished from Basic Autonomy in that the effect is a behavioral response to a set of conditions in addition to accomplishing a set of tasks in sequence. This level of autonomy is distinguished from Advanced Autonomy in that it applies a fixed set of rules to a fixed set of conditions in which the data used to evaluate the conditions is not actively sensed in real-time, but rather is known *a priori*.

Sensor: Intermediate Autonomy involves the ability to programmatically configure or reconfigure a sensor, setting values programmatically based those specified within the mission plan at defined points along the route. Examples of programmatically specified settings might include specifying within the mission plan an increase in side-scan sonar maximum range, knowing that the survey will progress into deeper water, Intermediate Autonomy is distinguished from Advanced Autonomy in that configuration (or reconfiguration) of the sensors is fixed, specified a priori in the mission plan, rather than adjusted according to sensed input.

Level 4: Advanced Autonomy (do as you're told, sense and react to what's not known)
Self-awareness: Advanced Autonomy involves the ability to recognize when the vehicle's movement or other sensed parameters do not fit the expected model and to react to

warn operators or other vessels, when possible, compensate for the effect, all to mitigate their impact on operations, risk to property or human life. Advanced Autonomy involves closed loop control in which, for example, movements of the rudder are tested against expected changes in heading, or increases in thrust are tested against changes in vessel speed. Advanced Autonomy also includes the ability to recognize when one of a redundant set of systems has failed and to switch operations to the second. Reactions to faults also might include for example, sounding five blasts of a whistle in accordance with International Regulations for Preventing Collisions at Sea 1972 (COLREGS) when a loss of propulsion is detected. Advanced Autonomy is distinguished from Intermediate Autonomy in that control actions are actively tested against a model of expected vehicle response and action is taken when the two do not match.

Operations: Advanced Autonomy involves the ability to adjust a pre-planned mission in a reactionary way to dynamically sensed conditions, for example, to detect and avoid previously unknown buoys, lobster pot floats, other vessels (COLREGS compliance), to follow and/or track another vessel and to moor by anchor or pier without user intervention. Advanced Autonomy is distinguished from Intermediate Autonomy in that it requires onboard sensing systems to actively measure dynamically changing conditions and well defined behaviors to react to the input from those sensors. Advanced Autonomy is distinguished from Planning in that the behaviors that result are generally short-term changes to operations, while Planning involves longer-term strategic changes to operation. Both may involve multiple competing objectives.

Sensor: Advanced Autonomy involves the ability to adjust sensor configurations in a reactionary way to input from other sensors or mission conditions. For example, a bathymetric sonar may increase transmit power levels when signal to noise ratio is deemed to be too low to obtain high quality bottom detections or for example, a camera's shutter speed may be increased when lighting threatens to saturate images. Advanced Autonomy is distinguished from Intermediate Autonomy in that it provides the ability for sensors to adjust their configuration to optimal parameters without operator interaction.

Level 5: Planning (think)
Self-awareness, Operations and Sensor: At the Planning Level of Autonomy, the three categories that have been useful to keep separate thus far merge into one. Planning involves the ability to make a major adjustment or totally create a pre-planned mission based on a deliberative consideration of objectives, fuel/power physical constraints, and both previously known fixed obstacles, and real-time sensed, possibly dynamic ones as well as sensor states and other parameters. Planning requires a holistic view of the vessel, all its subsystems and the environment in which it operates to make informed and complex decisions. Examples of Planning include solving "Traveling Salesman" type problems to optimize a set of objectives under various constraints in mid-mission.

Levels of Supervision

Having described the spectrum of environments and levels of vessel autonomy it is now useful to define yet a third axis of consideration for meeting the tolerable risk associated with any autonomous vessel operation, namely, that of the level of supervision. Levels of supervision are defined here as “Attended”, “Monitored” and “Independent” operation, described in detail below. When convolved with a particular environment and informed by levels of autonomy the level of supervision is chosen to meet a level of tolerable risk.

Attended

Attended operation involves continuous supervision of an autonomous vehicle by vigilant watchstanders ready to take action in the event of any untoward event. Remote piloting (Level 1 autonomy) is attended operation, by definition. However, any other level of autonomy may be attended or not. Operations without constant telemetry cannot be attended operation, but rather qualify as Monitored or Independent operation.

Monitored

Monitored operation involves cursory supervision of a vehicle, affording an operator the ability to focus on other tasks, but ensuring normal operation at regular periodic intervals and relying to some extent on warnings and alarms from the vehicle in the event operator assistance is required. Monitored operation requires a basic vehicle autonomy level at a minimum (the ability to follow a sequential mission plan), but also the ability to invoke remote piloting and possibly even physical intervention when necessary. Therefore, monitored operation requires a suitable telemetry link and the operation within a sufficiently close proximity to intervene if required.

Independent

Independent operation involves little direct supervision of a vehicle other than periodic review of operations and status, relying largely on warnings and alarms to notify the operator of faults and events requiring assistance. Independent operation also requires a complete mission plan composed of a sequential list of mission objectives and or vessel behaviors under various circumstances, autonomously executed (Levels 2-3 or above), for both the vessel and its payload sensors. When under Independent operation, telemetry links may be inadequate to support remote piloting and distances may be too far for any timely physical intervention.

