The Development and Deployment of a Programmable Water Sampling System Using an Autonomous Surface Vehicle

Dan Flanigan
SeaSatellites, Inc.
San Diego, CA, USA
dan@seasats.com

Jeff Bowman
Scripps Institition of Oceanograhy
La Jolla, CA, USA
jsbowman@ucsd.edu

Elizabeth Connors
Scripps Institition of Oceanograhy
La Jolla, CA, USA
econnors@ucsd.edu

Mike Flanigan
SeaSatellites, Inc.
San Diego, CA, USA
mike@seasats.com

Neil Trenaman
SeaSatellites, Inc.
San Diego, CA, USA
neil@seasats.com

***Abstract*— During January and February, 2021, SeaSatellites Inc, (Seasats) in collaboration with the Scripps Ecological Observatory at Scripps Institution of Oceanography, conducted a series of sea trials to demonstrate the capability of collecting ocean water samples using a newly developed Programmable Water Sampling System (ProWaSS) that had been integrated into a solar/battery powered 3m (9.0ft) Seasats Autonomous Surface Vehicle.**

During the past decade there has been a steady growth in the number of autonomous surface vehicles being deployed to conduct a variety of missions ranging in duration of only a few hours to multiple days, weeks and in some cases multiple months. For many, the idea of deploying an autonomous surface vehicle for extended periods of time, in all- weather conditions while still performing the allotted tasks is a welcomed option. Alleviating the need to go to sea for long periods and now having seen the impact of the Covid-19 pandemic curtailing crewed ship activities, the autonomous surface and subsurface vehicle option has proven invaluable.

Collecting water samples for microbial and eDNA analysis is key to better understanding the health of marine ecosystems. For example, knowing the location and density of organisms capable of producing a harmful algal bloom (HAB) is critical to predicting their landfall on beaches where they impact the health and safety of humans and marine wildlife with a potential for substantial financial loss due to closure of recreational and commercial enterprises on our coasts.

One way to provide an early warning of HABs landing on coastal beaches is through regular offshore water sampling at HAB initiation sites. This can sometimes be challenging due to rough seas and the unavailability or expense of vessels. The Seasats autonomous surface vehicle equipped with a Programmable Water Sampling System (ProWaSS) allows sampling to commence when other types of sampling are difficult or impossible or crewed vessels are unavailable or operationally prohibited.

Trials of the ProWaSS demonstrated the ability to repeatedly collect water samples at pre-determined GPS waypoints offshore of Scripps Pier, return to the pier where the Seasats vehicle was quickly and easily recovered and the samples sent to the laboratory for analysis.

This paper and presentation describe the Seasats vehicle and the ProWaSS and presents the results of the water sample analysis provided by Dr Jeff Bowman and Elizabeth Connors from the Scripps Institution of Oceanography, La Jolla, CA, and proposed further development to expand the ProWaSS to accommodate additional water samples and the inclusion of data from CTD and fluorometer sensors.

Keywords—unmanned systems, command-and-control, autonomy, BVLOS, UxS, eDNA, Harmful Algal Bloom

I. Introduction

a) Background

Over the last decade there has been a period of rapid growth and acceptance of the capability and affordability of Unmanned Systems (UxS). As an industry sector, UxS is the collective reference for unmanned systems across air, land, and maritime domains. Maritime UxS systems now exhibit the same potential (as proven by the aerial and terrestrial UxS systems), with robust, all-weather designs that enable long endurance, rugged missions for marine users. This research paper is the first product of a collaboration between the SCRIPPS Ecological Observatory and SeaSatellites Inc. that is intended to demonstrate the deployment of unmanned maritime system to augment existing eDNA sampling programs utilizing a newly developed Programmable Water Sampling System. An earlier pilot study using an Unmanned Autonomous Surface & Subsurface vehicle off the coast of Cape Flattery, WA successfully demonstrated the viability of using a UxS in lieu of a crewed vessel in times of inclement/rough sea conditions to collect water sample for HAB analysis [1].

b) UxS Technology Advancement

Unmanned systems have been changing the way scientists conduct experiments and gather data. In physical oceanography the transition from ships to persistent remote sensing buoys and then to mobile platforms such as Saildrone and Liquid Robotic Wave Gliders have been huge improvements in time, logistics, and volume of data that can be collected cost effectively. Even so, the systems of the last five years haven't achieved the simplicity and price point needed to enable large scale efforts. Seasats ASVs are another large step towards the goal of democratizing data and collection tools. The intent is to kick off a new paradigm where autonomous missions enable flexibility and scale for ocean data collection.

