The Use of Saildrones to Examine Spring Conditions in the Bering Sea:

Vehicle Specification and Mission Performance

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***Abstract*—During recent decades the US Arctic is experiencing a rapid loss of sea ice and subsequently increasingly warmer water temperatures. To better study this economically and culturally important marine ecosystem and the changes that are occurring, the use of new technologies is being explored to supplement traditional ship, satellite and mooring based data collection techniques. Unmanned surface vehicles (USV) are a rapidly advancing technology that has the potential to meet the requirement for long duration and economical scientific data collection with the ability for real-time data and adaptive sampling. In 2015, the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (NOAA-PMEL), the University of Washington (UW) and Saildrone Inc. (Alameda, California) explored the use of a novel USV technology in the Bering Sea and Norton Sound. Two Saildrones, wind and solar powered unmanned surface vehicles that can be used for extended research missions in challenging environments, were equipped with a suite of meteorological and oceanographic sensors. During the >3 month mission, the vehicles each traveled over 4100 nm, successfully completing several scientific survey assignments. This mission demonstrated the capability of the Saildrone vehicle to be launched from a dock to conduct autonomous and adaptive oceanographic research in a harsh, high-latitude environment.**

Keywords— Arctic, Bering Sea, oceanographic observations, Saildrone, NOAA, PMEL, ITAE, autonomous vehicle, unmanned surface vehicle, USV.

I. Introduction/Motivation

The vast, remote, and highly productive US Arctic is covered in sea-ice most of the year [1,2]. The Bering Sea ecosystem alone supports roughly 40 percent of all US fisheries catch, with an annual value of several billion dollars [3]. In addition to its economic value, the US Arctic Ocean ecosystem is crucial to the culture and subsidence diet, of its native Alaskan coastal communities [3,4]. Presently, this ecosystem is rapidly changing, severely under sampled and difficult to predict. These changes, including a rapid reduction in areal ice cover and an overall thinning of the historical ice, have the potential to affect the physical and chemical ocean systems as well as the dynamic and productive associated food web.

Ecosystem research in the Arctic presents its own unique challenges. The dynamic and fine-scale nature of the Arctic regions require responsive, high-resolution data collection over large areas in real time. The presence of sea ice, which can annually advance and retreat >1000 km, limits the efficacy of traditional surface moorings [5]. The remote and harsh environment also presents severe logistical challenges, and requires the use of expensive ice-strengthened vessels to maintain traditional observing platforms and sample during periods of ice.

With a rapidly changing Arctic come new demands on developing effective observing systems. To foster responsible Arctic stewardship, new technologies are being imagined and applied to supplement traditional research practices. Satellites, ships, moorings, and floats are the standard, but in an ice-covered region these platforms become costly and often ineffective [6]. USVs are poised to meet this new demand in a cost-effective manner. Unique approaches are being developed to use USVs as adaptive sampling tools that can be coordinate in real time with an interdisciplinary team of engineers and scientists to respond to societal needs.

The National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (NOAA-PMEL) has been experimenting with the use of USVs in the Arctic. In 2011, two Wave Gliders were successfully deployed for two months in the Beaufort Sea [7]. Through collaboration with Liquid Robotics, extensive engineering trials and scientific missions, the Wave Glider's capability for long-term autonomous operation in the open and coastal oceans was established. However, new scientific requirements for more accurate meteorological sensors located higher above the water, and larger biogeochemical payloads with greater

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platform speed, necessitated the development of new platforms in the US Arctic.

As part of the Innovative Technology for Arctic Exploration (ITAE) program, NOAA-PMEL partnered with two NOAA Cooperative Institutes (JISAO-UW and CIFAR-UAF) and Saildrone Inc. to deploy two Saildrones in the spring of 2015. These wind- and solar-powered unmanned surface vehicles (USV) can be used for extended research missions in challenging environments while reporting data in real-time.

Here, we examine the specifications and mission performance of these USVs in the eastern Bering Sea. The performance and efficacy of the Saildrone as a platform for collecting high-quality scientific data over a 97-day mission was demonstrated. This mission, a precursor to using these platforms in the Arctic Ocean included an extensive sensor data quality comparison between the Saildrone vehicles and the NOAAS *Oscar Dyson* [8], and a demonstration of the vehicles' science capabilities by mapping recent ice melt and the Yukon River plume.

