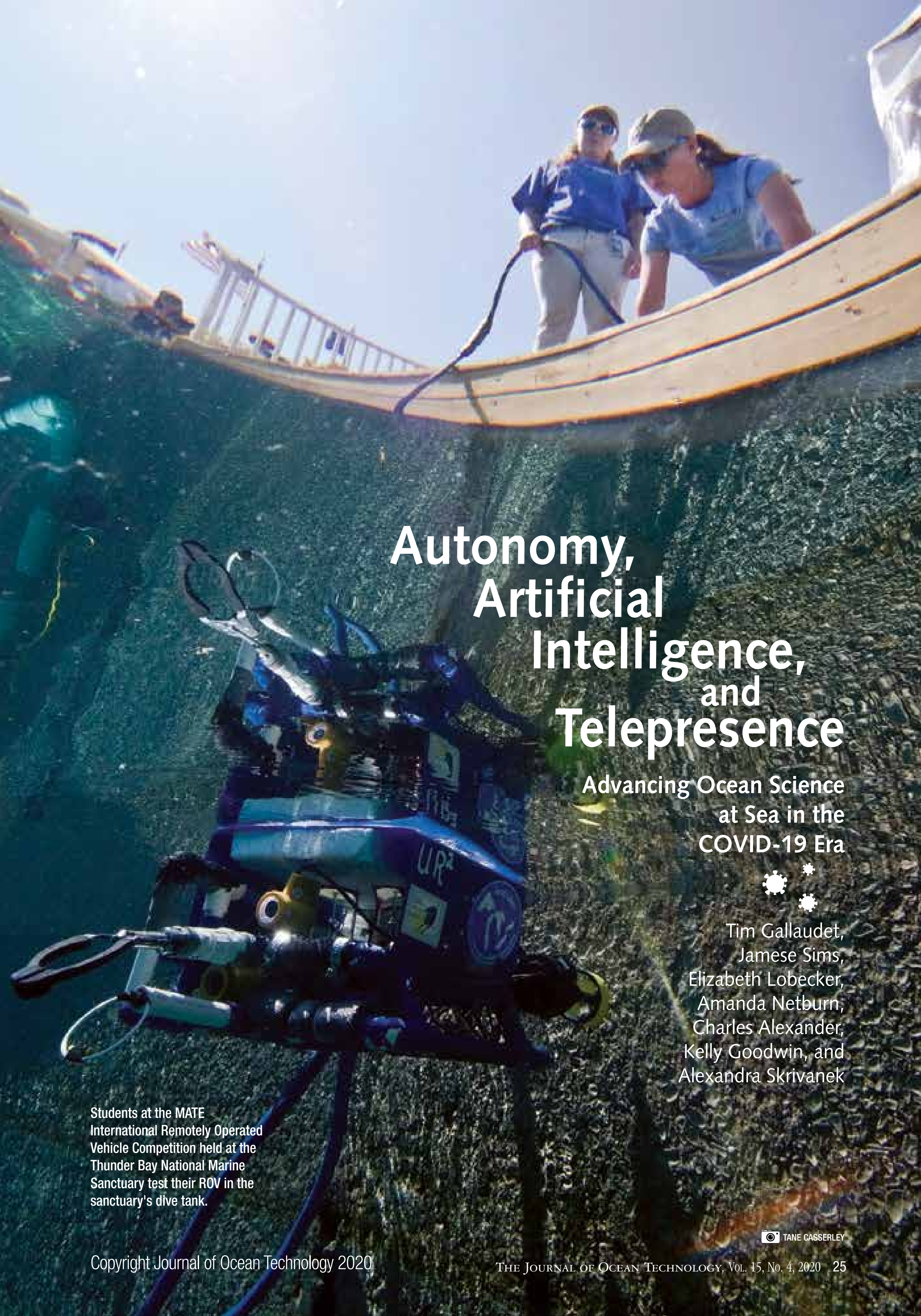

Autonomy, Artificial Intelligence, and Telepresence

Advancing Ocean Science at Sea in the COVID-19 Era

Tim Gallaudet, Jamese Sims, Elizabeth Lobecker, Amanda Netburn, Charles Alexander, Kelly Goodwin, and Alexandra Skrivanek

Students at the MATE International Remotely Operated Vehicle Competition held at the Thunder Bay National Marine Sanctuary test their ROV in the sanctuary's dive tank.

