Update on the Development and Testing of a New Long Duration Solar Powered Autonomous Surface Vehicle

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***Abstract*-This paper provides an update on the development and testing of a new long duration solar powered autonomous surface vehicle (ASV) for oceanographic and atmospheric scientific research missions. A fleet of three Ocean Atmosphere Sensor Integration System (OASIS) ASV platforms has been developed under a grant from the National Oceanic and Atmospheric Administration (NOAA) to provide a low-cost, reusable, re-configurable, long-duration, ocean observing capability to support ongoing research in key areas such as carbon dioxide air-sea flux and phytoplankton productivity. A brief overview of ASV applications and related research and development is provided to highlight the motivation for the development of a new ASV platform. A description of the OASIS ASV platform and key development considerations is provided. A description of the supporting hardware and software technology and resulting system architecture for the onboard control system, payload system, and ground system is also discussed. A summary of platform integration, testing, and operations, as well as future research and development activities is presented.**

Figure 1. OASIS (ASV3) Oceanographic research platform.

I. Introduction

Oceanography is largely an observational science and as such, it requires a broad spectrum of observational tools to enable researchers to peer into the often complex processes associated with the Earth's oceans and atmosphere which function as a coupled dynamic system. The required temporal and spatial observational scales are dependent on the specific processes to be studied. Temporal scales can range from decades to seconds while spatial scales can span the extent of the Earth's oceans down to a region of a few meters. National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) satellites, aircraft, and unmanned aerial vehicles (UAV) collect a wealth of remotely sensed measurements including sea surface temperature (SST), surface winds, salinity, color, wave height, and large scale circulation. While such observations provide immense perspective, in situ measurements are often required as remotely sensed measurements can be obscured by clouds and limited in their spatial and temporal resolution.

In situ oceanographic measurements have long been collected from research vessels (R/V) and moored buoys. R/V's are expensive to operate, especially with today's high

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fuel costs. Buoys are costly to build, deploy, and maintain and ultimately require R/V support throughout their lifecycle. Spatial limitations can also be an issue depending on process to be observed. Over recent years advances in technology as well as a push to develop a global ocean observing system have both enabled and stimulated considerable progress in the development of new sensors and autonomous marine platforms including drifters, profiling floats, gliders, autonomous underwater vehicles (AUV), and autonomous surface vehicles (ASV). These platforms provide varying levels of capability for payload, endurance, range, communication, mobility, and autonomy. A more in depth discussion on oceanographic platforms can be found at [2, 3].

This paper provides an update on recent activities associated with the development and testing of a new long duration solar powered ASV platform known as the Ocean Atmosphere Sensor Integration System (OASIS). The OASIS ASV is being developed to provide a low-cost, low-speed, navigable, reusable, re-configurable, long duration, ocean observing platform. The vision is to develop, test, and operate a fleet of ASV platforms hosting a diverse set of sensors to obtain biogeochemical and air-sea process measurements in a manner that reduces overall costs and increases spatial and temporal resolution. Section II provides a synopsis of ASV applications, related research and development, and challenges. Section III provides an overview of the platform design drivers and resulting systems including hull and deck assemblies. Section IV provides a platform systems description by discussing hardware and software technology and architecture associated with the onboard, payload, and ground systems. Section V highlights platform testing. Section VI presents an overview of collision avoidance considerations. Section VII highlights conclusions and future plans.

This work was supported under a grant from NOAA and in collaboration with NASA Goddard Space Flight Center's (GSFC) Wallops Flight Facility (WFF). To date, three solar ASV platforms have been developed for the OASIS project which is part of a larger coastal observations program managed by the Center for Innovative Technology (CIT) on behalf of NOAA. Platform research, development, integration, testing, and operations are jointly conducted by a team of engineers and technicians from Emergent Space Technologies, Zinger Enterprizes, and EG&G. Platform science missions are ramping up and are led by oceanographers at WFF with collaboration by guest researchers at various academic institutions. Current operations support CO_2 air-sea flux and harmful algal bloom (HAB) research. The coastal observations program provides monitoring of the influence of the Chesapeake Bay on the nearby Delaware, Maryland, Virginia (DELMARVA) coastal regions and includes the deployment of high frequency coastal radar (CODAR) systems, an off-shore buoy, sampling cruises, and education/outreach.

II. Motivation & Background

This section highlights applications, related research and development, and challenges to provide motivation for, development of a new ASV platform.

