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Demonstration of an Autonomous Sailing Vessel for Monitoring Nearshore and Offshore Marine Environments

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PURPOSE: This technical note describes the US Army Engineer Research and Development Center (ERDC) application of an autonomous sailing vessel (ASV) to monitor water quality near underwater unexploded ordnance in Vieques, Puerto Rico, and the Center for Acoustics Research and Education, University of New Hampshire, application of the ASV to monitor the ocean soundscape along the Atlantic Outer Continental Shelf.

BACKGROUND: In 2017, the United Nations declared a Decade of Ocean Science for Sustainable Development (2021–2030) would seek to achieve major changes in the knowledge and management of the ocean (IOC 2020; Ryabinin et al. 2019). Additionally, the 2019 Presidential Memorandum on Mapping and Characterizing the US Exclusive Economic Zone (EEZ) (Presidential Documents 2019) and the subsequent implementation plan (NOMEC 2021) highlights the need to acquire information from the 3.4 million square nmi of largely unexplored ocean within the US EEZ. To accomplish this, vast areas of the ocean will require characterizing and monitoring over large spatial and temporal scales. Yet the use of conventional manned vessels to survey these environments is often fraught with safety concerns and funding limitations leading to reduced spatiotemporal knowledge. One of the primary goals of unmanned surface vessels (USVs) is to create safe, cost-effective, and non-invasive opportunities to make environmental measurements in remote, dangerous, or high-risk areas with greater frequency (Lowery-Simpson 2020). Some USV designs, however, have low fortitude due to stability issues, excessive complexity, and power consumption and still require manned support vessels for near-real-time control of the USV (Liu et al. 2016). To achieve greater scientific resolution of marine environments, investigators are turning to ASV technologies that incorporate programmable navigation controls as well as simplified solar- and wind-power propulsion technologies that make the ASVs not only more tractable but also robust in the face of challenging ocean conditions (Whitt et al. 2020). The robustness comes in the form of less need for human supervision, longer-range missions, and remote communications (De Robertis et al. 2019). The ASV technology aligns with the motivation of UN Ocean Decade and Implementation Plan for Mapping and Characterizing the US EEZ, which encourages scientists to identify and use new opportunities to generate scientific knowledge about the ocean (Chai et al. 2020; Verfuss et al. 2019).

ERDC and the Center for Acoustics Research and Education has been experimenting with the use of ASVs for various environmental monitoring applications. Basic operating principles of ASV platforms have been observed; however, many questions remain regarding technology *readiness*.

Therefore, it is important to outfit sensors to the vessel to demonstrate potential monitoring applications and generate supporting information such as results from field tests performed to measure the parameters of interest. Water quality measurements of the physical, chemical, and biological properties of surface waters characterize the marine environment to assess potential threats to this resource. The importance of these measurements to the environment and human health is reflected in US federal environmental laws (e.g., Clean Water Act; Marine Protection, Research and Sanctuaries Act) and international treaties (e.g., London Convention and London Protocol). Water quality parameters such as dissolved oxygen, salinity, turbidity, and temperature contribute to a better assessment of the ocean environment. Turbidity, for example, is an optical property of water clarity and is important for monitoring nature-driven suspended sediment events or those created by anthropogenic disturbances (e.g., dredging). Turbidity is often used as a proxy for direct measurements such as total suspended sediments (in mg/L)[1,2] and can be an indicator of increased sedimentation near sensitive habitats such as coral reefs (Erftemeijer et al. 2012). Another important and emerging environmental monitoring program is the measurement of the ocean soundscape, or characterization of the ambient ocean sound in terms of its spatial, temporal, frequency attributes, and the types of sources that contribute to the sound field (ISO 2017). The ocean soundscape has attracted increasing interest as ocean sound level or acoustic quality has been identified as parameter of interest in the EU Marine Strategy Framework Directive (MSFD) (Dekling et al. 2014). The MSFD identifies ocean noise as a stressor and requires that European Union member states monitor and mitigate noise pollution as part of their efforts to obtain "good environmental status." Because of the recent increase in the availability of ocean soundscape data, ocean sound is also recognized as an Essential Ocean Variable by Global Ocean Observing System Biology and Ecosystem Panel (GOOS 2018). Ocean sound provides information vital to understanding vocalizing marine life, ocean dynamics, and human use of the ocean making this ocean parameter critical to sensing and understanding the marine environment (Hildebrand 2009; Howe et al. 2019; Miksis-Olds et al. 2018).

To evaluate the potential benefits of monitoring the physical and chemical properties of water as well as the ocean soundscape from ASVs, the performance and applicability of a solar- and wind-powered ASV was assessed. Specifically, the authors assessed (1) the ability of the vessel fitted with a water quality sensor to monitor water conditions in a restricted and potentially hazardous nearshore area containing underwater unexploded ordnance at sites in a former naval training range, Vieques, Puerto Rico, and (2) the ability of the vessel to characterize the ocean soundscape in support of acoustic water quality by sailing a hydrophone over many kilometers along the east coast of the United States.