Scenarios

It is useful to consider several scenarios to illustrate the way in which operators may choose to meet tolerable levels of risk when operating marine autonomous vehicles. These scenarios are provided for illustration purposes only. Individual organizations must define their own levels of tolerable risk and for a given vessel and environment, the appropriate level of autonomy and supervision to meet it.

Consider a 20 ft. autonomous vessel conducting hydrographic survey 10 nm from shore in lightly trafficked waters. Assume the weather is clear with sea-state 3 or less. Assume the vessel has Level 1 Self-awareness (ability to display some parameters but not log them or activate alarms), Level 2 Operational autonomy (ability to follow sequential list of mission objectives) and Level 1 Sensor autonomy (manual operation of sensors).

In this scenario, with no warning systems and only manual operation of sensors, an organization would likely operate with an “attended” level of supervision. Operational sensing systems such as video, radar or automatic identification system would require continuous manual monitoring and payload sensors such as sonars and navigation systems would require careful scrutiny to ensure successful data collection and to start and stop logging of sensor data when desired.

Now assume the same scenario, in which the vessel is enhanced with a Level 2 Self-awareness, being able to log parameters about its own systems and to provide operator warnings when systems go awry. Consider also that the sensor autonomy level is enhanced to Level 2, now being able to start and stop sensors automatically at each point within the mission. The vehicle is now able to warn the operator about faulty systems, low battery voltages, over currents and other warnings, freeing up one’s attention to focus on other things. Moreover, because these systems record a history of normal operation, an operator can scrutinize this history for common faults and conditions leading to malfunction. That history can then be used to anticipate faults and failures allowing one to mitigate their risk to mission success.

In addition, one need not manually manage starting and stopping of logging of sonar and other sensor data. At these levels of autonomy, the operation begins to feel something like a standard hydrographic survey launch. In this model of operation, the autonomous coxswain is “under-instruction”, that is, reasonably autonomous but unable to make decisions on his/her own. Level 2 Sensor autonomy puts in place a system not unlike the commercial data acquisition software Hypack; able to turn sonar data logging on and off at the beginning and end of each survey line respectively without operator action. A survey technician must still scrutinize the data and a knowledgeable operator must still provide situational awareness and directive to the autonomous coxswain when warranted.

As one gains experience operating in an area, learns common traffic patterns, understands a particular vessel’s likely faults and character, or, if one has a higher risk tolerance in general, one might operate in a monitored level of supervision with these levels of autonomy. The vessel would largely drive itself from waypoint to waypoint with few obstacles or other vessels with which to contend. If sensors can be statically configured and still collect quality data without readjustment, such operations might be successful. However, with no self-aware model of operation and no ability to monitor systems for expected behavior (Self-awareness at Levels 3 and 4), operators who will be forced to hope that nothing unexpected occurs. The vehicle will be unable to warn when propulsion systems are fouled, when the vessel snags on fishing gear or when navigation systems begin to provide estimated positions rather than measured ones. Therefore, while monitored operation is possible, is requires a considerably higher risk tolerance.

A common mode of operation under consideration is colloquially known as the “mother-duck and duckling” operation in which a manned surface vessel conducting hydrographic survey operations is flanked by one or more autonomous vessels that operate a fixed range and bearing from the manned ship with their own hydrographic payloads. In this configuration the manned vessel takes on the responsibility of both reactionary and deliberative collision avoidance for itself and the autonomous vessels under its care. The autonomous vessels might operate at an Operational Level 3 autonomy receiving real-time position, heading and speed of the parent ship via a telemetry link and automatically adjusting mission parameters to maintain relative position, or Operational Level 4 autonomy actively sensing the position of the mother ship in real time via sensors such as radar or Lidar to do the same. Similarly, vessels having Level 2 Self-awareness, i.e. the ability to monitor and log operating parameters and to generate faults to warn operators operate at much lower risk than those that do not. Preferable still, is Level 3 Self-awareness in which each vessel understands its own turn radius and other characteristics and can anticipate maneuvers to keep in lock-step with the manned vessel through turns and avoidance maneuvers. The autonomous vessels will operate sensor payloads and while this is possible at a Level 1 (piloting) level of sensor autonomy, the operation is more tractable at level's 2, 3 or 4, giving the sensors the ability to start and stop logging automatically and the ability for an operator to configure the sensor during the mission or for it to reconfigure itself automatically to optimize quality data collection.

Now consider a 20 ft. autonomous vessel conducting hydrographic survey with Level 4 Self-awareness (i.e. the ability to monitor internal systems, model their operation and that of the vessel as a whole and to recognize when they do not match expectations), Level 4 Operational autonomy (i.e. the ability to follow a mission plan, to sense obstacles and avoid them) and Level 4 Sensor autonomy (the ability to adjust sensor configurations to optimize data collection). When operating in distant waters such the Alaskan coast, where other vessel traffic and obstacles are unlikely, this vessel might operate securely in an independent mode of supervision. With systems in place to monitor, log and alarm on the vehicle's internal health and a model in place to verify the system is responding to commands appropriately, operators could feel secure that everything is working smoothly. Full COLREGS autonomy may not be in place, nor even necessary in this environment, but some ability to recognize a major obstruction and avoid it, or even simply to warn operators when such an obstruction exists will help ensure the vessel does not collide with an unexpected obstacle. Moreover, smart sensors capable of adjusting operating parameters as conditions change and processes capable of assessing data quality and/or sending data review information to the operator via low bandwidth telemetry link would ensure that data of high quality are collected. The vessel may operate independently because the vessel's systems closely monitor themselves and because external hazards are both unlikely and actively sensed, mitigating the risks involved.

