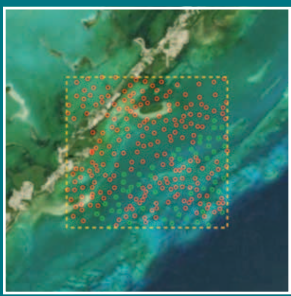
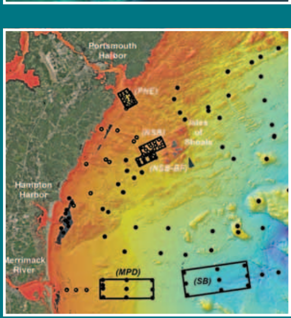
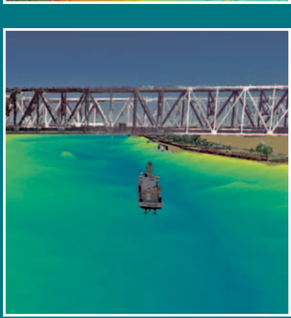






UNH/NOAA Joint Hydrographic Center

2022 Performance and Progress Report

Reporting Period: 01/01/2022–12/31/2022
Principal Investigator: Larry A. Mayer

NOAA Grant No: NA20NOS4000196

Flyers from the 2022 JHC/CCOM – UNH Dept. of Ocean Engineering Seminar Series.

The NOAA-UNH Joint Hydrographic Center (JHC/CCOM) was founded twenty-three years ago with the objective of developing tools and offering training that would help NOAA and others to meet the challenges posed by the rapid transition from the sparse measurements of depth offered by traditional sounding techniques (lead lines and single-beam echo sounders) to the massive amounts of data collected by the new generation of multibeam echo sounders. Over the years, the focus of research at the Center has expanded and now encompasses a broad range of ocean mapping technologies and applications, but at its roots, the Center continues to serve NOAA and the nation through the development of tools and approaches that support safe navigation, increase the efficiency of surveying, offer a range of value-added ocean mapping products, and ensure that new generations of hydrographers and ocean mappers receive state-of-the-art training.

An initial goal of the Center was to find ways to process the massive amounts of data generated by multibeam and sidescan sonar systems at rates commensurate with data collection; that is, to make the data ready for chart production as rapidly as the data were collected. We have made great progress over the years in attaining, and now far surpassing this goal, and while we continue our efforts on data processing in support of safe navigation, our attention has also turned to the opportunities provided by this huge flow of information to create a wide range of products that meet needs beyond safe navigation as well as meet the goals of the National Ocean Mapping Exploration and Characterization Strategy (e.g., marine habitat assessments, gas seep detection, fisheries management, disaster mitigation, and national security). Our approach to extracting "value added" from data collected in support of safe navigation was formalized with the enactment on the 30th of March 2009 of the Ocean and Coastal Mapping Integration Act. In 2010, the concept of IOCM was clearly demonstrated when we were able to quickly and successfully apply tools and techniques developed for hydrographic and fisheries applications to the Deepwater Horizon oil spill crisis.

In the time since our establishment, we have built a vibrant Center with an international reputation as the place, "where the cutting edge of hydrography is now located" (Adam Kerr, Past Director of the International Hydrographic Organization in Hydro International). In the words of Pat Sanders, then President of HYPACK Inc., a leading provider of hydrographic software to governments and the private sector:

> *JHC/CCOM has been THE WORLD LEADER in developing new processing techniques for hydrographic data. JHC/CCOM has also shown that they can quickly push new developments out into the marketplace, making both government and private survey projects more efficient and cost effective.*

Since our inception, we have worked on the development of automated and statistically robust approaches to multibeam sonar data processing. These efforts came to fruition when our automated processing algorithm (CUBE) and our new database approach (The Navigation Surface), were, after careful verification and evaluation, accepted by NOAA, the Naval Oceanographic Office, and many other hydrographic agencies, as part of their standard processing protocols. Today, almost every hydrographic software manufacturer has incorporated these approaches into their products. It is not an overstatement to say that these techniques have revolutionized the way NOAA and others in the ocean mapping community do hydrography. These new techniques can reduce data processing time by a factor of 30 to 70 and provide a quantification of uncertainty that had never been achievable in hydrographic data. The result has been: "gained efficiency, reduced costs, improved data quality and consistency, and the ability to put products in the hands of our customers faster." (Capt. Roger Parsons, former NOAA IOCM Coordinator and Director of NOAA's Office of Coast Survey).

The acceptance of CUBE and the Navigation Surface represents a paradigm shift for the hydrographic community—from dealing with individual soundings (reasonable in a world of lead line and single-beam sonar measurements) to the acceptance of gridded depth estimates (with associated uncertainty values) as a starting point for hydrographic products. The research needed to support this paradigm shift has been a focus of the Center since its inception and to now see it accepted is truly rewarding. It is also indicative of the role that the Center has played and will continue to play, in establishing new directions in hydrography and ocean mapping. The second generation of CUBE, CHRT (CUBE with Hierarchical Resolution Techniques) which supports the variable resolution grids, has been introduced to hydrographic community and the innovative approach that CUBE and CHRT offer are now being applied to high-density topobathy lidar data, incorporating new concepts of artificial intelligence and machine learning, and preparing for cloud-based deployment.

Another long-term theme of our research efforts has been our desire to extract information beyond depth (bathymetry) from the mapping systems used by NOAA and others. We have developed a simple-to-use tool (GeoCoder) that generates a sidescan-sonar or backscatter "mosaic," a critical first step in the analysis of seafloor character. NOAA and many of our industrial partners have now incorporated GeoCoder into their software products. Like CUBE's role in bathymetric processing, GeoCoder has become the standard approach to backscatter processing. An email from a member of the Biogeography Branch of NOAA's Center for Coastal Monitoring and Assessment said:

> *We are so pleased with GeoCoder! We jumped in with both feet and made some impressive mosaics. Thanks so much for all the support.*

While GeoCoder is focused on creating backscatter mosaics, BRESS (Bathymetry- and Reflectivity-based Estimator for Seafloor Segmentation provides tools for the segmentation and analysis of co-located bathymetry and backscatter, dividing the seafloor into a limited number of contiguous areas of similar morphology (land- or geoforms) and backscatter. This tool has found broad application in NOAA and others interested in defining seafloor habitat. BRESS is one of many tools developed at the Center that now form part of HydrOffice—an open-source collaborative effort led by the Center, in collaboration with NOAA, to develop a research software environment with applications to facilitate all phases of the ping-to-chart process. The environment facilitates the creation of new tools for researchers, students, and for those in the field; and can speed up both algorithm testing and the transfer from Research-to-Operation (R2O). Many of these tools are in daily use by NOAA field units, as well as scientists and researchers world-wide.

Beyond GeoCoder, BRESS and the other HydrOffice tools, our efforts to support the IOCM concept of "map once, use many times" are also coming to fruition. Software developed by Center researchers has been installed on several NOAA fisheries vessels equipped with Simrad ME70 fisheries multibeam echo sounders. These sonars were originally designed for mapping pelagic fish schools but, using our software, the sonars are now being used for multiple seabed mapping purposes. For example, data collected on the NOAA Ship *Oscar Dyson* during an acoustic-trawl survey for walleye pollock was opportunistically processed for seabed characterization in support of essential fish habitat (EFH) and also in support of safety of navigation, including submission for charts and identification of a Danger to Navigation. Seafloor mapping data from the ME70 was used by fisheries scientists to identify optimal sites for fish-traps during a red snapper survey. Scientists on board the ship said that the seafloor data provided by Center software were "invaluable in helping accomplish our trapping objectives on this trip." These tools are now being transitioned to our industrial partners so that fully supported commercial-grade versions of the software are available to NOAA. All of these examples (CUBE, GeoCoder, HydrOffice, and our fisheries sonar tools) are tangible examples of our (and NOAA's) goal of bringing our research efforts to operational practice (Research to Operations—R2O).

Ed Saade, President of Fugro (USA) Inc., in a statement for the record to the House Transportation and Infrastructure Subcommittee on Coast Guard and Maritime Transportation and Water Resources and Environment[1], stated:

> *…R&D/Innovation initiatives at UNH CCOM JHC, have combined to be the leading technologies creators, developing Multibeam Echo Sounder (MBES) and related applications and improvements that have ultimately been adopted and applied, and which have extensively benefitted industry applications. Since the early 2000s, a small sampling list of such applications includes TrueHeave™, MBES Snippets, and Geocoder. This small sampling of applications integrated, into various seabed mapping industries in the United States alone, directly benefits more than $200 million of mapping services annually.*

The tools and products of the Center were also called upon to help with an international disaster—the mysterious loss of Air Malaysia Flight MH370. As part of our Nippon Foundation/GEBCO Bathymetric Training Program researchers and students in the Center had compiled all available bathymetric data from the Indian Ocean.

[1]Hearing on Federal Maritime Navigation Programs: Interagency Cooperation and Technological Change 19 September 2016. Fugro is the world's largest survey company with more than 11,000 employees worldwide.

When MH370 was lost, the Government of Australia and several major media outlets came to the Center for the best available representations of the seafloor in the vicinity of the crash. The data we provided were used during the search and were displayed both on TV and in print media.

In the last decade, a new generation of multibeam sonars has been developed (in part, an outgrowth of research done at the Center) that have the capability of mapping targets in the water-column as well as the seafloor. We have been developing visualization tools that allow this water-column data to be viewed in 3D in real-time. Although the ability to map 3D targets in a wide swath around a survey vessel has obvious applications in terms of fisheries targets (and we are working with fisheries scientists to exploit these capabilities), it also allows careful identification of shallow hazards in the water column and may obviate the need for wire sweeps or diver examinations to verify least depths in hydrographic surveys. These water-column mapping tools were a key component to our efforts to map submerged oil and gas seeps and monitor the integrity of the Macondo 252 wellhead as part of the national response to the Deepwater Horizon oil spill. The Center's seep-mapping efforts continue to be of national and international interest as we begin to use them to help quantify the flux of methane into the ocean and atmosphere. The initial water-column studies funded by this grant have led to many new opportunities including follow-up work funded by the National Science Foundation, the Office of Naval Research, the Department of Energy, and the Sloan Foundation.

The tools and techniques that we had to quickly develop to find oil and gas in the water column during the Deepwater Horizon disaster have led to important spinoffs in the industrial sector. Again, citing Ed Saade's statement for the record to the House Transportation and Infrastructure Subcommittees:

> *More recently, the most significant ground-breaking technology discovery is based on the combination of MBES bathymetry, backscatter, and water column collection/detection applications. Initial applications were for a variety of reasons and disciplines, mostly scientific in nature as led by UNH CCOM JHC. These capabilities were quickly recognized by industry experts as new technologies with a variety of applications in the ocean mapping industry, including fisheries, aggregate materials surveys, various engineering design studies, and oil and gas exploration applications.*
>
> *An initial cost-benefit analysis of the impact in just the oil and gas exploration industry yields the following findings:*
>
> - *Detection of Seabed Seeps of Hydrocarbons: During the past decade, the utilization of MBES for bathymetry, backscatter, and water column mapping has been directly applied to the detection, precise location, and analysis of seabed gas and oil seeps, mostly in deep water hydrocarbon basins and frontier areas. This scientific application of the methods discovered and perfected under the leadership of NOAA NOS OCS and the CCOM/JHC has been embraced and applied by companies and projects in the United States specifically to aid in the successful exploration and development of oil and gas reserves in water depths exceeding 10,000 feet. These studies provide a service to find seeps, evaluate the seeps chemistry, and determine if the seeps are associated with significant reservoir potential in the area of interest. This information is especially useful as a means to "de-risk" the wildcat well approach and ensure a greater possibility of success. It should be noted that many of the early terrestrial fields used oil seeps and geochemistry to help find the commercial payoffs. This was the original method of finding oil globally in the first half of the 20th century onshore and along the coastline. Estimates run into the millions of barrels (billions of dollars) of oil directly related to, and confirmed by, the modern MBES based seep hunting methodology.*
> - *It is estimated that the current USA-based annual revenue directly related to operating this mapping technology is $70 million per year. Note that this high level of activity continues today, despite the current extreme downturn in the offshore oil and gas industry. The seeps-related industry is expected to grow at an annualized rate of 25% per year. Globally, this value projects to be nearly double, or approximately $130 million per year.*

Our ability to image targets in the water column has now gone beyond mapping fish and gas seeps. Over the past few years, we have demonstrated the ability of both multibeam and broad-band single beam echosounders to image fine-scale oceanographic structures, including thermohaline steps (an indicator of the process of mixing between two water masses with different properties and an important mechanism of heat transfer in the ocean), internal waves, turbulence, and the depth of the mixed layer (the thermocline). Recently, our water column imaging tools have been able to map the depth of the oxygen minimum in the Baltic Sea. This opening of a new world of "acoustic oceanography," with its ability to map ocean structure over long-distance from a vessel while underway, has important ramifications for our ability to understand and model processes of heat transfer in the ocean as well as our understanding of the impact of the water column structure on seafloor mapping.

As technology evolves, the tools needed to process the data and the range of applications that the data can address will also change. We are now exploring "autonomous" or "uncrewed" surface vehicles (ASVs or USVs) as platforms for hydrographic and other mapping surveys and are looking closely at the capabilities and limitations of airborne laser bathymetry (lidar), satellite-derived bathymetry (SDB), and the new IceSAT-2 satellite data in shallow-water coastal mapping applications. The Center is also bringing together many of the tools and visualization techniques we have developed to explore what the chart of the future may look like and provide research in support of NOAA's Precision Navigation efforts—including the potential role of virtual and augmented reality in the future of navigation.

The value of our visualization, water-column mapping, and chart of the future capabilities has also been demonstrated by our work with Stellwagen Bank National Marine Sanctuary aimed at facilitating an adaptive approach to reducing the risk of collisions between ships and endangered North Atlantic right whales in the sanctuary. We developed 4D (space and time) visualization tools to monitor the underwater behavior of whales and notify vessels of whales in the shipping lanes and to monitor and analyze vessel traffic patterns. Describing our interaction with this project, the director of the Office of National Marine Sanctuaries, said:

> *…I am taking this opportunity to thank you for the unsurpassed support and technical expertise that the University of New Hampshire's Center for Coastal and Ocean Mapping/NOAA-UNH Joint Hydrographic Center provides NOAA's Office of National Marine Sanctuaries. Our most recent collaboration to produce the innovative marine conservation tool WhaleAlert is a prime example of the important on-going relationship between our organizations. WhaleAlert is a software program that displays all mariner-relevant right whale conservation measures on NOAA nautical charts via iPad and iPhone devices. The North American right whale is one of the world's most endangered large animals, and its protection is a major NOAA and ONMS responsibility. The creation of WhaleAlert is a major accomplishment as NOAA works to reduce the risk of collision between commercial ships and whales, a major cause of whale mortality.*
>
> *…WhaleAlert brings ONMS and NOAA into the 21st century of marine conservation. Its development has only been possible because of the vision, technical expertise, and cooperative spirit that exists at CCOM/JHC and the synergies that such an atmosphere creates. CCOM/JHC represents the best of science and engineering, and I look forward to continuing our highly productive relationship."*

Understanding concerns about the potential impact of anthropogenic sound on the marine environment, we have undertaken a series of studies aimed at quantifying the radiation patterns of our mapping systems. These experiments, carried out at U.S. Navy acoustic ranges, have allowed us to determine the ensonification patterns of our sonars, but also, using the hydrophone arrays at the ranges, to quantitatively track the feeding behavior of sensitive marine mammals (Cuvier's beaked whales) during the mapping operations. The results of these studies, now published in peer-reviewed journals, have offered direct evidence that the mapping sonars we used do not change the feeding behavior of these marine mammals nor displace them from the local area. Hopefully, these studies will provide important science-based empirical information for guiding future regulatory regimes.

Statements from senior NOAA managers and the actions of other hydrographic agencies and the industrial sector provide clear evidence that we are making a real contribution to NOAA, the nation, and the international community. We will certainly not stop there. CUBE, the Navigation Surface, GeoCoder, water column mapping, support of precision marine navigation, our ASV efforts, and HydrOffice offer frameworks upon which innovations are being built, and new efficiencies gained. Additionally, these achievements provide a starting point for the delivery of a range of hydrographic and non-hydrographic mapping products that set the scene for many future research efforts.

Since 2005, the Center has been funded through a series of competitively awarded Cooperative Agreements with NOAA. The most recent of these, which was the result of a national competition, funded the Center for the period of January 2021 through December 2025. This document summarizes the highlights of this NOAA-funded effort during calendar year 2022, the second year of the current grant. Detailed progress reports from this and previous grants can be found at our website, ccom.unh.edu/reports.

Highlights from Our 2022 Program

This report represents the progress during the second year of effort on NOAA GRANT NA20NOS4000196. The overall objectives were specified in The Notice of Funding Opportunity (NOFO) under which the new grant was funded and are outlined in three programmatic priorities:

Advance Technology to Map U.S. Waters

Advance Technology for Digital Navigation Services

Develop and Advance Marine Geospatial and Soundscape Expertise

Under these, three sub-themes and 20 specific research requirements were defined:

Advance Technology to Map U.S. Waters

A. DATA ACQUISITION

1. Improvement in the effectiveness, efficiency, and data quality of acoustic and Lidar bathymetry systems, their included backscatter and reflectance capabilities, their associated vertical and horizontal positioning and orientation systems, and other sensor technologies for hydrographic surveying and ocean, coastal, and Great Lakes mapping.

2. Improvement in the understanding and integration of other sensor technologies and parameters that expand the efficiency and effectiveness of mapping operations, such as water column and sub-bottom profiling.

3. Improvement in the operation and deployment of unmanned systems for hydrographic and other ocean mapping and similar marine domain awareness missions. Enhancements in the efficiency and hydrographic and related data acquisition capability of unmanned systems in multiple scenarios including shore-based and ship-based deployments and in line-of-sight and over-the-horizon operation and long duration autonomous ocean and coastal mapping data acquisition operations.

4. Improvement of autonomous data acquisition systems and technologies for unmanned vehicles, vessels of opportunity, and trusted partner organizations.

B. DATA VALUE

5. Improvement in technology and methods for more efficient data processing, quality control, and quality assurance, including the determination and application of measurement uncertainty, of hydrographic and ocean and coastal mapping sensor and ancillary sensor data including data supporting the identification and mapping of fixed and transient features on the seafloor and in the water column and the resolution of unverified charted features.

6. Development of improved tools and processes for assessment, processing, and efficient application of ocean mapping data from emerging sources such as drones, cameras and optical sensors, satellites, and volunteer/crowd-sourced observing systems to nautical charts and other ocean and coastal mapping and coastal hazard products.

7. Application of artificial intelligence, cloud services, and machine learning to the processing and analysis of hydrographic and coastal and ocean mapping data from both established and emerging sources, as well as to data from associated systems such as water level and current sensors, and from regional and global precise positioning networks.

C. RESOURCES OF THE CONTINENTAL SHELF

8. Advancements in planning, acquisition, and interpretation of continental shelf, slope, and rise seafloor mapping data, particularly for the purpose of delimiting the U.S. Extended Continental Shelf and mapping the resources of the seabed.

9. Adoption and improvement of hydrographic survey and ocean mapping technologies, including the development of potential new approaches and technologies, in support of mapping the Exclusive Economic Zone and of "Blue Economy" activities in U.S. waters such as offshore mineral and resource exploration, renewable energy development, coastal hazard planning, and the responsible management of U.S. living marine resources.

10. New approaches to the delivery of bathymetric services, including, among others, elevation models, depth comparisons and synoptic changes, model boundary conditions, and representative depths from enterprise databases such as the National Bathymetric Source and national geophysical archives.

Advance Technology for Digital Navigation Services

11. Development of innovative approaches and concepts for electronic navigation charts and for other tools and techniques supporting precision navigation such as chart display systems, portable pilot units and prototypes that are real-time and predictive, are comprehensive of all navigation information water levels, charts, bathymetry, models, currents, wind, vessel traffic, etc.), and support the decision process (e.g., efficient voyage management and under keel, overhead, and lateral clearance management) in navigation scenarios.

12. Development of improved methods for managing hydrographic data and transforming hydrographic data and data in enterprise databases to electronic navigational charts and other operational navigation products, particularly in the context of the new S-100 framework and family of associated data standards.

13. Development of new approaches for the application of spatial data technology and cartographic science to hydrographic, ocean and coastal mapping, precision navigation, and nautical charting processes and products.

14. Application of hydrodynamic model output to the improvement and development of data products and services for safe and efficient marine navigation.

15. Improvement in the visualization, presentation, and display of hydrographic and ocean and coastal mapping data, vessel data, and other navigational support information such as water levels, currents, wind, and data model outputs for marine navigation. This would include real-time display of mapping data and 4-dimensional high-resolution visualization of hydrodynamic model output (water level, currents, temperature, and salinity) with associated model uncertainty and incorporate intelligent machine analysis and filtering of data and information to support precision marine navigation.

16. Development of approaches for the autonomous interpretation and use of hydrographic and navigational information, including oceanographic and hydrodynamic models in advanced systems such as minimally staffed and unmanned vessels.

Develop and Advance Marine Geospatial and Soundscape Expertise

17. Development, evaluation, and dissemination of improved models and visualizations for describing and delineating the propagation and levels of sound in the water from acoustic devices including echosounders, and for modeling the exposure of marine animals to propagated echosounder energy. Improvements in the understanding of the contribution and interaction of echo sounders and other ocean mapping-related acoustic devices to/with the overall ocean and aquatic soundscape.

18. Development, maintenance, and delivery of advanced curricula and short courses in hydrographic and ocean mapping science and engineering at the graduate education level, leveraging to the maximum extent the proposed research program and interacting with national and international professional bodies to bring the latest innovations and standards into the graduate educational experience for both full-time education and continuing professional development.

19. Effective delivery of research and development results through scientific and technical journals and forums and transition of research and development results to an operational status through direct and indirect mechanisms including partnerships with public and private entities.

20. Public education, visualization tools, and outreach to convey the aims and enhance the application of hydrography, nautical charting ocean coastal and Great Lakes mapping and related hydrodynamic models to safe and efficient marine navigation and coastal resilience.

These programmatic priorities and research requirements are consistent with those prescribed under earlier grants and much of the research being conducted under the current (2021-2025) grant represents a continuation of on-going research with some new directions prescribed.

To address the three programmatic priorities and 20 research requirements, the Center divided the research requirements into components, themes, and sub-themes, responding with 46 individual research projects or research tasks, each with an identified investigator or group of investigators as the lead (Figure ES-1).

These research tasks are constantly being reviewed by Center management and the Program Manager and are adjusted as tasks are completed, merged as we learn more about the problem, or modified due to changes in personnel. Inasmuch as these tasks represent the front end of the grant cycle, there are no modifications to report at this time.

While many COVID-related restrictions have been lifted, 2022 still saw some impact on research productivity from the pandemic. Some travel restrictions are still in place and COVID-related restrictions on vessels have impacted some of our field programs. Nonetheless, to the great credit of the Center faculty, staff, and students, we have had a very productive and successful research year. This executive summary offers an overview of just a few of the Center's 2022 efforts through the presentation of a subset of ongoing tasks within the context of the programmatic priorities; the complete progress report with descriptions of all efforts and the Center's facilities can be found at ccom.unh.edu/reports.

PROGRAM PRIORITIES	COMPONENT	THEMES	SUB-THEME	TASKS	PIs	TASK
ADVANCE THE TECHNOLOGY TO MAP US WATERS	DATA ACQUISITION	INTEGRATED SF MAPPING	ACOUSTIC BATHY AND BS	System Performance Assessment	PJ	1
				Underway Sensor Integration Monitoring	JHC	2
				Backscatter Calibration	TW/JHC	3
				Environmental Monitoring	JHC	4
				New Sensors	TW	5
			LIDAR	Lidar Systems, providing both Bathymetry and Reflectance	BRC/CP	6
			WATER COLUMN AND SB	Water Column Mapping	TW	7
				Subbottom Mapping	JHC/TW/LM	8
		OPS and DEPLOYMENT OF USV		Operation and Deployment of Uncrewed Vessels	RA/VS	9
				Camera Systems for Marine Situational Awareness	VS/TB/RA	10
				ML Training Data for Marine Applications	VS/KF	11
				Path Planning for Ocean Mapping	VS/RA	12
				Frameworks for Multi-Vehicle Operations	VS/RA	13
				Autonomous Sonars	VS/?	14
				Data Acquisition for Volunteer/Trusted Partner Systems	BRC	15
	DATA VALUE	DATA FROM TRAD SOURCES		Bathymetry Data Processing	BRC	16
				Backscatter Data Processing	MS/BRC	17
				Object Detection	AL	18
				Chart Features	BRC/CK	19
				Advanced Quality Assurance/Control Tools	GM/MS	20
		NON-TRAD DATA		sUAS Mapping for Safety of Navigation	VS/KG??	21
				Millimeter Resolution Mapping with Frame Sensors	YR	22
				Enhanced Underwater Data 3D Construction	JD/TB	23
				Volunteer Bathymetric Observations	BRC	24
				Alternative Uses for ICESAT-2 and Other Laser Altimeter Data	BRC/ USF?	25
		AI/ML/CLOUD		Ocean Mapping Data Analytics	KL	26
	RESOURCES OF CONT SHELF	ECS EFFORTS		Support of US ECS Efforts	LM	27
		TECHNOLOGIES IN SUPPORT OF BLUE ECONOMY		Offshore Mineral/ Marine Resources	LW	28
				Management of Living Marine Resources from ECS Including Use of ICESat-2	JD/CP	29
				Improvements in Change Detection	JHC/AL/JD	30
				Delivery of Bathymetric Data Services from Enterprise Databases	BRC?	31
ADVANCE THE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES				Innovative Approaches to Support Precision Navigation	TB	32
				Managing and Transforming Data to Navigation Products: Computer Assisted Cartography	CK/BS	33
				Spatial Data Technology in the Context of Charting and Ocean Mapping	PJ	34
				Application of Hydrodynamic Models to Navigation Products	TB/JHC	35
				Tools for Visualizing Complex Ocean Data Sets	TB	36
				General Semiotics	CW/BS	37
				Artificial Intelligence and Machine Learning for Analysis and Filtering	KL/TB/CK	38
				Hydrographic Data Manipulation Tools	TB	39
				Real-time Display of Ocean Mapping Data	TB	40
				BathyGlobe	CW	41
				Semantic Understanding of Nautical Charts for Autonomous Navigation	VS/TB	42
DEVELOP AND ADVANCE MARINE GEOSPATIAL AND SOUNDSCAPE EXPERTISE				Contributions of Echosounders to the Ocean Soundscape	MS/TW/JMO	43
				Curriculum Development	SD	44
				Delivery of Results: Publications and Presentations	LM/ALL	45
				Outreach	THJ/CM	46

Figure ES-1. Breakdown of Programmatic Priorities and Research Requirements of NOFO into individual projects or tasks with short descriptive names and PIs. Task numbers are shown on the far right.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

The first and by far the largest programmatic priority defined by the Notice of Funding Opportunity (NOFO) that was the basis for the Center's grant, focuses on the broad category of advancement of technology for mapping U.S. waters. Under this programmatic priority are three components (Data Acquisition, Data Value and Resources of the Continental Shelf) and within each of these components there are numerous research requirements reflecting the range of technologies and approaches used for ocean mapping. Below are brief summaries of some of the research tasks being undertaken to address these requirements; more detail is provided in the full progress report.

DATA ACQUISITION

System Performance Assessment

Multibeam Assessment Tools

The "total cost of ownership" (TCO) for hydrographic data, which includes not only the physical cost of collecting the data, but also the processing costs subsequent to initial collection increases significantly as problems are detected further from the point of collection. Thus, we have long focused on the development of tools to monitor data in real-time, or to provide better support for data collection and quality monitoring which have the potential to significantly reduce the TCO, or at least provide better assurance that no potentially problematic issues exist in the data before the survey vessel leaves the vicinity. These developments have been leveraged by our work with the Multibeam Advisory Committee (MAC), an NSF-sponsored project aimed at providing fleet-wide expertise in systems acceptance, calibration, and performance monitoring of the UNOLS fleet's multibeam mapping systems.

Since 2011, the MAC has performed systems acceptance and routine quality assurance tests, configuration checks, software maintenance, and self-noise testing for the U.S. academic research fleet. They have also developed a series of assessment tools and best-practices guidelines available to the broad community via web-based resources (Figure ES-2). These processes, software tools, and procedures are also applicable to many of the mapping systems in the NOAA fleet, as well as those installed aboard commercial and non-profit survey and exploration vessels. This past year, the MAC instituted a community Wiki (Figure ES-2) and has worked with NOAA to develop a web-based application that tracks areas used for multibeam sonar test sites (e.g., Patch Tests, extinction tests, accuracy tests, etc.). It also provides reports from, and examples of, previous test results.

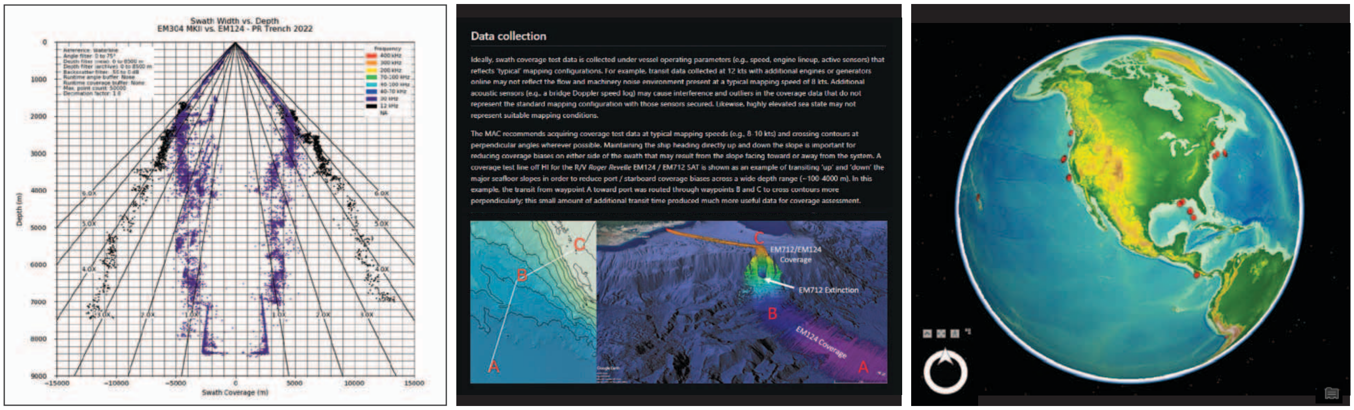


Figure ES-2. Left: Extinction Assessment Tools; middle: page from new Ocean Mapping Community Wiki simple interface for wiki collaboration scientific community (https://github.com/oceanmapping/community/wiki); and right: web-app with multibeam test site locations and database.

Sound Speed Manager

Acoustic sensors in modern surveys require an accurate environmental characterization of the water column. The quality of the adopted sound speed profile is critical for ray tracing and bottom detection algorithms. At the same time, the use of reliable measures for temperature and salinity is crucial in the calculation of absorption coefficients. In fact, those coefficients are used to estimate the gain settings in acoustic sensors and compensate the backscatter records.

Since 2016, Center researchers have been collaborating with NOAA Office of Coast Survey's Hydrographic Systems and Technology Branch (HSTB) on the development of an open-source application—Sound Speed Manager (SSM)—to manage sound speed profiles, provide editing and processing capabilities, and convert to formats in use by hydrographic acquisition packages (Figure ES-3). SSM has now reached a high level of maturity with a global user base of more than 6,500 users that spans the scientific community and the commercial sector. The tool is freely available through both HydrOffice and the official NOAA Python distribution (Pydro), which is also available to the public and is promoted by the NSF Multibeam Advisory Committee for use within the U.S. academic research fleet. Better integration with SIS and many new formats were added this past year, along with support for World Ocean Atlas 18 which is used for generating synthetic profiles.

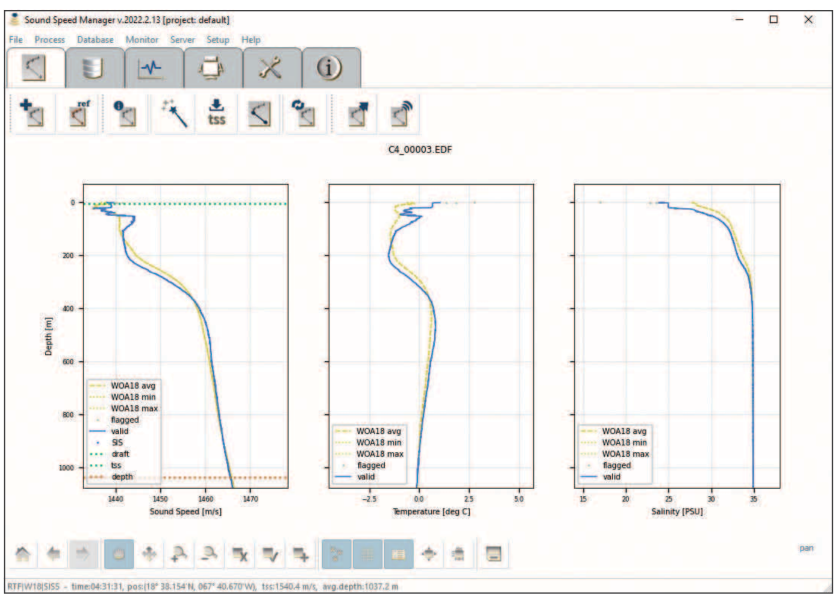


Figure ES-3. The main user interface of Sound Speed Manager with a loaded XCTD profile (in blue) compared with a WOA18 synthetic profile (in yellow).

State of the Art Sonar Calibration Facility

We continue to work closely with NOAA and the manufacturers of sonar and lidar systems to better understand and calibrate the behavior of the sensors used to make the hydrographic and other measurements used for ocean mapping. Many of these take advantage of our unique acoustic test tank facility—the largest of its kind in New England and now equipped with state-of-the-art test and calibration facilities. Upgrades to the calibration facility made by the Center include continuous monitoring of temperature and sound speed, a computer-controlled standard-target positioning system (z-direction), a custom-built vertical positioning system for the standard reference hydrophone, and the capability for performing automated 2D beam-pattern measurements.

The facility is routinely used by Center researchers and others for now-routine measurements of beam pattern, driving-point impedance, transmitting voltage response (TVR), and receive sensitivity (RS). In 2022, systems from Klein (MIND Technology), MITRE, and Kongsberg were calibrated.

Underway Sensor Integration

While the tools described above are focused on assessing the overall performance of multibeam sonar systems, we are also pursuing research aimed at understanding the causes of degradation of data quality that are the result of imperfect integration of the observed position and orientation of the sonar and the vessel. Among these is the development of the Rigorous Inter-Sensor Calibrator (RISC), the Ph.D. work of graduate student Brandon Maingot. RISC works by doing non-linear, least-squares estimation of six (at present) potential integration errors using a finite window of data that extends for a few ocean-wave periods. Within that window, the "true" seafloor is assumed to be a smooth surface and any beam's depth departure from that surface is used as a measure of the mismatch due to the six unknowns. RISC was field tested this year and performed successfully on operational data solving for five simultaneous integration errors (Figure ES-4). Future efforts will focus on decreasing the computation time needed to converge on a solution. In addition to this effort, John Hughes Clarke and students are also exploring a number of other sources of systematic artifacts in multibeam sonar data including inter-sector bathymetric mismatches, Doppler heave induced wobbles, and enigmatic "one-sided" wobbles.

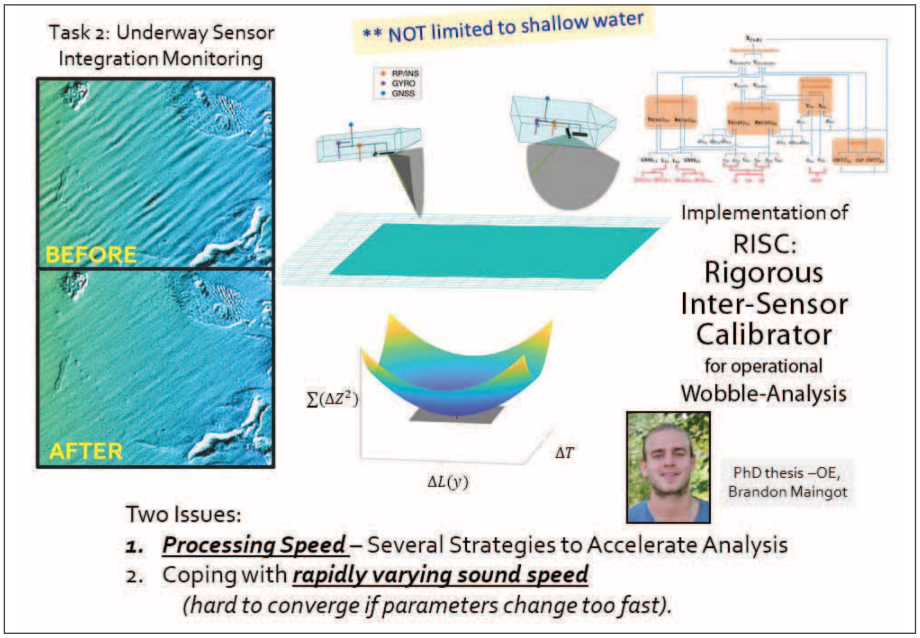


Figure ES-4. The RISC algorithm.

Backscatter Calibration

The collection of acoustic backscatter data continues to be an area of active interest across the research and industrial communities for its ability to infer characteristics of the seafloor. The large swaths and wide bandwidths of modern multibeam echosounders (MBES) permit the user to efficiently collect co-registered bathymetry and seafloor backscatter at many angles and frequencies. However, the backscatter data collected by multibeam echosounders is typically uncalibrated, limiting its useability to qualitative data products and comparison of one dataset to another. Multibeam echosounder calibration is not a trivial task and continues to be a difficult hurdle in obtaining accurate and repeatable backscatter measurements. Towards this end, the Center continues to leverage its state-of-the art facilities to develop and test new backscatter calibration methodologies as well as develop new approaches to calibrating backscatter in the field.

This year, we worked with the NOAA Office of Coastal Survey to analyze backscatter data collected annually from launches on the NOAA Ships *Rainier* and *Fairweather* over the identical seafloor in Puget Sound. These are repeated for all three main center frequencies (200-300-400 kHz) and for all utilized modes (various CW and FM pulse length/types). The results are illustrated in Figure ES-5 indicating that, from these comparisons, relative differences in backscatter can be compensated for and surveys from one launch then compared to those from another. Until an absolute reference is brought to those sites, however, the inter-calibrations are only relative.

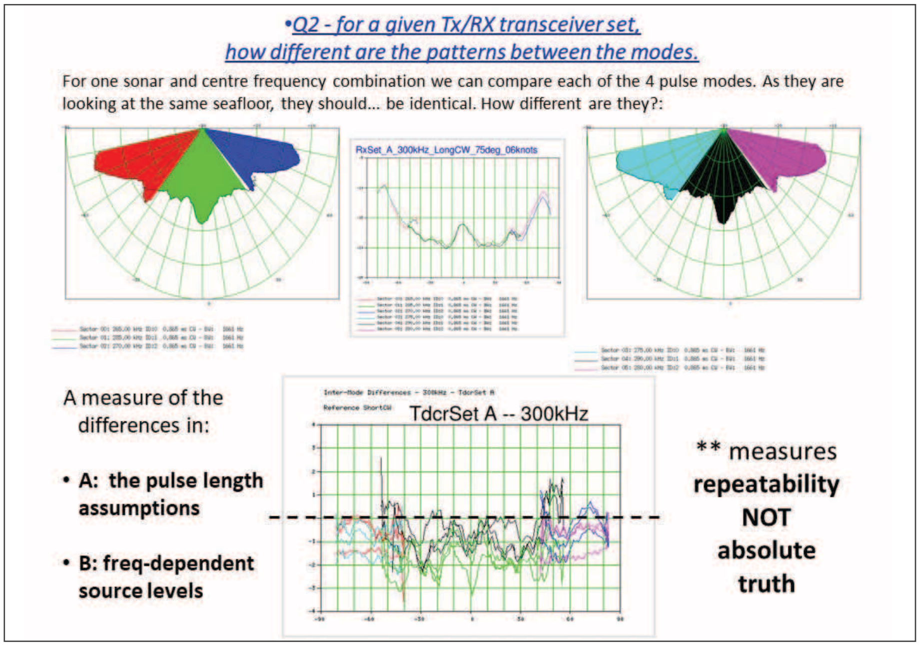


Figure ES-5. Extracted relative beam pattern for the multi-sector EM2040. For each sonar (three NOAA launches tested), as they operate in dual swath mode, there is a unique pair of patterns for the first and second swaths and that pair is unique for each pulse length/type and center frequency.

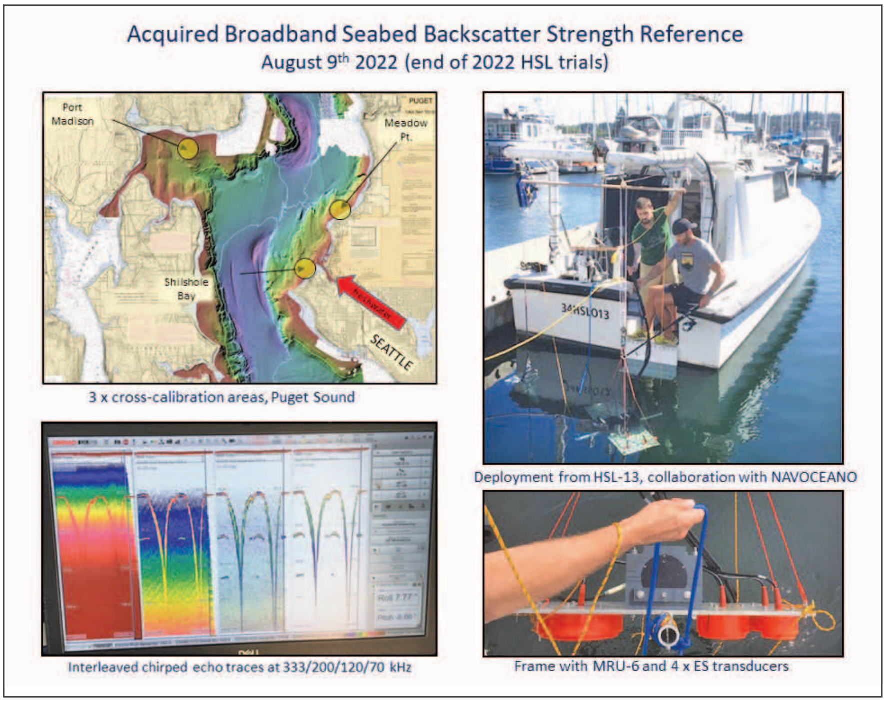


Figure ES-6. The location of the three backscatter calibration areas in Puget Sound and the logistics of deploying the 4xEK-80 chirped reference backscatter measurement hardware.

We have also continued our efforts to find efficient ways of providing absolute backscatter calibration for seafloor mapping multibeam sonars and for establishing reference surfaces that can be used by NOAA and other vessels to calibrate their systems. The approach uses an array of four calibrated ES transducers to measure the absolute backscatter of the seafloor over a range of angles and frequencies to establish a backscatter reference site. Once the the site is calibrated, uncalibrated systems can then be brought to the site for calibration (Figure ES-6). Efforts are also underway to develop approaches to transferring the reference data between sites by using the calibrated sonar on a launch to provide a cross-calibration of a new area.

Environmental Impacts on Hydrographic Data Quality

As the instruments we use to measure seafloor bathymetry and backscatter improve, we find that data quality is often degraded by local spatial or temporal changes in the oceanographic environment including variations in the daily or seasonal thermocline, internal waves, turbulence, and the presence of bubbles under the hull. We have been developing techniques to image these phenomena in real time so those collecting hydrographic data can adapt their surveys or sampling programs to minimize the impact of these phenomena (Figure ES-7).

To provide real-time input on these phenomena to the surveyor, graduate student Lynette Davis has developed an approach for displaying up-to-date water column data in continuously updating plots that provides a synoptic view of the underlying volume scattering field immediately below the vessel (Figure ES-8). Such a tool should be routinely available on the bridge of any hydrographic survey vessel so that, just as clouds are viewed as indicators of upcoming weather, this display can aid in deciding on the optimal sound speed and surveying sampling strategy.

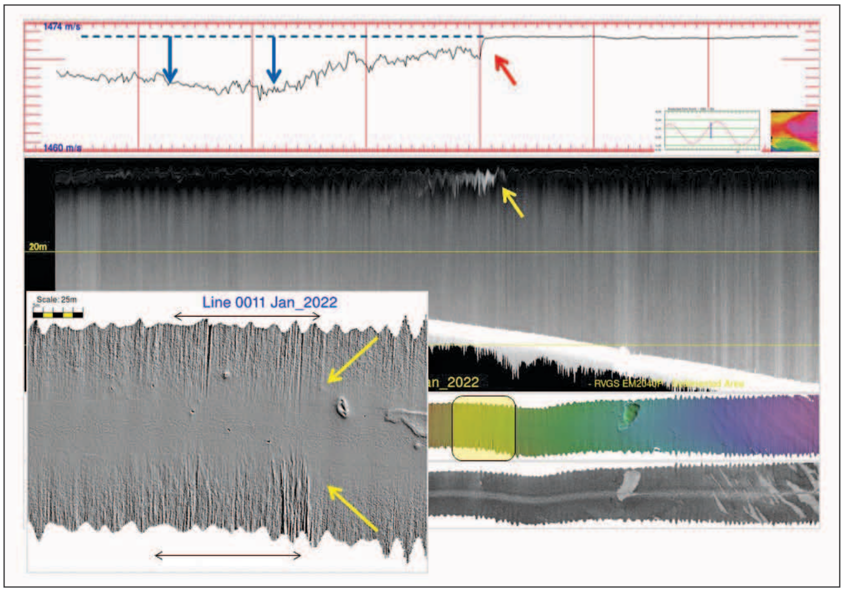


Figure ES-7. Geographically co-located sections showing impact of water column on multibeam data. Top to bottom plots show: the instantaneous surface sound speed, the near nadir vertical water column volume scattering and the corresponding bathymetry and seabed backscatter. The inset shows a zoom in of the bathymetry the moment the swath passes over the water mass boundary. Arrows correspond to the boundary location.

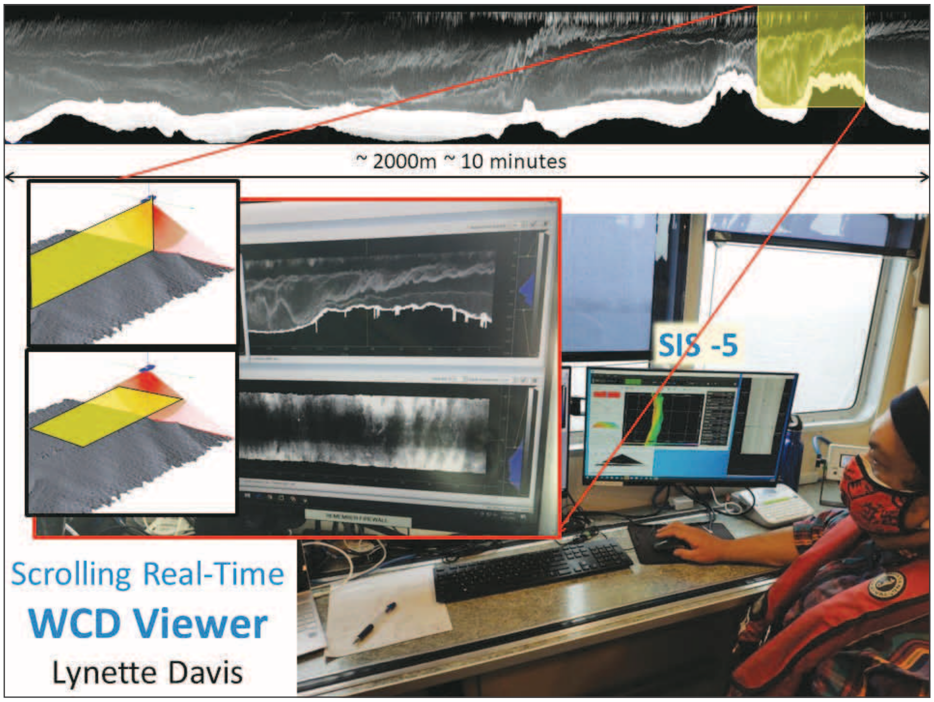


Figure ES-8. Real time displays of the EM 2040P water column nadir vertical curtain and horizontal slice views.

Navigator (BEN) a C-Worker 4 vehicle, was the result of collaborative design efforts between the Center and ASV Global, LLC beginning in 2015 with delivery in 2016. Teledyne Oceanscience donated a Z-Boat USV in 2016, and Seafloor Systems donated an Echoboat in early 2018. A Hydronalix EMILY boat, donated by NOAA, is in the process of being refit. Finally, through other NOAA funding (OER-OECI), we purchased a DriX USV from iXblue (now Exail), Inc. in 2021.

The fleet of vehicles owned by the Center provides platforms for in- and off-shore seafloor survey work, product test and evaluation for industrial partners and NOAA, and ready vehicles for new algorithm and sensor development at the Center. *BEN*, an off-shore vessel, is powered by a 30 HP diesel

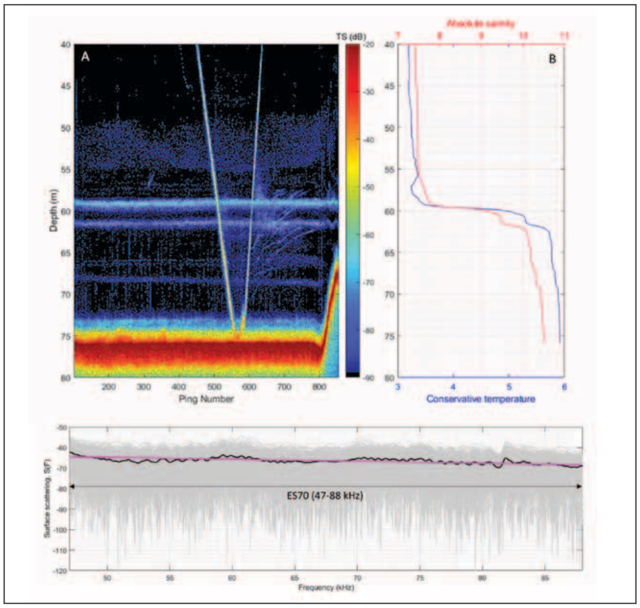


Figure ES-9. Testing of inversion on site in the Western Gotland basin. Panel A illustrates the broadband acoustic water column from the ES70-7C system while panel B illustrates the CTD profile data. The bottom panel illustrates the frequency dependent surface scattering response from the tracked stratification from which the layer thickness can be derived. Individual frequency-dependent curves are plotted in grey, the ensemble average in the thick black line, and the fitted trend line in magenta, proportional to R'.

Along with our efforts to image water column structure to improve the quality of our seafloor surveying, we have also focused on understanding the nature of scattering in the water column so that we can use water column backscatter to quantitatively understand processes in the water column. This year, Liz Reed-Weidner and Tom Weber expanded their model of stratification to investigate the frequency-dependent behavior of backscattering from ocean structure and applied it to a dataset from the Baltic Sea where a sharp interface exists. Initial analyses suggest that the thickness of the interface can be derived from broadband acoustic data, but without direct, high-resolution measurements of water column structure it is difficult to assess the accuracy of the acoustic inversion procedure (Figure ES-9).

Operation and Deployment of Uncrewed Surface Vessels

Even a casual perusal of trade magazines, conferences, and engineering/scientific literature in the offshore survey sector makes it very clear that the use of autonomous or uncrewed surface vessels (USVs) is getting a lot of attention. In an effort to fully evaluate the promise of USVs for seafloor survey and also to add capability and practical functionality to these vehicles with respect to survey applications, the Center has acquired—through purchase, donation, or loan—several USVs. The *Bathymetric Explorer and*

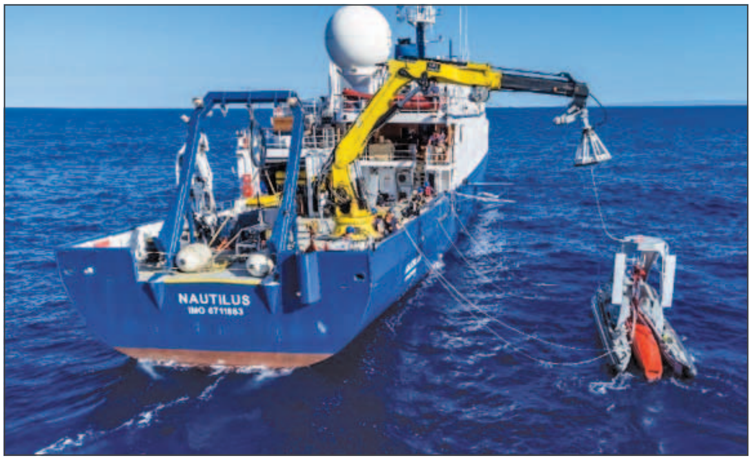


Figure ES-10. The Drix-8 was successfully integrated onto the E/V *Nautilus* and successfully completed several missions in 2022, including the demonstration of multi-vehicle operations.

jet drive, is 4 m in length, has a 20-hour endurance at 5.5 knots, and a 1 kW electrical payload capacity. The Z-Boat, Echoboat and EMILY vehicles are coastal or in-shore, two-person portable, have have battery powered systems with endurances of 3-6 hours at a nominal 3 knots (sensor electrical payload dependent). The DriX is also an ocean-going vessel, with a unique, purpose-built composite hull, a maximum speed exceeding 13 knots, and endurance exceeding four to five days at 7 knots.

This past year has been a remarkably busy one for Center uncrewed vehicle activities including the first-time integration of the DriX ASV aboard two vessels while preparing for a third in 2023. In 2022, the ASV group conducted four major shipboard deployments with DriX vehicles, three aboard the E/V *Nautilus* in the Central Pacific, and one aboard NOAA Ship *Thomas Jefferson* in Lake Erie. The expeditions aboard *Nautilus* included an initial OER-funded shakedown cruise where the complexities of launch, recovery, and operations of the DriX from the *Nautilus* in open waters were worked out and perfected (Figure ES-10). This was followed by a very successful OER-funded cruise that demonstrated the valuable role that DriX could play in allowing the simultaneous operation of multiple uncrewed vehicles while freeing the *Nautilus* to carry on other missions. Typically, a large expensive research vessel is dedicated to monitoring underwater vehicles during their deployment, precluding the research vessel from other operations. During this cruise, we were able to deploy DriX and have it track, follow, and communicate with the AUVs to direct them to specific targets, all while allowing the *Nautilus* to work independently and carry on her own mission. The final DriX leg on *Nautilus* was an OCS-funded leg to evaluate the ability of DriX as a force-multiplier in the collection of hydrographic data in support of safety of navigation. The DriX mapped shallow areas around the remote Nihoa Island of the Hawaiian Island Chain (Figure ES-11) working independently but in collaboration with the *Nautilus*, and clearly demonstrating the significant gains in efficiency provided by uncrewed systems.

The success of the work on the *Nautilus* led the NOAA Office of Marine and Aviation Operations to purchase another DriX (DriX-12) for hydrographic and fisheries missions. The Center played a key role in supporting the installation and seagoing acceptance trials of DriX-12 on the NOAA Ship *Thomas Jefferson* (Figure ES-12). These initial trials proved so successful that the DriX-12 was declared operational for hydrographic purposes. Early in 2023, the DriX-12 will be evaluated for use in support of NOAA fisheries operations.

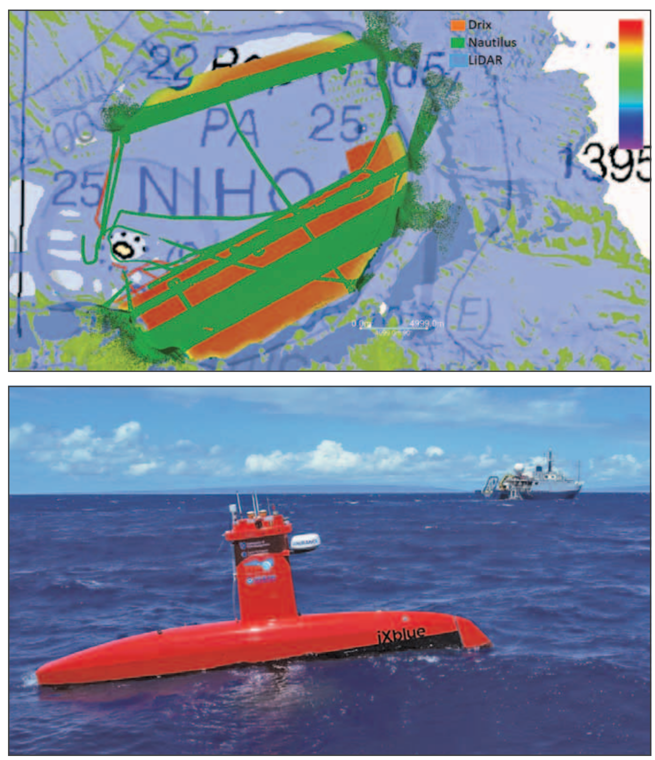


Figure ES-11. DriX was also used to map shallow waters around Nihoa Island while E/V *Nautilus* mapped in deeper water or in tandem (right).

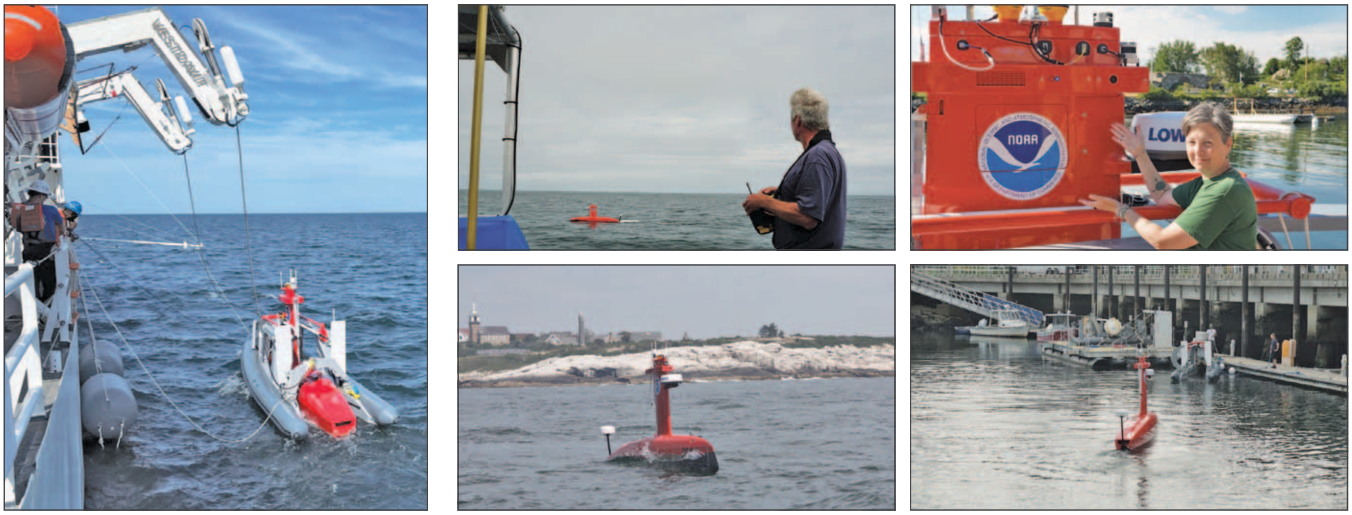


Figure ES-12. DriX-12 Sea Acceptance Tests and DriX Operator Training, hosted by the Center in August and October (left). Operations of DriX-12 from the NOAA Ship *Thomas Jefferson* in the approaches to Cleveland in Lake Erie (right).

Not all of this effort was funded through the Center's JHC grant. Purchase of DriX-8 in 2021, its integration into the E/V *Nautilus* in February and March of 2022, and its deployment for the Ocean Exploration Cooperative Institute's "Tech Challenge Cruise" were funded separately. However, many of the lessons learned in these operations were directly related to the goals funded under the JHC grant and were not explicitly funded elsewhere, and so they are reported here. While the research objectives for the two grants are different, it is the complementary effort that fills the gaps to provide a holistic consideration for practical aspects of operation.

Related Uncrewed Vessel Research

In addition to our field operations of uncrewed vessels, we have been pursuing research in many areas to support these operations, including the on-going development of our marine robotics software framework (Project 11) and our ROS-based backseat driver for uncrewed vehicles—the CCOM Autonomous Mission Planner (CAMP).

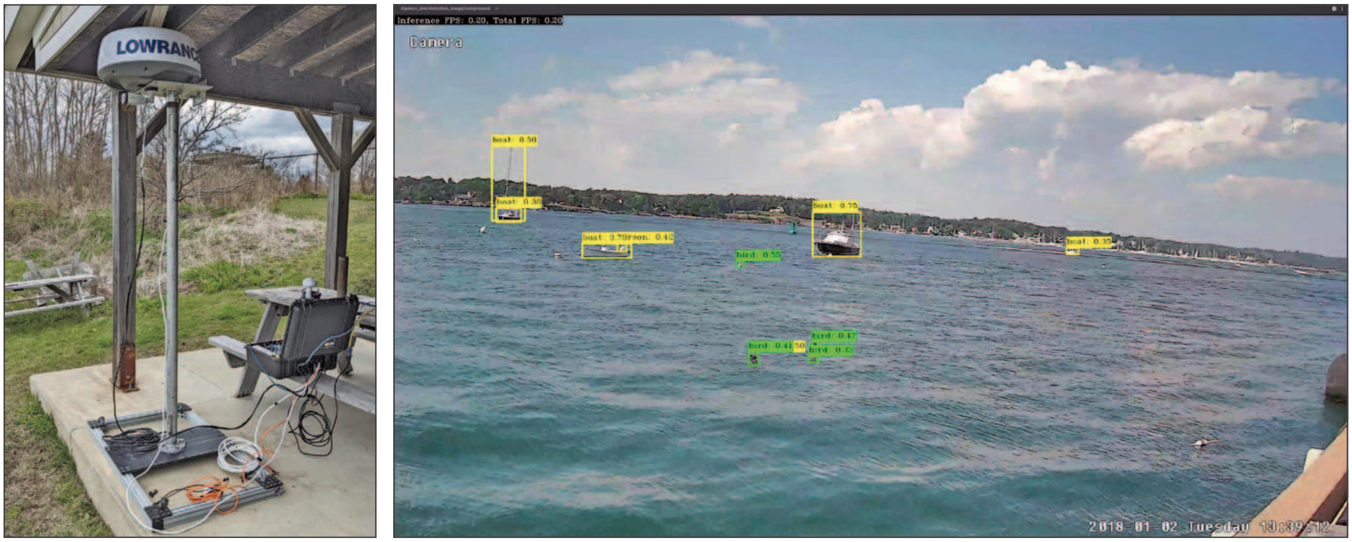


Figure ES-13. The MLTDMA (pronounced "Matilda") sensor package during prototype testing is shown (left) with an example of auto-detected objects in the camera's image (right). AIS data (not shown) will help to auto-annotate the images for ships that transmit it.

It was the flexibility of CAMP that contributed to our ability to manage the deployment and operation of multiple AUVs—along with DriX—this past summer on *Nautilus*. Improvements this year include the addition of a time-based path-following control and a software plugin architecture for integrating various AI vessel navigators. We improved our Wi-Fi telemetry capabilities by designing and building an antenna mast rotator control system that tracks the USV during operations to allow the use of highly directional antennas without regard to vehicle direction, and we have begun the implementation of Starlink low-earth orbiting satellite communications for our uncrewed vessels. We believe this new satellite capability will revolutionize our use of uncrewed vehicles, permitting their remote operation and data transmission from anywhere in the world.

Our USV-related research efforts also include work focused on the use of machine learning techniques to help uncrewed systems autonomously identify objects and hazards. This past year, we built a prototype sensor package for automated annotation of marine images (Figure ES-13). The package combines a marine radar, a camera, an Automatic Identification System (AIS) receiver, a GPS, an IMU, and a data logging system into a portable, easily deployed platform. Test deployments were made of the system in Portsmouth Harbor in June to verify hardware interfaces and data logging capability.

We also continued our efforts for automated path planning for robotic vehicles this year by building a standard set of interfaces and plugin architecture for path planners in our simulation and operational environment, and by using chart-derived information to derive the safest path between waypoints (Figure ES-14, left). This work is linked to our "Roads of the Sea" project which we hope to develop into a passage planning and prediction system that will support optimal marine navigation. This project aims to assist users—both humans and machines—to safely traverse the seas by providing routes customized to their specific vessels based on those routes previously taken by ships with similar characteristics and by predicting the trajectories of other ships (Figure ES-14, right).

Data Acquisition for Volunteer/Trusted Partner Systems

Continuing along the programmatic component of "Data Acquisition," the Center has also explored the potential for volunteer observers to contribute bathymetric (and other) observations for mapping purposes. The potential, however, has largely not been realized within the hydrographic mapping community due to concerns about quality and/or completeness of data. The "crowdsourced" concept has been advanced in multiple contexts as a solution for this problem—the assumption being that sufficient numbers of observers will allow for the "right" answer to emerge, even if some of the observers are incorrect. In the bathymetric world, however, the oceans are large, and ships are (relatively) small, meaning that effective crowds exist only in very limited locations. As we reported in previous years, we have addressed this problem through the development

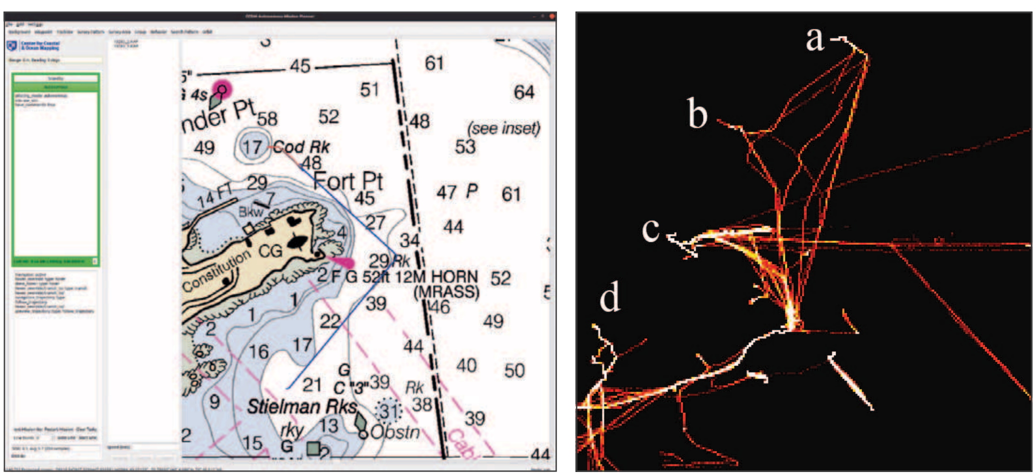


Figure ES-14. Left: CAMP—the Center's mission planning interface illustrates, in simulation, an auto-generated transit plan from Stielman Rocks to Cod Rock, using a cost-map derived from the S-57 chart. Right: a visual heatmap representation of the grid showing various routes that form between grid cells in New England area (a: Portland, ME; b: Portsmouth, NH; c: Boston, MA; and d: Providence, RI). Brighter colors represent more highly trafficked routes.

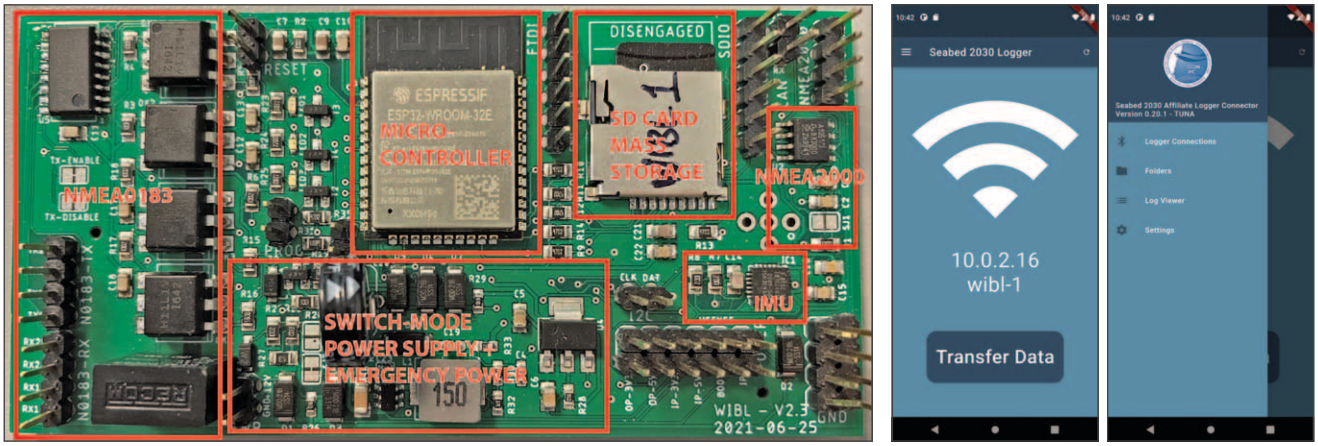


Figure ES-15. Prototype of the Wireless Inexpensive Bathymetry Logger (WIBL) for NMEA0183 and NMEA2000 data (left). Screenshots of the cross-platform mobile application for WIBL logger management and interaction (right).

of a Trusted Community Bathymetry (TCB) approach using trusted hardware with a reference GNSS receiver to provide qualified depths referenced to the ellipsoid through auto-calibration of vertical offsets and uncertainty estimates (with a cost of $1000-$2000) along with a mass-deployable, scalable, low-cost (~$10-$20) data collection system using the Wireless Inexpensive Bathymetry Logger (WIBL) platform. Both systems route data to the IHO DCDB database whenever there is access to the internet. The idea is that both will be deployed in the same area with the TCB loggers on a few vessels providing calibrated, ellipsoidally-referenced depths, while a large number of WIBL loggers provide mass observation through local volunteers who know the area well and are invested in having better bathymetry in their area. Where there are crossing observations between the two systems, cross-referencing observations allow for calibration transfer, making the WIBL data much more valuable for mapping purposes. The open-source nature of the WIBL project allows this model to be scaled without a single entity becoming a bottleneck, so each deployment controls their own data collection and retains control of their own data (which is often required by national authorities), while still ensuring that data reaches the international archive at the Data Center for Digital Bathymetry, hosted by NOAA's National Centers for Environmental Information in Boulder, CO. This year, the first deployable WIBL prototypes (Figure ES-15) were built and distributed to users at CIDCO in Canada and at the University of South Florida for testing. The results of these first trials will be presented in the next reporting period.

Programmatic Priority 1
ADVANCE TECHNOLOGY TO MAP U.S. WATERS

DATA VALUE

The second component of Programmatic Priority 1 is Data Value—representing the processing, analysis and quality assurance steps taken after the collection of the data. Within this component we have developed processing, analysis, and QC approaches for a range of relevant data sets including bathymetry, backscatter, lidar, video, and satellite-derived bathymetry.

Bathymetry Data Processing

Despite advances in processing techniques and technology in the last decade, processing large-scale, high-density, shallow-water hydrographic datasets is still a challenging task. Over the years, the Center has pioneered techniques to improve on processing times achievable, and new technologies that have conceptually redefined what we consider the output of a hydrographic survey. There is, however, still some way to go, particularly in the context of cloud-based, distributed, and real-time systems for automated survey.

Implementations of CHRT

The CHRT (CUBE with Hierarchical Resolution Techniques) algorithm was developed to provide support for data-adaptive, variable resolution gridded output. This technique provides for the estimation resolution to change within the area of interest, allowing the estimator to match the data density available. The technology also provides for large-scale estimation, simplification of the required user parameters, and a more robust testing environment, while still retaining the core estimation technology from the previously verified CUBE algorithm. CHRT is developed in conjunction with several of the Center's industrial partners who are pursuing commercial implementations. During the current reporting period work has been done with Leidos to implement the Level of Aggregation algorithm (see previous reports) and with MARUM (Bremen, Germany) to implement CHRT within the open source MB-System processing package.

Cloud-distributed Computing and Parallel Bathymetric Processing

The use of cloud technologies has been revolutionary for computing environments over the last ten years and there is great potential for significant advantage in the bathymetric processing field. An essential issue, however, is how to manage these resources and take advantage of the freedoms of the cloud environment while still maintaining guarantees about product correctness (and keeping costs in check). A proposed solution was to take current desktop bathymetry processing software and deploy it in the cloud. Earlier work at the Center demonstrated that this is possible but did not address the costs and performance issues. In the current reporting period, therefore, with auxiliary funding from OECI, Brian Calder and undergraduate student Jason Worden investigated the performance and cost structure of this idea in the Amazon Web Service infrastructure. The results of these investigations suggest that using standard desktop processing software in the cloud is possible, and can be optimized, but will likely always be cost-prohibitive. This is mostly because of the requirement for a combined compute and graphics resource for the software, which is expensive to provide in the cloud. Alternative approaches to cloud provisioning might potentially be found, but it seems likely that some more significant modification of the processing paradigm is required for efficient cloud deployment.