A. Applications

ASV platforms offer the potential to support a wide array of applications in the scientific, civil, military, and academic communities. Oceanographic applications include HAB research, carbon studies, acoustics, hurricane research, satellite calibration/validation, model refinement, climate research, forecasting, and many other physical and biogeochemical process studies. Military applications include mine countermeasures, anti-submarine warfare, and maritime security. Civil applications include water quality monitoring, pollution monitoring, surveillance, port security, and search and rescue. Academic applications include research in robotics and autonomy. ASV platforms offer the potential to decrease operational costs, decrease human workloads, reduce human exposure to hazardous environments, enable sustained observations, and to customize temporal and spatial scales observed.

B. Related Research & Development

ASV platforms vary in many aspects including application, cost, speed, endurance, power, payload, geometry, and level of autonomy. A wide range of military grade vehicles have been developed including Roboski, Owl MK II, SSC San Diego USV, Unmanned Harbor Security Vehicle, and Spartan. A survey highlighting these and many other platforms is available at [4]. While the progress is quite impressive, these platforms are not the best candidates for sustained oceanographic applications.

A number of lower cost short endurance platforms are commercially available or under development at academic institutions. Sea Robotics Corporation's USV-1000 provides a small low cost solution for deployment of short term sampling surveys [5]. At MIT the AutoCat Autonomous Surface Craft is being used for bathymetric mapping and experiments in networked vehicle operations [6] while the Surface Craft for Oceanographic and Undersea Testing (SCOUT) is being used as a low-cost test-bed for AUV algorithm development [7].

ASV platforms capable of harvesting solar, wind, and wave energy are starting to emerge. Although more AUV than ASV, the Falmouth Scientific, Inc. SAUV II is equipped with solar panels and supports longer duration oceanographic monitoring and profiling [8]. An autonomous self mooring surface vehicle (ASMV) is under development at Florida Atlantic University and has the capability to harvest solar power [9]. The Microtransat Challenge [10] has spawned progress in development of small autonomous sail boats that hold promise to support oceanographic applications in the future. The lack of a commercially available long-duration low-cost oceanographic ASV that meet our needs has motivated the development of the OASIS ASV platform.

C. Challenges

ASV platforms face a wide array of operational challenges at sea. Collision with other marine assets is a concern in the community and may gain additional attention as new platforms are developed and deployed. Platforms operating autonomously in oceans and bays should be designed to be self-righting. Hull design should ideally minimize drag and maximize payload capacity. Long duration remote surface operations for scientific applications suggest a need to harvest and store solar, wind, and wave energy. The region, time of year, size of platform, and type of mission are all drivers that ultimately influence system design. Platform geometry, weight, navigation, speed, and endurance are drivers for determining ease of deployment and recovery. The types of missions and locations will influence whether an ASV will be deployed from shore, ship, or aircraft. Acceptable costs for ASV platforms will be market driven and dependent on capability and alternative modes of in situ data collection. Platform and sensor servicing intervals is a driver for mission duration.

III. Platform Overview

This section highlights the ASV platform design drivers, goals, and decisions. It also provides an overview of platform systems, deck/hull design, and operations concept.

A. Design Drivers

The OASIS ASV is being developed to function as a low-cost, long duration, reusable, navigable, ocean platform. It is intended to be reconfigurable to support a range of missions. Initial applications are focused on CO_2 air sea flux and HAB research. Future missions will include satellite calibration/validation and storm/hurricane studies. Table I. highlights the key design drivers, goals, and decisions.

TABLE I
PLATFORM DESIGN DRIVERS, GOALS, AND DECISIONS

Drivers	Goals	Decisions
Missions	CO_2 Air-Sea Flux, Harmful Algal Bloom, Satellite Cal./Val.	ASV
Communications	Two-way, On Demand, Proximity to Global, Low-Cost, Commercial	Wi-Fi, Spread-Spectrum Radio, Cellular, Iridium Satellite
Cost	< Average AUV	Utilize COTS Hardware
Deployment, Recovery	Boat Ramp, Ship	Boat Trailer, Cleats and Lifting Points
Endurance	> Average AUV, Weeks to Months	Solar Powered
Navigation	Autonomous, Course Tracking, Station Keeping	Propulsion / Steering, GPS, Compass, AIS, Autopilot,
Payload	Up to 800lbs, Air-Sea Boundary, Payload Protection, > Average AUV	Large Interior Volume, Water Intake, Portals (ADCP, Fluorometer) Bow Mast
Power	Regenerative (solar), Low-Cost, Batteries at Any Angle	Flat Deck Areas, Solar Panels, Charger Controller Gel-Cell Battery Bank
Speed	Minimize Power, Maximize Endurance over Speed	1-2 knots Cruise, Sprints Possible
Region	Ocean	Self-Righting, Rugged