II. SAILDRONE

The Saildrone is an unmanned, autonomous sailing vessel. Forward thrust is provided by a 4 m hard wing, which is closer in design to an airplane wing than a traditional sailing vessel's soft sail. Wing trim, or sailing efficiency, is controlled by a novel tail flap design that also shares its roots with aeronautics. This innovative hard wing and tail flap configuration is the key design feature of the platform, greatly simplifying the vehicle's command and control functions, and eliminating the need for all of the winches, pulleys, and rigging commonly associated with sailing craft. The tail flap design acts as a throttle, allowing for the control of both vehicle speed and heel. By incrementally depowering the wing, vehicle dynamics can be tuned in order to maximize scientific sensor performance and accuracy. All of the vehicle's control functions are accomplished with the use of a small, low-power actuator that controls the wing's tail flap, and an actuator that controls a traditional rudder. Solar panels on the hull and wing provide energy for command and control, communications, and operation of scientific sensors.

TABLE I. SAILDRONE SPECIFICATIONS

Vehicle Specifications	
Length	19 ft
Breadth	7 ft
Height	15 ft AWL
Draft	6 ft
Average Speed	2–3 kn
Maximum Speed	10 kn
Propulsion	Wind
Payload Capacity	200 lb
Payload Power	5 W (steady state), 160 W (peak)
Deployment Duration	6–8 months

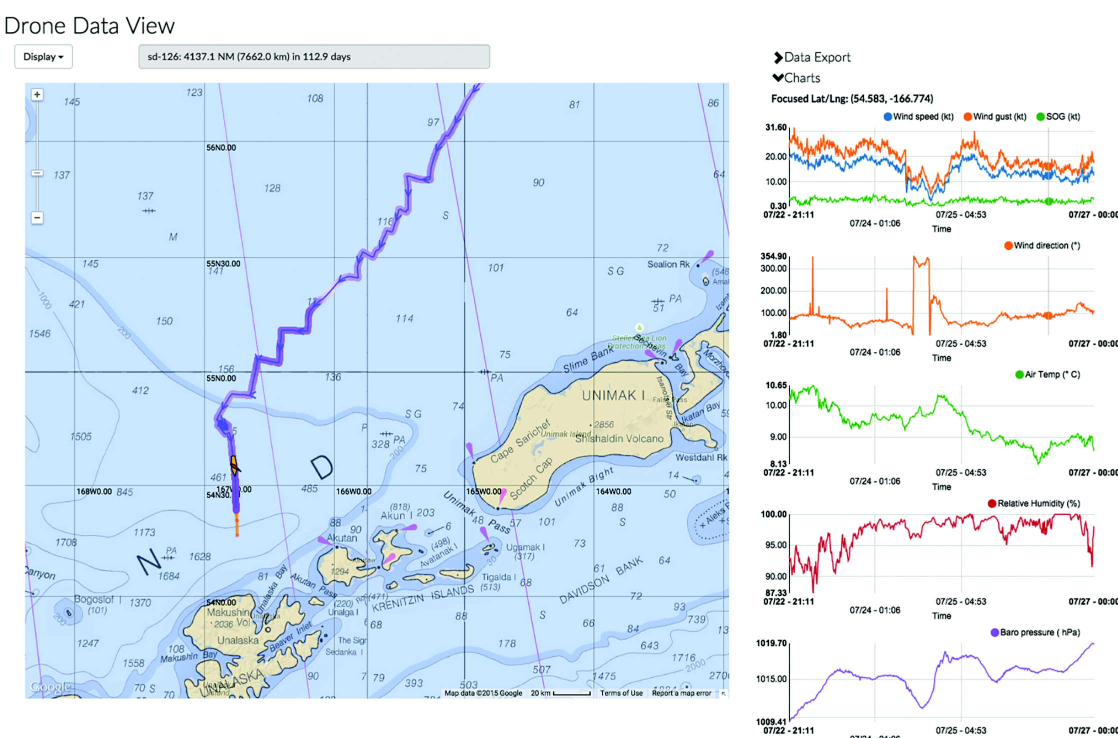


Fig. 1. Screen shot of the Saildrone Inc. shore-side user interface web application. (Left) Map view with NOAA Raster Charts overlayed with USV track. (Right) Data view, displaying the time-series sensor data updated in real-time. The user has the option to view the data spatialy via a color-coded trackline on the map view as shown.