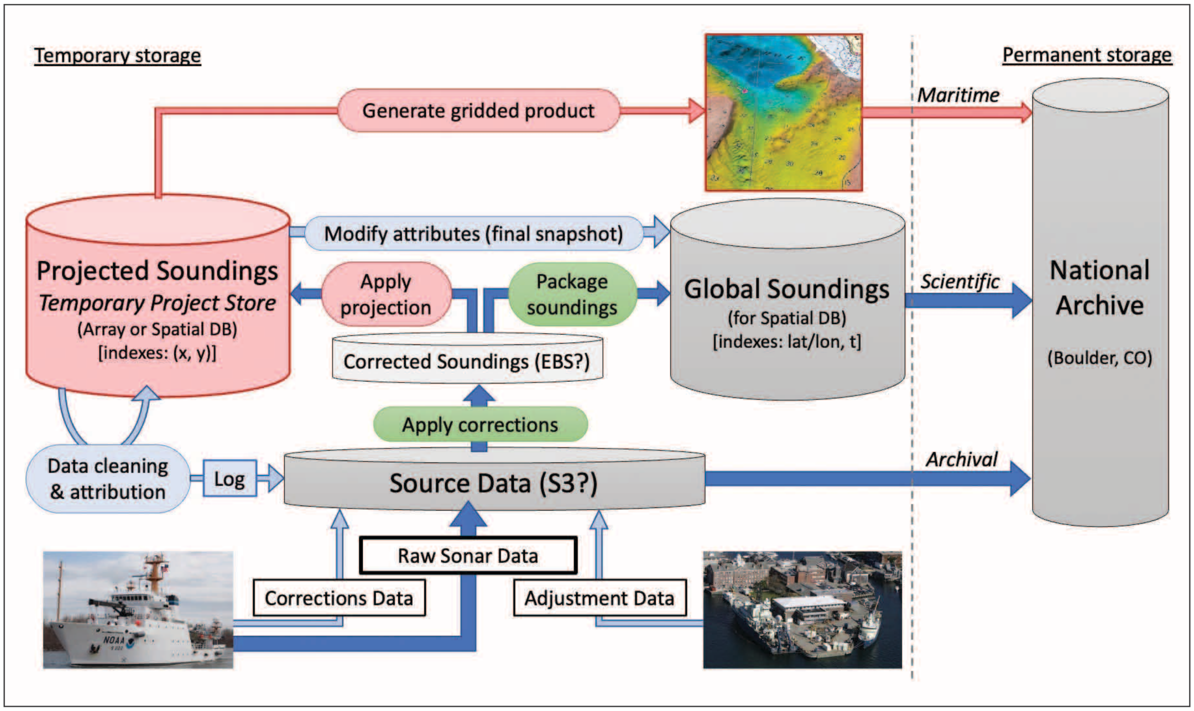


Figure ES-16. Proposed architecture for cloud-based bathymetric data flow and archival. Note the use of multiple storage media for different purposes to optimize costs and separate (but optional) database of point soundings for non-mapping or research purposes.

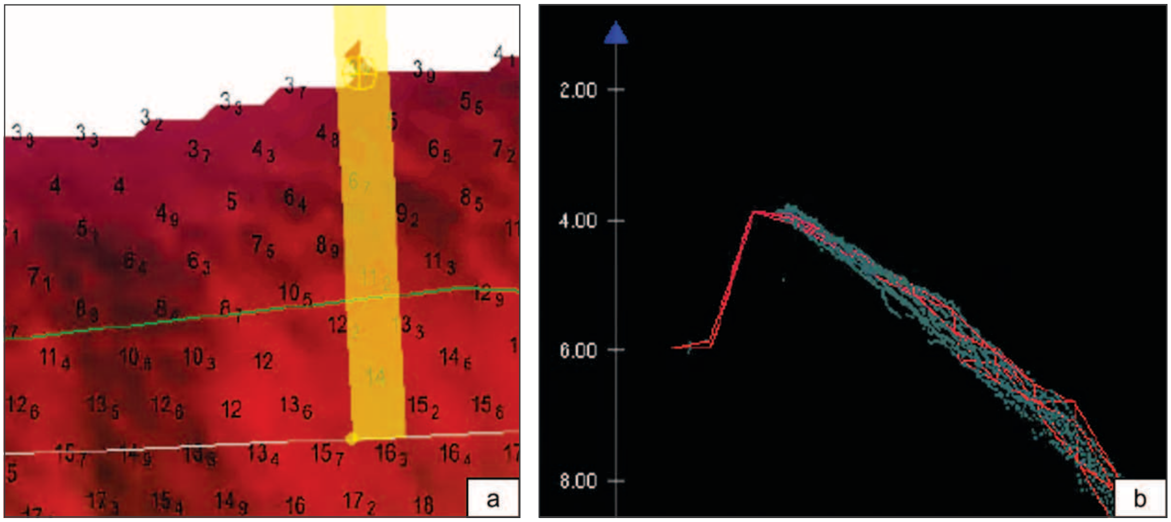


Figure ES-17. The Noisy Margins check is tailored to identify fliers along noisy swath edges. The algorithm crawls across empty cells to establish a margin. A margin is detected as noisy when the maximum depth difference with its neighbors is greater than an adaptive threshold. Pane 'a' (left) displays a detection of the Noisy Margins check (as a yellow circled cross). Pane 'b' (right) shows a side view of the area identified as being affected by the noise.

Given the costs associated with deploying desktop-based processing software in the cloud described above, Calder, Matt Plumlee, and Bocheng Cui have been working on an early implementation of a cloud-native processing structure that could be used to avoid the concerns highlighted and take advantage of the specific features of cloud-based processing that are not available in the desktop environment. The outline data flow, Figure ES-16, highlights using different types of storage at different times in the workflow to optimize costs, and envisions a difference between working-store for data points and archival data points to be delivered directly to the national archive. This approach will be further developed in the coming years.

Advanced Quality Assurance/Control Tools

Quality assurance and control of ocean mapping data continues long after the data are collected, and the Center has been instrumental in building tools to support this process at the interface between field and office processing, and the transition of these tools to operations through the NOAA/UNH HydrOffice and Pydro toolsets. These QA/QC tools provide application-specific support of NOAA Hydrographic Office workflows (specifically, NOAA OCS workflows), and have been influential in systematizing and automating procedures for data quality control. Although a certain level of maturity has been achieved with these tools, new ideas and algorithms continue to develop from field requirements, data foibles, and survey specification requirements.

In this reporting period, Giuseppe Masetti, Tyanne Faulkes (NOAA PHB), Matthew Wilson (NOAA AHB), and Julia Wallace (NOAA AHB) continued—in collaboration with NOAA's Hydrographic Systems and Technology Branch personnel—to develop the toolset. The application, which aggregates a number of tools within a single GUI, is available through NOAA Pydro (which delivers software to the NOAA hydrographic units) and through the HydrOffice website for non-NOAA users. Many mapping agencies, NOAA contractors, and other professionals have adopted some of these tools as part of their processing workflow. QC Tools is in active use with the NOAA field units, which are a valuable source of feedback and suggestions. Specifically, the BAG Checks algorithm, which analyzes BAG files to ensure compliance to both format specifications and other NOAA requirements before submission to the NOAA National Bathymetric Source (NBS) database has been extended and improved. Based on OCS feedback, BAG Checks has significantly helped to decrease the number of errors in BAG products by identifying issues during processing review. QC Tools was also updated to give the user the ability to ensure that all NOAA field units and offices can QC data to the latest requirements. Finally, QC Tools was improved to enhance the detection of anomalous data along the margin of MBES swaths by the newly introduced "Noisy Margins" check in the Find Fliers algorithm (Figure ES-17).

Automated Data Processing for Topobathy Lidar Data

Our data processing efforts extend to all sources of bathymetric data, including those derived from non-acoustic sources, such as airborne lidar. While traditional bathymetric lidar systems produced relatively sparse data that did not pose a serious processing challenge, the introduction of topo-bathy lidar represented a fundamental change in the density of lidar that seriously challenged traditional lidar processing approaches. To address this issue, the Center has been exploring the applicability of processing approaches developed for multibeam sonar data using CHRT, for application in topobathy lidar data. The overarching goal is the extraction of bathymetric soundings from lidar point clouds with a minimum of manual input and without the need for an ancillary *in situ* dataset. The adopted approach couples CHRT with machine learning (ML) to process individual 500m x 500m NOAA lidar tiles. The current reporting period has seen a focus on two primary tasks. The first task is gaining a better understanding of the uncertainty associated with the use of CHRT-ML through the comparison of depths produced by NOAA's bathy soundings to those produced by CHRT-ML (Figure ES-18). The result of this comparison is then used to further improve CHRT-ML and to identify CHRT-ML-processed tiles that may require human user examination and (re-)processing by alternative means. The second task is the automated elimination of above-sea-level areas using the Normalized Difference Vegetation Index (NDVI) in Sentinel-2 imagery (Figure ES-19).

ICESat-2 for Shallow Water Bathymetry

While airborne lidar systems have been used to collect bathymetry for many years, the use of satellite borne laser systems for bathymetry is quite recent. Satellite laser altimeter systems, such as the ICESat-2 ATLAS system, are typically used for measurement of surface phenomena, such as ice freeboard, but prior research has demonstrated that they can successfully be used to determine water depth in some areas—at least in clear, shallow water. While the data density and accuracy are not

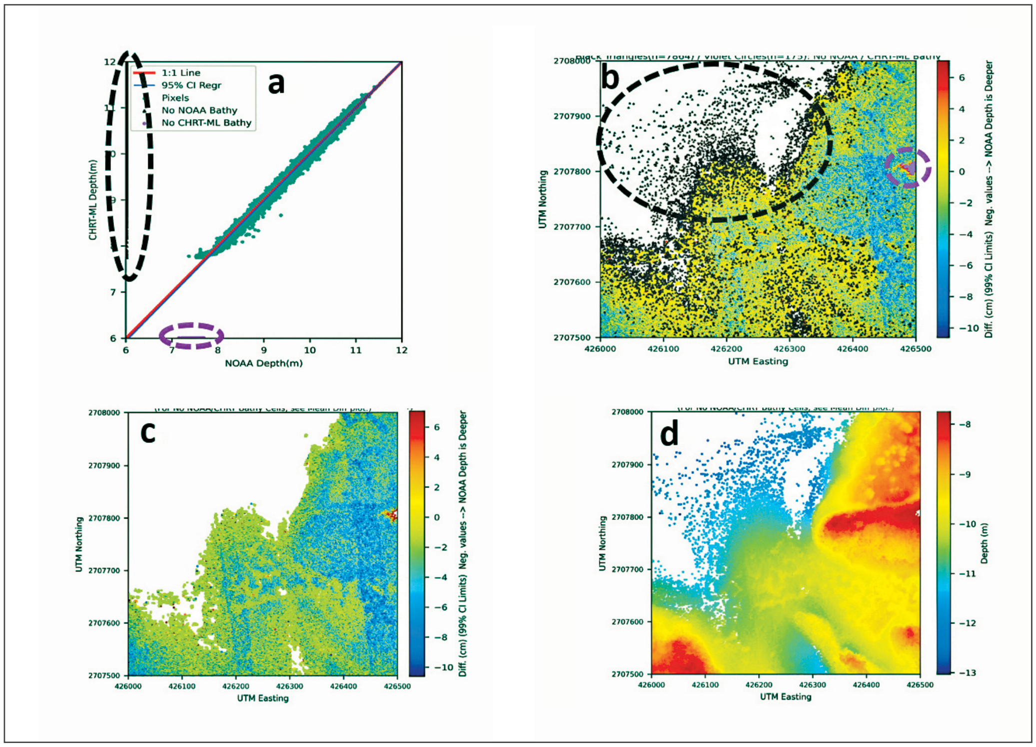


Figure ES-18. Statistical-spatial method of evaluating uncertainty on a lidar tile. Panel a) NOAA vs. CHRT-ML depth relationship. Panel b) Differences (cm) in NOAA and CHRT-ML depth with "no data" pixels indicated (See also Panel a). Violet points: pixels for which NOAA identified bathy soundings but CHRT-ML did not. Black points: pixels for which CHRT-ML identified bathy soundings but NOAA did not. Panel c) Differences (cm) in NOAA and CHRT-ML depths without "no data" pixels. Panel d) CHRT-ML depth (m).

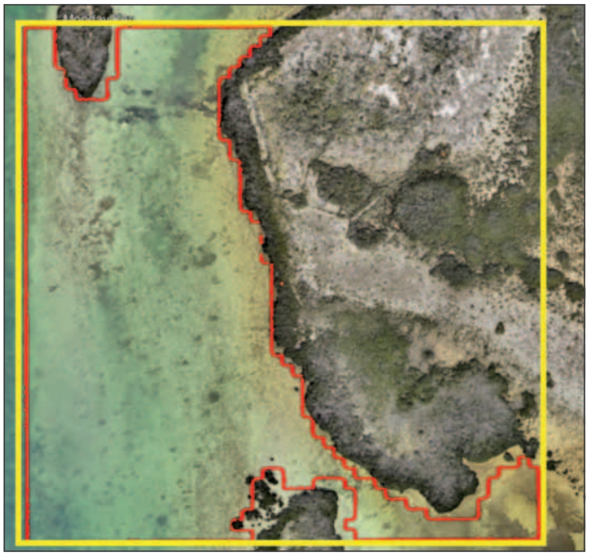


Figure ES-19. Example of lidar 500m x 500m tile (yellow) and the area identified as ocean/"not ground" (red) using Normalized Difference Vegetation Index analysis of Sentinel-2 10m imagery.

necessarily what might be expected from airborne lidar systems, the ubiquity of the data and ongoing collection campaign make for an interesting data set that may provide insight into other hydrographically significant features. The near-term goal of our efforts is to enable (quasi-) automated extraction of bathymetry from ICESat-2 data and couple such data with remotely sensed imagery using satellite-derived bathymetry (SDB) techniques to produce area-based depth maps. To achieve this goal, an algorithm has been developed to automatically extract "photon events" (the return from the laser) reflected from the seafloor (Figure 20). While the algorithm has shown promising results, issues such as the existence of multiple hypotheses of potential bathymetric clusters have yet to be addressed.

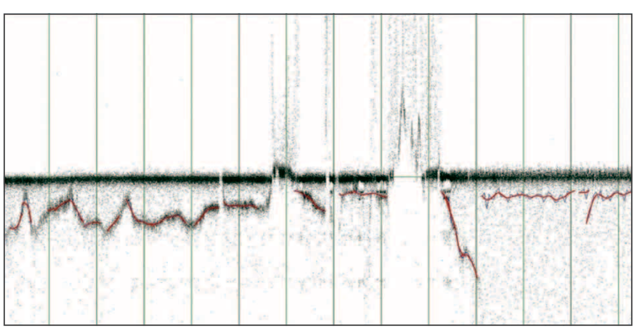


Figure ES-20. Example of bathymetry detected by the algorithm described in the text. Black dots are individual photon events (PEs), tiny lines "under" the red lines are potential bathymetric measurement (PBM) clusters, and the red lines are P-splines fit through the clusters and represent extracted bathymetry.

Satellite Derived Bathymetry: A Geographic Segmentation Approach

Satellite Derived Bathymetry (SDB) from multispectral remote sensing has shown potential as a supplement to traditional bathymetric surveys, particularly for mapping remote and shallow areas, due to its reduced cost and the absence of navigational risks in very shallow and unsurveyed areas. SDB has received significant attention since the 1970s, and multiple algorithms have been developed. The ability to retrieve bathymetric information from satellite imagery is based on observed radiance as a function of wavelength and depth. A main concern with SDB is that the accuracy of the method is not adequate for many coastal applications, including nautical charting. One of the reasons may be that the conventional approaches assume that bottom type and water clarity are constant within the entire image. To address the spatial heterogeneity within a scene and with the aim of increasing the accuracy and coverage of estimated depths, graduate student Juliane Affonso—under the supervision of Christos Kastrisios, Christopher Parrish (Oregon State University), and Brian Calder—investigated the use of multi-temporal, non-linear techniques, and the segmentation of the scene, both horizontally and vertically, into smaller spatial units. The application of spatial segmentation approaches provided significant improvements in depth estimation but needed more control points compared to the global models and required multiple processing steps compared to the conventional methods. Future work will attempt to refine the segmentation approaches, quantify their benefit and optimize the bin size for improving accuracy and coverage without overtraining the model and losing its predictive capabilities.

Enhanced Data Underwater 3D Construction

Finally, under the topic of Bathymetric Data Processing, we look at our efforts to directly use seafloor imagery to generate high-resolution 3D constructs of the seafloor. Structure from Motion (SfM) is an image processing technique that allows construction of accurate 3D models from overlapping successive photographs taken at various angles. SfM photogrammetry is a technique that has been used for the production of high-resolution morphometric 3D models and derived products, such as digital surface models and orthomosaics. SfM has been used in morphodynamic studies and reconstruction of complex coastal geoforms, coral habitats, and rocky

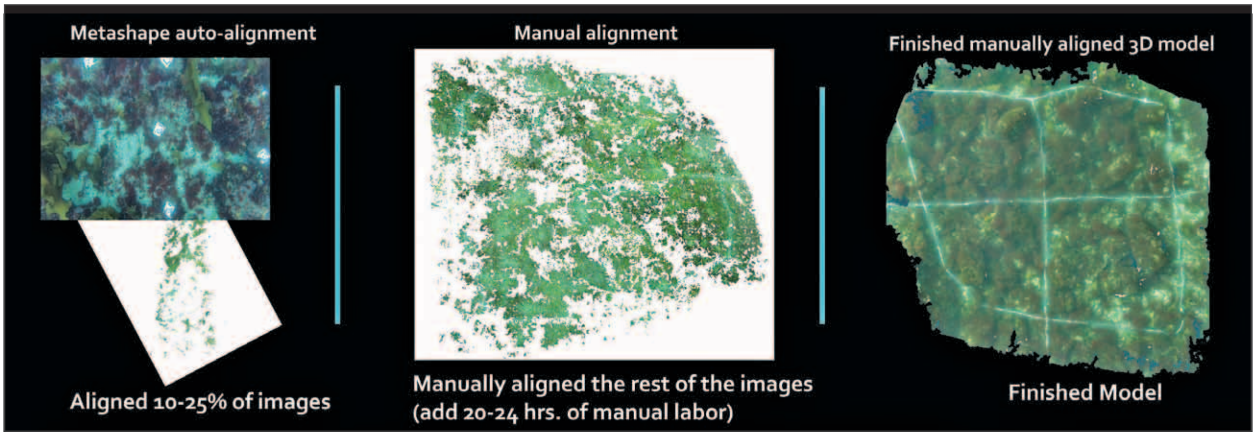


Figure ES-21. Metashape's auto-alignment function generally aligns a very small portion of the model. Middle: example of a full model that has been aligned using manual markers placed by a user – key is conducting survey all in same direction. Above right: example of a fully textured 3D model that has been manually aligned.

shores. It can provide small (< 1m^2) to large scale (10-100m^2) quantitative, three-dimensional information of seafloor and habitat characteristics that can be used for shoreline surveys and to monitor habitat change as well as provide ground-truth for quantitative backscatter and seafloor characterization studies. In the past year, we worked on several aspects of SfM and its relevance to survey work. These include developing methods for optimizing 3D reconstructions in areas where seafloor features are moving—such as seaweed-dominated habitats (Figure ES-21), understanding the uncertainties associated with various approaches to providing ground-control points for SfM imagery for intertidal zones (Figure ES-22), and a new spatial analysis method that fully captures rugosity within complex 3D scenes using SfM models of coral reefs and intertidal landscapes as input. This method was implemented in a rugosity calculator tool that gives users the ability to choose the scale at which to measure rugosity.

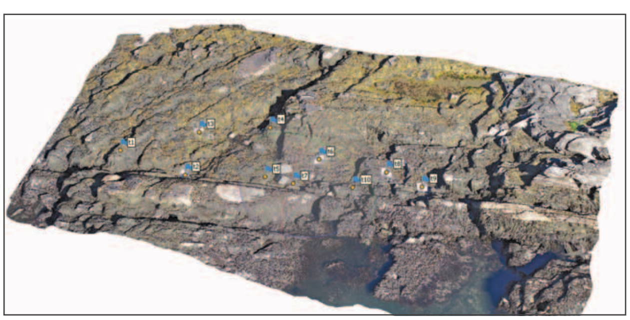


Figure ES-22. Bird's-eye view of 3D model with draped imagery showing one of the intertidal zone sites. Superimposed in yellow is the Ground Control Point locations as determined by the combined PPK GNSS and total station method vs. in blue the locations as determined by WAAS aided GNSS.

Backscatter and SAS Data Processing

Open BST

Along with bathymetry data, our sonar systems also collect backscatter (amplitude) data. Our efforts to develop techniques to appropriately correct backscatter for instrumental and environmental factors are covered under the Data Collection component of our efforts; here we discuss our work to develop community-verified open-source backscatter processing algorithms as well as develop new approaches to processing and deriving important information from synthetic aperture sonar (SAS) data. The OpenBST project was started in 2019 to help address and mitigate the discrepancies that arise in the backscatter processing workflow. OpenBST was designed to be an open-source, metadata-rich, and modular toolchain dedicated to backscatter processing. The goal of the project is to develop a set of open-source, community-vetted reference algorithms usable by both the developer and the user for benchmarking their processing algorithms. The project is written in Python and is available on GitHub for collaborative development. It uses the common NetCDF convention to efficiently couple metadata and processing results. The project has been restructured to use a graphical user interface, which will permit the user to navigate the back-scatter workflow and provide a number of comparison tools to facilitate investigation of the underlying data. With a re-invigoration of the International Backscatter Working Group and the Center being represented on the group by Mike Smith, we expect that OpenBST efforts will likely be spun up again in the coming year.

SAS Processing for Object Detection

Leveraging work supported by the Office of Naval Research, Tony Lyons has been exploring multi-look SAS techniques for target detection and classification. Multi-look coherence techniques focus on the information content of images by splitting the total angle and frequency spectral bandwidth of a complex synthetic aperture sonar image into sub-bands. The complex coherence of each pixel as a function of frequency and angle can then be exploited, yielding information on the type of scattering observed (e.g., specular, diffuse, point-like, resonance-related, etc.) Information pertaining to scattering type should improve the separability of man-made targets from the interfering background signal, as targets should have features that scatter coherently in frequency and/or angle versus the random seafloor interface or volume (or randomly rough, target-sized rock) which will scatter incoherently (Figure ES-23). The results of work performed this year are significant for: 1) understanding multi-look coherence from targets and natural seafloors estimated using wide-angle, broadband SAS imaging systems, 2) exploring potential methods to exploit coherence for both the detection and classification of proud and buried man-made targets in clutter, and 3) quantifying the performance of multi-look techniques for detection.

While the bulk of this effort is funded through the Office of Naval Research, the applications of novel techniques for automated target detection and classification are evident and Lyons will be identifying opportunities to apply these methods to locating and identifying objects on the seafloor which may pose hazards to navigation (e.g., wrecks or rocks), and working with colleagues at the Center to incorporate these approaches into mapping workflows.

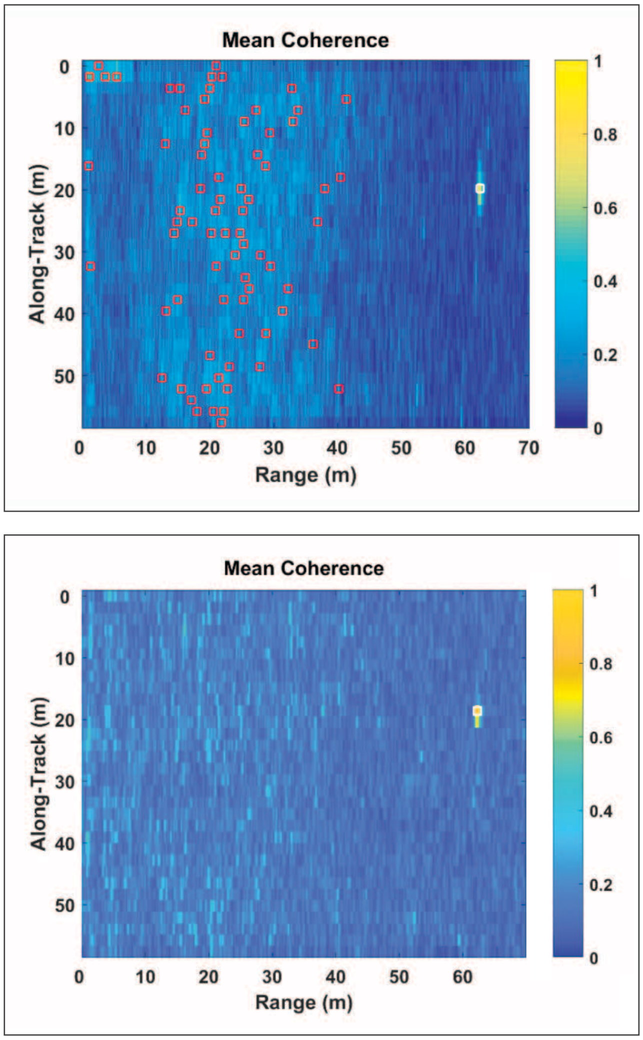


Figure ES-23. Example mid-frequency SAS target detections on a ripple field (top) and on the same image using the multi-look coherence technique before (bottom) and after including false alarm reduction strategies.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

RESOURCES OF THE CONTINENTAL SHELF

The third component of Programmatic Priority 1 specified by the Notice of Federal Opportunity is entitled "Resources of the Continental Shelf," representing the activities of the Center in support of the U.S. Extended Continental Shelf Project as well as several activities that are focused on supporting offshore mineral and resource exploration, renewable energy development, and the responsible management of U.S. living marine resources.

Support of U.S. ECS Efforts

Recognizing that the United Nations Convention on the Law of the Sea (UNCLOS), Article 76 could confer sovereign rights to resources of the seafloor and subsurface over large areas beyond the U.S. 200 nautical mile (nmi) Exclusive Economic Zone (EEZ), Congress (through NOAA) funded the Center to evaluate the nation's existing bathymetric and geophysical data holdings in areas surrounding the nation's EEZ in order to determine their usefulness for establishing an "Extended" Continental Shelf (ECS) as defined in Article 76 of UNCLOS. This report was submitted to Congress on 31 May 2002.

Following up on the recommendations made in the study, the Center was funded (through NOAA) to collect new multibeam sonar (MBES) data in support of a potential ECS claim under UNCLOS Article 76. Mapping efforts started in 2003 and since then the Center has collected more than 3.1 million square kilometers (about twice the area of Alaska) of new high-resolution multibeam sonar data on 32 cruises including nine in the Arctic, five in the Atlantic, one in the Gulf of Mexico, one in the Bering Sea, three in the Gulf of Alaska, three in the Necker Ridge area off Hawaii, three off Kingman Reef and Palmyra Atoll in the central Pacific, five in the Marianas region of the western Pacific, and two on Mendocino Fracture Zone in the eastern Pacific (Figure ES-24). Summaries of each of these cruises can be found in previous annual reports, and detailed descriptions and access to the data and derivative products can be found at http://www.ccom.unh.edu/law_of_the_sea.html. The raw data and derived grids are also provided to the National Centers for Environmental Information (NCEI) in Boulder, CO and other public repositories within months of data collection and provide a wealth of information for scientific studies for years to come.

As the field components of ECS activities have concluded (for now), the focus of our effort has turned to working with the ECS Task Force, which is producing the U.S. submission for an extended continental shelf. This year's activities included reviewing and commenting on drafts of the submission and responding to various actions by other Arctic nations as they revised their submissions. Paul Johnson continues to update the Center's ECS website, https://maps.ccom.unh.edu/portal/home, and has been working closely with the Project Office and NCEI to ensure that all data collected by the Center over the past 20 years are fully available and appropriately attributed in the Project Office and NCEI databases.

Offshore Mineral/Marine Resources

Locating and exploiting marine minerals in complex continental shelf environments that are characterized by a wide range of sediment types and numerous physiographic features (geoforms) such as outcropping bedrock, reef structures, or eroding glacial deposits is often difficult. For example, continental shelves found in paraglacial environments (previously glaciated) are common in the U.S., dominating much of New England, the Pacific Northwest, and Alaska.

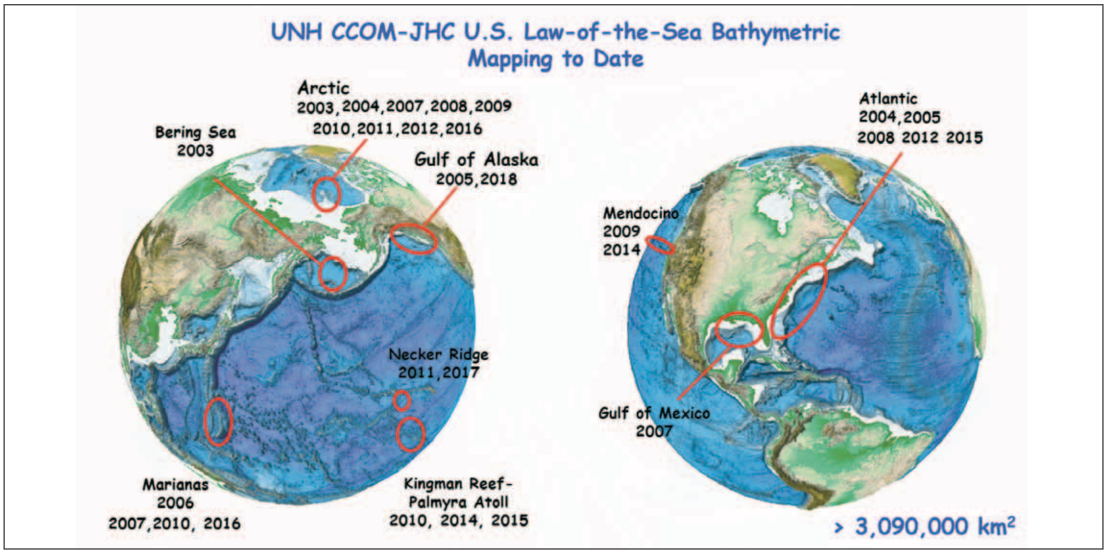


Figure ES-24. Summary of Law of the Sea multibeam sonar surveys mapped by the Center. The total area mapped represents more than 3.1 million square kilometers since 2003.

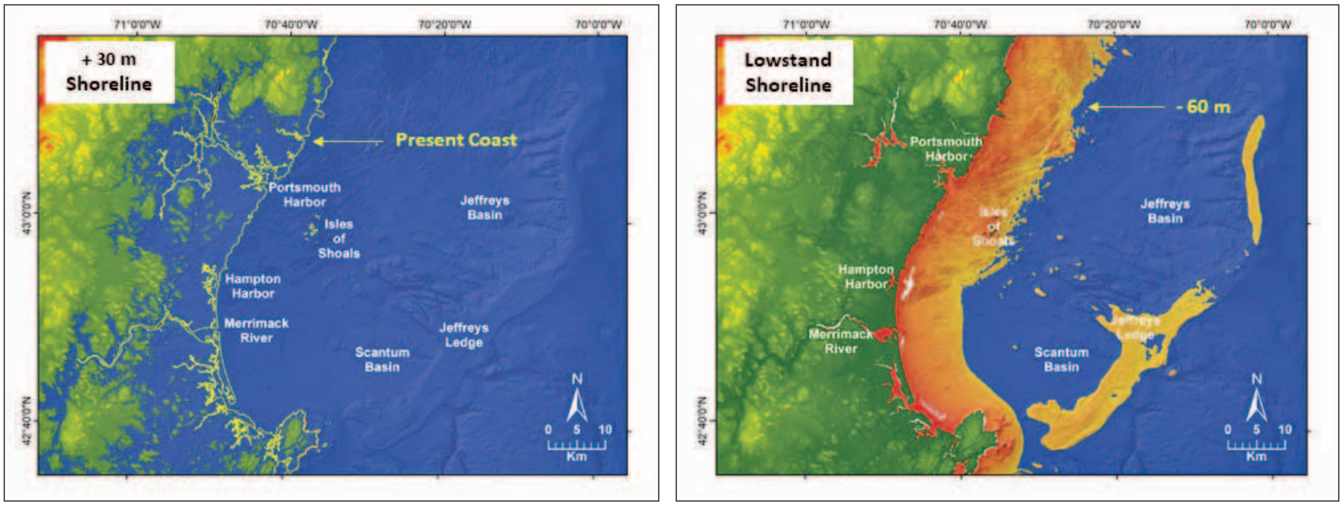


Figure ES-25. Changes in the location of the shoreline showing inundation of the upland ~13,000 years before present (ybp) (top figure) and exposure of the inner continental shelf ~12,500 ybp (lower figure) in the western Gulf of Maine (WGOM). Dark blue shows the ocean and shoreline. Positions of the shoreline were determined from the compilation of high-resolution lidar for the upland topography and multibeam echosounder surveys for the bathymetry, coupled with a well vetted sea level curve for the WGOM from the literature. Note the extent of inundation of the ocean resulting in the deposition of marine deposits. Also note the exposure of the inner shelf resulting in significant erosion and redistribution of the sediment deposits.

Glaciated environments on land typically have abundant sand and gravel resources and historically have been a major source of aggregates. Unfortunately, land resources are becoming depleted, creating the need to find and utilize new sources. Over the past decade, marine mineral resource studies carried out by the Center verified that many sand and gravel deposits located on the western Gulf of Maine (WGOM) continental shelf originated as glacial features. Unlike glacial deposits on land, these offshore sites are poorly mapped and have been exposed to the harsh marine environment including multiple sea-level transgressions and regressions (rise and fall), wave and tidal currents, and biologic modification (e.g., vegetated or bioturbated). Therefore, glacial deposits—which may contain sand and gravel resources—have been extensively eroded and the sediment redistributed, making identification and evaluation more difficult. Our research seeks to advance the understanding of the relationships between aggregate deposits and seafloor physiographic features in complex shelf environments. The work is focused on the WGOM which provides a variety of physiographic features or geoforms common to paraglacial environments around the world.

Previously, the Center developed high-resolution surficial geology maps depicting the bathymetry, major geoforms (physiographic features), and sediment distribution for the continental shelf off northern Massachusetts and New Hampshire extending seaward to Jeffreys Ledge and covering an area of ~3,250 km^2. More recently, we mapped changes in sea level over the last 13,000 years and the resultant transgressions (landward movement) and regressions (seaward movement) of the ocean that impacted the study area during that time were revealed. (Figure ES-25). During the present reporting period, a major field campaign was conducted directed at providing ground truth to support two priorities to further the understanding of the relationships between marine modified glacial deposits and marine mineral deposits (Figure ES-26). This large database will be processed and analyzed during the next reporting period.

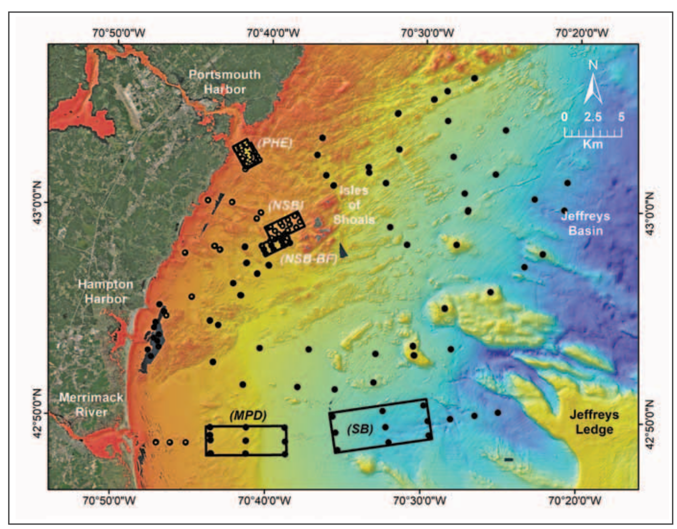


Figure ES-26. Location map for the sampling stations occupied during the 2022 field campaign. Black dots show the locations where bottom sediment samples were collected. Yellow dots represent locations where seafloor video was taken. The black rectangles show the locations of Reference Sites established for testing subbottom seismic and other acoustic systems.

Management of Living Marine Resources from ECS

Coastal regions are the powerful engines of our economy, providing billions of dollars in goods and services to the U.S economy. Hydrographic survey data and other marine mapping and charting data have tremendous potential to benefit NOAA marine resource management initiatives, in keeping with Integrated Ocean and Coastal Mapping (IOCM) best practices. Accurate seafloor characterization and multi-temporal data of marine living resources observed on the continental shelf are particularly valuable for assessing the efficacy of various restoration practices, and for monitoring changes at spatial extents and timescales that are relevant to management. To address these issues, the Center has embarked on several projects aimed at increasing our understanding of the changes in the seafloor—at various scales—over time.

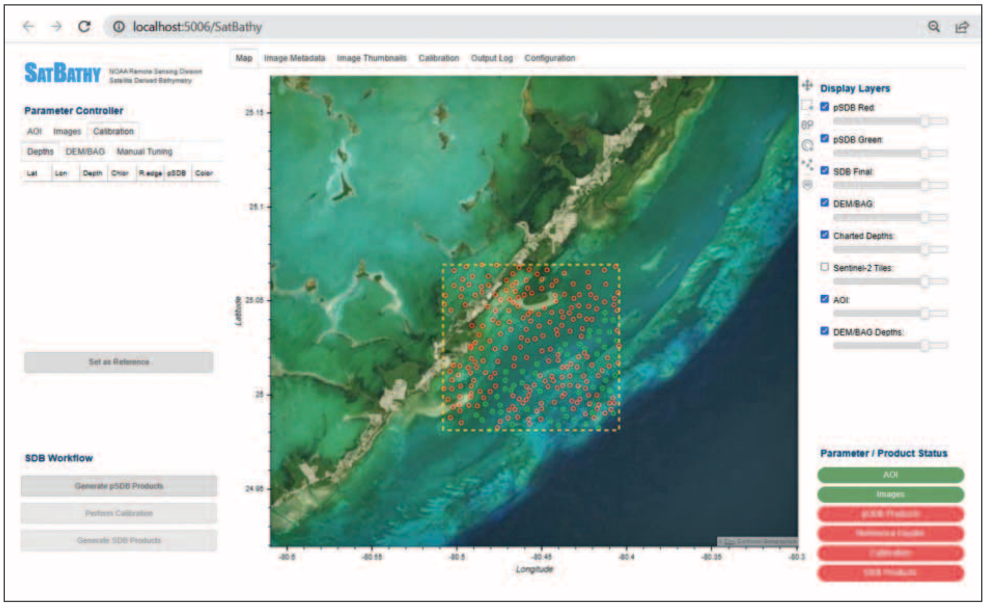


Figure ES-27. The true-false bathymetry segmentation algorithm and SDB geometric correction algorithm will be submitted to NOAA NGS for evaluation for possible inclusion in the NOAA SatBathy tool.

Multi-Modal Mapping for Change Detection on Coral Reefs

Obtaining accurate bathymetric data on the repeat cycles that are necessary for coral reef restoration site monitoring is nearly impossible using only single-source data. Hence, we have looked at methods of combining data from a wide range of platforms and sensors ranging from satellites to uncrewed aircraft systems (UAS), autonomous surface vehicles (ASVs), and diver-collected underwater imagery focused on a coral reef area in the lower Florida Keys. The bathymetric data from MBES and SBES are being integrated with SfM data from photo imagery, optimizing co-registration so that changes in corals can be mapped over time. Aerial imagery from UAS is being compared to the SfM results and used to test corrections for Satellite Derived Bathy-metry (SDB). Finally, the SDB data is being analyzed by Oregon State University graduate student Lt. Matt Sharr who is using machine learning techniques to segment the SDB data into true vs. false soundings (Figure ES-27).

Predicting Seaweed Habitat Types Using Supervised Machine Learning Classification

Identifying seafloor characteristics that can be used to detect areas of declining marine living resources is critical for their management. In temperate zones, kelp forests are ecologically significant and support many species of commercial importance. Due to anthropogenic activities, kelp forests are declining, yet there is evidence that pockets of healthy kelp forests exist. This project leverages ground-truth data and high-resolution bathymetric datasets collected over a decade by previous JHC-sponsored projects in combination with satellite imagery to identify areas of kelp forests.

In previous reports, Jenn Dijkstra and graduate student Matthew Tyler explored the use of the Seaweed Enhancing Index (SEI) produced from the Landsat 8 and 9 imagery to identify and locate submerged kelp beds with mixed results. In this reporting period, Dijkstra and Tyler worked on a macroalgae habitat classification using the Center developed Bathy-metry- and Reflectivity-based Estimator for Seafloor Segmentation. Geomorphic and seawater temperature rasters were uploaded into Google Earth Engine, where a Random-Forest-supervised classification was used to generate a raster predicting macroalgae habitat types across the extent of the imagery (Figure ES-28). Ground-truth work to determine the accuracy of these predictions is ongoing.

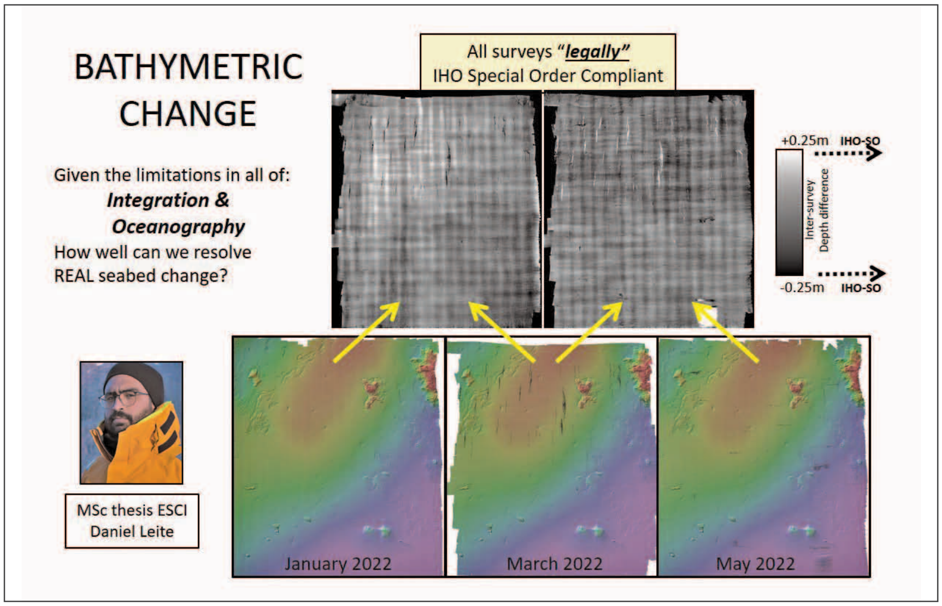


Figure ES-29. Bi-monthly bathymetric change. Lower: bathymetric surveys; upper: inter-survey difference map. The rectilinear grid represents the systematic biases due to changing sound speed in the area.

Improvements in Change Detection

As we strive to accurately measure and characterize the seafloor, we also must be cognizant that the seafloor can change—particularly in areas of strong currents and unconsolidated sediment. Therefore, as part of NOAA's mandate to both maintain chart veracity and to monitor dynamic seabed environments, change monitoring is a fundamental requirement.

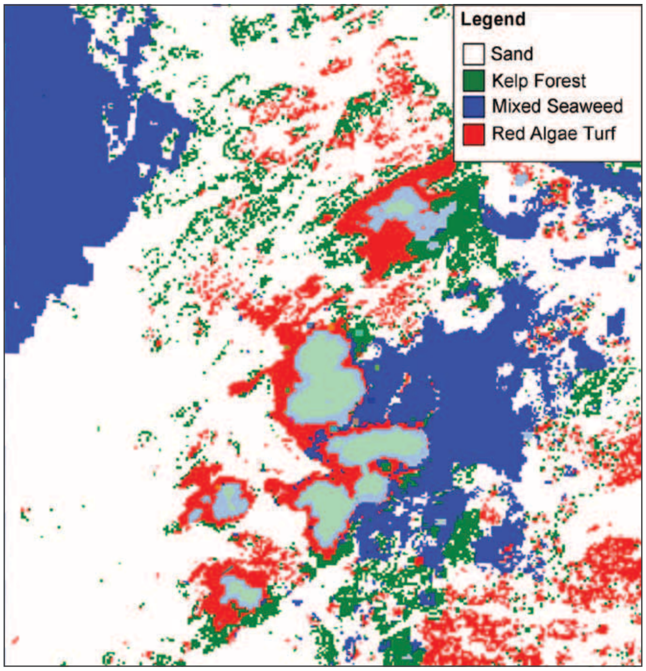


Figure ES-28. Random-Forest-supervised classification of macroalgae habitat types surrounding the Isles of Shoals. Light blue indicates areas of insufficient data.

However, separating real change from residual biases or intermittent bottom tracking errors in the survey data is a major limiting factor in confidently identifying such change, so we have also undertaken an effort to better understand the limits of our ability to measure change in both bathymetry and backscatter.

Bathymetric Change

To address the issue of limits of measurement of bathymetric change, graduate student Daniel Leite—under the supervision of John Hughes Clarke—has been conducting a series of bi-monthly repeat surveys in a sedimented seafloor region on the inner continental shelf off New Hampshire. These surveys have demonstrated that, while there are clearly seen systematic biases, inter-survey depth difference maps (Figure ES-29) suggest that a broad positive ridge in the sand sheet grew by about 10-15 cm from January to March, then deflated about the same amount from March to May. Such results, however, are close to or below the typical total-propagated vertical uncertainty inherent in the data. A much more detailed analysis of these surveys (continuing until summer 2023) will form the main part of Leite's thesis.

Backscatter Change

Building on instrumentation developed through parallel work funded through an ONR Task Force Ocean project (PI Tony Lyons), we have been monitoring long-term changes in seafloor backscatter on the New Hampshire inner shelf and relating these changes to both storm events and seasonal variability in micro-algae growth (Figure ES-30).

We have expanded this work to look at spatial variability around the instrument deployment tripod by conducting repeat surveys at two-month intervals (Figure ES-31). Initial results indicate a drop of about 2 dB toward the end of the winter wave period, followed by a ~3.5 dB rise through the storm-free summer period, but this work will be continued and expanded to include multispectral characterization of the seafloor as part of the masters' theses of Kaan Cav and Daniel Leite.

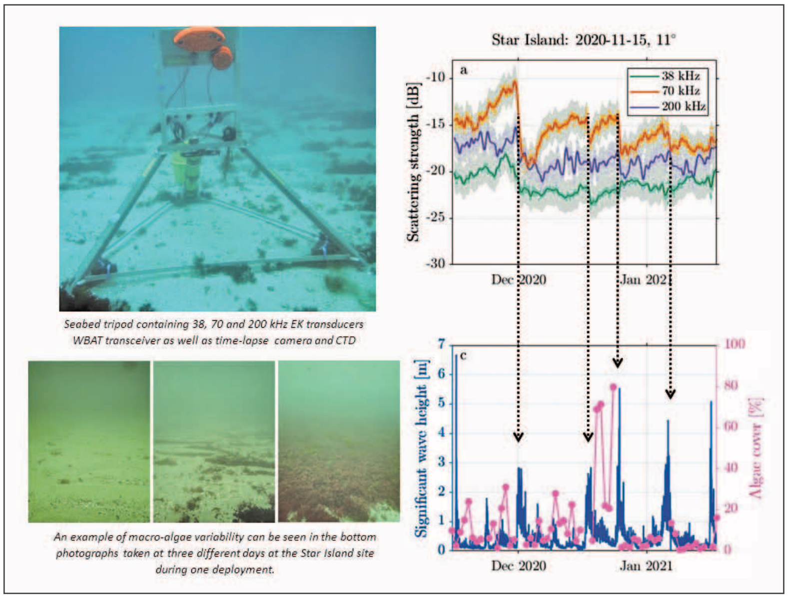


Figure ES-30. A two-month time series of bottom backscatter strength observations at three frequencies (38, 70 and 200 kHz) during the winter storm period. The abrupt changes (up to 10 dB) are clearly associated with storm wave events. That change, however, is strongly frequency dependent with the largest changes seen at 70kHz and much more subdued change at 200 kHz.

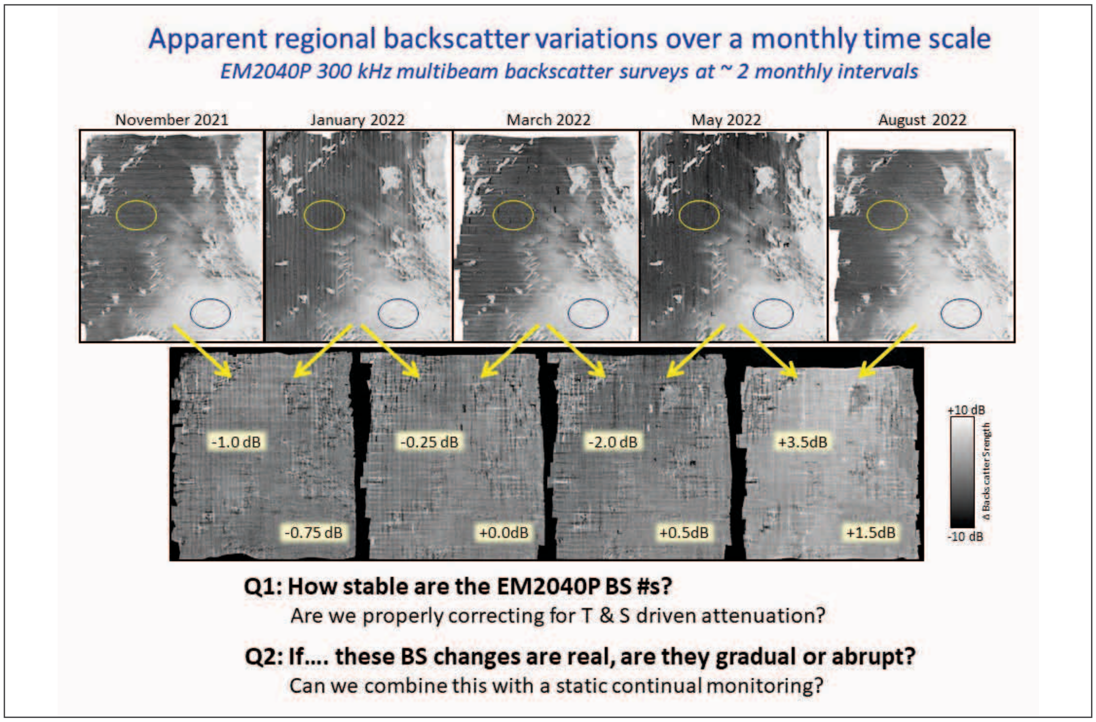


Figure ES-31. Top: 300 kHz backscatter strength mosaics showing the first five of the bi-monthly surveys (local mean ARC has been removed from the data to attempt a grazing-angle free image). Bottom: inter-survey differences. The lassoed areas represent two homogenous regions (high and low backscatter) and the #s in the lower figure indicate the average change over two months in grazing-angle-normalized backscatter strength in these regions.

Programmatic Priority 2

ADVANCE TECHNOLOGY FOR DIGITAL NAVIGATION

The second programmatic priority specified by the NOFO focuses on research to advance technology for digital navigation. Here the Center has undertaken a number of tasks that fall under the categories of delivery of bathymetric services from enterprise databases and innovative approaches to supporting precision navigation that include a range of innovative visualization techniques.

Delivery of Bathymetric Services from Enterprise Databases

As part of our efforts to Advance Technology to Map U.S. Waters, we have been asked to explore new approaches to the delivery of bathymetric services from enterprise databases such as the National Bathymetric Source—under development at NOAA's Office of Coast Survey—to provide a continuously updated, resolved estimate of bathymetry for all national hydrographic holdings. In addition to the internal database, NBS provides a publicly available abstract known as BlueTopo.

Access to this data set can be complex. Therefore, in the current reporting period, Paul Johnson—working with Glen Rice from NOAA's Office of Coast Survey—has been developing web accessible data services for the BlueTopo data set. The initial goal of this effort is to assess the ease of BlueTopo data tile transfers, data preparation and staging for serving, and the creation of publicly available web services hosted through the Center's ESRI GIS Enterprise Portal server (Figure ES-32).

In addition to our efforts supporting the National Bathymetric Source, the Center has, since its inception in 2003, played a key role in the Open Navigation Surface Working Group (ONSWG) and the Bathymetric Attributed Grid (BAG) file format defined through their efforts. The development of the BAG format was successful enough to be adopted by the IHO as standard S-102 (gridded bathymetry), and ongoing development of new approaches and facilities—for example, the metadata layer required by the National Bathymetric Source. In this reporting period, Brian Miles and Glen Rice worked closely together to generate a repository pull request for the new API, and Brian Calder and Rice led a sub-working group to develop new recommendations for managing coordinate reference systems (CRS) in BAG files.

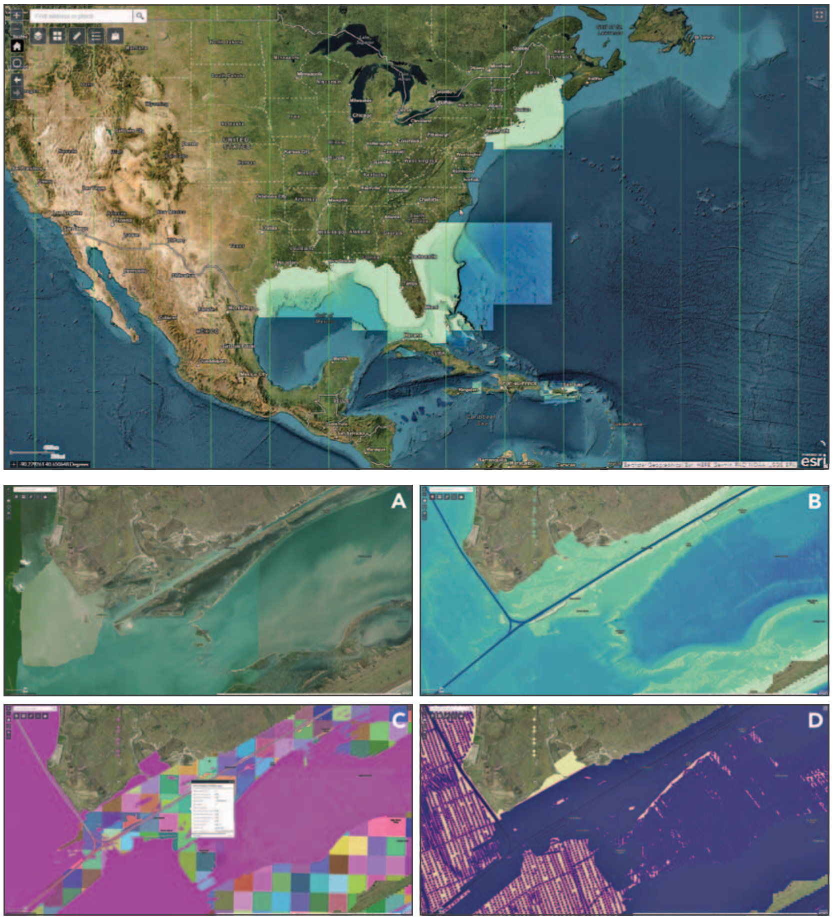


Figure ES-32. Top: Visualization of the BlueTopo Elevation layer using the Center's GIS Portal to show the current geographic bounds of the dataset.Bottom: Web services for the BlueTopo dataset hosted through the Center's GIS Portal. A. ESRI imagery layer served through the Center's webapp, B. Elevation with Hillshade, C. BlueTopo contributor's layer with interactive pop-ups, and D. BlueTopo uncertainty.

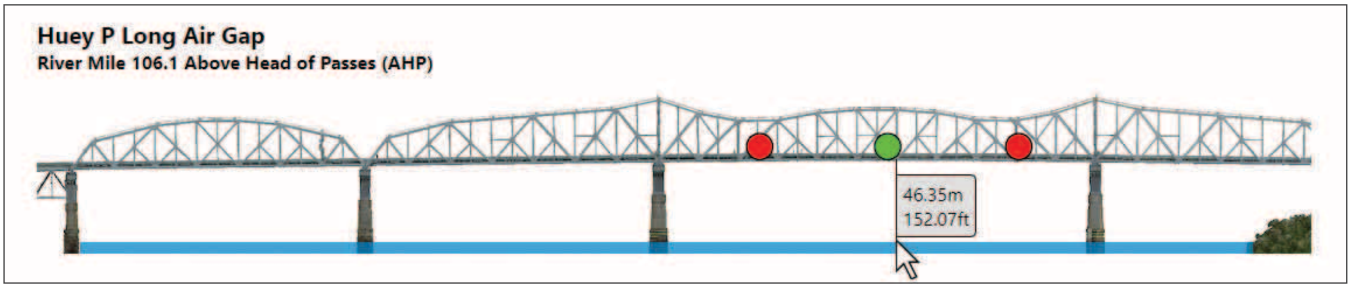


Figure ES-33. Example of the new dynamic air gap visualization, which can show air gap values anywhere under any span of the bridge.

Innovative Approaches to Support Precision Navigation

The Center has long pressed for innovative ways to bring high-resolution bathymetric and other data sets to the navigator in real-time. This has come to fruition in NOAA's new efforts to support Precision Marine Navigation. Several of our efforts to support Precision Navigation include:

Interactive Air Gap Visualizations

To aid precision navigation and safe passage of larger vessels, NOAA has been installing air gap sensors on bridges that cross important, high traffic waterways, such as the Mississippi River. These sensors report the distance to the water below, and this value is adjusted by a known offset to reflect the air gap at specific reference

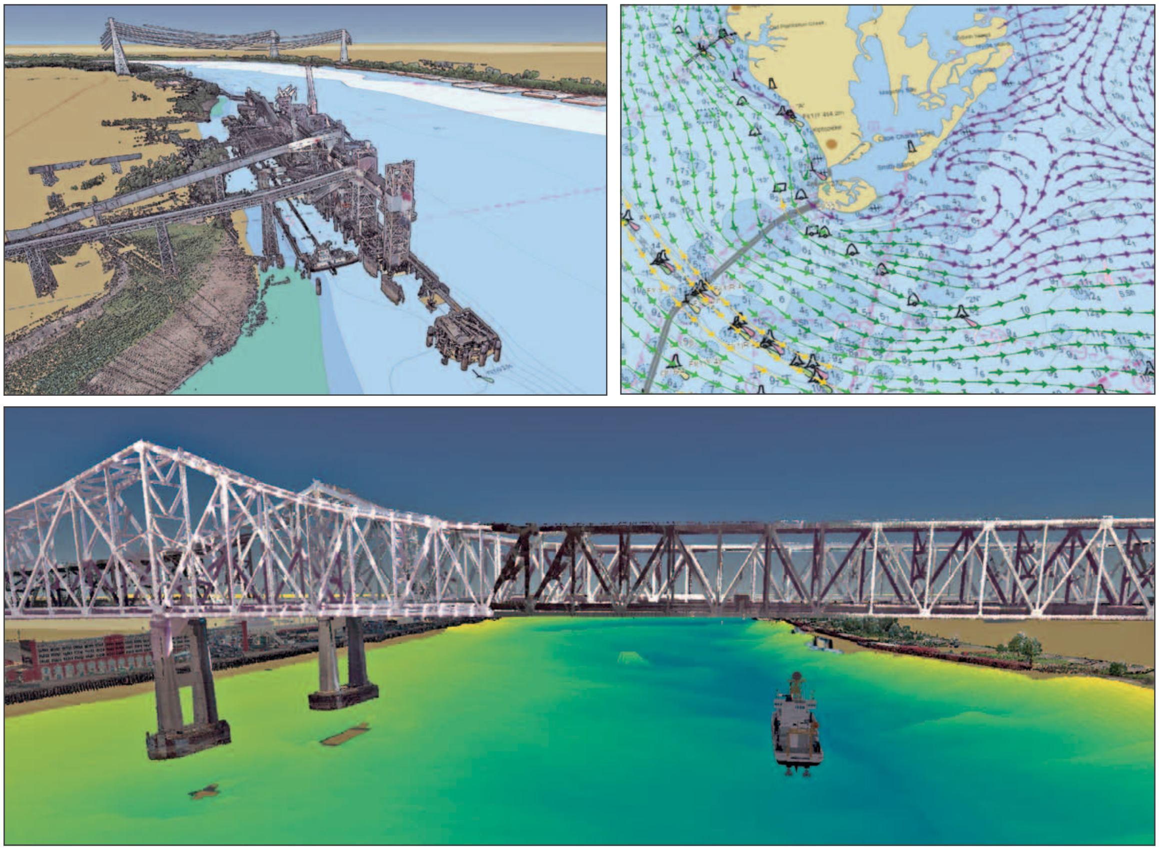


Figure ES-34. Example of the additional details of shoreline infrastructure that are provided by Mississippi River shoreline lidar points drawn over an ENC (top-left) and 3D based web map showing tiled S-111 Surface Current streamlines of CBOFS2 model output, drawn over NOAA ENC tiles (top-right); and high-resolution S-102 bathymetry as a 3D surface, with user-uploaded 3D model of ship (bottom).

Figure ES-35. The Visualization Lab's semi-immersive tiled display running a head-tracked bridge simulator with accessory monitor that can display ECDIS (reflecting a virtual ship's position/orientation) and augmented camera feeds generated from a virtual camera.

point on the bridge. Currently, only a single air gap value at the reference point is provided to pilots via the NOAA PORTS website, but Tom Butkiewicz and Ilya Atkin of the Center's Visualization Lab have developed an interactive web visualization that can replace these static air gap diagrams with a dynamic visualization that provides air gap values anywhere under a bridge (Figure ES-33).

Web-based 3D Visualization of Next Generation S-100 Datasets

The Center's Visualization Lab previously presented a web-based 3D visualization interface for viewing large point clouds on top of imagery from NOAA's ENCs web service. During this reporting period, the interface was further expanded to incorporate other datasets relevant to the Lower Mississippi River Precision Navigation Project, including lidar data and current information (Figure ES-34).

Evaluating Augmented Camera Feeds for Marine Navigation

As we develop tools to support precision navigation, we are also exploring the role that augmented reality may play. In past reports, we have demonstrated the performance and safety benefits of AR head-up displays of navigational information. For augmented camera feeds, as long as the perspective of the mariner and the camera are roughly the same (e.g., both at center of bridge, looking forward), there should be minimal cognitive load in terms of spatial transformations required when compared to a track-up ECDIS presentation (based on the Center's previous studies into handheld perspective displays). However, it is unknown how closely this approximates the benefits of head-coupled AR where no spatial transformations are required. To answer the questions, "Are these augmented camera feed systems good enough?" or "Do we really need head-up displays?", the Visualization Lab is preparing to run a new experiment to identify the performance differences between these two methods of providing navigational information to mariners (Figure ES-35).

Visualization and Integration of Bathymetric Data Quality on ENCs

The Center has long been looking at approaches to visualize uncertainty on charts. In the previous reporting periods, Christos Kastrisios, Colin Ware, Brian Calder, and Tom Butkiewicz—in collaboration with UNH Research Associate Professor Emeritus Lee Alexander and Rogier Broekman of the Nether-

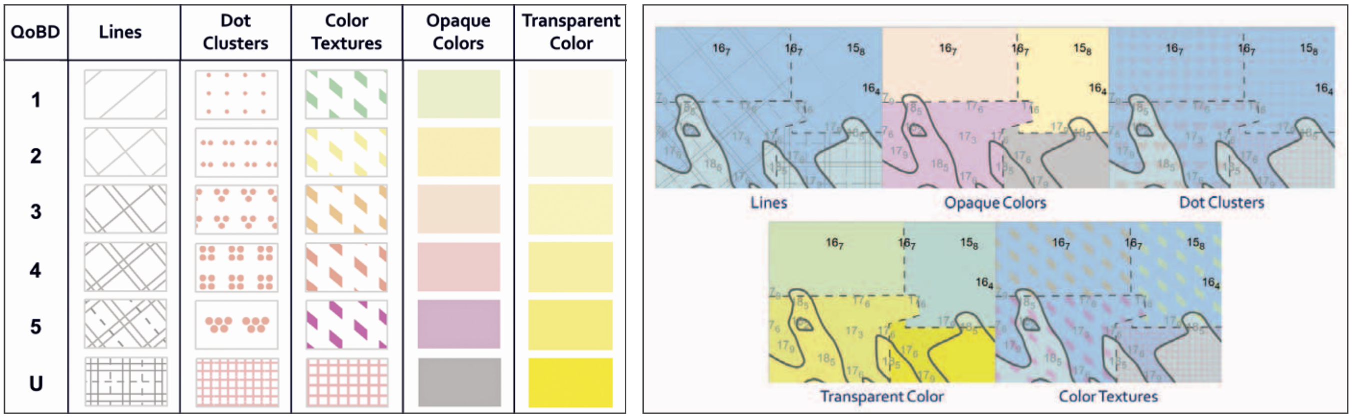


Figure ES-36. Left: The tested coding schemes. Right: Coding schemes over a chart section.

lands Ministry of Defense—reviewed the deficiencies of the current CATZOC symbology and integration in route planning and execution. After researching approaches to the display of bathymetric uncertainty, the team established the requirements that the new visualization method should satisfy in order to be effective for the application. The result of these efforts has been the proposed use of a sequence of textures created by combining two or more visual variables (Figure ES-36), followed by a survey of users presented with this approach. In the current reporting period, the research team published the results of the survey and the experiment and presented them at IHO relevant working groups (WG) meetings (i.e., Data Quality WG, Nautical Cartography WG, and S-101 Project Team meetings). The two proposed countable textures have been well received by the community, and the S-101 project team has decided to further test them in S-100 ECDIS simulators and at sea. To support this, the

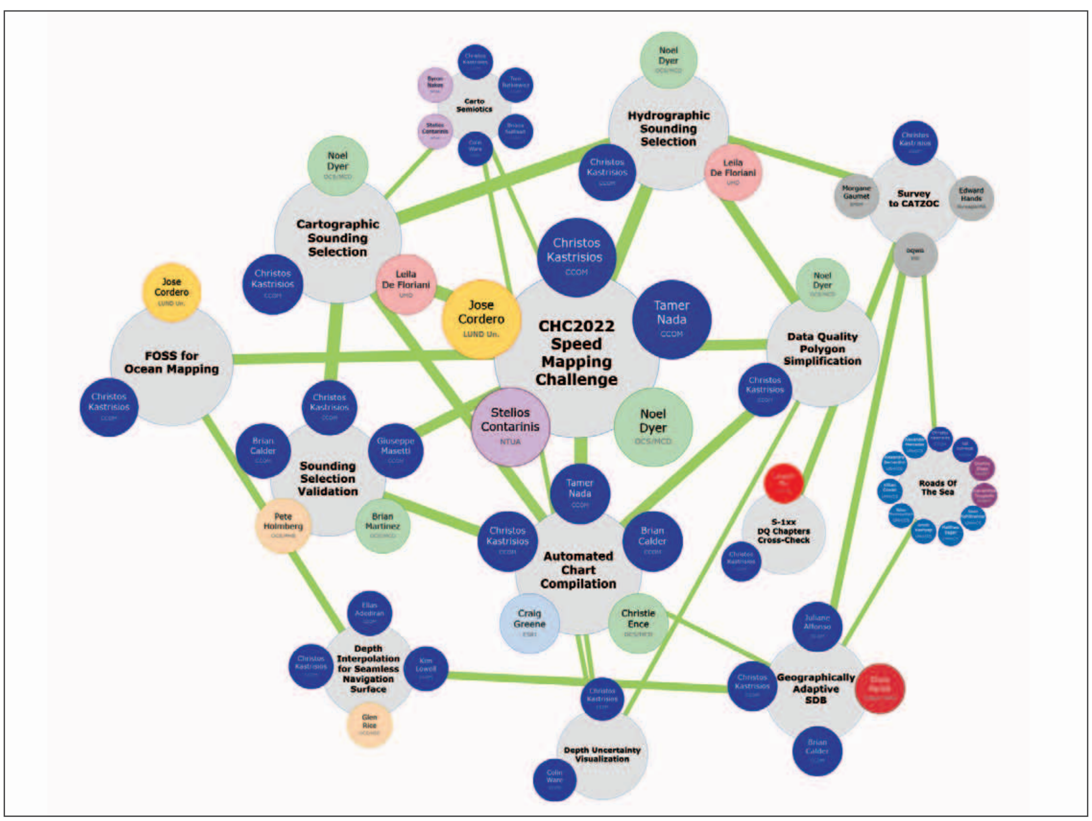


Figure ES-37. The constellation of research projects for chart compilation.

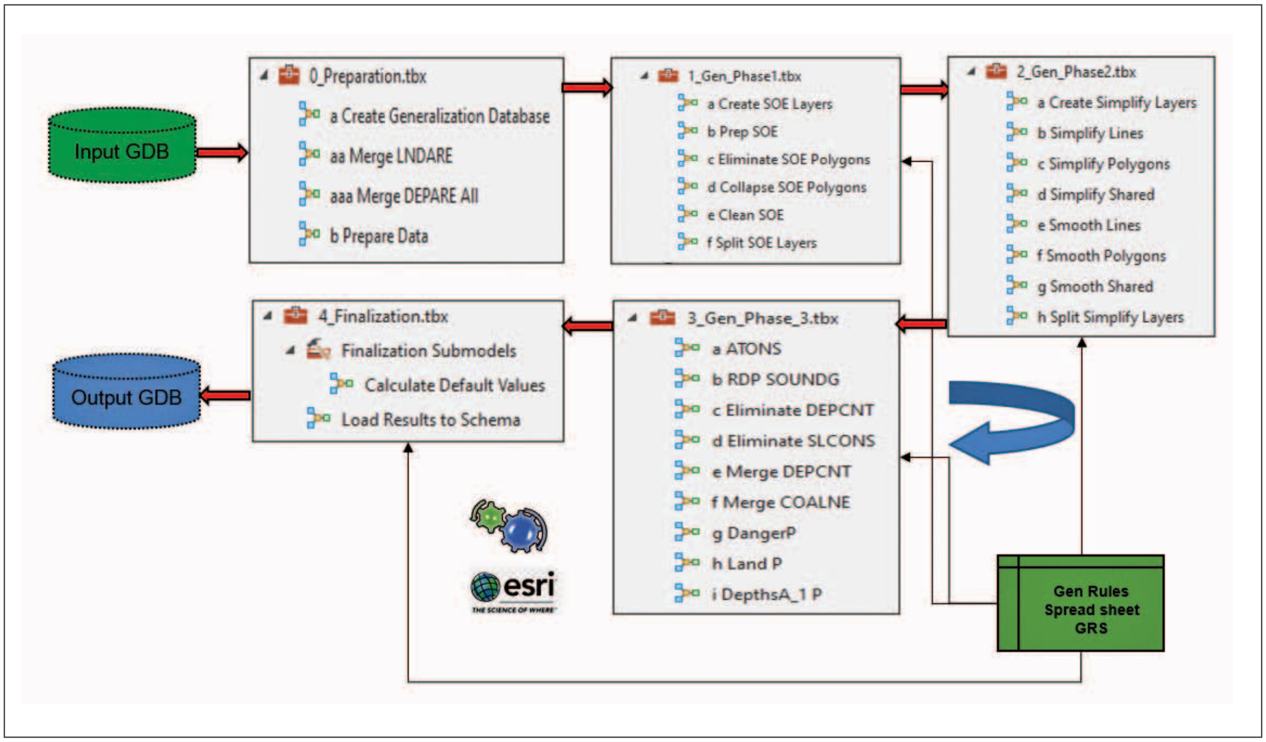


Figure ES-38. The Automated Nautical Generalization Model.

research team is investigating methods to translate the two textures into an appropriate format for use with ECDIS as well as fine tuning them so that they become part of the S-100 IHO Geospatial Information Registry's Portrayal register.

Managing and Transforming Data to Navigation Products: Computer Cartography

Over the years, nautical chart creation has evolved from a hand-drawn, manual process to a computer-assisted, semi-automated process. This has unquestionable advantages, especially relating to the access and transformation of data from enterprise databases and the ability to update and disseminate information to the end user more rapidly. Notwithstanding the technological advances, many of the tasks in chart compilation remain manual, time consuming, and prone to human error. Unquestionably, chart compilation—as with any other mapping product—is a largely subjective process and subject to interpretable guidelines, which is why products from two compilers, two production branches, or two Hydrographic Offices often look and feel very different to the end-user. To address these issues, the Center has undertaken a number of projects under the broad title of "computer cartography" with the hope that objective and uniform results may be achieved with generalization algorithms that contain contextual knowledge of cartographic practice and which can consistently be applied by an informed rule-based system to the chart.

The constellation of these projects (Figure ES-37), under the leadership of Christos Kastrisios with numerous collaborators from both NOAA and the international community, includes efforts focused on automated sounding selection techniques, sounding selection verification methods, automatic change detection tools to aid in the sounding selection process, tools to harmonize data quality metrics, and tools to assess their self-consistency and explain the differences of datasets produced by one or more adjacent Hydrographic Offices. An overarching goal of these projects is the automated compilation of ENCs. The team has made much progress in this area (Figure ES-38)—including winning an international "Speed Mapping Challenge" competition organized by the Canadian Hydrographic Service—to develop a prototype cartographic production chain using open data and free software.