B. Systems Overview

The platform is comprised of five major subsystems. The structural subsystem includes the deck/hull components, mast, and internal mounts. The power subsystem contains six 170 watt solar panels, automated charge controller, twelve 12-volt deep cycle gel cell marine batteries, DC-DC converters, isolators, power bus, and fuse bank. The propulsion subsystem includes the rudder and propeller control surfaces, as well as the motors, drivers, and controllers to operate them. The vehicle computer, communications hardware, navigation sensors, adapters, and relay bank are among the components contained in the onboard control subsystem. The payload subsystem includes a suite of standard water and atmospheric sensors.

C. Deck / Hull Design

Donald L. Blount and Associates, Inc. (DLBA) provided the naval architecture expertise required to design the platform's hull and deck parts. Temporary molds were fabricated and from them the fiberglass parts for the ASV1 and ASV2 platforms were produced. The resulting platform geometry is a function of requirements to be self-righting and to accommodate COTS solar panels. While the hull skin is self supporting the flat areas on the deck are reinforced with a stiffener to improve platform ruggedness. The ASV3 parts were fabricated at a small fiberglass shop and incorporated improvements in design and quality over the original R&D parts.

The deck and hull parts are sealed with a gasket, fasteners, and marine sealant. Three compartments are separated by two bulk heads. The forward section serves as the primary payload bay and includes water sampling system, de-bubbling system, and manifold connections to plumb flow through sensors. The compartment contains a downward pointed ADCP portal and horizontal pointed Wetlabs Triplet fluorometer portal. The middle section contains the battery compartment, onboard control system box, and may also accommodate additional payload. The aft compartment contains the propulsion and steering hardware. A vertical profiling system is under development and will be integrated into this area. A servicing hatch is located on the "dog house" and provides access to the central compartment. Internal hatches provide access to the forward and aft compartments.

TABLE II
PLATFORM PHYSICAL CHARACTERISTICS

Element	Specification
Hull / Deck	Custom Fiberglass Design
Length	~18 ft
Width	~5 ft
Height	~6 ft (keel base to "dog house" peak)
Draft	26 in
Mast Height (Deployed)	~15 ft
Weight	~3000 lbs

Figure 2. ASV3 platform on boat trailer.

D. Deployment & Recovery

The platform is transported, deployed, and recovered via boat trailer at most boat ramps. Deployment from ramps with subtle grades can be achieved with a hitch extension to gain the additional depth necessary to submerge the trailer roller bunks and float the platform. The mast is hinged and bolted to facilitate transport and can be easily raised and lowered in the field. Once in the water, the platform is piloted through portable remote control (R/C) unit or game controller device attached to the control station prior to engaging autonomous mode. This is the typical process for deployments at our estuary test sites. Ocean operations from WFF involve towing the platform out to sea through a long narrow winding channel prior to engaging autonomous operations. Recovery operations proceed by reversing the process.

IV. Platform Systems Description

Emergent Space Technologies, Inc. (Emergent) developed the platform's onboard and ground systems. The onboard system enables most major platform functions including communications, commanding, telemetry, data handling, guidance navigation and control (GN&C), diagnostics, health and safety, and payload. The ground system resides off-board and enables communications, monitoring and control of platform and payload through graphical user interface (GUI). The ground system also includes a middleware interface to facilitate integration with supporting ground systems in the mission operations environment or at guest observer facilities.

A. Development Approach

An iterative development process was adopted to incrementally design, develop, integrate, and test system capabilities early and often. Testing involved a combination of simulation, bench top testing, and dry and wet system testing. This approach provided an essential feedback loop enabling us to more quickly develop and refine the system. To maximize a lean development budget, we made use of commercial off the shelf (COTS) hardware and software and open source tools where possible to minimize costs.