A. *Command and Control*

For vehicle piloting, waypoints are sent from the shore side user interface (UI), along with corridor widths between the waypoints. The vehicle will navigate, autonomously between these waypoints, staying within the specified corridor, regardless of wind or tide, as long as sufficient wind is available. The shore-side UI is a web application, accessible from any web browser, including mobile devices (see Fig. 1).

Communication to shore is via Iridium satellite modems. A short-burst data (SBD) modem is used for mission-critical control, and a separate Iridium router-based unrestricted digital internetworking connectivity solution (RUDICS) modem for sensor data. The vehicle system telemetry and payload data, or Heartbeat data, are sent back every 10 minutes via SBD. Every six hours, the vehicle compresses high-resolution payload data and sends these back to shore, meaning all the collected data are returned to the shore-side database server in near-real time.

B. *Sensor Interface*

The Saildrone has a range of onboard communications options for interfacing with guest payloads. These include RS-232, 485, and also analog interfaces. All payload data are logged in raw form aboard the vehicle. The vehicle can be tasked to perform filtering on the data and compute a single representative value for any particular sampling period. Any filtered numbers are also stored aboard the vehicle. The operator can choose which numbers get sent back in the payload packets, either raw or filtered data, or both.

Payload sensors can be either always ON, always OFF, or power-cycled at any frequency between these extremes depending on scientific requirements. The power state for an individual sensor can be changed remotely and the schedule timing can also be adjusted remotely.

C. *Sensor Payload*

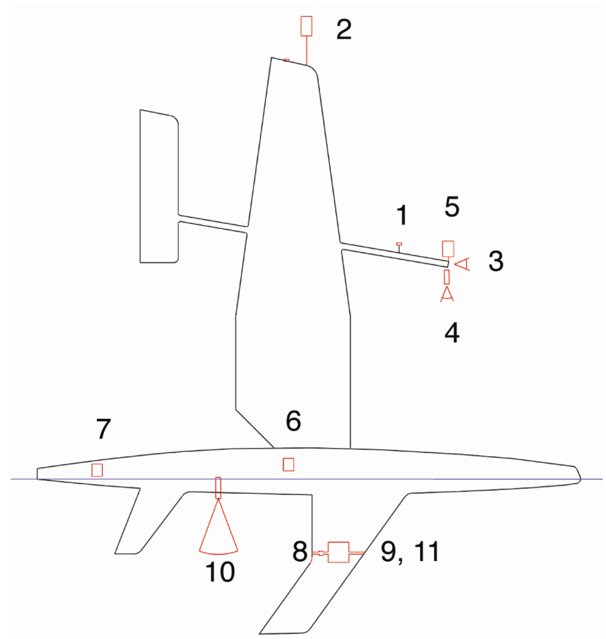
Sensors integrated into the Saildrone were based on NOAA-PMEL requirements for ocean research and provide data on winds, air temperature and humidity, barometric pressure, ocean surface temperature, and water properties of temperature, salinity, dissolved oxygen, and fluorescence. Four cameras also provided situational awareness. The full sensor suite can be seen in Figure 2.

III. Stages of Development

A. *R&D for a Multi-Mission Platform*

The PMEL and Saildrone Inc. engineering collaboration began in the Spring of 2014, with the goal of integrating a broad variety of ocean and atmospheric sensors on this emerging platform. At that time, Saildrone had completed several test missions, including a ~6000 nm mission from California to Palmyra via Hawaii. While this mission demonstrated the command and control and long endurance capabilities of the platform, the vehicle was not equipped with oceanographic sensors. After discussions between engineers of both groups, a plan was drafted to adapt some of the current PMEL climate quality sensors and techniques from previous platforms and integrate them into a Saildrone for ocean science.

To rapidly develop this innovative technology, a cooperative research and development agreement (CRADA) was signed by PMEL and Saildrone in May 2014. Under this agreement, Saildrone provides engineering expertise in vehicle design, software, electronics, and operations, and PMEL l provides engineering expertise on sensors, sensor sampling schemes, telemetry protocols, and access to calibration equipment and facilities.