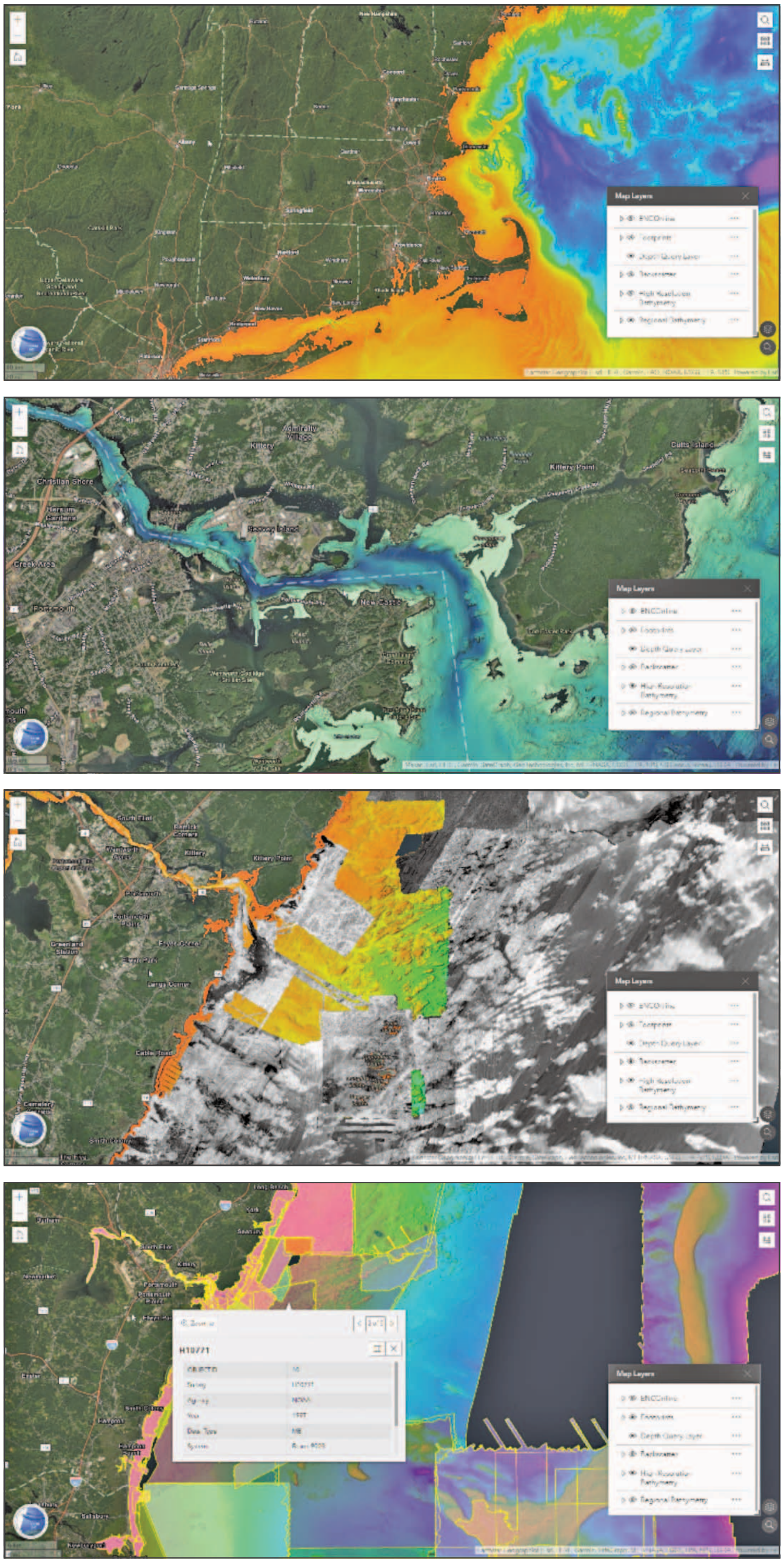


Figure ES-39. Examples of different datasets available through the Western Gulf of Maine, Long Island, and Southern New England Compilation (http://bit.ly/3G2Rrjc). Top: Regional shaded-relief bathymetry with a color palette that dynamically adjusts. Second from top: High resolution bathymetry with a blue-green color palette.

Enhanced Web Services for Data Management – Enterprise Geospatial Platform

The Center has maintained an online data access portal using different technologies since 2011. During the summer of 2022 Johnson and the IT team installed a new server to host the primary GIS portal. The new server is a significant upgrade from the previous server which had provided services for the Center for the last four years. Among the data sets provided on this new portal is the very popular Western Gulf of Maine, Long Island, and Southern New England map service. This compilation incorporates all publicly available bathymetry and backscatter, and tracks the contributing sources to the synthesis using survey domains with embedded metadata (Figure ES-39).

Programmatic Priority 3

DEVELOP AND ADVANCE MARINE GEOSPATIAL AND SOUNDSCAPE EXPERTISE

The final prescribed programmatic priority calls for the development and advancement of marine geospatial and soundscape expertise. Our efforts to support this programmatic priority focus on our research into the contribution of echosounders to the ocean soundscape (and in particular the impact of multibeam sonars on marine mammals) as well as our educational and outreach programs.

Contribution of Echo Sounders to Ocean Soundscape: Measuring MBES Radiation Patterns

NOAA's effort to map and characterize the seafloor relies on a wide variety of active acoustic systems such as multibeam echosounders (MBES), wide-bandwidth single- and split-beam echosounders, and sub-bottom profilers, among others. With the Presidential Memorandum on Ocean Mapping and the release of the NOAA Blue Economy Strategic Plan, activities in seafloor mapping and characterization are expected to increase, and likely so will the usage of active acoustic systems. With that expected increase comes the responsibility to ensure that these systems are used in a manner that protects marine life while preserving commerce, research, and exploration. Maintaining this balance requires knowledge of both the anthropogenic sound generated by commonly used scientific echosounders, and knowledge of the impact of these systems on the local soundscape.

The soundscape, formally defined by ISO 18405, is the characterization of the ambient sound in terms of spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field. By utilizing soundscape information, we can better understand environmental impacts on ocean dynamics, biodiversity and ecosystem health, and the risk of anthropogenic impacts on marine life. The Center currently conducts research into the modeling and measurement of scientific echosounder transmit radiation patterns, and practical analysis of their potential impact in soundscape studies.

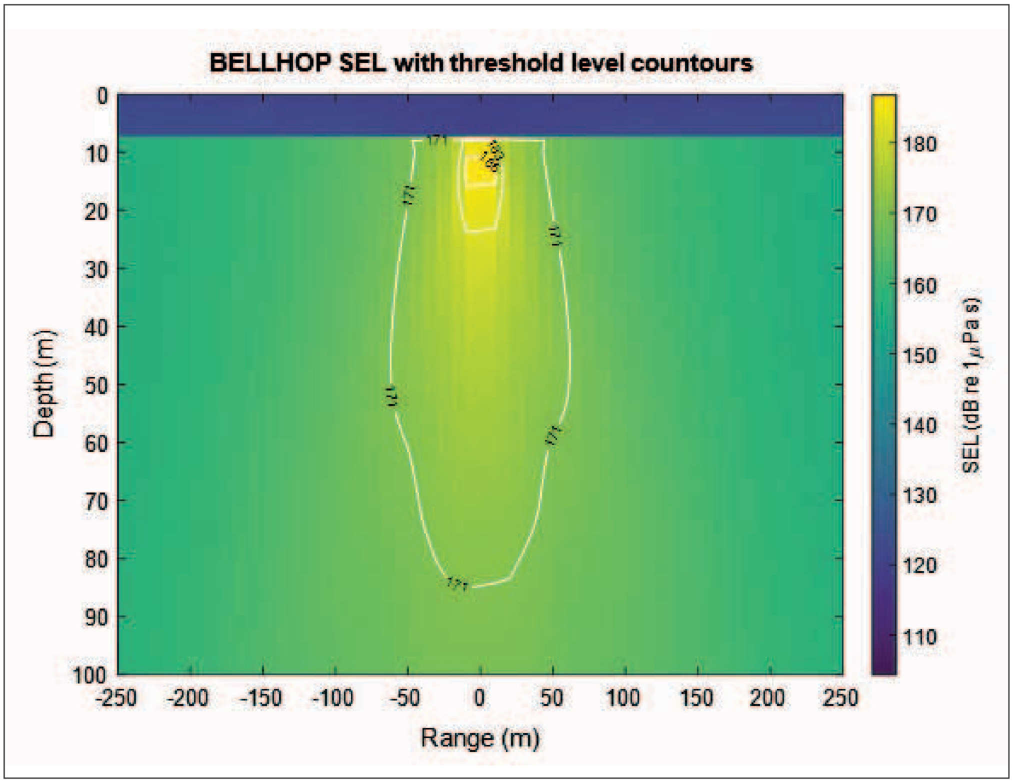


Figure ES-40. Cumulative SEL field for a 3000s transect during a simulated MBES survey. Contours corresponding to threshold levels from Southall, et al. (2007) have been overlain to demonstrate the effective safety radii for various animal/exposure criteria.

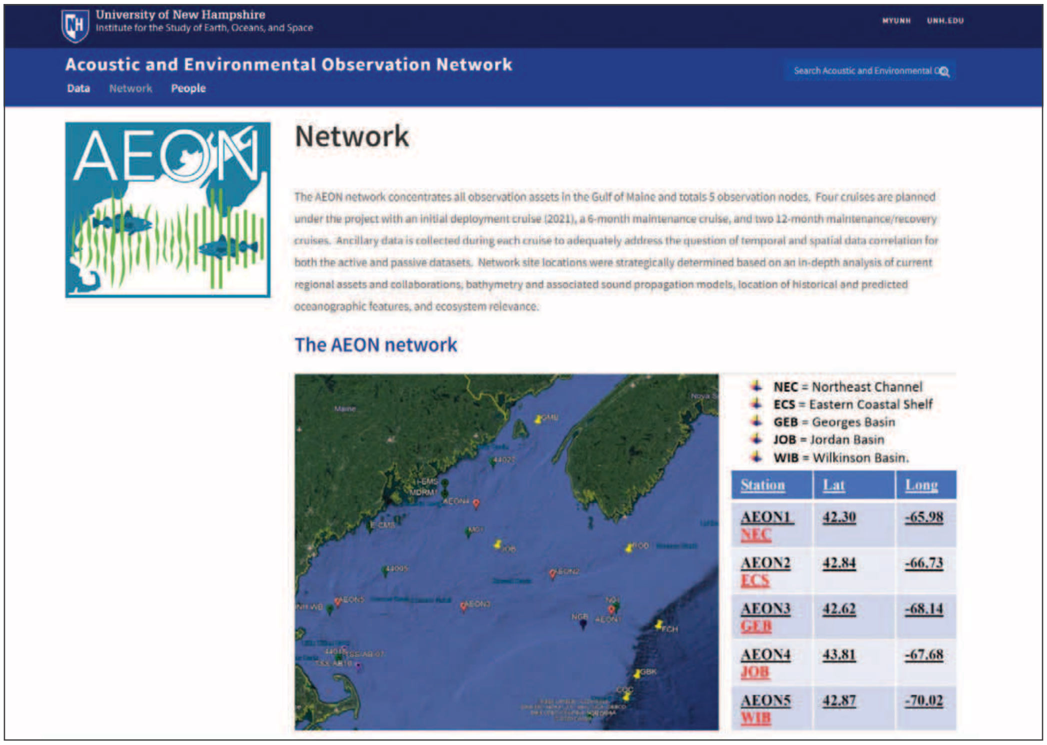


Figure ES-41. Website for the Acoustic and Environmental Observation Network (AEON), https://eos.unh.edu/aeon.

Source Modeling of Scientific and Hydrographic Systems

MBES have unique design and transmission characteristics that present challenges when attempting to model and regulate their impact. Historically, environmental regulations used simplified models of MBES which focused on the narrow main swath or transmit beam when assessing these systems for potential for impact. However, modern systems feature widely varying operational characteristics such as pulse length, bandwidth, and waveform that change in response to the survey environment. These dynamic parameters and complex transmit radiation patterns have made it difficult to accurately model and measure MBES systems. To better improve our understanding of the potential impact of these systems, the Center has conducted research on novel ways to measure deep-water MBES transmit radiation patterns as well as research to improve MBES modeling capabilities. Included in this is Mike Smith's work with IFREMER's Xavier Lurton to explore new approaches to modeling MBES and working with the international community to explain the differences between MBES and other sonar and seismic systems. These studies have important ramifications regarding how regulators view the impact of MBES on the marine environment (Figure ES-40).

Passive Acoustics and Acoustics Training

Jennifer Miksis-Olds, a research professor at the Center and the director of the new UNH Center for Acoustics Research and Education (CARE), is contributing to our ocean mapping mission through multiple projects that broaden the scope of ocean bottom mapping to water column, habitat, and soundscape mapping, as well as aiming to build a strong program for training in acoustics at UNH. For the most part, these efforts are funded by other sources, but still contribute to the overall aims and objectives of the Center and, in particular, to our efforts to understand the impact of our sonar systems on the marine environment. Among Miksis-Olds' projects are the monitoring of soundscapes from deepwater ecosystems in the Atlantic which includes the establishment of the Acoustic and Environmental Observation Network (AEON) in the northwest Atlantic (Figure ES-41), and the establishment of a new instrumented cabled acoustic array in the Gulf of Maine off Appledore Island. CARE is also working hard to build up acoustic expertise at the UNH and develop a series of comprehensive training programs in ocean acoustics, including a new Graduate Certificate in Acoustics.

Education and Outreach

Students and Curriculum

In addition to our research efforts, education and outreach are also fundamental components of our program. Our educational objectives are to produce a highly trained cadre of students who are critical thinkers able to fill positions in government, industry, and academia and become leaders in the development of new approaches to ocean mapping. We had 41 graduate students enrolled in the Ocean Mapping program in 2022, including six GEBCO students, four NOAA Corps officers, and one NOAA physical scientist (some as part-time). This past year, we graduated four masters' students and one Ph.D. student, while five GEBCO students received Certificates in Ocean Mapping.

We have continued our evolution to using Python as the preferred programing language for ocean mapping courses and continue to develop a Python E-Learning course and Python-based lab modules that are better aligned and sequenced with material taught in class. Our newly developed "Introduction to Ocean Mapping" course is explicitly for undergraduates and continues to be successful. This year, two students who took the course as undergraduates joined our graduate program. Once again, our Summer Hydrographic Field Course was well-subscribed and produced important hydrographic results in an area around Hampton Harbor, NH where high-resolution data did not previously exist (Figure ES-42). Each student was involved in the planning and execution of the survey, processing of the collected data, and report writing (Figure ES-43).

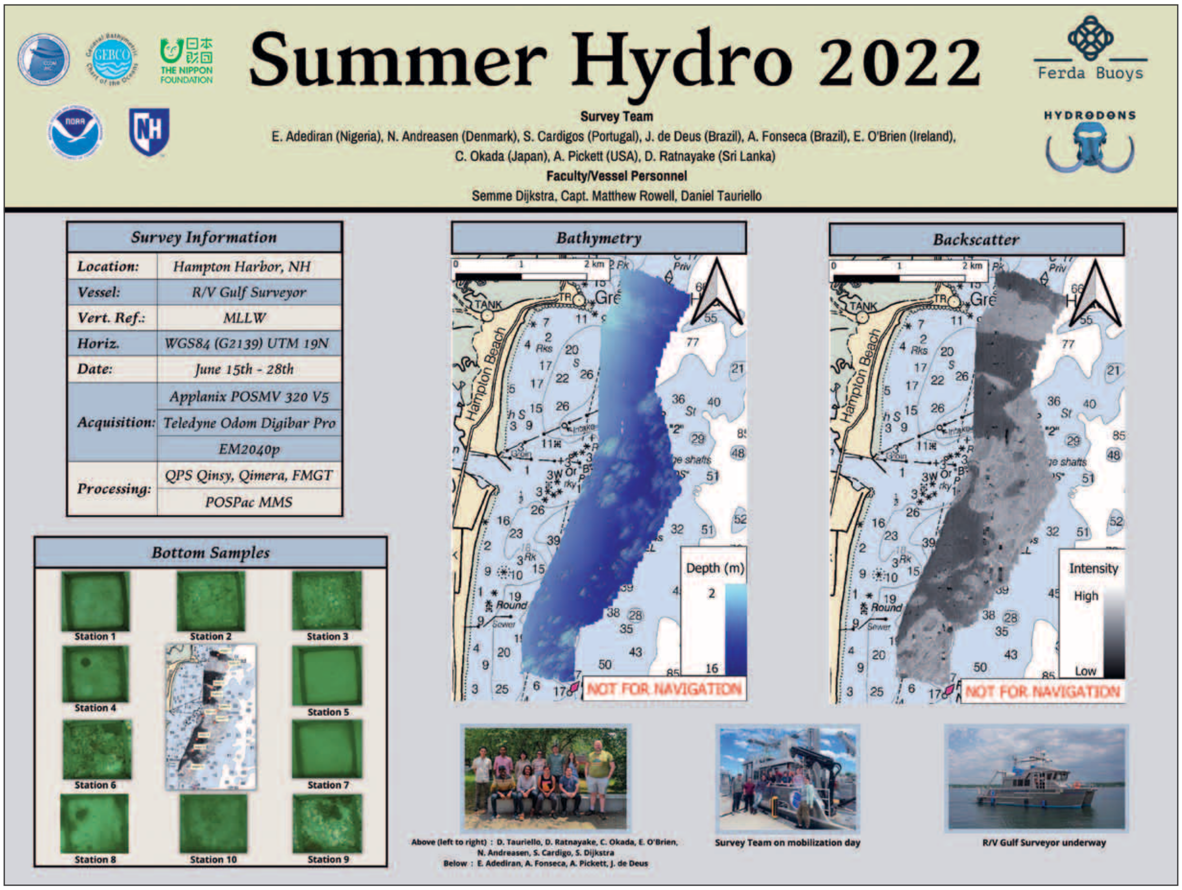


Figure ES-42. Poster representing the priority survey area near Hampton Beach, NH.

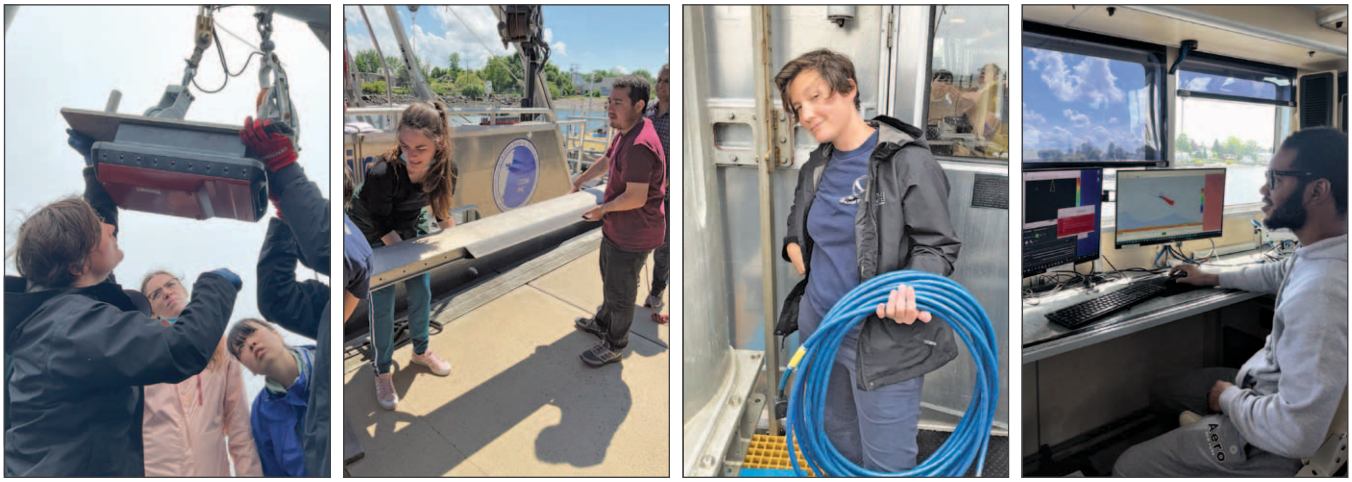


Figure ES-43. Scenes from the 2022 Summer Hydrographic Field Course.

Nippon Foundation/GEBCO Training Program

In 2004, the Center was selected to host the Nippon Foundation/GEBCO Bathymetric Training Program through an international competition that included leading hydrographic education centers worldwide. UNH was awarded a grant from the General Bathymetric Chart of the Oceans (GEBCO) to create and host a one-year graduate level training program that has been renewed now for 19 years. To date, 113 students from 46 coastal states have participated (Figure ES-44). This year's students are from Australia, Ireland, Kenya, Morocco, Nigeria, and Tanzania—significantly building capacity in African coastal states.

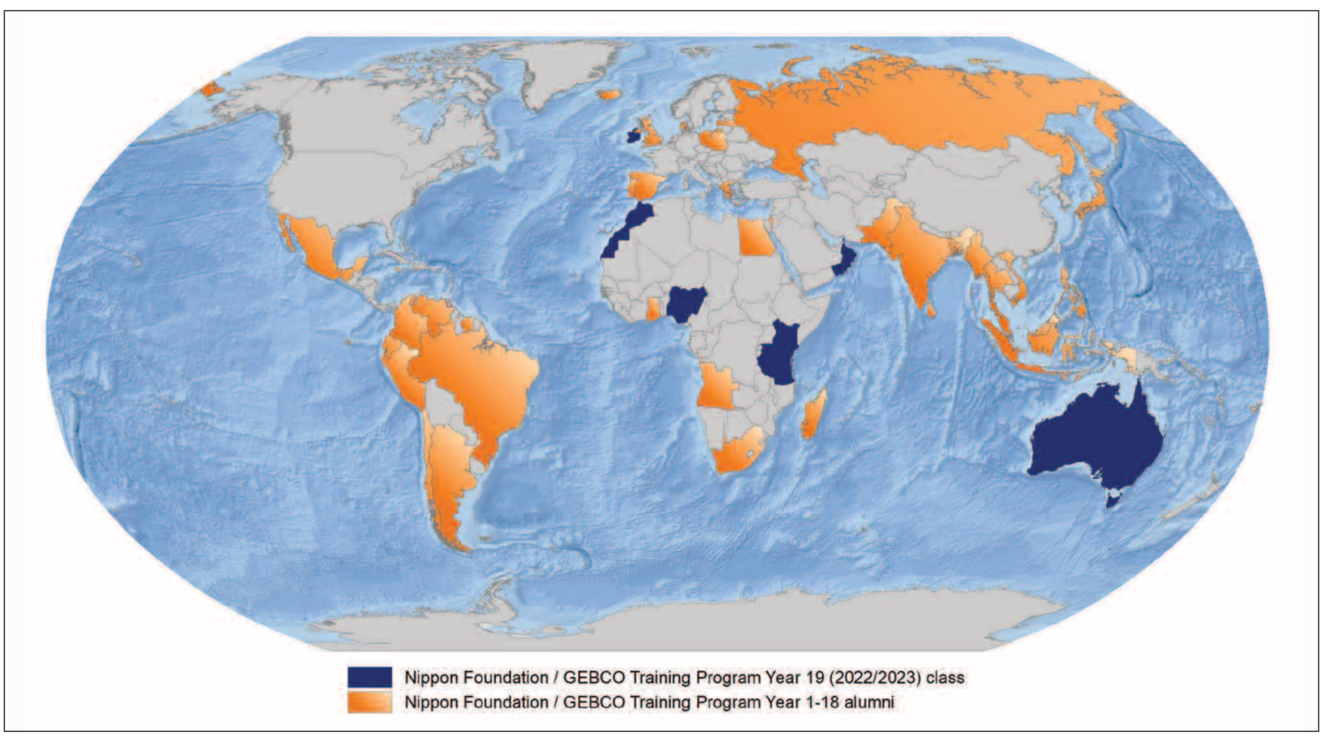


Figure ES-44. Distribution of Nippon Foundation GEBCO Training Program students.

Outreach

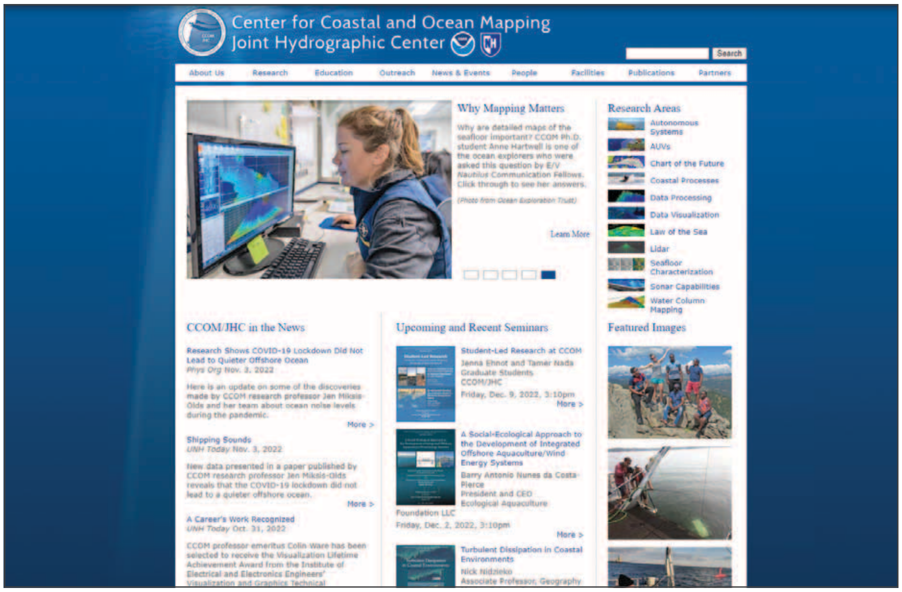


Figure ES-45. The homepage of the Center's website.

We recognize the interest that the public takes in our work and our responsibility to explain the importance of what we do to those who ultimately bear the cost. One of the primary methods of this communication is our website, ccom.unh.edu (Figure ES-45). There were 117,673 views from 43,215 unique visits to the site in 2022 from 193 different countries. We also recognize the importance of engaging young people in our activities to ensure that we will have a steady stream of highly skilled workers in the field. To this end, we have upgraded other aspects of our web presence including a Vimeo site, a Facebook presence, and a Twitter feed. Our Vimeo site has 177 videos that have been viewed a total of 56,883 times (1,883 in 2022). Our seminar series featured 34 seminars in 2022. The seminars are widely advertised and webcast, allowing NOAA employees and our industrial partners around the world to listen and participate in the seminars. They are also recorded and uploaded to Vimeo.

Along with our digital and social media presence, we also maintain an active "hands-on" outreach program of tours and activities for school children and the general public. Under the supervision of our full-time outreach manager, Tara Hicks-Johnson, several large and specialized events are organized by the Center outreach team, including numerous SeaPerch ROV events and the annual UNH "Ocean Discovery Day." These, of course, have still been impacted by the COVID pandemic, but we did have visits from 665 K-12 students this year. The large Ocean Discovery Day event, which attracts thousands of people to the lab over a weekend, was cancelled once again this year due to COVID concerns, but we did return to an in-person SeaPerch Competition this past April with teams from New Hampshire, Maine and Massachusetts competing for the chance to compete at the International SeaPerch Challenge (Figure ES-46).

Figure ES-46. Scenes from the 2022 Seacoast SeaPerch Regional Competition.

Center activities were featured in many international, national, and local media outlets this year including: *The New York Times*, *National Geographic*, *Hydro International*, *WebWire*, *Directions Magazine*, *Work-Boat*, Hawaii Public Radio, *Science X Daily*, *Marine Technology News*, *Boston Chronicle*, *Phys.org*, *Deep Blue*, *Popular Science*, and the *New Hampshire Union Leader*.

The highlights presented here represent only a fraction of the activities of the Joint Hydrographic Center in 2022; more detailed discussions of these and other activities, as well as a complete list of the Centers' publications and presentations can found in the full progress reports available at ccom.unh.edu/reports.

Figure ES-47. Sunset over the Center's home—the Jere A. Chase Ocean Engineering Lab on UNH's Durham campus.

On 4 June 1999, the Administrator of NOAA and the President of the University of New Hampshire signed a memorandum of understanding that established a Joint Hydrographic Center (JHC) at the University of New Hampshire. On 1 July 1999, a cooperative agreement was awarded to the University of New Hampshire that provided the initial funding for the establishment of the Joint Hydrographic Center. This Center, the first of its kind to be established in the United States, was formed as a national resource for the advancement of research and education in the hydrographic and ocean-mapping sciences. In the broadest sense, the activities of the Center are focused on two major themes: a research theme aimed at the development and evaluation of a wide range of state-of-the-art hydrographic and ocean-mapping technologies and applications, and an educational theme aimed at the establishment of a learning center that promotes and fosters the education of a new generation of hydrographers and ocean-mapping scientists to meet the growing needs of both government agencies and the private sector. In concert with the Joint Hydrographic Center, the Center for Coastal and Ocean Mapping was also formed in order to provide a mechanism whereby a broader base of support (from the private sector and other government agencies) could be established for ocean-mapping activities.

The Joint Hydrographic Center was funded by annual cooperative agreements from July 1999 until 31 December 2005. In 2005, a five-year cooperative agreement was awarded with an ending date of 31 December 2010. In January 2010, a Federal Funding Opportunity was announced for the continuation of a Joint Hydrographic Center beyond 2010. After a national competition, the University of New Hampshire was selected as the recipient of a five-year award, funding the Center for the period of 1 July 2010 until December 2015. In March 2016, a Federal Funding Opportunity was announced for the continuation of a Joint Hydrographic Center beyond 2015. Again, after a national competition, the University of New Hampshire was selected as the recipient of a five-year award, funding the Center for the period of 1 January 2016 until 31 December 2020. Given the closures and constraints of the COVID-19 pandemic, the efforts of this grant continued under a no-cost extension until 31 December 2021. In the spring of 2020, a new Notice of Funding Opportunity (NOFO) was issued by NOAA for the operation and maintenance of a Joint Hydrographic Center as authorized in the Ocean and Coastal Mapping Integration Act and the Hydrographic Services Improvement Act. The University of New Hampshire submitted a proposal under this solicitation and, after a national competition, was informed in the fall of 2020 that they were selected to continue to operate the Joint Hydrographic Center for the period of 2021 to 2025 under NOAA GRANT NA20NOS4000196. This report represents the progress during the second year of effort on NOAA GRANT NA20NOS4000196. A formal federally-mandated, web-based, Research Performance Progress Report (RPPR) has also been submitted for this project.

This report is the twenty-eighth in a series of what were, until December 2002, semi-annual progress reports. Since December 2002, the written reports have been produced annually. Copies of reports from all previous grants to the Joint Hydrographic Center and more in-depth information about the Center can be found on the Center's website, http://www.ccom.unh.edu. More detailed descriptions of many of the research efforts described herein can be found in the individual progress reports of Center researchers, which are available on request.

Infrastructure

Personnel

The Center has grown, over the past 23 years, from an original complement of 18 people to more than 100 faculty, staff, and students. Our faculty and staff have been remarkably stable over the years, but as with any large organization, there are inevitably changes. This past year, we saw the departure of **Briana Sullivan** from the research staff, and the addition of **Jenna Hare** as a new postdoctoral research associate and recent CCOM Ph.D. student—now Dr.—**Elizabeth Reed-Weidner** as a new research scientist. We have also seen transitions among the NOAA employees seconded to the lab with **Adam Gibbons** and **Abby Letts** joining the NOAA team at the Center and **Derek Sowers** leaving NOAA to join the Ocean Exploration Trust and **Meme Lobecker** leaving NOAA to join Kongsberg Maritime. Interestingly, both Derek and Meme will maintain offices at the Center while representing these Industrial Partners.

Faculty

Thomas Butkiewicz, Director of the Visualization Lab, specializes in creating highly interactive visualizations, which allow users to perform complex visual analysis on geospatial datasets through unique, intuitive exploratory techniques. His research interests include virtual and augmented reality, stereoscopic displays, human visual perception, and image processing/computer vision. His current research projects focus on using augmented reality to aid safe and efficient marine navigation, immersive telepresence, methods for integrating advanced data visualization methods within electronic navigational chart displays, and designing and developing new exploratory visual analysis environments for dynamic 4D ocean simulations. This includes experimentation with new visualization and interaction techniques as well as new hardware combinations, such as stereoscopic displays with multi-touch surfaces.

Brian Calder graduated with an M.Eng. (Merit) and a Ph.D. in electrical and electronic engineering in 1994 and 1997, respectively, from Heriot-Watt University in Scotland. His doctoral research was in Bayesian statistical methods applied to processing of sidescan sonar and other data sources, and his post-doctoral research included investigation of high-resolution seismic reconstruction, infrared data simulation, high-resolution acoustic propagation modeling and real-time assessment of pebble size distributions for mining potential assessment. Brian joined the Center as a founding member in 2000, where his research has focused mainly on understanding, utilizing and portraying the uncertainty inherent in bathymetric data, and in efficient semi-automatic processing of high-density multibeam echosounder data. He is a Research Professor, and Associate Director of CCOM, the Chair of the Open Navigation Surface Working Group, and a past Associate Editor of *IEEE Journal of Oceanic Engineering*.

Jenn Dijkstra received her Ph.D. in zoology in 2007 at the University of New Hampshire, has a B.A. from the University of New Brunswick (Canada), and a M.S. in marine biology from the University of Bremen (Germany). She has conducted research in a variety of geographical areas and habitats, from polar to tropical and from intertidal to deep-water. Her research incorporates observation and experimental approaches to address questions centered around the ecological causes and consequences of human-mediated effects on benthic and coastal communities. Her research at the Center focuses on the use of remote sensing (video and multibeam) to detect and characterize benthic communities. In 2022 Jenn was promoted to Research Associate Professor.

Semme Dijkstra is a hydrographer from the Netherlands with hydrographic experience in both the Dutch Navy and industry. He completed his Ph.D. at the University of New Brunswick, Canada, where his thesis work involved artifact removal from multibeam-sonar data and development of an echosounder processing and sediment classification system. From 1996 to 1999, Semme worked at the Alfred Wegner Institute in Germany where he was in charge of their multibeam echosounder data acquisition and processing. Semme's current research focuses on applications of single-beam sonars for seafloor characterization, small object detection and fisheries habitat mapping. In 2008, Semme was appointed a full-time instructor and took a much larger role in evaluating the overall Center curriculum, the development of courses and teaching. In 2020, the University re-classified Semme's position to that of Clinical Professor, recognizing his active role in teaching and curriculum development.

Jim Gardner is a marine geologist focused on seafloor mapping, marine sedimentology, and paleoceanography. He received his Ph.D. in marine geology from the Lamont Doherty Earth Observatory of Columbia University in 1973. He worked for 30 years with the Branch of Pacific Marine Geology at the U.S. Geological Survey in Menlo Park, CA where he studied a wide variety of marine sedimentological and paleoceanographic problems in the Bering Sea, North and South Pacific Ocean, northeast Atlantic Ocean, Gulf of Mexico, Caribbean and Mediterranean Seas, and the Coral Sea. He conceived, organized, and directed the eight-year EEZ-SCAN mapping of the U.S. Exclusive Economic Zone using GLORIA long-range sidescan sonar in the 1980s; participated in four Deep Sea Drilling Project cruises, one as co-chief scientist; participated in more than 50 research cruises, and was Chief of Pacific Seafloor Mapping from 1995 to 2003, a project that used high-resolution multibeam echosounders to map portions of the U.S. continental shelves and margins. He also mapped Lake Tahoe in California and Crater Lake in Oregon. Jim was the first USGS Mendenhall Lecturer, received the Department of Interior Meritorious Service Award and received two USGS Shoemaker Awards. He has published more than 200 scientific papers and given an untold number of talks and presentations all over the world. Jim retired from the U.S. Geological Survey in 2003 to join the Center. Jim was an Adjunct Professor at the Center from its inception until he moved to UNH in 2003 when he became a Research Professor affiliated with the Earth Science Department. Jim officially retired in 2020 but remains an Emeritus Research Professor.

John Hughes Clarke is a professor jointly appointed in the departments of Earth Sciences and Mechanical Engineering. For 15 years before joining the Center, John held the Chair in Ocean Mapping at the University of New Brunswick in Canada where he was a Professor in the Department of Geodesy and Geomatics Engineering. During that period, he also ran the scientific seabed mapping program on board the CCGS Amundsen undertaking seabed surveys of the Canadian Arctic Archipelago. As a complement to his research and teaching, he has acted as a consultant, formally assessing the capability of the hydrographic survey vessels of the New Zealand, Australian, British and Dutch Navies as well as the U.S. Naval Oceanographic Office TAGS fleet. For the past 21 years, John, together with Larry Mayer, Tom Weber, and Dave Wells, has delivered the Multibeam Training Course that is presented globally three times per year. This is the world's leading training course in seabed survey and is widely attended by international government and commercial offshore survey personnel as well as academics. John was formally trained in geology and oceanography in the UK and Canada (Oxford, Southampton, and Dalhousie). He has spent the last 27 years, however, focusing on ocean mapping methods. His underlying interest lies in resolving seabed sediment transport mechanisms.

Christos Kastrisios graduated from the Hellenic Naval Academy (HNA) in 2001 as an Ensign of the Hellenic Navy Fleet with a B.Sc. in Naval Science. After his graduation, he served aboard Frigate HS *Aegean* and Submarines HS *Protefs* and HS *Poseidon*, mostly as the Navigator and Sonar Officer, and participated in several deployments at sea. In 2008, he was appointed to the Hellenic Navy Hydrographic Service (HNHS) where he served in various positions including that of deputy chief of the Hydrography Division and the Head of the Geospatial Policy Office; he also represented his country at international committees and working groups. In 2013, he received a master's degree in GIS from the University of Maryland at College Park; in 2015, he graduated from the Hellenic Naval War College; and in 2017, he was awarded a Ph.D. in cartography from the National Technical University of Athens (NTUA) for his work on the scientific aspects of the Law of the Sea Convention. From 2014 to 2017, he worked as a part-time lecturer in GIS and Cartography at the HNA and NTUA. In September 2017, he started employment at the Center as a post-doc researcher focusing on data generalization, chart adequacy, and computer-assisted nautical cartography. He joined the Center's full-time staff as a Research Scientist in 2018, became an Assistant Research Professor in 2020, and was promoted to Research Associate Professor in 2023.

Anthony P. Lyons received a B.S. degree (*summa cum laude*) in physics from the Henderson State University, Arkadelphia, AR, in 1988 and M.S. and Ph.D. degrees in oceanography from Texas A&M University, College Station, TX, in 1991 and 1995, respectively. He was a scientist at the SACLANT Undersea Research Centre, La Spezia, Italy, from 1995 to 2000, where he was involved in a variety of projects in the area of environmental acoustics. Tony was awarded, with the recommendation of the Acoustical Society of America, the Institute of Acoustics' (U.K.) A.B. Wood Medal in 2003. He is a Fellow of the Acoustical Society of America and a member of the IEEE Oceanic Engineering Society. He is also currently an Associate Editor for the *Journal of the Acoustical Society of America* and is on the Editorial Board for the international journal *Methods in Oceanography*. Tony conducts research in the field of underwater acoustics and acoustical oceanography. His current areas of interest include high-frequency acoustic propagation and scattering in the ocean environment, acoustic characterization of the seafloor, and quantitative studies using synthetic aperture sonar.

Giuseppe Masetti received an M.Eng. in ocean engineering (ocean mapping option) from the University of New Hampshire in 2012, and a master's degree in marine geomatics (with honors) and a Ph.D. degree in system monitoring and environmental risk management from the University of Genoa, Italy, in 2008 and 2013, respectively. In addition, he graduated (with honors) in political sciences from the University of Pisa, Italy, in 2003 and in diplomatic and international sciences from the University of Trieste, Italy, in 2004. Giuseppe achieved the FIG/IHO Category A certification in 2010, and he is a member of IEEE and The Hydrographic Society of America. He served with the Italian Navy from 1999 and has been Operations Officer aboard the hydrographic vessels ITN *Aretusa* and ITN

Magnaghi. Beginning in August 2013, he was a Tyco Post-Doctoral Fellow with the Center, where he focused on signal processing for marine target detection. He joined the faculty as a Research Assistant Professor in January 2016 and, in 2020, moved to the Danish Hydrographic Service. Giuseppe retains his affiliation and continues to work closely with the Center as an Adjunct Associate Research Professor.

Larry Mayer is the founding Director of the Center for Coastal and Ocean Mapping and Co-Director of the Joint Hydrographic Center. Larry's faculty position is split between the Ocean Engineering and Earth Science Departments. His Ph.D. is from the Scripps Institution of Oceanography (1979), and he has a background in marine geology and geophysics with an emphasis on seafloor mapping, innovative use of visualization techniques, and the remote identification of seafloor properties from acoustic data. Before coming to New Hampshire, he was the NSERC Chair of Ocean Mapping at the University of New Brunswick where he led a team that developed a worldwide reputation for innovative approaches to ocean mapping problems.

Jennifer Miksis-Olds is the Director of the Center for Acoustics Research and Education, also holding a research position in the Center for Coastal and Ocean Mapping. Jen is the University Member Representative and on the Board of Trustees of the Consortium for Ocean Leadership. She is a member of the Scientific Committee of the International Quiet Ocean Experiment Program and serves as a Scientific Advisor to the Sound and Marine Life Joint Industry Program (International Oil & Gas Producers) which is devoted to the study of effects of sound on marine organisms. Jen was the recipient of an Office of Naval Research Young Investigator Program award in 2011 and the Presidential Early Career Award in Science and Engineering in 2013. She is also a newly elected Fellow in the Acoustical Society of America. Jen received her A.B. *cum laude* in biology from Harvard University, her M.S. in biology from the University of Massachusetts Dartmouth. She was a guest student at Woods Hole Oceanographic Institution, and then received her Ph.D. in biological oceanography from the University of Rhode Island.

David Mosher is a Professor in the Department of Earth Sciences and the Center for Coastal and Ocean Mapping at the University of New Hampshire. He graduated with a Ph.D. in geophysics from the Oceanography Department at Dalhousie University in 1993, following an M.Sc. in Earth sciences from Memorial University of Newfoundland in 1987 and a B.Sc. at Acadia in 1983. In 1993, he commenced work on Canada's West Coast at the Institute of Ocean Sciences, in Sidney on Vancouver Island, studying marine geology and neotectonics in the inland waters of British Columbia. In 2000, he took a posting at Bedford Institute of Oceanography. His research focus was studying the geology of Canada's deep-water margins, focusing on marine geohazards using geophysical and geotechnical techniques. From 2008 to 2015, he was involved in preparing Canada's submission for an extended continental shelf under the Law of the Sea (UNCLOS) and, in this capacity, he led four expeditions to the high Arctic. In 2011, he became manager of this program and was acting director from 2014. In 2015, he joined UNH to conduct research in all aspects of ocean mapping, focusing on marine geohazards and marine geoscience applications in Law of the Sea. He has participated in over 45 sea-going expeditions and was chief scientist on 27 of these. In 2018 David took a leave of absence from UNH to represent Canada as a Commissioner on the Limits of the Continental Shelf.

Yuri Rzhanov, a research professor, has a Ph.D. in physics and mathematics from the Russian Academy of Sciences. He completed his thesis on nonlinear phenomena in solid-state semiconductors in 1983. Since joining the Center in 2000, he has worked on a number of signal processing problems, including construction of large-scale mosaics from underwater imagery, automatic segmentation of acoustic backscatter mosaics, and accurate measurements of underwater objects from stereo imagery. His research interests include the development of algorithms and their implementation in software for 3D reconstruction of underwater scenes, and automatic detection and abundance estimation of various marine species from imagery acquired from ROVs, AUVs, and aerial platforms.

Gabriel Venegas is a research assistant professor in the Center for Acoustics Research and Education and Center for Coastal and Ocean Mapping. He conducts research in the fields of underwater acoustics, acoustical oceanography, and plant and animal bioacoustics. Specific areas of interest include sediment acoustics in hydrodynamically and biologically dynamic environments, understanding the effect organic carbon sequestration has on sediment geoacoustic properties, and the acoustic scattering from underwater flora and fauna. Dr. Venegas received his B.S. degree *magna cum laude* in mechanical engineering from Boston University, and his Ph.D. degree in mechanical engineering with a focus on physical acoustics from The University of Texas at Austin. He is a member of the Acoustical Society of America, the Coastal Estuarine Research Federation, and the American Geophysical Union.

Larry Ward has an M.S. (1974) and a Ph.D. (1978) from the University of South Carolina in Geology. He is a research associate professor with the Center for Coastal and Ocean Mapping and the Department of Earth Sciences. His primary research interests include coastal and inner shelf morphology and sedimentology. His most recent research focuses on seafloor characterization and the sedimentology, stratigraphy, and Holocene evolution of nearshore marine systems. Present teaching topics focus on continental margins

Colin Ware received a Ph.D. in psychology from the University of Toronto in 1980 and an M.Math in Computer Science from the University of Waterloo in 1982. He is Professor (Emeritus) of Computer Science and Director (Emeritus) of the Data Visualization Research Lab at the Center for Coastal and Ocean Mapping. He is the author of *Visual Thinking for Design* (2008) which discusses the science of visualization and has published more than 140 research articles on the subject of data visualization. His other book, *Information Visualization: Perception for Design* (4th Edition 2020) has become the standard reference in the field. Fledermaus, a visualization package initially developed by him and his students, is now the leading 3D visualization package used in ocean mapping applications. He currently works on methods and tools for visualizing ocean and littoral data, including the representation of wind, wave and current information on electronic chart displays, the visualization of the state of global seafloor mapping to support the Seabed 2030 project, and methods for improving the processing of multibeam sonar data.

Research Scientists and Staff

Roland Arsenault joined the Center in 2000 after receiving his bachelor's degree in computer science and working as a research assistant with the Human Computer Interaction Lab at the Department of Computer Science at the University of New Brunswick. A longtime member of the Center's Data Visualization Research Lab, Roland combines his expertise with interactive 3D graphics with his experience working with various mapping-related technologies to help provide a unique perspective on some of the challenges undertaken at the Center. With the Center's addition of Autonomous Surface Vehicles (ASVs), Arsenault has become the ASV Lab's chief software engineer—developing a cross-platform ocean mapping focused framework for the Center's ASV fleet.

KG Fairbarn holds a B.A. in geography from UC Santa Barbara and an M.S. in remote sensing intelligence from the Naval Postgraduate School. He has worked extensively at sea as a researcher, marine technician, captain, and research diver. He most recently worked as the oceanographic specialist aboard the University of Delaware's R/V *Hugh R. Sharp*. At UNH, KG works as an engineer on the autonomous surface vehicle project and will assist with the multibeam advisory committee duties.

Will Fessenden is the Center's systems manager and has provided workstation, server, and backup support to the Center's researchers and staff since 2005. Will has a B.A. in political science from the University of New Hampshire and has more than 15 years of experience in information technology.

Jenna Hare is a postdoctoral research associate at the Center. Her research interests lie at the intersection of the fields of physical oceanography and underwater acoustics. Her current project focuses on measuring the temporal change in sound scattering from the seafloor and its relationship with environmental variability. Dr. Hare received her Ph.D. from Dalhousie University (Canada) in oceanography studying sediment transport processes using high-frequency acoustics.

Tara Hicks Johnson has a B.S. in geophysics from the University of Western Ontario, and an M.S. in Geology and Geophysics from the University of Hawaii at Manoa where she studied meteorites. In June 2011, Tara moved to New Hampshire from Honolulu, Hawaii, where she was the outreach specialist for the School of Ocean and Earth Science and Technology at the University of Hawaii at Manoa. While there she organized educational and community events for the school, including the biennial Open House event, and ran the Hawaii Ocean Sciences Bowl, the Aloha Bowl. She also handled media relations for the School and coordinated television production projects.

Tara also worked with the Bishop Museum in Honolulu developing science exhibits, and at the Canadian Broadcasting Corporation in Toronto (where she was born and raised).

Tianhang Hou was a research associate with the University of New Brunswick Ocean Mapping for six years before coming to UNH in 2000. He has significant experience with the UNB/OMG multibeam processing tools and has taken part in several offshore surveys. He is currently working with Briana Sullivan on the charting projects.

Kevin Jerram completed his M.S. Ocean Engineering (Ocean Mapping option) in 2014 through the Center, where his research focused on detection and characterization of marine gas seeps using a split-beam scientific echo sounder. He has participated in seafloor and midwater mapping expeditions throughout the Atlantic, Pacific, and Arctic Oceans in support of Center projects, and works with the NSF-funded Multibeam Advisory Committee to enhance mapping data quality across the US academic fleet. Before joining the Center, he received a B.S. in mechanical engineering from UNH and worked in engineering positions for Shoals Marine Laboratory and Ocean Classroom Foundation.

Paul Johnson has an M.S. in Geology and Geophysics from the University of Hawaii at Manoa where he studied the tectonics and kinematics of the fastest spreading section of the East Pacific Rise. Since finishing his master's degree, he has spent time in the remote sensing industry processing, managing, and visualizing hyperspectral data associated with coral reefs, forestry, and research applications. More recently, he was the interim director of the Hawaii Mapping Research Group at the University of Hawaii where he specialized in the acquisition, processing, and visualization of data from both multibeam mapping systems and towed near bottom mapping systems. Paul started at the Center in June of 2011 as the data manager. When not working on data related issues for the Joint Hydrographic Center, he is aiding in the support of multibeam acquisition for the U.S. academic fleet through the National Science Foundation's Multibeam Advisory Committee.

Juliet Kinney is a Multibeam Mapping and Data Research Analyst at the Center where she applies her expertise in acquisition, processing and troubleshooting all sorts of bathymetric data. She is now involved in Seabed 2030 and applies her expertise to finding data, processing, organizing, and wrangling data and metadata to enable creation of new composite grids on a regular basis. She has been assisting with Environmental Compliance at JHC. As a Hydrographic Analyst for the Center for two years, she worked on a variety of projects using GIS mapping, sonar data re-use and processing, QA/QC expertise, and experience with OCS standards. Juliet spent close to five years as Hydrographic Analyst with ERT, and NOAA's Office of Coast Survey at the Center. Close to two years of that was working on the National Bathymetric Source Project, including learning more about Python, databases, and metadata standards and new IHO standards. For a little over three years as hydrographic analyst with ERT, she was Team Lead with NOAA's Sandy IOCM Center focusing on research to operations and how to re-use data collected for other purposes and bring data collection and management best practices into action in different groups. She received her Ph.D. in Marine & Atmospheric Sciences from Stony Brook University. Her dissertation, "The Evolution of the Peconic Estuary 'Oyster Terrain,' Long Island, NY," focused on 3D high resolution morphology data and geochemical analyses of stable and radiogenic isotopes to guide the interpretation of sediment samples from the paleoenvironment. Prior to joining the Center Juliet was a temporary full time faculty member in the Department of Geological Sciences at Bridgewater State University in MA. She also worked at the USGS as an ECO intern for two years in Menlo Park, CA with the Coastal and Marine Geology Program. She has a B.S. in Earth systems science from the UMass-Amherst Geosciences Department.

Carlo Lanzoni received a master's degree in ocean engineering from the University of New Hampshire. His master's research was the design of a methodology for field calibration of multibeam echo sounders using a split-beam sonar system and a standard target. He also has an M.S. and a B.S. in electrical engineering from the University of New Hampshire. Lanzoni has worked with different calibration methodologies applied to a variety of sonar systems. He is responsible for the operation, maintenance, and development of test equipment used in acoustic calibrations of echo sounders at the acoustic tank in the Chase Ocean Engineering Lab. His research focuses on the field calibration methodology for multibeam echo sounders.

Kim Lowell is a Research Scientist at the Center and an Affiliate Professor in the Ocean Engineering program. His primary focus is the application of machine learning, deep learning, and other data analytics to extract shallow-water bathymetry from lidar data. He also collaborates with colleagues to apply data analytics to, for example, automated ocean image analysis, impacts of anthropogenic noise, and extracting shallow-water bathymetry from ICESat-2. Kim has a M.Sc. (University of Vermont, USA) and a Ph.D. (Canterbury University, New Zealand) in Forest Biometrics, and a M.Sc. in Data Science and Analytics (University of New Hampshire, USA). He has considerable experience in geospatial data analysis, data quality, spatial statistics, and image processing gained from working as a senior researcher in academia, government agencies, and independent research centers in Canada, Australia, and the United States.

Andy McLeod received his B.S. in Ocean Studies from Maine Maritime Academy in 1998. His duties at the Center include supporting autonomous vehicle projects from conception and pre-production through to completion, providing technical support, managing project budgets, overseeing maintenance and operations, completion of documentation, producing test plans and reports, preparing contract documentation for procurement services and materials, and carrying out effective liaison with research partners.

Kristen Mello-Rafter is a UNH alumna with a B.Sc. in Zoology. She obtained a Rutman Fellowship from the Shoals Marine Laboratory to study invasive macroalgae species at the Isles of the Shoals. Soon after completion of her fellowship, she began working as a research technician at the Center focusing on mapping temporal and spatial distribution of macroalgae and fine-scale distribution of deepsea coral habitats in the Northwest Atlantic Ocean. As a project research specialist, she continues to work on various topics such as invasive macroalgae, and fine-scale habitat mapping in local subtidal, tropical subtidal, and deepsea environments. She specializes in all SCUBA diving related tasks including planning, executing, and analyzing data collected during dives.

Brian Miles is trained as a software engineer and physical geographer. His Ph.D. research focused on ecohydrology modeling in urbanized and forested watersheds; this work included tools to support reproducible ingest and transformation geospatial data, as well as model calibration and uncertainty estimation using HPC resources. He has current and prior experience in software engineering, Internet of Things (IoT), environmental monitoring, geospatial data storage and analysis, and managing SAFe Agile teams. His professional interests include developing workflows for reproducible analyses. As a Senior Research Project Engineer at the Center, Dr. Miles is currently focused on translating research codes and algorithms into deployable software artifacts supported by robust documentation, automated testing, continuous integration and deployment, observability, fault tolerance, and scalability.

Colleen Mitchell has a B.A. in English from Nyack College in Nyack, NY and a master's in education from the State University of New York at Plattsburgh. She began working for the Environmental Research Group (ERG) at UNH in 1999. In 2009, Mitchell joined the Center as a graphic designer where she is responsible for the Center's graphic identity and creates ways to visually communicate the Center's message in print and digital media. In addition, Colleen manages the Center's website and develops content for the Center's social media platforms.

Avery Muñoz is a Research Project Engineer in the Center's ASV lab. He holds a B.S. in Computer Science from Wentworth Institute of Technology, with a background in robotics, custom automation and AUVs. At the Center, Avery works as an engineer on the autonomous surface vehicle project developing control systems and tools to assist research.

Elizabeth Reed-Weidner received her Ph.D. from UNH/CCOM in 2023 (and concurrently received a Ph.D. from Stockholm University) with both of her theses focusing on broadband acoustic characterization of water column structures. Before coming to UNH, Liz graduated from the University of Washington in 2012 with a B.S. in oceanography and then worked as a geophysicist for C&C Technologies. In May of 2018, she received her master's degree in Earth sciences: ocean mapping from the University of New Hampshire with her thesis titled, "A Wideband Acoustic Method for Direct Assessment of Bubble-Mediated Methane Flux." At the Center, Liz is continuing her research on broadband acoustic characterization of water column structures as well as teaching the introductory ocean mapping course to ocean engineering undergraduates.

Matthew Rowell joined the Center in 2017 as the captain of the R/V *Gulf Surveyor*. Capt. Rowell first came to the University of New Hampshire in 2011 to pursue a graduate degree in mechanical engineering with a focus on hydrokinetic energy. Upon completion of his master's degree, he filled a research project engineering position at UNH in the Ocean Engineering Department and, in that capacity, was instrumental in the design and construction of the R/V *Gulf Surveyor*. Prior to UNH, Capt. Rowell studied mechanical engineering at Clarkson University and spent eight years as an officer in the U.S. Navy studying surface warfare and nuclear power.

Val Schmidt received his bachelor's degree in physics from the University of the South, Sewanee, TN in 1994. During his junior undergraduate year, he joined the Navy and served as an officer in the submarine fleet aboard the USS *Hawkbill* from 1994 to 1999. In 1998 and 1999, the USS *Hawkbill* participated in two National Science Foundation sponsored "SCICEX" missions to conduct seafloor mapping from the submarine under the Arctic ice sheet. Val served as Sonar and Science Liaison Officer during these missions. Val left the Navy in 1999 and worked for Qwest Communications as a telecommunications and Voice over IP engineer from 2000 to 2002. Val began work in 2002 as a research engineer for the Lamont Doherty Earth Observatory of Columbia University where he provided science-engineering support both on campus and to several research vessels in the U.S. academic research fleet. Val acted as a technical lead aboard the U.S. Coast Guard Icebreaker *Healy* for several summer cruises in this role. Val completed his master's degree in ocean engineering in 2008 at the Center where his thesis involved the development of an underwater acoustic positioning system for whales that had been tagged with an acoustic recording sensor package. Val continues to work as an engineer for the Center where his research focuses on hydrographic applications of ASVs, AUVs, and Phase Measuring Bathymetric sonars.

Chris Schwartz is a desktop administrator in our IT group which he has been part of since 2017. His responsibilities include maintaince, upgrades and trouble shooting of computers and associated software for the large array of desktop and laptop systems and software packages scattered throughout the lab.

Erin Selner has worked in research support roles for UNH since 2000. Her background includes research administration and accounting, as well as conference administration and project support. She received a B.A. from the College of William and Mary in Virginia.

Michael Sleep is a systems administrator with nine years of IT experience. His focus is on providing automation and wrangling Linux-based systems, network monitoring, and doing a little bit of everything else. He is working towards becoming a certified Red Hat Linux systems administrator.

Michael Smith joined the Center in 2016 as a master's student in ocean engineering/ocean mapping. Upon graduating in 2020, he accepted a position as an Acoustics and Scientific Software Engineer. Prior to joining the Center, Michael graduated from the University of Rhode Island's International Engineering Program (IEP) with a B.S. in ocean engineering and a B.A. in Spanish. His time in IEP placed him in internships aboard the E/V *Nautilus* and the University of Las Palmas AUV team. At the Center, Michael is involved with a number of projects related to deep and shallow water multibeam echo sounders. His work includes the development of open-source software solutions for hydrographic surveying and MBES backscatter processing. He continues to expand his thesis work on deep-water multibeam sound source verification and assessment. Michael has also worked on shallow water multibeam echo sounder calibration methodologies, both in the acoustic tank and in field. Michael greatly enjoys time out at sea, having participated in a number of research and mapping cruises.

Andrew Stevens joined the Center in 2014 as a graduate student in the Center's Data Visualization Research Lab, earning his M.S. and Ph.D. degrees in computer science in 2017 and 2021. His doctoral research examined the perceptual effectiveness of 3D flow field visualization techniques, and he has published research in 3D data interaction, virtual and augmented reality, and scientific data visualization. He now works as a research scientist at the Center, applying his experience to address the research priorities of the Data Visualization Research Lab. Prior to coming to New Hampshire, Drew worked as a scientist at an environmental consulting company in Oakland, CA and as a web engineer at a boutique music company in Encino, CA. He also holds a B.A. in music composition from the University of California, Davis.

Dan Tauriello graduated from UNH in 2014 with a B.S in marine biology and a minor in ocean engineering. At the Center, he wears many hats including graduate student, IT technician, and first mate aboard the Center's research vessels. In 2020, his position was changed to Seagoing Laboratory Specialist. As a master's student in Earth sciences/ocean mapping, he is focused on hardware testing and development related to system design for a trusted method of collecting crowdsourced bathymetric data. In the past, he has served as an Explorer in Training aboard NOAA Ship *Okeanos Explorer*, and run a variety of experimental aquaculture projects in the Portsmouth Harbor area.

Rochelle Wigley has a mixed hard rock/soft rock background with a master's in igneous geochemistry (focusing on dolerite dyke swarms) and a Ph.D. in sedimentology/sediment chemistry, where she integrated geochemistry and geochronology into marine sequence stratigraphic studies of a condensed sediment record in order to improve the understanding of continental shelf evolution along the western margin of southern Africa. Phosphorites and glauconite have remained as a research interest where these marine authigenic minerals are increasingly the focus of offshore mineral exploration programs. She was awarded a Graduate Certificate in Ocean Mapping from UNH in 2008. Rochelle concentrated largely on understanding the needs and requirements of all end-users within the South African marine sectors on her return home, as she developed a plan for a national offshore mapping program from 2009 through 2012. As Project Director of the GEBCO Nippon Foundation Indian Ocean Project, she is involved in the development of an updated bathymetric grid for the Indian Ocean and management of a project working to train other Nippon Foundation-GEBCO scholars. In 2014, Rochelle took on the responsibility of the Director of the Nippon Foundation-GEBCO training program at the Center.

In addition to the academic, research and technical staff, our administrative support staff, **Wendy Monroe**, **Valerie Tillinghast**, and **Kris Tonkin** ensure the smooth running of the organization.

NOAA Employees

NOAA has demonstrated its commitment to the Center by assigning eleven NOAA employees (or contractors) to the Center.

Capt. Andrew Armstrong, founding co-director of the JHC, retired as an officer in the National Oceanic and Atmospheric Administration Commissioned Officer Corps in 2001 and is now assigned to the Center as a civilian NOAA employee. Captain Armstrong has specialized in hydrographic surveying and served on several NOAA hydrographic ships, including the NOAA Ship *Whiting* where he was Commanding Officer and Chief Hydrographer. Before his appointment as Co-Director of the NOAA/UNH Joint Hydrographic Center, Capt. Armstrong was the Chief of NOAA's Hydrographic Surveys Division, directing all of the agency's hydrographic survey activities. Captain Armstrong has a B.S. in geology from Tulane University and an M.S. in technical management from the Johns Hopkins University. Capt. Armstrong is overseeing the hydrographic training program at UNH and organized our successful Cat. A certification submission to the International Hydrographic Organization—most recently in 2018. In 2020, Capt. Armstrong received the Department of Commerce Gold Medal for his contributions to delineate the U.S. extended continental shelf.

Sam Candio is a physical scientist with the NOAA Office of Ocean Exploration and Research (OER). He splits his time between conducting field operations aboard the NOAA Ship *Okeanos Explorer* as an expedition coordinator/mapping lead, and conducting shoreside responsibilities at JHC/CCOM including mission planning, data QC, and data archival. Sam received his Bachelor of Science in marine biology from the University of North Carolina, Wilmington, with minors in environmental science and oceanography. Following graduation, he worked as an instructor for UNCW's MarineQuest, leading a suite of marine science experiential learning programs ranging from the generation of biodiesel from algae to the operation of side scan sonars and ROVs. Prior to signing on with OER, Sam spent four years aboard the NOAA Ship *Fairweather*, serving as the Chief Hydrographic Survey Technician leading coastal bathymetric surveys ranging from the Alaskan Arctic to the Channel Islands in California.

Adam Gibbons is a software engineer with Spatial Front Inc. supporting the NOS Coast Survey Development Lab. Adam is a recent Graduate of Rensselaer Polytechnic Institute with a B.S. in computer science. He spent the summer of 2019 with CSDL as a Geospatial Development/DevOps intern through Earth Resources Technology (ERT), developing and testing prototype cloud infrastructure for the nowCOAST in the Cloud exploratory project. Adam joined the Precision Navigation/nowCOAST team in 2020 and has been primarily focused on cloud-based infrastructure development, distributed system design, full-stack web development, and nowCOAST in the Cloud operations under the management of John Kelley.

Shannon Hoy is a physical scientist with the NOAA Office of Ocean Exploration and Research (OER). She assists in both field operations aboard the NOAA Ship *Okeanos Explorer* as a mapping coordinator and with shoreside responsibilities, such as mission planning and data archiving. Shannon has a multidisciplinary background, having received a Bachelor of Science in marine biology from the College of Charleston, and having worked with the Submarine Geohazards Group at the U.S. Geological Survey. She will soon complete her master's degree in ocean mapping at the University of New Hampshire's Center for Coastal and Ocean Mapping (CCOM). Shannon began mapping the seafloor in 2009 and has since participated with numerous expeditions. Prior to her position with OER, the majority of her time at sea was spent as a mapping lead for University of Bristol's (UK) palaeoceanographic group, where she implemented multiple habitat mapping technologies and methodologies to search for deep-sea corals.

Carl Kammerer is an oceanographer with the National Ocean Service's Center for Operational Oceanographic Products and Services (CO-OPS), now seconded to the Center. He is a specialist in estuarine and near-shore currents and has been project manager for current surveys throughout the United States and its territories. His present project is a two-year survey of currents in the San Francisco Bay region. He acts as a liaison between CO-OPS and the JHC and provides expertise and assistance in the analysis and collection of tides. He has a Bachelor of Science degree in oceanography from the University of Washington and an MBA from the University of Maryland University College.

John G.W. Kelley is a research meteorologist and coastal modeler with NOAA/National Ocean Service's Marine Modeling and Analysis Programs within the Coast Survey Development Lab. John has a Ph.D. in Atmospheric Sciences from Ohio State University. He is involved in the development and implementation of NOS's operational numerical ocean forecast models for estuaries, the coastal ocean and the Great Lakes. He is also the PI for a NOAA web mapping portal to real-time coastal observations and forecasts. John is working with JHC/CCOM personnel on developing the capability to incorporate NOAA's real-time gridded digital atmospheric and oceanographic forecast into the next generation of NOS nautical charts.

Abby Letts is a NOAA Corps officer who is currently serving as the Operations Support Team Lead for NOAA Ocean Exploration. In this role, she assists with shoreside coordination and field operations on the NOAA Ship *Okeanos Explorer*. She attended Haverford College, graduating with a B.S. in geology and a B.A. in Spanish. She received an M.S. in Earth science from University of California, Santa Barbara with a focus on paleoclimate. For her master's thesis, she analyzed trace elements and structural changes in speleothems to reconstruct the precipitation history of Central Asia. Post graduate school, she was commissioned into the NOAA Corps and sailed for two years as a deck officer aboard the *Okeanos Explorer*.

Thomas Morrow is a physical scientist with NOAA Ocean Exploration. He spends his time working as an expedition coordinator with the mapping team on the NOAA Ship *Okeanos Explorer* and supporting NOAA's Ocean Exploration mission. Thomas is a marine geologist and geophysicist who started his ocean exploration career during his B.S. in geology at the University of Florida. He then moved to the University of Idaho for an M.S. and a Ph.D in geological sciences, studying mid-ocean ridges, fracture zones, and hotspot seamounts. Prior to joining NOAA Ocean Exploration, Thomas spent several years as a postdoctoral research fellow at Boston College, coordinating missions to explore the Gofar Transform Fault with R/V *Atlantis* and R/V *Thomas G Thompson*.

Erin Nagel focused her undergraduate studies at the University of Colorado at Boulder on Geographic Information Systems and Atmospheric and Oceanic Sciences and worked as a Physical Scientist for the U.S. Army Corps of Engineers and with NOAA's Atlantic Hydrographic Branch for the Office of Coast Survey before joining the Center in 2014. She has supported USACE and FEMA in emergency operations during Super Storm Sandy and Irene with emergency response mapping and pre- and post-storm analysis of bathymetry and lidar. Erin joined the nowCOAST effort in 2017, working as a Scientific Programmer focusing on surface current data.

Glen Rice started with the Center as a Lieutenant (Junior Grade) in the NOAA Corps stationed with at the Joint Hydrographic Center as Team Lead of the Integrated Ocean and Coastal Mapping Center. He had previously served aboard the NOAA Hydrographic Ships *Rude* and *Fairweather* along the coasts of Virginia and Alaska after receiving an M.Sc. in Ocean Engineering at the University of New Hampshire. In 2013, Glen left the NOAA Corps and became a civilian contractor to NOAA. In 2014, Glen became a permanent Physical Scientist with NOAA. He maintains his position as Team Lead of the IOCM Center at UNH.

Katrina Wiley is part of NOAA's Office of Coast Survey, Hydrographic Surveys Division, Operations Branch. Prior to Operations Branch, Katrina served as Chief of Survey Section at U.S. Army Corps of Engineers New England District in Concord, MA and previously worked for NOAA's Hydrographic Surveys Division Operations Branch in Silver Spring, MD and Atlantic Hydrographic Branch in Norfolk, VA. She has a B.S in marine biology from College of Charleston and an M.S. in earth sciences from University of New Hampshire.

Other Affiliated Faculty

Lee Alexander is a research associate professor emeritus. He was previously a research scientist with the U.S. Coast Guard, and a Visiting Scientist with the Canadian Hydrographic Service. His area of expertise is applied Research, Development, Test and Evaluation (RDT&E) on electronic charting and e-Navigation-related technologies for safety-of-navigation and marine environmental protection. Lee has published over 150 papers and reports on shipborne and shore-based navigation systems/technologies, and is a co-author of a textbook on Electronic Charting. He received an M.S. degree from the University of New Hampshire, and a Ph.D. from Yale University. He is also a captain (now retired) in the U.S. Navy Reserve.

Brad Barr received a B.S. from the University of Maine, an M.S. from the University of Massachusetts, and a Ph.D. from the University of Alaska. He is currently a senior policy advisor in the NOAA Office of National Marine Sanctuaries, affiliate professor at the School of Marine Sciences and Ocean Engineering at the University of New Hampshire, and a visiting professor at the University Center of the Westfjords in Iceland. He is a member of the IUCN World Commission on Protected Areas, the International Committee on Marine Mammal Protected Areas/IUCN Marine Mammal Protected Areas Task Force. He has served on the Boards of Directors of the George Wright Society in the U.S., the Science and Management of Protected Areas Association (SAMPAA) in Canada, and, currently, on the Board of Directors of the Coastal Zone Canada Association (CZCA). He also serves on the Editorial Board of the World Maritime University *Journal of Maritime Affairs*. He has published extensively on marine protected areas science and management, whaling and maritime heritage preservation, with a primary research focus on the identification and management of ocean wilderness.

Jonathan Beaudoin earned his undergraduate degrees in geomatics engineering and computer science from the University of New Brunswick (UNB) in Fredericton, NB, Canada. He continued his studies at UNB under the supervision of Dr. John Hughes Clarke of the Ocean Mapping Group, and after completing his Ph.D. studies in the field of refraction related echo sounding uncertainty, Dr. Beaudoin took a research position at JHC/CCOM in 2010. While there, he carried on in the field of his Ph.D. research and joined the ongoing seabed imaging and characterization efforts. He also played a leading role in establishing the Multibeam Advisory Committee, an NSF-funded effort to provide technical support to seabed mapping vessels in the U.S. academic fleet. Jonathan returned to Canada in late 2013 where he joined the Fredericton, NB office of QPS.

Ann E. A. Blomberg received her M.Sc. and Ph.D. degrees in signal processing from the University of Oslo, Norway, in 2005 and 2012, respectively. From 2005 to 2008, she worked as a processing geo-physicist at CGGVeritas in Norway. In 2012, she was at the Centre for Geobiology (CGB) at the University of Bergen, working with sonar and seismic data acquisition, processing, and interpretation. She is currently a postdoc at the University of Oslo, working on a project entitled, "Advanced sonar methods for detecting and monitoring marine gas seeps."

Margaret Boettcher received a Ph.D. in geophysics from the MIT/WHOI Joint Program in Oceanography in 2005. She joined JHC/CCOM in 2008 as a post-doctoral scholar after completing a Mendenhall Postdoctoral Fellowship at the U.S. Geological Survey. Although she continues to collaborate with scientists at the Center, Margaret has been a member of the faculty in the Earth Science Department at UNH since 2009. Margaret's research focuses on the physics of earthquakes and faulting and she approaches these topics from the perspectives of seismology, rock mechanics, and numerical modeling. Margaret seeks to better understand slip accommodation on oceanic transform faults. Recently she has been delving deeper into the details of earthquake source processes by looking at very small earthquakes in deep gold mines in South Africa.

David Bradley received bachelor's and master's degrees in physics from Michigan Technological University in Houghton in 1960 and 1963, respectively, and a doctorate in mechanical engineering from the Catholic University of America in 1970. He served as director of the NATO Underwater Research Center, La Spezia, Italy; superintendent of the Acoustics Division of the Naval Research Laboratory; and mine warfare technical adviser to the Chief of Naval Operations. His seminal contributions to the field of acoustics have been recognized with many awards and leadership positions within the ASA. They include the Meritorious Civilian Service Award in 1982, and the Superior Civilian Service Award in 1993 from the Department of the Navy. He recently retired as a Professor of Acoustics at Penn State University and started as an Affiliate Faculty member with the Center in 2017.

Dale Chayes has been an active instrument developer, troubleshooter, and operator in the oceanographic community since 1973 and has participated in well over 150 field events. He has worked on many projects, including hull-mounted multibeams, submarine (SCAMP) and deep-towed mapping sonars (SeaMARC I), real-time wireless data systems, database infrastructure for digital libraries (DLESE) and marine geoscience data (MDS), satellite IP connectivity solutions (SeaNet), GPS geodesy, trace gas water samplers, precision positioning systems, and backpack mounted particle samplers. In his spare time, he is a licensed amateur radio operator, Wilderness EMT/ NREMT and is in training (with his dog Frodo) for K9 wilderness search and rescue.