c) UxS User Acceptance

The ASV requirements for these missions fit into two categories: payload and operational requirements. For payload requirements a sufficient number of samples (6) and sample volume size (500ml) were determined to suit the experiment needs. For operations it was important that the vehicle be able to launch and recover quickly with minimal staff from the Scripps pier. System design discussions led to launch and recovery that could be done with two people in under 30 minutes for launch and the same for recovery.

d) UxS Capability Development

For these experiments the water collection system was a new integration for the ASV and so had to be tested for function and reliability. Early deployments were validated with an onboard camera confirming the correct functioning of the system. The X3 has a modular payload system built in to minimize integration time for new sensors. Future extension or repeat missions would be good candidates for expanding the mission capability to include relevant meta data collected by a CTD or fluorometer.

II. RESEARCH OBJECTIVES

The pilot missions conducted had two primary objectives. First was to collect water samples at set points extending out from the pier and to a location over the mouth of the underwater canyon. The intent of those samples was to analyze them and validate that the pier samples are representative of the sample data collected from over the ocean pier. The second objective was to validate and quanitfy the logistical efforts needed to run autonomous water sampling efforts. By validating and gaining a detailed understanding of the level of effort needed future operations such as pre-emptive and reactionary sampling at river and estuary outflows during preciptiation events can be enabled and planned with high confidence.

III. TECHNOLOGY OVERVIEW

a. SeaSats X3 Overview

The vessel used for the Scripps water sampling missions was the Seasat X3 ASV. The X3 is an autonomous vessel capable of long range and duration missions, three meters in length and 0.6 meters in beam. The X3 is powered by a 240-watt solar array mounted on the deck, and a 2-kWh battery. Stability is provided by an 11 kg bulb keel, and it is propelled by a high efficiency 1 horsepower motor integrated into the keel fin. The X3 is steered by a transom hung rudder actuated by a high torque servo.

The compact size and light weight of the Seasat vehicle facilitate easy launch and recovery by one person. The X3 can be launched from a beach or boat ramp on its rolling trolley, hand launched from a dock, or launched by crane with a user-friendly two-point bridle (Fig.1).

Once launched the X3 can be controlled by the user with a low-latency remote control, ideal for moving the boat away from the launch area or positioning the vehicle for recovery. A button on the remote toggles the Seasat into autonomous mode, and it then begins its mission.

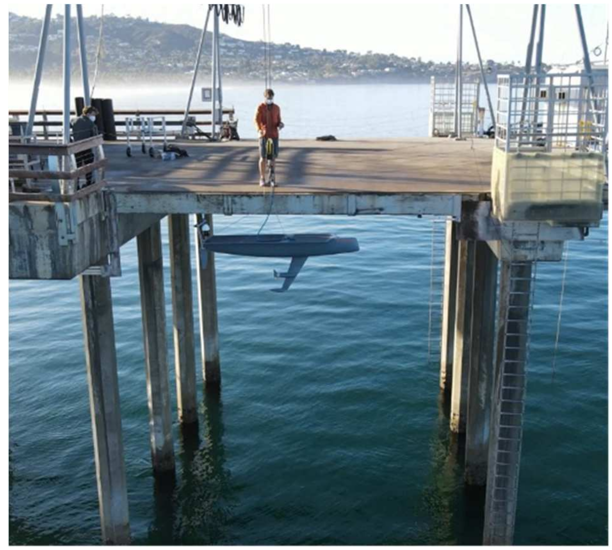

Figure1. X3 Crane Launch & Recovery off Scripps Pier, La Jolla CA

b. Standard and optional sensor packages

The X3 comes standard with several systems for navigation, communication, and sensing. Standard navigation and location sensors include a commercial-grade GPS and IMU (Inertial Measurement Unit). Standard communications are Wi-Fi for close range, cellular for near-coast operations, and automatic fallback to an Iridium satellite transceiver offshore. Standard sensors on the X3 include a camera, a weather station, and a depth sounder. The camera is a controllable pan/tilt/zoom (PTZ) camera with IR capability mounted on a small tower at the stern of the boat. Weather data is gathered with an Airmar 200WX-IPX7 ultrasonic weather station. Water temperature, depth, and boat speed are measured by a 235kHz DST800 single beam echo sounder (SBES). The X3 can also be equipped with a variety of optional sensors and systems to suit specific client needs. Optional systems include a sipper pump for collecting water samples, high resolution bathymetric sensors, and water quality sensors.

c. Adaptive sampling capability based on modes of operation.