Operate this same vessel in New York Harbor however, even with full COLREGS compliant autonomy, and the level of risk involved might not warrant fully independent operation. In this case the multitude of both static and dynamic obstacles combined with the high visibility of the location might increase the level of risk beyond comfort levels for most operators. One can imagine, what now seems futuristic, a scenario in which sensor systems to detect other vessels and obstacles as well as algorithms to respond appropriately mature enough that operation by an autonomous vessel in a busy harbor might be possible safely and with little operator supervision.

Summary on Autonomy

With five levels of autonomy clearly defined among three categories of Self-awareness, Operations and Sensor payloads, engineers may more clearly define design goals, manufacturers may more clearly communicate capabilities, customers may more clearly describe requirements and operators may more systematically assess risk. The levels provide a common language between us and while any given vehicle's capabilities will be a blend of levels, having defined the levels makes the strengths and weaknesses of any vessel more clear. These levels, when considered with respect to the three levels of operator supervision, allow an operator to better assess the impact of the loss of any one sensor or routine and to devise methods to mitigate the risk associated with the loss, whether by compensating with other systems to meet the same level of autonomy or by increasing the level of supervision appropriately (Schmidt, 2015).

Workshop Recommendations

Collectively acknowledging that ASV development has lagged behind underwater autonomous vehicle development, the workshop participants made the following recommendations for continuing the improvement of ASV use and operation and assessing user needs in both the short and long term. The goal of the recommendations below is to further develop these technologies in order to meet needed requirements and opportunities. It is further recognized that user criteria for particular parameters/operational scenarios may vary depending on use, region, environment, and technology costs.

The workshop participants recommend that ASV researchers, vendors and manufacturers:

1. Continue development of base, open source systems for broader use and greater adoption. Provide necessary sensor documentation for proprietary systems to allow for customization, flexibility and integration into ASV platforms.
2. Establish an ASV Technical Committee to advise future development towards recommendation 5 and encourage ASV developers and users to follow the guidelines established in other developed resources including:
   a) *Unmanned Systems Integrated Roadmap FY2013 – 2036* (U.S. Department of Defense, 2013)
   b) Autonomy Levels for Unmanned Systems, resource Website (NIST, 2010)
   c) *Legal Research Digest 69: A Look at the Legal Environment for Driverless Vehicles* (Glancy D., Peterson R. W., and Graham, K.F., February 2016)
   d) Mainstreaming Unmanned Undersea Vehicles into Future U.S. Naval Operations (Navel Studies Board, 2016)

These reports outline a long-term strategy for the continued development, production, testing, training, operation, and sustainment of unmanned systems technologies being developed by other agencies, much of which is applicable to ASVs.

3. Develop and communicate success cases to aid in greater adoption and use of ASV platforms for a wide variety of survey and water quality monitoring applications. The community needs examples of successful uses of ASVs in a variety of contexts and to make the successes public to illustrate what can be done, to innovate new modes of operation and new missions and where failures exist to inspire new solutions.
4. Identify funding partners for continued research and development. Specifically, funding sources should be identified that can aid in product development that, unlike Small Business Innovation Research grants, don't necessarily involve sensor development or innovative technologies, but simply require careful engineering and system integration that leads to higher levels of autonomy, more tightly integrated sensors and better situational awareness for operators.
5. Based upon recent successes, develop a U.S. version of the *Maritime Autonomous Systems (Surface) – MAS(S): Being a Responsible Industry – An Industry Code of Practice* as currently exists in the U.K., as a set of recommended best practices. Early discussions with NOAA and the U.S. Coast Guard are strongly encouraged as well as with vessel operators to assess liability issues and to avoid the need for stricter regulation of ASV operations.
6. Create a national/international, repository/database of available platforms and sensor technologies.
7. Develop expectations for responsible conduct of "at sea" operations as a function of survey complexity (environment) based upon the Levels of Autonomy and Supervision presented in this workshop.
8. Develop a strategy for adoption by: a) looking at levels of autonomy and best practices in other modes-terrestrial, aerial, etc.; and b) incorporate maturing technologies into next generation ASVs.

ACT could help stimulate multiple markets and resource needs to demonstrate capacity. For example, the IOOS Marine Sensor Innovation: Ocean Technology Transition appears ideal to aid in further developing ASV technology for ocean applications (Department of Commerce, 2015).