Sensor:	Height / Depth frm Waterline	Manufacturer & Model
1. PAR Sensor	2.2 m	LI-Cor LI-192SA
2. 3D Ultrasonic Anenomenter 20 Hz	4.5 m	Gill Windmaster
3. Cameras: Up/Down/Left/Right—wide angle	2.2 m	Saildrone Custom Design
4. SST IR Pyrometer	2.2 m	Heitronics KT15 II
5. AT/RH - S3 with Radiation Shield	2.2 m	Rotronic HC2
6. Barometric Pressure	0.2 m	Vaisala PTB 210
7. Magnetometer	0.2 m	Bartington MAG 648
8. Dissolved Oxygen	0.5 m depth	Aanderaa 4831
9. Thermosalinograph	0.5 m depth	Teledyne Citadel
10. Fluorometer cdom fluorescence and backscatter	0.2 m depth	Wetlabs Triplet
11. PMEL-provided CTD	0.5 m depth, strapped to keel	Seabird SBE37SM

Fig. 2. Full 2015 mission sensor suite

B. *San Francisco Bay Testing*

The first platform with meteorological (met) instruments was launched in September 2014 from the Saildrone dock in San Francisco Bay, CA. Frequent in-situ testing is critical for the development of new ocean technology and the shore-side location of Saildrone's facilities is ideal. The more complicated water sensors were gradually installed and brought online throughout the winter of 2014, culminating with a vehicle carrying the full sensor suite deployed in January 2015. From September through March, a vehicle was permanently deployed in South San Francisco Bay, running a small repeated course to test endurance and reliability of systems, sensors, and code. Numerous evolutions of code were installed and tested during this period in order to optimize how the vehicle integrated the sensors, data management, and transmission scheme.

PMEL provided calibrated Seabird Microcats that Saildrone engineers mounted on the keel alongside the RDI Citadel CTD, which is located inside a specially design pass-through in the keel that protects the CTD and DO sensors. Initial indications are that the data compare favorably and no heating of the water is observable in the pass-through in the keel. PMEL also provided a standard ATLAS (Autonomous Temperature Line Acquisition System) wind sensor and datalogger to compare wind speed and direction with the Saildrone Gill WindMaster. This comparison was more difficult because of the large variability over very short distances in San Francisco Bay and by necessity, the wind sensors were at different heights. Nonetheless, the directions were similar and detailed comparisons were completed in the Spring 2015 test mission in the Bering Sea with ships and buoys [8].

In March 2015, the vehicles were declared mission ready. On March 30th, two Saildrones (SD-126 and SD-128) were disassembled in Alameda, CA, and packed into a 40 ft shipping container heading to Dutch Harbor, AK, where the platforms would begin their three-month Bering Sea test mission.

IV. Test Mission—Bering Sea/US Arctic

A. *Mission Planning*

The mission plan included four goals during the three month operation across the Bering Sea and Norton Sound. The overarching goal was to test the platforms/vehicles performance in the US Arctic including: 1) seaworthiness; 2) power generation and management at high latitudes; 3) sensor comparison to standard measurements on known platforms; and 4) remote science tasking to investigate areas of recent sea ice melt and river outflows.

Mission planning and piloting activities were divided between NOAA-PMEL and Saildrone Inc. NOAA-PMEL was responsible for developing the mission plan, coordinating and conducting sensor intercomparisons, monitoring the scientific sensor payload data, and validating the accuracy of the scientific data collected. Saildrone Inc. was responsible for cruise logistics and vehicle piloting tasks. This included uploading waypoints, plotting courses, issuing vehicle commands, monitoring the vehicles' health, and staffing watch standers. To take advantage of the USVs' ability to adapt its behavior in real time to changing environmental conditions, a small working group of scientists and engineers was established at PMEL. During the mission, members of this group monitored the scientific data streams on a daily basis. The group would convene when needed in order to adapt the mission plan as conditions warranted. PMEL continues to actively develop this autonomous vehicle mission management structure and has found it to be a very efficient tool that helps scientists to take advantage of the unique adaptive sampling capabilities of USVs. Additionally, Saildrone Inc.'s user-friendly web-hosted scientific and vehicle data UI was an invaluable resource for keeping members of the working group apprised of the mission.

B. *Deployment*

The two Saildrones arrived on cradles inside a 40 ft shipping container and were staged at the Offshore Supply Inc. dock in Dutch Harbor, AK. The sensors and electronic systems were fully installed prior to shipping for ease of deployment. All components are man-portable. The mast and wing are easily inserted into the mast fitting by two people. The platforms were assembled on their shipping cradles and after two days of dockside testing and sensor evaluation they were hoisted with a ~500 lb rated crane and placed in the water. They were launched ~24 hours apart from the dock in moderate winds and grey skies. The vehicles left the dock under their own power, but were escorted out of the harbor by a small boat as an added measure of safety.