For the Scripps mission, the team used a location-based sampling method. Researchers provided points of latitude and longitude for sampling locations. These coordinates were used to define the mission in the browser-based user interface. The vessel was deployed, navigated to the coordinates, collected the samples, and returned to shore with the bagged samples which were then analyzed by the researchers. Each 3-mile mission was completed in approximately 1.2 hours.

The X3 is also capable of adaptive sampling missions. Rather than taking samples at predetermined locations, the X3 can be programmed to choose sampling locations autonomously based on environmental factors measured onboard in real time. The X3 can also function as part of a mesh network with other Seasat vessels, allowing researchers to conduct larger scale missions. For example, multiple vessels could be sent out to different sectors of a large-scale grid. When one or more vehicles encounter the desired sensor parameters for sampling, the other vessels can adjust their missions to survey the newly realized area of interest.

d. Command & Control (C^2) Interface

Once the X3 is launched, command of the vessel can be switched from line-of-sight radio control to the web based C2 interface. The Seasats interface allows full control from any computer with internet access and can be used to monitor a mission by smartphone or tablet. The C2 interface (Fig. 2) displays a map with mission parameters, boat location and heading, along with real time sensor data. Interface widgets enable live video streaming and user-directed pan, tilt, and zoom of the onboard PTZ camera, as well as control of sensors and payloads. The user has the ability to modify mission parameters in real time while the X3 is mid mission and can configure SMS updates to keep the user apprised of the mission's progress.

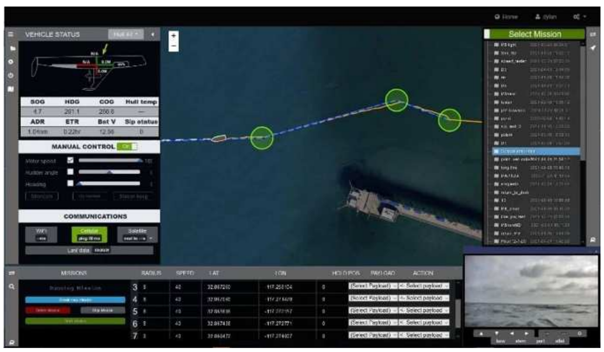

Figure 2. – Command & Control (C^2) Interface

e. Integrated Autonomy

The X3 platform is designed from its core for autonomous operations. Missions are defined by the user and then the vehicle executes that mission step by step. Autonomy follows set predefined rules such as payloads to execute at specified waypoints or under certain conditions. Decision making under significant uncertainty is handled by alerting the operator for input.

IV. Test and Evaluation of Progammable Water Sampling System (ProWaSS)

a. Design Criteria

For the SCRIPPS Ecological Observatory missions the X3 was equipped with a Programmable Water Sampling System (ProWaSS). The ProWaSS system was designed and built with the following criteria.

- System must fit within the 750mm x 300mm x 180mm payload bay in the X3.
- No cross contamination between samples
- The pumps in the system must self-priming.
- The system must be robust, with a design rated to IP67.
- There must be easy access to, and replacement of, the sample bags.
- System must be battery operated and have reasonably low power draw.

b. System Architecture

For the SCRIPPS Ecological Observatory missions the X3 was equipped with a Programmable Water Sampling System (ProWaSS) (Fig. 3). The ProWaSS is a customizable array of peristaltic pumps that take water samples from a moon pool. Each pump has its own inlet and outlet, with the outlet terminating in a sample collection bag to store the sample for later laboratory analysis. Using a separate pump for each sample provides the highest quality sample by avoiding cross contamination of samples introduced by a shared pump or plumbing. The custom ProWaSS system for Scripps included six sampling pumps and collection bags.