TANE CASSERLEY

Introduction

The COVID-19 pandemic has impacted all aspects of society, including seagoing marine science. Social distance measures and quarantine restrictions have required smaller scientific teams and crews on oceanographic ships. Advances in technology offer the potential to continue marine science discovery as the impacts of the pandemic persist. Robotics and uncrewed systems are already widely used in place of in-situ, human-operated systems, while autonomy and artificial intelligence are dramatically increasing the efficiency and effectiveness of nearly every ocean science discipline, including biological observations. Telepresence is a proven capability that can transform any vessel into a virtual international laboratory. We will describe how these tools are applied at the National Oceanic and Atmospheric Administration (NOAA), and how they provide capabilities to move ocean science forward over the course of the COVID-19 pandemic and beyond.

Figure 1: Saildrone uncrewed surface vessels were deployed in Alaska in the spring of 2020 to support winter stock assessments for Pollock during the COVID-19 pandemic.

Autonomy

Once deployed, uncrewed or autonomous airborne and maritime systems (together referred to as UxS) can execute data collection missions without a human presence on board. They therefore expand NOAA capacity for data collection, enhance the pace and safety of that process, and reduce the human footprint in ocean science operations, thereby allowing science to continue at sea in accordance with U.S. Centers for Disease Control and Prevention protocols.

Recent advances in materials science and information technology are driving exponential growth in the application of sophisticated, relatively inexpensive UxS to support investigations in Earth science. In February 2020, NOAA published a new NOAA Uncrewed Systems Strategy to guide transformative advances in UxS applications and to dramatically expand the use of these systems in every NOAA mission area. Strategy goals included strengthening and centralizing key support functions, expanding UxS applications across NOAA's mission portfolio, sustaining research, accelerating the transition of research to operations, expanding partnerships, and increasing workforce proficiency in UxS use and operations.

The onset of the COVID-19 pandemic in the spring of 2020 disrupted much of NOAA's field science and research operations to an unprecedented degree. NOAA scientists and engineers acted quickly, mobilizing available uncrewed systems to mitigate impacts to operations and ensure the timely delivery of critical data and services. In Alaska, Saildrone uncrewed surface vessels were deployed to support stock assessments for Pollock – the nation's largest fishery by volume – and to produce updated nautical charts ensuring safe passage of commercial vessels along the North Slope (Figure 1). Along the U.S. Gulf of Mexico and South Atlantic Coasts, a picket-line of underwater gliders were deployed to provide sustained ocean temperature profiles to augment hurricane forecasts as the season for severe storms approached (Figure 2). These, and other NOAA UxS projects activated in response to COVID-19,

Figure 2: Underwater gliders were deployed off the U.S. Gulf of Mexico and South Atlantic Coasts to provide sustained ocean temperature profiles to augment hurricane forecasts in advance of the 2020 severe storm season. a) NOAA and partners from the Cooperative Institute for Marine and Atmospheric Studies at University of Miami and CARICOOS launched 11 ocean gliders to collect data in July 2020 to improve predictions. b) One of the 30 ocean gliders that NOAA and partners launched is headed out to sea off Puerto Rico in July 2020 to begin collecting data that will be used to improve hurricane forecast models.

demonstrate how unique public-private partnerships can quickly pivot in a crisis to support NOAA's science priorities when traditional methods are not possible.

The use of UxS is not new to NOAA. Our scientists and engineers have been experimenting with vehicles, robotics, portable and miniaturized sensors, power sources, and communications – and delivering operationally capable systems – for decades. In fact, NOAA's ability to meet its mission relies on a continuous process of testing and evaluation of new technologies that routinely deliver new applications into operational and sometimes commercial use. The rapid increase in the use of UxS has been a force multiplier for many NOAA programs, augmenting data collection often at lower cost, increased safety, and reduced risk – especially in remote or extreme environments. Examples include the applications described above that were mobilized this spring in response to COVID-19, as well as habitat mapping, ocean exploration, marine mammal conservation, emergency response, and at-sea observations that improve forecasting of extreme events including harmful algal blooms and hypoxia.

'Omics

'Omics describes a suite of cutting-edge tools used to analyze DNA, RNA, proteins, or metabolites. Advances in 'omics have revolutionized biological study, benefitting many fields including public health, medicine, agriculture, and conservation. In ocean science, 'omics technologies can be effectively combined with other emerging technologies, such as uncrewed systems or robotics, to support safe, continuous ecosystem analyses while minimizing the need for direct human engagement in data collection at sea. Autonomous instruments and vehicles can conduct aquatic sampling for 'omics analysis, and the process may be monitored remotely onshore.