George (Randy) Cutter is a research oceanographer for NOAA Fisheries in San Diego, California. His research focuses on developing and implementing advanced tools and techniques for remotely sensing marine organisms. He has developed underwater imaging systems and methods for multibeam echosounders that have improved our ability to detect, locate, and identify fish and other organisms to improve biological assessments as well as increase resolution and characterization of the seabed and habitats. He is working to develop methods for automated detection and classification of fish and other animals in imagery from underwater images, including stereo-cameras and tools for measuring fish from stereo imagery and creating dense three-dimensional reconstructions of the seabed and demersal fish. Randy has also led the development of the NMFS Fisheries AUV and is a representative of NOAA's Strategic Initiative for Automated Image Analysis. Randy is an alumnus of CCOM having completed his Ph.D. in Earth sciences/oceanography in 2005.

Vicki Ferrini has a Ph.D. in coastal oceanography (2004) and a master's degree in marine environmental science (1998), both from Stony Brook University. Over the past 20+ years, she has worked in environments from shallow water coastal areas to the deep sea, using ships, boats, submersibles, and towed platforms to map the seafloor at a variety of resolutions. Vicki is also heavily involved in the fields of geoinformatics and data management. She is a research scientist at Columbia University's Lamont-Doherty Earth Observatory where she spends much of her time working on projects focused on making high-quality marine geoscience research data publicly accessible.

Denis Hains is the Founder, President and CEO of H2i (Hains HYDROSPATIAL international inc.); the representative appointed by the United States and Canada Hydrographic Commission (USCHC) on the International Hydrographic Review (IHR) Editorial Board of the International Hydrographic Organization (IHO); Vice President of the Board of Directors of the Interdisciplinary Center for Ocean Mapping Development (CIDCO) in Rimouski, Canada; and is also an active member of the Canadian Hydrographic Association (CHA), and the Association of Professional Executives of the Public Service of Canada (APEX). Denis holds a B.Sc. in geodetic science from Laval University in Québec City, Canada. He is a Retired Québec Land Surveyor and had a successful 35+ year career with the Public Service of Canada, where he worked for 20 years for Fisheries and Oceans Canada at the Canadian Hydrographic Service (CHS) in Mont-Joli and Ottawa, including two years with the Canadian Coast Guard. He also spent 15 years with Natural Resources Canada, particularly as the National Executive Director of the Canadian Geodetic Survey (CGS). He retired in 2018 as Director-General of the CHS and Hydrographer General of Canada in Ottawa, Canada.

John Hall spent his sabbatical from the Geological Survey of Israel with the Center. Dr. Hall has been a major influence in the IBCM and GEBCO compilations of bathymetric data in the Mediterranean, Red, Black, and Caspian Seas and is working with the Center on numerous data sets including multibeam-sonar data collected in the high Arctic in support of our Law of the Sea work. He is also archiving the 1962 through 1974 data collected from Fletcher's Ice Island (T-3).

Martin Jakobsson joined the Center in August of 2000 as a Post-Doctoral Fellow. Martin completed a Ph.D. at the University of Stockholm where he combined modern multibeam sonar data with historical single-beam and other data to produce an exciting new series of charts for the Arctic Ocean. Dr. Jakobsson has been developing robust techniques for combining historical data sets and tracking uncertainty as well as working on developing approaches for distributed database management and Law of the Sea issues. In April 2004, he returned to a prestigious professorship in his native Sweden but remains associated with the Center.

Scott Loranger defended his Ph.D. in oceanography from the University of New Hampshire in November 2018. He is interested in acoustical oceanography and specifically in the use of broadband acoustics to understand physical and biological processes in the water column. His current position is with a project called ACT4Storage: Acoustic and Chemical Technologies for environmental monitoring of geological carbon storage. Geological carbon storage has emerged as a promising method for reducing greenhouse gas emissions and reaching international climate goals. The ACT4Storage project is a collaborative effort aimed at improving the cost-efficiency and effectiveness of environmental monitoring of offshore geological carbon storage sites. Scott's role is in using broadband acoustic systems to detect and quantify potential leaks from storage sites.

Xavier Lurton graduated in Physics in 1976 (Universite de Bretagne Occidentale, Brest) and received a Ph.D. in Applied Acoustics in 1979 (Universite du Maine, Le Mans), specializing first in the physics of brass musical instruments. After spending two years of national service as a high-school teacher in the Ivory Coast, he was hired by Thomson-Sintra (the leading French manufacturer in the field of military sonar systems—today Thales Underwater Systems) as an R&D engineer and specialized in underwater propagation modeling and system performance analysis. In 1989 he joined IFREMER (the French government agency for Oceanography) in Brest, where he first participated in various projects in underwater acoustics applied to scientific activities (e.g., data transmission, fisheries sonar, and ocean tomography). Over the years, he specialized more specifically in seafloor-mapping sonars, both through his own technical research activity (in physical modeling and sonar engineering) and through several development projects with sonar manufacturers (Kongsberg, Reson); in this context he has participated in tens of technological trial cruises on research vessels. He has been teaching underwater acoustics for 20 years in several French universities, and consequently wrote *An Introduction to Underwater Acoustics* (Springer), heavily based on his own experience as a teacher.

Christopher Parrish holds a Ph.D. in civil and environmental engineering with an emphasis in geospatial information engineering from the University of Wisconsin-Madison and an M.S. in civil and coastal engineering with an emphasis in geomatics from the University of Florida. His research focuses on full-waveform lidar, topographic-bathymetric LIDAR, hyperspectral imagery, uncertainty modeling, and UAVs for coastal applications. Dr. Parrish is the Director of the American Society for Photogrammetry and Remote Sensing (ASPRS) Lidar Division and an associate editor of the journal *Marine Geodesy*. Prior to joining Oregon State University, Dr. Parrish served as lead physical scientist in the Remote Sensing Division of NOAA's National Geodetic Survey and as an affiliate professor at the Center.

Shachak Pe'eri received his Ph.D. degree in geophysics from the Tel Aviv University in Israel. In 2005, he started his post-doctoral work at the Center with a Tyco post-doctoral fellowship award. His research interests are in optical remote sensing in the littoral zone with a focus on experimental and theoretical studies of LIDAR remote sensing (airborne lidar bathymetry, topographic lidar, and terrestrial laser scanning), hyperspectral remote sensing, and sensor fusion. Shachak is a member of the American Geophysical Union (AGU), the Ocean Engineering (OE) and Geoscience and Remote Sensing (GRS) societies of IEEE, and of The Hydrographic Society of America (THSOA). Dr. Pe'eri moved to a position with NOAA's Marine Chart Division in 2016.

Kurt Schwehr received his Ph.D. from Scripps Institution of Oceanography studying marine geology and geophysics. Before joining the Center, he worked at JPL, NASA Ames, the Field Robotics Center at Carnegie Mellon, and the USGS Menlo Park. His research has included components of computer science, geology, and geophysics. He looks to apply robotics, computer graphics, and real-time systems to solve problems in marine and space exploration environments. He has been on the mission control teams for the Mars Pathfinder, Mars Polar Lander, Mars Exploration Rovers and Mars Science Laboratory. He has designed computer vision, 3D visualization, and on-board driving software for NASA's Mars exploration program. Fieldwork has taken him from Yellowstone National Park to Antarctica. At the Center, he worked on a range of projects including the Chart of the Future, visualization techniques for underwater and space applications, and sedimentary geology. He has been particularly active in developing hydrographic applications of AIS data. Kurt is currently Head of Ocean Engineering at Google and an affiliate faculty member of the Center.

Derek Sowers worked as an expedition coordinator for NOAA's Office of Ocean Exploration and Research (OER) for the past eight years leading ocean mapping cruises on NOAA Ship *Okeanos Explorer*. He recently took a position as the Mapping Lead for the Ocean Exploration Trust. He holds a B.S. in environmental science from the University of New Hampshire (1995), an M.S. in marine resource management from Oregon State University (2000), and a Ph.D. in oceanography from the University of New Hampshire. Derek has 14 years of previous coastal research and management experience working for NOAA's National Estuarine Research Reserve network and EPA's National Estuary Program in both Oregon and New Hampshire. Derek has participated in oceanographic expeditions spanning remote areas of the Arctic, Pacific, and Atlantic oceans.

Arthur Trembanis is the director of the Coastal Sediments, Hydrodynamics, and Engineering Laboratory (CSHEL) in the College of Earth, Ocean, and Environment at the University of Delaware. The work of CSHEL involves the development and utilization of advanced oceanographic instrumentation, particularly autonomous underwater vehicles for seafloor mapping and benthic habitat characterization. He received a bachelor's degree in geology from Duke University in 1998, a Fulbright Fellowship at the University of Sydney in 1999 and a Ph.D. in marine sciences from the Virginia Institute of Marine Sciences in 2004.

Lysandros Tsoulos is an associate professor of cartography at the National Technical University of Athens. Lysandros is internationally known for his work in digital mapping, geoinformatics, expert systems in cartography, and the theory of error in cartographic databases. At the Center, Lysandros worked with NOAA student Nick Forfinski exploring new approaches to the generalization of dense bathymetric data sets.

Tom Weber received his Ph.D. in acoustics at The Pennsylvania State University in 2006 and has B.S. (1997) and M.S. (2000) degrees in ocean engineering from the University of Rhode Island. He joined the Center in 2006 and the Mechanical Engineering department, as an assistant professor, in 2012. Tom conducts research in the field of underwater acoustics and acoustical oceanography. His specific areas of interest include acoustic propagation and scattering in fluids containing gas bubbles, the application of acoustic technologies to fisheries science, high-frequency acoustic characterization of the seafloor, and sonar engineering. In 2021, Tom joined the staff of the Office of Naval Research but retains a position with the CDenter as an affiliate research professor.

Dave Wells is world-renowned in hydrographic circles. Dave is an expert in GPS and other aspects of positioning, providing geodetic science support to the Center. Along with his time at UNH, Dave also spends time at the University of New Brunswick and at the University of Southern Mississippi where he is participating in their hydrographic program. Dave also helps UNH in its continuing development of the curriculum in hydrographic training.

Neil Weston's research appointment serves as a way to strengthen the academic and research ties between the Center and the Office of Coast Survey, NOAA. His focus will be to collaborate on research activities related to GNSS/GPS positioning, geophysical phenomena affecting land/ocean interfaces, data visualization, digital signal processing, and modeling. Dr. Weston is also interested in advising and mentoring graduate students, giving invited talks and seminars, promoting OCS, NOS and NOAA scientific and technological endeavors, and strengthening high-level collaborations between the academic community and NOAA. Neil received his doctorate from Catholic University of America in 2007 in biomedical engineering and physics, and has master's degrees from

Johns Hopkins University in physics (sensor systems) and the University of South Florida in physics (laser optics and quantum electronics). He also holds positions as a Science/Technical Advisor with the U.S. State Department and as a Technical Advisor for the United Nations.

Dana Yoerger is a Senior Scientist at the Woods Hole Oceanographic Institution and a researcher in robotics and unmanned vehicles. He supervises the research and academic program of graduate students studying oceanographic engineering through the MIT/WHOI Joint Program in the areas of control systems, robotics, and design. Dr. Yoerger has been a key contributor to the remotely-operated vehicle *Jason*; to the pioneering underwater robot ABE and its successor *Sentry*; and the hybrid remotely operated vehicle, *Nereus* which reached the bottom of the Mariana Trench in 2009. Dr. Yoerger has gone to sea on over 80 oceanographic expeditions exploring the Mid-Ocean Ridge, mapping underwater seamounts and volcanoes, surveying ancient and modern shipwrecks including the *Titanic* discovery expedition in 1985, studying the environmental effects of the Deepwater Horizon Oil Spill, and the recent effort that located the Voyage Data Recorder from the merchant vessel *El Faro*. Dr. Yoerger's current research focuses on robots for exploring the midwater regions of the world's oceans, which hold much of the worldwide ocean biomass and biodiversity yet are largely unexplored. He heads a team developing a new underwater robot called Mesobot, which is designed to observe midwater fish and zooplankton to better understand their complex lives and their role in regulating global climate. The Mesobot project is a foundational element of WHOI's new Ocean Twilight Zone effort, the largest private research grant in WHOI's history. The Ocean Twilight Zone project, which seeks to advance our understanding of the midwater ocean through an integrated program of scientific research, technological development, and public engagement, is sponsored by the Audacious Project.

Visiting Scholars

Since the end of its first year, the Center has had a program of visiting scholars that allows us to bring some of the top people in various fields to interact with Center staff for periods of between several months and one year.

Jorgen Eeg (October–December 2000) is a senior researcher with the Royal Danish Administration of Navigation and Hydrography and was selected as our first visiting scholar. Jorgen brought a wealth of experience applying sophisticated statistical algorithms to problems of outlier detection and automated cleaning techniques for hydrographic data.

Donald House (January–July 2001) spent his sabbatical with our visualization group. He is a professor at Texas A&M University where he is part of the TAMU Visualization Laboratory. He is interested in many aspects of the field of computer graphics, both 3D graphics and 2D image manipulation. Recently his research has been in the area of physically based modeling. He is currently working on the use of transparent texture maps on surfaces.

Rolf Doerner (March–September 2002) worked on techniques for creating self-organizing data sets using methods from behavioral animation. The method, called "Analytic Stimulus Response Animation," has objects operating according to simple behavioral rules that cause similar data objects to seek one another and dissimilar objects to avoid one another.

Ron Boyd (July–December 2003) spent his sabbatical at the Center. At the time, Ron was a professor of marine geology at the University of Newcastle in Australia and an internationally recognized expert on coastal geology and processes. He is now an employee of Conoco-Phillips Petroleum in Houston. Ron's efforts at the Center focused on helping us interpret the complex, high-resolution repeat survey data collected off Martha's Vineyard as part of the ONR Mine Burial Experiment.

John Hall (August 2003–October 2004). See Dr. Hall's biography under **Affiliate Faculty**.

LCDR Anthony Withers (July–December 2005) was the Commanding Officer of the HMAS Ships *Leeuwin* and *Melville* after being officer in charge of the RAN Hydrographic School in Sydney, Australia. He also has a Master of Science and Technology in GIS Technology and a Bachelor of Science from the University of New South Wales.

LCDR Withers joined us at sea for the Law of the Sea Survey in the Gulf of Alaska and upon returning to the Center focused his efforts on developing uncertainty models for phase-comparison sonars.

Walter Smith (November 2005–July 2006) received his Ph.D. in geophysics from Columbia University's Lamont-Doherty Earth Observatory in 1990. While at Lamont, he began development of the GMT data analysis and graphics software. From 1990-1992 he held a post-doctoral scholarship at the University of California, San Diego's Scripps Institution of Oceanography in the Institute for Geophysics and Planetary Physics He joined NOAA in 1992 and has also been a lecturer at the Johns Hopkins University, teaching Data Analysis and Inverse Theory. Walter's research interests include the use of satellites to map the Earth's gravity field, and the use of gravity data to determine the structure of the sea floor and changes in the Earth's oceans and climate.

Lysandros Tsoulos (January-August 2007). See Dr. Tsoulos's biography under **Affiliate Faculty**.

Jean-Marie Augustin (2010) is a senior engineer at the Acoustics and Seismics Department of IFREMER focusing on data processing and software development for oceanographic applications and specializing in sonar image and bathymetry processing. His main interests include software development for signal, data and image processing applied to seafloor-mapping sonars, featuring bathymetry computation algorithms and backscatter reflectivity analysis. He is the architect, designer, and main developer of the software suite, *SonarScope*.

Xabier Guinda (2010) is a postdoctoral research fellow at the Environmental Hydraulics Institute of the University of Cantabria in Spain. He received a Ph.D. from the University of Cantabria. His main research topics are related to marine benthic ecology (especially macroalgae), water quality monitoring and environmental assessment of anthropogenically disturbed sites as well as the use of remote sensing hydroacoustic and visual techniques for mapping of the seafloor and associated communities. His tenure at the Center was sponsored by the Spanish government.

Sanghyun Suh (2010) is a senior research scientist at the Maritime and Ocean Engineering Research Institute (MOERI) at the Korea Ocean Research and Development Institute (KORDI) in Daejeon, Republic of Korea (South Korea). Dr. Suh received his Ph.D. from the University of Michigan in GIS and remote sensing. He worked with Dr. Lee Alexander on e-Navigation research and development (R&D) related to real-time and forecasted tidal information that can be broadcast via AIS binary application-specific messages to ship-borne and shore-based users for situational awareness and decision-support.

Xavier Lurton (August 2010–March 2012). See Dr. Lurton's biography under **Affiliate Faculty**.

Seojeong Lee (April 2012–April 2013) received her Ph.D. in computer science with an emphasis on software engineering from Sookmyung Women's University in South Korea. She completed an expert course on software quality at Carnegie Mellon University. With this software engineering background, she has worked at the Korea Maritime University as an Associate Professor since 2005 where her research has been focused on software engineering and software quality issues in the maritime area. As a Korean delegate of the IMO NAV sub-committee and IALA e-NAV committee, she contributes to the development of e-navigation. Her current research topic is software quality assessment of e-navigation, and development of e-navigation portrayal guidelines. She is also interested in AIS ASM and improvement of NAVTEX message.

Gideon Tibor (April 2012–November 2012) was a visiting scholar from the Israel Oceanographic and Limnological Research Institute and the Leon H. Charney School of Marine Sciences in the University of Haifa. Gideon received his Ph.D. in geophysics and planetary sciences from Tel-Aviv University. His main research interest is the development and application of high-resolution marine geophysics and remote sensing using innovative methods in the study of phenomena that influence the marine environment and natural resources. By means of international and local competitive research grants, he uses a multi-disciplinary approach for studying the Holocene evolution of the Levant margin, the Sea of Galilee, and the northern Gulf of Eilat/Aqaba.

Anne E.A. Blomberg (December 2014–February 2015). See Dr. Blomberg's biography under **Affiliate Faculty**.

Tor Inge Lønmo (June 2016–December 2016) received a master's degree in mathematics and physics at the Norwegian University of Science and Technology in 2012. His thesis was done in cooperation with the Norwegian Defence Research Establishment (FFI). Shortly after, he started working for Kongsberg Maritime in Horten. He is currently working on improving the beam forming for the EM2040 multibeam echo sounder through a Ph.D. at the University of Oslo.

Christian Stranne (January 2017–December 2017) received his Ph.D. in 2013 in physical oceanography from the University of Gothenburg, where he studied large-scale Arctic sea ice dynamics and coupled ocean-sea ice-atmosphere interactions. He has held a two-year postdoc position at Stockholm University, focusing on methane hydrate dynamics and numerical modelling of multiphase flow in hydrate-bearing marine sediments. Dr. Stranne is funded by the Swedish Research Council for a three-year research project of which two years are based at the Center. The project involves the modelling of methane gas migration within marine sediments, and studies of the interaction between gas bubbles and sea water in the ocean column with an over-arching aim to set up a coupled model for methane transport within the sediment-ocean column system. He is also involved in a project evaluating water column multibeam and single-beam sonar data for its potential of revealing detailed oceanographic structure.

Kelly Hogan (January 2018–March 2018) is a marine geophysicist with the British Antarctic Survey in Cambridge England who specializes in reconstructing past Arctic and Antarctic ice sheets. Specifically, Dr. Hogan uses glacial geomorphology and sedimentary processes at the seafloor (imaged and sampled from ships) to determine past patterns of ice flow and how quickly the ice retreated since the last glacial some 20,000 years ago. She links these results to past, natural changes in climate helping to improve our understanding of the response of the Cryosphere to future climatic change. At the Center, Dr. Hogan worked with Larry Mayer and graduate student Erin Heffron on the interpretation of multibeam, sub-bottom, and water column data from the Arctic Ocean.

Dana Yoerger (January and June 2022). See Dr. Yoerger's biography under **Affiliate Faculty**.

Walter Roest (January to October 2022) obtained a Ph.D. in marine geophysics from the University of Utrecht in the Netherlands. After a 3-year post doc at the Atlantic Geoscience Center (Bedford Institute in Dartmouth, Nova Scotia, Canada), he worked at the Geological Survey of Canada (GSC), in Ottawa, Ontario, primarily on continental magnetic and gravity acquisition and interpretation. Over the years, he also occupied several management positions at the GSC. In 2003, Walter was appointed director of the Marine Geosciences Department of Ifremer, the French Public Institute for Marine Research, in Brest, France. He led the French program for the extended continental shelf (ECS) in the framework of the UN Convention on the Law of the Sea from 2003 to 2012, including many mapping cruises offshore the French overseas territories. He served as a member and one of the vice-presidents of the UN Commission on the Limits of the Continental Shelf from 2012 to 2017. His research interests are in plate tectonics, fracture zones, the evolution of continental margins. He also participated actively in the development of several large-scale open access geophysical data compilations. Walter Roest's stay at CCOM is sparked by his interest in seafloor mapping, Seabed2030, the Map the Gaps initiative, the GEBCO/Nippon training program, as well as the ECS work in which CCOM is involved

Facilities, IT and Equipment

Office and Teaching Space

The Joint Hydrographic Center has been fortunate to have equipment and facilities that are unsurpassed in the academic hydrographic community. Upon the initial establishment of the Center at UNH, the University constructed an 8,000 square foot building dedicated to JHC/CCOM and attached to the unique Ocean Engineering high-bay and tank facilities already at UNH. Since that time, a 10,000-square-foot addition has been constructed (through NOAA funding), resulting in 18,000 sq. ft. of space dedicated to Center research, instruction, education, and outreach activities. In 2016, construction began on 12,000-square-foot expansion to the building that was completed in September 2017 (Figure I-1). This includes six large labs and office space for the undergraduate ocean engineering program, nine new offices (1,600 sq. ft.) dedicated for Center personnel, and a new shared 84-seat amphitheater-style class/seminar room with the latest in projection facilities (Figures I-1 and Figure I-2).

The Center now has approximately 20,000 sq. ft. of dedicated space, of which approximately 4,000 sq. ft. are devoted to teaching purposes and 16,000 sq. ft. to research and outreach, including office space. This does not include the new lab or seminar space which are shared with the Center for Ocean Engineering and the B.S. program in Ocean Engineering. Our dedicated teaching classroom can seat 45 students and has a high-resolution LCD projector capable of widescreen display. There are now 43 faculty or staff offices. With the influx of NOAA OER, IOCM and NOAA contractors, the Center is now providing office space, under a separate contract with NOAA, for 14 NOAA personnel. In 2016, graduate student space was upgraded to accommodate 31 student cubicles plus an additional seven seats for the GEBCO students including space for up to three NOAA students. Two additional NOAA cubicles are available for NOAA Marine Operations Center employees at the pier support facility in New Castle, NH (see below).

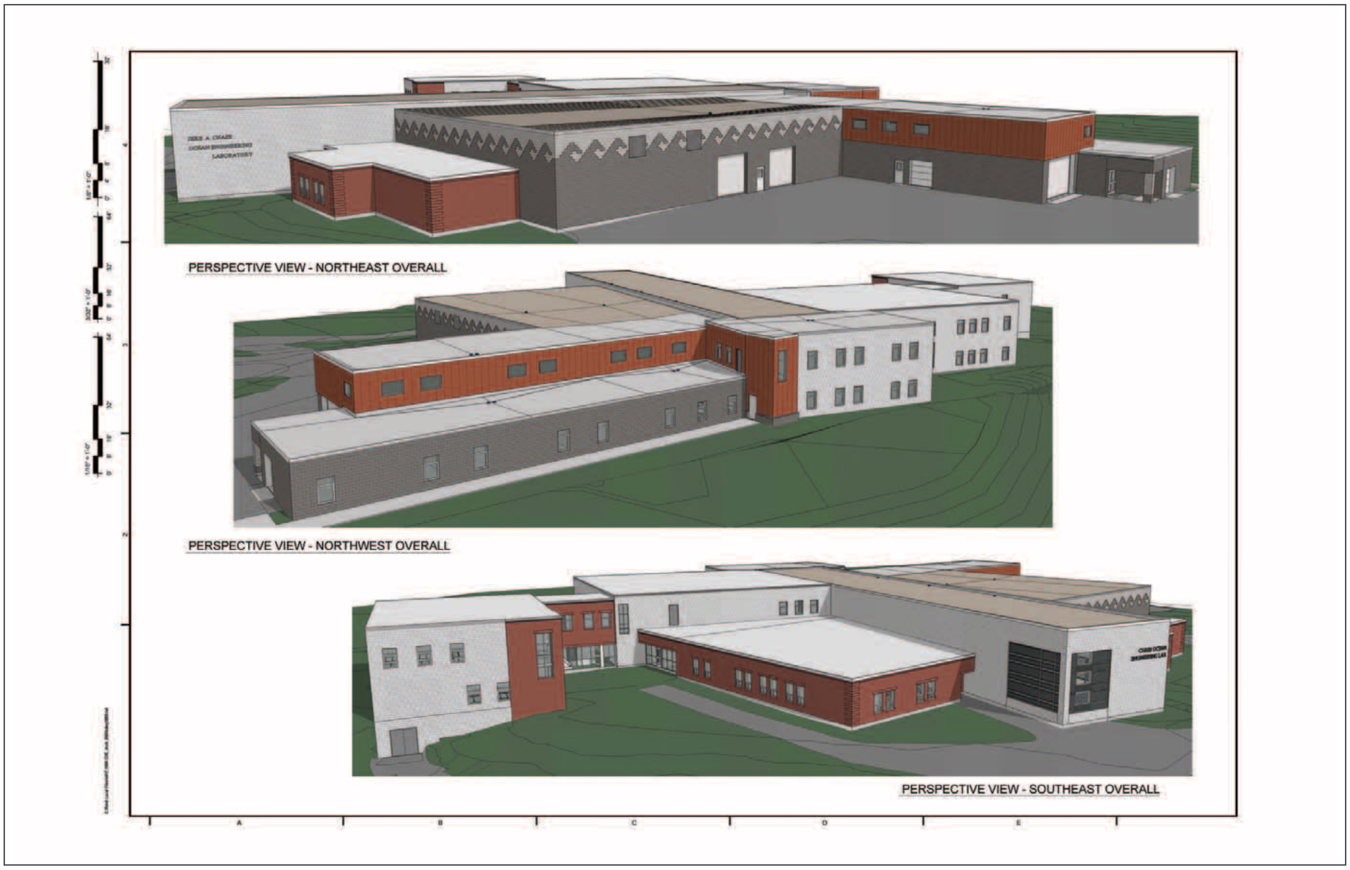


Figure I-1. Perspective views of Chase Ocean Engineering Lab and the NOAA/UNH Joint Hydrographic Center including new lab and office construction (left side of upper frames) and large classroom/seminar room (right side of lower frame).

Figure I-2. Eighty-four-seat seminar/classroom built as part of the 2017 expansion of the Chase Ocean Engineering Lab.

Laboratory Facilities

Laboratory facilities within the Center include a map room with light tables and map-storage units, and a number of specialized labs for training, equipment testing and development, visualization, and "telepresence interactions." The Center has a full suite of printers, as well as a large format, multifunction plotter. Users have the ability to print documents as large as 44 inches on the short side, as well as scan documents and charts up to 36 inches. The Center has phased out single-function laser printers in favor of fewer, more efficient multi-function printers capable of printing, scanning, copying, and faxing documents, with the last of the single function printers being retired in late 2017. A UNH-contracted vendor provides all maintenance and supplies for these multifunction printers, reducing overall labor and supply costs.

The JHC/CCOM Presentation Room houses the Telepresence Console (Figure I-3) as well as the Geowall high-resolution multi-display system. The Geowall, which features four, 55-inch 4k displays, is a multipurpose system utilized for the display of additional video streams from Telepresence-equipped UNOLS vessels, as well as educational and outreach purposes.

The hardware for the Telepresence Console consists of three high-end Dell Precision workstations used for operations and data processing, one Dell multi-display workstation for streaming and decoding real-time video, three 50" HDTV displays through which the streams are presented, and a voice over IP (VoIP) communication device used to maintain audio contact with all endpoints. The multi-display Dell workstation provides MPEG-4 content streaming via URI's Inner Space Center live streams. All systems

Figure I-3. Center Telepresence Console with the next generation of ocean mappers in command.

Figure I-4. The Center's Computer Teaching Lab.

within the Presentation Room are connected to UPS systems to protect against power surges and outages. Over the last several field seasons, the Center has remotely participated in research aboard the NOAA Ship *Okeanos Explorer* and Ocean Exploration Trust's exploration vessel *Nautilus* on their respective cruises. The Center's IT Group expects to use both the Telepresence Console and the Geowall to support these research efforts in the future, as well as utilize the hardware for additional programs, including plans to livestream local vessel ops during the 2023-24 seasons, and provide support for a number of JHC/CCOM outreach initiatives.

The Center's Computer Classroom consists of 15 Dell workstations (Figure I-4). A ceiling-mounted NEC high resolution projector is used to provide classroom instruction. All training that requires the use of a computer system is conducted in this room. Students also frequently use the classroom for individual study and collaborative projects. In addition to these purposes, a high-resolution camera allows for web conferencing and remote teaching.

The Center's Video Classroom provides a smaller space as an alternative to Chase Lab's 84-seat lecture hall for web conferencing, remote teaching, and hosting webinars and other talks.

The IT Group collaborates with two grad student coordinators—who represent the Center and the Center for Ocean Engineering—to host a weekly live seminar/webinar. The seminar series is now in its 13th year. The IT Group plans to continue making improvements to both the quality and accessibility of these seminars through better video and audio hardware, as well as streamling the distribution of the finished product through the Center's website, Vimeo, and YouTube. A key component of these improvements is the use of UNH's Zoom web conferencing software, which provides a reliable, flexible platform for web collaboration and communication of all kinds. Additionally, the Center uses Microsoft Teams for internal collaboration, and for day-to-day communication with other groups at UNH.

The Center's Visualization Lab includes a VIVE Pro Eye eye-tracking system and a room-wide SteamVR Base Station 2.0 tracking system for collecting data in human factors studies, a range of VR headsets, an immersive large-format tiled display, custom 3D multi-touch monitors, Microsoft HoloLens and Nreal augmented reality headsets, and a virtual reality ship simulator with custom force-feedback ship's wheel and throttle. The immersive tiled display consists of six vertically mounted 82-inch 4K monitors, in a curved arc (Figure I-5), allowing it to completely fill the field-of-view of users. Its 50-megapixel resolution permits viewing of extremely large datasets without loss of detail, and is used for collaborative analysis, ship simulations, ROV telepresence, and presentations to large groups. Custom-built multi-touch stereoscopic 3D displays are used for interactive exploratory analysis of ocean flow models and other complex datasets. A Valve Index virtual reality system with a high resolution stereoscopic 3D head-mounted display, two hand-held six degree-of-freedom controllers, and a laser-based system for precisely tracking these components anywhere within the lab, allows users to naturally walk around virtual environments, e.g., a ship's bridge.

The Center is co-located with the Chase Ocean Engineering Lab. The Lab contains a high-bay facility that includes extensive storage and workspace in a warehouse-like environment. The high bay consists of two interior work bays and one exterior work bay with power, lights, and data feeds available throughout. A 5000-lb. capacity forklift is available.

Two very special research tanks are also available in the high bay. The wave/tow tank is approximately

Figure I-5. Bob Ballard, Ocean Exploration Trust president, gets a demonstration of the VisLab's Semi-Immersive Large-Format Tiled Display with Larry Mayer (left) and VisLab Director Tom Butkiewicz (right).

120 ft. long, 12 ft. wide and 8 ft. deep. It provides a 90-foot length in which test bodies can be towed, subjected to wave action, or both. Wave creation is possible using a hydraulic flapper-style wave-maker that can produce two-to-five second waves of maximum amplitude approximately 1.5 feet. Wave absorption is provided by a saw-tooth style geo-textile construction that has an average 92% efficiency in the specified frequency range. The wave-maker software allows tank users to develop regular or random seas using a variety of spectra. A user interface, written in LabView, resides on the main control station PC and a wireless LAN network allows for communication between instrumentation and data acquisition systems. Data acquisition has been vastly improved with 32 channels of analog input, four channels of strain measurement, and Ethernet and serial connectivity all routed through shielded cabling to the main control computer. Power is available on the carriage in 120 or 240 V.

The engineering tank is a freshwater test tank 60 ft. long by 40 ft. wide with a nominal depth of 20 ft. (Figure I-6). The 380,000 gallons that fill the tank are filtered through a 10-micron sand filter twice per day providing an exceptionally clean body of water in which to work. This is a multi-use facility hosting the UNH SCUBA course, many of the OE classes in acoustics and buoy dynamics, as well as providing a controlled environment for research projects ranging from AUVs to zebra mussels. Mounted at the corner of the Engineering Tank is a 20-foot span, wall-cantilevered jib crane. This crane can lift up to two tons with a traveling electric motor controlled from a hand unit at the base of the crane. In 2003, with

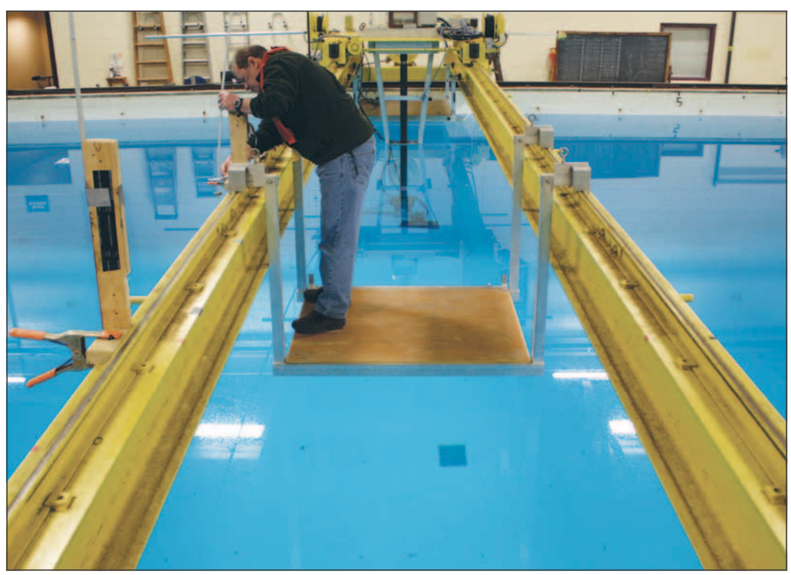


Figure I-6. Researcher Carlo Lanzoni uses the engineering tank's gantry crane to set up a field calibration test.

funding from NSF and NOAA, an acoustic calibration facility was added to the engineering tank. The acoustic test-tank facility is equipped to do standard measurements for hydrophones, projectors, and sonar systems. Common measurements include transducer impedance, free-field voltage sensitivity (receive sensitivity), transmit voltage response (transmit sensitivity), source-level measurements and beam patterns. The standard mounting platform is capable of a computer-controlled full 360-degree sweep with 0.1-degree resolution. We believe that this tank is the largest acoustic calibration facility in the Northeast and is well suited for measurements of high-frequency, large-aperture sonars when far-field measurements are desired. In 2022, the engineering tank saw approximately 30 days of use by the Center.

Several other specialized facilities are available in the Chase Ocean Engineering Lab to meet the needs of our researchers and students. A 720 sq. ft. machine shop equipped with a milling machine, a tool-room lathe, a heavy-duty drill press, large vertical and horizontal band saws, sheet metal shear and standard and arc welding capability are available for students and researchers. A 12 ft. x 12 ft. overhead door facilitates entry/exit of large, fabricated items; a master machinist/engineer is on staff to support fabrication activities.

Since 2015, dedicated space has been made available to support our autonomous vehicle activities and since 2018, the Center has also leased 1600 sq. ft. of secure warehouse space at an offsite facility near the campus (the Olson Center) to support the new Exail (formerly iXblue) DriX Autonomous Surface Vehicle which was made available to the Center in collaboration with NOAA and Exail to explore the viability of this new system for hydrographic surveys. To support these activities, we built a 30′ x 60′ cage with biometric and network monitored security, electrical power, workstation space, workbenches, tools, and tool storage. The facility also boasts overhead laterally translating cranes with lift capacity of 5 and 10 tons per bridge which allow for the maneuvering of the DriX ASV—with its launch and recovery system—into and out of this facility and onto and off of a dedicated 26′ flatbed. Additionally, the cranes are able to move the 40′ custom-built container into this facility for protection from weather. This past year, we increased the size of the facility in collaboration with Exail who will be fabricating and servicing systems there.

Pier Facilities

In support of the Center and other UNH and NOAA vessels, the University constructed a pier facility in New Castle, NH, in 2008. The pier is a 328-foot-long and 25-foot-wide concrete structure with approximately 15 ft. of water alongside. The pier can accommodate UNH vessels and in 2013 became the homeport for the NOAA Ship *Ferdinand R. Hassler*, a 124-foot LOA, 60-foot breadth, Small Waterplane Area Twin Hull (SWATH) Coastal Mapping Vessel (CMV)—the first of its kind to be constructed for NOAA. Services provided on the new pier include 480V-400A and 208V- 50A power with TV and telecommunications panel, potable water, and sewerage connections. In addition to the new pier, the University constructed a pier support facility, approximately 4,500 sq. ft. of air-conditioned interior space including offices, a dive locker, a workshop, and storage. Two additional buildings (1,100 sq. ft. and 1,300 sq. ft.) are available for storage of the variety of equipment and supplies typically associated with marine operations.

Information Technology

The IT Group currently consists of four full-time staff members and two part-time helpdesk staff. Will Fessenden fills the role of Systems Manager and deals primarily with the day-to-day administration of the Center's network and server infrastructure, as well as the development of the Information Technology strategy for the Center. Paul Johnson, JHC/CCOM's Data Manager, is responsible for maintaining, organizing, and cataloging the Center's electronic data stores. Systems Administrator Michael Sleep serves as the IT Group's primary Linux and network administrator, as well as the backup for many other system administration roles. Christopher Schwartz fills the role of desktop administrator and coordinates the IT Group's hourly L1/L2 technicians in the upkeep of endpoint technology. In addition to the full-time staff, Seagoing Laboratory Specialist Daniel Tauriello provides systems administration for R/V *Gulf Surveyor*, and serves as technical liaison between the IT Group and the Center's marine research platforms and teaching facilities.

IT facilities at JHC/CCOM consist of a primary data center, four network closets (two at Chase Lab, one at the Olson Center, and one at the UNH Pier Support Facility), an information technology laboratory, two technology-equipped classrooms, a computer teaching lab, and several staff offices. The primary data center in the south wing of Chase houses the majority of the backend IT infrastructure at the Center. This space, combined with the two other network closets, give JHC/CCOM's data centers the capacity to house 22 full-height server racks. The primary data center is equipped with redundant air conditioning, temperature and humidity monitoring, security cameras, and FE-227 fire suppression systems. Additionally, the IT Group employs a natural gas generator to provide power to the primary data center in the event of a major outage. The IT lab provides ample workspace for the IT Group to carry out its everyday tasks and securely store sensitive computer equipment. The IT staff offices are located adjacent to the IT lab.

All JHC/CCOM servers, storage systems, and network equipment in the primary data center are consolidated into nine full height cabinets with one or more uninterruptible power supplies (UPS) per cabinet. At present, there is a total of 20 physical servers, 38 virtual servers, two NetApp storage systems fronting 16 disk arrays, and two compute clusters consisting of 12 total nodes. A Palo Alto Networks PA-5250 firewall provides boundary protection for the Center's 25-gigabit (25Gb), 10-gigabit (10Gb) and 1-gigabit (1Gb) Local Area Network (LAN). The Center's network is a LAN segment connected to the greater UNH network, and in early 2021, with a current throughput to the Internet at 10Gb. In addition, the Center has access to NSF's Science DMZ, a non-public network designed for high-speed transport of data between educational and government institutions. JHC/CCOM has a 20Gb link at Chase Lab to and from there, a 10Gb connection to many other endpoints, including data centers at NOAA's headquarters in Silver Spring, MD, and NOAA's National Centers for Environ-mental Information in Boulder, CO.

In addition to the Center's PA-5250 firewall, core internal networking equipment consists of 9x Dell N-series switches in a logical stack configuration. This provides 168x 25Gb/10Gb Ethernet ports for both edge network equipment and endpoints, as well as 288x 1Gb ports to that same end. The 25Gb throughput allows for high-speed interconnect between compute cluster, storage, application servers, and select endpoints, with sufficient connectivity for future upgrades. At the edge of the JHC/CCOM network, a Brocade ICX 6610 switch stack provides 192x 1Gb Ethernet ports for workstation connectivity and 32x 10Gb Ethernet ports, to be used for access to the network backbone as well as for certain workstations needing high-speed access to storage resources. These Brocade edge switches are supplemented with three Dell N-series enterprise-class edge switches for 120x additional 1Gb ports, a Ubiquiti Unifi wireless network platform with 10x 802.1ac access points, and a Dell Brocade 6505 16Gb Fibre Channel switch. The Dell and Brocade switches, at both core and edge, also provide Power-over-Ethernet (PoE) ports power the wireless access points as well as the various Axis network cameras used to monitor physical security in the Chase Lab data centers. The Ubiquiti wireless access points provide wireless network connectivity for both employees and guests. Access to the internal wireless network is secured through the use of the 802.1x protocol utilizing the Extensible Authentication Protocol (EAP) to identify wireless devices authorized to use the internal wireless network.

In addition to providing traditional firewall security for the JHC/CCOM network, the Palo Alto Networks PA-5250 threat prevention appliance also provides high-performance packet filtering, intrusion prevention, malware detection, and malicious URL filtering. Further, the appliance also serves as an SSL VPN portal, which permits access to the Center's network services remotely. This not only allows offsite employees continued access to all facets of the Center's network, but facilitates site-to-site connection for R/V *Gulf Surveyor*, as well as the control van for the ASV Group.

Server infrastructure at JHC/CCOM can be classified in three different categories: physical, virtual, and hosted. Traditional server-based infrastructure at JHC/CCOM currently consists of a Windows Server 2016 domain controller, VMWare host servers, CPU and GPU compute clusters, two backup servers, two GIS web portal servers, and a few other application servers.

In the virtual space, the IT staff utilizes a three-host VMware ESX cluster managed as a single resource with vSphere. The cluster utilizes VMware High Availability and vMotion to provide a flexible platform for hosting virtual machines. All virtual machines in the cluster are stored in the Center's high-speed SAN storage system, which utilizes snapshots for data protection and deduplication for storage efficiency. An additional VMware ESXi host serves as a test platform. Together, these systems can serve over 100 virtual servers at any time, though the typical virtual server load is between 30 and 50. Current JHC/CCOM servers in the virtual space include the primary email server, SpamTitan email security appliance, CommVault Simpana management server, Visualization Lab web server, the ASV Lab application server, JHC/CCOM's Certification Authority server, several Linux/Apache web servers, a

Figure I-7. Center SAN and NAS infrastructure in the primary server room.

Windows Server 2016 domain controller, a FTP server, two Oracle database servers, and a ESRI ArcGIS development server, and several application servers.

Akin to the local virtual server infrastructure is the Center's growing cloud/hosted infrastructure, which currently utilizes three different providers – Amazon Web Services (AWS), Microsoft Azure, and Digital Ocean (DO). Currently, the IT Group administers five Center-specific platforms in the cloud space – CommVault Metallic (AWS), HydrOffice (DO), EPOM (DO), and SmartOcean (Azure) and Netapp FSX (AWS). As needs evolve, the IT Group plans to continue the trend towards cloud computing where efficient, convenient, and cost-effective.

The Center currently hosts onsite enterprise storage for its research, academic, and administrative needs The JHC/CCOM's storage area network (SAN) cluster consists of two NetApp FAS8020 nodes and two NetaApp FAS2650 nodes, with a total usable capacity of roughly 900TB (Figure I-7). Like the previous generations of NetApp storage systems at the Center, the SAN nodes operate in a high-availability cluster, offer block-level de-duplication and compression to augment efficiency of disk usage, and support a number of data transfer protocols, including iSCSI, Fibre Channel, NFS, CIFS, and NDMP. In addition to the robust management tools available in NetApp's OnCommand software, the IT Group utilizes Microsoft's Distributed File System (DFS) to organize all SAN and NAS data shares logically by type. A custom metadata cataloging web application was developed to make discovering and searching for data easier for both IT Staff and the Center as a whole.

Constantly increasing storage needs create an ever-increasing demand on JHC/CCOM's backup system. To meet these demands, the IT Group utilizes a CommVault Simpana backup solution which consists of two physical backup servers, three media libraries, and the Simpana software management platform. This environment provides comprehensive protection for workstation, server, and storage systems. Simpana utilizes deduplicated disk-to-disk backup in addition to magnetic tape backup, providing two layers of data security and allowing for more rapid backup and restore capabilities. For magnetic tape backup, the IT Group utilizes a pair of Dell PowerVault TL4000 LTO7 tape libraries, capable of backing up 250TB of data without changing tapes. Full tapes from both libraries are vaulted in an off-site storage facility run by Iron Mountain. Additional upgrades were made to the system in 2022, including a platform update to for newer OS support (namely Windows Server 2022, RHEL 9, and ARM-based MacOS), as well as the addition of cloud-based CommVault Metallic backup clients for laptop and offsite users. Metallic allows for remote users to have better backup coverage while reducing the network throughput burden on JHC/CCOM's core network services, instead utilizing a NIST-compliant private backup cloud for backup processes.

The IT Group maintains two modern compute clusters: an eight-node, 160-core Dell compute cluster, running Windows HPC Server 2012 R2 (Figure I-8), and a four-node, 96-core custom built cluster, running Windows Server 2016. The Dell cluster utilizes eight enterprise-class servers with 20 CPU cores and 64 GB of RAM per system, totaling 160 CPU cores and 512 GB of RAM. The custom-built cluster has 24 cores and 64GB of RAM per system, but specializes in GPU-based data processing, employing 2x RTX-based Nvidia video cards per node. Presently, the Dell cluster serves as a platform for development of Windows cluster-based applications, while also running MATLAB Distributed Compute for both academic and research purposes. The custom-built cluster serves as both a development platform, and a GPU-based data processing platform Agisoft Metashape software, and for other image processing applications. The last 2-3 years has also seen increase in the use of AWS and Azure for project-specific data processing, and in 2021-22, the IT Group assisted in the deployment of several projects for the purposes of evaluating scalability of data processing on those respective platforms.

The Center has continued to upgrade end users' primary workstations, as both computing power requirements, and the number of employees and students have increased. There are currently 328 Windows, Linux, and MacOS workstations. All Windows workstations at the Center are running Windows 10 or Windows 11 Professional. With Microsoft introducing Windows 11 in the second half of 2021, the IT Group, in conjunction with UNH IT, are evaluating it for day-to-day use. On the Apple side, MacOS 11 on ARM have become the standard configuration for the Center's handful of Mac users. Linux servers are a mix of CentOS 7/8 and Rocky 8, with the Center's Linux desktop environment primarily using Ubuntu 20.04/22.04 LTS. In late 2020, CentOS Project announced that their long-term support model was being changed, limiting version longevity, so the IT Group made the decision to evaluate other Red Hat-based Linux platforms, and ultimately settled on the Rocky platform, which has adopted a support model similar to the CentOS model from previous versions. While evaluation continued throughout 2022, the first production Linux running Rocky were deployed in October. Deployment of Linux systems is accomplished via the IT Group's PXE server and Ansible, while deployment of Windows workstations utilizes Windows Deployment services, as well as the use of an in-house application deployment tool based on MS PowerShell and wget, developed by CCOM's desktop administrator, and aptly named "CCOM Auto-Installer."

Information security is of paramount importance for the IT Group. For the last several years, members of the JHC/CCOM staff have been working with NOS and OCS IT personnel to develop and maintain a comprehensive security program for both NOAA and JHC/CCOM systems. The security program is centered on identifying systems and data that must be secured, implementing strong security baselines and controls, and proactively monitoring and responding to security incidents. This past year, JHC/CCOM IT and NOAA OCS renewed that contract and commitment. Recent measures taken to enhance security include the installation of a virtual appliance-based email security gateway, designed to reduce the amount of malicious and spam email reaching end users. The aforementioned Palo Alto firewall was installed in 2020 to replace JHC/CCOM's legacy Palo Alto threat prevention hardware. JHC/CCOM also utilizes Windows Defender and Crowdstrike Falcon antivirus protection on Windows and MacOS systems at the Center, with Clam AV being utilized on Linux workstations and servers. Microsoft Windows Server Update Services (WSUS), upgraded to version 2021, is used to provide a central location for JHC/CCOM workstations and servers to download Microsoft updates. WSUS allows the IT staff to track the status of updates on a per-system basis, greatly improving the consistent deployment of updates to all systems.

In an effort to tie many of these security measures together, the IT Group utilizes Nagios for general network and service monitoring, and CruzOC for advanced network traffic monitoring. Nagios not only provides for enhanced availability of services for internal JHC/CCOM systems, but has been a boon for external systems that are critical pieces of several research projects, including AIS ship tracking for the U.S. Coast Guard, and for monitoring service availability of offsite JHC/CCOM projects. CruzOC provides advanced network traffic monitoring, aggregates networking logs, and gives IT staff additional administrative controls on a host of local network switches and appliances. External monitoring of JHC/CCOM network uptime is also accomplished using a service called Uptime Robot, which serves as an offsite-redundant check on systems hosted on CCOM and UNH networks. In addition to Nagios, CruzOC and Uptime Robot, a security event management system, utilizing Open Source Security (OSSEC) and Splunk, is utilized for security event monitoring and reporting. OSSEC performs threat identification, and log analysis. Splunk is used for data mining and event correlation across systems and platforms.

Figure I-8. Custom GPU compute cluster in its rack, installed in 2020.

Where physical security is concerned, the Center's wing of Chase Lab utilizes an electronic door access system, which provides 24/7 monitoring and alerting of external doors and sensitive IT areas within the facility. This system was updated in 2019 to include additional security features, and to monitor additional entry and exit points. The primary data center utilizes two-factor authentication to control physical access. Security cameras monitor the data center as well as the primary network closet in the building. Redundant environment monitoring systems—one managed internally at the Center and another centrally through UNH Campus Energy—keep tabs on temperature and humidity sensors in the data center and the network closet.

The IT Group utilizes Request Tracker, a helpdesk ticket tracking software published by Best Practical. Center staff, students, and faculty have submitted over 29,000 Request Tracker tickets since its introducton in mid-2009. Through mid-2022, the IT Staff was able to address nearly 100%, and resolve over 93% of tickets within three business days. The software is also used for issue tracking by the JHC/CCOM administrative staff, lab and facilities support team, web development team, and scientists supporting the NSF Multibeam Advisory Committee (MAC) project.

JHC/CCOM continues to operate within a functional Windows 2016 Active Directory (AD) domain environment. This allows the IT Group to take advantage many modern security and management features available in Windows 10 and 11 operating systems. The Active Directory environment also provide DHCP, DNS, RADIUS, and DFS services. Configurations can be deployed via Active Directory objects to many computers at once through Group Policies, thus reducing the IT administrative costs in supporting workstations and servers. This also allows each member of the Center to have a single user account, regardless of computer platform and/or operating system, reducing the overall administrative cost in managing users. In addition, the Center's IT Group maintains all NOAA computers in accordance with OCS standards. This provides the NOAA-based employees located at the Center with enhanced security and data protection. When support for Windows Server 2008 R2 and Windows 7 ended in January 2020, the IT Group migrated all AD and related services in its environment to Windows Server 2016, and is now utilizing Windows Server 2019 for current server deployments.

JHC/CCOM utilizes Bitbucket to facilitate software collaboration between its own members as well as industrial partners and other academic colleagues. Bitbucket is a source control management solution that hosts Mercurial and Git software repositories. Atlassian, the company behind Bitbucket, states that Bitbucket is SAS70 Type II compliant and is also compliant with the Safe Harbor Privacy Policy put forth by the U.S. Department of Commerce. Given Bitbucket's flexibility and ease-of-use, the IT Group migrated its local SVN/Mercurial repositories hosted locally to the Bitbucket platform in 2019-20. This move reduces the administrative overhead while giving users more options for collaboration, particularly with government and industry partners. In addition to Bitbucket, Github repositories are also used on a project-specific basis.

The Center's website, http://ccom.unh.edu, utilizes the Drupal content management system which allows content providers within the Center to make changes and updates with limited assistance from web developers. Drupal also allows for the creation of a more robust platform for multimedia and other rich content, enhancing the user experience of site visitors.

Work also continues on several other web-based platforms, providing services for users within the Center, as well as for the general public. The Center continues to utilize an Intranet services platform using Drupal content management software. The Intranet provides a centralized framework for a variety of information management tools, including the Center's wiki, purchase tracking, library, data catalog, and progress reporting systems. The progress reporting system is now in its ninth reporting period and has been an instrumental tool in the compilation of this annual progress report. Launched in 2019, the aforementioned JHC/CCOM ePOM platform now provides current and future students, as well as other members of the academic community, with educational resources for the learning of the Python programming language, which is an important component of the Center's academic program. Additionally, the Center's ArcGIS data services server recently received both a hardware upgrade and an ESRI Portal update, which provides a wide variety of web-based GIS resources. This platform now serves data more efficiently than the two Legacy servers it replaced, and can be customized for project-specific workflow, as it's currently doing for both JHC/CCOM's Law of the Sea research, as well as its contributions to the Seabed 2030 initiative. As all of these web resources evolve, more web services may be brought online to assist in the search for Center-hosted data and access to this data through Intranet-based mapping services. Work is currently underway to develop additional functionality for the Intranet, including a more comprehensive inventory management system, and updates to Request Tracker.

Research Vessels and Platforms

For many years the Center operated two dedicated research vessels, the 40-foot R/V *Coastal Surveyor* (owned and operated by the Center) and the 34-foot R/V *Cocheco* (NOAA owned, and Center maintained and operated). Several years ago, it became increasingly clear that our workhorse survey vessel, the R/V *Coastal Surveyor*, was reaching the limit of its useable service life and that the R/V *Cocheco* was not a suitable candidate to take over the role as a bathymetric sonar-mapping platform. The *Coastal Surveyor's* fiberglass hull was delaminating, and a number of drivetrain failures had been encountered, some in hazardous areas with students on-board. *Coastal Surveyor* was also very limited in her capabilities as an educational platform due to the limited space in the cabin. R/V *Coastal Surveyor's* greatest strength was the versatile transducer strut that allowed for the robust installation of many different instruments, albeit that the installation of these systems was cumbersome and not without risk. Given this situation, we embarked in 2015 on the acquisition of a new vessel that offers the same versatility for instrument deployment (in a much easier fashion), while providing better cabin space to accommodate students, researchers, and navigation crew. We took delivery of this new vessel—the R/V *Gulf Surveyor*—in April 2016 and have been successfully using her since. Given the success and utility of the R/V *Gulf Surveyor*, the R/V *Cocheco* was retired in 2019.

R/V Gulf Surveyor

(48 ft. LOA, 18 ft. beam, 4.6 ft. draft, cruising speed 14 knots)

The *Gulf Surveyor* (Figure I-9) was designed specifically for coastal hydrography and was constructed by All American Marine, Inc. (AAM) in Bellingham, WA and delivered in 2016. The overall design is based on the success of the R/V *Auk* that AAM built for NOAA in 2006, and the 45-foot R/V *David Folger* built for Middlebury College in 2012. At an overall length of 48 feet and beam of 18 feet, the catamaran vessel follows the advanced Teknicraft Design, Ltd. (Auckland, New Zealand) model. This includes a signature hull shape with symmetrical bow, asymmetrical tunnel, and integrated wave piercer. Main propulsion is provided by twin Cummins QSB 6.7 Tier 3 engines rated 250 bhp at 2600 rpm. Auxiliary power is supplied via a Cummins Onan 21.5kW generator. The suite of deck gear includes a hydraulic A-frame, a knuckle boom crane, a scientific winch, a side mount sonar strut, a davit, and a moon pool with a deployable sonar strut.

The vessel has been active with a variety of projects this year serving mostly internal CCOM projects (Figure I-10) ranging from teaching, research, ground truthing, and SCUBA diving, as well as some additional external industry projects.

The most significant enhancement to the vessel is an ongoing project to improve the scientific winch level wind to improve functionality and safety for all work off the transom and specifically for towing side scan sonars.

Figure I-9. R/V Gulf Surveyor during dive operations in the Gulf of Maine.

Figure I-10. Summer Hydro students working on the R/V *Gulf Surveyor.*

The current list of scientific, navigation and support equipment includes:

Scientific Equipment

- Teledyne RD Instruments WH Mariner 600 kHz Coastal Vessel Mounted DR ADCP
- Odom THP 200/24-4/20 Transducer
- Applanix POS/MV Version 5
- Trimble Trimark 3 Radio Modem
- (2) Custom Dell Precision Rack 3930
- (4) 24" Dell Monitors
- (1) SmartOnline 6000 VA Power Module
- (1) APC 3000 VA Power Module
- Dell N303800EP-ON Network Switch
- Pepwave Max BR1 Wireless Router

Navigation Electronics

- Custom Dell Optiplex 7070 Micro Running Rose Point Coastal Explorer
- Custom Dell Optiplex 7070 Small Form Factor for CCTV Network
- AXIS Q6045 Mk II PTZ Dome Network Camera
- (2) AXIS M2014 Cameras
- FLIR M324S Stabilized Thermal Camera
- Standard Horizon VLH-3000 Loud Hailer
- Airmar 200WX Weather Station
- (2) UTEK 4-port RS-485/422 Serial to USB Converters
- (2) ICOM M-4240 Radios
- 8x8 Black Box HDMI Matrix Switch
- (4) 19" Dell Monitors

Simrad Systems

- DX64s Radar
- Broadband 4G Radar
- AP70 Autopilot
- AC80S Autopilot Processor
- RF45X Rudder Feedback Unit
- (2) QS80 Remote Steering Control
- NSO evo2 Processor
- NSO OP40 Controller
- (2) MO19T Monitors
- GS25 GPS Antennae
- RC42 Rate Compass
- RI10 Radar Junction Box

Garmin Systems

- GNX 21 Data Display
- GSD 25 Sonar Module
- GT51M-TH Transducer
- GPSMAP 8500 Processor
- GRID Remote Input Device
- GPSmap 840xs
- GCV 10 Transducer

Various multibeam sonar systems have been deployed through the moon pool using the custom designed strut for the *Gulf Surveyor.*

R/V Gulf Surveyor Research and Education Operations for 2022

Month	Days	User	Day Count
Jan	6, 7, 11 ,12, 13, 19, 21	John Hughes Clarke	7
Jan	14, 20	Klein	2
Jan	25	Semme - Lab	1
Jan	27	BAE	1
Feb	1, 8, 11, 15, 22, 25	Semme - Lab	6
Feb	9	USCG Annual Inspection	1
Feb	23	OPAL Buoy Check	1
Mar	1, 2, 8, 15, 22	Semme - Lab	5
Mar	4, 7, 11, 28	Klein	4
Mar	10, 21-25	John Hughes Clarke	6
Mar	18	Crew Training	1
Apr	1	Crew Training	1
Apr	5, 12, 19	Semme - Lab	3
Apr	18, 25	Seamanship Class	2
Apr	28, 29	Klein	2
May	11, 12, 13	John Hughes Clarke	3
May	16	Jenn Dijkstra - Diving	1
May	17-19, 24-26, 31	Larry Ward - Bottom Sampling	7
Jun	1	Larry Ward - Bottom Sampling	1
Jun	2, 3	Klein	2
Jun	6	Jenn Dijkstra - Diving	1
Jun	9-30	Summer Hydro	15
Jul	5-8	Summe Hydro	4
Jul	11-22	Jenn Dijkstra - Diving	10
Jul	25-29	Larry Ward - Bottom Sampling	5
Aug	1-2	Kongsberg	2
Aug	3-5	John Hughes Clarke	3
Aug	8-19	ASV	8
Aug	22-31	Larry Ward - Bottom Sampling	8
Sep	1-2	Larry Ward - Bottom Sampling	2
Sep	7, 14, 21	Semme - Lab	3
Sep	16	Crew Training	1
Sep	19	Outreach	1
Sep	20	Jenn Dijkstra - Diving	1
Oct	12-18	ASV	5
Oct	19-31	John Hughes Clarke	9
Nov	1-7	John Hughes Clarke	5
Nov	8	Liz Weidner - Lab	1
Nov	15	John Hughes Clarke	1
Dec	12-14	Klein	3
Dec	15-19	John Hughes Clarke	3
		TOTAL DAYS	148

ZEGO Boat—Very Shallow Water Mapping System

The Zego Boat Hydrographic Survey System is a second generation shallow water mapping research vessel (Figure I-11). The Zego Boat is a twin-hulled catamaran with a 30 hp outboard motor constructed in New Zealand with durable plastic material (distributed in the U.S. by Higgs Hydrographic, Inc.). The vessel has a very shallow draft allowing it to operate in depths as little as 40-50 cm and is very stable in the presence of both waves (breaking and nonbreaking) and strong current conditions. The vessel has a front ram assembly that allows testing and integrating of equipment much easier than possible for other vessels of this size (such as waverunner-based systems like the Center's Coastal Bathymetry Survey System; CBASS). Central to the system is an Applanix POS-MV 320 for highly accurate positioning, heading and attitude that can be integrated with a variety of multibeam echo sounders. Additional instrumentation integrated into the hulls of the vessel includes an Imagenex Delta-T MBES, Teledyne Odom Echotrac CV-100 SBES with dual frequency (200 & 24 kHz) Airmar transducer, and modular portal for a variety of RD Instruments acoustic Doppler current profilers. System displays (Figure I-12) are provided by two waterproof touch-screen monitors and with navigation by supported by Hypack.

Figure I-11. The JHC Zego Boat, a highly maneuverable and stable twin-hulled catamaran that is being outfitted into a state-of-the-art shallow water survey vessel with MBES, SBES, and ADCP capabilities.

Figure I-12. System displays on JHC Zego Boat.

Autonomous Surface Vessels

ASV BEN

In its effort to explore new and more efficient ways of collecting hydrographic data the Center has acquired a C-Worker 4 (named *Benthic Explorer and Navigator*—BEN—in honor of Capt. Ben Smith) autonomous surface vehicle from ASV Global Ltd. The C-Worker 4 is the result of a design collaboration with ASV Global with the goal of creating a platform whose sea keeping, endurance, and payload capacity are suitable for production survey operations and whose interfaces are adaptable for academic research. The vessel is approximately 4 m in length, is powered by a diesel jet drive, has a 16-hour design endurance, a 1kW electrical payload, and is outfitted with central sea-chest with retractable sonar mount (Figure I-13).

An Applanix POS/MV GNSS-aided IMU system has been installed to provide precise positioning and attitude, and a Kongsberg EM2040P multibeam echosounder, graciously provided by Kongsberg through the Center's industrial partnership program (Appendix C), has been installed for seafloor survey. Beyond the factory sensors listed below, numerous other sensors, hardware, and software systems have been integrated into BEN. These will be discussed further under Tasks 9-14.

ASV BEN Specifications

Physical

- Length overall: 3.95 m (13')
- Beam overall: 1.58 m (5'2")
- Draft: 0.4 m approx. (1'4")
- Full load displacement: 1,900 lbs. (approx.)
- Central payload seachest: 80 cm x 55 cm x 34 cm
- Hull material: 5083 marine grade aluminum with fiberglass composite hatch/superstructure
- Hull color: Signal Yellow

Payload and Sensors (Factory)

- Navigation lights
- Loud hailer
- AIS Transceiver
- Lowrance Halo20+ Dual-Band Radar
- Simrad Marine-band radar
- Axis forward-looking color camera
- Six color camera panoramic array with 360 degree coverage
- FLIR (TAU2) forward-looking infrared camera
- FLIR (AX-8) Engine Room observation camera
- Various removable UW cameras mounted to sonar plate(e.g. GoPro Hero7)
- Velodyne VLP-16 Hi-Res PUCK Lidar
- Speed through water and water temperature sensor
- Electrically actuated retractable sonar pole mount into center seachest
- Windows and Linux computers for payload and back-seat driver support
- 24V 1kW electrical payload with current monitoring and remote switching
- Kongsberg 2040P multibeam echosounder

Propulsion

- 30 hp Yanmar 3YM30 diesel engine
- Almarin water jet drive system with centrifugal clutch
- Hydraulic steering system
- Fuel Capacity: 100 liters
- Endurance: 16 hrs at 5.5 knots
- Top speed: 5.5 knots (speed through water)

Electrical

- 1.5kW 24V Alternator
- 120 Ah 24V DC Hotel Battery Bank
- 12V Starter battery
- Filtered electrical payload capacity: 1kW

Telemetry

- 35W UHF RS232 Satel Radio Modem for low-level communications and watchdog timer (watchdog timers secure fuel to engine when link is broken) Functional Range: 8-10 km.
- Kongsberg Marine Broadband Radio (MBR-179 and MBR-144): Functional Range: 12-16 km at 8 Mbps, fixed.
- Cobham COFDM IP Radio (8Mbps max, decreasing with range) Functional Range: 2 nmi at 6 m base antenna height, 4 nmi at 8 m base antenna height –not currently in use.
- 2.4GHz WiFi upgrade functional Range: 2000m
- 5.6GHz WiFi upgrade functional Range: 4000m
- Starlink High Performance dish with Roam service functional Range: Global
- Iridium Short-Burst Data. Basic telemetry updates can be provided through this system at 10-20 m intervals. *This system is installed but not currently configured.*
- AIS Class B Transceiver

Figure I-13. The Bathymetric Explorer and Navigator (BEN), C-Worker 4 model vehicle operating in the vicinity of Portsmouth Harbor, Portsmouth, NH.

Teledyne Oceansciences Z-boat, Seafloor Systems Echoboat, and Hydronalix EMILY Boat

The Center has also been given a Teledyne Oceansciences "Z-Boat," and a Seafloor Systems "Echoboat," each donated under the Center's industrial partnership program (Figure I-15). In addition. NOAA has provided a Hydronalix EMILY boat to add to the Center's fleet (Figure I-15). The Z-boat is equipped with an Odom CV100 single beam echo sounder and Trimble GPS and heading system. The Echoboat has been outfitted with an Ardu-Pilot based control system with commodity GPS and compass for navigation. The Emily boat is being outfitted with an Emlid Navio2 based control system with integral GPS and dual IMU. The Center has written interfaces to all of these vessels allowing them to be driven from the Center's "Project 11" robotics framework, providing a convenient platform for shallow water survey and research into new behaviors and levels of autonomy for ASVs. These vessels have proven to be a very useful platform for prototyping and testing autonomous control algorithms (see Tasks 9-16).

Figure I-14. Seafloor Systems' "Echoboat" (upper), Hydronalix "Emily Boat" (middle,) and Teledyne Oceansciences' "Z-Boat," small autonomous surface vessels used by the Center to develop autonomous command and control algorithms.

DriX Autonomous Surface Vessel

In a collaborative effort with Exail (formerly iXblue), the Center, and NOAA, several DriX Autonomous Surface Vessels have been housed and supported by the Center since December 2018. The DriX is a 7.7 m long, wave-piercing, composite composition vehicle, capable of meeting NOAA's hydrographic survey specifications at speeds exceeding 10 kts (Figure I-15). In addition, the DriX has a demonstrated endurance of three to five 24-hour days at 7 knots, providing a long-endurance capability not possible by most other vehicles of its size. The Center has facilitated installation of both an EM2040 multibeam system and an EM712 multibeam system on the DriX, a Starlink Maritime satellite communication system, and a Kongsberg MBR long-range radio for vehicle evaluation and testing both at the Center and in trials aboard NOAA and other vessels. In support of this goal, a Universal Deployment System has been tested and modified to support NOAA vessels and vessels of opportunity. See Tasks 9-14 for further details.

Figure I-15. Exail (iXblue) DriX autonomous surface vehicle being lowered into the water in its Launch and Recovery System.

DriX Specifications

Physical
- Length overall: 7.7 m
- Beam overall: 0.8 m
- Draft: 2.0 m

Telemetry
- Kongsberg Marine Broadband Radio
- Wifi

Electrial
- 24V system
- 900 W AC for survey payload

Propulsion
- Engine: 37 Hp Nanni Diesel
- Prop-driven
- Fuel capacity: 250 liters
- Endurance: Seven 24-hour days at 7 knots
- Top speed: >12 knots

Payload
- Kongsberg EM2040
- Simrad EK80 70/200 kHz
- Sonardyne HPT3000 USBL Transceiver
- iXblue PHINS AHRS with Septentrio GPS

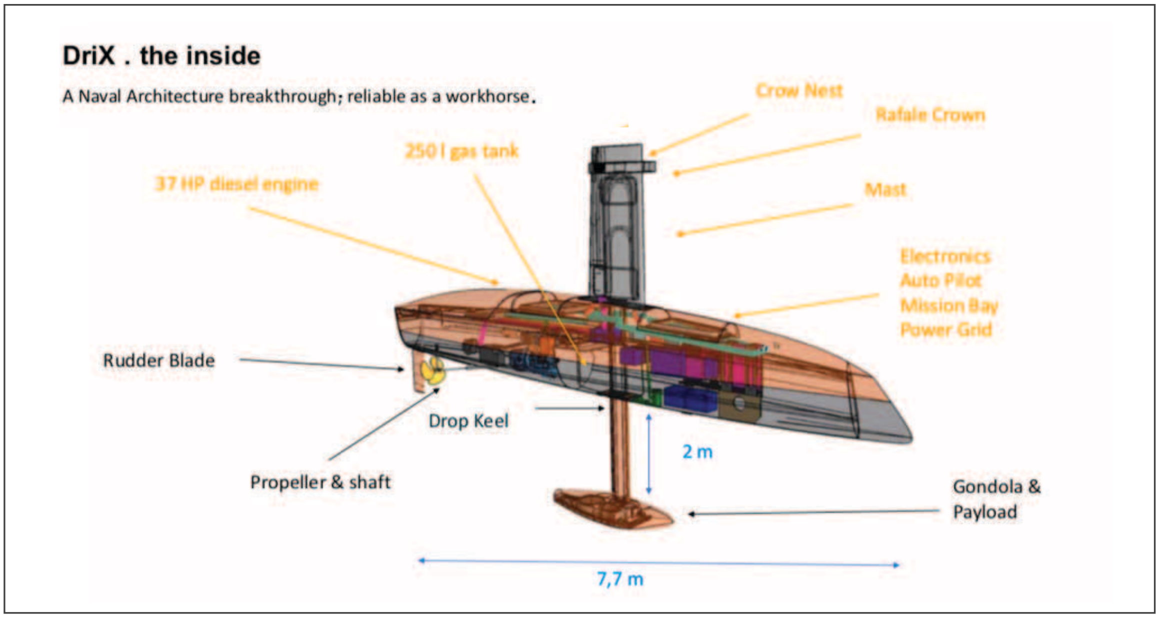


Figure I-16. Schematic of the iXblue DriX autonomous surface vehicle.

Status of Research: January–December 2022

This progress report represents reporting on the activities of the Joint Hydrographic Center during the second year of its activities under NOAA Grant NA20NOS4000196 competitively awarded to the Center for the period of 2021-2025. The Federal Funding Opportunity under which the new grant was funded outlined three programmatic priorities:

Advance Technology to Map U.S. Waters

Advance Technology for Digital Navigation Services

Develop and Advance Marine Geospatial and Soundscape Expertise

Under these, three sub-themes and 20 specific research requirements were defined (denoted by the lettered paragraphs below):

Advance Technology to Map U.S. Waters

A. DATA ACQUISITION

1. Improvement in the effectiveness, efficiency, and data quality of acoustic and Lidar bathymetry systems, their included backscatter and reflectance capabilities, their associated vertical and horizontal positioning and orientation systems, and other sensor technologies for hydrographic surveying and ocean, coastal, and Great Lakes mapping.
2. Improvement in the understanding and integration of other sensor technologies and parameters that expand the efficiency and effectiveness of mapping operations, such as water column and sub-bottom profiling.
3. Improvement in the operation and deployment of unmanned systems for hydrographic and other ocean mapping and similar marine domain awareness missions. Enhancements in the efficiency and hydrographic and related data acquisition capability of unmanned systems in multiple scenarios including shore-based and ship-based deployments and in line-of-sight and over-the-horizon operation and long duration autonomous ocean and coastal mapping data acquisition operations.
4. Improvement of autonomous data acquisition systems and technologies for unmanned vehicles, vessels of opportunity, and trusted partner organizations.

B. DATA VALUE

5. Improvement in technology and methods for more efficient data processing, quality control, and quality assurance, including the determination and application of measurement uncertainty, of hydrographic and ocean and coastal mapping sensor and ancillary sensor data including data supporting the identification and mapping of fixed and transient features on the seafloor and in the water column and the resolution of unverified charted features.
6. Development of improved tools and processes for assessment, processing, and efficient application of ocean mapping data from emerging sources such as drones, cameras and optical sensors, satellites, and volunteer/crowd-sourced observing systems to nautical charts and other ocean and coastal mapping and coastal hazard products.
7. Application of artificial intelligence, cloud services, and machine learning to the processing and analysis of hydrographic and coastal and ocean mapping data from both established and emerging sources, as well as to data from associated systems such as water level and current sensors, and from regional and global precise positioning networks.