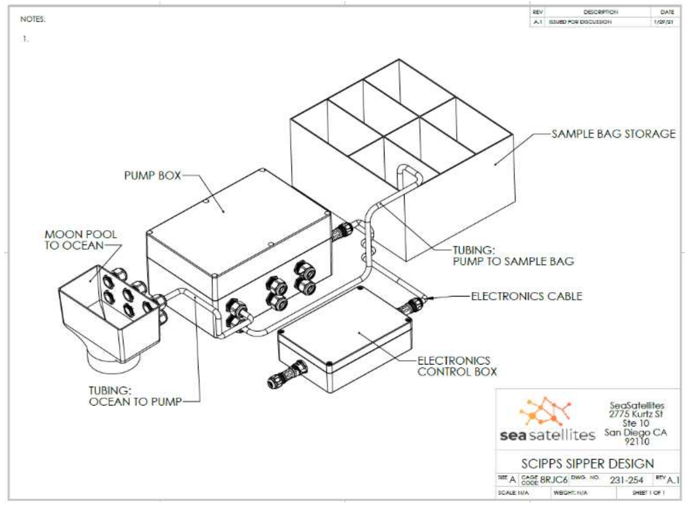

Figure 3. – ProWaSS Components

c. Modular expandability

The ProWaSS is system is a modular proprietary Seasat technology and can be customized for different volumes and sample amounts. The ProWaSS is a transferable system that can be integrated into a variety of vessels. In the future, outfitting ProWaSS with the capability to concentrate and preserve samples would enable long-range and large-scale sampling missions, mitigating range and duration limitations imposed by the threat of sample degradation. Concentrating samples into smaller, longer shelf-life volumes would not only expand the reach of each vehicle, but also lower the transport burden of each sample, enabling one ProWaSS to collect many samples over large areas of interest for the purposes of monitoring eDNA changes over time.

V. Water Sample Analysis & Results

a. eDNA description

Marine microbial communities are often analyzed by DNA sequencing. This involves collecting microbial cells on a filter, lysing them via mechanical and chemical mechanisms, extracting DNA from the lysate, and sequencing. Similar techniques are increasingly being applied to analyze marine metazoan communities via environmental DNA (eDNA) analysis. In the case of metazoans, the collected particles are typically skin cells or fecal material.

b. Sample collection requirements(using ASV's)

Sample collection for eDNA analysis relies on expensive autonomous instrumentation or a vessel. Because these are limitations for many observational programs, a low-cost, mobile, autonomous system for eDNA sample collection is desirable. To minimize sampler complexity and cost we relied on maintaining *in situ* temperature over short deployments to minimize artifacts associated with sample storage. Samples were collected autonomously using a peristaltic pump to fill 1 L acid-washed Tedlar bags (Cole-Parmer). The sample bags were collected at the end of the mission and 300 ml of seawater was filtered for DNA extraction, sequencing, and analysis.

Sample collection took place along a transect starting from the Ellen Browning Scripps Pier at Scripps Institution of Oceanography (Fig. 4) on 7 days over a 3-week period from 18 January 2021 to 11 February 2021. For each sample day a comparison sample was available from the ongoing Scripps Ecological Observatory microbial time-series. To test for sample stability, a sample was collected at the start of the outbound leg, and the same spot was sampled again at the end of the inbound leg. The remaining samples were collected on the inbound leg.

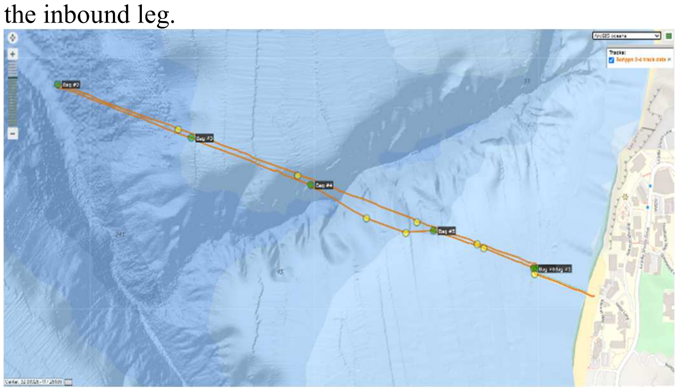

Figure 4. ProWaSS Sample Collection Transect

c. Sample Analysis

The sequencing effort yielded 49 16S rRNA gene libraries. The libraries were denoised and QC'd with dada2 before determining community and predicted metabolic structure with paprica [2]. The paprica pipeline depends on Infernal for alignment [3], EPA-ng for phylogenetic placement [4], RAxML-ng for reference tree construction [5], and Gappa for parsing output files [6]. Sample similarity was evaluated by nonmetric multidimensional scaling (NMDS) using the 'metaMDS' function in the R package vegan [7] (Fig. 5). Bray-Curtis was used for distance and 3 dimensions were used. Stress for the final solution was 0.090. A permutational multivariate analysis of variance (PERMANOVA) was used to assess variations among samples grouped by sample site and date. PERMANOVA was carried out using the function 'adonis2' in vegan. Sequence data is archived at the SCRIPPS Ecological Observatory BioProject PRJNA662174 on NCBI SRA.