Once through the harbor, they transited Unalaska Bay to the open ocean for testing. The vehicles were then sent northeast to PMEL's M2 surface mooring site (56.86°N 164.05°W) and to rendezvous with the NOAAS *Oscar Dyson* for sensor intercomparison (Figure 4 – 1). The plan included setting the Saildrones at various points of sail, and wing trim angles with the NOAAS *Oscar Dyson* near the M2 mooring to compare all sensors. The two days of ship comparisons went very well in both light and moderate wind conditions. Data from both Saildrones, the ship, and the buoy were collected and analyzed [8].

During the transit to the M2 site, both Saildrones experienced ~50 kn winds with 12–15 ft seas. It is believed that during this gale an actuator on the tail became damaged, which resulted in a condition where SD-126 could only sail on a starboard tack. SD-126 emerged otherwise unscathed and all sensors remained fully functional. Remarkably, SD-126 was able to sail close to St. Paul harbor in the Pribilofs after the ship comparisons were completed where, with the help of a small RHIB, SD-126 was towed to the dock. The actuator was replaced in a couple of hours and SD-126 returned to its

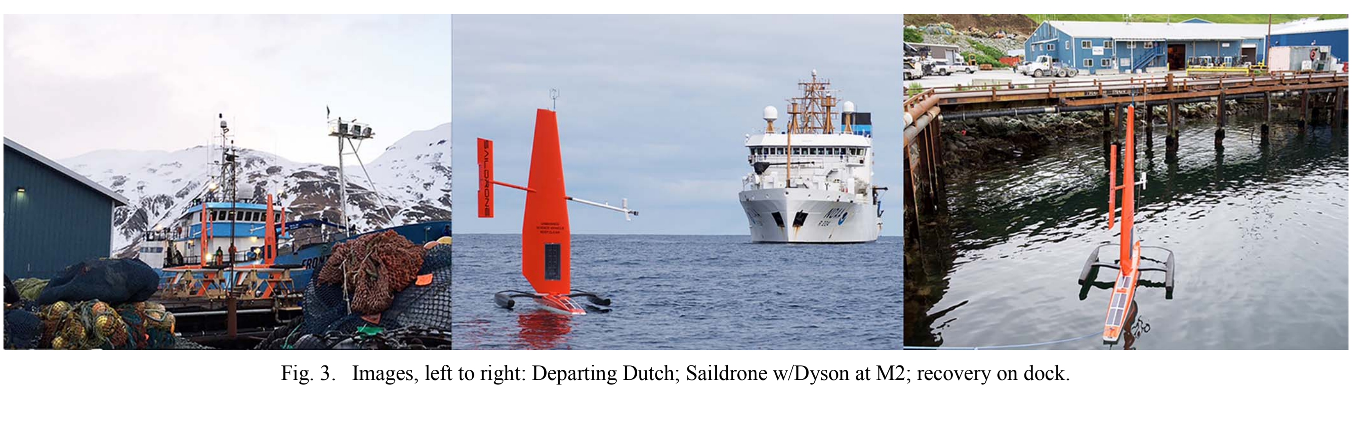


Fig. 3. Images, left to right: Departing Dutch; Saildrone w/Dyson at M2; recovery on dock.

mission. While SD-128 did not experience any problems, a vehicle weakness had been identified. SD-128 was sent to Dutch Harbor as a precautionary measure to replace the vulnerable component before being sent north to investigate and map areas of recent sea ice melt.

In late May, the two Saildrones were used in tandem for two weeks to map the spatial extent and heat content of recently melted ice southwest of St. Matthew Island (Figure 4 – 2). The vehicles followed a sawtooth pattern, centered on the 31.5 psu salinity, heading northwest as the ice was melting, but never entering any areas with 1% ice concentration or higher.

Having completed the recent sea ice melt study and with satellite data showing no ice remaining in the northern Bering Sea, the vehicles were next sent to the Yukon outflow, to monitor the interaction of warm river water with the Alaskan Coastal Current (Figure 4 – 3). The vehicles again worked in a tandem sawtooth pattern but phase-delayed by 24–48 hours to resolve any tidal influence on the suite of oceanographic measurements collected. As expected, very high cdom and chl-*a* were measured while the vehicles sailed in water just a few meters deep in the river outflow. On July 3rd the vehicles reached their northernmost point near 64°N before turning south to revisit several PMEL reference sites and moorings. The southward journey included visiting waypoints running along the 70 m and 50 m isobaths in order to investigate cross-shelf flow.