AUTONOMOUS SAILING VESSEL: The wind- and solar-powered SubSeaSail Generation 6 autonomous semi-submersible sailing vessel used in this demonstration consisted of a wingsail above water and the bulk of the structure and weight below water with a keel and rudder connected to the hull in the shape of an A-frame (SubSeaSail, San Diego, CA, USA; Table 1; Figure 1). The

[1]For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

vessel is described in detail by Donaldson (2020) and thus briefly described here. The wind propulsion technology consists of a passively controlled wingsail that can rotate 360° around a carbon fiber mast. Inside the submerged hull are ballast weights, a nickel metal hydride battery pack, and an auxiliary thruster at the stern. Solar panels fixed to the float module above the waterline charge the battery pack that powers the navigation system, communications, on-board sensors, and thruster. The guidance system uses an adaptive algorithm to adjust the rudder while the passive wingsail control mechanism positions the wingsail to maximize the velocity toward a waypoint. Software allows the operator to program a path defined by a series of waypoints and a *keep-in* zone around the path that turns on the thruster for course corrections if the ASV sails outside of the zone. Communication with the vessel is accomplished through Wi-Fi or satellite for remote operations. The guidance system creates a log file containing navigation data such as latitude, longitude, speed over ground, course over ground, pitch, roll, heading, and other parameters.

Table 1. Specifications of the wind- and solar-powered SubSeaSail Generation 6 autonomous sailing vessel (ASV).

ASV Parameter	**Result**
Weight, total	28 kg
Max payload weight	20 kg (neutrally buoyant)
Length	1.5 m
Height, total	3.04 m
Max beam	0.25 m
Hull draft	1.3 m
Wing sail height	1.52 m
Wing sail area	1 m^2
Max sailing speed	3 kn (1.5–2 kn common)
Max wind speed resistance	45 knots (8 to 12 kn optimal)
Max wave height resistance	3.5 m observed (5 m calculated)
Propulsion, main	Wind
Propulsion, auxiliary	Thruster
Battery	450 W/h nickel metal hydride
Solar	30 W peak on wing sail, 10 W peak on deck
Communication	Wi-Fi (line of site)/ Satellite (remote operations)

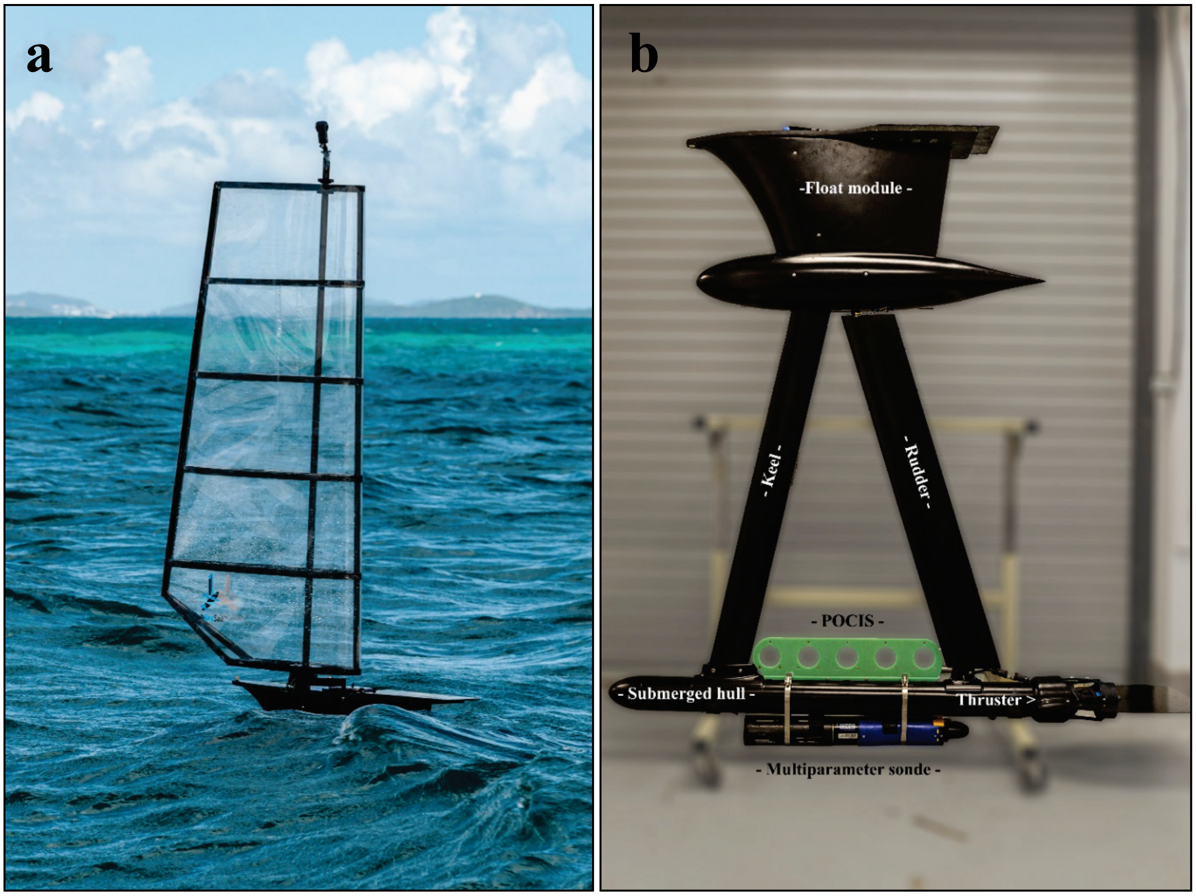

Figure 1. (a) Image of the wind- and solar-powered SubSeaSail Generation 6 ASV deployed near Mosquito Pier area (18.1368, -65.5222), Vieques, Puerto Rico, in east winds and mean wave heights of 1.2 m. (b) Image of ASV structure below the water surface which includes the keel and rudder connected to the float module and submerged hull in the shape of an A-Frame. A polar organic compounds integrative sampler (POCIS) and multiparameter water quality sonde were fitted to the submerged hull while deployed in nearshore areas in Vieques, Puerto Rico.