Ecosystem sampling is critical to better understand the productivity of marine ecosystems, and disruptions can have consequences for research and subsequent resource management. Information about ecosystem state is needed whether or not human operated sampling is an option. Autonomous underwater vehicles (AUVs) can navigate to places where ship sampling might not be possible due to weather, hazards, or environmental sensitivity. Recently, uncrewed capability came in handy when NOAA ship operations were curtailed due to the COVID-19 pandemic. In collaboration with NOAA's Atlantic Oceanographic and Meteorological Laboratory and the Marine Biodiversity Observation Network, samples for 'omics analysis were successfully collected by an AUV developed by the Monterey Bay Aquarium Research Institute (MBARI; Figure 3).

During this "shipless" survey, MBARI scientists combined autonomous acoustics and 'omics by collecting both high-resolution echo sounder observations and samples of environmental DNA (eDNA) to study where and when groups of anchovies and other animals congregate in the vicinity of a submarine canyon located offshore of Monterey, California. Through innovative 'omics techniques, eDNA can be analyzed to characterize distributions of organisms in the ocean by extracting DNA from seawater samples and comparing it with known DNA sequences, efficiently providing comprehensive biological information without needing to directly capture the animals of interest. Uncrewed systems further enhance the efficiency of this process, and, therefore, public access to biological information. This collaborative effort points to the utility of autonomous 'omics sampling and the need to continue its development.

Artificial Intelligence

The integration of artificial intelligence (AI) with seagoing science operations enhances the efficiency and accuracy of monitoring, data collection, and data management, reducing the cost of observers and time needed for manual data processing. NOAA's

Figure 3: A shark bit a MBARI AUV during a July 2020 autonomous 'omics mission. Researchers pulled several fragments of shark teeth from the hull of the vehicle.

AI applications continue to advance science, public safety, and security in arenas as diverse as deep-sea exploration, habitat characterization, and processing of Earth observations during the COVID-19 pandemic. Here, we discuss ongoing initiatives that implement AI and advance mission areas across the agency.

AI in Electronic Fisheries Longline Monitoring: Artificial intelligence is used to reduce costs associated with the monitoring and data collection of commercial fishing operations. NOAA Fisheries has partnered with Kitware Inc. to apply the Video and Image Analytics for Marine Environments (VIAME) toolkit with machine learning (ML) algorithms to automate the processing of images from electronic monitoring (EM) via ML scanning video aboard fishing vessels (Figure 4). ML automated detection eliminates approximately 90% of footage that does not contain any information and reduces data storage, resulting in more efficient data processing and analysis. The application of ML with EM will be expanded to significantly reduce the cost of observers and manual data processing aboard fishing vessels, thereby providing more accurate and timely information for fishery management.

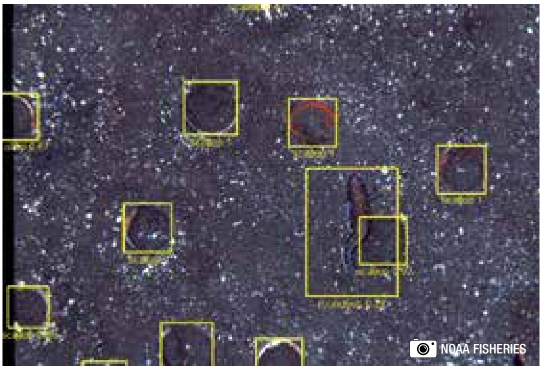

Figure 4: HabCam image of the seafloor annotated by VIAME sea scallop and fish detectors.

CoralNet Automated, Human-in-the-loop, Point Annotation of Coral Reef Imagery: CoralNet is an operational AI application to efficiently annotate coral reef images in support of the NOAA National Coral Reef Monitoring Program mission. NOAA's National Ocean Service and NOAA Fisheries have worked collaboratively with academic partners to improve CoralNet architecture with new ML capabilities and expanded training data, decreasing the error rates by 22% over the operational product. CoralNet performs automated common coral taxonomic identification as well as human annotations of data (Figure 5). Overall, the CoralNet team has shortened the time needed to process survey data from months to weeks, and reduced human annotation time by ~25%. It has also enabled enhanced Photogrammetric and Structure-From-Motion surveys, produced higher resolution (1-metre) products, decreased error rates by ~10-15%, and developed an application programming interface (API) with script-level access to public classifiers to serve smaller-scale, agency, academic, and citizen-science projects.

Automated Detection and Characterization of Seafloor Hazards: NOAA's Office of Coast Survey is advancing the goals of the Presidential Memorandum on Ocean Mapping through the use of new and emerging technologies to map the seafloor, particularly in the areas of sensor development and testing as well as data processing and automation. This AI application uses machine learning to identify "contacts" in side scan sonar imagery, presenting them to a user for review and exporting and replacing cumbersome software for automated detection and characterization of seafloor hazards. Field tested in 2019 on NOAA Ship *Thomas Jefferson*, this approach is intended to be more widely used once fleet operations resume in 2020.