Conclusions

- At the current state of technology, Autonomous Surface Vehicles are better referred to as *Unmanned* Surface Vehicles, given the current level of operator intervention and monitoring that is required for safe and effective operations.
- Unmanned systems, regardless of level of autonomy, should not be considered as viable one-for-one replacements for manned survey platforms, nor should their adoption be driven by a desire to reduce staffing. Unmanned systems are best applied where they

can provide a unique operational capability or data observation that is not currently available or safely achievable by a manned resource. It should be acknowledged that unmanned systems may even require additional personnel to operate, monitor, and maintain, and those personnel may require skills and training that differ significantly from current survey personnel.

- It would be beneficial to identify specific operational environments, observation requirements, or concepts of operations for which unmanned systems are well-suited and to fund operational demonstrations to strengthen the case for their transition to operational acceptance.

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Appendix A – Workshop Participants

Technical Committee

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Michael Annis
NOAA Office of Coast Survey

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Guy Meadows
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Mark Luther
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NOAA Office of Coast Survey

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Tim Battista
NOAA National Center for Coastal Ocean Science

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	Shannon Searing Teledyne Oceanscience	Michael Redmayne CARIS USA
	Geoffrey Douglass SeaRobotics Corp	Michael Johnson Sea Machines
	Alex Lorman Sea Machines	Bob Lautrup Hydronalix, Inc
	Thomas Chance ASV, LLC	Don Darling SeaRobotics Corp
	Frank Johnson CSA Ocean Science, Inc	
Other Participants	Val Schmidt University of New Hampshire	David Loewensteiner ACT/UMCES
	Kevin Manganini Woods Hole Oceanographic Institute	Michael Walker Webb Institute
	Elizabeth Hoy Michigan Technological University	Dylan Froriep Webb Institute
	Peter Traykovski Woods Hole Oceanographic Institute	Tim Pilegard University of Delaware
	Lawrence Harvey Gulf Unmanned System Center	

Appendix B – Workshop Agenda

Wednesday, 18 November 2015 - Holiday Inn Marina and Conference Center

8:00 - 8:30 am	**Continental Breakfast and Registration**
8:30 - 9:00 am	**Introductions and Workshop Objective** – Drum Point Room *Mark Luther, University South Florida*
9:00 - 9:15 am	**Overview of ACT** *Mario Tamburri, University of Maryland Center for Environmental Sciences*
9:15 - 9:30 am	**IOOS Program Overview** *Gabrielle Canonico Hyde, U.S. IOOS*
9:30 - 10:00 am	**Overview of Partner NOAA Programs** *Rob Downs, NOAA OCS*
10:00 - 10:15 am	**Coffee Break**
10:15 - 10:45 am	**Overview of Autonomous Surface Vehicles** *Val Schmidt, University of New Hampshire*
10:45 - Noon	**Overview of Technologies from Vendors/Manufacturers** *Each vendor/manufacturer will have three minutes to present one slide (due in advance) followed by three minutes for Q&A with participants*
Noon - 1:00 pm	**Lunch and Networking**
1:00 - 3:30 pm	**Breakout Session: User Needs** (see discussion questions)* a. Mapping – Drum Point Room b. Water Quality Monitoring – Cedar Point Room
3:30 - 3:45 pm	**Coffee Break**
3:45 - 5:00 pm	**Breakout Session Report Back: User Needs** – Drum Point Room *Sam Greenaway (facilitator), NOAA OCS*
5:15 - 5:45 pm	**Review and Adjourn** *Guy Meadows, Michigan Tech*
6:00 pm	**Dinner**, Isaacs Restaurant – Holiday Inn

Thursday, 19 November 2015 - Chesapeake Biological Lab (CBL) – Nice Hall

8:00 - 8:30 am	**Continental Breakfast**
8:30 - 10:00 am	**Participant Discussion of Operation and Maintenance Requirements**

Val Schmidt (facilitator), University of New Hampshire

Logistics Support Requirements (launch/recovery, etc.)

- *Physical Configurations*
- *Survivability*

10:00 - 10:15 am **Coffee Break**

10:15 - 11:15 am **Discussion of Field Demonstration Design**

Guy Meadows, Michigan Tech

11:15 - Noon **Summary, Consensus, and Final Remarks**

Mark Luther, University of South Florida

Noon - 1:00 pm **Lunch**

1:00 - 4:00 pm **ASV Field Demonstrations – Data Collection**

Join the vendors/manufacturers at the marina adjacent to CBL for a field and data collection demonstration

Friday, 20 November 2015 - Chesapeake Biological Lab – Nice Hall

8:00 - 8:30 am **Breakfast – Coffee**

8:30 - Noon **ASV Field Demonstrations – Data Presentations**

Join the vendors/manufacturers as they present the data from Thursday's field and data collection demonstration

Noon **Workshop Adjourns**

*NOTE: On Wednesday, the group elected to combine the breakout session discussions of user needs and remained as one large group.

Appendix C – Breakout Session Challenge Questions

The following challenge questions were provided to workshop participants in advance of the workshop to frame the discussion towards tangible recommendations. NOTE: Prior to the lunch break on the first day of the workshop the group agreed to remain as a single discussion group to address the challenge questions.

Background: NOAA's ocean observation and mapping requirements include near shore, shallow water (less than 10 meters). Traditional shipboard observations may not be possible or effective in these areas, and small boat survey operations may be laborious or unsafe. NOAA is investigating the feasibility of using unmanned systems, particularly Autonomous Surface Vehicles (ASVs), to meet these shallow water requirements. While the initial scope of the investigation is focused on shallow water, the lessons learned are expected to inform decisions regarding the broader application of ASVs.