B. Operations Concept

The platform's onboard control system currently supports two main modes of control. The first enables direct manual control of the vehicle's propulsion and steering system via portable R/C unit or game controller unit connected to the control station. This mode is useful for deployment, recovery, and basic system testing. The second mode supports autonomous guidance navigation and control (GN&C) for course tracking and station keeping. In course tracking mode, the platform transect course segments between waypoints, and compensates for disturbance such as wind, tides, and currents. Station keeping uses a weather optimal approach and focuses on staying within a user defined radius of a specified location. After arriving at the final waypoint in a course the platform automatically enters station keeping mode. Additional modes of control are in the early stages of development and will enable behaviors new behaviors such as feature tracking and obstacle avoidance.

Two-way communication with the vehicle is supported through Wi-Fi, radio, cell modem, and satellite modem. While continuous communication is an option it is not required to operate the platform. Some communication services such as Iridium require a per minute usage charge which may ultimately influence the frequency and duration of communications. State data is archived on board and can be dumped to coverage communication outages. When the communications link is up the platform relays platform and payload state information via the telemetry stream. Commands can also be uploaded at anytime to set a new path plan or adjust system parameters.

C. Hardware Technology

The majority of the hardware components integrated onboard and off-board in the ground system are COTS rather than custom solutions. This section highlights some of the key hardware subsystems we have integrated to facilitate navigation, propulsion, communications, and environmental monitoring.

Navigation functions are supported through a standard suite of onboard sensors including GPS receiver, digital compass, roll/pitch inclinometers, and 3-axis inertial sensor. A forward looking camera also provides situational awareness useful for remote operations.

Propulsion functions are supported through the use of a 2-axis motion controller which provides signals to drive the propulsion servo motor and rudder stepper actuator. The rudder stepper actuator is attached to a tiller arm to create rudder deflection. Position feedback is achieved through the use of an absolute optical encoder.

Communications functions are supported through four different systems which provide flexibility and redundancy. Standard Wi-Fi communications are available for vehicle integration and testing. A 900 MHz FreeWave spread-spectrum radio system is used for line-of-sight operations. Cellular communications provide an always on connection useful for regional operations. An Iridium satellite modem supports global operations. All of our communications antennas are omni-direction and mast mounted with the exception of the Iridium antenna which is mounted on the “dog house” to ensure that communications are not lost in the event of mast damage.

Control functions are executed and managed onboard a rugged single board vehicle computer. Onboard system components interface with the computer via Ethernet LAN or direct RS-232 interface. An adapter bank connected to the LAN enables communications with a large number or RS-232 and A/D devices. A bank of relays is also available and is useful for controlling payload power.

Environmental sensing functions are achieved through a suite of core payload sensors from standard vendors such as WETLabs, R.M. Young, and Sea-bird Electronics. Meteorological measurements include wind speed and direction, barometric pressure, relative humidity, pressure, and temperature. Water measurements include temperature, salinity, depth, CDOM, chlorophyll, phycoerythrin, and rhodamine. An ADCP provides subsurface current profiles. Work is underway to integrate additional sensors to support PAR measurement, hyper-spectral ocean color, and water column water profiles. Mission specific payloads may be installed onboard and operate as standalone or loosely coupled systems.

D. Software Technology

The onboard control computer runs a Linux Operating System (OS). Both the onboard and ground system software is implemented in Java and runs on the Standard Edition (J2SE) Java runtime environment (JRE). Third-party open source technologies and standards have been adopted where possible to reduce development and maintenance costs. We utilize the GSFC Instrument Remote Control (IRC) framework to simplify development of the overall system by providing a flexible and extensible foundation on which to develop.

E. Onboard System Architecture

The onboard system architecture was designed to be highly modular, re-configurable, and extensible to support R&D, customization, and flexibility. The IRC framework contributed to the modular architecture by facilitating a software design pattern consisting of device proxies, input/output adapters, connections, messages, and state models to interface with each hardware component in a standard way. Connection classes facilitate communication with hardware by providing common support for serial, TCP/IP, UDP and other communication interfaces. Input adapters attach to data streams from connections and provide the ability to parse data from hardware into messages. Output adapters operate conversely by processing messages to format commands that are streamed to a connection for transmission to hardware. Device proxies exchange message with adapters and the rest of the system. State models help proxies track hardware state. Extensible Markup Language (XML) technology is an integral component of IRC and helps facilitate system reconfiguration without software recompilation. XML descriptions are used extensively onboard to define devices and associated adapters, connections, and configuration parameters. The ability to maintain different system configurations for development, bench testing, and onboard environments is extremely useful. Extensibility is supported through the use of Java and an object oriented architecture that provides default implementations and standard interfaces for key system components.