STUDY LOCATIONS AND ASV MODIFICATIONS

Vieques, Puerto Rico. Vieques (18.1263, -65.4401) is an island located approximately 11 km off the eastern end of the main island of Puerto Rico, a US territory in the Caribbean Sea. From the 1940s until 2003, the Department of the Navy managed the Vieques Naval Training Range (VNTR) on the eastern side of the island during which munitions were fired as part of military training operations and vessels were used as targets. A multiparameter sonde (EXO3, YSI, Yellow Springs, Ohio, USA) was fitted to the ASV with 3D-printed brackets and hose clamps and mounted parallel along the bottom of the submerged hull (Figure 1). The sonde weight was 2 kg with a full payload of four probes (turbidity x2, salinity, and pressure transducer), one antifouling wiper, and protective probe guard installed and internally powered. Optical sensors (Hero 6 Black, GoPro, Inc., San Mateo, CA, USA) set in time-lapse mode (image acquired every 5 s) were attached to the top of the mast and underwater to the hull to collect images of sailing conditions, water column, and ocean bottom. Survey mission areas along the southeastern shore in the former (VNTR) included (1) Bahía Salina del Sur (18.1310, -65.3020), a shallow semicircle shaped bay where rectangular shaped survey areas were programmed to survey water landward of two small islands near the mouth of the bay in 5–7 m of water (Figure 2); (2) Ensenada Honda (18.1174, -65.3644), a large lagoon. A third and relatively undisturbed site on the northwestern shore, Mosquito Pier area (18.1368, -65.5222), was surveyed down a path that followed the coastline in 4 to 10 m of water. The survey mission goals were to demonstrate the capability of the ASV to carry a water quality sonde and optical sensors while safely sailing in potentially hazardous nearshore areas to support integration of the sensor for water quality monitoring applications and to characterize bottom substrate in shallow water areas. The vessel was also outfitted to hold a series of polar organic compounds integrative samplers (POCIS), for the detection of munitions constituents. However, the demonstration timeline did not allow deployment for a length of time sufficient for the detection of munitions constituents, which are present in this area in the part-per-trillion range (Rosen et al. 2021).