To answer the question of feasibility NOAA and other users must determine if ASVs can provide one or more of the following benefits:

- Reduce the efficiency of data acquisition, includes time, personnel, and operating costs.
- Improve the quality of the data acquired
- Improve the safety of survey operations
- Provide data that is beneficial, but otherwise unattainable

User Needs: In terms of both Mapping and Water Quality Monitoring, please address as many of the following points as possible.

Challenge Questions

1. Describe acceptable physical & technical characteristics of the ASV. Include a) Physical dimension and weight, b) Energy source (battery or fuel type) and propulsion system, c) Endurance at survey speed, and d) Charging time.

2. Describe acceptable physical and technical characteristics of any required shipboard or shore-side equipment, such as operator console, battery charging unit, or communication interface. Include a) Physical dimensions, b) Power requirements, and c) Cabling requirements.

3. Describe desired ASV payload capabilities. Include a) Positioning and motion systems, b) Data logging and telemetry capabilities, c) Standard payload packages, d) Interfaces or tools for user-integrated payloads, and e) Maximum size, weight, and energy capacities.

4. Describe acceptable ASV launch and recovery requirements. Can it be operated from shore, small boats, and ships? How many people are need for safe launch and recovery? Is a Launch and Recovery System (LARS) necessary or an available option?

5. Describe desired ASV operating environment capabilities. Include a) Maximum sea state (wind and wave height), b) Maximum current, c) Can the ASV operate in the surf zone? What are the effects of precipitation or visibility on operations? And what are the operating, charging, and shipping/storage temperature ranges?

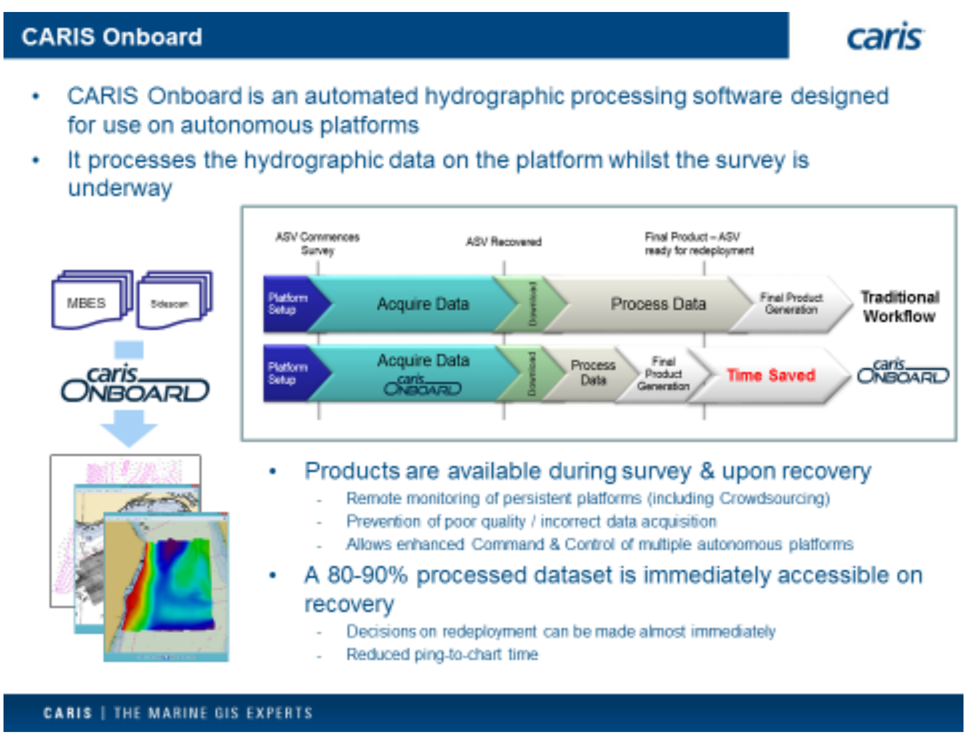
6. Describe desired systems and behaviors the ASV employs for navigation safety. How does it avoid stationary obstacles, such as shoals, piers, buoys, and rocks? How does it avoid collision with other vessels?