The core control system is composed of seven major subsystems—propulsion, communications, command and data handling (C&DH), guidance navigation & control (GN&C), attitude determination, power, and payload. The propulsion subsystem supports rudder angle deflection and propulsion motor speed and direction control through the use of a dual axis motion controller that drives the rudder actuator and propulsion servo. This subsystem also monitors rudder position, motor current draw, and fault conditions. The communications subsystem manages hardware including Freewave radios and Iridium satellite modems and handles the low level packet protocol associated with the command/telemetry link. The C&DH subsystem provides support for onboard command validation and processing, real time and playback telemetry generation, onboard communication bus, data archiving, state distribution, event logging, and scheduling. It also provides a watchdog capability, which monitors subsystem operation. The GN&C subsystem interfaces with navigation sensors including a GPS receiver and digital compass to obtain time, position, velocity, and heading measurements. The subsystem enables direct manual control or autonomous control through the use of a custom autopilot implementation. The autopilot provides support for course and mode management, station keeping, course tracking, diagnostics, and control law interfacing. The attitude determination subsystem interfaces with roll/pitch inclinometers and a 6 degree of freedom (DOF) inertial sensor to provide vehicle rates and accelerations. The power subsystem provides support for main bus voltage and current monitoring and provides for control of a relay bank which is useful for controlling payload power. Core meteorological and water sensors are integrated in a standard way similar to other system components.

F. Ground System Architecture

The ground system is built using the same technologies and architectural approach as described for the onboard system. The core ground system is composed of a suite of applications. A standalone gateway application manages a bank of hardware used to communicate with the platform. A graphical control station application provides an interface for an operator to monitor platform telemetry via strip chart and tabular display as well as view images received from the onboard camera. The control station also enables an operator to browse, edit, and upload commands to the vehicle to configure the path plan, change navigation mode, cycle payload power, request data dumps, and configure system parameters. The control station interfaces with a charting application to facilitate planning and situational awareness. The control station can also be interfaced with Google Earth. Finally the ground system provides a message oriented middleware which facilitates sending telemetry to and receiving commands from systems at guest observer institutions.

V. Platform Testing

This section summarizes some of the historical milestones occurring during the lifecycle of the OASIS ASV R&D program. It also highlights some of the key engineering and science test operations that have recently occurred. An iterative development and testing approach was adopted at program inception and has provided an important feedback loop for incrementally advancing platform capabilities.

A. *Summary of Historical Milestones*

ASV research and development began in April 2004 under a grant from NOAA which helped established a coastal observations program in the Delaware, Maryland, and Virginia (DELMARVA) region. Although funding for this program ended in July 2008, platform R&D, testing, and operations continue through a number of parallel initiatives including science missions, internal research and development, and emerging opportunities.

In 2004, we focused on preliminary systems design, development, and hardware/software integration for the ASV1 platform. By the fourth quarter fabrication of the fiberglass deck/hull parts was completed and the first wave of control system hardware had been procured and began arriving, which enabled bench-top integration and testing to begin.

In 2005 we continued to focus on ASV1 onboard and ground systems development, integration, and testing. During the first quarter the initial version of the platform control system including, computer, radios, and propulsion and steering hardware were installed on the platform. The first on water test activity was completed in March on the Chincoteague Bay and demonstrated manual R/C of the platform by enabling an operator to adjust rudder and throttle settings via a handheld controller. The second and third quarters focused on hardware integration and continued bench testing to support integration of navigation and wind sensor hardware. The propulsion system motor and controller were also upgraded based on experience gained from the initial wet test. The solar panels and charge controller system were installed and tested. The mast fabrication and installation were completed. Autopilot design and development also got underway. The platform main control box was redesigned to make room for a growing number of components and to simplify our ability to install and remove the entire box from the platform. By July, the second major wet test had demonstrated a basic yet stable platform that again operated under manual R/C but now with telemetry monitoring available via shore side control station. The focus of the fourth quarter was on continued development and checkout of the control system with focus on autopilot support. By the end of the year multiple wet tests demonstrated the platforms ability to track short courses of closely spaced (<0.5km) waypoints.