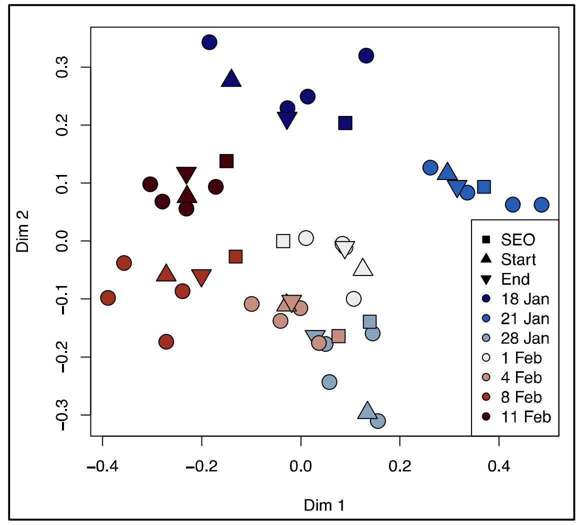

Fig. 5. Nonmetric multidimensional scaling of microbial community structure collected by the ProWaSS system and traditional sampling.

d. Results and comments

Samples strongly clustered by date. This suggests that time has a much greater influence on microbial community structure than space at the scale of our observations. This was supported by our PERMANOVA analysis; only time had a statistically significant impact on sample similarity ($p = 0.001$). These results indicate that sampling with the ProWaSS system yields results consistent with traditional sampling.

Samples designated as SEO refer to time-series collections by the Scripps Ecological Observatory. Samples designated as start and end refer to samples collected from the same point at the start and end of the transect.

VI. Future Applications

The deployment of multiple autonomous surface vehicles such as the SeaSats X3 equipped with a modular ProWaSS sampling system would rapidly increase the ability to detect and geo-locate the extent of Harmful Algal Blooms (HABs). Coastal communities exposed to the impacts of HABs would be better equipped to mitigate the potential Harmful Algal Bloom events to specific locations instead of having to go to a regional shutdown. Similar uses could be taking water samples during an oil spill that would allow timely laboratory analysis.

VII. Summary

ASV functioned as intended. Met design criteria to be quick to use and launch. Samples matched showing Seasats is a statistically comparable system to a fixed pier-based system with the added benefit of flexible mission collection locations. Samples were successfully collected without operator intervention. The structure of the microbial community – which is highly sensitive to sampling and storage conditions – was statistically indistinguishable between samples collected at the start and stop of the transect, and between samples collected by the ProWaSS and traditional sampling.

VIII. Acknowledgments

We would like to thank Matt Heron for assistance with sampling and laboratory analysis. EC was supported by NSF-OPP 1846837 to JB. JB was supported by a grant from the Simons Foundation Early Career Marine Microbial Investigator program.

IX. References

[1] Tiffany C. Vance, John Mickett, Jan A. Newton, Richard W. Osborne, Vera L. Trainer, Neil Trenaman (2019). "Hybrid Autonomous Underwater Vehicle and Unmanned Surface Vehicle Sampling for Harmful Algal Blooms (HABs)—Prototype and Results of a Field Trial." American Meteorological Society 99th Annual Meeting, Phoenix AZ, 2019.

[2] Bowman JS, Ducklow HW (2015) "Microbial Communities Can Be Described by Metabolic Structure: A General Framework and Application to a Seasonally Variable, Depth-Stratified Microbial Community from the Coastal West Antarctic Peninsula". PLoS ONE 10(8): e0135868. https://doi.org/10.1371/journal.pone.0135868

[3] Nawrocki, E.P. and Eddy, S.R., 2013. "Infernal 1.1: 100-fold faster RNA homology searches". *Bioinformatics*, 29(22), pp.2933-2935.

[4] Barbera, P., Kozlov, A.M., Czech, L., Morel, B., Darriba, D., Flouri, T. and Stamatakis, A., 2019. "EPA-ng: Massively Parallel Evolutionary Placement of Genetic Sequences". *Systematic biology*, 68(2), pp.365-369.

[5] Kozlov, A. M., Darriba, D., Flouri, T., Morel, B., & Stamatakis, A. (2019). "RAxML-NG: a fast, scalable and user-friendly tool for maximum likelihood phylogenetic inference". *Bioinformatics*, *35*(21), 4453-4455.

[6] Czech, L., Barbera, P. and Stamatakis, A., 2020. "Genesis and Gappa: processing, analyzing and visualizing phylogenetic (placement) data". *Bioinformatics*, 36(10), pp.3263-3265.

[7] Jari Oksanen, F. Guillaume Blanchet, Michael Friendly, Roeland Kindt, Pierre Legendre, Dan McGlinn, Peter, R. Minchin, R. B. O'Hara, Gavin L. Simpson, Peter Solymos, M. Henry H. Stevens, Eduard Szoecs and Helene Wagner (2019). "vegan: Community Ecology Package. R package version 2.5-6. https://CRAN.R-project.org/package=vegan"