Data Cleaning and Archive Compression: Data cleaning and data compression are important aspects of NOAA's management of the vast amount of ocean data collected daily through advanced technology. The use of AI/ML applications are being explored in these areas to efficiently and effectively manage data. For example, experimental machine learning models were trained to interpret incorrect "flier" spikes in multibeam echo sounder ping data, resulting in a high accuracy of -0.02% missed erroneous sounding. For the near term, this application has pivoted to assessing commercial implementation of similar processing in Computer Aided Resource Information System (CARIS) software. Additionally, recent experimentation for data compression with training machine learning models on VDatum have demonstrated a reduction in data volume by 20 times, while preserving 99% of the required surface information within 1 mm. The remaining 1% of data can be stored separately to preserve integrity for the full dataset.

NOAA's Office of Ocean and Atmospheric Research (OAR) continues to conduct ocean exploration pilot and research projects. Currently, the OAR Office of Ocean Exploration and Research (OER) is identifying priority AI applications for processing multibeam echo sounder data, automated or semi-automated annotation of video and imagery data, and applying AI to oceanographic data processing. The NOAA Global Systems Laboratory, National Severe Storms Laboratory, and OER are also collaborating on a pilot project titled *Artificial Intelligence and Machine Learning Cloud*

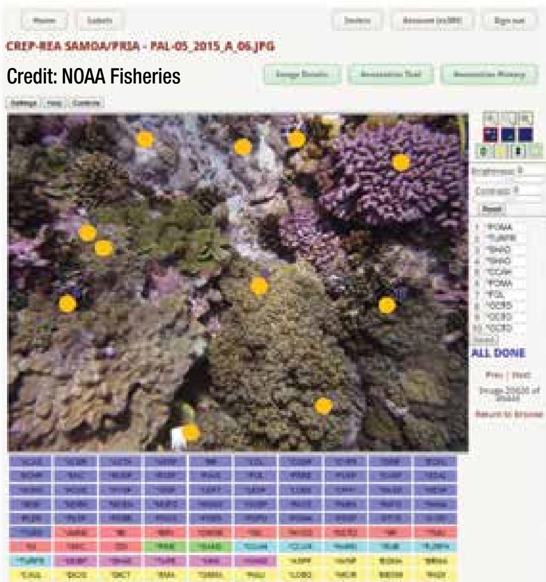

Figure 5: CoralNet: Automated, Human-in-the-loop, Point Annotation of Coral Reef Imagery. CoralNet performs automated common coral taxonomic identification as well as human annotations of data. NOAA has worked collaboratively with academic partners to enhance CoralNet architecture with new machine learning capabilities.

Computing Capabilities, Ocean Exploration Use Case. This project is centred on the theme of investigating the AI and ML capabilities in the cloud with two main objectives: 1) leveraging the cloud environment to advance data processing bottlenecks of OAR data and 2) leveraging the cloud environment to provide improved data synthesis and synopsis using AI and ML technologies. This use case will investigate how to develop a workflow that leverages the cloud AI/ML capabilities to reduce the data processing time and provides insights as to how the current (manual) data processing and archival workflows can be augmented by cloud computing.

The application of AI, including ML algorithms, has enhanced automated detection capabilities and operational efficiencies during aerial and underwater surveys from ships and autonomous platforms to assess the abundance of marine mammal and fish populations (Figure 6). ML has also advanced data assimilations and forecast modelling. Specific examples of improvements include quality control of environmental or satellite

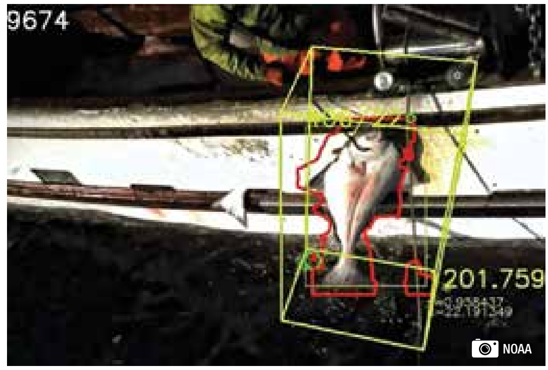

Figure 6: NOAA's Alaska Fisheries Science Center advanced the application of machine learning to fisheries independent stock assessments in the Gulf of Alaska.

observations, physical parameterization for environmental modelling including ecosystems, physical and computational performance of numerical Earth system models, and operations of uncrewed systems for a wide range of environmental observations. By advancing the efficient collection and distribution of data that is required for accurate monitoring, forecasts, and guidance for decision support services, NOAA continues to stand ready to meet its scientific and technological missions and to advance partnerships when faced with a crisis such as the COVID-19 pandemic.