In 2006 we continued the onboard control system development and platform wet testing. The first half of the year focused on integration of additional core onboard hardware to add support for vehicle dynamics monitoring (roll/pitch angle, angular rates, and accelerations), rudder position feedback, satellite communications, enhanced radio communications, and water sampling. Water tests activities emphasized increasing the operational duration and test course size to check out autopilot updates as well as overall platform robustness. In May, we transitioned the water tests to the Pocomoke Sound on the Chesapeake Bay to provide for a more expansive test site and more challenging environmental conditions. Courses up to six nautical miles were now routinely transected with waypoints spaced at one nautical mile intervals. Visual monitoring was conducted from a small on water support boat as well as from a shore side control station which enabled telemetry monitoring and commanding. During the second half of the year we completed fabrication of the ASV2 platform, incorporating substantial experience gained from the ASV1 platform development and testing. ASV2 incorporated a completely redesigned control box that greatly simplified future development and maintenance. In October we conducted the first major wet testing of the ASV2 platform and in November we successfully completed the first ocean deployment of the program with this platform. The remainder of the year focused on core environmental sensor integration and preparations for preliminary science missions.

In 2007 we focused on additional control system hardware/software updates, payload sensor integration, early science mission support, ASV1 platform upgrades, and ASV3 platform production. During the first half of the year we integrated and tested new support onboard the ASV2 platform including AIS, improved manual R/C, cellular communications, onboard digital imaging, and atmospheric monitoring. We also completely overhauled the ASV1 platform to new ASV2 standards. Additionally we began supporting the preliminary phases of our CO_2 air sea flux and HAB science missions and continued to conduct engineering tests to demonstrate increased duration and multiplatform operations. In October, the first overnight ocean operation was conducted as a joint science and engineering mission. During this test, the ASV2 platform transited fourteen nautical miles and performed station keeping operations. Additional tests focused on multi-day station keeping operations. During the remainder of the year we completed fabrication and testing of the ASV3 production prototype platform which further improved the overall ASV platform and ground system designs through improvements in most major subsystems.

In 2008 our focus has been on supporting increased capabilities and operations for our air-sea flux and HAB missions. The onboard and ground systems have continued to evolve to support new payload sensors, improve fault detection and recovery, add scheduling capabilities, and provide additional commanding and telemetry support to simplified monitoring and control during longer missions. Additionally we completed fabrication, testing, and deployment of a 3-meter discuss buoy for a parallel project within our coastal observations program.

B. Engineering Activities

Engineering test operations have been conducted year round on a near monthly basis throughout most of the program. Over past year, extended duration dry testing has spanned periods of weeks and months and has been instrumental in tuning the power subsystem components including battery bank and solar charge controller configuration. Extended duration dry testing has also provided valuable feedback on the stability of the onboard and ground systems and has resulted in modifications to enable these systems to better recover from faults and telemeter new data to support improved monitoring. Recent wet test operations have focused on a variety of aspects including repeated transects in estuaries, longer open ocean transects, estuary and ocean station keeping, platform maneuverability for small scale raster scans, and multi-platform operational logistics.

Figure 3. First Open Ocean Deployment (ASV2), North Atlantic.

Figure 4. Multi-platform operations (ASV2, ASV3), Chincoteague Bay.

Figure 5. OASIS ASV control systems enable 3-m buoy project, North Atlantic.

As part of a parallel research and development effort, we have integrated an OASIS ASV control system onboard a 3-m discus buoy located 22 nautical miles off-shore. This approach eliminated the need for the buoy project to develop a separate control system. The parallel buoy effort is providing useful engineering data and operational experience to the ASV project through long term exposure of the ASV systems to the ocean environment. The power and Iridium communications systems are performing exceptionally well. As of the time of this writing the platform has completed two months of operations in the Atlantic.

C. Harmful Algal Bloom Activities

Nutrient loading of our waters is a consequence of increased human population growth. Sewage discharge and agricultural run off are contributing factors. Increased nutrient levels can lead to higher concentration of algal biomass that can be dominated by high concentrations of certain species which may result in the formation of a HAB. HABs have undesirable impacts on human life as they can result in large fish kills and seafood contamination. In an effort to protect human health, policy makers often close shellfish beds and beaches which impact the local economies. HAB lifecycles are not well understood and new technologies are required to support HAB research and aid public officials in HAB related decision making.

In collaboration with a NASA funded team of researchers from government, academia, and industry, the OASIS ASV team is supporting platform and ground system customizations, sensor integration, testing, and field operations to facilitate HAB research which will contribute to the development of new systems and techniques for understanding and monitoring HABs. A detailed discussion of the Telesupervised Adaptive Ocean Sensor Fleet (TAOSF) project can be found in [11]. The overall goal of the effort is develop systems to enable human operators to more effectively monitor and coordinate multiple autonomous assets such as the OASIS ASV platforms. The project also seeks to increase data harvesting potential and decrease operator work load.