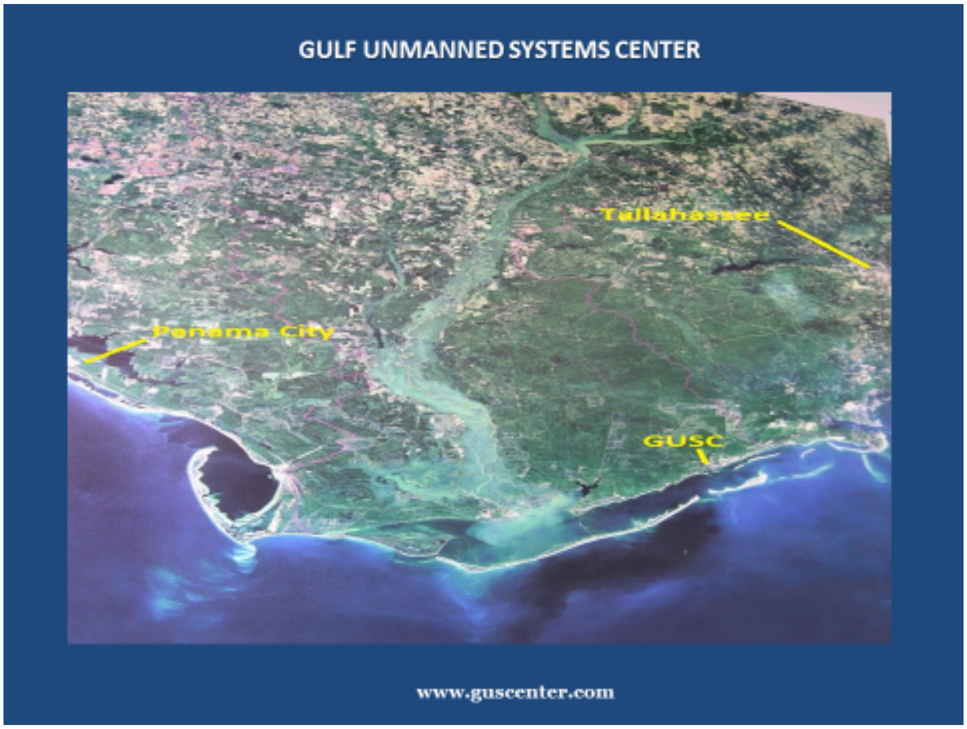
7. Describe desired Command & Control systems. Include a) Communication capabilities b) Short range, medium range (line-of-sight), long range (over-the-horizon), c) Remote control functions, d) User interface, e) Range limits, f) Autonomous functions, g) Pre-planned missions (Waypoints, survey patterns), and h) Adaptive routes (contour following, channel following).

8. Fault Tolerance and Response-How does the ASV respond to a system fault? Does it reset and continue, return to user defined waypoint, or abort operations? Is the ASV able to self-right if capsized? Is it durable enough to with stand a striking an obstacle at survey speed? Does it include systems or communications to aid in the recovery if the ASV is lost?

Other User Needs or Requirements?