C. RESOURCES OF THE CONTINENTAL SHELF

8. Advancements in planning, acquisition, and interpretation of continental shelf, slope, and rise seafloor mapping data, particularly for the purpose of delimiting the U.S. Extended Continental Shelf and mapping the resources of the seabed.

9. Adoption and improvement of hydrographic survey and ocean mapping technologies, including the development of potential new approaches and technologies, in support of mapping the Exclusive Economic Zone and of "Blue Economy" activities in U.S. waters such as offshore mineral and resource exploration, renewable energy development, coastal hazard planning, and the responsible management of U.S. living marine resources.

10. New approaches to the delivery of bathymetric services, including, among others, elevation models, depth comparisons and synoptic changes, model boundary conditions, and representative depths from enterprise databases such as the National Bathymetric Source and national geophysical archives.

Advance Technology for Digital Navigation Services

11. Development of innovative approaches and concepts for electronic navigation charts and for other tools and techniques supporting precision navigation such as chart display systems, portable pilot units and prototypes that are real-time and predictive, are comprehensive of all navigation information water levels, charts, bathymetry, models, currents, wind, vessel traffic, etc.), and support the decision process (e.g., efficient voyage management and under keel, overhead, and lateral clearance management) in navigation scenarios.

12. Development of improved methods for managing hydrographic data and transforming hydrographic data and data in enterprise databases to electronic navigational charts and other operational navigation products, particularly in the context of the new S-100 framework and family of associated data standards.

13. Development of new approaches for the application of spatial data technology and cartographic science to hydrographic, ocean and coastal mapping, precision navigation, and nautical charting processes and products.

14. Application of hydrodynamic model output to the improvement and development of data products and services for safe and efficient marine navigation.

15. Improvement in the visualization, presentation, and display of hydrographic and ocean and coastal mapping data, vessel data, and other navigational support information such as water levels, currents, wind, and data model outputs for marine navigation. This would include real-time display of mapping data and 4-dimensional high-resolution visualization of hydrodynamic model output (water level, currents, temperature, and salinity) with associated model uncertainty and incorporate intelligent machine analysis and filtering of data and information to support precision marine navigation.

16. Development of approaches for the autonomous interpretation and use of hydrographic and navigational information, including oceanographic and hydrodynamic models in advanced systems such as minimally staffed and unmanned vessels.

Develop and Advance Marine Geospatial and Soundscape Expertise

17. Development, evaluation, and dissemination of improved models and visualizations for describing and delineating the propagation and levels of sound in the water from acoustic devices including echosounders, and for modeling the exposure of marine animals to propagated echosounder energy. Improvements in the understanding of the contribution and interaction of echo sounders and other ocean mapping-related acoustic devices to/with the overall ocean and aquatic soundscape.

18. Development, maintenance, and delivery of advanced curricula and short courses in hydrographic and ocean mapping science and engineering at the graduate education level, leveraging to the maximum extent the proposed research program and interacting with national and international professional bodies to bring the latest innovations and standards into the graduate educational experience for both full-time education and continuing professional development.

19. Effective delivery of research and development results through scientific and technical journals and forums and transition of research and development results to an operational status through direct and indirect mechanisms including partnerships with public and private entities.

20. Public education, visualization tools, and outreach to convey the aims and enhance the application of hydrography, nautical charting ocean coastal and Great Lakes mapping and related hydrodynamic models to safe and efficient marine navigation and coastal resilience

The overarching programmatic priorities and research requirements outlined above are not inconsistent with those prescribed under earlier grants and thus the research being conducted under the current (2020-2025) grant represents a combination of the continuation of on-going research with the introduction of new research directions.

To address the three programmatic priorities and 20 research requirements, the Center divided the research requirements into themes and sub-themes and responded with 46 individual research projects or research tasks, each with an identified investigator or group of investigators as the lead (Figure I-16).

These research tasks are constantly being reviewed by Center management and the Program Manager and are adjusted as tasks are completed, merged as we learn more about the problem, or are modified due to changes in personnel. Inasmuch as we are still near the beginning of the new grant cycle, there are no modifications to report at this time, however a review will take place in the current year.

PROGRAM PRIORITIES	COMPONENT	THEMES	SUB-THEME	TASKS	PIs	TASK
ADVANCE THE TECHNOLOGY TO MAP US WATERS	DATA ACQUISITION	INTEGRATED SF MAPPING	ACOUSTIC BATHY AND BS	System Performance Assessment	PJ	1
				Underway Sensor Integration Monitoring	JHC	2
				Backscatter Calibration	TW/JHC	3
				Environmental Monitoring	JHC	4
				New Sensors	TW	5
			LIDAR	Lidar Systems, providing both Bathymetry and Reflectance	BRC/CP	6
			WATER COLUMN AND SB	Water Column Mapping	TW	7
				Subbottom Mapping	JHC/TW/LM	8
		OPS and DEPLOYMENT OF USV		Operation and Deployment of Uncrewed Vessels	RA/VS	9
				Camera Systems for Marine Situational Awareness	VS/TB/RA	10
				ML Training Data for Marine Applications	VS/KF	11
				Path Planning for Ocean Mapping	VS/RA	12
				Frameworks for Multi-Vehicle Operations	VS/RA	13
				Autonomous Sonars	VS/?	14
				Data Acquisition for Volunteer/Trusted Partner Systems	BRC	15
	DATA VALUE	DATA FROM TRAD SOURCES		Bathymetry Data Processing	BRC	16
				Backscatter Data Processing	MS/BRC	17
				Object Detection	AL	18
				Chart Features	BRC/CK	19
				Advanced Quality Assurance/Control Tools	GM/MS	20
		NON-TRAD DATA		sUAS Mapping for Safety of Navigation	VS/KG??	21
				Millimeter Resolution Mapping with Frame Sensors	YR	22
				Enhanced Underwater Data 3D Construction	JD/TB	23
				Volunteer Bathymetric Observations	BRC	24
				Alternative Uses for ICESAT-2 and Other Laser Altimeter Data	BRC/ USF?	25
		AI/ML/CLOUD		Ocean Mapping Data Analytics	KL	26
	RESOURCES OF CONT SHELF	ECS EFFORTS		Support of US ECS Efforts	LM	27
		TECHNOLOGIES IN SUPPORT OF BLUE ECONOMY		Offshore Mineral/ Marine Resources	LW	28
				Management of Living Marine Resources from ECS Including Use of ICESat-2	JD/CP	29
				Improvements in Change Detection	JHC/AL/JD	30
				Delivery of Bathymetric Data Services from Enterprise Databases	BRC?	31
ADVANCE THE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES				Innovative Approaches to Support Precision Navigation	TB	32
				Managing and Transforming Data to Navigation Products: Computer Assisted Cartography	CK/BS	33
				Spatial Data Technology in the Context of Charting and Ocean Mapping	PJ	34
				Application of Hydrodynamic Models to Navigation Products	TB/JHC	35
				Tools for Visualizing Complex Ocean Data Sets	TB	36
				General Semiotics	CW/BS	37
				Artificial Intelligence and Machine Learning for Analysis and Filtering	KL/TB/CK	38
				Hydrographic Data Manipulation Tools	TB	39
				Real-time Display of Ocean Mapping Data	TB	40
				BathyGlobe	CW	41
				Semantic Understanding of Nautical Charts for Autonomous Navigation	VS/TB	42
DEVELOP AND ADVANCE MARINE GEOSPATIAL AND SOUNDSCAPE EXPERTISE				Contributions of Echosounders to the Ocean Soundscape	MS/TW/JMO	43
				Curriculum Development	SD	44
				Delivery of Results: Publications and Presentations	LM/ALL	45
				Outreach	THJ/CM	46

Figure I-17. Breakdown of Programmatic Priorities and Research Requirements of NOFO into individual projects or tasks with short descriptive names and PIs. Task numbers are on far right.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: DATA ACQUISITION

NOFO Requirement 1

Improvement in the effectiveness, efficiency, and data quality of acoustic and lidar bathymetry systems, their included backscatter and reflectance capabilities, their associated vertical and horizontal positioning and orientation systems, and other sensor technologies for hydrographic surveying and ocean, coastal, and Great Lakes mapping.

JHC/CCOM responded to NOFO requirement 1 with six tasks:

Task 1: System Performance Assessment (Acoustic Mapping Systems)

Task 2: Underway Sensor Integration Monitoring

Task 3: Backscatter Calibration

Task 4: Environmental Monitoring

Task 5: New Sensors

Task 6: Lidar Systems (Bathymetry and Reflectance)

TASK 1: System Performance Assessment

JHC Participants: Carlo Lanzoni, Giuseppe Masetti, Paul Johnson, Kevin Jerram, Larry Mayer

NOAA Collaborators: Tyanne Faulkes (NOAA PHB); Barry Gallagher, and Chen Zhang (NOAA HSTB), Shannon Hoy (NOAA Ocean Exploration)

Other Collaborators: Colleen Peters (Saildrone)

An overarching theme of much of the work at the Center is to assure that the very best data possible is produced from our efforts and those of our sponsors. We have approached this in many ways trying to assure quality and performance improvements at all steps along the data processing pipeline. This starts with a full understanding of the capabilities and limitations of the sonars and acquisition systems being used which we address through a state-of-the-art sonar calibration facility. We also focus on ensuring that the best data possible is collected early in the process to minimize the "total cost of ownership" (TCO) for hydrographic data, which includes not only the physical cost of collecting the data, but also the processing costs after initial collection. A characteristic of hydrographic and ocean mapping data seems to be that the cost to correct a problem increases the further from the point of collection it is detected. Consequently, we have also focused on the development of tools to monitor data in real-time, or to provide better support for data collection and quality monitoring have the potential to significantly reduce the TCO, or at least provide better assurance that no potentially problematic issues exist in the data before the survey vessel leaves the vicinity. In this context we have been investigating algorithms that could be used for real-time, or near real-time, monitoring of multibeam data, including methods for establishing baseline performance metrics for different systems, comparison methods for individual systems, and means to allow tracking of performance over time. We will also consider common methods pioneered through our NSF-funded Multibeam Advisory Committee for adaptation into shallow water environments, and visual feedback mechanisms that allow for clarity of real-time alerts for the operator.

Project: **Sonar Calibration Facility**

JHC/CCOM Participants: Carlo Lanzoni, Michael Smith, Paul Lavoie, Mike Tuttle

In order to better understand the performance of the systems we use, the Center maintains a state-of-the-art sonar calibration facility. This facility resides in the UNH Center for Ocean Engineering's large engineering tank, measuring 18m x 12m x 6m (LWD). The facility is equipped with a rigid (x,y)-positioning system, a computer-controlled rotor with better than 0.1 degree accuracy, and a custom-built data acquisition system. Added upgrades to the tank made by the Center include continuous monitoring of water temperature and sound speed, a computer-controlled standard target positioning system (z-direction), a custom-built vertical positioning system for the standard reference hydrophone (Reson TC4034), and the capability for performing automated 2D beam-pattern measurements (coupled and decoupled transmit and receive). This facility is routinely used by Center researchers for now-routine measurements of beam pattern, driving point impedance, transmitting voltage response (TVR), and receive sensitivity (RS). During 2022, measurements were made of (Figure 1-1):

1. Beam pattern evaluation of Klein 150 kHz transmit/receive array, by Carlo Lanzoni, Jay Larsen (Klein), and Jeremy Moss (Klein).

2. Beam pattern evaluation of three MITRE multi-channel arrays, by Carlo Lanzoni, Justin Tufariello (MITRE), Jeffrey Rowan (MITRE), and Andrew Dominijanni (MITRE).

3. Impedance measurements of a Kongsberg ES70-7CD, by Carlo Lanzoni and Miguel Candido.

4. Beam pattern evaluation of two MITRE autonomous transducer arrays, by Carlo Lanzoni, Justin Tufariello (MITRE), Matt Adams (MITRE), and Jeff Rowan (MITRE).

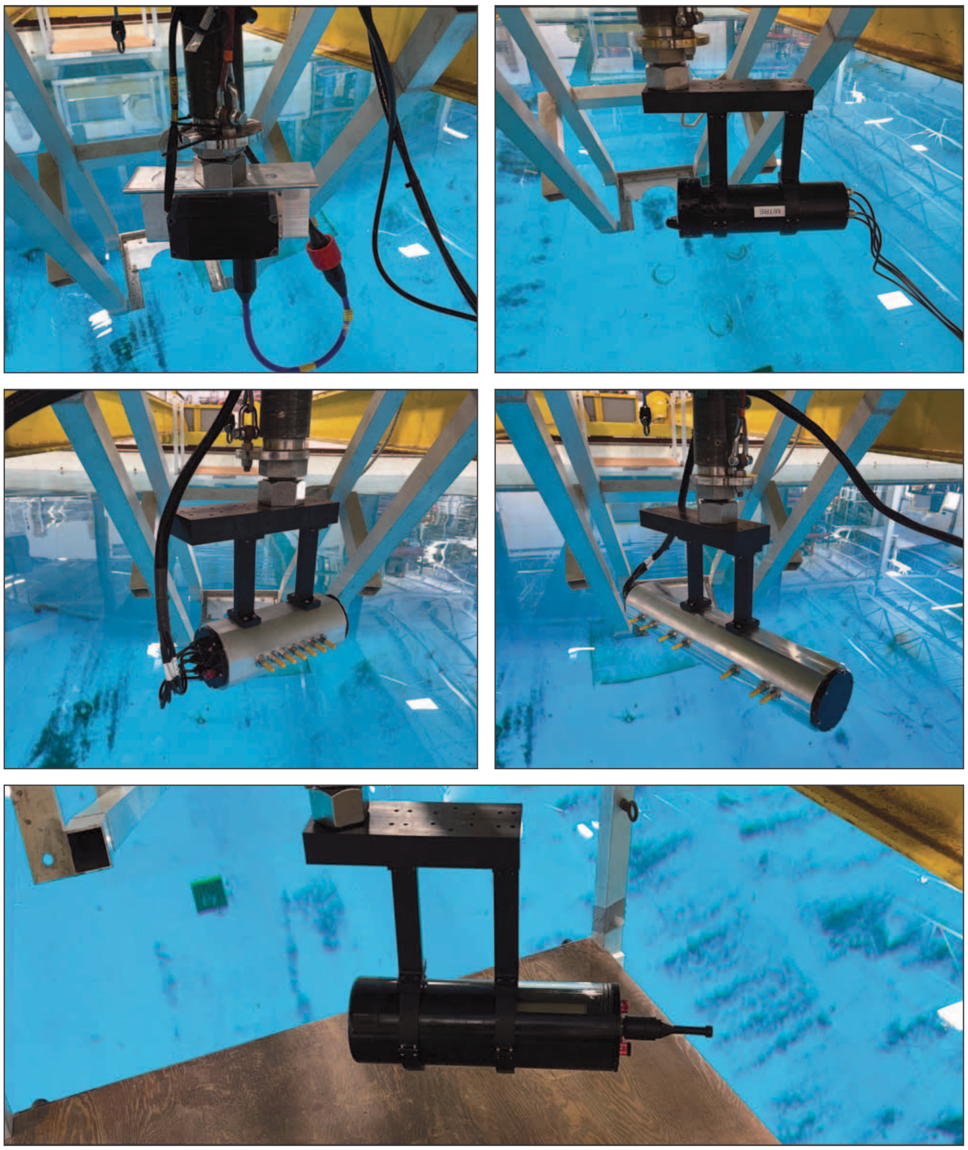


Figure 1-1. Tests in the acoustic tank in 2022. Top left: Klein 150 kHz array; Top right: MITRE multi-channel array 1; Middle: MITRE multi-channel arrays 2 and 3; Bottom: MITRE autonomous array.

Project: **Sound Speed Manager (HydrOffice)**

JHC/CCOM Participants: Giuseppe Masetti, Paul Johnson, Kevin Jerram, Larry Mayer

NOAA Collaborators: Tyanne Faulkes (NOAA PHB); Barry Gallagher, and Chen Zhang (NOAA HSTB)

To ensure high-quality hydrographic data we must also ensure that we have the tools to appropriately monitor and correct for variations in the water column that impact the quality of the data, in particular sound speed variations in the water column. The quality of the adopted sound speed profile is critical for ray tracing and bottom detection algorithms. At the same time, the use of reliable measures for temperature and salinity is crucial in the calculation of absorption coefficients. In fact, those coefficients are used to estimate the gain settings in acoustic sensors and compensate the backscatter records.

Since 2016, Giuseppe Masetti and other researchers from the Center have been collaborating with NOAA Hydrographic Systems and Technology Branch (HSTB) on the development of an open-source application to manage sound speed profiles, their processing and conversion to formats in use by hydro-graphic acquisition packages. The Sound Speed Manager (SSM) project combines HSTB's Velocipy and the Center's SSP Manager (both of which have significantly longer development histories, going back to the 1980s in the case of Velocipy). This combination merges the best of both original applications, removing code duplication and enabling a long-term support plan. SSM has now reached a good level of maturity, with an important users base spanning from the scientific community to several commercial companies. The tool is freely available through both HydrOffice and the official NOAA Python distribution (Pydro) which is also available to the public, and is promoted by the NSF Multibeam Advisory Committee. It is widely used both within the US and world-wide with nearly 6000 downloads to date and about three to four new downloads each day (Figure 1-2).

During 2022, most development was incremental, often driven by user feedback received during the year. One of the most relevant improvements has been the added support for WOA18 atlas (characterized by an increased number of profiles and thus more reliable synthetic profiles). Another focus of the ongoing development has been a better integration with Kongsberg SIS, by easing the integration with different flavors of SIS 4 and SIS 5. Furthermore, the Server Mode has been enhanced to support user customization to specific vessel needs (for instance, limited Internet bandwidth).

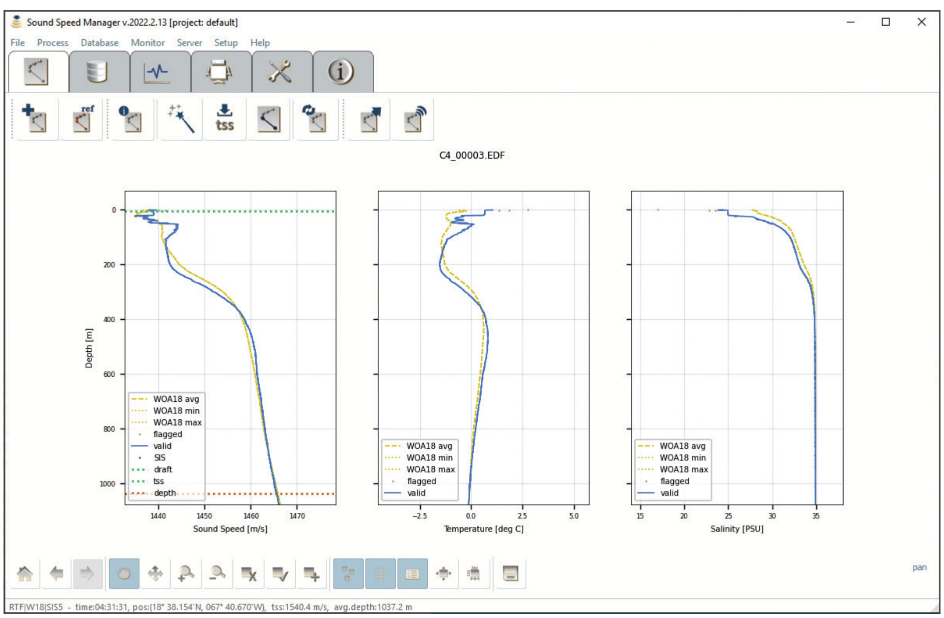


Figure 1-2. The main user interface of Sound Speed Manager with a loaded XCTD profile (in blue) compared with a WOA18 synthetic profile (in yellow).

The set of currently supported profile formats has been extended and improved. For instance, by following an active collaboration with CSIRO, their new format was added to the supported formats (Figure 1-3). Finally, a few changes have been required during the year to extend and improve supported formats (e.g., extended VPD format to support Valeport MIDAS SVP and the VP2 format to support Valeport SWIFT CTD, improved the MVP m1 format and the PSD2000 protocol).

Sound Speed Manager is a collaborative project with the Multibeam Advisory Committee (MAC) discussed below.

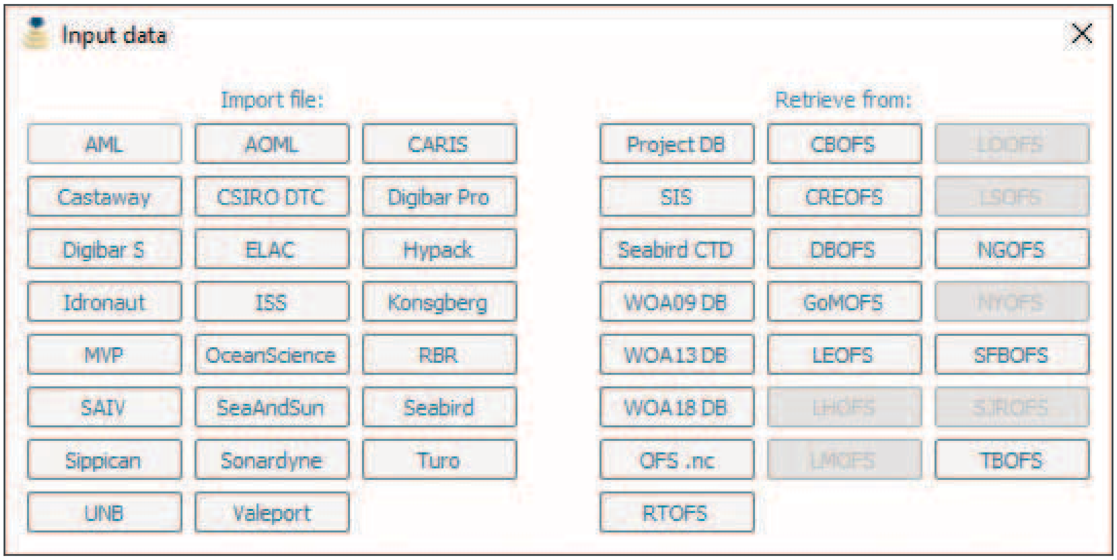


Figure 1-3. The Sound Speed Manager input dialog showing the updated list of supported profile raw formats.

Project: **Multibeam Echosounder Assessment Tools**

JHC/CCOM Participants: Paul Johnson and Kevin Jerram

NOAA Collaborators: Shannon Hoy (NOAA Ocean Exploration)

Other Collaborators: Colleen Peters (Saildrone)

Additional Funding Source: NSF Multibeam Advisory Committee

Center personnel are also working on the development of a suite of Multibeam Echosounder Assessment tools through the Multibeam Advisory Committee (MAC), sponsored by NSF. The MAC is an on-going project dedicated to providing fleet-wide expertise in systems acceptance, calibration, and performance monitoring of the UNOLS fleet's multibeam mapping systems. Since 2011, the MAC has performed systems acceptance and routine quality assurance tests, configuration checks, software maintenance, and self-noise testing for the U.S. academic fleet. These processes are also applicable to many of the mapping systems in the NOAA fleet as well as those installed aboard commercial and non-profit survey and exploration vessels.

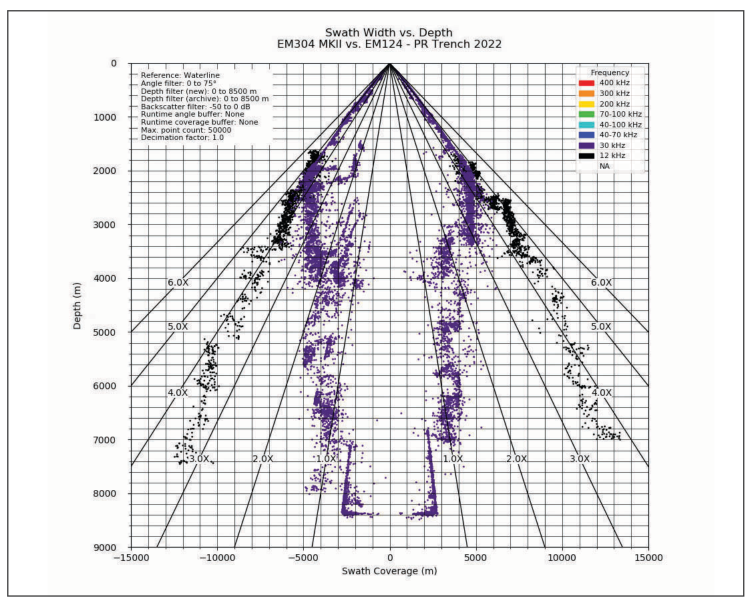


Figure 1-4. Swath coverage comparison for two different multibeam systems over the Puerto Rico Trench using MAC assessment tools. These data collected by R/V *Atlantis* and NOAA Ship *Okeanos Explorer* in 2022 will help vessel operators to select appropriate systems and maximize survey efficiency in their intended depth ranges.

Throughout 2022, Center and MAC personnel have continued the development of open-source resources to help mappers across platforms and programs. These include refinements to Python-based software tools for assessing mapping system performance and tracking hardware health. Recent feedback and lessons from NOAA, UNOLS, and manufacturers have been

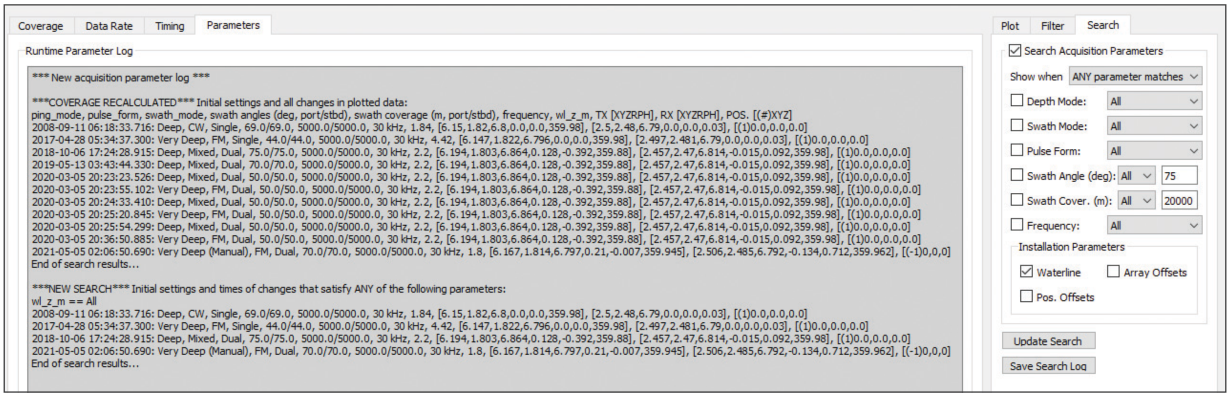


Figure 1-5. Acquisition parameter tracking and search options within the MAC swath coverage plotter. Large survey datasets or archives can be scanned to find installation and runtime parameter adjustments, such waterline changes or swath angle limitations.

incorporated in the applications, and user documentation has been expanded with 'benchmark' data examples.

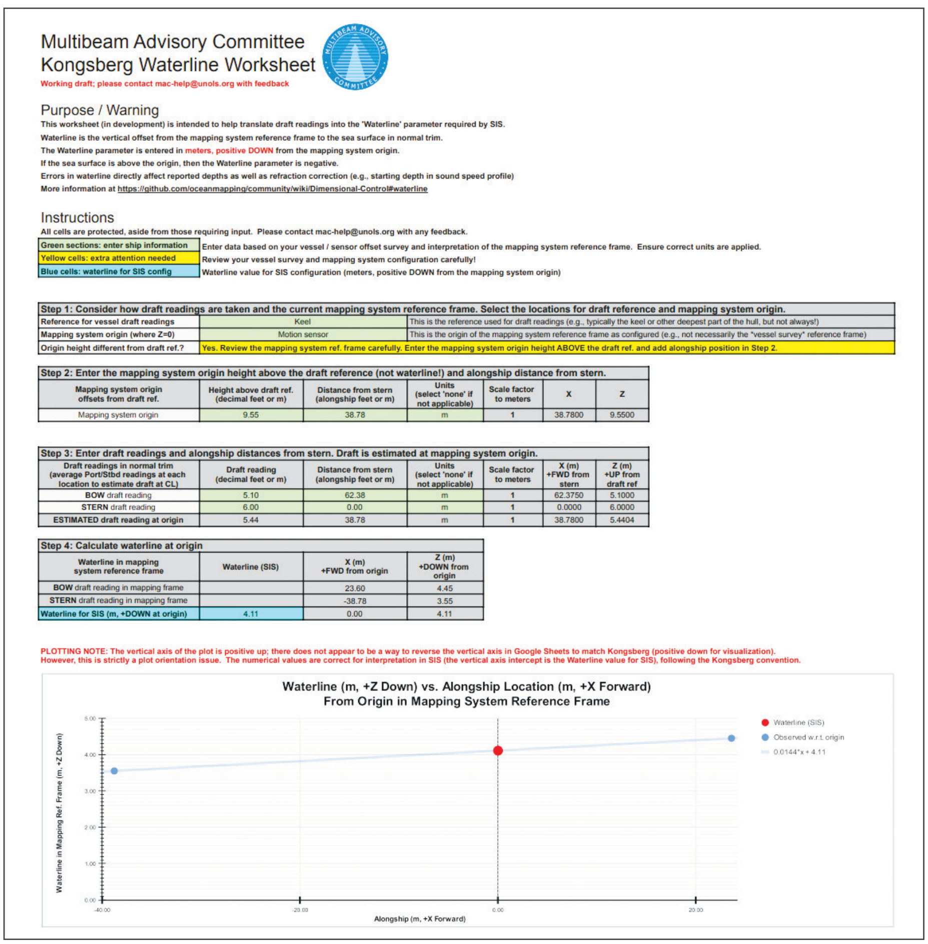


Figure 1-6. Waterline worksheet in development to help address a common point of confusion in multibeam configuration. The simplified steps translate vessel draft readings into the mapping system reference frame and estimate the waterline parameter required for SIS.

Center, MAC, and NOAA experiences show that operator engagement and early detection of complications translate to improved data quality and operational efficiency. The software tools and documentation under development are freely available and enable operators to take an active role in monitoring system performance, tracking hardware health across time, and comparing test data across systems or platforms to detect and resolve issues as early as possible.

These tools have been applied broadly in 2022, primarily for routine quality assurance testing across several UNOLS vessels. Technicians have continued to become more familiar with the tools and procedures, improving the MAC's capacity to provide remote support and develop opportunistic test plans. The tools have also been applied beyond the UNOLS fleet during performance testing aboard E/V *Nautilus*, R/V *OceanXplorer*, NOAA Ship *Okeanos Explorer*, and *Saildrone Surveyor*.

Recently, the MAC worked with UNOLS and NOAA partners to coordinate a head-to-head comparison of R/V *Atlantis* EM124 and *Okeanos Explorer* EM304 MKII swath coverage performance over the Puerto Rico Trench (Figure 1-4). The outcomes of these assessments help ensure that vessels working around the world and contributing to global mapping efforts are selecting the appropriate systems for their intended working areas and, consequently, maintaining higher data quality and operational efficiency.

Serious data quality issues and lingering complications with sonar configurations have been documented using new features in these tools, helping users and manufacturers to identify and avoid problems.

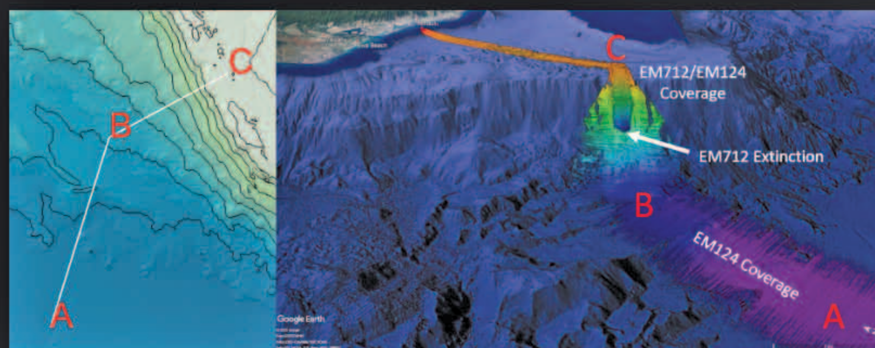
Occasionally, the solutions are relatively simple. Recent examples include acquisition parameter tracking (Figure 1-5) and a simplified worksheet to help technicians translate vessel draft readings into a waterline parameter for multibeam configuration (Figure 1-6).

Last year, the MAC partnered with Shannon Hoy (NOAA) and Colleen Peters (Saildrone, Kongsberg) to create the Ocean Mapping Community Wiki (https://github.com/oceanmapping/community/wiki). In 2022, wiki contributors focused on broadening the framework of mapping topics; expanding sections on data

Data collection

Ideally, swath coverage test data is collected under vessel operating parameters (e.g., speed, engine lineup, active sensors) that reflects 'typical' mapping configurations. For example, transit data collected at 12 kts with additional engines or generators online may not reflect the flow and machinery noise environment present at a typical mapping speed of 8 kts. Additional acoustic sensors (e.g., a bridge Doppler speed log) may cause interference and outliers in the coverage data that do not represent the standard mapping configuration with those sensors secured. Likewise, highly elevated sea state may not represent suitable mapping conditions.

The MAC recommends acquiring coverage test data at typical mapping speeds (e.g., 8-10 kts) and crossing contours at perpendicular angles wherever possible. Maintaining the ship heading directly up and down the slope is important for reducing coverage biases on either side of the swath that may result from the slope facing toward or away from the system. A coverage test line off HI for the R/V *Roger Revelle* EM124 / EM712 SAT is shown as an example of transiting 'up' and 'down' the major seafloor slopes in order to reduce port / starboard coverage biases across a wide depth range (~100-4000 m). In this example, the transit from waypoint A toward port was routed through waypoints B and C to cross contours more perpendicularly; this small amount of additional transit time produced much more useful data for coverage assessment.



Runtime parameters

The purpose of testing is to let the multibeam system achieve its maximum coverage under the mode it selects automatically for the given depth.

The following settings are generally recommended for Kongsberg EM systems to best illustrate 'automatic' system performance. Vessels that use different parameters during routine mapping should apply those settings where appropriate, aside from the maximum angle, coverage, and depth gates that may inadvertently limit the coverage test data.

Parameter	Recommended	Notes
Depth mode	Automatic	
Dual swath	Dynamic	
FM Transmission	Enabled	Read checkbox carefully [1]
Max angles	75°/75°	70°/70° for some systems
Max coverage	Maximum	Varies by model
Depth limits	As needed	Adjust as needed[2]
TX power	Maximum	0 dB
Frequency	Typical	Match 'typical' mapping freq. [3]
Pitch stabilization	Enabled	
Alongship direction	0	
Auto tilt	Off	
Yaw stabilization	RMH	Relative Mean Heading (Med.)

Figure 1-7. Example of data collection guidelines for performance testing on the new and expanding Ocean Mapping Community Wiki (https://github.com/oceanmapping/community/wiki). The GitHub platform was selected for its widespread adoption in the scientific community, issue-tracking features, and ease of linking to other code repositories (e.g., Assessment Tools, Ocean Data Tools).

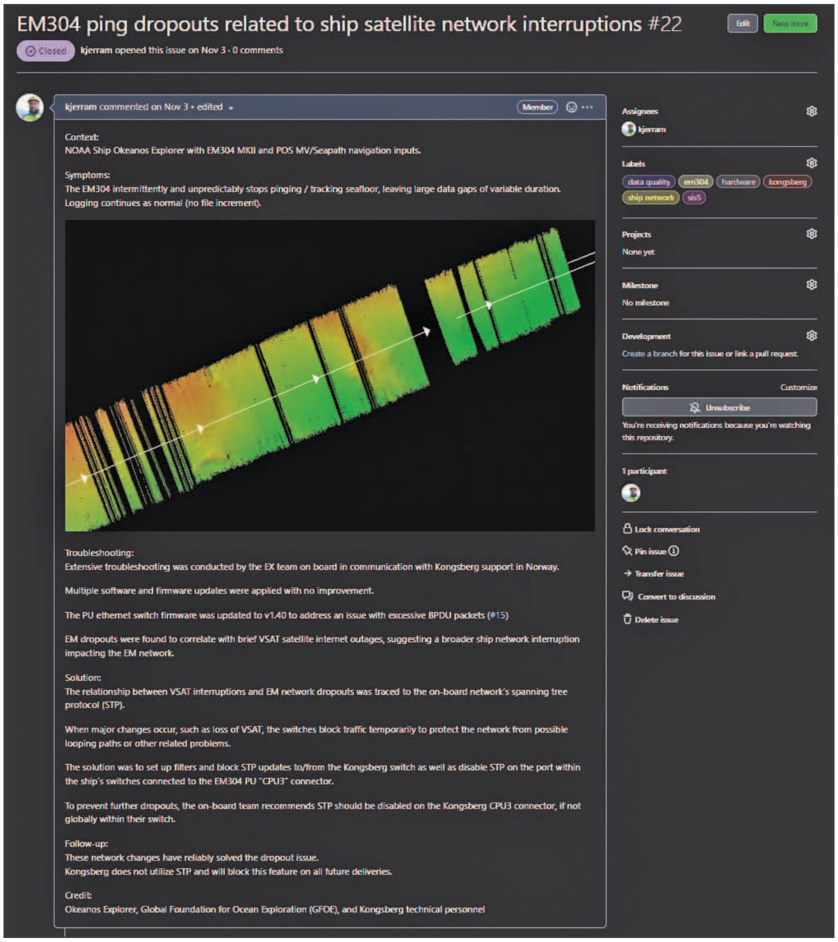


Figure 1-8. A major focus of the Ocean Mapping Community Wiki is improving the troubleshooting process by more rapidly sharing hard-won lessons across institutions. In this example from the Okeanos Explorer, a persistent sonar dropout issue was solved by NOAA, GFOE, and Kongsberg personnel and shared with the broader community.

collection for performance testing (Figure 1-7) and adding troubleshooting examples from several different fleets using GitHub's issue-tracking features. For example, a solution to a challenging sonar dropout issue provided by NOAA is highlighted in Figure 1-8. A core group of wiki users have continued to raise awareness of this resource, inviting expert contributors and presenting the concept to a variety of audiences (e.g., UNOLS RVTEC, Map The Gaps Symposium, and NOAA Survey Tech Training).

The wiki is still in an early stage and will augment (not replace) other resources hosting fixed documents, such as the MAC website and Ocean Best Practices System. While the wiki has been focused on MAC-related examples and approaches in its initial content development, it has received an enthusiastic response and helped to facilitate communications among expert and non-expert mappers, especially in sharing troubleshooting experiences. The benefit of having a central and easily updatable resource has become clear to users across the community who see opportunities to contribute their hard-won expertise and learn from other programs.

Project: **Multibeam Echosounder Test Site Database and Web Application**

JHC/CCOM Participants: Paul Johnson and Kevin Jerram

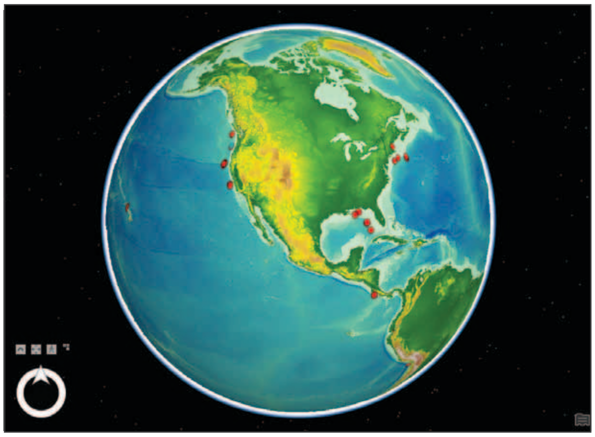


Figure 1-9. An early version of a web application for interacting with multibeam test site locations.

One of the challenges of challenges of conducting multibeam testing whether it be performance, noise, accuracy, swath, water column, or backscatter is knowing suitable locations that have the proper seafloor morphology, depths, or bottom type. As Johnson and Jerram have been working with ships of the U.S. academic fleet, oceanographic research groups, and private foundations they have had the opportunity to conduct tests in a wide variety of geographic locations, and with many different ships and sonar systems. This has allowed them to establish a number of sites that are suitable to conduct a range of multibeam tests (Fig 1-9).

In order to provide this information to the multibeam community at large, Johnson and Jerram have been assembling this information into an organized database which tracks information on each test site, including line files for each site, linkages to reports on the site, downloads of related data (e.g. reference surfaces), quality of the site, depth range of the site, and information tracking use of each of the sites. Currently Johnson and Jerram have been validating this information and incorporating it into a geodatabase (Figure 1-10) for sharing through the Center's GIS Portal (see Task 34). Once this data has been ingested and fully verified, Johnson plans on incorporating data from other contributors with test site locations, and expand the knowledge of multibeam test sites for the community.

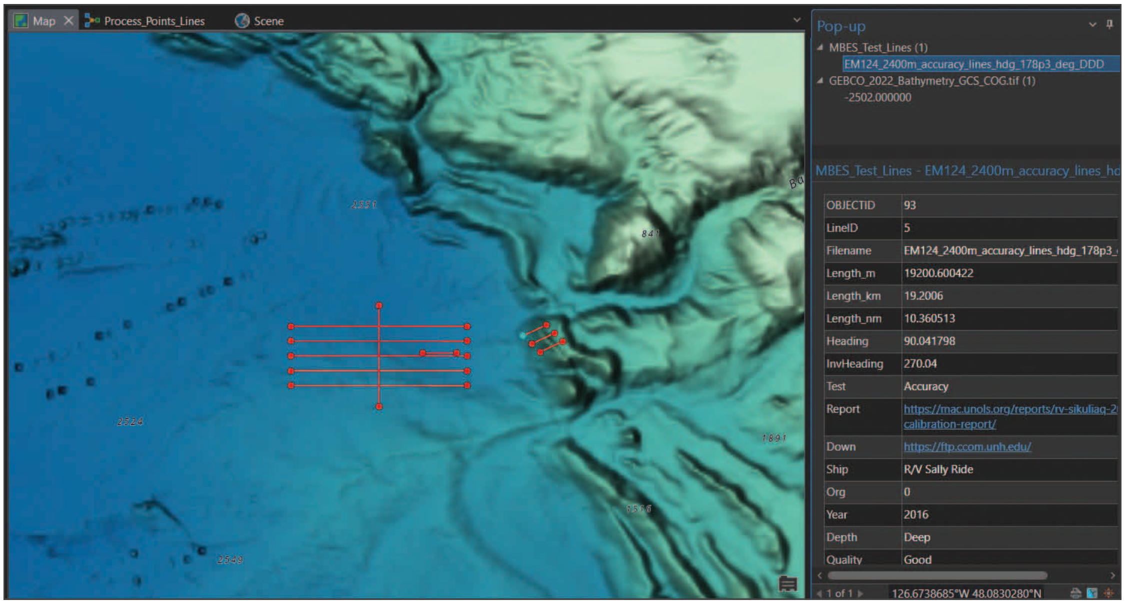


Figure 1-10. An example of an accuracy reference surface site and calibration site with metadata associated with each of the sites.

TASK 2: Underway Sensor Integration Monitoring

JHC Participants: John Hughes Clarke, Brandon Maingot, Brian Calder

NOAA Collaborators: Harper Umpress, HSPT

Other Collaborators: Rebecca Martinolich, U.S. Naval Oceanographic Office; Lt. Cdr. Juan Manzano Ruiz, Spanish Hydrographic Institute

Additional Funding Source: Kongsberg

While the tools described above are focused on assessing the overall performance of multibeam sonar systems, the tools developed in Task 2 are focused on trying to understand the causes of degradation of data quality that are the result of imperfect integration of the observed position and orientation of the sonar and the vessel. This task seeks to develop improved means of assessing performance degradation by looking at correlations between the acquired bathymetric data and the external driving forces (trajectory, rotations, and sea-state).

Project: Imperfect Integration

JHC/CCOM Participants: John Hughes Clarke, Brandon Maingot

With the ever-improving accuracy of the component sensors in an integrated multibeam system, the resultant residual errors have come to be dominated by the integration rather than the sensors themselves. Identifying the driving factors behind the residual errors (the periodic ones routinely referred to as "wobbles"), requires an understanding of the way they become manifest. As the NOAA/OCS fleet increasingly switches to multi-sector multi-swath sonars to improve operational performance, there is a growing need to rapidly identify integration errors in these complex systems. To address this issue, Brandon Maingot has evolved his M.Sc. simulation-driven analysis algorithms to work on real multibeam data streams and developed the Rigorous Inter-Sensor Calibrator (RISC) algorithm utilizes a geo-referencing model with the signature of integration errors embedded.

The RISC algorithm works by doing non-linear least-squares estimation of six (currently) potential integration errors using a finite window of data that extends for a few ocean-wave periods. Within that window, the "true" seafloor is assumed to be a smooth quadratic surface and any beam's depth departure from that surface is used as a measure of the mismatch due to the six unknowns. Because the window typically has 105 mismatched observations, minimization of the residuals is used to estimate the integration errors. The window slides forward through the data, making independent estimates. The best estimate is an increasingly-confident asymptotic average.

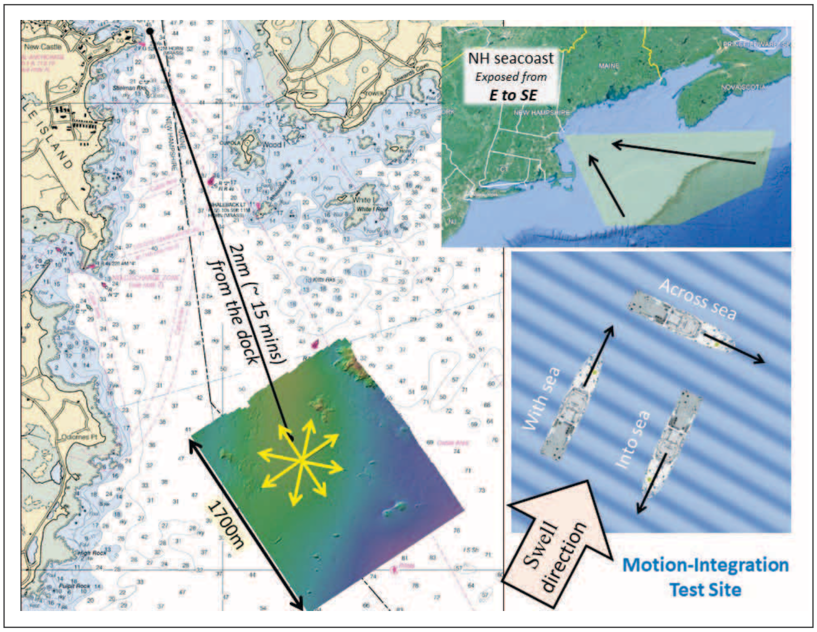


Figure 2-1. Wobble test area utilized just off Portsmouth for motion integration error analysis. By collecting data over a very flat natural terrain at different azimuths relative to the incoming wave and swell directions, a wide range of periods of roll, pitch, yaw and heave can be generated to evaluate algorithms.

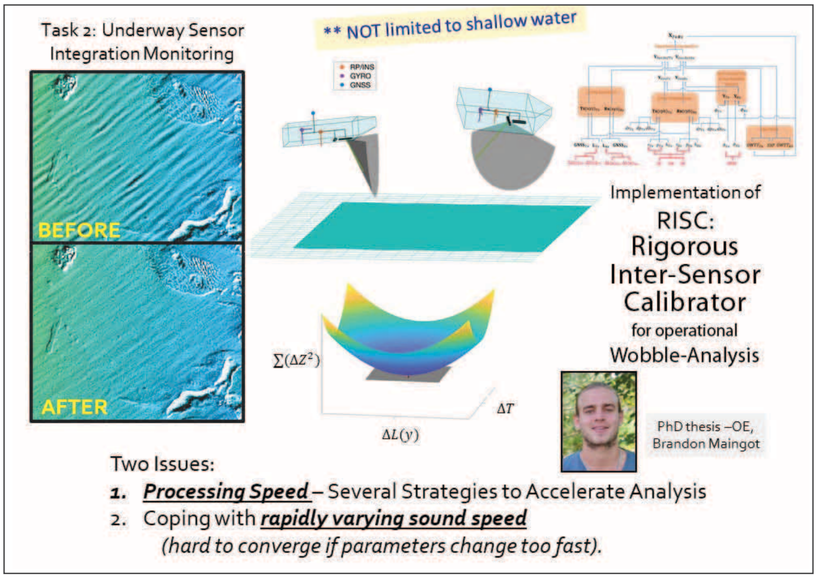


Figure 2-2. The RISC algorithm of Brandon Maingot.

Field Testing of RISC (Rigorous Inter-Sensor Calibrator)

Throughout 2022, in collaboration with Tasks 3, 4 and 30, EM2040P multi-beam data were collected over an inner-shelf sand sheet (Figure 2-1) and analyzed under varying wave conditions to test the Rigorous Inter-Sensor Calibrator (RISC) tool.

The results (Figure 2-2) clearly indicate the success of the methodology on operational data. Maingot was able to solve for five simultaneous integration errors. The only variable that could not be reliable converged on was surface sound speed. As it turned out this reflected the complex oceanographic environment due to ebb tide Piscataqua river plume (see Task 4, Indra Prasetyawan's Ph.D. thesis).

The results of the 2022 testing were presented at the CHC 2022 conference by Maingot. Besides the above-mentioned sound speed complications, the largest remaining issue is computation time. The algorithm currently requires dedicated usage of the UNH supercomputer facility.

Inter-Sector Bathymetric Mismatches—Fine Tuning Multisector Data

While we move closer to automating the management of standard integration errors, there remains a long-standing issue of inter-sector depth offsets that appear and disappear as the vessel actively yaw-stabilizes (Figure 2-3). This is common amongst OCS datasets that are acquired using EM710/2 and EM2040 systems. The short-term operational solution to this has been to disable the yaw compensation. Such an act, however, removes one of the main benefits of these sys=tems (guaranteeing even sounding density irrespective of short-period yaw motion). Recent analysis of the origins of these offsets indicates that they are due to systematic, but subtler misalignments between the Tx and the Rx. By analyzing the correlation of port and starboard sector offset signs, the likely origin is apparent. Future work needs to be done to come up with an automated method to detect and quantify the associated misalignments.

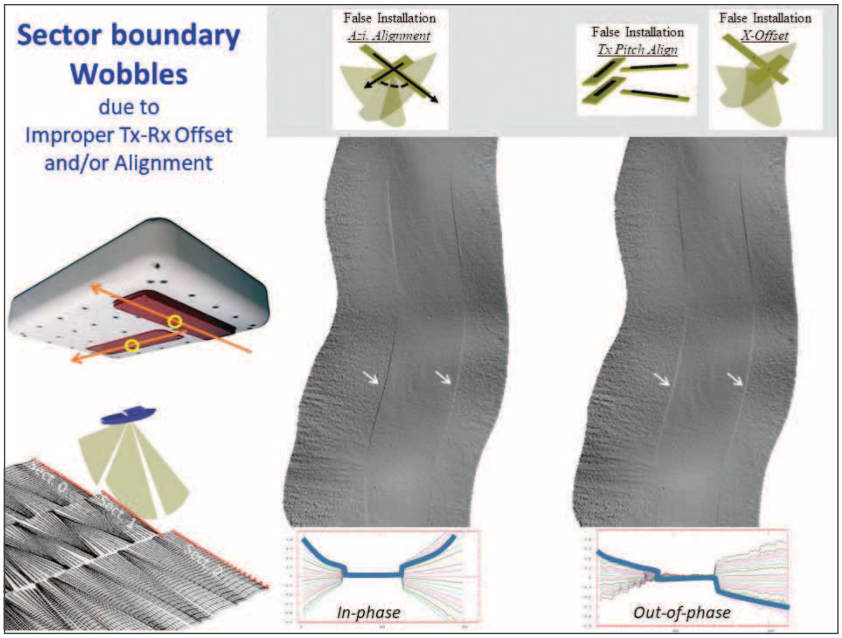


Figure 2-3. Systematic inter-sector depth offsets due to imperfect Tx-Rx alignment or offsets.

FM-Doppler Heave Wobbles

Both the OCS EM2040 and the EM710/2 multibeams utilize FM pulses in deeper waters. These are increasingly being used to extend the range performance of these higher frequency sonars. The downside of the FM pulses used is that they are sensitive to Doppler distortion of both the outgoing pulse and received echo due to instantaneous vessel velocity at Tx and Rx time respectively. To ameliorate this effect, Kongsberg monitors the 3D vessel velocities (heave, surge and sway), to calculate the resulting distortion and associated bias in the matched filtered result.

While this correction is being applied, it is apparent that it does not work perfectly. Figure 2-4 illustrates the visibility of this artefact uniquely associated with the sectors utilizing FM pulses. While these artefacts are well within IHO standards (typically only manifesting at +/-0.1-0.2% of Z), they are visible in the data under high vessel motion conditions.

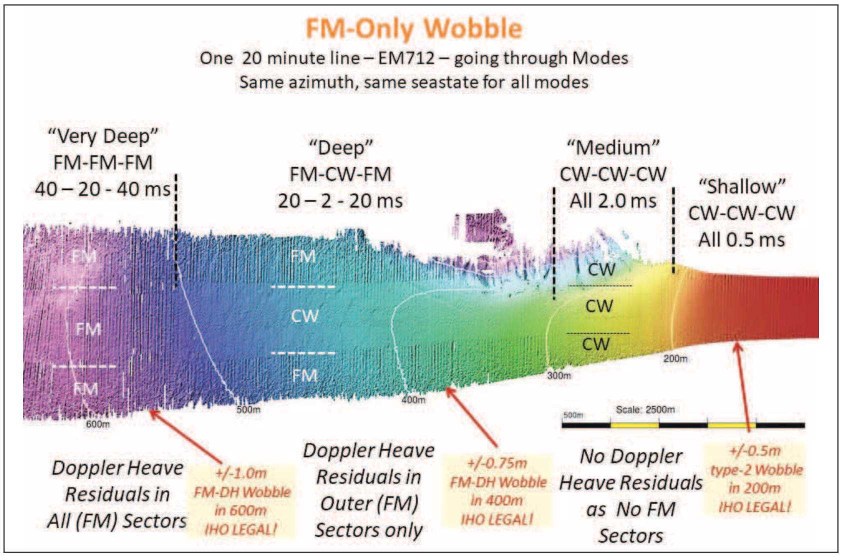


Figure 2-4. The appearance and scale of the FM-only ribbing seen in those sectors of a EM712 as it passes through almost all the available operational modes (going from < 200m to > 500m). While the FM-only ribbing is very apparent when finely gridded, it is all well within survey specifications.

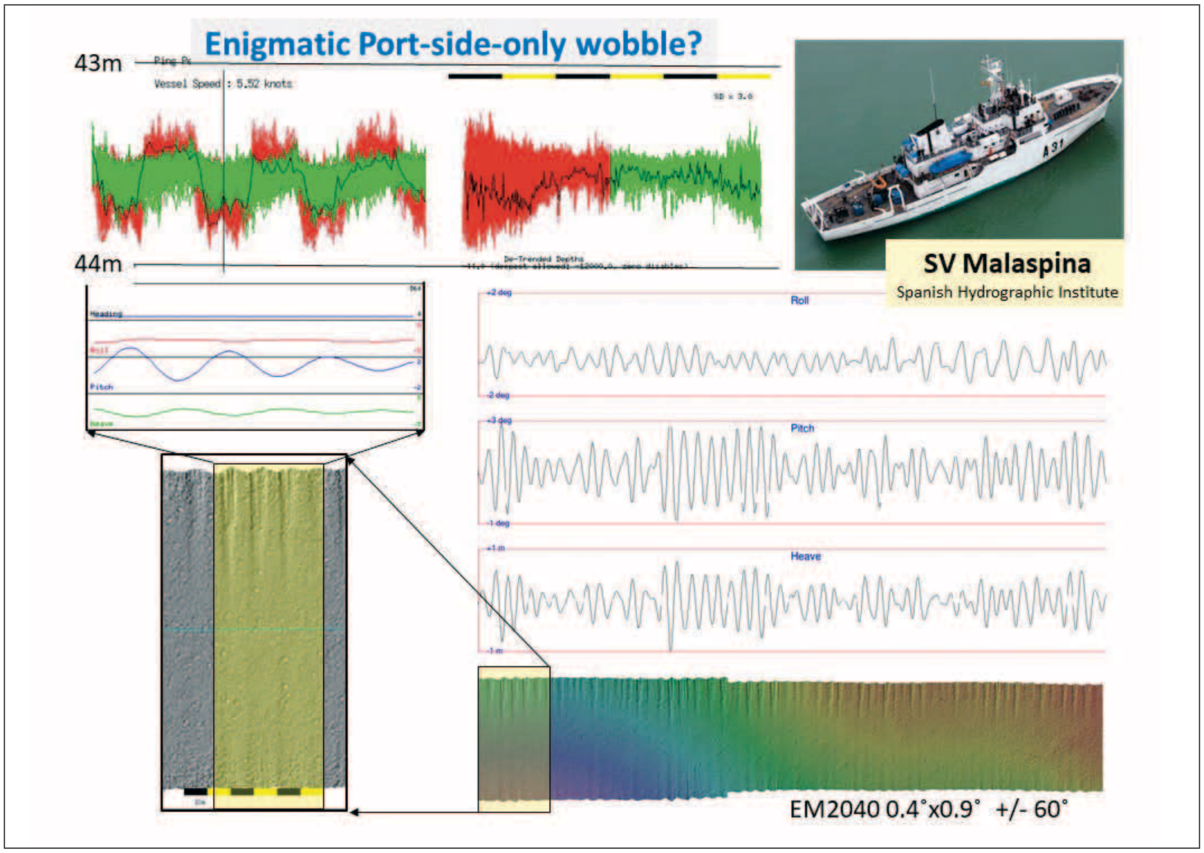


Figure 2-5. Showing the currently unexplained one-sided wobble (~1% Z) developed in EM2040 data from a system installed offset on a large gondola. Data kindly provided by LCDR Juan Manzano-Ruiz, CO of Malaspina.

Unexplained Wobbles

Even with our ever-increasing comprehension of possible sources, there still remain periodic artifacts, clearly related to vessel motion, that cannot be adequately explained by the conventional integration errors described previously. For example, NAVOCEANO, between 2007 and 2016 had a one-sided wobble, potentially related to lopsided installation on a large gondola. This has still not satisfactorily been explained. A more recent example (Nov 2022) is an artifact noted by the Spanish Hydrographic Office who operate EM2040s. The example they show (Figure 2-5) illustrates yet another one-sided wobble that cannot be explained by imperfect alignments, latency or Doppler heave related effects.

The unexplained wobble is again one-sided, is developed using the Short or Medium CW pulses (so no FM) and in only 43m of water generates a lopsided periodic error of up to 1% (0.4 m). There are no near surface sound speeds anomalies in the area. It is speculated that it is related to its lop-sided installation on a large gondola (along-side an EM304). Note that this would be exactly this same setup as is being proposed for the new NOAA AGOR-variant and Class B hydrographic ships.

TASK 3: Backscatter Calibration

JHC Participants: John Hughes Clarke, Michael Smith, Miguel Candido

NOAA Collaborators: Harper Umpress, HSTP

Other Collaborators: Anand Hiroji, USM; Rebecca Martinolich, U.S. Naval Oceanographic Office; Kjell Nilsen and Kjetil Jensen, Kongsberg Maritime; Lars Anderson and Jeff Condiotty, Simrad- KM

Additional Funding Source: Kongsberg

Our concerns about data quality during acquisition extend beyond bathymetric data to include the other major product of multibeam surveying, seafloor backscatter data. Task 3, "Backscatter Calibration," addresses a known deficiency in our current handling of backscatter strength measurements obtained by underway swath systems and supports NOAA's long-standing efforts in seabed substrate identification which, with the November 2019 announcement of the Presidential Memorandum on Ocean Mapping, now specifically calls for characterization of the U.S. EEZ as a priority objective. The operational problem faced with backscatter data collection is that no two (nominally identical) multibeam systems provide the same estimate of the bottom backscatter strength. Even for a single instance of a multibeam system, as the mode of operation changes (pulse length and sector-frequency combination), the backscatter estimate often changes.

Inter-Platform Cross Calibration

Following on from long-standing NOAA OCS backscatter inter-calibrations performed on the *Rainier* and *Fairweather* at a calibration site in Puget Sound, NAVOCEANO has been utilizing

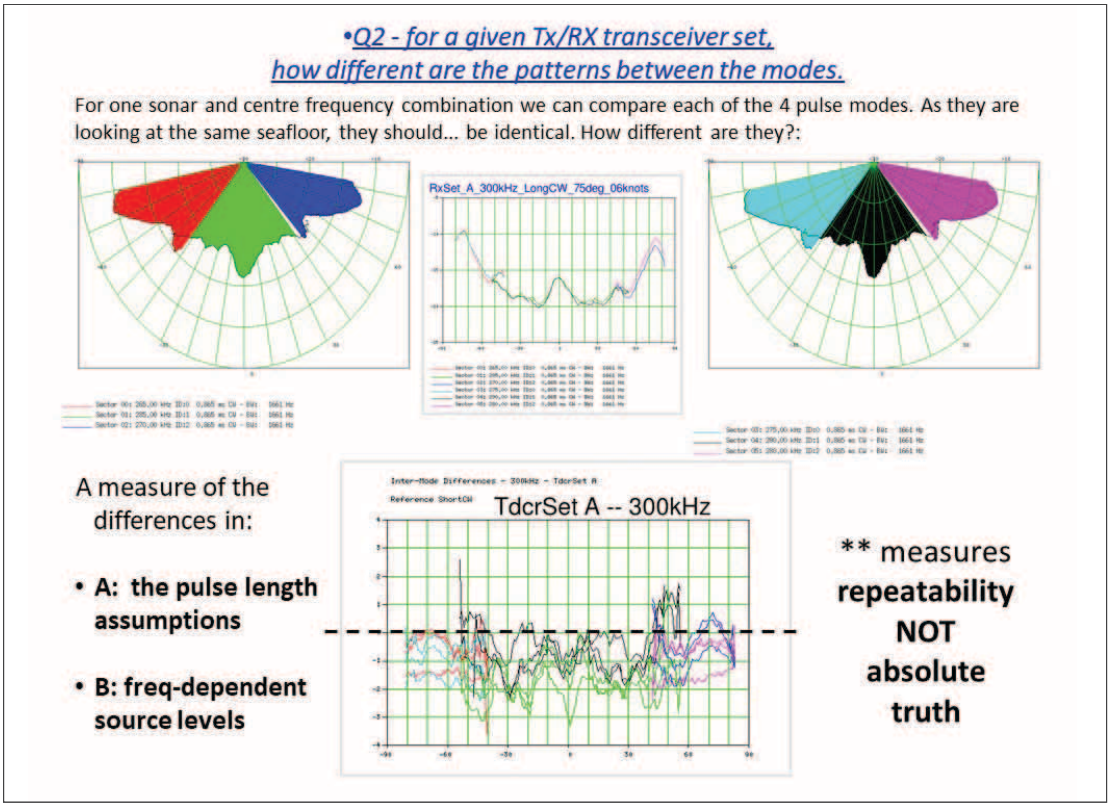


Figure 3-1. A comparison of the apparent bottom backscatter strength output by a single EM2040 Tx/Rx-transceiver combination, sorted by elevation angle for 4 different pulse modes and for each of the 3 sectors for each of the two swaths. The upper plot shows the patterns for the first (left) and second (right) swaths of a single mode. The bottom plot illustrates the inter-mode differences, using one as a reference. As can be seen the typical difference is up to 2dB.

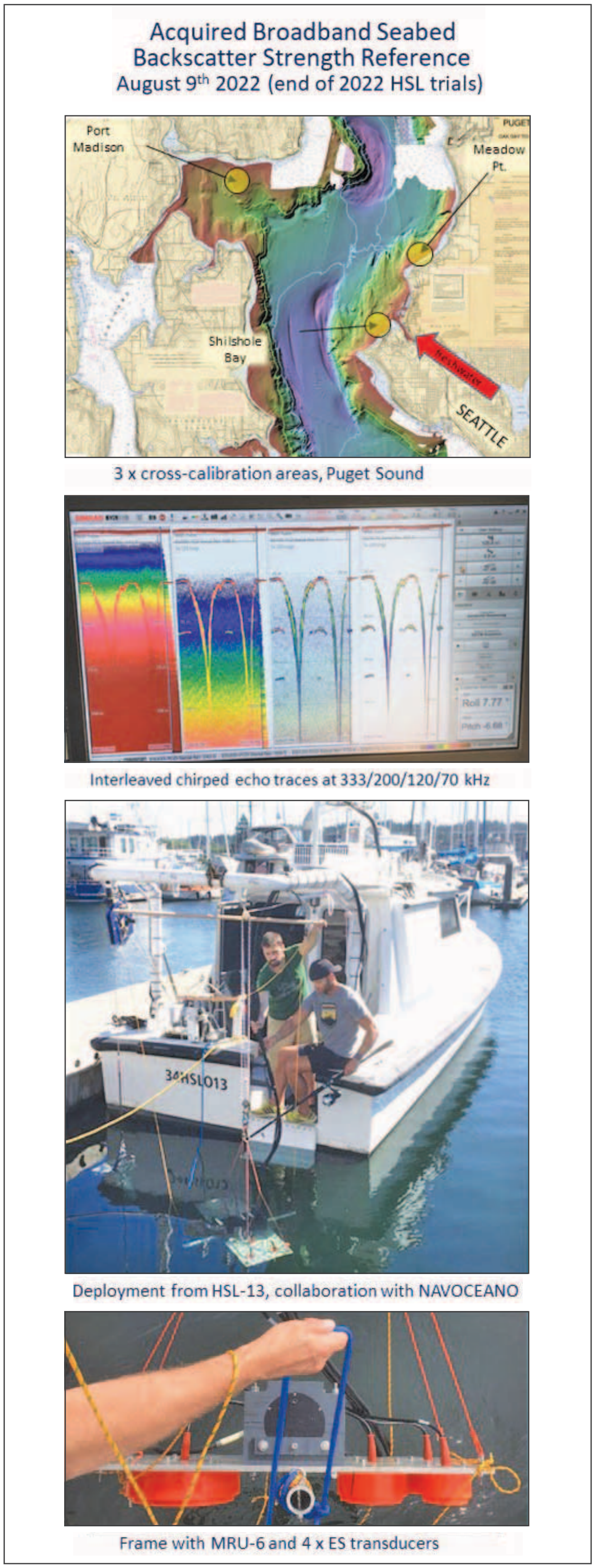


Figure 3-2. The location of the three backscatter calibration areas in Puget Sound and the logistics of deploying the 4xEK-80 chirped reference backscatter measurement hardware.

the same areas in 2021 and 2022 to cross-calibrate the backscatter from their EM2040Ds. Using this approach, one can test whether backscatter strength observation of the identical seafloor between different sonars or different modes of a single sonar (Figure 3-1) provide the same result. In practice they don't. Thus, using an arbitrary (i.e., relative) reference, correctors may be applied to each installation/mode to bring all the systems to a common (if not absolutely defined) level.

OCS originally utilized two areas in Puget Sound—Shilshole and Port Madison (Figure 3-2). These areas, however, suffer from sound speed variability and seabed heterogeneity respectively. Thus, a third area off Meadow Point was selected for current and future work. To tie the archived data collected in all the three areas together, a subset of the NAVO launches occupied all three areas utilizing the same settings. Ultimately all these three relative calibration areas need to be tied to an absolute reference. To address this, in August of this year, the same 4 ES transducer configuration, originally utilized as part of Ivan Guimaraes's thesis, was deployed over the three Puget Sound sites (Figure 3-2).

The data has not yet been processed, but the intent is that all the OCS launches, and the NAVO launches can be brought to a common absolute backscatter reference. To do so however, requires the development of improved processing algorithms that properly account for the multi-sector multi-swath geometry utilized by the EM2040 systems used by both NOAA and NAVO.

Implementation of EM-EK Adjustment Methodology

In September 2022, Miguel Candido successfully defended his M.Sc. thesis on the implementation of a methodology to apply EK-derived reference backscatter data to operational EM (2040 or 712) backscatter data. That methodology fully acknowledges and accounts for the fact that the EM2040/710/712s are multi- sector and multi-swath systems. Furthermore, because the Tx source level and Rx sensitivity patterns are fixed in the sonar reference frame, the data must be reduced in that reference frame and properly account for the significant Tx steering that implies sampling the Rx pattern along track. Figure 3-3 illustrates the "heat-map" output of Candido's algorithm. That set of matrices provides two-dimensional (along and across track) sector-specific correctors for each of the six sectors operating at discrete center frequencies.

Note that that the corrections are unique to a specific operating mode (e.g., short/medium/long CW or FM pulses) and thus has to be derived independently.

Methodology to Transfer a Reference Dataset Between Sites

Given the significant effort needed to directly collect a multiple frequency reference backscatter dataset at a specific site, it would be advantageous to be able to transfer that reference to other locations without having to redeploy the full EK sonar suite. A particular example of this is where the data are required for cross-calibration at different depths and/or areas with less maneuvering restrictions. This was the case for applying the 2019 vintage EK80 reference data set from the Canadian Gulf Islands to the calibration of EM710/EM712 systems on larger vessels. The original data were acquired in shallow (14-45m), heavily trafficked and restricted waters. Larger EM712-equipped vessels cannot easily access that region and the desired operational modes are sub-optimal in those depths (a minimum of 100m is necessary to get reasonable data with medium and long pulse modes). The transfer vessel utilized was the CSL *Heron*, a 10m launch uniquely equipped with an EM712. It was pre-calibrated over the inshore sites, and then steamed to the offshore site.

One of the concerns noted in this depth transfer was that the assumptions about

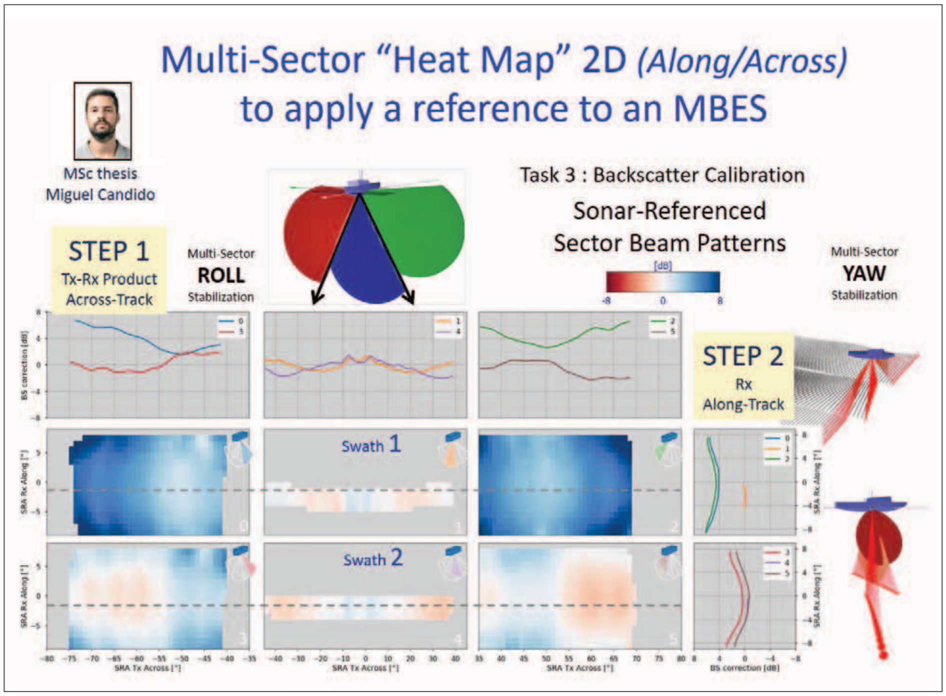


Figure 3-3. Heat map of backscatter strength calibration output from Miguel Candido's thesis. The six matrices indicate the sonar-relative corrections, indexed by across-track (x axis) and along-track (y-axis) angle, that need to be applied to each of the sectors of an EM710 operating in Very Shallow Mode.