Collaboration on this effort began in mid-2006. Joint end-to-end field operations were in full swing by mid-2007. A joint exercise in July 2008 demonstrated the ability for remote operators at Carnegie Mellon University (CMU) to upload path plans to map a surrogate "bloom" in moving water and receive telemetry to monitor progress. Commands and telemetry pass through the GSFC Adaptive Sensor Fleet (ASF) system and the WFF ASV ground systems prior to being uploaded to the platforms. Telemetry from the platforms is transmitted in near real time to remote operators to monitor progress. Platform operations were also jointly monitored and controlled by operators at GSFC and WFF.

Rhodamine dye deployed from a small support boat serves as a surrogate to create a visible yet harmless "bloom" in the water for the platforms to map. Rhodamine fluorometers onboard the platforms detect the dye levels and report them via the telemetry link. The ASV also captures images from a forward looking digital camera. An August 2007 field exercise, utilized an aerostat to provide increased situational awareness. In the year ahead, we plan to enhance and demonstrate the integrated system in the presence of an actual HAB, ideally in the Chesapeake Bay region.

Figure 6. Creating a visible yet harmless surrogate "bloom" for HAB exercises through the deployment of Rhodamine dye from small support boat.

Figure 7. ASV2 transecting surrogate "bloom", during HAB Exercise, Chincoteague Bay.

Figure 8. ASV onboard camera image captured during HAB exercise.

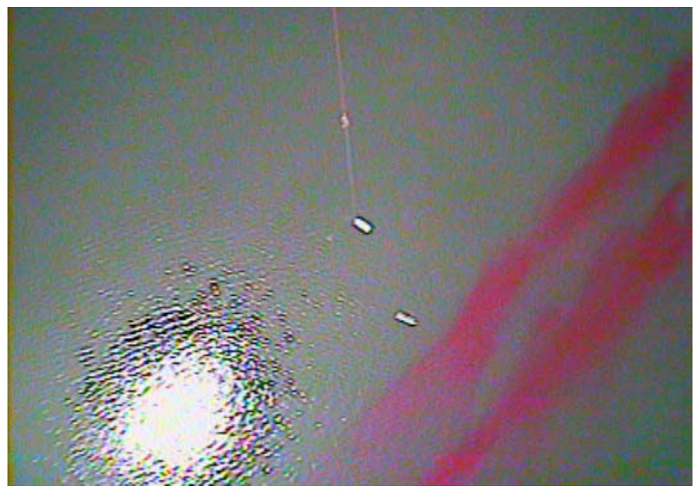

Figure 9. Aerostat view of ASV2 platform approaching "bloom" during HAB exercise.

D. CO_2 Air-Sea Flux Activities

Understanding the Earth's carbon cycle involves studying the planet's land, atmosphere, and ocean systems all of which function as carbon sinks and sources. Since the industrial revolution humans have altered atmospheric composition through fossil fuel burning, industrial emissions, and deforestation. This has contributed to increased levels of carbon dioxide, a greenhouse gas, in the atmosphere which influences changes in Earth's radiative heat and climate. Human induced changes occur in the presence of dynamic natural physical and biogeochemical processes that promote air-sea CO_2 exchange. The Ocean Carbon and Climate Change program provides a plan for observation of carbon cycle processes and suggests a balanced use of autonomous sensor platforms to augment measurements collected from satellites [12].

Through a collaborative effort with the Lamont Doherty Earth Observatory of Columbia University, we are supporting continental cross shelf air-sea CO_2 flux research through the instrumentation and operation of an OASIS ASV platform. A custom CO_2 eddy flux payload has been integrated and tested onboard the ASV2 platform enabling a wide array of measurements in the upper-ocean and atmospheric boundary layer. The payload provides for eddy covariance flux measurements at a height of 2.5m and closed path CO_2/H_2O measurements from below the surface (0.5m depth) and above the surface (0.5m and 5.0m). Measurements are collected at 10Hz. The eddy flux covariance flux measurements include 3D wind speed and direction, open path infrared CO_2/H_2O, 3D angular rates and accelerations. Two closed path infrared CO_2/H_2O sensors facilitate the subsurface and atmospheric measurements. A 600kHz Acoustic Doppler Current Profiler (ADCP) was also integrated to support collection of water velocity profile measurements below the platform. Additional details on the air sea payload are available in [13, 14].