Telepresence

Telepresence permits continued, expeditious, and safe operations at sea during the COVID-19 pandemic by increasing opportunities for remote engagement with and access to ongoing ocean expeditions. In the past, ocean expeditions allowed for only a very limited number of people to venture to sea for months to years, in isolation, and with limited mechanisms to share findings upon return. With technological advancements, including satellite communications and the use of remotely operated vehicles (ROVs) for ocean science, telepresence has become a critical tool to foster inclusive ocean exploration and discovery (Figure 7).

The NOAA OER has supported the innovation of telepresence for ocean exploration since the

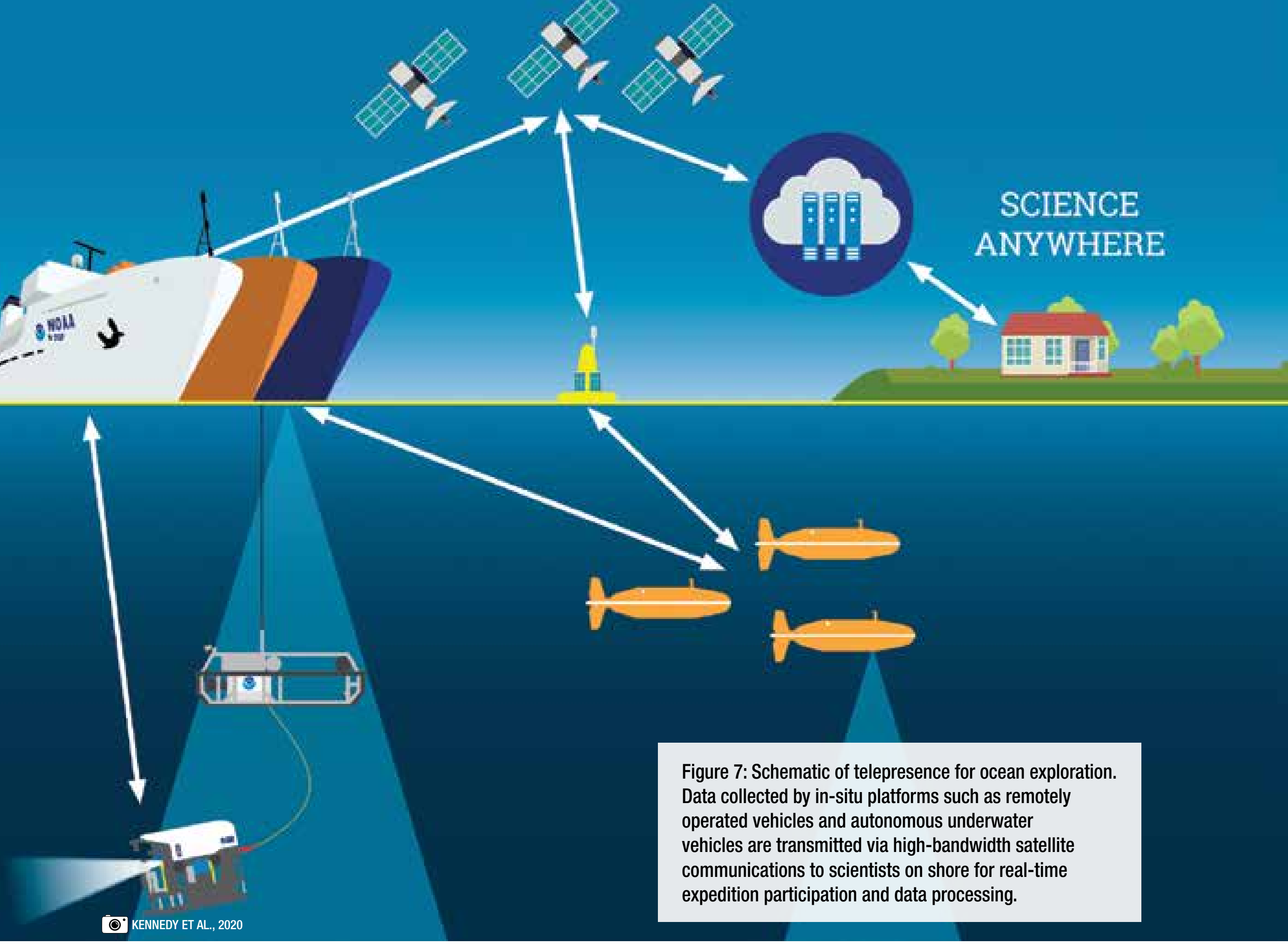

Figure 7: Schematic of telepresence for ocean exploration. Data collected by in-situ platforms such as remotely operated vehicles and autonomous underwater vehicles are transmitted via high-bandwidth satellite communications to scientists on shore for real-time expedition participation and data processing.