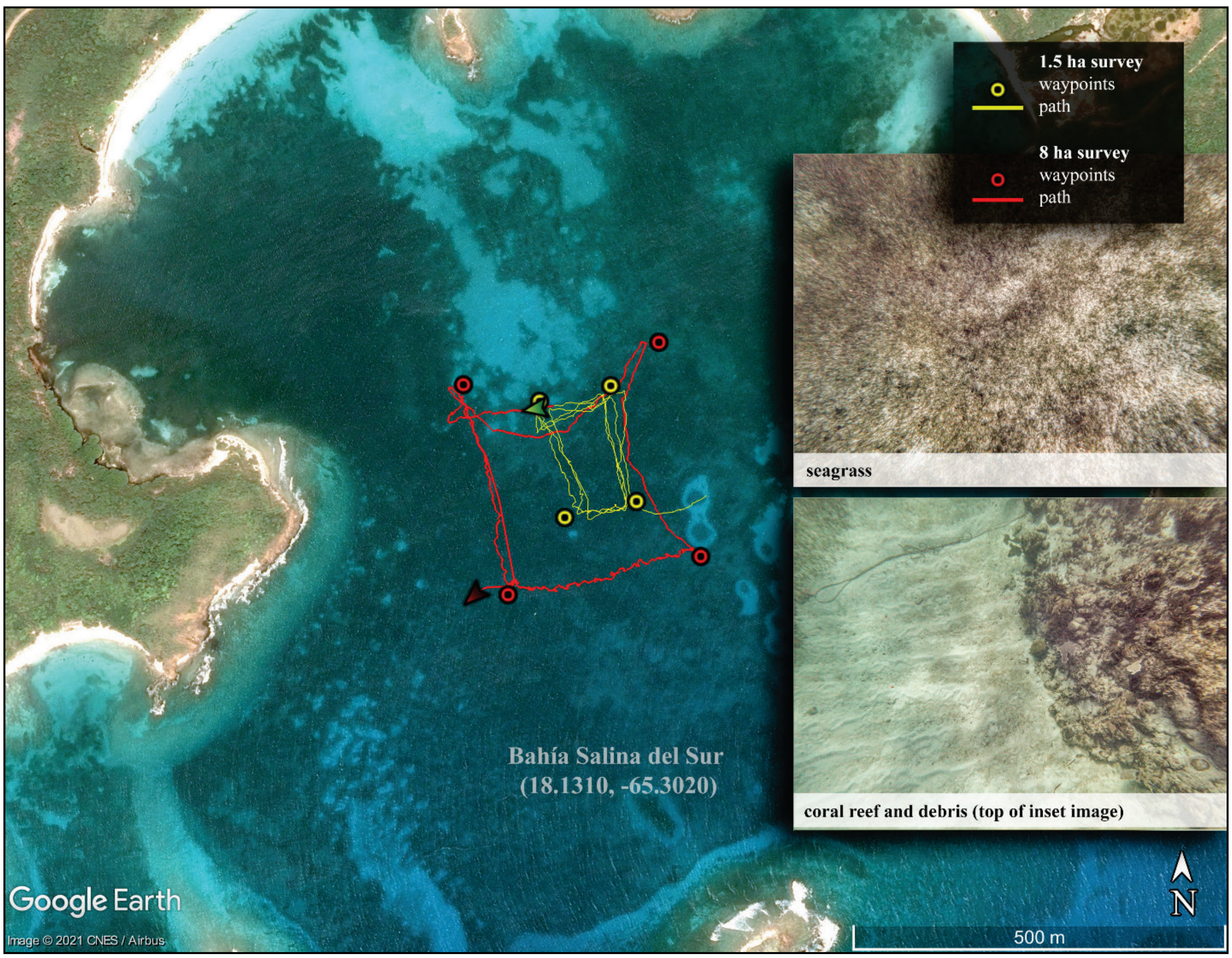

Figure 2. Map of Bahía Salina del Sur (18.1310, -65.3020), a live impact area in the former Vieques Naval Training Range, Vieques, Puerto Rico, showing the ASV track for two survey missions: (1) yellow track around a ~1.5 ha area; (2) red track around an ~8 ha area. The vessel carried an optical sensor to image the ocean bottom where seagrass (top inset image) and coral reefs and interspersed debris (bottom inset image) were easily identified in 5 m water depth.

Atlantic Outer Continental Shelf (OCS). The Atlantic Deepwater Ecosystem Observatory Network (ADEON) deployed in November 2017 supports a multi-year study of underwater soundscape ecology in the US Mid- and South Atlantic OCS (University of New Hampshire, n.d.). As part of ADEON, ocean bottom landers fitted with passive acoustic monitoring systems and water quality sensors were deployed at seven sites along the OCS shelf break (Ainslie et al. 2018). To contribute to a more comprehensive spatiotemporal assessment of the soundscape between ocean bottom lander sites, multiple manned research cruises towed acoustic sensors between sites. In December 2020, the SubSeaSail was incorporated into the ADEON network's final sail cruise plan, which called for simultaneous ocean soundscapes measurements from a manned vessel as well as the ASV (Heaney 2020). The ASV was transported to the Jacksonville ocean bottom lander mooring site (JAX; 30.4940, -80.0023; Figure 3) where it was outfitted with a single hydrophone (µRUDAR-mk2 micro Remote Underwater Digital Acoustic Recorder, Cetacean Research Technology, Seattle WA, USA) with onboard recorder (96 kHz sample rate) and then manually launched from the side of the support vessel. A pre-programmed survey mission uploaded to the ASV started at the JAX site, headed northeast, and ended at the Charleston Bump bottom lander mooring site (CHB; 32.0705, -78.3730).