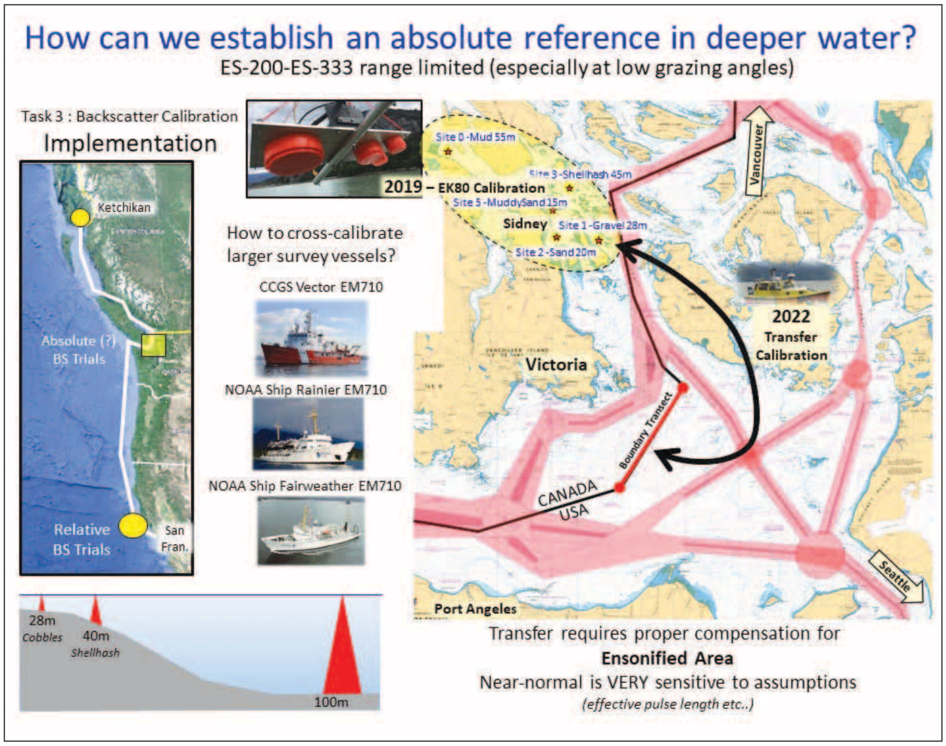


Figure 3-4. Illustrating the geographic location of the transferred reference site. The deeper site was selected based on its depth, its apparent seabed sediment homogeneity and lack of relief. Furthermore it is outside the main shipping lanes and lies along an international border allowing vessels from either nation to access it without border restrictions.

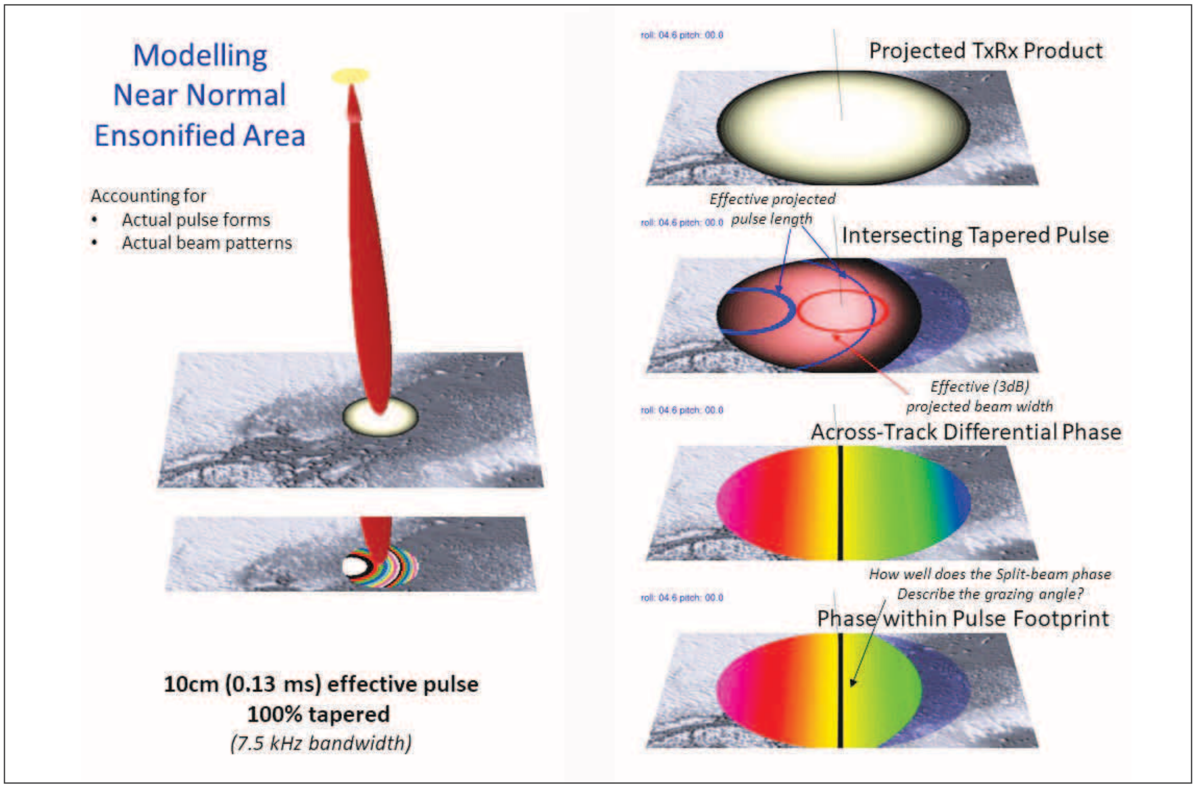


Figure 3-5. Full geometry of the instantaneously ensonified area at near normal incidence. The pulse used here is fully tapered and the radiation pattern includes the full roll-off of the two-way pattern down to the -30 dB limit. The usual approximation is to use the effective pulse length and equivalent beam width (e.g. 3dB limits) as bounds of a rectangular area.

ensonified area are imperfect close to normal incidence. Within a narrow depth range, those simplifying assumptions generally cancel out between reference and calibrating sonar. But in this case, with a 4x depth increase, the near–normal incidence values are problematic (especially within the 5° two-way beamwidth area of the reference EK sonars). To address this better, a new more-complete model of a tapered pulse interacting with a continuously varying beam pattern is now being developed (Figure 3-5).

TASK 4: Environmental Monitoring

JHC Participants: John Hughes Clarke, Indra Prasetyawan, Lynette Davis

Other Collaborators: Rebecca Martinolich and Natalie Lamberton, NAVOCEANO; Mathew Wells, University of Toronto; Phil Hill, Geological Survey of Canada; Ian Church, OMG/UNB

Additional Funding Source: Kongsberg, Indonesian Government

While OCS's focus remains on nautical charting, the quality of their product is often hampered by the presence of rapid sound speed variability. Such variability is a result of local spatial or temporal changes in the oceanographic environment with rapid changes are often characterized by variations in the daily or seasonal thermocline and/or halocline, often resulting in internal waves and turbulence. This task addresses the potential to image these phenomena in real time so that operational staff can adapt their surveys or sampling programs to minimize the impact. As an aside, those oceanographic phenomena are of high interest to NMFS as they often represent areas of enhanced biological activity.

Main Task Accomplishments in 2022

Understanding the Impact of River Plume Tidal Fronts on Data Quality

As part of a joint project overlapping with Tasks 2, 3, 8 and 30, bi-monthly surveys are being performed on a low relief area off Odiorne Point. The area is particularly challenging to survey in that as a dynamic sand sheet, it is incredibly smooth and thus residual artifacts are very visible. This area is ideal for testing integration problems (Task 2), is the focus of upcoming sub-bottom profiler studies (Task 8), a potential backscatter calibration site (Task 3) and is the focus of a study looking at mobility of the sand sheet (Task 30).

As became apparent as part of these surveys, however, the sound speed environment is particularly challenging. Originally it was envisaged that a rapidly dipping MVP was the solution, but after twice losing the fish due to fishing gear hook-up, that had to be abandoned. As a result, manual CTD profiles are conducted at the end of every third line (~30 minute intervals). Even that sampling however was found to be inadequate. As a result, the continuously logged surface sound speed at the sensor was investigated and mapped (Figures 4-1 and 4-2). What became immediately apparent is that over the duration of the survey (eight hours) there often was a distinct boundary in surface sound speed, whose position migrated across the area as the tide changed.

When the surface sound speed map is examined in detail (Figure 4-2), it is clear that there are two discrete domains separated by an abrupt boundary. Inshore there is a notable (5-10 m/s) drop in sound speed and the sound speed is continually oscillating +/- 1m/s particularly closest to the boundary. Seaward of the boundary, the sound speed is higher and

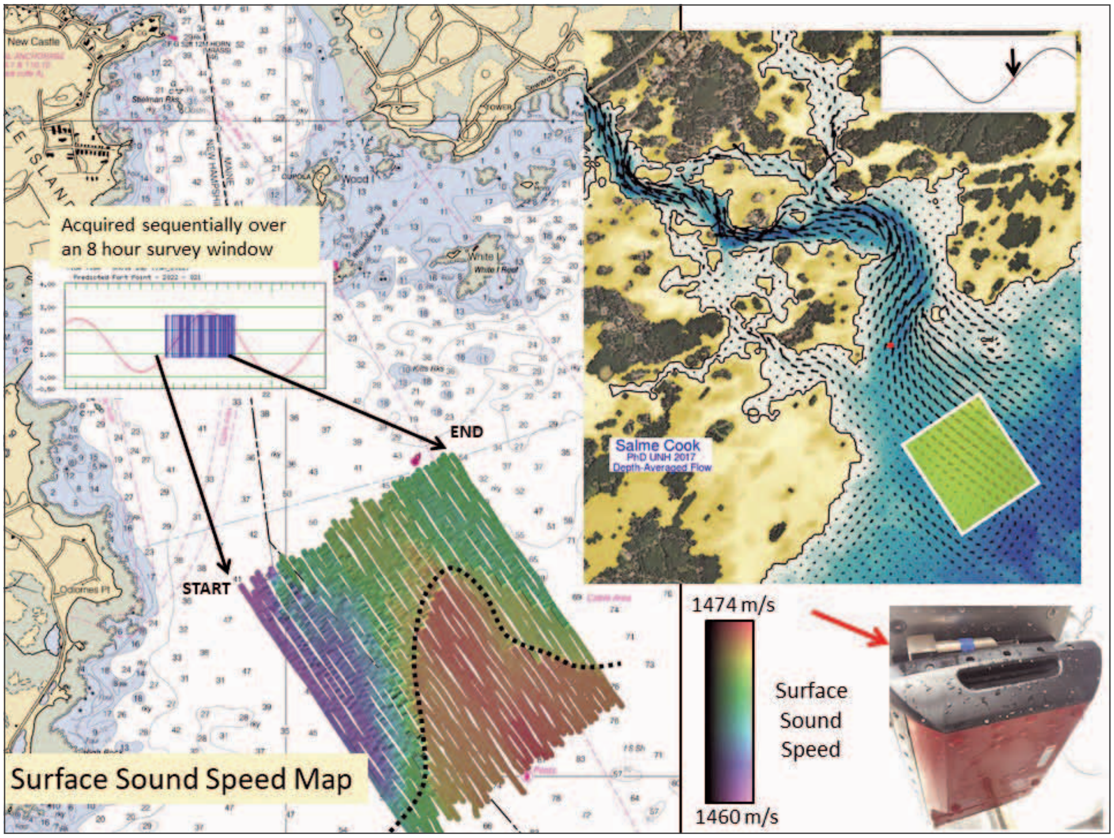


Figure 4-1. Location of the bi-monthly surveys and a map of the surface sound speed as measured over an eight hour window during one survey. The inset shows the location of the survey relative to the ebb-tide plume of the Piscataqua estuary (model derived from Ph.D. thesis of Salme Cook, UNH).

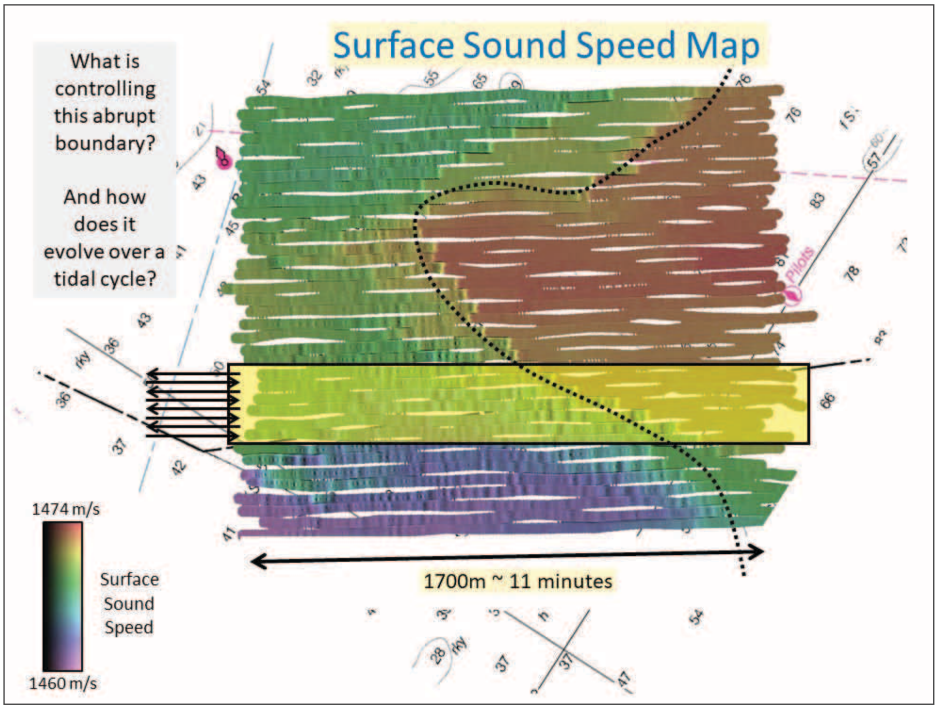


Figure 4-2. Detail of the spatial variations in the surface sound speed. Note that this is the instantaneous (1 Hz sampling) sound speed. The sound speed actually applied to the MBES to do beam steering is a 1 minute running causal median filter and thus does not perfectly reflect the rapid variations seen here.

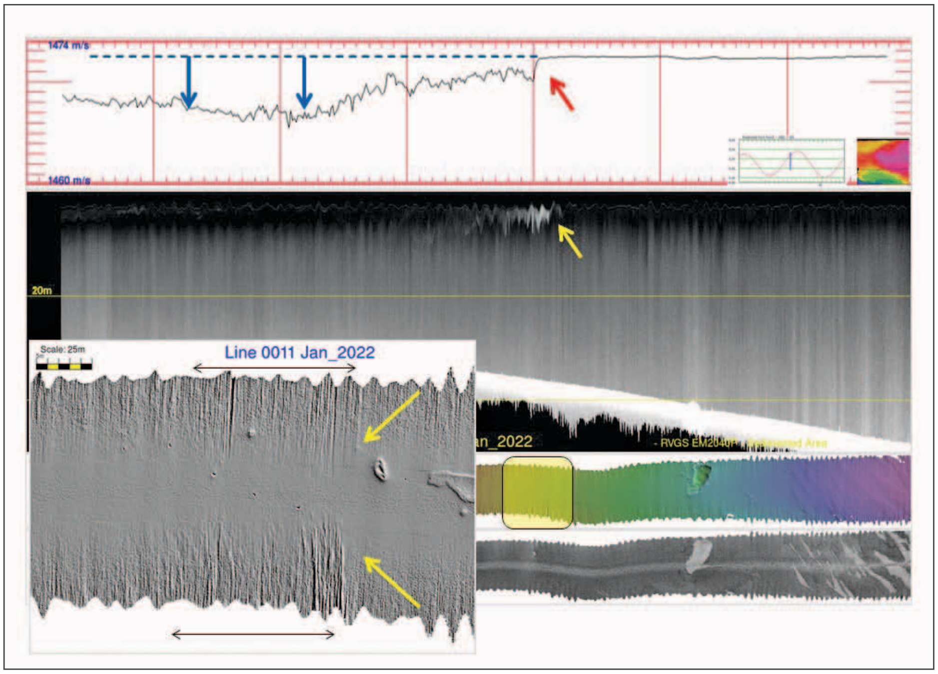


Figure 4-3. Geographically co-located sections of one survey line in the sedimented area. Top to bottom plots show: the instantaneous surface sound speed, the near nadir vertical water column volume scattering and the corresponding bathymetry and seabed backscatter. The inset shows a zoom in of the bathymetry the moment the swath passes over the boundary. Arrows correspond to the boundary location.

notably uniform. Every survey line (typically about 10-12 minutes long) crosses this abrupt boundary and the boundary is seen to gradually migrate up toward the estuary on the flood tide and out to sea on the ebb tide.

As part of the Ph.D. thesis of Indra Prasetyawan, combined ADCP, CTD and EM2040P water column imagery is being obtained to try to better comprehend the origin of these discontinuous oceanographic artifacts. While the focus is on the oceanographic phenomena (typically haloclines in estuaries and river plume in the adjacent offshore), the impact is very apparent on the quality of multibeam data. Figure 4-3 shows geographically co-located plots of the surface sound speed, the vertical water column imagery and the associated EM2040P bathymetry and backscatter imagery. As can be seen, the boundary between the two domains is very abrupt and the inshore side of it corresponds to a localized zone of enhanced near-surface scattering in the multibeam water column. The low grazing angle part of the multibeam bathymetric swath acquired just inshore of the boundary is notably degraded for a distance of a few hundred meters.

The abrupt boundaries seen actually represent the seaward edge of the ebb-tide estuary plume as it passes out to sea. On low wind-speed days one can sometimes actually see the boundary on the sea surface (Figure 4-4). Detail of the multibeam water column scattering imagery of the plume boundary are also presented in Figure 4-4 where one can clearly see the buoyant front and the associated turbulence at its base as it moves over the denser saltier offshore water. CTD Profiles indicate that the plume is only 2-5 m thick and thus it is hard/impossible to resolve the associated current shear from ADCP measurements on the RVGS as the sensor is at a depth of 2 m and has a 1.5 m blanking distance.

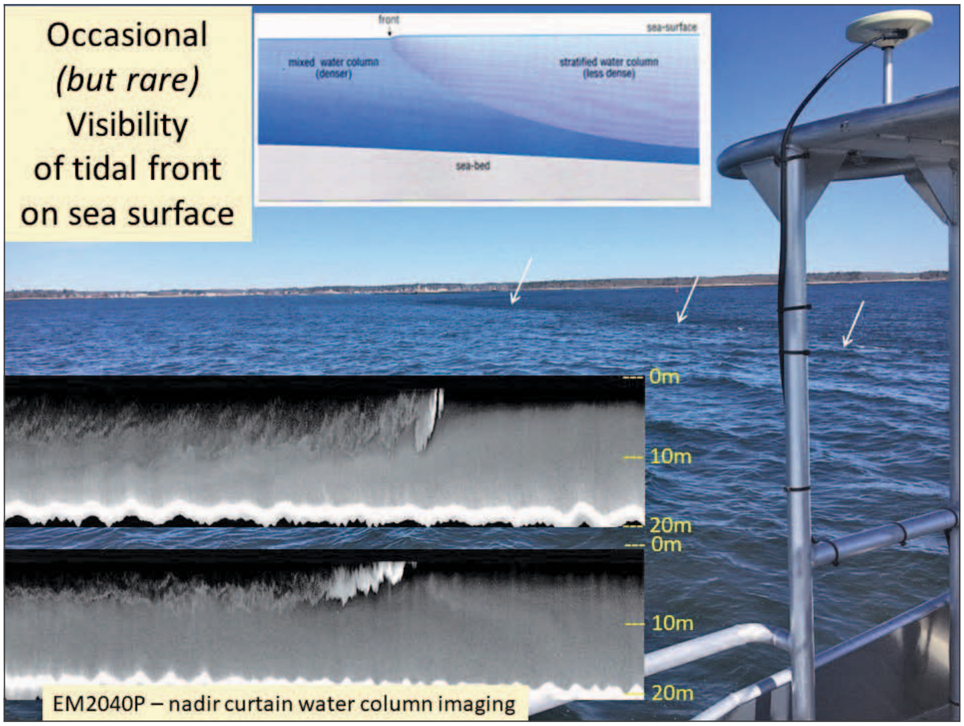


Figure 4-4. Background image is surface expression of the plume front. Lower left inset shows two vertical sections of EM2040P water column imaging that reveal details of the associated turbulence just behind the head of the plume. The inset figure on the top is a schematic of the character of a typical tidal front (from Open University notes).

To better understand the dynamics of the front, Prasetyawan is developing a nested 3D baroclinic model extending from the Memorial Bridge to about 5 km offshore. The boundary conditions are obtained from wind speed and air temperature weather models, river discharge climatologies, and tidal constituents from the Gulf of Maine. Because the freshwater discharge into the Piscataqua/Great Bay watershed is so low, his model recognizes that the plume is actually a more brackish body derived from tidal mixing upstream. Nevertheless, the offshore boundary is not at all gradational, but rather very sharp fronts, as observed from RVGS data are clearly seen. Their location is very dependent on both tidal magnitude (neap v. spring) as well as offshore winds. Figure 4-5 shows an example model output during the mid flood period (with the survey area superimposed).

Application to Harbor Sedimentation Studies

The same software tools, combining MBES water column imaging, underway ADCP and rapid-dipping MVP are being applied to a sedimentation problem in the Fraser River in British Columbia. The mouth of the Fraser is a major shipping conduit into the Port of Vancouver. The river, however, carries an extremely high suspended sediment load that fluctuates with the seasonal discharge of the river, peaking in the summer. Public Works Canada are required to perform continual multibeam surveys to monitor bathymetric changes and oversee dredging to ensure sufficient under-keel clearance. The manner in which the sediment (mainly fine sand) is eroded and deposited depends on the location of the salt wedge which migrates over 30 kilometers seasonally as well several kilometers in and out of the river mouth over a single tidal cycle.

The work is being performed in collaboration with Mathew Wells from University of Toronto and Phil Hill from the Geological Survey of Canada. The aim is to understand how the high suspended load in the overlying brackish water passes through into the saltier water below. Figure 4-6 illustrates the combined information content that can be extracted from an enhanced hydrographic survey to support such studies. CSL *Heron* is equipped with both an EM712 and EM2040C allowing water column imaging at two widely separated frequencies. Additionally, the *Heron* has a 600 kHz ADCP to monitor the currents and their shear as well as an MVP-30 which is being utilized here on a two minute repetition basis. That MVP has both a CTD and an optical backscatter probe allowing the delineation of suspended sediment load. Figure 4-6 is one section on the mid flood period. Over a period of three days, while collecting regular offset longitudinal bathymetric sections of the channel, the same structure can be monitored at different phases of the tide to understand the evolution of the salt wedge over a tidal cycle and ultimately provide an insight into the likely distribution of seabed erosion and deposition.

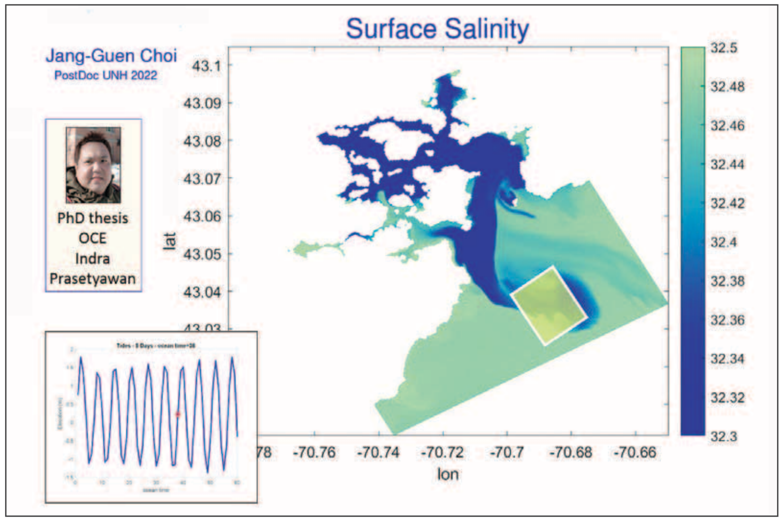


Figure 4-5. 3D baroclinic model of the Piscataqua estuary mouth. The inset rectangle shows the location of the surveyed area. Model being developed by Indra Prasetyawan nested within the larger domain of a regional model produced by Jang-Geun Choi.

Real-Time Tool Development

While there has already been much development in post-processing of multibeam water column data, for operational decisions, the user would ideally like to see the results in real-time. As part of the master's thesis of Lynette Davis, a real-time scrolling tool has been developed that accesses the MWC packets via the UDP broadcast, allowing the operator to see the imagery in real time. Figure 4-7 shows the operational testing of Davis's tool on board the R/V *Gulf Surveyor*. While operating an EM2040P in real time, an additional

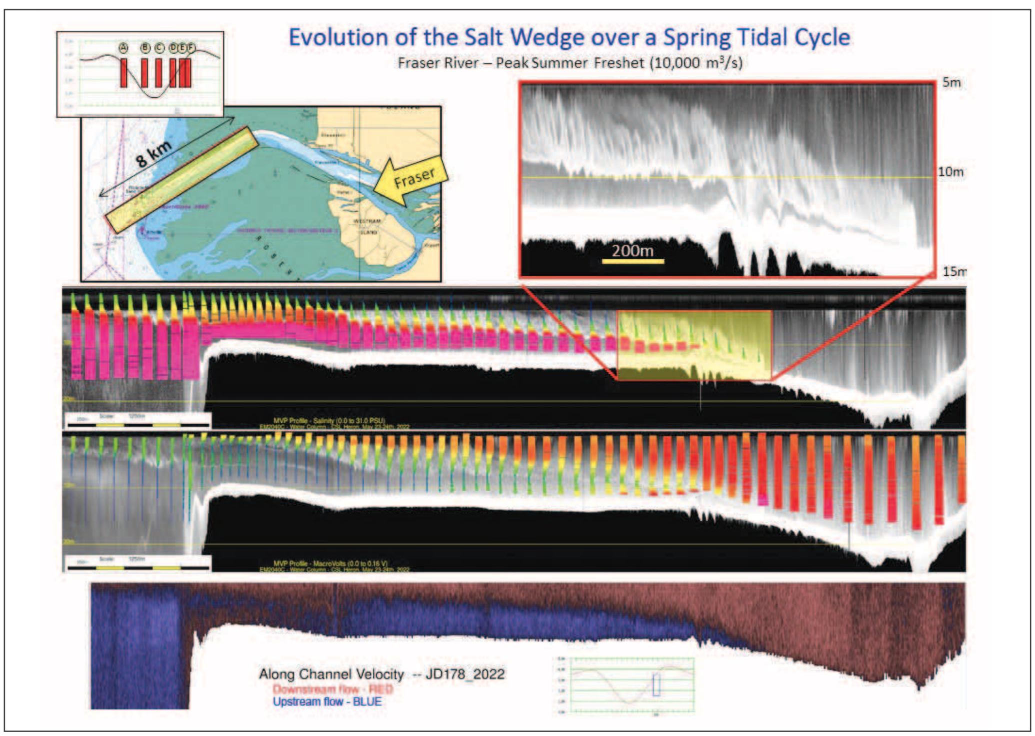


Figure 4-6. Multiple complementary data sets that can be acquired from an enhanced hydrographic survey platform. The figure shows three views of an 8km section of the Fraser river mouth. Top: EM712 water column imaging with MVP salinity superimposed. Center: EM2040C water column imaging with MVP suspended sediments superimposed. Bottom: ADCP currents—blue shows inshore flow, red shows offshore flow. Zoom: detail of Kelvin Helmholtz waves developed on the nose of the incoming salt wedge.

display is available to the surveyor which provides synoptic views of the underlying volume scattering field immediately below the vessel. In this case, the nose of the salt wedge in the Piscataqua River can be seen forming downstream of a rock sill. Later, during the flood tide, that salt wedge is seen to advance up the estuary. Such imagery, while strictly qualitative, can—with the aid of complementary sparse SV profiling—be used as an intuitive indicator of the likely spatial variability of the sound speed. Such a tool should be routinely available on the bridge of any hydrographic survey vessel so that, just as they view the clouds as indicators of upcoming weather, this display can aid in deciding on the optimal sound speed sampling strategy.

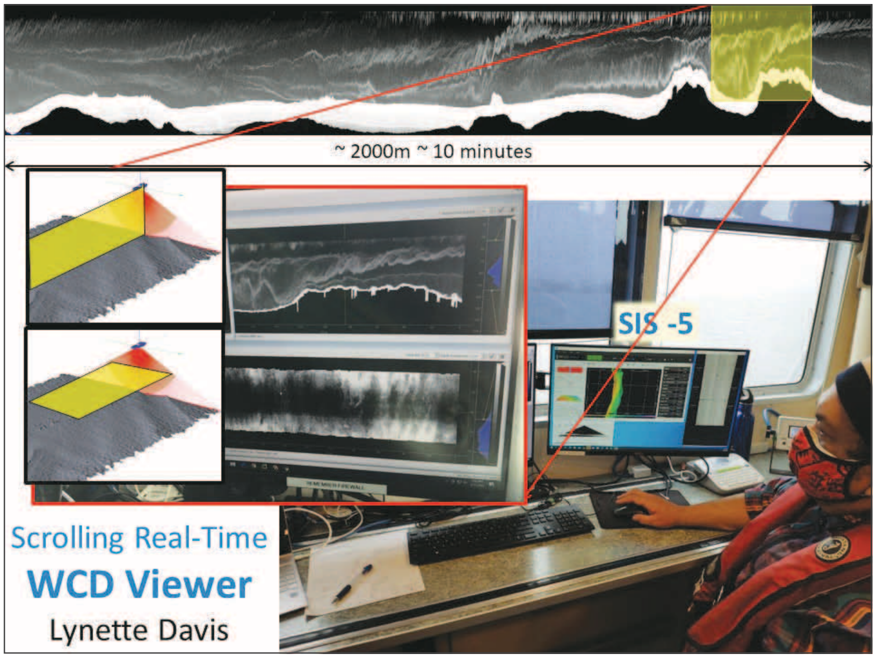


Figure 4-7. Real time displays of the EM2040P water column nadir vertical curtain and horizontal slice views.

TASK 6: Lidar Systems – Providing Both Bathymetry and Reflectance

JHC Participants: Brian Calder

NOAA Collaborators: Gretchen Imahori (RSD)

Other Collaborators: Chris Parrish and Forrest Corcoran, Oregon State University

Modern topobathymetric lidar systems have great potential in shallow water, particularly where they can achieve data densities on par with acoustic systems. The large volumes of data generated by such systems can be problematic as more sophisticated processing systems—including clustered processors and high-speed disc arrays—are generally required for efficiency. However, many of the data points collected are either noise, or unwanted non-bathymetric data. If these points could be removed from the data stream before significant effort was expended on them (e.g., attempting refraction corrections), then the volume of data could be reduced, and more moderate processing requirements would be the norm. The challenge, of course, is to avoid removing points that might be hydrographically significant during this pre-processing. Early identification of water surface points would also allow for more efficient identification of refraction model start points, speeding subsequent processing.

The Center is separately examining late-stage processing for these types of lidar systems (see Task 24); here, we consider only the early-stage processing, typically before the data are translated into industry-standard LAS files, refraction corrected, or reduced to datum on the ellipsoid. This means working with data that is partially or completely unprocessed, often in manufacturer's file formats, and at volume. The ultimate goal is to reduce data volume as efficiently as possible while maintaining hydrographic integrity in the data stream. A key component of this is to understand the uncertainty of the data, typically through the types of Total Propagated Uncertainty (TPU) models developed by the Center in conjunction with our partners at Oregon State University. Reducing the data volume also puts less load on the later stage processing tools we are developing (Task 24).

Project: **Expanded Total Propagated Uncertainty Models for Operational Lidars**

In a collaborative, multi-year project between the Center, Oregon State University (OSU), and NOAA National Geodetic Survey (specifically Remote Sensing Division), a bathymetric lidar total propagated uncertainty (TPU) model and production software, cBLUE, have been developed and deployed. The software tool is currently being used operationally by NOAA NGS and NOAA lidar contractors for generating lidar point clouds and surfaces containing uncertainties. In the current reporting period, significant enhancements were made to the model and software, resulting in cBLUE version 3.0 (Figure 6-1). Specific enhancements included adding support for the Hexagon Leica Chiroptera 4X and HawkEye 4X, adding the ability to select 1-sigma or 95% confidence level values for output TVU and THU, adding a comma-separated text output option, in addition to the LAS ExtraBytes output option, adding support for .laz (compressed LAS) files, updating from laspy 2.0 to laspy 3.0, and adding sample datasets to the cBLUE GitHub repository .

Additional cBLUE enhancements are currently underway. The project team is working with Areté Associates Inc., the Naval Oceanographic Office Hydrographic Department, and NOAA NGS to incorporate support for the Areté PILLS system. Additionally, modeling for the Teledyne Optech CZMIL is complete, and the tool will be updated to include this system. The team is also working on creating a cBLUE Developer's Manual, to accompany the User's Manual, which was released with cBLUE v3.0. Lastly, the project team is participating in an effort led by the American Society for Photogrammetry and Remote Sensing (ASPRS) and Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) on standards for bathymetric lidar, including contributing to development of the TPU sections of the standards.

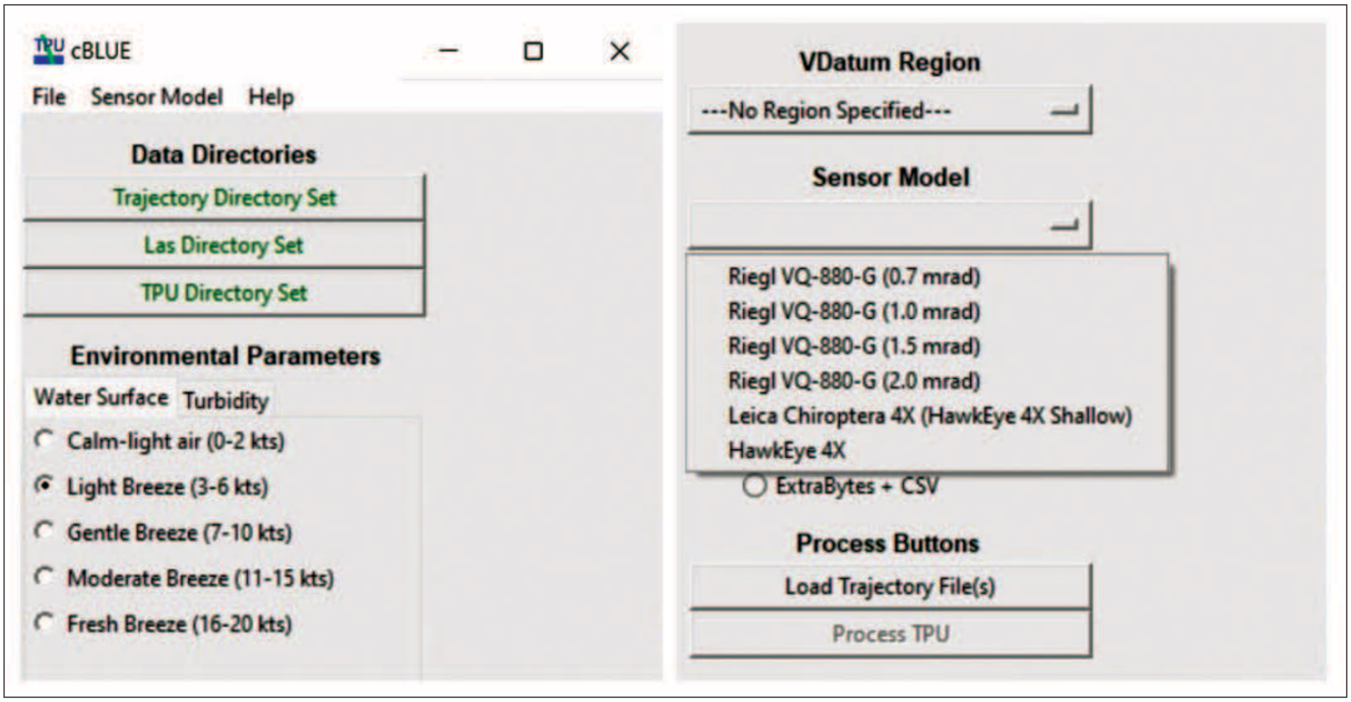


Figure 6-1. cBLUE (comprehensive bathymetric lidar uncertainty estimator) version 3.0, including support for new systems, new output options, and several other new features added in 2022.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: DATA ACQUISITION

NOFO Requirement 2

Improvement in the understanding and integration of other sensor technologies and parameters that expand the efficiency and effectiveness of mapping operations, such as water column and sub-bottom profiling.

JHC/CCOM responded to NOFO requirement 2 with two tasks:

Task 7: Water Column Mapping

Task 8: Sub-bottom Mapping

Task 7: Water Column Mapping

JHC Participants: Elizabeth Reed-Weidner, and Tom Weber

Along with our efforts to image water column structure to improve the quality of our seafloor surveying, we have also focused on understanding the nature of scattering in the water column so that we can use water column backscatter to quantitatively understand processes in the water column. This past year, Liz Reed-Weidner and Tom Weber expanded the acoustic scattering model they developed in 2021 for the quantification of scattering from sharp oceanic stratification interfaces. The intensity of the stratification influences internal mixing dynamics and entrainment, facilitating the transport of dissolved constituents and heat. Of particular interest are regions of "sharp" stratification, where sound speed and density rapidly change at the interface (e.g., haloclines, thermohaline staircases, the base of the mixed layer) and which have been studied previously by Center researchers using broadband acoustic systems. The goal of this effort is to be able to remotely measure stratification intensity through broadband acoustic inversion.

Reed-Weidner and Weber derived a model for describing scattering from a smooth stratification interface between two bodies of water with different physical properties (Figure 7-1).

The 1D model, which incorporates both the characteristic vertical scale of the interface and the frequency at which the interface is ensonified, is based on the weak-scattering model initially developed to describe scattering from random perturbations in medium density and compressibility. This model is widely applicable to horizontally flat regions of sound speed change where the stratification interface is far from the projector/receiver and has minimal spatial variability.

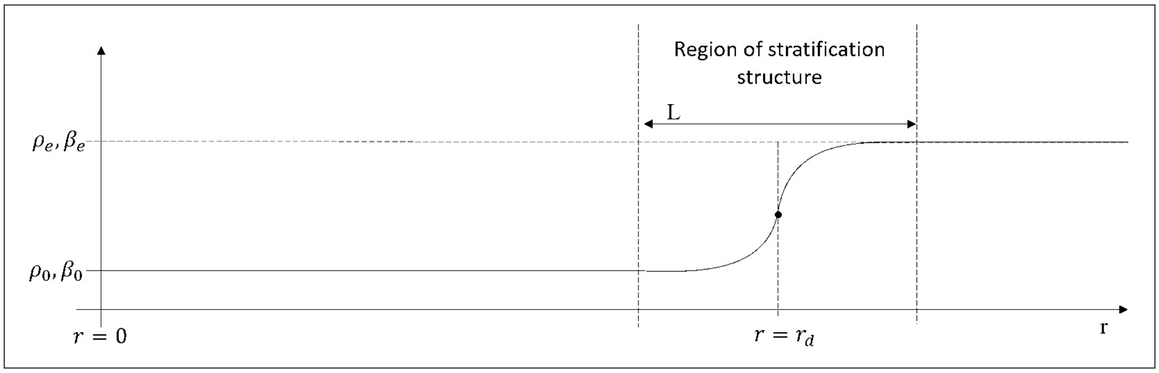


Figure 7-1. Scattering geometry for a one-dimensional, far field, backscattering system where an incident plane wave scatters from a region of stratification interface composed of changes in density and bulk modulus. Profiles of the system density and bulk modulus along the vector r. The stratification interface is centered at position r=rd.

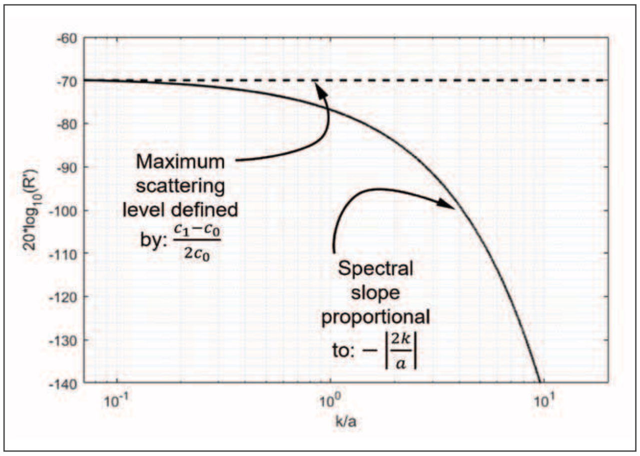


Figure 7-2. Predicted frequency-dependent scattering behavior from ocean stratification based on the 1D pressure reflection coefficient.

This year the model was expanded to investigate the frequency-dependent behavior of backscattering from ocean structure (Figure 7-2), which is defined by the sharpness parameter (a) of the and the acoustic wavenumber (k). If the acoustic wavelength is larger than the vertical extent of the stratification, the structure can be treated like a sharp discontinuity and scattering will be at a maximum, defined by the sound speed term. As the frequency is increased and wavelengths shorten, the model predicts a gradual decay in the reflected wave amplitude with a spectra slope defined by the exponentially decaying term. Assuming inverse tangent is a good representation of the ocean structure, and a large frequency range is available, the sharpness parameter could be estimated from acoustic data alone.

To evaluate the effect on the backscattered field from an increasingly rough stratification surface a Monte Carlo type simulation workflow was implemented. Eighty simulations were run with unique levels of surface roughness, but with otherwise identical parameters for the water column (e.g., sound speed values), stratification interface (e.g., sharpness parameter, depth). The magnitude of surface roughness was limited to those within the Kirchhoff criterion of validity - smooth enough to avoid shadowing effects and multiple reflections on surface.

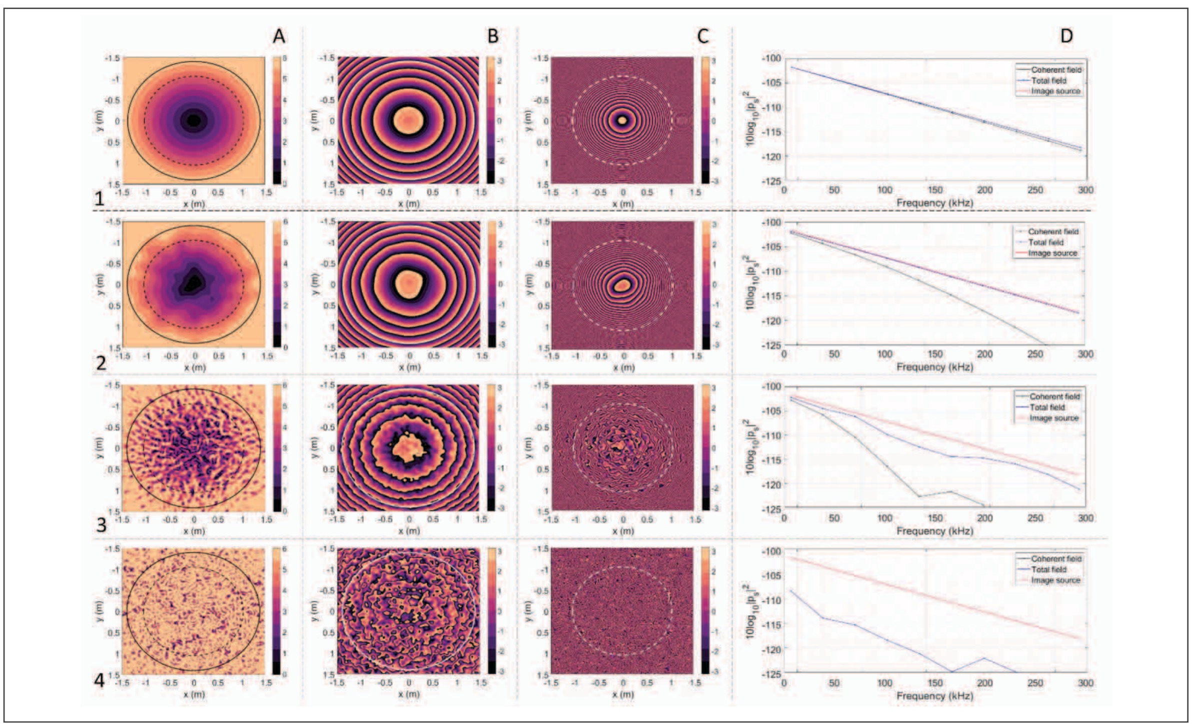


Figure 7-3. The general behavioral trends of scattered pressure from surfaces with increasing surface roughness. Column A shows the backscatter field from a single surface realization, quantified by the angle (ψ) between the surface normal vector for each surface element (*dS*) and the backscatter direction. Columns B and C show the phase of the scattered pressure from every surface area element; Column B is phase at 45 kHz and C is phase at 270 kHz. Column D illustrates the frequency dependent intensity of the image source solution (red), the ensemble average coherent field (black) and the ensemble average total field (blue). Surface roughness increases from row 1 to 4 via increasing correlation length (4.2163m, 0.2635m, 0.0658m, 0.0658m), RMS height (1.7156e-4m, 6.8625e-4m, 0.0014m, 0.0055m), and RMS surface slope angle (0.0033°, 0.2110°, 1.688°, 6.721°).

Model results indicated that surface roughness does impact the frequency dependent scattering from the stratification interface, deviating away from the predicted behavior for a smooth surface (Figure 7-3). For normal incidence geometry the specular (reflected) and backscatter directions are the same for the mean plane of the interface and when the surface is smooth the backscatter field is defined by the specular return and the phase of the scattered pressure from across the surface is defined by a series of Fresnel zones. As surface roughness increases, both the backscatter field and the Fresnel zones become increasingly distorted. The backscatter field becomes defined by individual roughness area elements distributed across the surface, with increasingly more energy scattered away from the backscatter direction. Similarly, as roughness increases the phase of the scattered pressure across the surface becomes increasingly distorted; this effect is strongly frequency dependent and is observed at higher frequencies first. The combined result of these effects is a loss in the ensemble average coherent and total field intensity away from the predicted spectral slope as a function of increasing surface roughness, which sets limits on the potential for broadband acoustic inversion for the sharpness parameter (a).

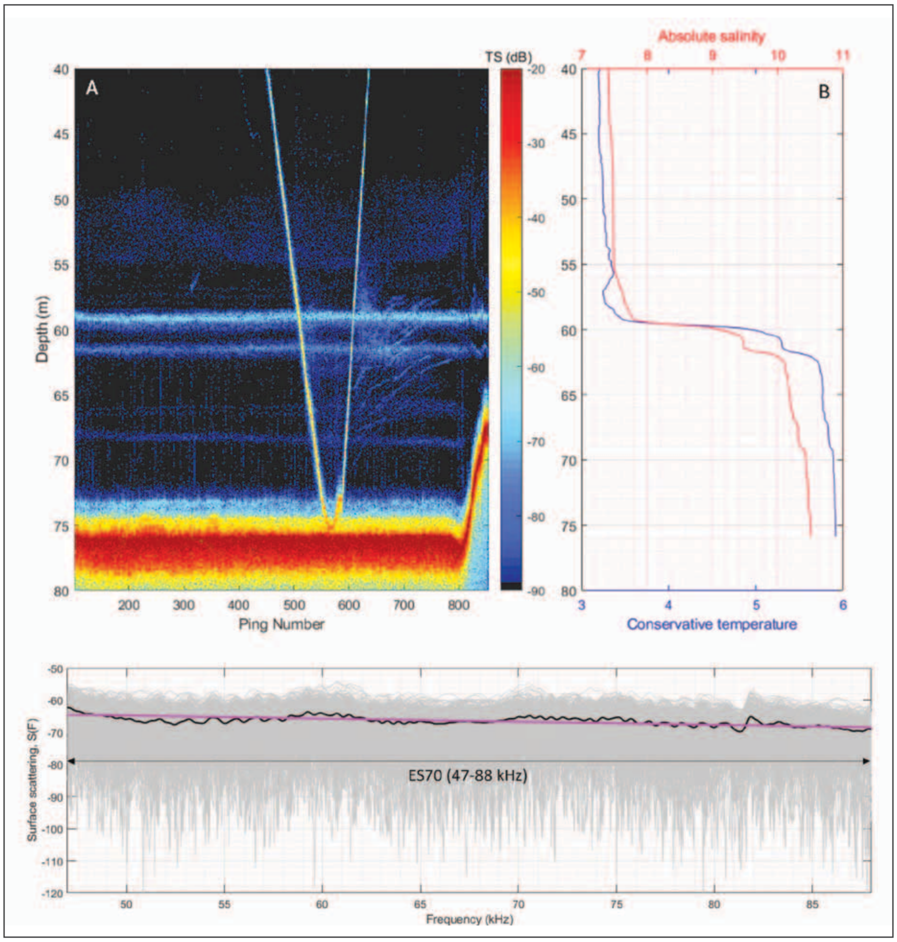


Figure 7-4. Testing field site in the Western Gotland basin. Panel A illustrates the broadband acoustic water column from the ES70-7C system and panel B illustrates the CTD profile data. The bottom panel illustrates the frequency dependent surface scattering response from the tracked stratification. Individual frequency-dependent curves are plotted in grey, the ensemble average in the thick black line, and the fitted trend line in magenta, proportional to R'.

Preliminary application of the broadband acoustic inversion method for the sharpness parameter (a) was performed on a field data set from the Baltic Sea collected in the Western Gotland Basin (Figure 7-4). Broadband acoustic profiles were extracted from the thin regions of elevated scattering in the echogram and ensemble average, frequency dependent surface scattering (s) a was computed from the ensemble of the extracted acoustic profiles.

The stratification sharpness parameter, a, was estimated from the spectral slopes of the backscatter intensity using the method of least squares. The sharpness parameter was measured to be 850, corresponding to a vertical extent of 0.058 m. The magnitude of the vertical extent of the stratification interface measured in the Western Gotland basin agrees with previously published direct measurements from oceanographic studies of double diffusive environments. This suggests that the broadband acoustic measurement of the interface thickness is plausible; however, without direct, high-resolution measurements of water column structure it is difficult to assess the accuracy of the acoustic inversion procedure. Regardless, the inversion effort illustrates the potential for remote, rapid measurement of stratification interface metrics using broadband acoustic water column data.

Task 8: Subbottom Mapping

JHC Participants: John Hughes Clarke, Larry Ward, Larry Mayer

Subbottom profilers (SBP) have not traditionally been a survey instrument utilized by hydrographic agencies. However, given the objectives of the newly adopted national strategy for ocean mapping, exploration, and characterization (NOMEC), the ability to characterize the shallow subsurface will become increasingly important for a variety of applications such as wind farm siting, aggregate volume estimation, and delineation of ferro-manganese crusts. As the OMAO fleet already undertakes systematic surveys in the U.S. EEZ, adding SBP capability would maximize the ship time investment as long as it does not compromise their prime charting or fish stock assessment mission. However, before the OCS fleet can consider including subbottom profiling as part of their standard data collection procedures, there are a number of technical challenges that need to be addressed to ensure that the collection of subbottom seismic data does not compromise their primary mission. These include installation, interference, synchronization, crew disturbance, and required data management (quality control and archiving). If these aspects can be overcome, SBP would add data value in support of a national seabed characterization program. During the present reporting period (while awaiting final environmental approvals for use of SBP systems), additional work was conducted to develop and characterize Reference Sites in the western Gulf of Maine (WGOM) to be used as standards to compare SBP systems.

Once environmental clearances are obtained, a number of the viable SBP systems will be leased and run in Reference Sites located in the WGOM (Figure 8-1). The four Reference Sites selected represent different physiographic features such as a sandy shoal, a paleodelta, and a muddy basin, each with different sediment composition and subbottom structures. Use of the Reference Sites facilitates a qualitative, but geologically-informed, comparison, to be made between selected SBP systems to assess their relative penetration and resolution capabilities. Additionally, the SBP systems potential to interfere with other core OCS/NMFS active sonar systems will be tested against EM2040 and EK80 sonars operating simultaneously. As part of the assessment, we will seek advice from other federal agencies, already operating subbottom profilers in tandem with mapping systems.

During the previous reporting period (see 2021 JHC Performance and Progress Report, Task 8), the four Reference Sites were identified. The primary criteria for choosing the Reference Sites were the presence of strong subsurface reflectors at various depths and scales, a detailed knowledge of the surficial sediment, and, if possible, existing vibracores to help evaluate and interpret the seismic images. The four sites identified that meet these criteria are Portsmouth Harbor Entrance (PHE), Northern Sand Body (NSB), Merrimack Paleodelta (MPD), and Scantum Basin (SB) (Figure 8-1). All the sites have archived SBP records that show each location has strong seismic reflectors. Two of the sites, NSB and PHE, have been studied extensively by the Center. The MPD has been previously studied by the U.S.G.S. and the subbottom seismic data is available, as well as archived vibracores.

During the present reporting period, two tasks were undertaken including (1) a field campaign to obtain bottom sediment samples and seafloor video in the Reference Sites, and (2) analysis of archived analog subbottom profiles located within the Reference Sites. The 2022 field campaign was part of a larger effort to obtain ground truth on the shelf off northern Massachusetts and New Hampshire in order to enhance and expand the Center's surficial geology mapping program. The 2022 field campaign is described in more detail in this report under Task 28 and Figure 28-2.

The subbottom seismic surveys used to identify sites were run in 1982 and 1985 by the University of New Hampshire using an E. G. & G. uniboom system and recorded on dry paper. The analog records were scanned and converted to digital records during an earlier study by the Center. During the present study, the seismic records were analyzed in SonarWiz 7 V 7.06.04 and reviewed to assess the presence and strength of subsurface reflectors. Two examples are shown in Figure 8-1. The Northern Sand Body (NSB) is likely an abandoned sand shoal that has strong reflectors including basement bedrock and a major unconformity which reflects erosion during a period of lower sea level. Also shown is a SBP from Scantum Basin (SB), a muddy offshore region with strong reflectors including bedrock, glaciomarine mud, and Holocene mud. Also present in the SB record are areas where the acoustic returns are lost, certainly due to gas. These records are of additional value as they were obtained with a boomer system and will allow comparison to the chirp systems that will be tested.

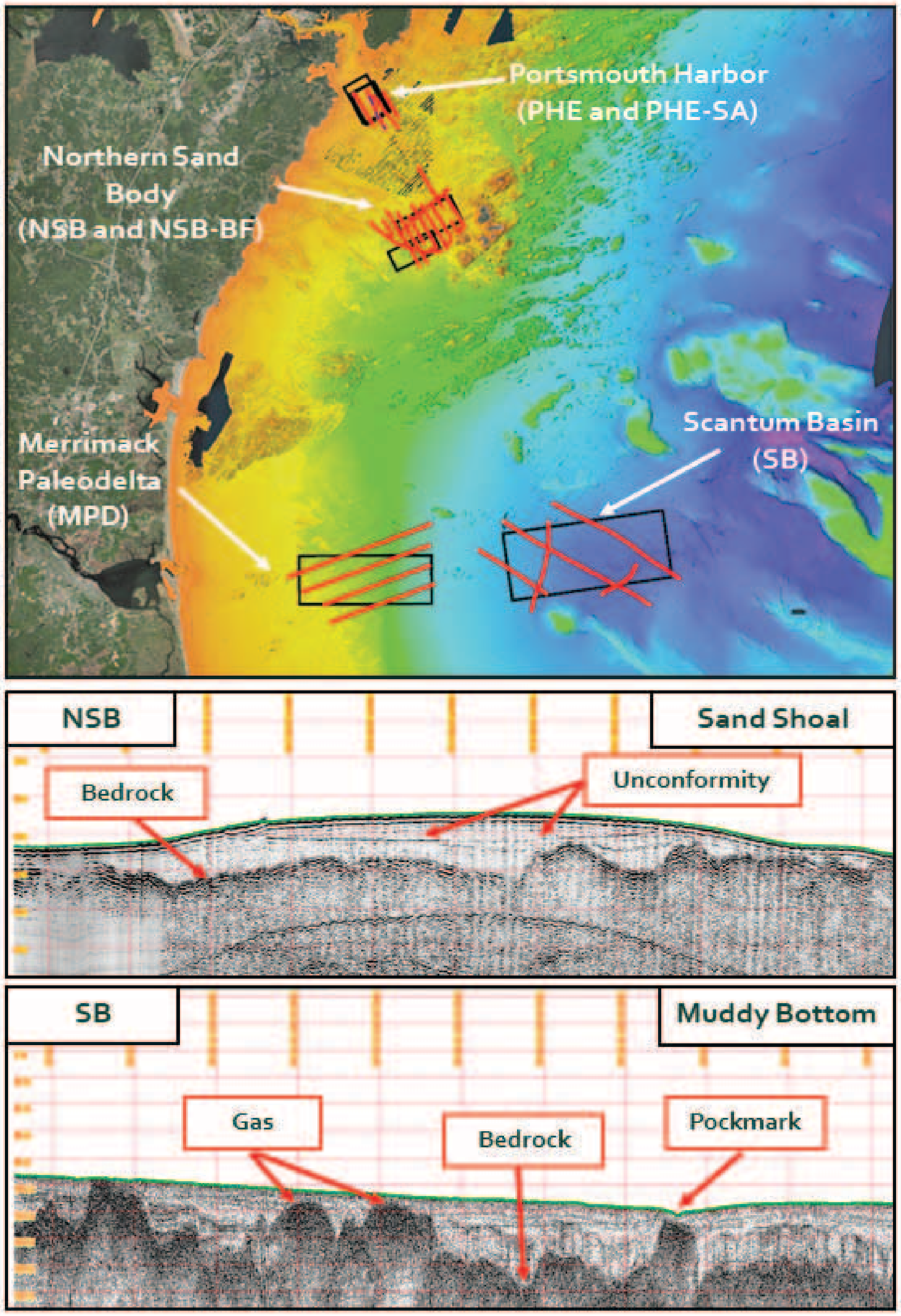


Figure 8-1. Location map of the Reference Sites and associated subbottom seismic profiles on the MA and NH inner continental shelf (upper) and two examples of subbottom seismic profiles and interpreted reflectors (middle and lower figures). The Reference Sites are outlined by black rectangles. The SBP transects are shown by red lines. The SBPs for PHE, NSB, and SB are from the Center's archives. The SBPs in MPD were collected by the U.S.G.S. (Woods Hole, MA).

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: DATA ACQUISITION

NOFO Requirement 3

Improvement in the operation and deployment of unmanned systems for hydrographic and other ocean mapping and similar marine domain awareness missions. Enhancements in the efficiency and hydrographic and related data acquisition capability of unmanned systems in multiple scenarios including shore-based and ship-based deployments and in line-of-sight and over-the-horizon operation and long duration autonomous ocean and coastal mapping data acquisition operations.

In its initial response to the FFO, JHC/CCOM responded to NOFO requirement 3 with five tasks which represent sub-components of our uncrewed systems activities:

Task 9: Operation and Deployment of Uncrewed Surface Vessels

Task 10: Camera Systems for Marine Situational Awareness

Task 11: ML Training Data for Marine Applications

Task 12: Path Planning for Ocean Mapping

Task 13: Frameworks for Multi-vehicle Operations

As our efforts have evolved, we have found that these sub-components are not fully representative of the breadth of our uncrewed vessel activities and we have thus combined these into a Task 9 "super-task" representing much of our collective work on uncrewed systems.

Task 9: Operation and Deployment of Uncrewed Surface Vessels

JHC/CCOM Participants: Val Schmidt, Andy McLeod, Roland Arsenault, K.G. Fairbarn, Avery Muñoz, Larry Mayer, and interns Natalie Cook and Jenna Ehnot

NOAA Collaborators: Rob Downs, John Doroba, Alex de Robertis, Michael Gallagher, Don Jones, Erica Fruh, Scott Furnish, Dexter Malley, the captain and crew of NOAA Ship *Thomas Jefferson*, Captain Bill Mowitt, OAR OER Ocean Exploration Cooperative Institute, and NOAA Sanctuaries Program

Other Collaborators: Basile Rose, Mathieu Kerjean, Antoine Diers, Axel Durbec, Sebastian Grall – iXblue (now Exail); Josh Chernov, Jon Zand; the captain and crew of the E/V *Nautilus* (The Ocean Exploration Trust)

Additional Funding Source: NOAA OER - Ocean Exploration Cooperative Institute

In an effort to fully evaluate the promise of uncrewed surface vehicles (USVs) for seafloor survey, and to add capability and practical functionality to these vehicles with respect to hydrographic applications, the Center has acquired, through purchase, donation or loan, several USVs. The Bathymetric Explorer and Navigator (BEN) a C-Worker 4 model vehicle, was the result of collaborative design efforts between the Center and ASV Global LLC beginning in 2015 and delivered in 2016. Teledyne Oceansciences donated a Z-boat USV, also in 2016, and Seafloor Systems donated an EchoBoat in early 2018. A Hydronalix EMILY boat, donated by NOAA is in the process of refit. And finally, through other NOAA funding (OER), a DriX USV was purchased from iXblue (now Exail) Inc.

These various vehicles provide platforms for in- and off-shore seafloor survey work, product test and evaluation for these industrial partners and NOAA, and ready vehicles for new algorithm and sensor development at the Center. BEN, an off-shore vessel, is powered by a 30 HP diesel jet drive, is 4 m in length, has a 20-hour endurance at 5.5 knots, and a 1 kW electrical payload capacity. The Z-boat, Echoboat and EMILY vehicles are coastal or in-shore, two-person portable, battery powered systems with endurances of 3-6 hours at a nominal 3 knots (sensor electrical payload dependent). The DriX is also an ocean-going vessel, with a unique, purpose-built composite hull, giving it a maximum speed exceeding 13 knots and endurance exceeding four days at 7 knots.

Figure 9-1. DriX-8 deployed from the E/V *Nautilus* during shipboard integration and at-sea trials in March, 2022.

The marine autonomy group within the Center focuses on the practical use of robotic systems for marine science and in particular seafloor survey. Practical auto-nomy is defined here as the engineering of systems and processes that make the operation of robotic vehicles safe, effective and efficient. These systems and processes are designed to mitigate the operational risk of an operation by increasing the autonomy and reliability of its sensors and algorithms. Practical autonomy is viewed in a holistic way, including not only the safe navigation of the vehicle through the environment, but also the systems and processes that allow for unattended operation of sonars, data quality monitoring, and even data processing, and allow for operator-guided operation of these systems when necessary.

Progress in special projects called out under other tasks can be found under Tasks 10 through 14, while general contributions are described below.

Operations

This year has been a very busy one for Center uncrewed vehicle activities including the first-time integration of the DriX ASV aboard two vessels with preparation for a third in 2023. In 2022, the ASV group conducted four major shipboard deployments with DriX vehicles, three aboard the E/V *Nautilus* in the Central Pacific, and one aboard NOAA Ship *Thomas Jefferson* in Lake Erie. Finally, the Center's ASV group supported three major local deployments to support sea acceptance testing, training, and engineering trials of various vehicles and personnel here in New Hampshire.

Not all of this effort was funded through the Center's JHC grant. The purchase of DriX-8 in 2021, its integration into the E/V *Nautilus* in February and March of 2022, and deployment for the Ocean Exploration Cooperative Institute "Tech Challenge Cruise" were funded separately. However, many of the lessons learned in these operations were directly related to the goals funded under the JHC grant, were not explicitly funded elsewhere, and so are reported here. While the research objectives for the two grants are different, it is the complementary effort that fills the gaps to provide a wholistic consideration for practical aspects of operation.

Lessons Learned From DriX-8 Deployments

In February and March of 2022, the Center began integration and sea trials of the DriX-8 ASV into the ship E/V *Nautilus*, supported through other funding, and set sail again in May for a "Tech Challenge Cruise" focused on multi-vehicle operations (Figure 9-1). Then in July and August, DriX-8 was deployed in a collaborative mapping effort with NOAA's Office of Coast Survey to map the island atoll of Nihoa, northwest of Kauai. The cruises were staged out of the University of Hawaii Marine Facility in Honolulu, Hawaii.

Don Jones, responsible for emerging technologies at NOAA's Pacific Marine Operations Center who was coordinating many of the technical logistics for the shipboard installation of NOAA's own DriX vehicle (delivered in July 2022) and subsequent operations aboard NOAA Ships *Thomas Jefferson* and *Oscar Dyson*, was our guest and collaborator for these initial operations. Mr. Jones was able to observe and often participate in the Center's shore logistics with the DriX, its pre-underway sea-trials, shipboard crew integration discussions, crane operations, and DriX operating station shipboard installation. At our invitation Mr. Jones participated in casualty procedure discussions with the ship's bridge

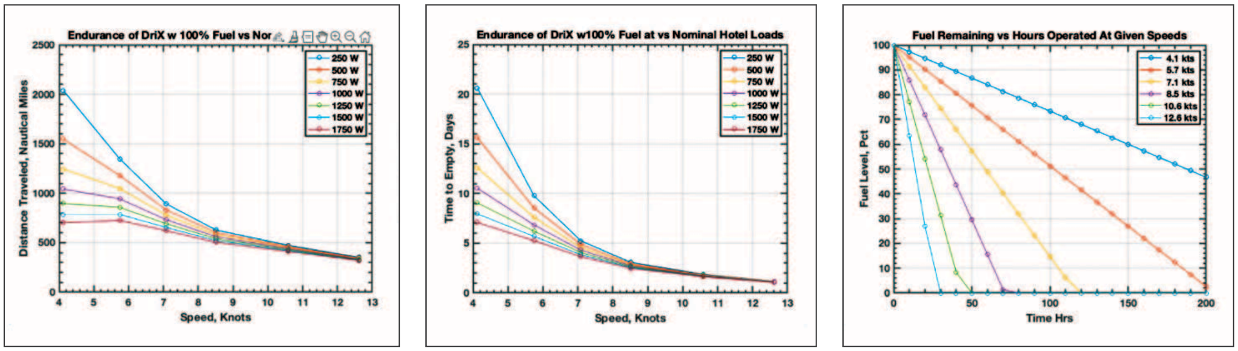


Figure 9-2. Typical outputs from the Center's DriX endurance model, which provide total distance travel (left) and time to empty (middle) vs speed for several payload power levels. Or alternatively, for 700W of payload systems one can predict the fuel level as a function of vessel speed vs time (right).

and engineering crew, as the Center facilitated the development of the ship's standard operating procedures and best practices. Close collaborations of this type are critical to the success of these complex systems as we transition from operational research to production operations.

A post-deployment review was conducted of the integration of DriX-8 aboard the *Nautilus* and subsequent shipboard operations. Schmidt produced a report from this review ("A Summary of Major Evolutions and Lessons Learned During NA136 aboard the E/V *Nautilus*") and presented this orally to representatives from NOAA's Office of Marine Operations and Office of Coast Survey, with an eye to future hydrographic operations with DriX-8 and the soon to be acquired NOAA DriX-12 aboard NOAA ships. The report included details of logistics required prior to deployment, crane and painter boom installation, and DriX deck cradle design and manufacture. It described DriX emergency recovery procedures that were developed by the Center and ship's crew, and the challenges presented by each. Practice evolutions facilitated by the Center to train the ship's crew in these procedures were also provided in the report. The report also described installation of operator stations and radio telemetry systems for command and control of DriX, and the methods and results of measurements made to characterize the coverage of these systems. The report provided guidance regarding tuning of

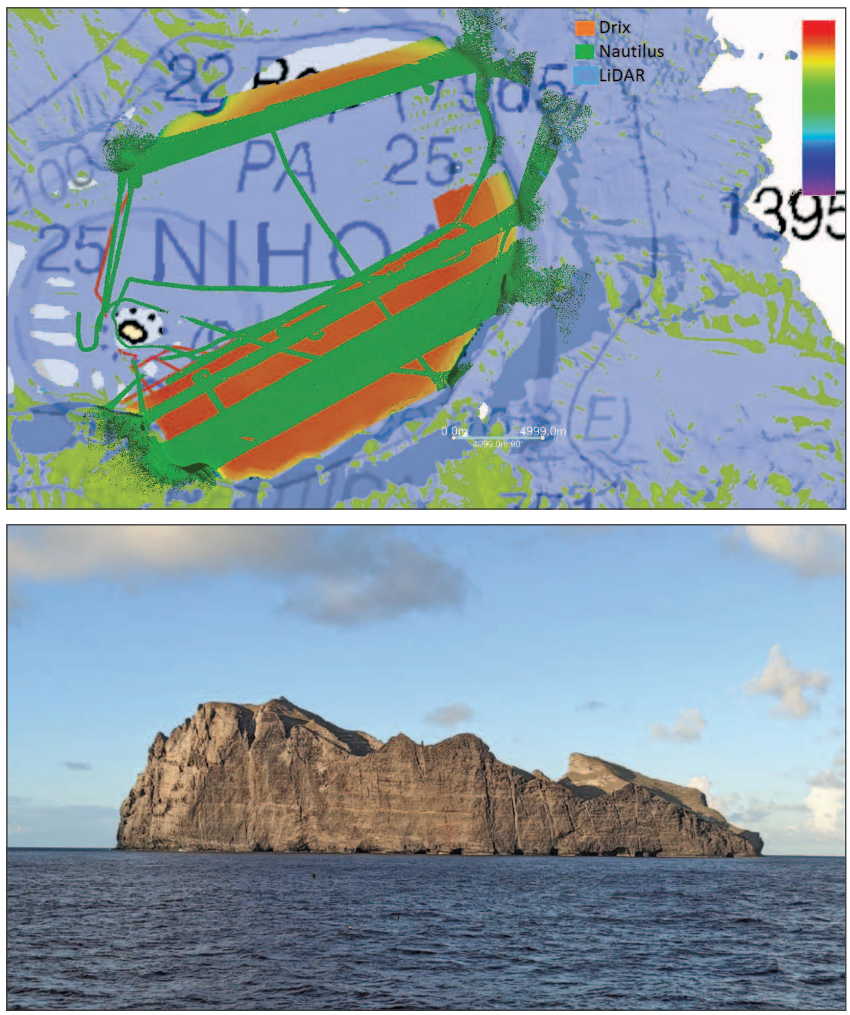


Figure 9-3. Mapping coverage (top) obtained around the island of Nihoa (below) during the NA142 OCS funded mapping expedition aboard the E/V *Nautilus*.

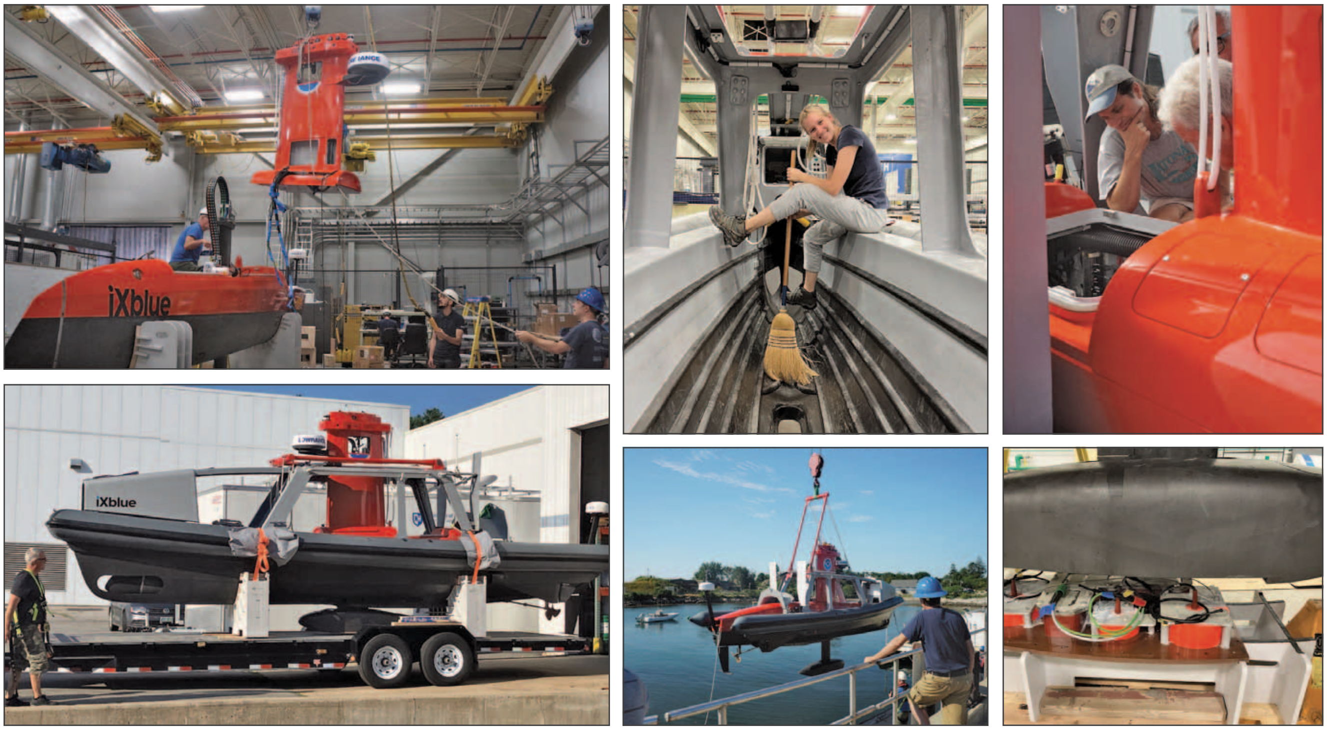


Figure 9-4. Assembly and initial deployment of the DriX-12 ASV by Center, NOAA and Exail personnel.

video and other real-time data streams to ensure telemetry systems do not become saturated during operations. The report detailed measurements of DriX RPM vs Speed, which are critical for the endurance modeling that the Center has performed, allowing operators to optimize distance traveled by DriX during casualty or poor weather conditions. Example plots of vehicle endurance vs speed were provided (Figure 9-2) and the model itself will be made available to NOAA operators separately. Finally, the report detailed numerous challenges incurred during these operations, including malfunctions of hardware components within DriX (lidar, CTD winch, etc.), firmware bugs identified in the telemetry and other systems, efforts to troubleshoot a fire suppression system leak, efforts to troubleshoot DriX auto-docking, and many others. NOAA was provided the complete list of corrective actions generated for Exail and tracked by the Center in an Appendix to this report.