On July 28th after 97 days at sea, both Saildrones were recovered from the same dock they were launched from in Dutch Harbor. Over the course of the mission, SD-126 sailed 4137 nm and SD-128 sailed 4393 nm. One person from Saildrone was sent to recover, inspect, and load the container to be shipped back to Alameda, CA. The recovery, breakdown, and re-packing into a container took just one day.

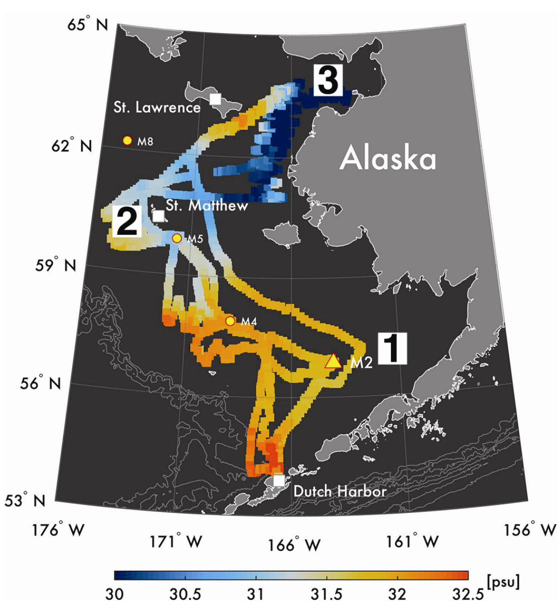


Fig. 4. (1) USV to NOAAS Oscar Dyson comparisons (2) sawtooth pattern (3) Yukon River Plume

C. *Engineering Performance*

The Saildrones each averaged 600 samples per minute (raw), ~2 million samples per day, which were all stored, raw and unfiltered, onboard the vehicle. Per minute filtered data were sent back to shore via Iridium every 6 hours in a compressed format.

Power generation from the 160W panels exceeded expectations even in the overcast conditions of the US Arctic. Throughout the mission, the batteries were always topped off before midday and were never depleted by more than 20% before sunrise the following day. Though there is room on the wing to double the solar panel area if required, the Saildrones in their current configuration have significantly more power available for scientific payloads than currently needed. Both vehicles were in very good condition, with minimal biofouling growth on the hull and no growth on the sensors. All control surfaces and solar panels were in excellent condition.

V. FUTURE

We will further develop the Saildrone for ocean research by adding new sensors and testing against established standards. Potential sensors include echosounders for fish and hydrographic surveys, and carbon sensors for ecosystem monitoring and research. The addition of long- and short-wave radiometers and direct flux measurements to study ocean heat content will be explored as well.

PMEL and Saildrone plan to continue to follow the successful developmental model outlined in this paper. First, developing and testing the vehicle outfitted with new sensor suites in inshore waters. Then, verifying the vehicle and sensor data through deployments in areas of scientific interest with intercomparisons to established sensors and platforms.

VI. CONCLUSION

High quality and cost-effective ocean observations are critical to understand and predict our oceans, atmosphere, and fisheries resources. This is particularly true in the rapidly changing Bering Sea and US Arctic. While satellites, ships, and buoys can make many such observations, unmanned systems such as the Saildrone fill a critical gap and can uniquely respond to real-time conditions and scientific requirements.

The test deployment of two Saildrones in the US Arctic during the spring/summer of 2015 collected data from physical, biogeochemical, and meteorological sensors for 97 days and over 4100 nm, averaging 1.9 kn, with a top speed of 7.2 kn. An ambitious mission plan that included ship and buoy intercomparisons, and mapping areas of recent ice melt and the Yukon River plume was completed as planned. The ability for a team of engineers and scientists to respond and re-task the vehicles in real time, based on vehicle observations viewed on a shared web display, was also demonstrated.

The ambitious project goal of integrating, testing, and deploying a novel USV in the US Arctic within 18 months was successfully completed through cooperative development and resulted in a platform that is ready for ocean research missions from the tropics to the Arctic.

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