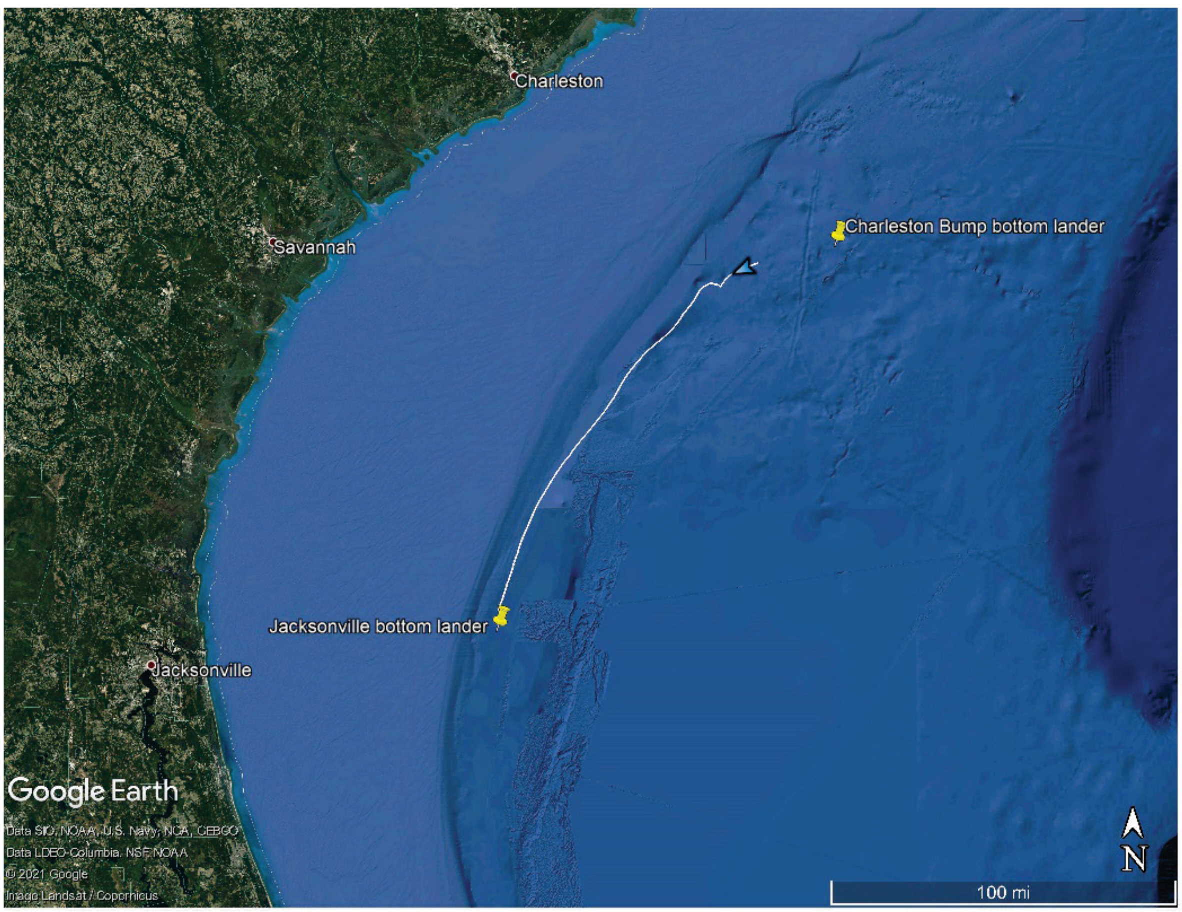

Figure 3. Map of SubSeaSail ASV track. The ASV was deployed with a single hydrophone near the Jacksonville bottom lander, sailed northeast along the Atlantic outer continental shelf, and ended southwest of the Charleston Bump bottom lander.

DATA ANALYSIS: At Vieques, study area conditions were measured at a nearby oceanographic data buoy (Vieques buoy, Caribbean Coastal Ocean Observing System) where wind direction was predominantly from the east. Post-deployment, the ASV's navigation log and water quality sonde data were analyzed to generate descriptive statistics for vessel performance and water quality conditions. Water quality data and images were georeferenced based on location data from the ASV's navigation log file. A KML file with the georeferenced image data and a link to each image was generated and imported into Google Earth where images were viewed along the ASV's path to determine bottom characteristics. At the Atlantic OCS, study area conditions were measured and averaged from nearby oceanographic data buoys (National Oceanic and Atmospheric Administration, National Data Buoy Center Stations: 41004, 41008, 41010, 41047, and 41048). To illustrate the utility of the ASV soundscape measurement, the characteristic u-shape of a commercial vessel closest point of approach was identified in acoustic recordings and used to generate a spectrogram (Verlinden et al. 2017). Additionally, an acoustic field simulation was performed using the Peregrine propagation model, which is a modernized version of the RAM parabolic equation model (Heaney et al. 2017). The simulation was used to estimate sound propagation transmission loss in decibels (relative to 1 µPa at 1m) of a 100 Hz sound source at 20 m depth and a 20 Hz sound source at a 10 m depth and plotted for a single ASV geographic position on 4 December 2020.

RESULTS AND DISCUSSION

Vieques, Puerto Rico. From 5 and 6 February 2020, the ASV was deployed at Bahía Salina del Sur, then Ensenada Honda, and finally Mosquito Pier where survey missions sailed a total distance of 13.5 km over the deployment duration of ~8 hr. During deployments, mean (± standard deviation or range [min to max]) wind speeds were 13 ± 2.3 kn with peak gust speed of 16.2 kn (11.3 kn to 24.5 kn) while wave height was 1.2 m (1.1 m to 1.5 m). The ASV's neutral buoyancy occurs when fitted with 20 kg of weight. Based on the navigation log and visual observations, the effects of the 2 kg outfitted sonde and POCIS on vessel performance under these sea conditions was negligible. The ASV's mean speed was 1.2 kn and 95% of vessel speeds were <2 kn, while mean pitch was -4.8 ± 3.3° and roll was 1.9 ± 3.6° all within the ASV's normal operating limits. Mean salinity, turbidity, and temperature measured by the sonde were 35.7 ± 0.1 ppt, 0.5 ± 0.1 NTU, and 27.5 ± 0.4 °C, respectively. The spatial and temporal conditions of salinity, turbidity, and temperature were unremarkable with no obvious trends through the ASV's paths. At Bahía Salina del Sur, an estimated 5.2 ha of the bottom substrate was digitally imaged in which a seagrass community, coral reefs, and some debris (e.g., steel cable) were visible in 5 m water depths along the ASV's path (Figure 2). Observations of the Bahía Salina del Sur bottom in this demonstration agree with previous observations by Hernández-Cruz et al. (2006) who described a dense seagrass community and a fringing coral reef in the area. Although the origin of the debris is unknown, it is plausible the debris is from military training operations that took place in the bay (Deslarzes et al. 2002).