early 2000s. For the past decade, NOAA has routinely used telepresence on well over 100 exploratory ROV and ocean mapping missions, developing a model for community-driven ocean exploration that can be applied across platforms. On NOAA Ship *Okeanos Explorer*, the only federal ship dedicated to ocean exploration, a high-bandwidth satellite connection (40 megabits per second) is used to livestream ROV video and sonar data acquisition screens in real time (typically a two-four second delay). It is also used to transmit data to shore. Such data include video files, seafloor mapping sonar data files, and seawater measurements (e.g., temperature and dissolved oxygen). Access to these data enables scientists to actively participate in expeditions from shore, either at exploration command centres, where scientists can convene to contribute their expertise to an expedition, or from their traditional or home offices. Onshore scientists support operational planning and execution, troubleshoot hardware and software, and interpret data.

In addition to ROV expeditions, telepresence technology has been incorporated into mapping protocols, collectively called "telemapping," minimizing the number of onboard staff required to execute complex seafloor mapping missions (Figure 8). Telemapping includes streaming live feeds of onboard sonar acquisition screens, controlling sonars and deploying gear remotely, and automating raw data transfer to shore where personnel anywhere in the world can immediately process and quality control data collected only hours before. Remote access to sonars is becoming more commonplace through remote desktop protocols and virtual private networks, and new remote functionality incorporated directly into sonar acquisition software. Commercial survey companies are using remote services as well, connecting shore personnel to ship operations

Figure 8: NOAA Office of Ocean Exploration and Research Explorers-in-Training interns Brandon O'Brien (left; University of New Hampshire) and Claudia Thompson (middle; American Samoa Community College), and Senior Mapping Expedition Coordinator Elizabeth "Meme" Lobecker (right) conducting telemapping operations in Samoa and American Samoa from shore at the Exploration Command Center at the University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center.

to collect and process data during lower intensity times like transits.

During the COVID-19 pandemic, telepresence technologies are becoming ubiquitous in day-to-day activities, such as medical examinations ("telemedicine"), education, and business. Telepresence can also sustain ocean science operations during the pandemic in several ways: maintaining scientific expertise while limiting shipboard personnel, allowing organizations to meet stringent data delivery timelines, and providing remote internship opportunities to train the next generation of ocean scientists.

Expeditions that have taken place since the COVID-19 pandemic began are operating with limited staff, and telepresence is a tremendous resource to facilitate ongoing participation in field activities where crew and science party sizes are limited, enabling NOAA to carry out its ocean exploration mission. COVID-related restrictions are affecting the ability to staff ships at traditional levels. Social distancing requirements necessitate the reduction of the size of onboard teams, and pre- and post-cruise quarantine periods can significantly extend the length of an expedition, posing a challenge to participants with professional, medical, and personal commitments. Telepresence expeditions have enabled continued and safer operations during the pandemic by allowing nimble onboard teams to conduct scientific data collection even with much of the mission team on shore.

Telepresence allows organizations to meet stringent data delivery timelines, enabling resource managers, scientists, and explorers to

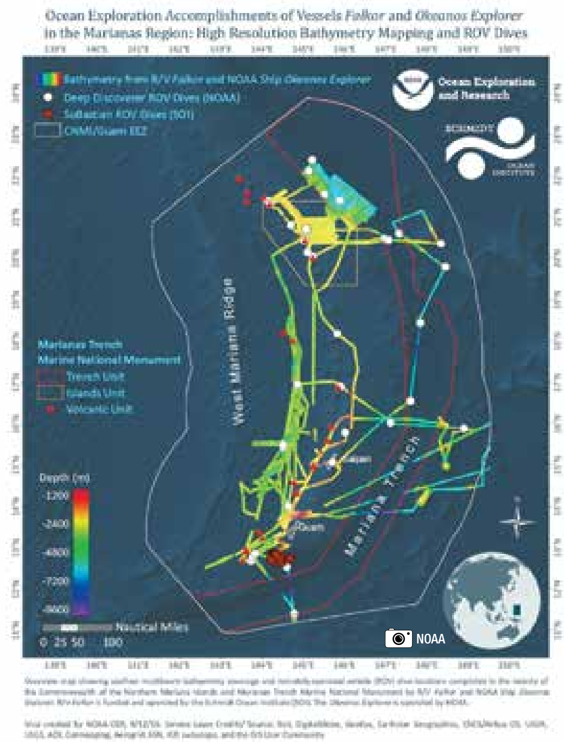

Figure 9: A map demonstrating joint seafloor mapping efforts from NOAA's Office of Ocean Exploration and Research vessel *Okeanos* and Schmidt Ocean Institute's research vessel *Falkor*.