Appendix D – Vendor/Manufacturer Slides

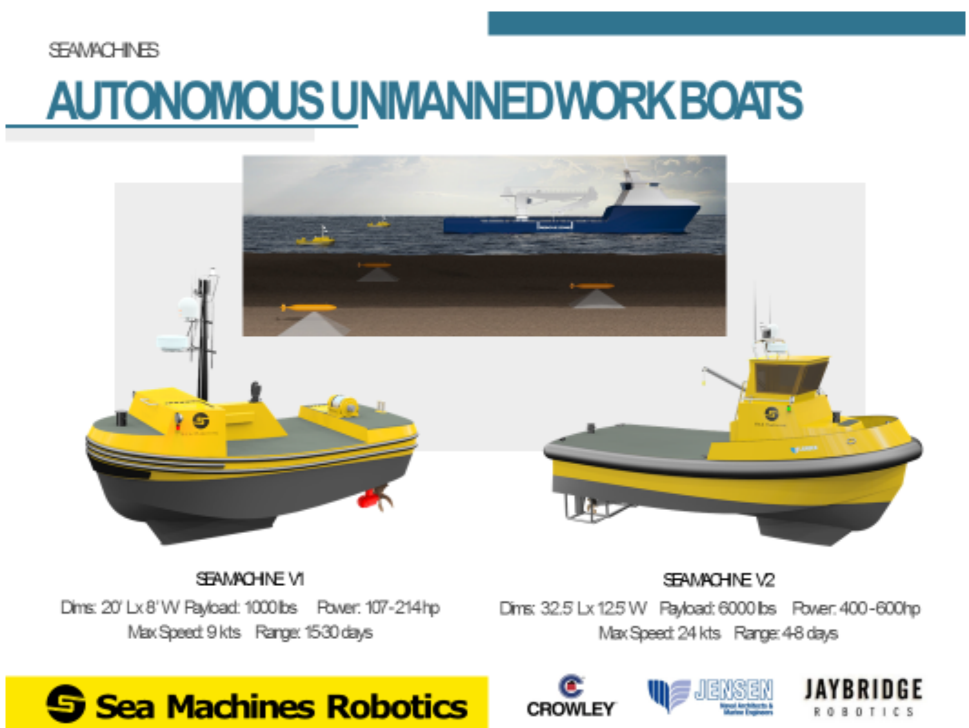




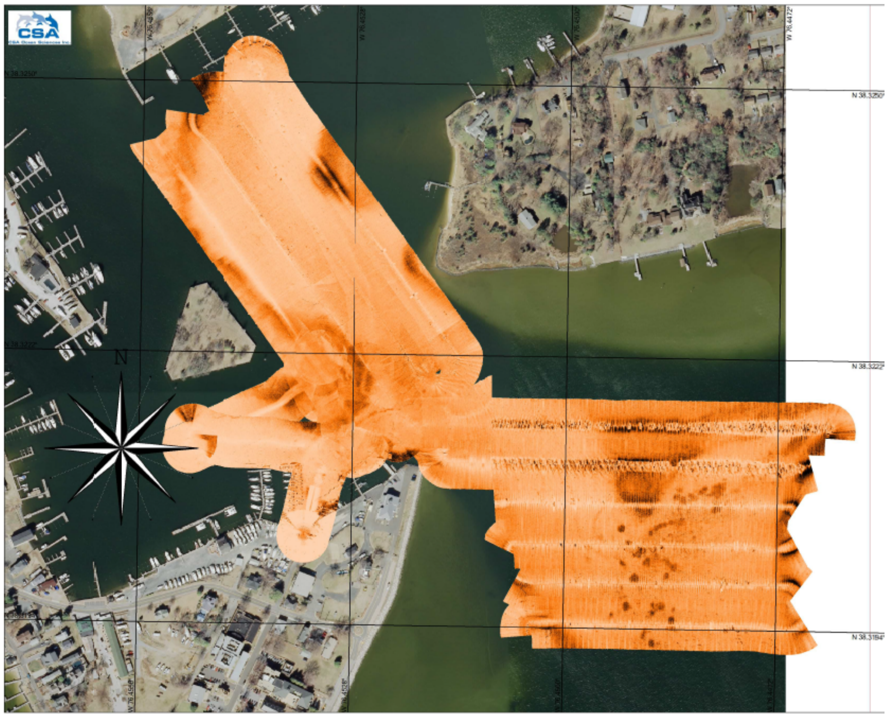
GULF UNMANNED SYSTEMS CENTER
Tallahassee
Panama City
GUSC
www.guscenter.com

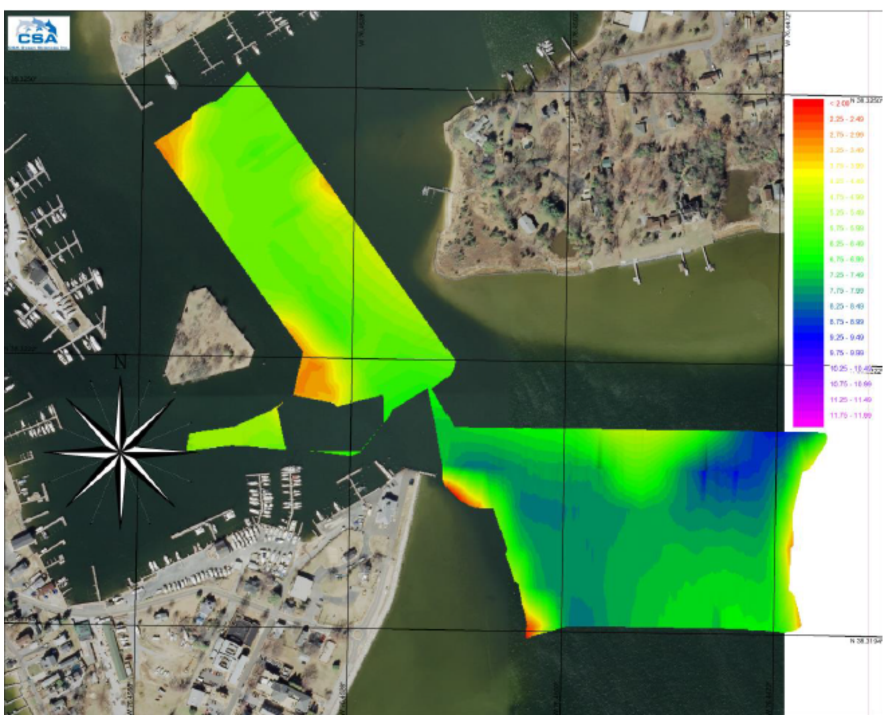
Stuart, FL
Don Darling
ddarling@searobtoics.com
(561) 627-2676 ext 301
Geoff Douglass
gdouglass@searobtoics.com
(561) 627-2676 ext 304
Size Range: 2.5-11 Meters
Endurance at Survey Speed (3-5 kts): 6 hrs to 60 days
Communications:
2-13 km line of sight
Cellular modems
SATCOMs
Propulsion:
Electric
Combustion
Gas- electric hybrid, Diesel-electric hybrid
Solar
Jet drives, inboards, outboards
Integrated Payloads:
HYPACK
Motion Reference Units
Vector GPS
Multibeam sonar
Singlebeam sonar
Side Scan Sonar
Sub-bottom Profilers
ADCPs
LIDAR
CTD, DO, Fluorometer, ABS
Camera Systems
Winch deployment systems
USV 2.5
USV 4.0
USV 5.7
USV 9.0
USV 11.0
High Speed USVs


Teledyne Oceanscience Z-Boat 1800
IMAGING • INSTRUMENTS • INTERCONNECT • SEISMIC • VEHICLES
TELEDYNE
MARINE
Everywhereyoulook


SEAMACHINES
AUTONOMOUS UNMANNED WORK BOATS
SEAMACHINE V1
Dims: 20' L x 8' W Payload: 1000 lbs Power: 107-214 hp
Max Speed: 9 kts Range: 15-30 days
SEAMACHINE V2
Dims: 32.5' L x 12.5' W Payload: 6000 lbs Power: 400-600 hp
Max Speed: 24 kts Range: 4-8 days
Sea Machines Robotics
CROWLEY
JENSEN
JAYBRIDGE
ROBOTICS