Atlantic Outer Continental Shelf. The ADEON manned support vessel and ASV were to measure the soundscape simultaneously around the ocean bottom landers, but rough sea conditions posed a safety risk to the crew. Instead, the ASV was manually launched from the support vessel and began the 207 km soundscape survey along a single one-way northeast path closely following the Atlantic OCS between the JAX and CHB sites (Figure 3) from 3 to 6 December 2020, while the crew returned to Charleston, SC, for safe harbor. During deployment, wind speeds were 11.8 ± 5.3 kn (0.4 kn to 33.2 kn) with average peak gust speed of 15.9 kn (1.4 kn to 48.0 kn). The average wave height during the survey was 1.4 ± 0.6 m (0.4 m to 3.4 m) and 80% of wave heights were <2 m. The survey path approximately followed the shoreward boundary of the Gulf Stream, the western boundary current in the North Atlantic, where average current speed is ~3.5 kn. Along the survey route, the ASV's mean speed was 2.1 kn, and satellite services were used to track progress of the vessel in near real-time. A challenge for monitoring underwater sounds from vessels is accounting for vessel noise signature, acoustic properties, and ambient noise. Because this ASV relies on wind propulsion and – with the bulk of the vessel including the hull underwater – the hull drag and noise were negligible (i.e., hull slap caused by wave action). Based on the transmission loss model the best opportunity for detecting a 20 Hz or 100 Hz sound source such as a ship or whale in all directions from the ASV hydrophone occurred within a ~15 nmi radius, after which the probability a sound source will be detected decreases as refraction begins to effect sound propagation resulting in a larger spread of acoustic energy paths (Figures 4 and 5). Although the probability of detection decreased with distance, the model supported the potential for detection of sound sources as far as 50 to 100 nmi landward and seaward of the ASV. The detection distance depended on the frequency of the sound source and relative position to the Gulf Stream current and Atlantic OCS. As suspected, the lower frequency did not propagate landward into shallower water as far as the 100 Hz sound source due to the larger wavelengths of the lower frequency being absorbed into the ocean bottom at shorter distances. Along the ASV track, acoustic input from a commercial vessel was detected approximately 2 nmi north of the ASV as shown in a spectrogram (Figure 6). These data provide evidence of future opportunities to improve the spatial and temporal scales of underwater sound measurements between stationary monitoring stations. Overall, these field trials were a successful *proof-of-efficacy* for the deployment of the ASV, especially in rough sea conditions, for collection occurring over >200 km over multiple days, for the purposes of passive acoustic monitoring.