rapidly incorporate the newest baseline ocean exploration data in their work. This also ensures timely contribution to global initiatives like Seabed 2030, the international effort to map the entire seafloor by the year 2030. Scientists traditionally hand-carry multiple copies of data on hard drives home at the end of their expeditions. Frequent (e.g., hourly) data transfer to shore using telepresence infrastructure is a major leap forward, ensuring that the value of ship time spent collecting sonar data is never lost due to unforeseen data management challenges such as physical damage to or corruption of onboard servers.

Internships can be and have been conducted through telepresence. These opportunities allow students to learn highly technical data analysis and management routines and participate in operations planning from shore. Remote training and guidance enabled through cloud services, screen sharing, and video conferencing are quickly becoming part of everyday routines. Telepresence allows onshore experts to continue to train interns without leaving land. When COVID-19 subsides, and operations resume at full capacity, there will be a well-trained cohort ready to sail and pursue careers in ocean exploration and mapping. Telepresence also empowers the differently-abled or those with disabilities to engage in ocean exploration.

Despite COVID-related restrictions, some NOAA-supported and partner expeditions have been able to proceed because they were already equipped with telepresence capabilities. Schmidt Ocean Institute's Research Vessel *Falkor* was underway, exploring waters off western Australia, when COVID-19 lockdowns began. The scientists disembarked from that expedition to a world changed by the pandemic. The next expedition took place with the ship's crew and only a few expert technicians on board to conduct scientific work, effectively accomplishing the goals of a fully shore-based science team by using telepresence. In the Fall of 2020, NOAA OER supported two ROV-based expeditions and additional strategic mapping on Exploration Vessel *Nautilus* (which is operated by the Ocean Exploration Trust) off the U.S. West Coast to help meet NOAA's Blue Economy objectives. The 2020 *Nautilus* season is sponsored in part by NOAA OER through the NOAA Ocean Exploration Cooperative Institute and the NOAA Office of National Marine Sanctuaries, which is exploring sanctuary sites along the Washington and California coasts. To limit the number of people on board for these expeditions, science, technical, and outreach personnel have been reduced to a minimum, and shore-based science parties are increasingly being relied on to provide their expertise through telepresence.

Telepresence for ocean science – though not yet ubiquitous – is now used across the federal (*Okeanos Explorer*), private (*Nautilus, Falkor*), and academic fleets to engage scientists and the public in real-time exploration of the deep sea (Figure 9). With the cost of satellite bandwidth decreasing, and the demand for it increasing, the protocols established by NOAA and its partners through hundreds of telepresence-enabled expeditions will be adopted across the U.S. scientific fleet to maximize expedition value during and long after the COVID-19 pandemic.

Conclusion

As with biomedical efforts to develop a vaccine, marine technology innovation is providing safe solutions to continue seagoing ocean science during the COVID-19 pandemic. This progress is critical to post-pandemic economic recovery. Ocean mapping and exploration, for example, support safe maritime commerce, offshore energy development, and pharmaceutical and critical mineral extraction. Likewise, commercial fisheries in the U.S. were valued at $5.6 billion in 2018. Building on years of research and development, NOAA has leveraged UxS, AI, and telepresence technologies to continue its applied-science mission during the pandemic. Currently, these technologies are transforming ship design. We expect their provision to be the standard in research vessels throughout the COVID-19 era and beyond.

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Dr. Tim Gallaudet, Rear Admiral, U.S. Navy (Ret.), is the Assistant Secretary of Commerce for Oceans and Atmosphere and Deputy Administrator of the National Oceanic and Atmospheric Administration (NOAA). From 2017-2019, he served as the Acting Undersecretary of Commerce for Oceans and Atmosphere and NOAA Administrator. Before these assignments, he served for 32 years in the U.S. Navy, completing his service in 2017 as the Oceanographer of the Navy. In his current position, Rear Admiral Gallaudet leads NOAA's Blue Economy activities that advance marine transportation, sustainable seafood, ocean exploration and mapping, marine tourism and recreation, and coastal resilience. He also leads the execution of the NOAA science and technology strategies for artificial intelligence, uncrewed systems, 'omics, cloud, data, and citizen science. Rear Admiral Gallaudet has a bachelor's degree from the U.S. Naval Academy, and master's and doctorate degrees from Scripps Institution of Oceanography, all in oceanography.