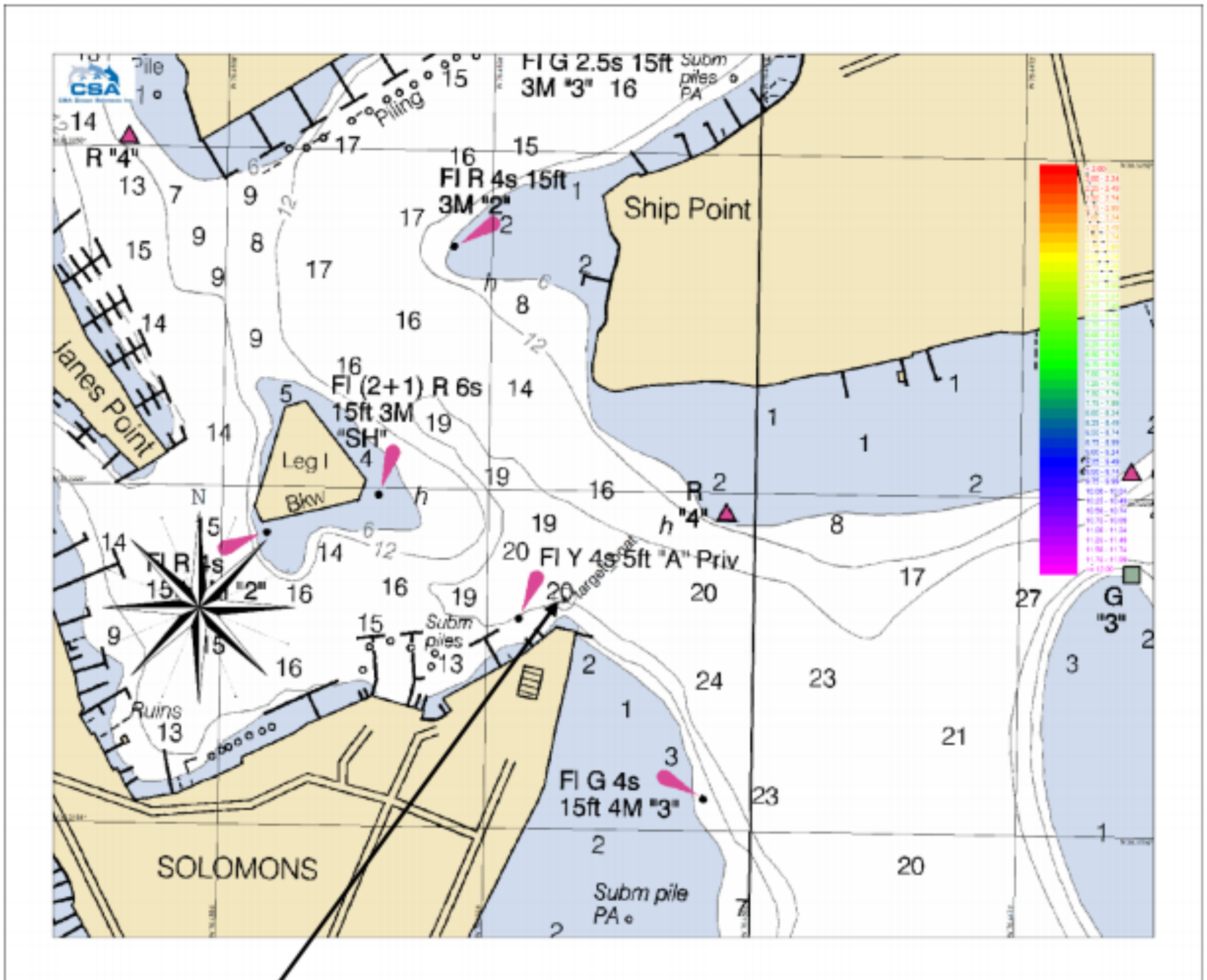
Appendix E – Other Manufacturer Demonstration Output

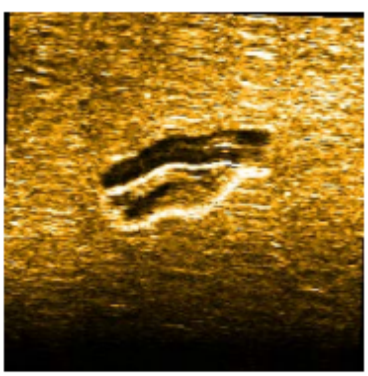




Side scan (top) and Bathymetic (bottom) output from field demonstration provided by Don Darling, Sea Robotics, ddarling@searobotics.com

Location of a submerged target near the launch area. Image provided by Don Darling, Sea Robotics, ddarling@searobotics.com





38 19.2800 N

076 27.11811 W

Length 7m, Width 3m, H .5 m

Group photo of 2015 ACT Autonomous Surface Vehicle Workshop participants standing outside Nice Hall at the University of Maryland's Chesapeake Biological Laboratory in Solomons, Maryland.

ALLIANCE FOR COASTAL TECHNOLOGIES