In July, the Center lead Expedition NA142 aboard the E/V *Nautilus* to conduct survey operations in the vicinity of the island atoll of Nihoa, northwest of Kauai. DriX-8 provided hydrographic mapping survey, able to reach depths not reached by aerial lidar surveys earlier in the year.

High winds and seas made this deployment particularly challenging, forcing the team to adapt, sometimes deploying more than 120 km away in the lee of Kauai to then transit to the survey area, survey, and if necessary, transit back for recovery. In addition, the team demonstrated the ability to conduct mapping operations largely independent of the vessel, which continued in its own survey operations nearby.

During operations of DriX-8 operators learned the value of an endurance model allowing one to predict the capability of the vehicle to operate as a function of speed in terms of "distance traveled" or "time to empty." Such an endurance model was developed by Schmidt during a pre-cruise quarantine period prior to *Nautilus* deployment and refined over subsequent operations. Typical outputs from the model (Figure 9-3) allow operators deployed during NA142 to develop the deployment and recovery plan ensuring the vehicle would not be unlikely to run out of fuel prior to completion.

During the *Nautilus* operations, both in earlier cruises and the expedition to Nihoa, the Center identified corrective actions to ensure successful hydrographic survey for future operations with DriX-8, or NOAA's newly acquired DriX-12. For example,

Figure 9-5. DriX-12 Operations during the Sea Acceptance Tests and DriX Operator Training hosted by the Center in August and October.

tests with DriX-8 showed interference in the reception of MarineStar GPS corrections when the DriX handheld controller is in operation. These corrections allow the navigation system to operate with sufficiently low vertical uncertainty for hydrography. Testing during NA142 showed that application of an RF filter to the controller's telemetry system could mitigate the effect, and after verifying the corrective action on DriX-8, it was applied to DriX-12 at UNH on arrival and future construction at Exail. Understanding the source of

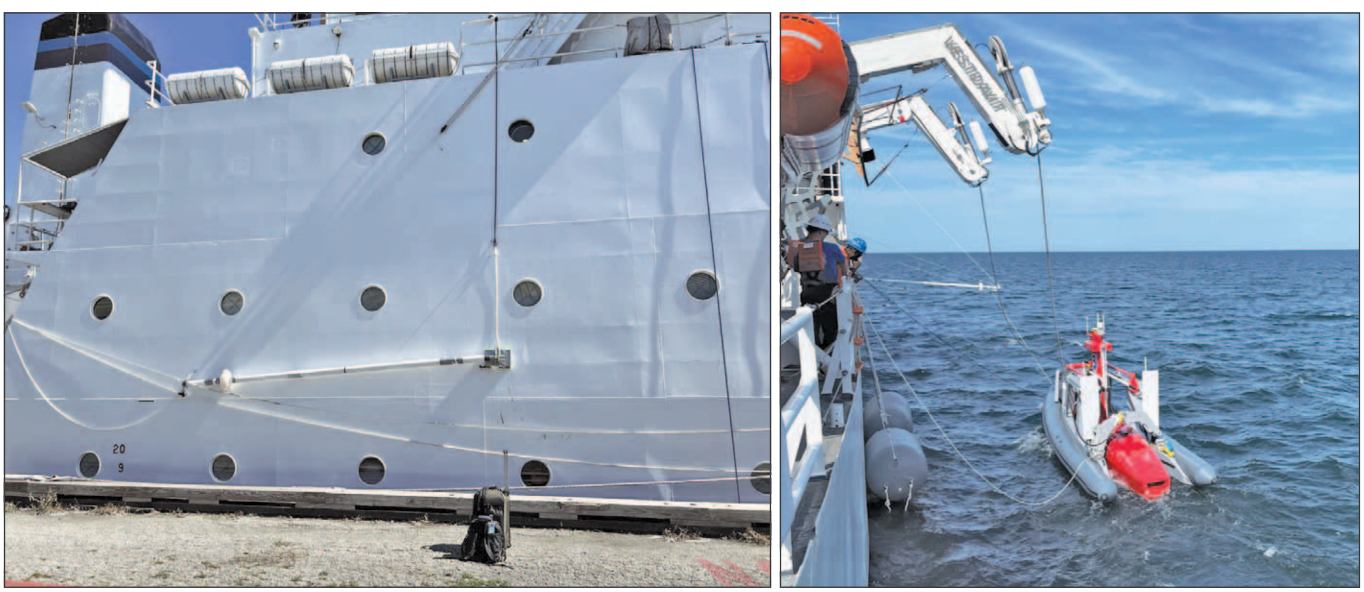


Figure 9-6. A magnetic mount designed by the Center for the painter boom utilized aboard NOAA Ship *Thomas Jefferson* during DriX-12 operations in the approaches to Cleveland.

this problem took considerable time and effort and helps to illustrate the utility of shared engineering efforts across systems with different mission objectives.

Shipboard Recommendations for USV Operator Stations

In July 2022, Russ Metzler, NOAA OMAO contractor, visited the Center for discussions focused on the Class B vessel acquisition, specifically requirements for operator stations and telemetry systems to support USV operations. In preparation, Schmidt, McLeod and Fairbarn wrote a whitepaper "Shipboard Recommendations for USV Operator Stations." The paper describes the kinds of displays that are necessary for safe USV operations, requirements for radio systems, interconnections to shipboard navigation systems and ways to minimize the cognitive loading of USV operators. The paper was later also provided for the commanding officers aboard NOAA Ships *Thomas Jefferson* and *Oscar Dyson* in preparation of DriX-12 integration.

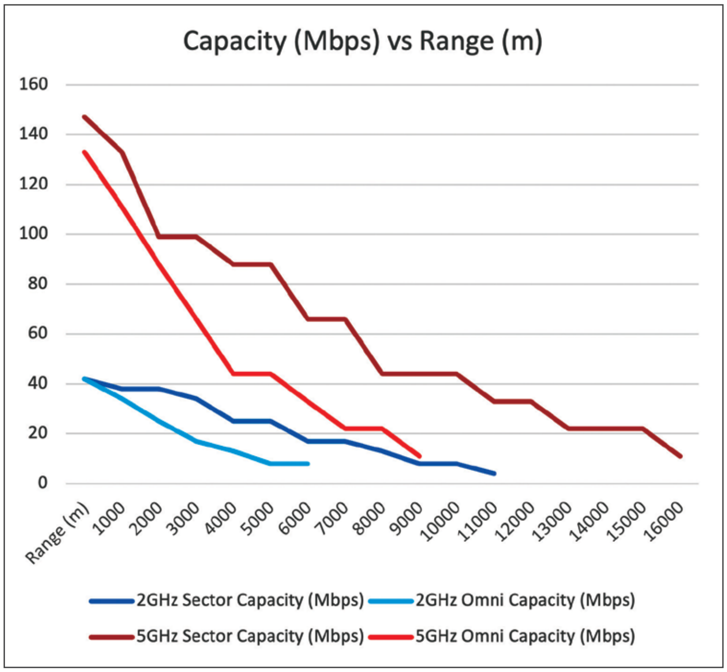


Figure 9-7. The theoretical improvement in throughput (Mbps) as a function of range is shown for a typical installation for the Ubiquiti 2GHz and 5GHz systems deployed aboard the Center's USV, BEN, and USV Control Van. For any given range, high-gain directional antennas (bold) are seen to greatly improve the bandwidth vs low-gain omnidirectional antennas.

DriX-12 Sea Acceptance Test and DriX Supervisor Training

The Center hosted Sea Acceptance Testing (SAT) and DriX Supervisor Training for NOAA's newly acquired DriX-12 in August 2022. DriX-12 was acquired as a collaborative effort between NOAA's Office of Coast Survey and NOAA Fisheries to provide a proof of concept in the use of the DriX system to achieve their respective mission objectives aboard NOAA vessels. DriX-12 was received at UNH and assembled at UNH's facilities, (Figure 9-4) followed by several days of SAT and operator training aboard the Center's R/V *Gulf Surveyor* (Figure 9-5).

After the DriX-12 Sea Acceptance Tests and first round of training were completed at UNH, DriX-12 was transported to Cleveland, Ohio to meet NOAA Ship *Thomas Jefferson* for two weeks of vehicle integration as well as pier-side and at-sea shipboard training. These efforts in the first two weeks of September were in preparation for two follow-on weeks of production survey time, with DriX-12 replacing one of the ship's three crewed launches. Schmidt, McLeod, and Muñoz deployed the Center's mobile USV Lab to Cleveland to provide a pier-side workspace during integration, and a shore-side DriX operator station and observation point, where VIPs could observe operations via satellite link. In collaboration with NOAA's project lead, Rob Downs, Schmidt aided the ship in integration of the DriX, DriX cradle, docking system, radio telemetry systems, operator's station, and bridge displays. Schmidt also provided "An Introduction to DriX" walk-throughs for the ship's crew, and role-play-based training sessions for watch stander communications and casualty scenarios. Schmidt sailed with the ship the second week, aiding in the development of the crew's best practices for deployment and recovery, operations, and emergency recovery procedures.

To safely deploy a DriX vehicle from the davits over the side, the DriX docking system (DDS) is ideally towed from a painter boom while the vessel is underway. The boom ensures the DDS and DriX are free and clear of the hull to provide clear passage during docking maneuvers and prevents damage to either system. Unfortunately, due to restrictions in the St. Lawrence Seaway locks, the ship could not mount anything permanent external to the hull. Schmidt and McLeod developed a magnetic mount

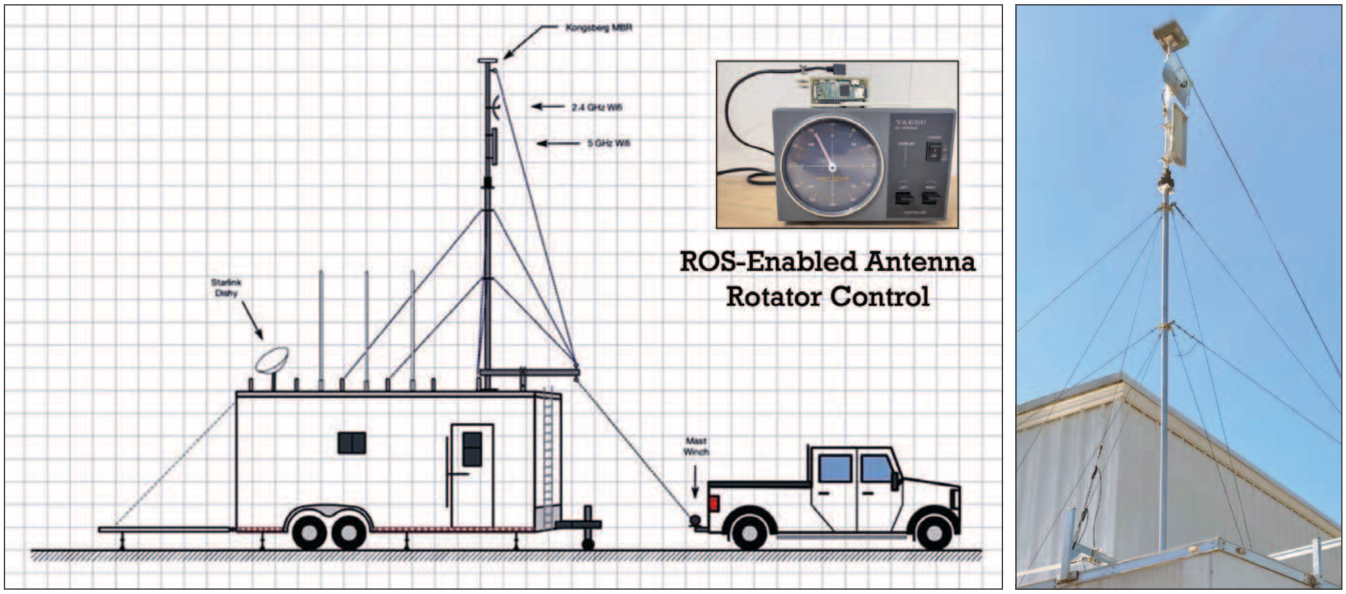


Figure 9-8. The Center's re-designed antenna mast with Robotic Operating System enabled antenna rotator controller.

system to overcome this limitation. Designed with dual 725 lb. industrial lift magnets, the system attached a prefabricated carbon fiber painter boom to the ship's hull (Figure 9-6). Three lines, each with block and tackle held the boom horizontal and orthogonal to the ship's hull during operation and allowed the boom to fold against the hull otherwise.

NOAA and Exail contract personnel continued operations aboard the *Thomas Jefferson* after the initial field trials were complete. Schmidt disembarked but provided additional remote support to the ship during their continued production survey operations the last two weeks of September.

NOAA's original planning for DriX-12 provided for a week of SAT followed by a couple of two-week training sessions but international shipping delays reduced the time available in August. To accommodate the change in schedule, the Center hosted NOAA and Exail personnel, along with DriX-12, for two additional weeks in October. The second event unfortunately was nearly canceled when a death in the family of the Exail instructor cut his stay short just one day after arrival. Schmidt, McLeod and Fairbarn, having taken the training themselves, and having had the experience of four deployments just this year, stepped in and provided both dockside and at-sea training for NOAA personnel from October 12–18 before aiding NOAA in disassembly and shipment of the DriX to NOAA's Marime Operations Center – Pacific.

Other Ongoing Research and Engineering

As part of the Center's research into the use of ASVs for marine science, Arsenault, Muñoz and Schmidt developed and maintain, a marine robotics framework named "Project 11." Project 11 and the CCOM Autonomous Mission Planner, CAMP, were begun in 2016 and provide a backseat driver for our vehicles and a place to develop new behaviors and integrate new sensors outside commercial implementations. In the spring of 2022, several improvements were made to the framework. These include the addition of time-based path following control, which makes the robot attempt to reach waypoints at specified times rather than using a pre-defined speed. This feature is necessary for obstacle avoidance and CPA management. Arsenault also developed a software plugin architecture within the Center's marine robotics framework for switching between various AI vessel navigators. This facilitates switching between operating modes for different conditions and allows comparison between algorithms designed for the same tasks. Muñoz developed "bag_manager," a software tool to manage log files generated by vessels using a Robotic Operating System (ROS) software framework (e.g., the Center's ASV-BEN and all DriX vehicles). This tool improves reporting of vessel operation and forensic analysis. Arsenault also improved Project 11's "udp_bridge," to reduce the chances of dropped packets. This tool provides data connectivity across wireless and other networks between USVs and one or more operator stations.

Maintaining good telemetry with high bandwidth between USV and operator is always a critical part of safe USV operations. In non-actively beam-formed telemetry systems like Wifi, a tradeoff exists between omni-directional antennas which provide 360-degree azimuthal coverage but relatively poor gain, or highly directional antennas which boast high gain but narrow angular sector coverage. Figure 9-7 illustrates the potential difference in throughput when higher gain antennas are used. In an effort to improve our WiFi telemetry links, McLeod, Muñoz, and undergraduate intern Anthony Lee prototyped an antenna mast rotator control system that tracks the USV during operations, allowing the use of highly directional antennas without regard to vehicle direction. The system is shown in Figure 9-8 and includes a Raspberry PI embedded processor combined with an off-the-shelf antenna rotator. The system was field tested for the first time in December with promising results.

The additional weight of the antenna rotator also required us to re-engineer the mast structure for safety and ease of deployment. McLeod designed a new lifting arm and winch system which allows a team to assemble the mast horizontally, and then winch it into place with just two people. This new configuration is shown in Figure 9-8.

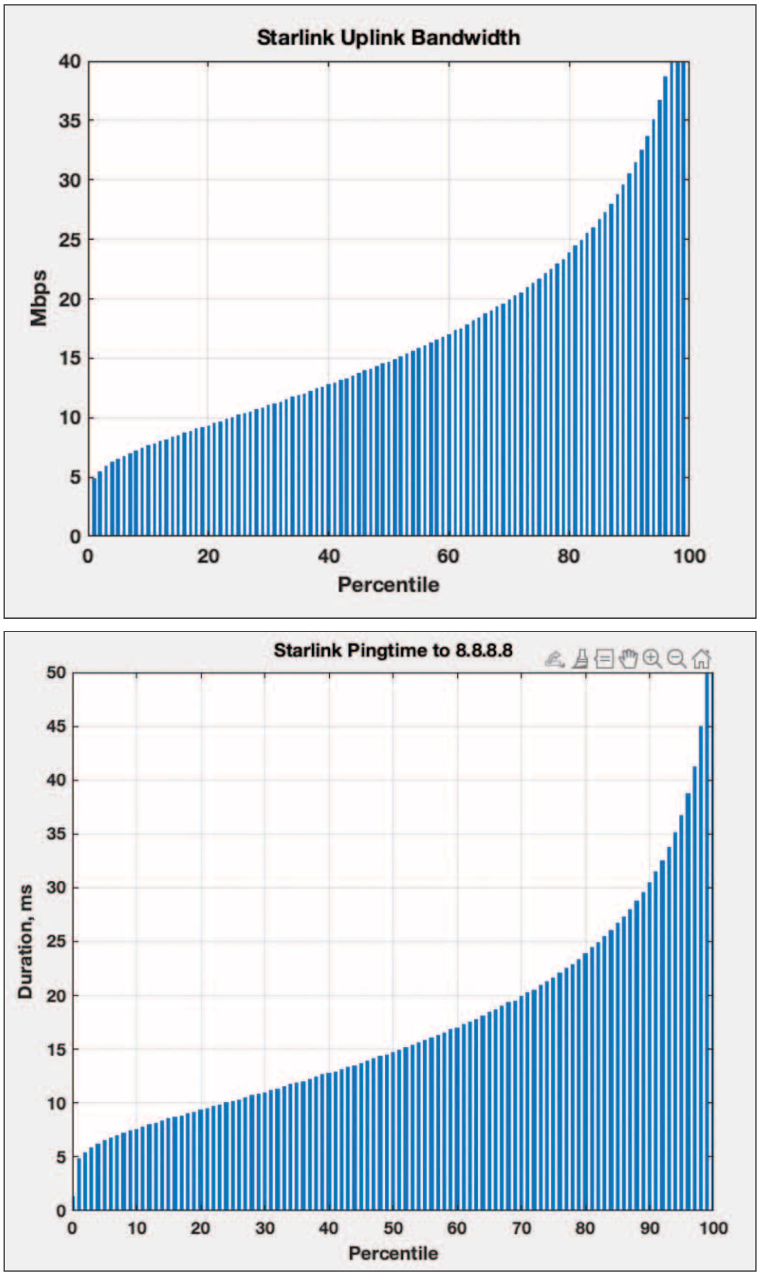


Figure 9-9. Cumulative probability distribution plots of Starlink uplink bandwidth (top) and "ping" time to Google's DNS server from a terrestrial Starlink system in Durham, NH.

In 2022 Starlink released its first retail antennas for satellite-based internet service. The Center believes that satellite-based services of this kind will revolutionize USV operations by removing the short range line-of-sight telemetry constraint allowing a USV operator to be anywhere on earth and increasing telemetry reliability between USVs and operators. To begin systematic testing of these systems for eventual use for USVs and other marine science applications, the Center purchased a terrestrial Starlink system in early 2022. Figure 9-9 provides cumulative probability distributions of upload bandwidth and ping time to an internet server, showing mean (50%) values of 15 Mbps and 15 ms, respectively. These values exceed or match those the Center is able to achieve with terrestrial line-of-sight systems and are highly encouraging. In addition, over 22 days of testing at 1 minute intervals (>30k measurements) an uptime of 99.9% was measured.

Based on these promising results the Center has purchased 4 additional units to upgrade telemetry systems on DriX-8 and its operator station, the Center's C-Worker 4 vehicle, *BEN* and the R/V *Gulf Surveyor*.

Task 11: Machine Learning Training Data for Marine Applications

JHC Participants: Val Schmidt, Kim Lowell, Andy McLeod, Roland Arsenault, K.G. Fairbarn, Avery Muñoz

Safe navigation of autonomous vehicles requires a semantic understanding of nearby objects that might be viewed by an onboard camera or other sensors, but not by an operator. While there are increasingly large databases of terrestrial images for the training of machine learning algorithms for detection and classification of this type, there is much less data available specifically annotated for marine environments and marine navigation. This research effort aims to collect, annotate, and serve as an archive of images for this express purpose.

In the spring of 2022, the Center built a prototype sensor package for automated annotation of marine images (Figure 11-1). The package combines a marine radar, camera, Automatic Identification System (AIS) receiver, GPS, IMU and data logging system into a portable, easily deployed platform. Test deployments were made of the system in Portsmouth Harbor in June to verify hardware interfaces and data logging capability.

Figure 11-1. The MLTDMA (pronounced "Matilda") sensor package during prototype testing is shown (left) with an example of auto-detected objects in the camera's image (right). AIS data (not shown) will help to auto-annotate the images for ships that transmit it.

Task 12: Path Planning for Ocean Mapping

Project: **Roads of the Sea**

JHC/CCOM Participants: Christos Kastrisios, Val Schmidt

Other Collaborators: Dimitris Zissis and Alexandros Troupiotis (University of the Aegean, Greece, and MarineTraffic), and Sean Kohlbrenner, Matthew Eager, Nilan Phommachanh, Alesandra Bernardini, Killian Cowan, Amith Kashyap, Alexander (Alex) Mercedes, Bobby DeVito, Eric Klein, and Forrest Mitchell (UNH/CS)

In our efforts to develop approaches for optimized path planning for uncrewed vehicles, we begin with a more general effort to optimize vessel transit routes. Unlike land routing that is constrained to strict road networks, sea navigation takes place in "free-space" and, thus, there are countless different routes a ship can take to get from point A to point B. To ensure safety of passage, mariners tend to use commonly traveled routes as best practice. Nautical and routing charts provide information regarding dangers to navigation and shipping routes and distances between major ports, however they are often outdated or not complete, while the routes can only be considered as recommendations.

When a ship takes a route for the first time or strays from previously followed and recommended routes (e.g., due to weather) it is at its greatest risk for grounding. Having a system to inform mariners if the new route has been travelled by similar size vessels would help alleviate that risk. Furthermore, in areas of high traffic, there lies the highest risk of collision with other vessels in the area. ARPA and AIS have been great advancements as they provide information about the current speed and course of nearby vessels, but the prediction of their most likely route/destination for the area remains one of the main tasks / challenges for the officer of the watch. Such a route prediction is currently impossible for autonomous vessels, and, hence, they are often forced to steer for almost every course change of the other vessels in the area and re-calculate their own path.

Mapping the most frequently traveled sea routes using historical AIS data and predicting ship trajectories is a rising research topic, mostly with the aim to identify irregular behavior of vessels. However, we lack a readily available system aboard ships for use by both mariners and autonomous systems.

The Roads of the Sea project aims to address the issue of non-uniform marine navigational schemes through a passage planning and prediction system that can support optimal marine navigation. This project aims to assist users, both humans and machines, in safely traversing the seas by providing routes customized to their own ship, based on those that have been previously taken by ships with similar characteristics, and by predicting other ships' trajectories. Additional parameters, such as the current weather conditions of the area or the period (month and time of day) of the vessel's journey will also be included in order to generate more suitable paths. The aim of this project is the development of a weighted graph of the routes that ships commonly use, the junctions and the global ports. The Roads network will be classified from small to major based on the traffic density and the type of the vessel that can safely follow them. The graph will be utilized for the development of a route suggestion system, where, based on the ship characteristics, the system will calculate the recommended route; and for a ship prediction system, where, given a ship's location and its proximity to the network, it will predict the ship's most likely route. These features will be developed by filtering and analyzing Automatic Identification System (AIS) and chart data. At the end of the first phase of the project the above functionalities will be made available in the form of a web map service, but, ultimately, their incorporation in USVs and ECDIS will be pursued. The final system of Roads and intermediate products may also be utilized in other research efforts, such as the evaluation of existing charts, setting survey priorities, the need for the establishment of new traffic separation schemes, and the protection of cetaceans from ship strikes.

In the previous reporting periods, Christos Kastrisios and Val Schmidt, in collaboration with Sean Kohlbrenner, Matthew Eager, Nilan Phommachanh, and Amith Kashyap, senior students majoring in computer sciences, started with processing AIS data and planning for the future requirements. That included defining good and bad data (e.g., data with issues with the MMSI, speed, and location), filtering out invalid AIS data, researching optimal data compression and merging methods, exploring capabilities to read compressed data to increase efficiency of the planned product, investigating available libraries to process the data, visualizing data, creating heat maps, and designing the route planning and ship prediction algorithms to account for future requirements.

Furthermore, the team worked on data exploration and processing through the usage of Python libraries, database design and development utilizing PostgreSQL, density map generation and visualizations through our own developed libraries, an A*

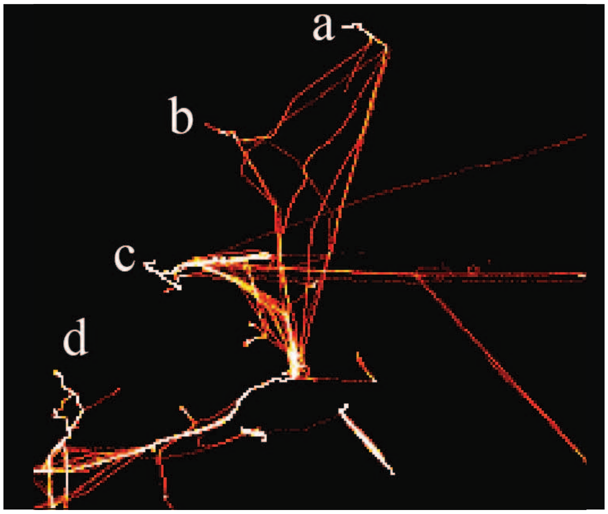


Figure 12-1. Visual heatmap representation of the grid showing various routes that form between grid cells in New England area (a: Portland, ME, b: Portsmouth, NH, c: Boston, MA, and d: Providence, RI). Brighter colors represent higher trafficked routes.

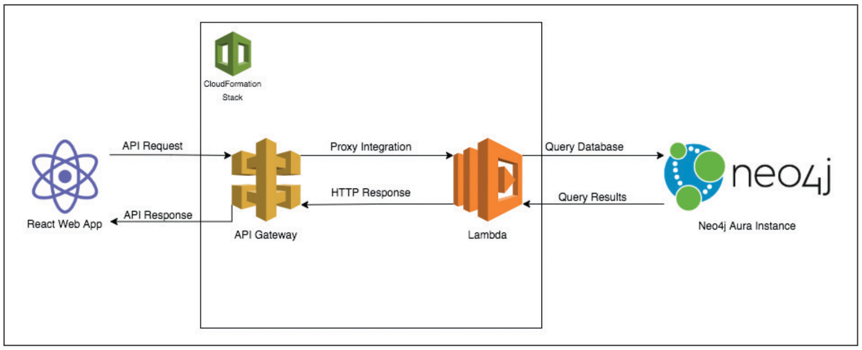


Figure 12-2. Overview of system's architecture

pathfinding algorithm implementation, and an early implementation of an Amazon Web Services deployment. The AIS data was processed through the usage of available and customized Python libraries for outliers, i.e., to omit data that is deemed as faulty or out of range to keep results representative of true maritime traffic, and for building the database of ship characteristics to be utilized when planning routes. An equal-area grid over the Lambert cylindrical equal-area projection was implemented to store the sum of ships that have passed through each grid cell. The grids are stored as serialized object files in an S3 bucket and utilized to create heat maps of traffic density, such as that illustrated in Figure 12-1. The A* pathfinding algorithm was utilized for generating the best route between grid cells with the lowest cost associated with the cumulative weight of possible paths. The generated routes are customizable within a user-specified vessel draft range and follow historical data while still having the flexibility to deviate when there is no existing route/data.

Toward the overarching goal for an ENC validated vector-based graph of the representative Roads of the Sea, in this reporting period we collaborated with Dimitris Zissis and Alexandros Troupiotis from the University of the Aegean, Greece and MarineTraffic who have also been working on the extraction of representative vector geometries from historic AIS data using unsupervised learning techniques capable of identifying the spatiotemporal dynamics of historic ship routes. With Alesandra Bernardini, Killian Cowan, and Alexander Mercedes, undergraduate CS students, we utilized sample "Roads of the Sea" in the New England area to build a prototype route suggestion and route prediction system. This system pulls data from a remote database hosted on a remote cloud platform and suggests optimal routes between ports (Figure 12-2). An additional front-end application provides access to the system's services, letting users view routes and request route predictions and suggestions for specific vessel types (Figure 12-3). Though connected, these components are designed to be loosely coupled, allowing for changes to and improvements on the utilized graph while permitting the system to provide services to other applications as an API.

Furthermore, with Sean Kohlbrenner and Matthew Eager we explored trajectory extraction and prediction methods in the literature. This included expanding previous work done on data extraction and processing as well as implementing various machine learning models used in the studies to identify useful solutions. AIS data was processed using the method developed in previous reporting periods to remove outliers and to isolate data to the area surrounding the gulf coast ports of New Orleans, LA and Houston, TX. This was done to take advantage of

Figure 12-3. Sample output of the route suggestion front-end application (main map) and the utilized network of roads in the database (inset map).

the ample non-passenger vessel traffic found in those areas. Single ships' trajectories were then split into approximately 10-minute-long sections which were then interpolated to fit regular one-minute intervals as shown in Figure 12-4. This data was used to train the two machine learning models, based on neural networks, that the team worked with: a bidirectional-GRU and bidirectional-LSTM. The objective of using these models was to be able to input a sequence of processed AIS data points and have the model return its prediction for the next 1+ points based on information from the given points.

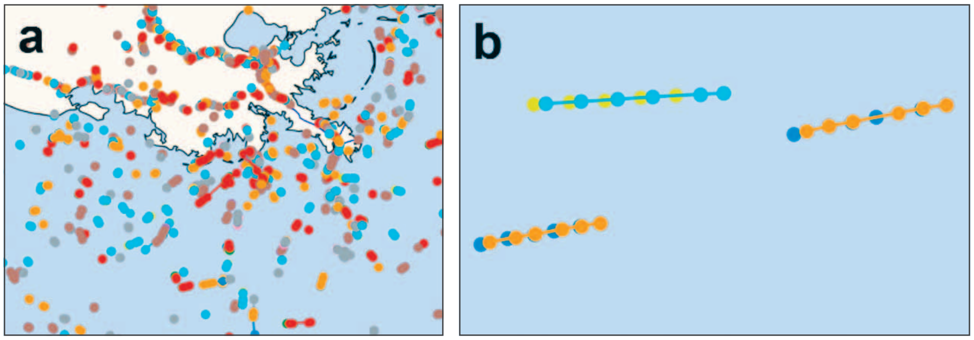


Figure 12-4. (a) Subset of interpolated trajectories surrounding southern Louisiana. Each single trajectory group is shown in a different color. (b) Three detailed examples of interpolated trajectories overlaid on top of original data points.

Subsequently, Christos Kastrisios, in collaboration with Alexandros Troupiotis, Dimitris Zissis, Sean Kohlbrenner, and the current UNH Computer Science senior project team consisting of Bobby DeVito, Eric Klein, and Forrest Mitchell, started working on identifying features of interest (e.g., shallow depths, rocks, and land) in ENC database to characterize the representative geometries of vessel paths along the route between Boston and New York City. Combined with static information regarding the size of vessels traversing the area, this approach would provide useful annotation upon the routes. The undergraduate research team has begun their work by setting up a program to automatically read in the chart and route geometry data for processing.

Project: Path Planning for Marine Robotic Vehicles

JHC/CCOM Participants: Val Schmidt, Roland Arsenault, Wheeler Ruml

Building on the route optimization efforts described above, we are also developing approaches to ensure that the appropriate algorithms and information can be utilized on an uncrewed vessel in an operational situation. It has become apparent that we could aid the Center's students and researchers in robotic path planning immensely if we were to build a standard set of interfaces and plugin architecture for path planners in our simulation and operational environment. Such an architecture would facilitate switching between planners to facilitate evaluations of their relative merits and capabilities more easily, or even to facilitate different modes of operation where a planner suited to a particular task could be switched out for another more suited to another task. This architecture was developed in spring of 2022 by Arsenault (and example plan is shown in Figure 12-5), and field tested on DriX during the Center's "Tech Challenge" cruise aboard the E/V *Nautilus* in May. Recent work has focused on attempts at implementing other planners within the framework, either developed by previous students or as a plugin through the Robotic Operating *System Open Motion Planning Library.*

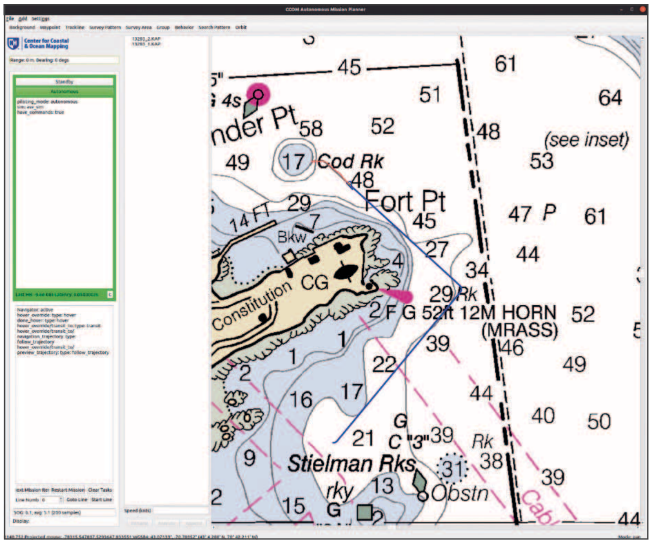


Figure 12-5. Here CAMP, the Center's mission planning interface illustrates in simulation an auto-generated transit plan from Stielman Rocks to Cod Rock, using a cost-map derived from the S-57 chart. The underlying stock planner will be replaced with one more suitable to USV navigation in future work.

Project: **Mission Planning for Uncrewed Sail-powered Surface Vessels**

JHC/CCOM Participants: Brian Calder, Larry Mayer, Sally Jarmusz

Other Collaborators: Brian Connon, Colleen Peters, Richard Jenkins – Saildrone

Traditionally, ocean mapping requires crewed mapping vessels, which can be costly due to vessel time constraints and the need for fuel, required supplies, and onboard crew. Technological advances have started to remove these constraints in systems such as Uncrewed Surface Vessels (USVs), and one of the latest developments is to eliminate or reduce fuel requirements by sailing for the majority of the time. Saildrone, Inc. designs sailing vessels for oceanographic purposes, including mapping through the Saildrone *Surveyor*, a 22 m USV. These vessels are monitored and operated by a human pilot landside, via satellite communications.

The Center partnered with Saildrone, Inc. on the development of the Saildrone *Surveyor*. Designed for open-ocean seafloor mapping and increased mission durations, the *Surveyor* uses a combination of sail and motor for propulsion. During the 2021 reporting period, the Center and Saildrone, Inc. oversaw the first ocean crossing of the Saildrone *Surveyor*, where it completed a transit from California to Hawaii during June and early July of 2021.

During the current reporting period, M.S. student Sally Jarmusz, along with Larry Mayer and Brian Calder, worked to increase the at-sea duration of the Saildrone *Surveyor* by optimizing the type of propulsion used given the data acquisition objectives and environment. Optimizing the point of sail for propulsion and determining when motoring is needed, this research is expected to reduce the need to return to port for fuel, thus advancing ocean mapping survey capabilities for USVs with similar modes of propulsion.

Data acquired on environmental conditions and vehicle behavior from the Saildrone *Surveyor* during the 2021 California to Hawaii transit are being analyzed. The variables in the dataset include wind vectors, wave height, Speed Over Ground (SOG), Course Over Ground (COG), heading, and pitch and roll. By extracting from the variables the segments of data where the vessel was under sail or motor, the variables can be analyzed according to the periods of their propulsion type, looking for correlations. From this information, predictive models are built that can provide insight on how the behavior changes depending on the use of sail or motor for propulsion. The conclusion of these analyses and predictive modeling is expected.

Task 13: Frameworks for Multi-ASV Operations

JHC Participants: Val Schmidt, Andy McLeod, Roland Arsenault, K.G. Fairbarn, and Avery Muñoz

Increased gains in efficiency from ASV operation will come when multiple vehicles can be operated simultaneously by just a few operators. For this reason, the Center has proposed development of new software frameworks better aimed at accommodating multiple vehicle operation.

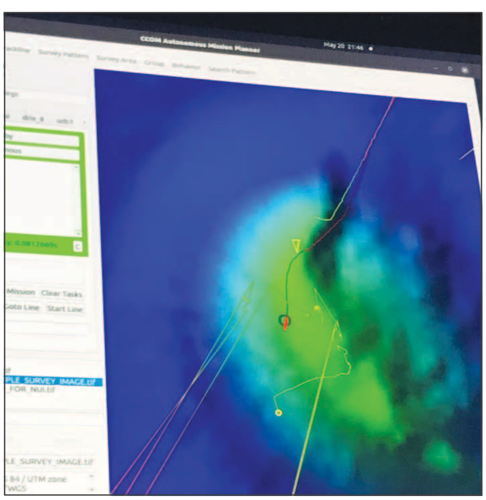


Figure 13-1. UNH CAMP mission planner tracking, communicating with and displaying location of multiple vehicles (AUVs, ASV and *Nautilus*) simultaneously.

In 2022, Roland Arsenault added the ability to simulate and display multiple vehicles simultaneously to the Center's mission planner—CAMP. As part of this effort, the underlying message passing infrastructure and topic naming scheme were reworked to specify platform names within each message topic. This simple step provided the ability to duplicate data types from multiple sources—position from several different vehicles, for example—without interference or confusion. CAMP was also reworked to display these multiple platforms within the same map GUI interface. In addition, the building blocks are in place for the behavior of a simulated vehicle to be influenced by another, paving the way for simulation of adversarial moving navigation hazards and cooperative survey operations. This capability was successfully demonstrated aboard the E/V *Nautilus* during the "Technical Challenge" cruise that deployed and operated the DriX and Woods Hole's AUVs Mesobot and NUI simultaneously, while the *Nautilus* operated independently. CAMP provided location and behavior information for all four vehicles at the same time, giving operators full situational awareness during this complex operation (Figure 13-1).

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: DATA ACQUISITION

NOFO Requirement 4

Improvement of autonomous data acquisition systems and technologies for unmanned vehicles, vessels of opportunity, and trusted partner organizations.

JHC/CCOM responded to NOFO requirement 4 with two tasks:

Task 14: Autonomous Sonars (work not yet started)

Task 15: Data Acquisition for Volunteer/Trusted Partner Systems

Task 14: Autonomous Sonars

JHC/CCOM Participants: Val Schmidt and John Hughes Clarke

In our efforts to fully realize the promise of autonomous hydrographic survey systems, we have also been working to ensure that our data acquisition systems are autonomous as well. This includes both acquisition of data, and real-time monitoring of performance, survey completion and data quality. Much of what we are doing in many of the previously described data acquisition tasks address some of these issues, and the work of Lynette Davis described under Task 4, developing a real-time water column monitoring tool is also very relevant. This tool is aimed to provide human operators the ability to monitor water column properties, which might affect bathymetric measurements during data acquisition. While the tool provides real-time display for human operators it also provides a data extraction and pre-processing step for algorithms to be developed for operation aboard autonomous systems. Most importantly, the introduction of Starlink communications with its ability to allow near real-time high-bandwidth transmission of data from anywhere in the world, may obviate the need for great efforts to be put into onboard data processing. This issue will be evaluated over the next year as we gain more experience with Starlink and fully understand its capabilities and limitations.

Task 15: Data Acquisition for Volunteer/Trusted Partner Systems

JHC Participants: Brian Calder, Larry Mayer, Brian Miles, Dan Tauriello, Adriano Fonseca, and Sally Jarmusz

NOAA Collaborators: Jennifer Jencks and Georgiana Zelenak (NOAA NCEI DCDB)

Other Collaborators: Kenneth Himschoot and Andrew Schofield (SeaID), Helen Snaith and Pauline Weatherall (British Oceanographic Data Center/Seabed 2030 Global Center), Jamie McMichael-Phillips and Jennifer Cheveaux (Seabed 2030), Guillaume Morissette (CIDCO), Sarah Grasty, Sherryl Gilbert, Alex Silverman, Chad Lembke, Matt Hommeyer, Mark Luther (University of Southern Florida COMIT)

Additional Funding Source: Seabed 2030

Over the last decade, there has been increasing interest in the potential for volunteer observers to contribute bathymetric (and other) observations for mapping purposes. The potential, however, has largely not been realized within the hydrographic mapping community due to concerns about quality and/or completeness of data. The "crowdsourced" concept has been advanced in multiple contexts as a solution for this problem, the assumption being that sufficient numbers of observers will allow for the "right" answer to emerge, even if some of the observers are incorrect. In the bathymetric world, however, the oceans are large and ships are (relatively) small, so that effective crowds only exist in very limited locations (e.g., in traffic separation schemes or narrow passages), most of which are well surveyed anyway.

Volunteer data have been used, however, for mapping purposes, for example to indicate where follow-up investigation is required. This is an extension of the hydrographic world's acceptance of mariner reports, which has a long history in most hydrographic offices. However, if there is to be real advantage of volunteer data, stronger guarantees of quality, and more dense data observations, are required. In previous reporting periods we have therefore outlined a model for Trusted Community Bathymetry (TCB) using trusted hardware with a reference (but low-cost) GNSS receiver to provide qualified depths referenced to the ellipsoid through auto-calibration of vertical offsets and uncertainty estimates; and a mass-deployable, scalable, low-cost data collection system using the Wireless Inexpensive Bathymetry Logger (WIBL) platform.

The Concept of Operations (CONOP) is a hybrid deployment of a few TCB loggers (cost order $1-2k each) to provide calibrated ellipsoidally referenced depths in a circumscribed area, along with a large number of WIBL loggers (cost order $10-20 each) in the same area to provide mass observation through local volunteers who know the area well and are invested in having better bathymetry in their area. Where there are crossing observations between the two systems, cross-referencing observations allows for calibration transfer, making the WIBL data much more valuable for mapping purposes. The open-source nature of the WIBL project allows this model to be scaled without a single entity becoming a bottleneck, allowing each deployment to control their own data collection, and retain control of their own data (which is often required by national authorities), while still ensuring that data reaches the international archive at the Data Center for Digital Bathymetry, hosted by NOAA/NCEI in Boulder, CO.

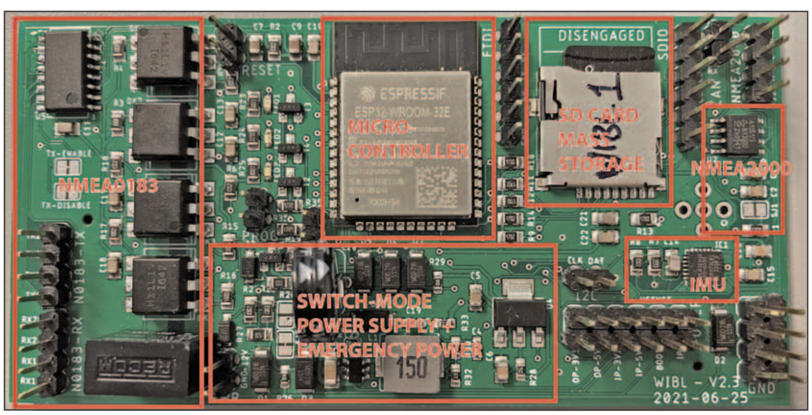


Figure 15-1. Hardware, version 2.3 of the Wireless Inexpensive Data Logger (WIBL) for NMEA0183 and NMEA2000 data.

In the previous reporting period, we described the WIBL project's development to prototype stage, and the first tests of the system in the field. In the current reporting period, incremental development of the system has been conducted, readying the system for demonstration-scale deployments with external partners. We have also continued to collaborate nationally and internationally to extend the project and potential deployment models, including work to improve the metadata expected of such systems to support FAIR (Findable, Accessible, Interoperable, Reusable) data models.

In addition to volunteer observation systems, non-traditional sources or collection platforms are likely to play an increasing role in mapping in the future, particularly in the context of global compilation models such as Seabed 2030. In the current reporting period, therefore, we have begun to investigate other models for non-traditional data collection, and in particular investigated how to optimize collection using sail powered USVs such as the Saildrone *Surveyor*.

Project: Wireless Inexpensive Bathymetry Logger (WIBL)

Starting in the 2020 reporting period, Brian Calder was asked by NCEI DCDB and Seabed 2030 to recommend data loggers that could be used for volunteer bathymetric information (VBI) collection. Having reviewed the then-available loggers and made recommendations, it was clear that at $250 (approximately) each, it would be financially difficult to scale up deployments of such loggers; there was also no data infrastructure associated with the loggers, making it very difficult for data collectors to contribute their data. The Wireless Inexpensive Bathymetry Logger (WIBL) project was therefore initiated to define a low-cost, open-source system (including hardware and software for data collection and processing) that could be readily scaled to multiple data collection events. The ultimate goal is to provide the model for a full-stack data collection, manipulation, and processing environment that could be cloned by any group interested in managing their own data collection in a given area, reducing the barriers to entry while still ensuring that properly formatted data, with metadata, was always received by the appropriate archive.

In the previous reporting period, we outlined the Concept of Operation (CONOP) for the WIBL project, fabricated the first deployable prototypes (Figure 15-1) and demonstrated an initial data collection event. In the current reporting period, incremental hardware and software developments have been undertaken to ready the system for larger-scale demonstration deployments as described below.

On-going supply-chain issues initiated by the coronavirus pandemic have made it difficult to procure some parts required for fabrication of WIBL loggers. An effort has therefore been made to use and document updated parts with better availability and longevity so that the design files for the project will remain valid for longer between refresh events. A particular example is the six degree-of-freedom MEMS motion sensor used for v 2.3 of the board, which was deprecated by its manufacturer, and became hard to procure; a newer model (STMicroelectronics LSM6DS3) was therefore selected and integrated for v 2.4 boards, and a software library was developed to fully integrate with the WIBL controller. Events such as this are likely to continue for at least another year as the manufacturing facilities settle back to a more stable "normal."

While operational, the Python implementation of the cloud-based processing chain for WIBL data was "research grade," which had started to cause difficulties in scaled-up deployments of the system. Therefore, Calder and Brian Miles worked to rebuild the software as a separate package, and Miles added "pythonic" installation information, better package structuring and dependency management, continuous integration methods, and extensive regression testing as a prelude to making the cloud-segment code a sub-repository (making management and development easier in the future). This also included porting the software data simulator to Python. This development also highlighted the complexity of deploying the cloud-segment using the Amazon Web Services (AWS) console, despite the detailed instructions in the repository. Calder and Miles therefore developed a scripted interface to facilitate deployments ("infrastructure as code") so that deployments of the cloud-segment code can be constructed by editing a local file of parameters and then running a single script. In addition to making individual deployments significantly simpler, this also allows for multiple deployments to be managed through a single AWS account, opening the possibility of a commercial (or non-profit) entity offering Software-as-a-Service WIBL deployments for any implementations that do not care to host their own cloud processing chain (or who do not have the resources to do so).

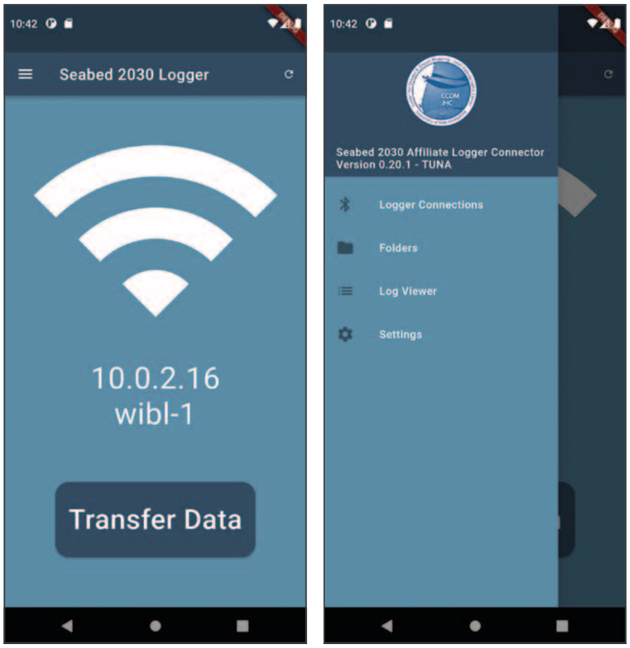


Figure 15-2. Screenshots of the cross-platform mobile application for logger management and interaction.

As reported previously, the WIBL project has been advanced by the addition of teams of undergraduate Computer Science students working on their senior projects. In the current reporting period, the foci for this group were to develop a cross-platform mobile app (Figure 15-2) to allow both iOS and Android deployments of the logger management and data upload software; and to demonstrate a more modular cloud-segment based on a state-machine model through AWS Step functions. Both project components are now complete, and available within the WIBL project. Full integration of the Step function approach will be considered in the next reporting period.

Finally, although it is expected that most implementations of a WIBL data collection system will likely use prefabricated logger boards from a commercial or non-profit vendor, in order to complete the deployment model, Calder, Michael Smith, and graduate student Adriano Fonseca have collaborated on the design of a 3D-printable enclosure that can be used to host WIBL boards. This will allow any interested implementation group to fully deploy WIBL loggers in the field, if desired. The design files for the box prototype will be hosted on the project repository when finalized early in the next reporting period.

Project: Volunteer Bathymetric Information Metadata (IHO CSBWG)

The International Hydrographic Organization (IHO) has, since 2014, sponsored the development of a guidance document for the collection of volunteer bathymetric data (B.12[2]). As part of this effort, Calder has supported the working group meetings with technical advice and recommendations. In the previous reporting period, Calder collaborated with colleagues from the IHO Crowdsourced Bathymetry Working Group to develop an extended and restructured metadata format for inclusion in the IHO guidance document on volunteer bathymetry (Report B.12); this was presented to the Working Group's IHO sponsor in the current reporting period and accepted as part of version 3.0.0 of B.12.

As a recommendation document (rather than a standard), B.12 provides guidance for minimal, recommended, and desired metadata, but does not provide detailed methods for the encoding of this information in the data files uploaded to DCDB. In consequence, there is currently fairly wide latitude in structure and formatting of metadata, and little specific guidance on how the various fields should be formatted. This could, potentially, result in widely varying metadata contributions, making ingestion difficult for the NCEI personnel at DCDB. In the current reporting period, therefore, Calder and Brian Miles have collaborated with Georgiana Zelenak (NCEI DCDB) to develop a schema document for the JSON format metadata for version 3.0.0. This document, itself in JSON format, specifies directly the contents and syntax for the metadata in a human- and machine-readable form, which allows any given example of metadata to be validated (through appropriate code, developed by Miles) according to the requirements of the B.12 recommendation document. In effect, therefore, this document provides the encoding guidance, controlled vocabulary, and syntax rules required for vendors to unambiguously specify metadata for VBI.

The prototype JSON schema document and validation software are scheduled to be proposed for adoption (and likely further development) by the Working Group at the next meeting (CSBWG13, January 2023). It is expected that the schema and code will be adopted by IHO and transitioned to an Open-Source model for community development among the interested vendors and Member States.

Project: Field Trials, National, and International Support (NCEI, Seabed 2030, SeaID, USF, CIDCO)

A key component of the research on the WIBL system is to demonstrate field data collection and determine an operable strategy for seeding data collection events. Consequently, in the current reporting period, Calder has collaborated with many interested parties to support volunteer bathymetry collection in general, and field deployments of WIBL loggers in particular. This has included explaining expectations and technical requirements for data collection to potential IHO Trusted Nodes (with Jennifer Jencks and Georgiana Zelenak of NOAA/NCEI DCDB); working with the Seabed 2030 Global Centre (Helen Snaith and Pauline Wetherall) to establish a WIBL-based data flow path for other data loggers, thereby making them effective data collection devices; and collaborating with SeaID (Ken Himschoot and Andrew Schofield) in the development of their WIBL-compatible NEMO-30 logger. A collaboration with Seabed 2030 has included supporting commercial logger field deployments in Palau and South Africa, qualifying data from the SeaKeepers initiative, and trouble-shooting data format problems (with the Global Centre). This exposure to commercial data loggers and data from many, varied sources in the current reporting period has significantly improved test coverage for the WIBL processing code and brought about feature enhancements such as much more robust metadata editing facilities that allow the Global Centre to inject metadata into data files generated by loggers which do not have the facility to support internal metadata management (as in the WIBL model).

Calder has also supported, with Adriano Fonseca and Dan Tauriello, field trials of a hybrid TCB and WIBL deployment in Tampa Bay, FL with the University of Southern Florida's COMIT program. Funded through a separate NOAA grant, this program has a goal of using trusted partners to host the auto-calibrating TCB loggers and deploying the WIBL loggers to other volunteer observers. Calder and Fonseca fabricated five WIBL loggers in field-deployable boxes, while Tauriello re-qualified a prototype TCB logger. Data collection is underway and should provide data for cross-calibration experiments in the next reporting period. In the current reporting period, Calder has also collaborated with Guillaume Morissette and others at CIDCO (Rimouski, Québec) to explore the possibility of a second hybrid field trial using WIBL loggers and CIDCO's HydroBox loggers, which offer similar functionality to the TCB loggers. The proposed goal is to have a field deployment in the first half of 2023.

[2] https://iho.int/uploads/user/pubs/bathy/B_12_CSB-Guidance_Document-Edition_3.0.0_Final.pdf

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: DATA VALUE

NOFO Requirement 5

Improvement in technology and methods for more efficient data processing, quality control, and quality assurance, including the determination and application of measurement uncertainty, of hydrographic and ocean and coastal mapping sensor and ancillary sensor data including data supporting the identification and mapping of fixed and transient features on the seafloor and in the water column and the resolution of unverified charted features.

JHC/CCOM responded to NOFO requirement 5 with five tasks:

Task 16: Bathymetry Data Processing

Task 17: Backscatter Data Processing

Task 18: Object Detection

Task 19: Chart Features (work not yet started)

Task 20: Advanced Quality Assurance/Control Tools

Task 16: Bathymetry Data Processing

JHC Participants: Brian Calder, Kim Lowell, Matt Plumlee, Adriano Fonseca, Bocheng Cui, Jason Worden

NOAA Collaborators: Eric Younkin (HSTB)

Other Collaborators: Shannon Byrne (Leidos), Dave Caress, Dale Chayes, and Christian dos Santos Ferreira (MBSystem)

Despite advances in processing techniques and technology over the last decade, processing of large-scale, high-density, shallow-water hydrographic datasets is still a challenging task. JHC/CCOM has pioneered a number of techniques to improve on the processing times achievable, and new technologies that have conceptually redefined what we consider as the output of a hydrographic survey. There is, however, still some way to go, particularly in the context of cloud-based, distributed, and real-time systems for automated survey.

Project: Implementations of CHRT

The CHRT (CUBE with Hierarchical Resolution Techniques) algorithm was developed to provide support for data-adaptive, variable resolution gridded output. This technique provides for the estimation resolution to change within the area of interest, allowing the estimator to match the data density available. The technology also provides for large-scale estimation, simplification of the required user parameters, and a more robust testing environment, while still retaining the core estimation technology from the previously verified CUBE algorithm. CHRT is being developed in conjunction with the Center's Industrial Partners who are pursuing commercial implementations.

In the current reporting period, Brian Calder has supported two current implementation efforts. First, he has been collaborating with Shannon Byrne (Leidos) to finalize the implementation of the Level of Aggregation (LoA) algorithm, an alternative to the base data density estimation algorithm used in the reference version of CHRT. The LoA algorithm has theoretical advantages, but also minimizes code dependencies which can be a significant implementation advantage. The code has been prepared as a pull request for the CHRT source code and is likely to be merged into the main branch early in the next reporting period. Second, Calder has worked with MARUM

(Bremen, Germany) to progress the implementation of CHRT for the open source MBSystem multibeam processing system, providing technical assistance with the code base and advice on implementation issues. The process continues.

In the previous reporting period, the Center declared its intention to provide an open-source licensed version of the CUBE source code. CUBE was the first-generation bathymetry processing algorithm developed by the Center and licensed to Center Industrial Partners starting February 14, 2003. Over a dozen licenses were subsequently issued, leading to CUBE being implemented in almost all bathymetric data processing packages. After formal consultation with current licensees led to no objections, the CUBE source code repository was relicensed using the MIT open-source license and made public during this reporting period.

Project: Performance of Cloud-distributed Desktop Software

The use of cloud technologies has been revolutionary for computing environments over the last ten years. The availability of always-available, scalable compute resources and associated services has changed the way developers think about software systems and has allowed various industries to grow beyond what would be feasible if they had to provide their own hardware and server rooms. There is potential for significant advantage in the bathymetric processing field by taking data into the cloud, for example by allowing for dynamic scaling of compute resources as more data is made available, speeding up processing. An essential issue, however, is how to manage these resources and how to take advantage of the freedoms of the cloud environment while still maintaining guarantees about product correctness (and keeping costs in check).

One previously proposed solution was to take current desktop bathymetry processing software and deploy it in the cloud. The idea here is to retain the familiar processing environment while allowing for better data and software sharing, while also avoiding having to purchase local hardware. Some prototype implementations of this idea by the Center, and NOAA Ocean Exploration demonstrated that this was possible (with some constraints covered below) but did not address the costs and performance issues. In the current reporting period, therefore, with auxiliary funding from the Ocean Exploration Cooperative Institute (CloudMap project), Calder and undergraduate student Jason Worden investigated the performance and cost structure of this idea in the Amazon Web Service infrastructure.

QPS Qimera software suite was chosen for benchmarking, and was deployed in three configurations: in the Elastic Cloud Compute (EC2) environment, where individual servers can be chosen and instantiated by the user; in the WorkSpaces environment, where servers are generated automatically by AWS (i.e., a "virtual desktop" system); and in a local server within the Center's server room, which provides as close a match as possible to current desktop systems deployments while still allowing for different connected storage types. Within each environment, different available storage media were attached to the compute resource in order to test their relative performance. The different storage media have different cost structures in the cloud environment and therefore present a different cost-performance tradeoff. The different media are described in detail below. In each case, each combination of compute resource and storage medium had the same operation tested 10 times, with Qimera's logged duration noted. Care was taken to deploy the compute and storage resources in the same AWS Availability Zone to avoid cross-zone delays and costs; us-east-2c was used in this case.

Due to constraints with licensing in Qimera, special permission was sought from QPS Ltd. for licenses that could be cloud deployed. Care was taken to ensure that the licenses were disabled on each instance before stopping it, since the specific configuration of the instance becomes part of the licensing structure: a restarted instance usually causes the license to fail, which must be reset by QPS customer service. (This is a particular problem with desktop software being deployed in the cloud.) Special permission was also required from AWS to instantiate g4ad.2xlarge EC2 instances and Graphics WorkSpaces instances since Graphics Processing Unit (GPU) enabled instances are a limited resource within AWS.

Three basic operations were tested corresponding to typical compute-heavy bathymetric processing tasks: converting data into the processing system; applying line-based corrections and manipulation (e.g., adding water levels, refraction correction, uncertainty computation); and generating a gridded surface. The dataset chosen for test was EX2203 from the NOAA Ship *Okeanos Explorer* (277 files, 25GB not including water column data) just south of Puerto Rico.

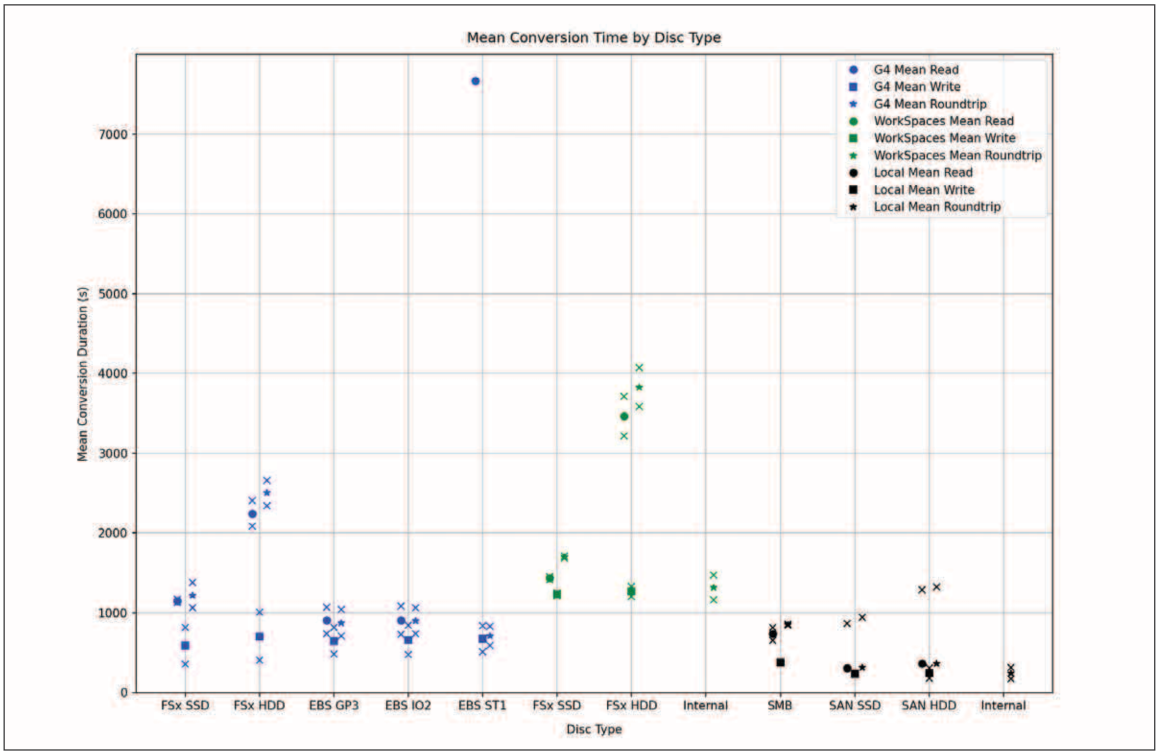


Figure 16-1. Comparison of data conversion times for three different configurations of compute resource, and associated storage media. "G4" was a g4ad.2xlarge EC2 instance (8 vCPU based on AMD EPYC 7R32 cores, 32GB memory, AMD Radeon Pro GPU (8GB), 300GB NVMe working store, 10Gb/s network); "WorkSpaces" was a Graphics instance (8vCPU, 16GB memory, 4GB GPU, 100GB OS, 100GB working store); "Local" was a 24-core AMD "Threadripper" server (128GB memory, 8GB Nvidia RTX 2070 GPU, 100GB NVMe working store, 10Gb/s network). "FSx" is AWS FSx for Windows storage (SSD is solid state discs, HDD is hard discs); "EBS" is AWS Elastic Block Storage (GP3 general purpose; IO2 throughput biased; ST1 hard disc backed); "SMB" is a Windows server share, "SAN SSD" is network-connected iSCSI (block based) storage backed by SSDs, "SAN HDD" is network-connected iSCSI (block based) storage backed by HDDs with an SSD front-side cache; "internal" is local disc.

The results of data conversion, Figure 16-1, demonstrate the difference in performance between different storage types, and between compute resources in general. For each storage type, three experiments were conducted: reading the data from the storage media and writing locally; reading locally and writing to the storage media; or reading and writing to the storage media. In many cases the performance in these cases are similar, but for hard disc media (i.e., spinning platter discs), there is an obvious difference between read and write speeds, likely due to write caching. For the G4 instances (i.e., the EC2 servers), there is also a significant difference between FSx for Windows (managed file storage) and EBS (block storage), although surprisingly little difference between the three different types of EBS despite their significantly different nominal performance characteristics and price points. This is thought to be because the access patterns for Qimera do not flood the channel to the discs, so that throughput optimized (IO2) advantages are not observed. The performance of the G4 instances is obviously better in each category than the WorkSpaces equivalents, but worse than the local implementation. In fact, for each rough equivalent media type, the local implementation is significantly better and more consistent.

The results of line-based data processing, Figure 16-2, demonstrate even more significant differences between the compute resources and storage types. Here, the managed storage ("FSx") is significantly slower in all cases, although surprisingly the internal ("G4 NVMe") and EBS storage performance is similar in the EC2 case. The local server, however, is significantly faster (order four times) even when using the network connected ("SAN") storage. This demonstrates clearly the time-cost associated with deployment of this type of processing software in the cloud.

The gridding performance, Figure 16-3, shows perhaps the most significant difference between storage media performance, and again emphasizes the performance difference between local servers and cloud-based instances. In all cases, hard disc storage performed poorly (the SAN HDD in the local instance has SSD front-end cache), and the local server performance is again significantly faster than even the fastest cloud-deployed instance.

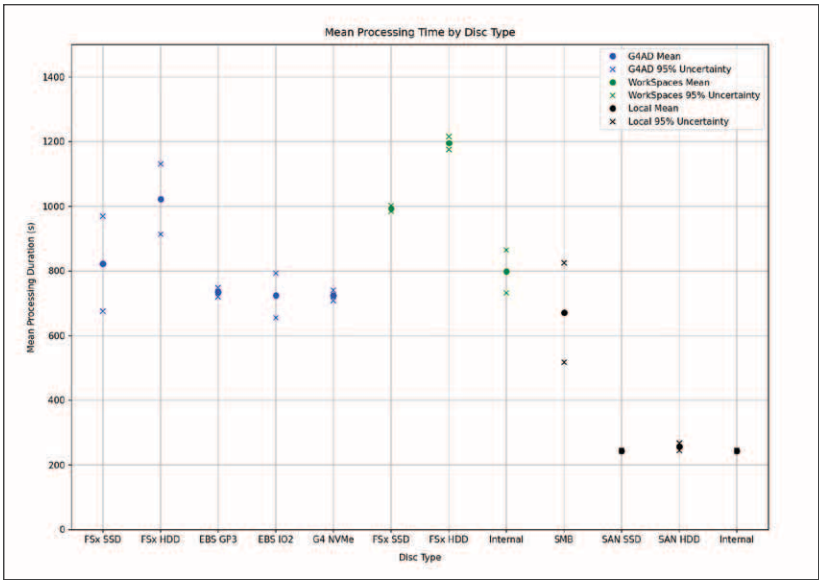


Figure 16-2. Comparison of line-based data processing time for three different configurations of compute resource, and associated storage media. See Figure 16-1 for key and specifications.

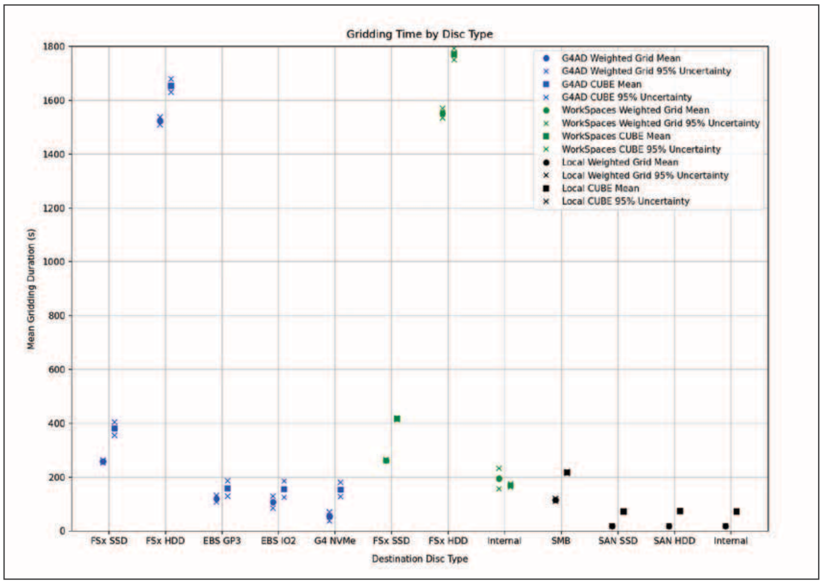


Figure 16-3. Comparison of grid construction time for three different configurations of compute resource, and associated storage media. See Figure 16-1 for key and specifications.

Since data conversion and line-based processing (Figures 16-1 and 16-2) are typically only done once, some reduction in performance could be considered acceptable if there was some significant benefit in another area. Since most modern data processing relies heavily on grids, however, performance reduction in grid construction (Figure 16-3) is harder to excuse. The results here demonstrate that EBS storage on EC2 would likely be recommended if a cloud deployment is required, and that there would be a preference for EC2 instances over WorkSpaces in most cases, despite the higher management overhead.

However, the cost structure of "desktop in the cloud" is problematic. Assuming a 90-day "ping to product" interval, the cost of the recommended G4 instance and EBS GP3 storage would be approximately $2,050 (96% from the EC2 instance fees, predominantly because of the required GPU), not including the cost of the Qimera license. Costs could be reduced by carefully disabling the license and turning off the instance between workdays, but this would be a complex process and could cause work-stops if the license was not handled properly. The cost is, however, close to that of a new local desktop machine, and this is just for a single survey: if there were multiple missions and multiple data sets being considered simultaneously, it would be significantly cheaper to just use a local machine.

These results suggest that using standard desktop processing software in the cloud is possible, and can be optimized, but is always likely to be cost-prohibitive. Mostly, this is because of the requirement for a combined compute and graphics resource for the software, which is expensive to provide in the cloud. Alternative approaches to cloud provisioning might potentially be found, but it seems likely that some more significant modification of the processing paradigm is required for efficient cloud deployment.

Project: **Distributed/Parallel Bathymetric Processing**

The costs associated with deploying desktop-based processing software in the cloud discovered in this reporting period suggest that such a strategy is currently cost-prohibitive. Calder, Matt Plumlee, and Bocheng Cui therefore worked in the current reporting period on design and early implementation of a cloud-native processing structure that could be used to avoid the concerns highlighted and take advantage of the specific features of cloud-based processing that are not available in the desktop environment. The outline data flow, Figure 16-4, highlights using different types of storage at different times in the workflow to optimize costs and envisions a difference between working-store for data points and archival data points to be delivered directly to the national archive. Note also the different output products, considering different use cases for the same data.

Several components of this proposed system (e.g., message queuing, spatial databases, scaling compute resources) are available from different cloud providers and may be possible to adapt and assemble to support this proposed model, but the domain specific components to handle bathymetric data and generate depth estimates will have to be generated.

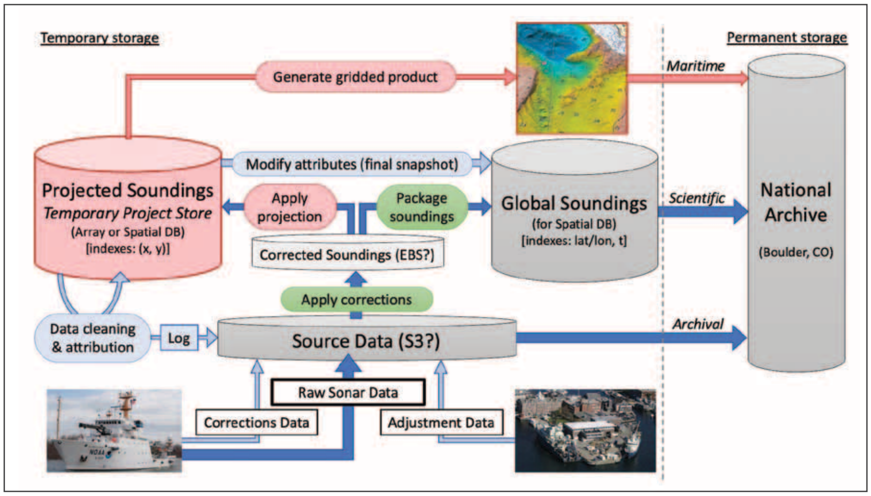


Figure 16-4. Proposed architecture for cloud-based bathymetric data flow and archival. Note the use of multiple storage media for different purposes to optimize costs and separate (but optional) database of point soundings for non-mapping or research purposes.

A more detailed view of the proposed processing structure is given in Figure 16-5. Here, the proposal envisions a structure that maintains an always up-to-date estimate of the depth in any given area, which can be updated at any time as new data is added, or data is removed by automated processes or human inspection. Multiple simultaneous users can access the data from their desktop systems (using a dataset broker service to identify dataset locations in the cloud), and the depth service arranges for the commands to be sequenced as required and for the back-end compute resource to be scaled as appropriate to meet any given response time required by the user. This structure keeps the data and compute together in the cloud, minimizing data egress, and assumes that GPU-heavy visualization for product inspection and data remediation happens on the desktop where it is significantly cheaper.