Dr. Jamese Sims is a Senior Physical Scientist at the Office of the Federal Coordinator for Meteorological Services and Supporting Research where she manages inter-agency committees and working groups to coordinate meteorological services across the Federal Weather Enterprise. Topics of special interest to this role are operational environmental satellites, climate services, and coastal inundation. Dr. Sims is the NOAA Special Advisor for Artificial Intelligence where she leads coordination of artificial intelligence initiatives across the NOAA Line Offices and builds partnerships with the federal government, private-sector, and academia. In this role, Dr. Sims has also established the NOAA Science and Technology Synergy Committee to coordinate interdependencies of the NOAA emerging science and technology focus areas including artificial intelligence, 'omics, unmanned systems, cloud computing, data, and citizen science.

Elizabeth "Meme" Lobecker is the Senior Mapping Expedition Coordinator on contract through Cherokee Federal to the NOAA Office of Ocean Exploration and Research (OER). In her 11 years with OER, she has planned and led over 40 cruises on NOAA Ship *Okeanos Explorer*, pioneered telepresence mapping-enabled operations, and spearheaded record-setting data collection and archival operations. She currently heads the OER mapping team. She holds a master's degree in marine affairs from the University of Rhode Island and a bachelor's degree in

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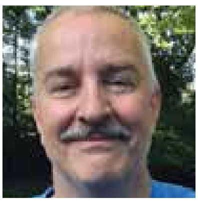
Dr. Amanda N. Netburn is an oceanographer at NOAA's Office of Ocean Exploration and Research, where she is a Grants Program Manager and advises on exploration expeditions. She leads efforts to explore the water column and works to develop interagency and cross-sector partnerships for ocean exploration. Dr. Netburn has a doctorate in oceanography and a master's degree in marine conservation and biodiversity from the Scripps Institution of Oceanography at the University of California San Diego. In the past, she has researched sustainable seafood at a non-governmental organization, taught scuba, captained small boats, and worked in aquaculture. She has sailed on 15 oceanographic expeditions.



Charles Alexander joined NOAA's Office of Marine and Aviation Operations (OMAO) as Chief of the Planning and Performance Management Division in 2014 where his portfolio includes strategic planning, annual operating plans and performance metrics, coordinating OMAO's Leadership Team, and special projects and analyses. He is currently on a special assignment to the NOAA Assistant Secretary of Commerce for Oceans and Atmosphere, leading the development of a strategy and implementation plan for a NOAA Uncrewed Systems Program. His 30+ year career at NOAA has covered a wide range of assignments as a program manager and analyst including seven years at the Integrated Ocean Observing Programs managing projects on observing, modelling, and data management, a series of applied analyses on ocean resources, estuaries, wetlands, nutrients, and shellfish, and 10 years with NOAA's National Marine Sanctuary Program managing the execution of an interdisciplinary science support program that included a six-month detail in Hawai'i focused on the Northwestern Hawaiian Islands. He has a B.A. in biology/geology from Whitman College in Walla Walla, Washington, and an M.S. in marine science and a Master of Public Administration from Louisiana State University (LSU). He received a Thomas J. Watson Fellowship for post-graduate independent study his senior year of college (1978), a Sea Grant Fellowship while at LSU (1983) that took him to Capitol Hill as a Legislative Assistant, and a Presidential Management Fellowship (1985) that brought him to NOAA.

Dr. Kelly Goodwin is a Microbiologist with NOAA's Atlantic Oceanographic and Meteorological Laboratory where she primes development, validation, application, and technology transfer of molecular methods to improve the efficiency and utility ecosystem status assessments. She leads development of the NOAA 'omics strategy and implementation plan. Dr. Goodwin received M.S. and PhD degrees from the California Institute of Technology in environmental engineering science and a minor in oceanography obtained in residence at the Scripps Institution of Oceanography.

Dr. Alexandra Skrivanek is a Policy Analyst and 2020 NOAA Sea Grant Knauss Marine Policy Fellow in the Office of the Assistant Secretary of Commerce for Oceans and Atmosphere/Deputy NOAA Administrator. Currently, she supports NOAA leadership in the areas of coral reef health and marine protected areas and serves as the Executive Secretary of the NOAA Blue Economy Executive Committee. Previously, as a National Science Foundation Graduate Research Fellow, she assimilated evidence preserved in ancient Caribbean coral reefs for the response of sea level and ice sheets to a past warm climate to improve projections of future sea-level changes, and developed outreach activities with technological integration to support evidence-based discussions on coastal resilience and ocean chemistry. Dr. Skrivanek earned a bachelor's degree in Earth and environmental sciences with minors in museum studies and oceanography at the University of Michigan (2014), and a PhD in geology at the University of Florida (2019).