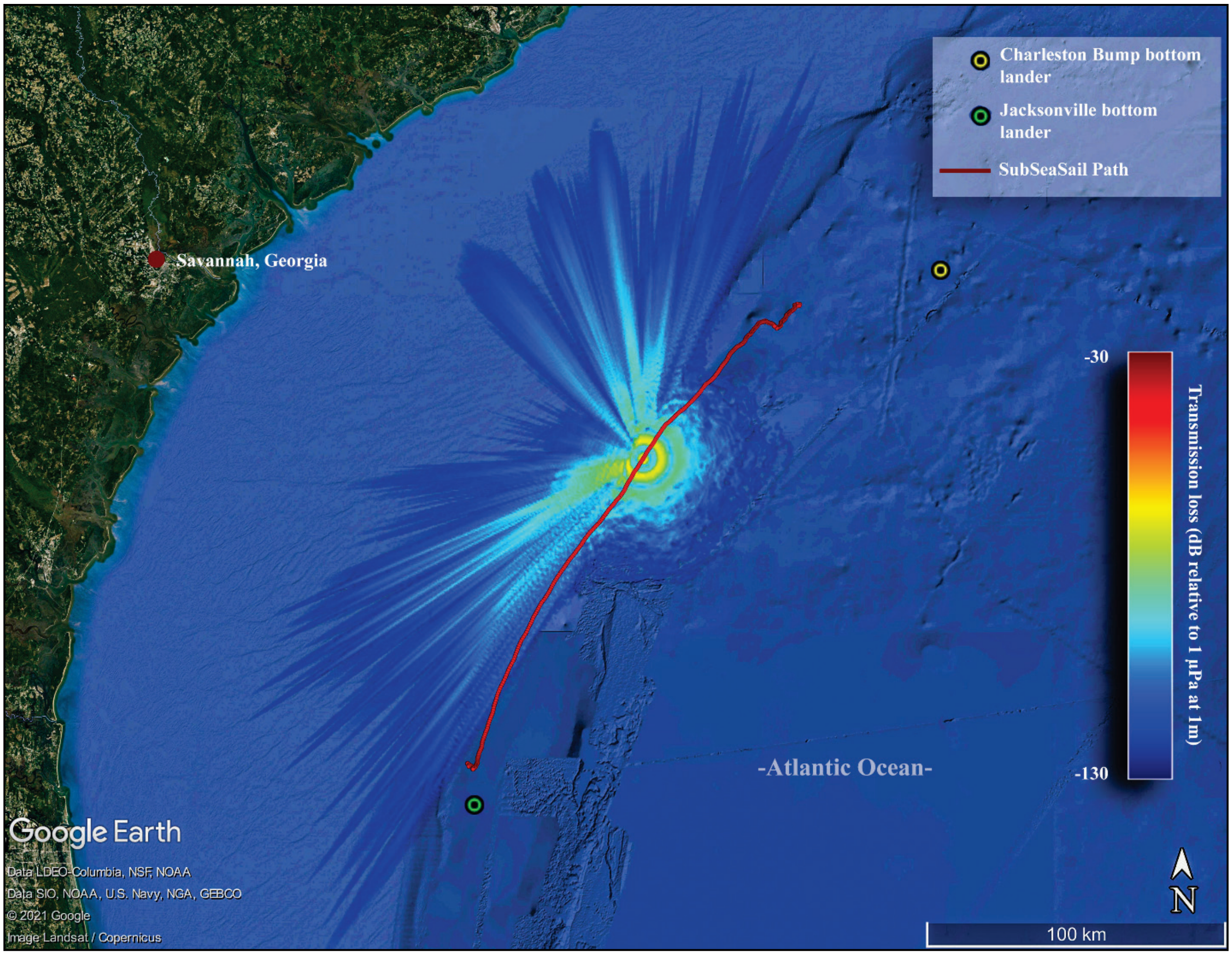

Figure 4. Map of SubSeaSail ASV track. The ASV was deployed with a single hydrophone near the Jacksonville bottom lander, sailed northeast along the Atlantic outer continental shelf, and ended southwest of the Charleston Bump bottom lander. The estimated sound propagation transmission loss in decibels (relative to 1 µPa at 1m) of a 100 Hz sound source at 10 m depth was plotted for a single geographic position on 4 December 2020.

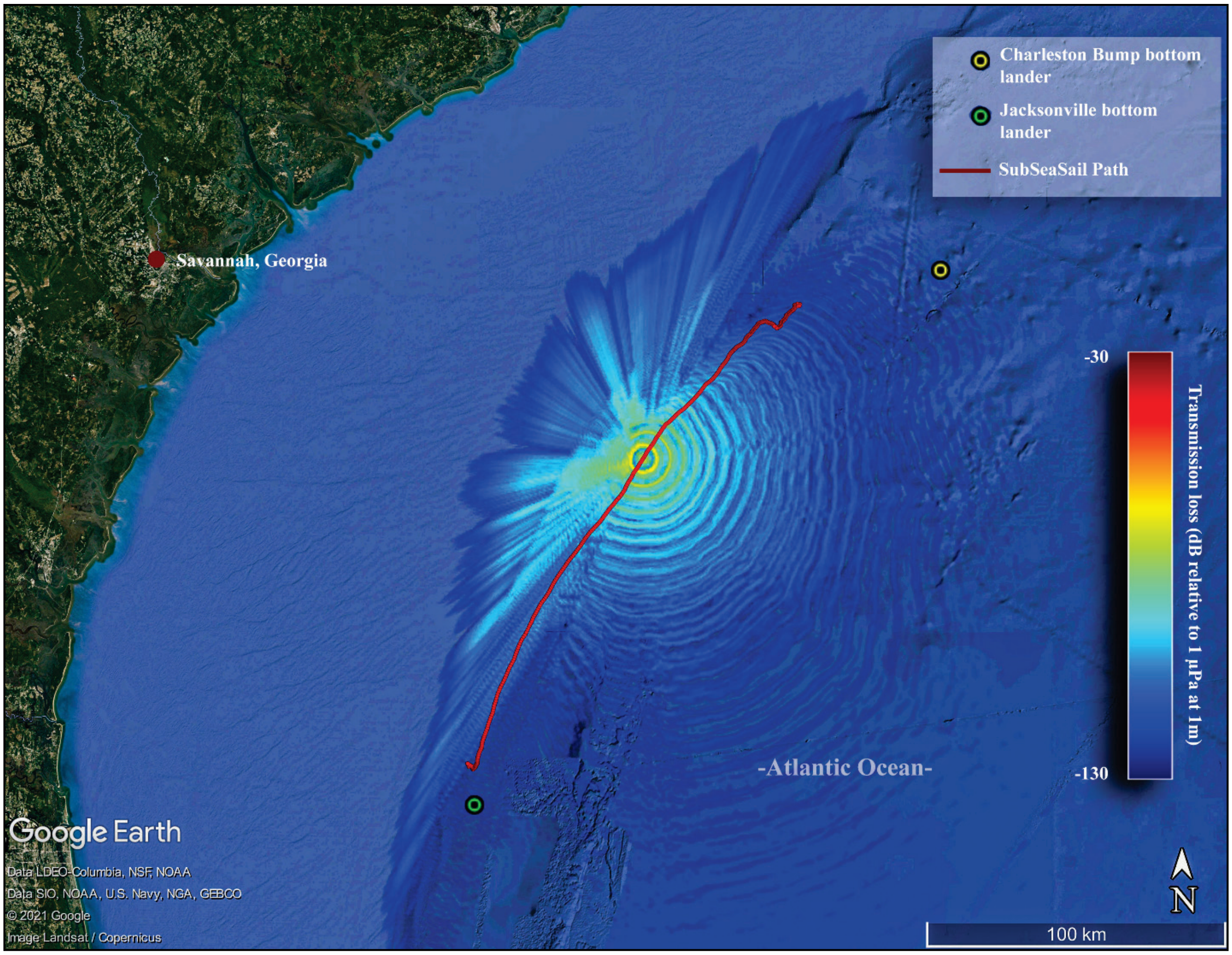

Figure 5. Map of SubSeaSail ASV track. The ASV was deployed with a single hydrophone near the Jacksonville bottom lander, sailed northeast along the Atlantic outer continental shelf, and ended southwest of the Charleston Bump bottom lander. The estimated sound propagation transmission loss in decibels (relative to 1 µPa at 1m) of a 100 Hz sound source at 20 m depth was plotted for a single geographic position on 4 December 2020.