Researchers from Lamont have operated a similar air-sea flux payload onboard a small moored pontoon platform in the Hudson River. While this worked well in the river environment migrating the payload to the coastal ocean environment through integration on an OASIS ASV provided several notable advantages over the pontoon platform including increased payload capacity and protection, mobility, platform communications, regenerative power, and access to supporting measurements (salinity, water temperature, chlorophyll, CDOM, air temperature, relative humidity, barometric pressure, etc.) at no additional cost.

A preliminary test of the air-sea flux payload was conducted in February 2007. The payload has continued to evolve and has been onboard for many of our engineering and HAB operations. In April 2008 we conducted a coastal ocean transect of 34 nautical miles, and completed virtual mooring operations in support of the air-sea mission. Interest in demonstrating the platform as a temporary mooring to replace the pontoon platform prompted a 24-hour proof of concept deployment in June 2008. Future operations are planned and will focus on longer distance and longer duration cross-shelf transects as well as continued testing of the payload and the ASV platform in the ocean environment.

Figure 10. Lamont pontoon platform deployed on Hudson River with CO_2 air-sea flux payload installed.

Figure 11. ASV2 with CO_2 air-sea flux payload installed, North Atlantic.

VI. COLLISION AVOIDANCE CONSIDERATIONS

The International Regulations for Prevention of Collisions at Sea, 1972 (72 COLREGS), defines the international navigation rules that "apply to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels" [15]. The OASIS ASV currently displays mast mounted day shapes and lights as prescribed by the COLREGS Rule 27, to alert vessels in proximity, that the platform is not under command (NUC) or restricted in her ability to maneuver. Day shapes are implemented on the platform through the display of two black spherical radar reflectors in vertical line. Two groups of all around red lights in vertical line are also displayed. Vessels encountering another vessel displaying the NUC designation have the responsibility to "give way" to avoid collision. The platform also displays red and green sidelights and a white stern light as prescribed by Rule 27. A white all-round mast head light is also installed.

The COLREGS address vessel responsibilities and conduct in the proximity of other vessels and define the display of lights and shapes, and the use of sounds and light signals. The COLREGS rules were developed for use by vessels with human operators onboard and do not currently address the unique class of autonomous marine platforms. Regardless, researchers are working to adapt ASV platforms to operate within as many of the COLREGS rules as possible. A discussion on legal issues associated with the operation of autonomous marine vehicles and approaches for implementation of COLREGS rules onboard is covered in [16].

The emergence of low cost hardware to support the shipboard Automatic Identification System (AIS) may aid an ASV in implementation of some of the COLREGS rules. Vessels carrying AIS transponders broadcast state messages over VHF to vessels and Vessel Traffic Services (VTS) in proximity. Messages provide information about the vessel including its name, call sign, size, type, speed over ground (SOG), and course over ground (COG). ASV platforms equipped with AIS receivers can acquire this information and render in on their electronic charting systems to provide improved situational awareness to enable the crew to react as necessary to avoid collision. The OASIS ASV currently integrates an AIS receiver. The onboard system processes AIS messages and inserts them into the telemetry stream. AIS equipped ships are then rendered on control station chart displays to provide enhanced operator situational awareness. In the future, we will be adding the capability for the platform to autonomously adjust course based on output from AIS and onboard radar. Algorithm development and simulation is currently underway to support this effort. We also plan to install an AIS Class B transponder to enable the platform to broadcast messages to nearby vessels. While the US Coast Guard has approved this technology in the US to enhance marine safety and homeland security, the FCC has not. Vendors and users are thus left unable to move forward with this technology until the FCC approval is completed. Although AIS Class B equipment is not available in the US, it is being used abroad. Additional background on AIS can be found at [17].

VII. Conclusions and Future Work

The OASIS ASV team has made significant accomplishments in development, integration, and testing of a fleet of long duration ASV platforms. Preliminary oceanographic missions are now underway and expected to grow in size and scope. Future work includes sensor integration, testing, operations and continuation of research and development. We will be focusing on autonomous behaviors such as collision avoidance and dynamic feature mapping. We will also be moving forward on development, integration, and testing of a new vertical profiling capability. Internal research and development work is underway to develop the next generation ASV platforms that incorporate lessons learned through development of our fleet.

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