Figure

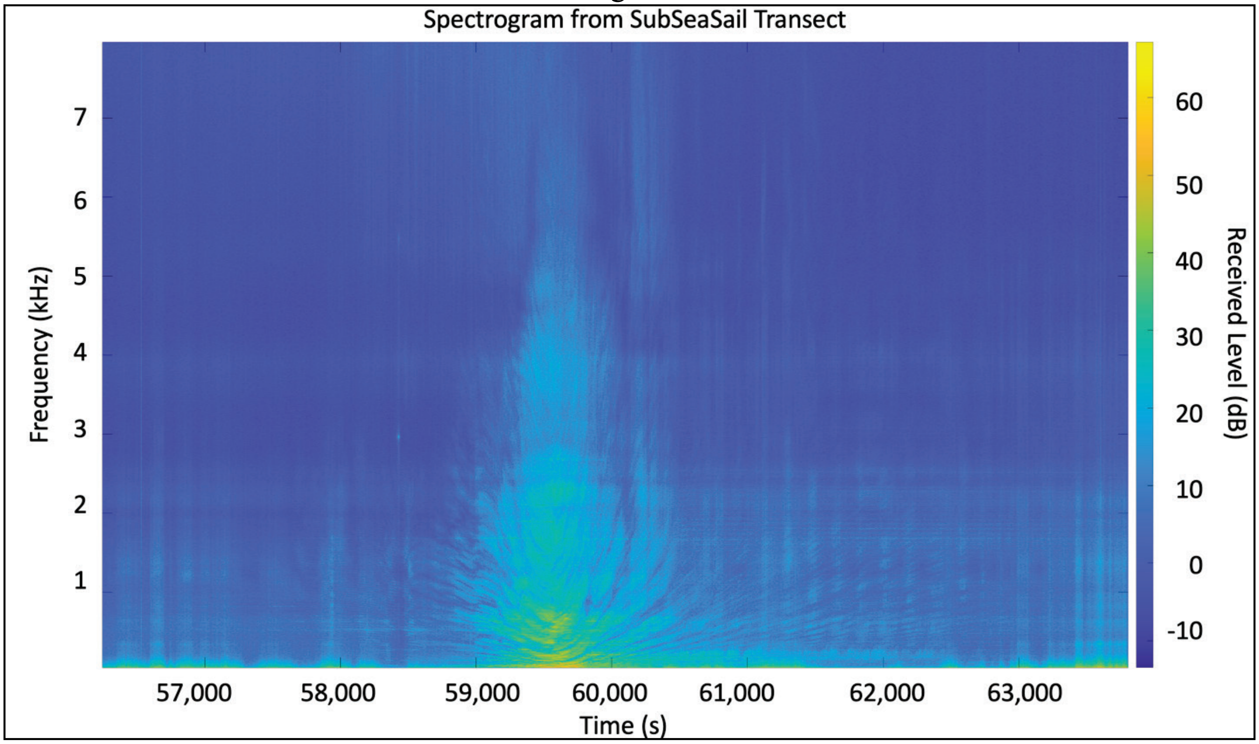

Figure 6. Spectrogram of acoustic data recorded from the SubSeaSail ASV deployed with a single hydrophone near the Jacksonville bottom lander, sailed northeast along the Atlantic outer continental shelf, and ended southwest of the Charleston Bump bottom lander. A characteristic u-shape of a commercial vessel passing approximately 2 nmi north of the ASV is shown at 59,500 s.

SUMMARY: The ocean is a difficult environment in which to make observations over large spatial and temporal scales. To meet the UN's Ocean Decade initiative and the Implementation Plan for Mapping and Characterizing the US EEZ, large areas of the ocean will require monitoring over weeks and months to generate scientific knowledge about the ocean. The ASV reported herein demonstrated proof-of-efficacy in relatively large ocean survey areas (>100 km) in scenarios where monitoring using traditional (manned vessel) options was limited due to unexploded ordnance vessel restrictions or adverse weather conditions. The ASV water quality monitoring application in Vieques provided evidence for the relative robustness of the platform to accept outfitted sensors and maintain sailing performance while operating safely in restricted and potentially hazardous nearshore environments. The ASV acoustic survey mission along the Atlantic OCS helped to contribute to a more comprehensive spatiotemporal assessment of the ocean soundscape between previously deployed bottom landers equipped with acoustic sensors as part of the ADEON network. The transmission loss simulation used along with bottom lander sound data could help predict the number of ASVs needed to survey the entire EEZ to increase the detection probability of acoustic inputs from sound sources such as commercial vessels, submarines, or whales.

Basic operating principles of the ASV outfitted with sensors was observed and the field results support further integration of sensors to develop more capable applications to include georeferenced near real-time data uploads to support more rapid development of data visualization products such as heatmaps to complement existing ocean observation networks.

Looking ahead, the advancements in ASV technologies and environmental sensors used collectively and creatively with other ocean observation platforms (e.g., manned vessels, buoy sondes, ocean bottom landers, scuba diving, satellite imagery) will contribute to a more comprehensive assessment of marine environments through deployment of economical multi-ASV arrays that will lead to repeatable missions and reduced revisit times.

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