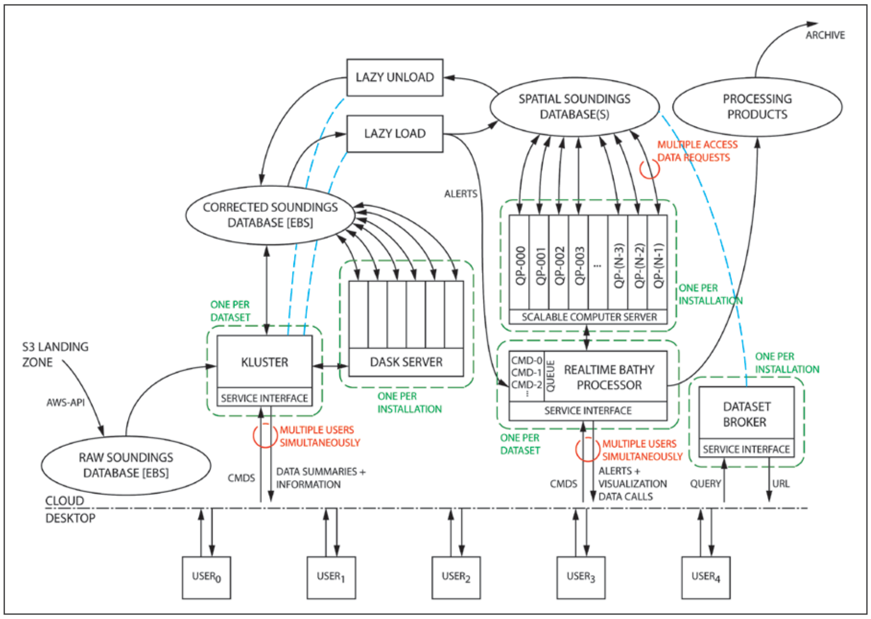


Figure 16-5. Detail of proposed processing architecture with simultaneous multi-user interaction with each dataset, scalable compute resources, and a centralized dataset broker to allow desktop installations to access each dataset. Note that the system provides a time-series processor (with Kluster) and a spatial-organized processor for each active dataset, but one shared scalable resource per installation to carry out the actual computations.

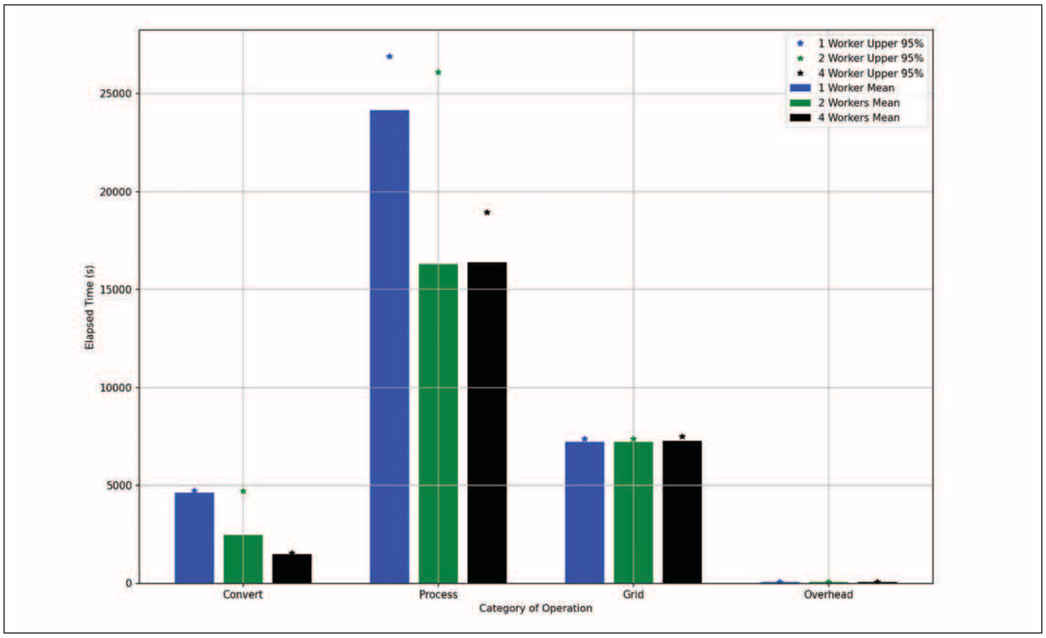


Figure 16-6. Performance characteristics of the modified Kluster library inside a Docker container as a function of number of Dask workers provided. "Convert" is data conversion into Kluster working format; "Process" is time-series processing; "Grid" is grid construction; "Overhead" is time added by the Docker container and network interface.

In the current reporting period, therefore, Calder and Cui have started this development by working with Eric Younkin (formerly at NOAA/HSTB) to adapt the Kluster open-source processing software to be cloud-deployable, and to generate a stateless, scalable version of the CHRT algorithm that can be run in the parallel compute model proposed. The Kluster source code was designed as a library with a GUI front-end but had never been deployed as a service; a network service interface was therefore retrofitted, and the whole packaged in a Docker container to allow it to be more easily deployed. Kluster uses Dask to scale compute services in parallel, but implicitly assumes that this will run on the same computer as the rest of the code; modifications to the code were therefore made to allow for an external Dask server to be used, which can significantly reduce startup times. Performance testing with this modified Kluster, Figure 16-6, shows variable benefit from multiple Dask workers in this configuration. Data conversion improves significantly with the number of workers, but after moving to two workers line-based processing does not improve; grid construction does not improve at all. Limitations at this scale are likely due to resource bottlenecks on the particular implementation and will be investigated further in the next reporting period.

Project: Automated Data Processing for Topobathy Lidar Data

Work undertaken in this project is also a major component of Task 26, and is discussed in the narrative there.

This project maintains its focus on (semi-) automated extraction of soundings representing shallow-water bathymetry from airborne Lidar point clouds. At the end of the previous reporting period, the CHRT-ML 1.0 algorithm that links CHRT with machine learning (ML)—specifically outlier screening and k-means clustering—had been completely revised. Most notably, CHRT-ML 2.0 improves considerably the accuracy of bathymetry extraction for those 500m-by-500m airborne Lidar tiles that cover areas having three dominant depths (ocean surface, shallow reef, and deeper channel/dredged bottom). Also accomplished in the last reporting period was the revision and restructuring of CHRT-ML 2.0 Python code by Brian Miles to bring the code under version control and have the code conform to existing Python norms.

The current reporting period has seen a focus on two primary tasks. The first is gaining a better understanding of the uncertainty associated with the use of CHRT-ML, the knowledge gained being used to further improve CHRT-ML and to identify the CHRT-ML-processed tiles that may require human user examination and (re-)processing by alternative means. The second is the automated elimination of above-sea-level areas; this will be discussed subsequently.

To date, CHRT-ML accuracy has been defined by "classification"—i.e., identifying each sounding as the same class (Bathy or NotBathy) as NOAA procedures. Various statistics, (e.g., global accuracy, true positive rate), have been calculated from the cross-tabulation/confusion matrix of NOAA Bathy/NotBathy vs. CHRT-ML 2.0 Bathy/NotBathy. Examining these statistics relative to various tile "types"—e.g., reef with channels or sparse bathymetry—has provided useful information for improving CHRT-ML and identifying still-existing weaknesses. However, it has become apparent that confining the uncertainty analysis to confusion-matrix-based statistics only indirectly addresses the overarching goal of improving nautical charts. Hence an additional more comprehensive way of examining CHRT-ML uncertainty has been developed that includes additional statistical analysis including the addition of a spatial component.

The method reflects the reality that a lack of agreement between the NOAA and CHRT-ML Bathy/NotBathy classifications may be less important than depth agreement between the two. Moreover, the classification-based approach implicitly assumes that the NOAA classification is 100% accurate—something that is clearly untrue. Hence the approach developed is to divide a tile into pixels of a user-specified size, estimate the depth produced by NOAA's Bathy soundings and by CHRT-ML's Bathy soundings, and compare the two statistically and spatially. Figure 16-7 shows an example for 1 m pixels.

This particular tile has a relatively poor NOAA vs. CHRT-ML classification agreement of 85%. (The average across 100+ tiles examined was about 90%.) Figure 16-7(a) shows that despite a low classification agreement, depth agreement for pixels in which both NOAA and CHRT-ML identified Bathy soundings is very good; statistics (not shown) such as the correlation coefficient (0.998) and the root-mean-square-error (4 cm) support this. Coupled with the "missing data" violet and black points along the x- and y-axes in Figure 16-7(a), Figure 16-7(b) allows the spatial distribution of these classification disagreements to be assessed. In this example NOAA's procedures found Bathy soundings in a small relatively shallow area in the northeast, while CHRT-ML did not. Conversely, CHRT-ML extracted Bathy soundings in the deeper area in the northwest where NOAA did not. Figure 16-7(c) provides a means for examining the spatial distribution and magnitude of depth differences with light green being a difference of 0 cm. Finally, Figure 16-7(d) shows the classification and depth differences relative to depth and spatial distribution; in this case,

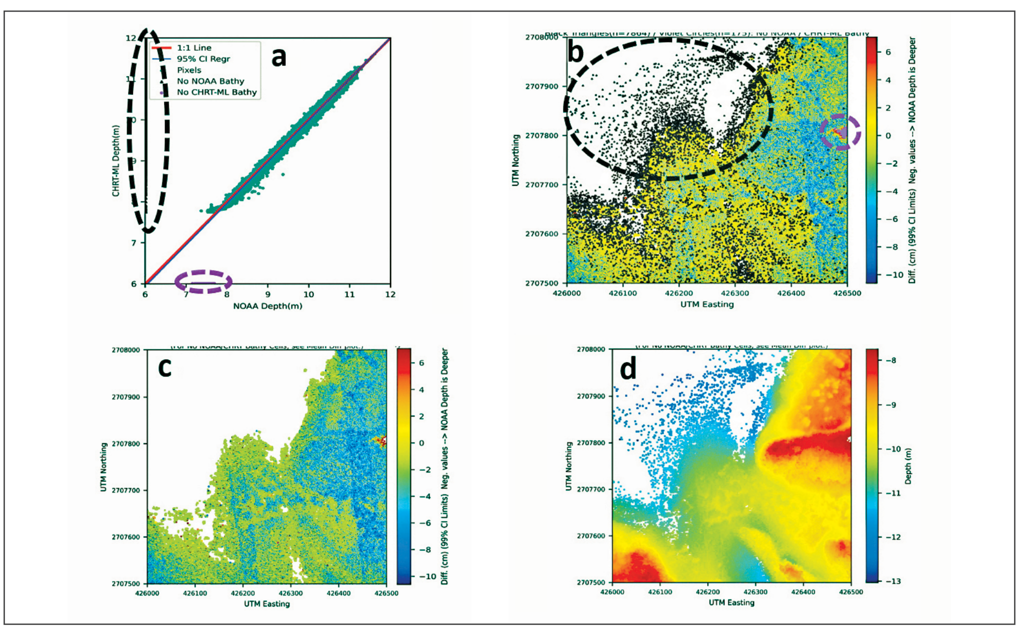


Figure 16-7. Statistical-spatial method of evaluating uncertainty on a Lidar tile. a. NOAA vs. CHRT-ML depth relationship. b. Differences (cm) in NOAA and CHRT-ML depth with "no data" pixels indicated (See also panel a.): Violet points: Pixels for which NOAA identified Bathy soundings but CHRT-ML did not. Black points: Pixels for which CHRT-ML identified Bathy soundings but NOAA did not. c. Differences (cm) in NOAA and CHRT-ML depths without "no data" pixels. d. CHRT-ML depth (m).

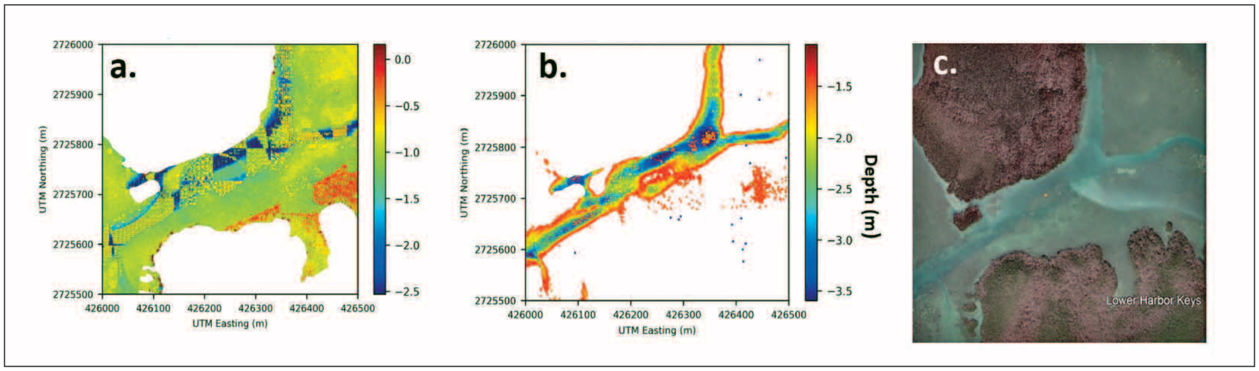


Figure 16-8. Example of different depth surfaces (a. and b.) produced by CHRT-ML that employ different methods of outlier screening and k-means cluster seed selection. c. GoogleEarth™ image of the area covered.

large differences (deep blue) were concentrated in the relatively shallow area in the east-central portion of the tile. Moreover, CHRT-ML depths for the areas where CHRT-ML extracted bathymetry but NOAA did not (black points) seem visually reasonable.

Such information will form the basis of quality control protocols being developed. One goal of these is continuous improvement of CHRT-ML. The broader goal, however, is to allow for the relatively rapid processing of Lidar tiles that CHRT-ML provides. A component of the output of such processing will be the identification of those tiles having data or geographic characteristics known to be difficult for CHRT-ML and that might require more detailed processing.

Such information has already contributed to continuous improvement of CHRT-ML. The ML component is based on k-means clustering after eliminating outlier depth hypotheses generated by CHRT. Not only is outlier screening a process that employs subjectively determined thresholds, but k-means clustering relies on initial cluster seeds that can be selected various ways. Examination of information such as that presented in Figure 16-7 for 100+ tiles revealed that the classification and depth accuracy of CHRT-ML are sensitive to the specifics of both outlier screening and initial seed selection methods. Figure 16-8 provides an (admittedly extreme) example.

The second major activity of this reporting period for Task 16 is the pre-processing step of eliminating "Ground." CHRT-ML 2.0 requires that there not be a "substantial area" that is above sea level in a tile. With a major contribution from Miles, considerable effort was made to develop an efficient and reliable method to eliminate above-sea-level (ASL) areas on tiles using the Lidar .las file alone; Figure 16-8(c) provides an example of a tile where this is necessary. Notably NOAA's classification of "Ground" soundings was not used for this purpose since the goal of CHRT-ML is to be independent of NOAA's processing procedures. It became apparent, however, that eliminating ASL soundings would require ancillary data sets and processing. Repositories of high-resolution shapefiles were examined as were various remotely sensed digital image sources. Ultimately, the best solution found relies on the European Spaces Agency's Sentinel-2 satellite imagery having 10m pixels for its red and near infrared bands. For each tile, the Normalized Difference Vegetation Index (NDVI) is calculated for all pixels. Any whose NDVI value exceeds a threshold determined via review of published scientific literature are removed. Importantly, however, this step includes an evaluation of spatial contiguity of pixels including examination of tiles that

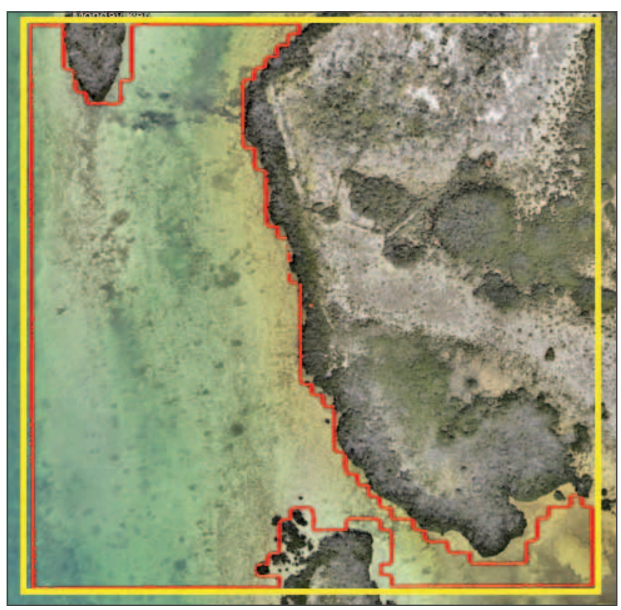


Figure 16-9. Example of Lidar 500m-by-500m tile (yellow) and the area identified as ocean/"not ground" (red) using Normalized Difference Vegetation Index analysis of Sentinel-2 10m imagery.

are immediate neighbors of the subject tile. This ensures detection of ocean/water areas that appear non-contiguous on the tile being processed. Figure 16-9 shows an example of the result.

Project: Graph-Based Bathymetric Data Processing

The techniques that are typically currently used to process Multibeam Echosounder (MBES) data involve gridded statistical processing, such as CUBE and CHRT, followed by manual cleaning of outliers and data deemed unreliable. Most of time, this manual cleaning can involve hours of point-by-point inspection. The costs of producing a chart or map are not only associated to the cost of vessel and acquisition but also by the hours of work required by cartographers and oceanographers.

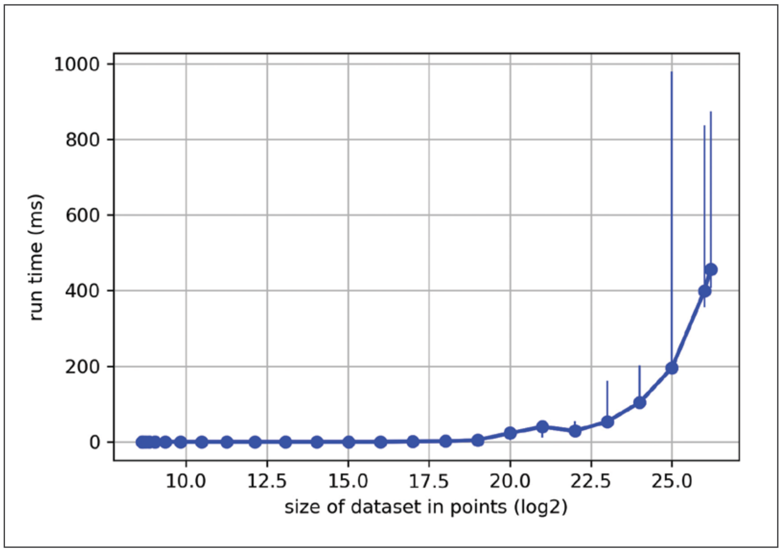


Figure 16-10. Run time median, best and worst case for different dataset sizes. (Note logarithmic axis for dataset size.)

Machine learning, more specifically deep learning, has become an important trend in data processing, achieving excellent performance in non-trivial classification and regression challenges. This class of algorithms can learn from large sets of data and generalize to unseen data, as demonstrated in the previous project. Work at the UKHO has also attempted a voxel CNN approach for filtering MBES data. While both works seem promising, they both suffer from gridding the data and sampling into pixels or voxels, which can induce structure in the data that is not naturally there.

The historical decision to sample sounding into images, 2D or 3D, came from the prohibitive processing power required to work on individual soundings as point cloud data. Recent advances in deep learning, however, have brought about Graph Neural Networks (GNN). GNNs relate points in a data cloud as nodes in a graph and avoid adding any gridding or interpolation to the data. Points are interconnected on the unstructured 3D space in which they are acquired. Works such as Luo et al[3] bring the powers of GNN to point cloud denoising, in their score-based network. Points in the data cloud are assigned scores related to their reliability and are then filtered based on it. This idea can be expanded to the world of MBES data clouds and assigning uncertainty to points similarly to the concepts in CUBE/CHRT.

In the current reporting period, graduate student Adriano Fonseca has been applying the novel Dynamic Graph CNN (DGCNN)[4] to MBES data acquired by Center students off the coast of Hampton Beach, New Hampshire. Survey datasets have data volumes beyond those employed previously in DGCNN research, and therefore typical operations, such as k-nearest neighbor determination, are difficult in this context. Therefore, the focus has been on optimizing the way these nearest neighbors are found, currently through a density-directed re-sampling approach. This technique uses estimated data density to determine an approximate distance about a given point in which the required k neighbors will be found (adjusted for overlapping data files and depth), allowing the dataset to be filtered and sub-sampled.

Figure 16-10 shows the median run time of each iteration of this process for different data set sizes with the error bar identifying fastest and slowest cases. There is an apparent linear relation between the runtime and the size of the data set, which has implications for sizes of datasets that can be processed with this method, and therefore for how the problem should be structured for a distributed implementation. Although some effort has been made to solve the nearest neighbor problem, it is still very much an open question. The proposed solution is still not efficient enough when the volume of data required to process a single survey is considered. The work continues.

[3] Luo, S., & Hu, W. (2021). Score-based point cloud denoising. In Proceedings of the IEEE/CVF International Conference on Computer Vision (pp. 4583-4592).

[4] Yue Wang, Yongbin Sun, Ziwei Liu, Sanjay E. Sarma, Michael M. Bronstein, and Justin M. Solomon. 2019. Dynamic Graph CNN for Learning on Point Clouds. ACM Trans. Graph. 1, 1, Article 1 s.

Task 17: Backscatter Data Processing

JHC/CCOM Participants: Michael Smith, Giuseppe Masetti, Brian Calder

NOAA Collaborators: Mashkoor Malik

Other Collaborators: Alex Schimel, M, Dolan, J. Le Deunf

Seafloor acoustic backscatter collected by multibeam echosounders (MBES) has been shown as a useful input for seafloor characterization through the use of backscatter products such as angular response curves and mosaics. Efforts under Task 2 of the grant have made great strides towards calibration of the MBESs and improving our ability to collect quantified backscatter data. With the 2019 announcement of the Presidential Memorandum on Ocean Mapping, the call to characterize the US EEZ has raised the importance of collecting and processing backscatter. Despite the efforts under Task 2 to improve the quality of the collected backscatter, there are still issues with respect to processing the data. The Backscatter Intercomparison Project (BSIP) found that given the same dataset, backscatter results varied widely across the different processing stages, including the first step of decoding the raw data. The lack of clearly identifiable reasons for the variability and closed processing chains of commercial processing software erodes the confidence in both the processed data and the derived products. Under task 17, the Center is conducting research to improve the clarity and availability of processing algorithms for backscatter data.

Project: OpenBST

The OpenBST project was started in 2019 to help address and mitigate the discrepancies that arise in the backscatter processing workflow. OpenBST was designed to be an open-source, metadata-rich, and modular toolchain dedicated to backscatter processing. The goal of the project is to develop a set of open-source, community-vetted, reference algorithms useable by both the developer and the user for benchmarking their processing algorithms. The project is written in Python and is available on GitHub for collaborative development. It uses the common NetCDF convention to efficiently couple metadata and processing results. The initial efforts were based around Jupyter notebooks as the user interface and the development and sharing of various backscatter processing methodologies from the OpenBST library. However, during development, it was determined that Jupyter Notebooks were not ideal for the goals of the project. As a result, in 2021 Smith and Masetti decided to restructure the project with a graphical user interface, which permits the user to navigate the backscatter workflow, and provide a number of comparison tools to facilitate investigation of the underlying data. This work is currently in an incubatory phase, developing the essential tasks required to manage a multi-file backscatter processing project. This includes developing an organized datafile format in which backscatter and bathymetry data from different sonar manufacturers are translated to a common format to be used by the OpenBST library. Like the processing files, the converted datafiles will utilize NetCDF convention to facilitate data access and metadata coupling. With a re-invigoration of the international Backscatter Working Group and the Center represented by Michael Smith on this group, OpenBST efforts may be spun up again in the coming year.

Task 18: Object Detection

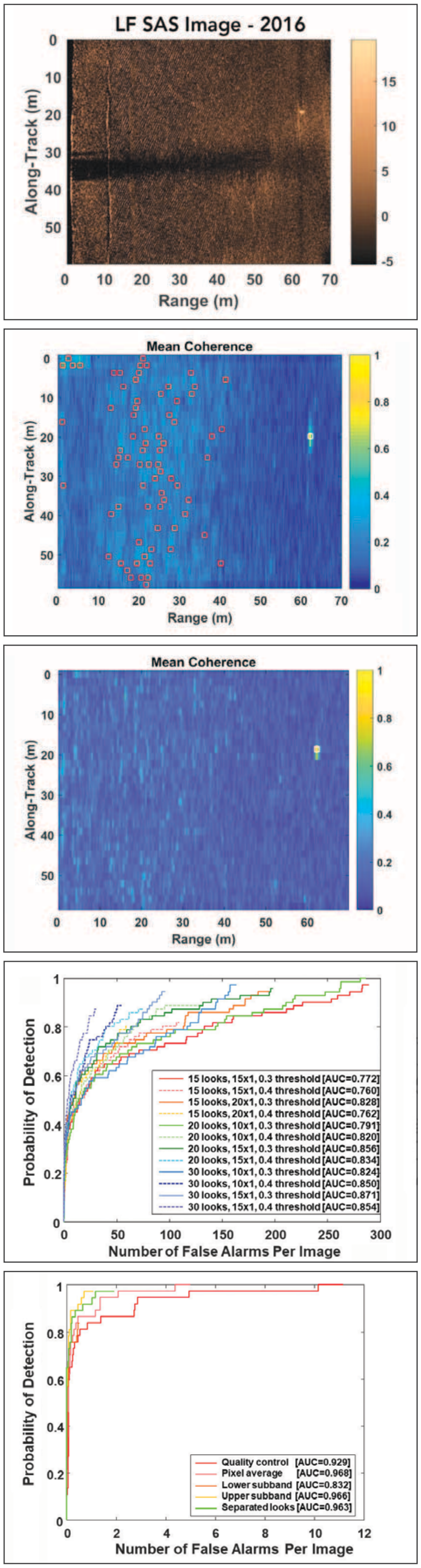
JHC/CCOM Participants: Anthony Lyons

Other Collaborators: Thayer-Mahan, Kraken Robotics

Additional Funding Sources: ONR

Project: Multilook Coherence for Automated Target Detection and Classification

Anthony Lyons has been supported by the Office of Naval Research to explore multi-look SAS techniques for target detection and classification. Multi-look techniques are optimally suited for high-resolution synthetic aperture sonar (SAS) systems which operate with large relative bandwidths and transmit beamwidths. Multi-look coherence techniques focus on the information content of images by splitting the total angle and frequency spectral bandwidth of a complex synthetic aperture sonar image into sub-bands. The complex coherence of each pixel as a function of frequency and angle can then be exploited, yielding information on the type of scattering observed (e.g., specular, diffuse, point-like, resonance-related, etc.). Information pertaining to scattering type would



improve the separability of man-made targets from the interfering background return and clutter, as targets should have features that scatter coherently in frequency and/or angle versus the random seafloor interface or volume (or randomly rough, target-sized rock) which will scatter incoherently. The results of work performed this year are significant for: 1) understanding multi-look coherence from targets and natural seafloors estimated using wide-angle, broadband SAS imaging systems, 2) exploring potential methods to exploit coherence for both the detection and classification of proud and buried man-made targets in clutter, and 3) quantifying the performance of multilook techniques for detection.

For multi-look coherence-based detection or classification, the key parameter is the magnitude of the complex correlation coefficient. For two complex images, this parameter is an estimate of the coherence between the two sub-looks. This year's effort included exploring ways of improving the performance of this metric for detecting objects in a variety of seafloor environments. To determine ways of optimizing detection while reducing numbers of false alarms we examined a variety of strategies, including: 1) removing data that was corrupted by cross talk caused by other systems operating in the vicinity of the system collecting SAS data used in our study; 2) trimming edges of coherence maps which included areas corrupted by high-coherence caused by the windowing technique; 3) averaging pixels in the coherence map as it was seen that targets exhibit coherence extending over multiple pixels; 4) using only images formed from the upper (or lower) half of the frequency band; and 5) using separated looks (every 4th) to attempt to remove glints as a source of false alarms. Example comparisons before and after using the various false alarm reduction strategies are shown in Figure 18-1 for data collected in various seafloor environments in 2015 and 2016. All the various strategies improved performance with respect to reducing false alarms, with the best results including all strategies combined (i.e., quality control of data, followed by using only the upper half of the frequency band, followed by using separated looks, followed by averaging pixels in the coherence maps), but using only the upper half of the frequency band. It is expected that the multilook coherence technique would prove useful for buried objects as well as the proud objects used for the datasets used for our work.

While the bulk of this effort is funded through the Office of Naval Research, the applications of novel techniques for and automated target detection classification are evident and Lyons will be identifying opportunities to apply these methods to locating and identifying objects on the seafloor which may pose hazards to navigation (e.g., wrecks or rocks) and working with colleagues at the Center to incorporate these approaches into mapping workflows.

Figure 18-1. Example mid-frequency SAS image with target on a ripple field (top), detection on the same image using the multilook coherence technique before (middle left) and after including (middle right) false alarm reduction strategies, and ROC curves for a larger data set before (bottom left) and after (bottom right) using various false alarm reduction strategies in the multilook technique.

Project: **Measuring and Modeling Internal Wave Properties and Their Effects on High-Frequency Imaging Sonar**

Also of interest to the automated detection of hazards to navigation are the degrading effects that internal waves and related features—such as boluses—have on high-resolution imaging sonar systems used object detection and classification. Internal waves and related features such as boluses change the water column sound speed structure and therefore will affect images of the seafloor by focusing or defocusing transmitted acoustic energy. Impacts of uncompensated water column sound speed in beamforming can reduce the resolution of seafloor imaging systems. "Shadows" in areas of defocus, can make any targets essentially invisible as there will be little acoustic energy hitting regions around the target location. Propagating features in the water column would cause differences between images acquired at different times, adversely impacting target detection using change-detection methods. A more complete understanding of shallow-water internal waves effects on high-frequency imaging sonar is required to aid in the development of techniques designed to detect and mitigate the impacts of internal waves on sonar systems.

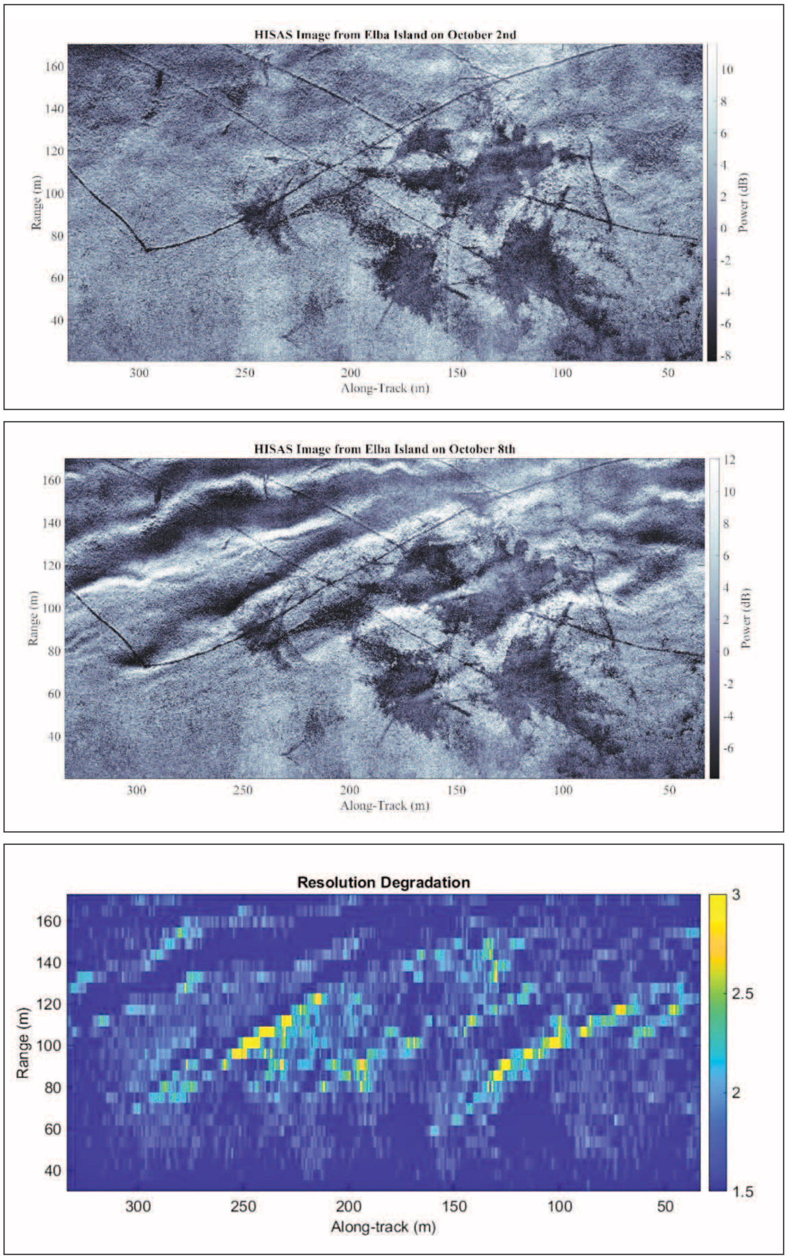


Figure 18-2. HISAS image taken in the 2013 Elba Island survey with internal waves absent (top). The lighter areas are regions of seagrass while the darker areas depicted are sand. HISAS image with high internal wave activity in the same region as the image above taken 6 days later (middle). Acoustic lensing caused by refraction through internal waves is obvious in this image. (Data provided by Roy Hansen at Forsvarets Forskningsinstitutt (FFI)). The average along-track resolution degradation is shown in the bottom image—using the point scatter technique (bottom). Degradation of resolution by a factor of 2 to 4 exists in the regions of the SAS image with internal wave bolus activity (note the color scale is clipped a value of 3 however to highlight the effects).

Nicholas La Manna and Anthony Lyons worked this year to quantify and model the effects of internal wave boluses on the performance of SAS imaging systems, namely the reduction in resolution caused by imaging through an unknown sound speed feature. As part of this year's efforts, Lyons and La Manna have worked with researchers from the Applied Research Laboratory at Penn State University and from the Norwegian Defence Research Establishment. The quantification of the effects on resolution was performed utilizing point targets within the SAS image (Figure 18-2). The point spread function of the point targets was estimated and used as a proxy for the image resolution and showed that internal waves can cause resolution loss on the order of two to four times than in the absence of a bolus or sound speed error. Various modeling techniques were used to predict the effects of internal wave boluses on image resolution, including ray tracing to model timing errors caused by bolus induced refraction, an analytical technique which simulates the phase errors caused by boluses and a beamforming method (Figure 18-3). The different modeling techniques agreed with each other and with the estimates of resolution degradation made using the point target method. The results of work performed this year are significant for 1) understanding the effects of internal waves and related features on the performance of broadband SAS imaging systems; 2) exploring potential methods to exploit SAS datasets to quantify attributes such as the size of internal wave boluses; and 3) using knowledge gained to inform efforts on both modeling the effects of internal wave features on the performance of SAS systems and on refocusing images to remove degradation caused by internal wave features.

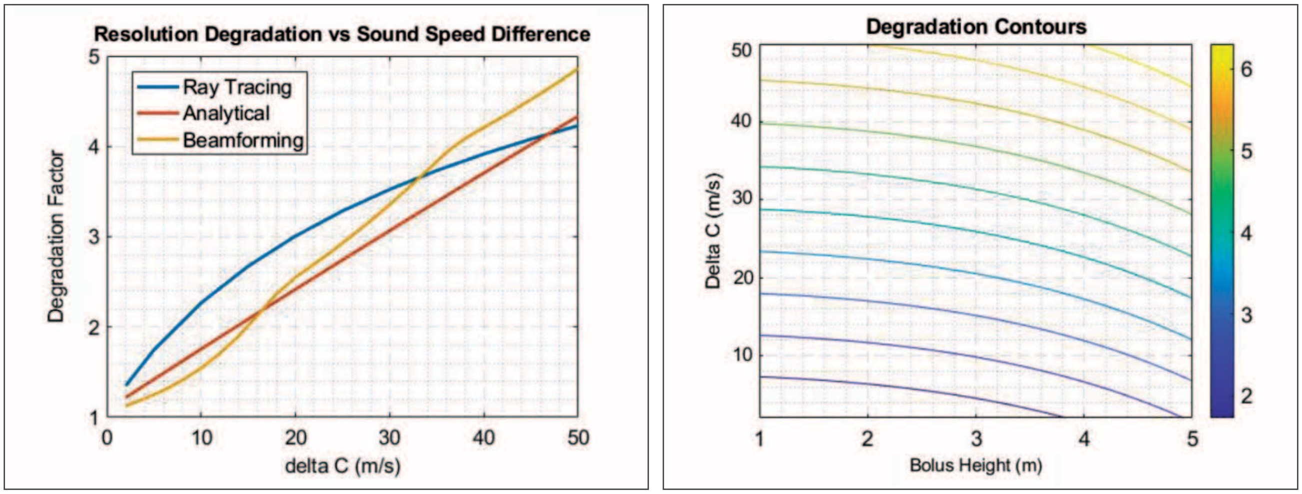


Figure 18-3. A comparison of the estimation of the along-track resolution degradation factor as a function of sound speed difference inside and outside the bolus for a fixed bolus height of 2.25m and a bolus range of 75m (top) and resolution degradation contours calculated for each bolus height for each sound speed difference computed using results of the models (bottom).

Task 20: Advanced Quality Assurance/ Control Tools

JHC/CCOM Participants: Giuseppe Masetti

NOAA Collaborators: Tyanne Faulkes (NOAA PHB); Julia Wallace and Matthew Wilson (NOAA AHB); Damian Manda, Glen Rice, Jack Riley, Barry Gallagher, Chen Zhang, and Eric Younkin (NOAA HSTB)

Other Collaborators: Mathieu Rondeau and Yan Bilodeau (Canadian Hydrographic Service); Kim Picard and Justy Siwabessy, (Geoscience Australia), Ian Church (UNB), Anand Hiroji (USM), and Ove Andersen (University of Aalborg)

Quality assurance and control of ocean mapping data continues long after the data is collected, and the Center has been instrumental in building tools to support this process at the interface between field and office processing, and the transition of these tools to operations through both the HydrOffice and Pydro toolsets. These QA/QC tools provide application-specific support of Hydrographic Office workflows (specifically, OCS workflows), and have been influential in systematizing and automating procedures for data quality control. Although a certain level of maturity has been achieved with these tools, new ideas and algorithms continue to develop from field requirements, data foibles, and survey specification requirements.

Through many years of development by hydrographic offices and other mapping agencies, thousands of experience-based rules that are reflected in survey specifications are often subject to human interpretation. They can also be, sometimes deliberately, vague. Given the data volume of modern survey, it is then challenging to evaluate each observation for correctness and quality individually (for example, identifying sparse outliers in a multi-million node grid). At the same time, it can be difficult, or at least very time consuming, to confirm that all the required specifications for a given survey are being met (for example, does every S-57 attributed object have a corresponding bathymetric expression?). Fortunately, these types of problems have the potential to be identified using automated and semi-automated algorithms on the assumption that the required specifications can be translated into coded rules. Recent field experience shows that the adoption of the tools described below can result in significant gains in workflow efficiency, with the additional advantage of applying the same, objective, algorithm each time to large amounts of data.

The efforts in this task are focused in translating (and concurrently enhancing) these rules into computable form, and re-formulation of the rules, where required, to obtain a computable and consistent result. This is not to suggest that all rules can be so transformed: some will always require the "judgment of an expert hydrographer." However even identifying the subset that are transformable is a useful endeavor since it informs the potential for automation: the more rules that require human intervention, the less automation is possible. Understanding the extent to which this is the case will also help to inform decisions about the future structure of survey workflows.

Project: QC Tools (HydrOffice)

Since 2015, Giuseppe Masetti has collaborated with NOAA HSTB personnel to develop a suite of analysis tools designed specifically to address quality control steps in the NOAA hydrographic workflow. Built within the HydrOffice tool-support framework (https://www.hydroffice.org), the first version of QC Tools was released in June 2016, and have since been enthusiastically adopted by NOAA field units and processing branches. Indeed, yearly updates and edits to NOAA's Hydrographic Survey Specifications and Deliverables (HSSD) are now made with an eye toward automation, anticipating implementation via QC Tools.

In the current reporting period, Masetti, Tyanne Faulkes (NOAA PHB), Matthew Wilson and Julia Wallace (NOAA AHB) have continued, in collaboration with NOAA HSTB personnel, to develop the toolset. The application, which aggregates a number of tools within a single GUI is available through NOAA Pydro (which delivers software to the NOAA hydrographic units) and through the HydrOffice website for non-NOAA users. A number of mapping agencies, NOAA contractors, and other professionals have adopted some of these tools as part of their processing workflow. QC Tools is in active use with the NOAA field units, which are a valuable source of feedback and suggestions.

In the current reporting period, the BAG Checks algorithm – introduced in February 2021 – was extended and improved (Figure 20-1). With BAG Checks, QC Tools acquired the ability to check outgoing Bathymetric Attributed Grid (BAG) files from the NOAA Hydrographic Services Division. The tool analyzes the BAG structure, metadata, elevation, uncertainty, and tracking layers to ensure compliance to both format specifications and NOAA additional requirements, to guard against common errors, and to facilitate a smooth transition of bathymetry into the NOAA National Bathymetric Source (NBS) database. Additional checks to evaluate the file content compatibility with the popular GDAL software library were also added. Based on OCS feedback, BAG Checks has significantly helped to decrease the number of errors in BAG products, by identifying issues during processing review. BAG Checks has been incorporated into an OCS tool called HDR Boost. BAG Checks has also been run on all available BAG files on the NOS Archive at NCEI to identify issues in advance of

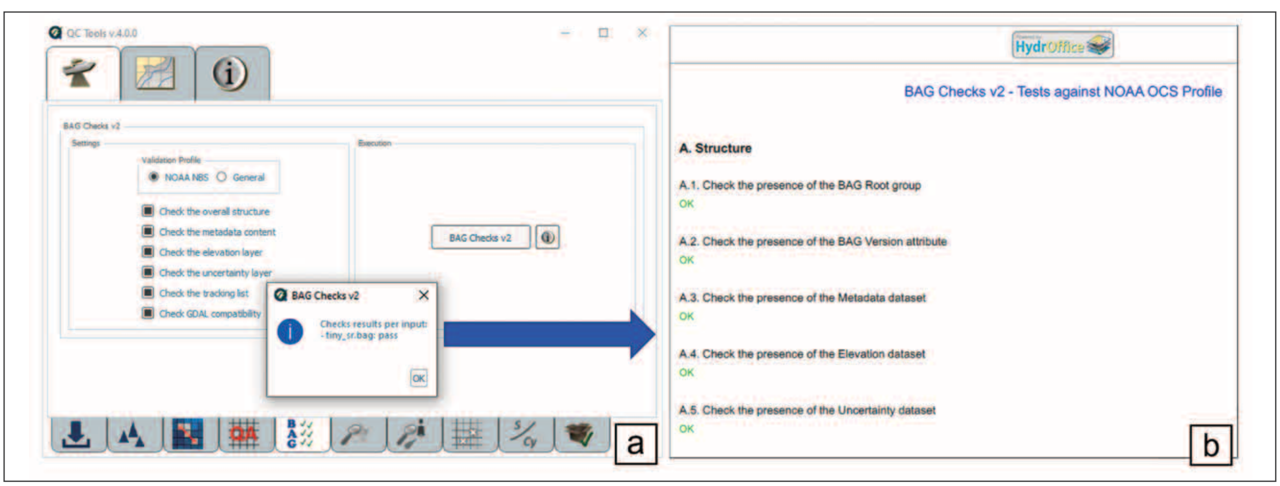


Figure 20-1. The new BAG Checks tool evaluates both the structure and the content of BAG files as well as the compatibility with the GDAL software library. As shown in pane 'a', the user can select to validate the files just against the BAG format specifications (General validation profile) or extend the checks with the additional NBS requirements (NOAA NBS validation profile). Pane 'b' shows an extract of the PDF report that is automatically generated after the execution of the algorithm.

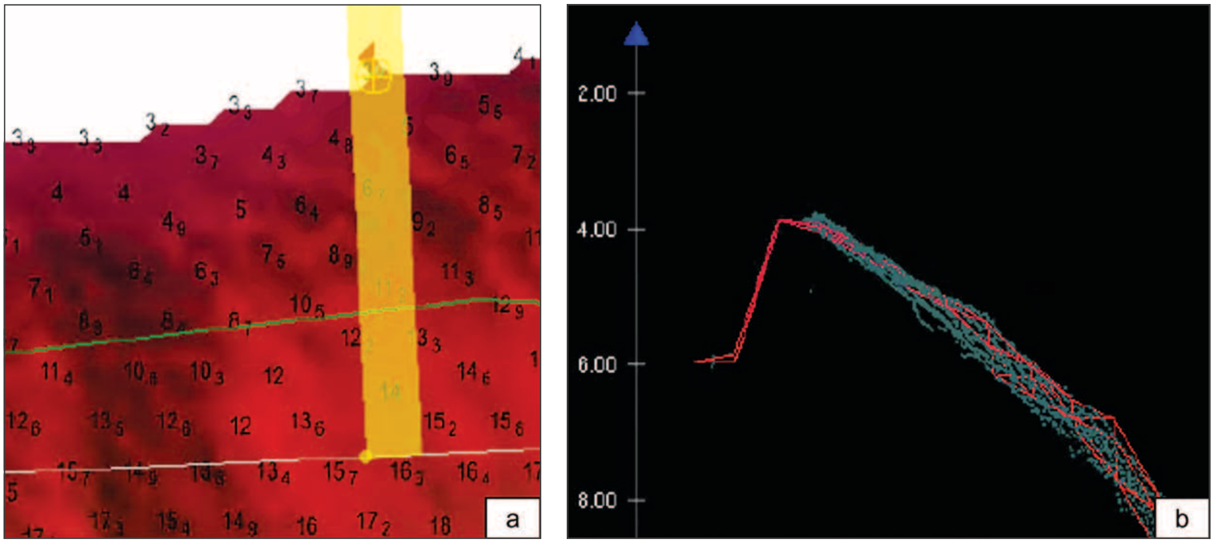


Figure 20-2. The Noisy Margins check is tailored to identify fliers along noisy swath edges. The algorithm crawls across empty cells to establish a margin. A margin is detected as noisy when the maximum depth difference with its neighbors is greater than an adaptive threshold. Pane 'a' displays a detection of the Noisy Margins check (as a yellow circled cross). Pane 'b' shows a side view of the area identified as being affected by the noise.

applying the data to the NBS. Via this method, 2,472 BAG files across three NBS regions were analyzed in an automated fashion, and 467 errors were flagged to be resolved prior to NBS ingestion, improving overall data quality to the NBS.

QC Tools was updated to fulfill the requirements of the 2022 NOAA HSSD. The approach taken is to provide the user with the ability to select one among recent HSSD editions to be used to verify the data against. The changes applied to Feature Scan, Submission Checks and VALSOU Check algorithms ensure that all NOAA field units and offices can QC data to the latest requirements. Furthermore, QC Tools was improved to enhance the detection of anomalous data along the margin of MBES swaths by the newly introduced "Noisy Margins" check in Find Fliers algorithm.

Due to a major ongoing OCS rewriting of the HSSD for 2023, the work to support the new changes has already started. Furthermore, in collaboration with Eric Younkin (NOAA HSTB), the compatibility of QC Tools with Kluster, an open-source hydrographic processing software recently developed by OCS, was improved.

The QC Tools application is supported by publicly available documentation as well as NOAA-generated instructional videos, available through the HydrOffice website, or directly via YouTube. A steady international interest in the adoption of QC Tools in workflows different from the NOAA's has been observed. The related collaborations are useful for collecting feedback and ideas for future developments of QC Tools (e.g., processing of Crowd-Sourced Bathymetry data).

Finally, Masetti is leading—as a guest editor along with Ian Church (University of New Brunswick), Anand Hiroji (University of Southern Mississippi) and Ove Andersen (University of Aalborg)—a special issue of *Geomatics* entitled "Advances in Ocean Mapping and Nautical Cartography." With a significant amount of data being collected for many purposes beyond just the safety of navigation, data handling will likely push the adoption by cartographic agencies of more automated and smarter algorithms/workflows. The aim of the special issue is to contribute to such a scenario by presenting QC Tools and similar initiatives.

Masetti has also contributed to the mentioned special issue with two articles. The first one, named "Effective Automated Procedures for Hydrographic Data Review" and written together with OCS Atlantic and Pacific Hydrographic Branches' representatives, describes the set of automated procedures developed over the past few years, translating a significant portion of OCS specifications for hydrographic data review into code (i.e., the HydrOffice applications called QC Tools and CA Tools). The second article, "Denmark's Depth Model: Compilation of Bathymetric Data within the Danish Waters," illustrates the workflow adopted to compile and quality assess of a bathymetric model based on a variety of sources (from modern surveys to historical data), as well as its distribution through publicly available products and services.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: DATA VALUE

NOFO Requirement 6

Development of improved tools and processes for assessment, processing, and efficient application of ocean mapping data from emerging sources such as drones, cameras and optical sensors, satellites, and volunteer/crowd-sourced observing systems to nautical charts and other ocean and coastal mapping and coastal hazard products.

JHC/CCOM responded to NOFO requirement 6 with five tasks:

Task 21: sUAS Mapping for Safety of Navigation

Task 22: Millimeter Resolution Mapping with Frame Sensors

Task 23: Enhanced Data Underwater 3D Reconstruction

Task 24: Volunteer Bathymetric Observations

Task 25: Alternative Uses for ICESat-2 and other Laser Altimeter Data

Task 21: sUAS Mapping for Safety of Navigation

JHC Participants: Val Schmidt, Andy McLeod, Roland Arsenault, K.G. Fairbarn, and Avery Muñoz

Hydrographic survey operations from ships, launches and ASVs often come with the danger of running aground, inadvertent operation in white water, unwanted entanglements in kelp or other biological material, allisions, fouling on fishing gear or inadvertent meetings with marine mammals. In this research effort the Center has proposed building tools to provide improved situational awareness for vessel operators, prior to commencement of survey, using aerial drones.

Efforts thus far have been focused on a survey of existing commercial technologies that might serve this purpose. This project remains in nascent stages and work is ongoing to determine the best combination of technologies.

Task 22: Millimeter Resolution Mapping with Frame Sensors

JHC Participants: Yuri Rzhanov and Carlo Lanzoni

Many of our efforts, particularly those that focus on quantitative backscatter measurements and habitat mapping, require the highest resolution imagery possible of the seafloor to provide the "ground truth" of what is actually there. Time-of-flight (ToF) cameras provide direct frame (simultaneous 2D array) measurements of range along with imagery and are now common tools for various imaging tasks in air. However, their use underwater is impossible due to high absorption of infrared illumination (used in ToF cameras) by the medium. Use of green or blue laser diodes instead of IR LEDs would allow for reliable underwater sensing with ranges up to 5 meters and sub-centimeter resolution. The main advantage of TOF sensors is that they simultaneously acquire a two-dimensional array of measurements – frame pseudo-imagery, unlike a conventional lidar. Redundancy in measurements due to overlap of the frames eliminates inaccuracies in platform positioning and allows the application of Simultaneous Localization and Mapping (SLAM) techniques to improve a digital elevation model and detection and recognition of various objects.

Our experiments attempting to replace the IR diodes in with blue or green ones in order to adapt a ToF camera for underwater 3D sensing have thus far been unsuccessful. The first camera we evaluated, (DepthEye), produced a modulating signal (~100 MHz) that was buffered (separated from the camera circuits) and proved to be too weak to be used for modulation of powerful (~1W) green laser diodes (wavelength 520 nm) NDG7475 manufactured by Nichia Corporation

Figure 22-1. 520 nm laser diode NGD7475. Manufactured by Nichia Corporation, Japan.

Figure 22-2. TOFcam-660 time-of-flight camera. Manufactured by ESPROS Photonics Corporation.

(Figure 22-1). The second camera (Blaze-101), produced by Basler AG, Germany, stopped working due to the failure of the integrated circuit that was not possible to replace at UNH or via the manufacturer. Thus, it was decided to purchase a cheaper camera, TOFcam-660 (Figure 22-2), produced by ESPROS Photonics Corporation, Switzerland, that allowed for easy removal of the IR filter and generated sufficiently strong modulating signal for operation of three NDG7475 laser diodes.

The holder for all three diodes has been made at CCOM. The experiments with the TOFcam-660 have shown that the glass for the camera strongly absorbs green light and it had to be removed. First results with the setup shown in Figure 22-3 demonstrated that the system works well, although currently at a very short range. Further work will be related to optimization of the setup to extend the detection range.

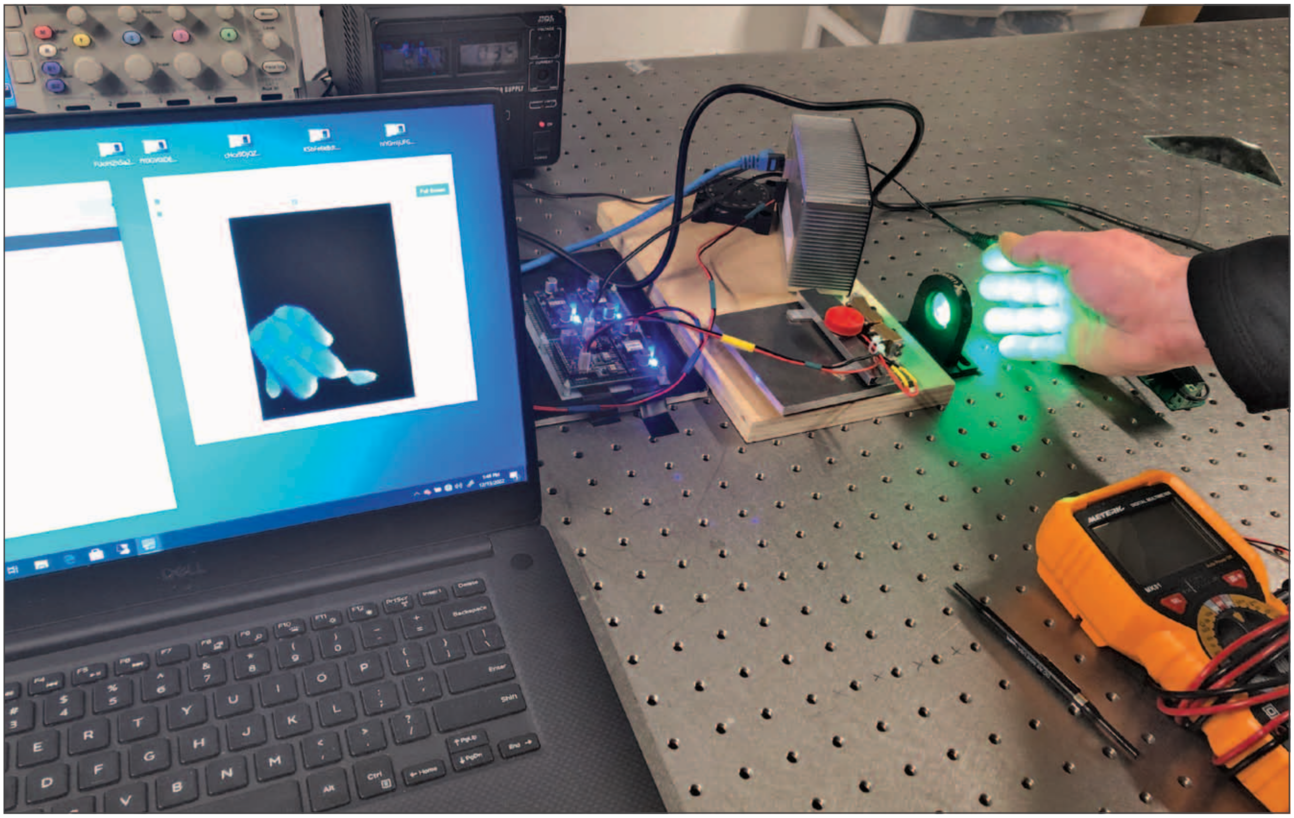


Figure 22-3. Experimental setup with three laser diodes illuminating an object through a diffuser.

Task 23: Enhanced Data Underwater 3D Construction

JHC Participants: Jenn Dijkstra, Tom Butkiewicz, Semme Dijkstra, Kindrat Beregovyi, and Kristen Mello-Rafter

Other Collaborators: Caitlin Spind (Northeastern University)

Stucture from Motion (SfM) is an image processing technique that allows construction of accurate 3D models from overlapping successive photographs taken at various angles. SfM photogrammetry is a technique that has been used for the production of high-resolution morphometric 3D models and derived products such as digital surface models, and orthomosaics. SfM has been used in morphodynamic studies and reconstruction of complex coastal geoforms, coral habitats and rocky shores. These models can provide small (< 1m^2) and large scale (10-100m^2) quantitative three-dimensional information of seafloor and habitat characteristics that can be used for shoreline surveys and to monitor habitat change as well as provide ground-truth for quantitative backscatter and seafloor characterization studies. Preliminary testing of a stereo-camera system and SfM techniques were performed and model accuracy determined with the goal of assessing complex habitat structure in habitats designated as Essential Fish Habitats (EFH) or Habitats of Particular Concern (HPC). In previous reporting periods, a comprehensive workflow on 3D model construction was developed for small coral patch reefs (2 x 5m) (Pierce et al., 2021).

Project: Method Development for 3D Reconstruction of Moving Objects

SFM algorithms reconstruct scenes by identifying common key-points or features within multiple images that are invariant to changes in scale, lighting and rotation. With sufficiently dense key-points and estimations of the intrinsics of the camera used (e.g., focal length, focal distance), points can be assigned a relative 3rd dimension in some arbitrary space. However, when there is moving flora and fauna on the seafloor, methods for image collection of images and 3D reconstruction must be modified from traditional methods. For this reporting period, the Jenn Dijkstra and Kristin Mello-Rafter have continued to develop a workflow for 3D reconstruction of large, highly rugose and moving seaweed dominated habitats. Capturing still images of moving objects for 3D reconstruction is difficult and the traditional method of swimming in a lawnmower pattern is not suitable for creating accurate 3D models of seaweed communities. Instead, we determined that images should be captured, not through the typical boustrophedonic pattern, but in a parallel pattern so images are always captured in the same direction. Capturing the images in the same direction helps with image alignment. Having said that, building a full, accurate 3D model of seaweed communities using the Metashape software package requires manual alignment that adds 20-24 hours of manual labor. Automated photo alignment in Metashape aligns ~10-25% of images average (Figures 23-1 and 23-2).

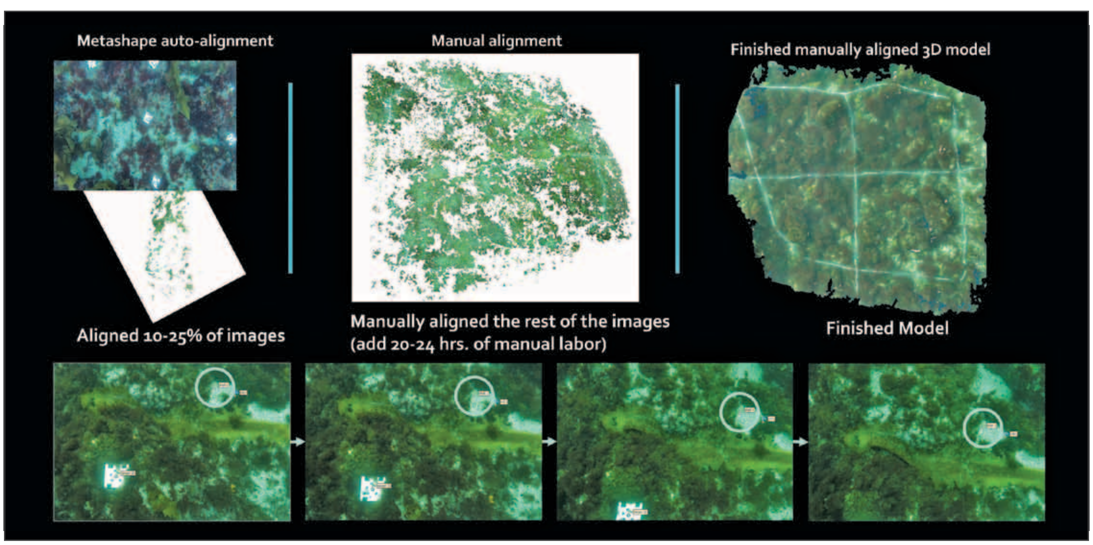


Figure 23-1. Methods: Above left: Metashape's auto-alignment function which generally aligns a very small portion of the model. Above middle: example of a full model that has been aligned using manual markers placed by a user. Above right: example of a fully textured 3D model that has been manually aligned. Below: an example of 4 consecutive photos where a manual target was placed.

Project: **Comparing Uncertainty in Local and Global Coordinates of 3D Reconstructed Intertidal Zones**

The establishment of relationships between the physical structure of the seafloor and species distribution within the benthic habitat through the analysis of high-resolution 3D seafloor bathymetric models is becoming commonplace (Figure 23-3). Where it is possible to collect optical imagery, Structure-from-Motion (SfM) surveys from aerial drones have become a prevalent photogrammetric data collection method. This is due to the ability to perform simultaneous seafloor property and species assemblage change detection, all while requiring low material investment and relatively little in terms of logistics.

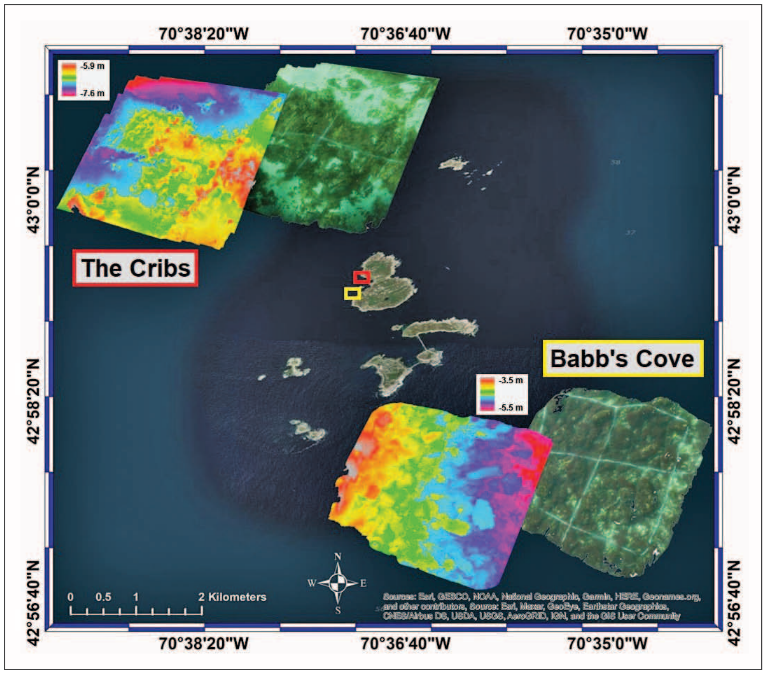


Figure 23-2. DEM_modelSeaweed: Examples of 3D models and DEMs from macroalgae habitats.

For the results from SfM to be meaningful it is critical to understand how various data collection and processing methods influence the quality of the geometry of the 3D model. This is both in terms of the accuracy of measurements derived from within the 3D model (local uncertainty), as well as the placement of the model in the world (global accuracy). The scale and placement of the survey may be determined through knowledge of either the location of the observation platform at the time of the survey, or through the creation of points with known locations within the scene for which a model will be generated. These points are then known as Ground Control Points (GCPs). The first method is then often, somewhat erroneously, referred to as an unconstrained SfM survey, the second as a GCP constrained survey. Though it is often assumed that a constrained survey more accurately represents the real-world geometry this is not a given. Unfortunately, this assumption leads many to spend time and effort on the creation of GCPs on the ground, and additional effort in recognizing and managing the GCPs during processing.

To characterize the uncertainty of various SfM positioning and illustrate the danger of relying on improperly established GCPs, Semme Dijkstra, M.S. student Caitlin Spind, and Jenn Dijkstra devised an experiment to compare the results using three positioning approaches for the SfM data. All three positioning approaches involve the use of Global Navigation Satellite System (GNSS) receivers, whose solutions are either aided through the real-time Wide Area Augmentation System (WAAS: better than 3 m accuracy 95% of the time), or improved through Post Processed Kinematic (PPK) processing (here better than 2 cm accuracy 95% of the time).

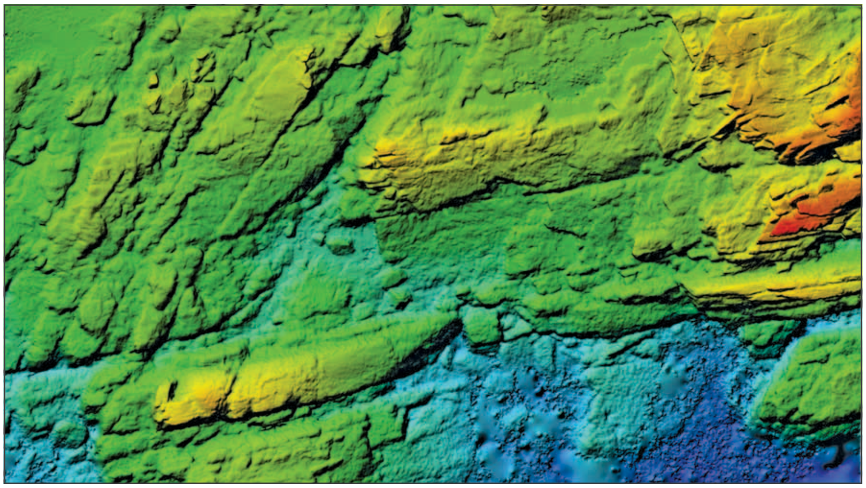


Figure 23-3. Terrainmodel: 3D SfM model with color coded heights showing an intertidal zone site.

1. SfM Survey sans GCPs, constraining the 3D model using WAAS aided GNSS data obtained by the drone.
2. SfM with low accuracy GCPs, constraining the model using WAAS aided GNSS GCP data
3. SfM with high accuracy GCPs, constraining the model using GCP coordinates derived from a combination of survey techniques, including PPK GNSS

The first two methods are routinely used by practitioners in the field, the third is devised by the authors and based on routinely applied geodetic surveying techniques. This third method made use of the high accuracy that may be obtained through PPK GNSS. In this method a baseline was established by simultaneously collecting data at two points using survey grade GNSS (Trimble SPS986) receivers placed at least 20 meters apart over a two-hour period. The data were then submitted for processing to the NOAA National Geodetic Survey (NGS) Online Positioning User Service (OPUS), which returned coordinates for the baseline endpoints with a better than 2 cm uncertainty estimate (global uncertainty). However, the length and orientation of the baseline may be determined with much better accuracy since the data at the end points was collected simultaneously, resulting in the expected errors, except for receiver noise, to be the same at either end. Thus, the expected local accuracy (the location of the baseline end points relative to each other) is on the order of a millimeter. A total station (Trimble SPS 730: optic device capable of accurately measuring horizontal and vertical angles, as well as distances) was then positioned through a resection. A resection is a standard geodetic survey method to determine an unknown point relative to known points; in this case the two baseline end points. This resection also allowed the establishment of the North direction relative to the total station and thus the 3D position of any point may be determined by measuring the angles and distance from the total station. The station used is a robotic total station that automatically tracks a prism that may be positioned above GCPs by the operator. Thus, after establishing the baseline and performing the resection, positioning GCPs takes the time of walking between them and holding the prism over them for a few seconds each. The resulting position uncertainty of the GCPs is on the order of a millimeter locally and 2 cm globally.

Figure 23-4. Ground level view of 3D Model: Ground level view of 3D model with draped imagery showing one of the intertidal zone sites. Note the high resolution and low visible distortion due to the high local accuracy of the model whose geometry is constrained by accurately positioned GCPs.

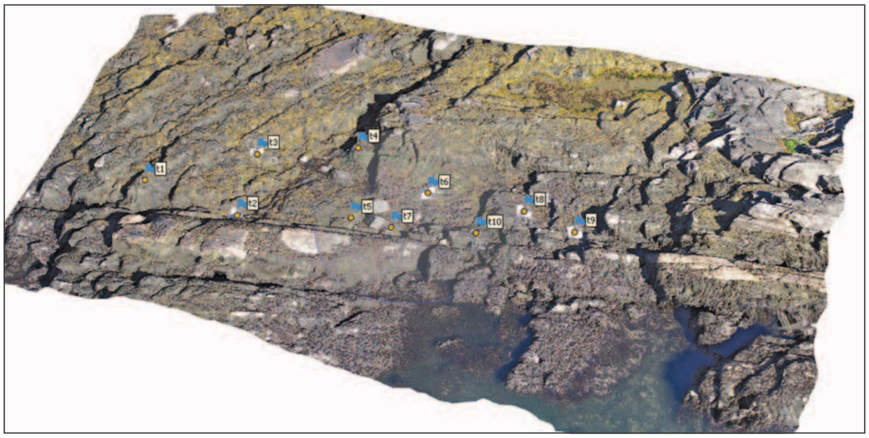


Figure 23-5. Birdseyeview 3Dmodel: Birds eye view of 3D model with draped imagery showing one of the intertidal zone sites. Superimposed in yellow is the GCP locations as determined by the combined PPK GNSS and total station method vs. in blue the locations as determined by WAAS aided GNSS.

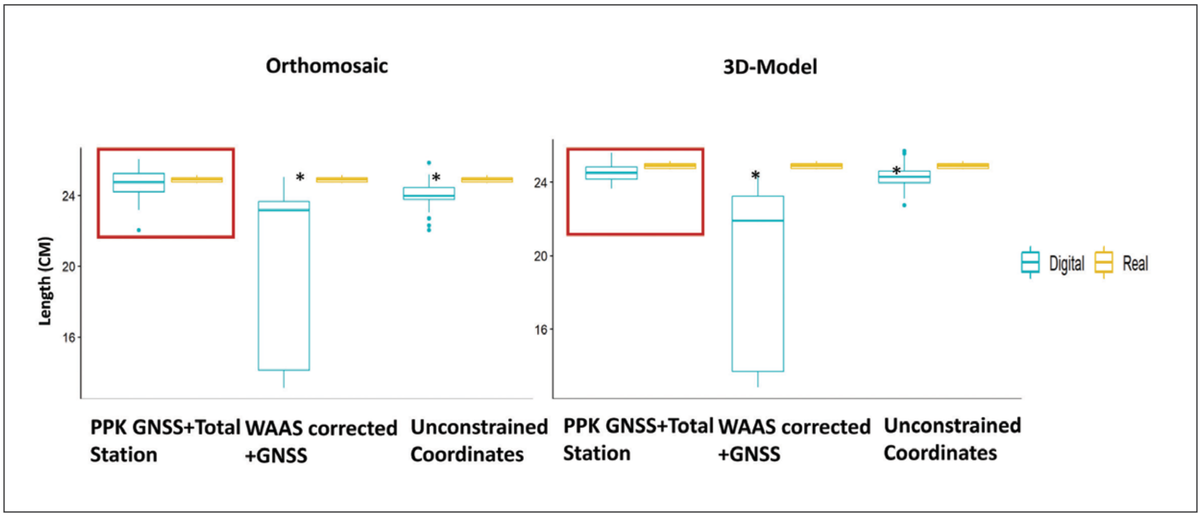


Figure 23-6. Measurement comparisons: Comparison of real-world quadrant measurements (25 cm) to those obtained through orthomosaics (left) and 3D models (right).

For the comparison experiment between the three positioning methods four intertidal sites were chosen at which the drone was flown in a lawn-mower pattern to survey approximately 400 m^2. For the second positioning method (using GCPs positioned using WAAS aided GNSS receivers) position data were collected at the GCP sites using a NIKON ruggedized camera. For the third method a baseline was constructed in the immediate vicinity so that a single set-up of the total station could be used to obtain high accuracy GCP coordinates. To evaluate local accuracy a quadrant i.e., an object of known size, was placed in the scene (Figures 23-4 and 23-5).

Images in Metashape were then processed using either PPK GNSS+Total Station GCPs, WAAS corrected GNSS GCPs or WAAS corrected drone GNSS data. Thus, three models per site were constructed with slightly different geometries as a result of the applied positioning techniques. Analysis of the quadrant size in each of the resulting models revealed that:

1. Using only the positioning of the drone may lead to dimensional observations from within the 3D model with a precision on the order of a millimeter, but with a slight bias on the order of a few mm, i.e., a reasonable local accuracy (global accuracy is commensurate with WAAS GNSS positioning: approximately 3 m)
2. Using GCPs positioned at the same level of accuracy as the positioning of the drone significantly degrades the precision of observation from within the model to several centimeters and introduces significant bias on the order of 2 cm, i.e., a poor local accuracy (global accuracy is commensurate with WAAS GNSS).
3. Using highly accurately positioned GCPs marginally degrades the precision of observation from within the model by fractions of a millimeter, and all but removes bias, reducing it to a millimeter level i.e., excellent local accuracy (global accuracy is commensurate with typical PPK GNSS positioning: here on the order of 2 cm)

Comparing the dimensions of the quadrant with those obtained from the SfM models show that the PPK GNSS GCN constrained models leads to an unbiased estimate of the quadrant size with high precision (Figure 23-6). The WAAS GNSS GCN constrained model leads to significant bias and low precision, finally using the solution constrained by GCPs lead to significant bias with high precision.

Normally the users of these models are primarily interested in obtaining measurements from within, thus the local uncertainty is of much higher importance than the global uncertainty. The recommendation is to use the drone data unconstrained by GCPs, or if the needed uncertainty warrants: constrained by GCPs positioned with a mm local level of uncertainty. Using GCPs positioned with a level of uncertainty on the order of the positioning uncertainty of the drone is under no circumstance recommended—the survey results are degraded while the cost and effort is increased.

Project: **Leveraging Imagery to Build Spatial Analysis Tools for Structure-from-Motion Datasets**

Photogrammetry and Structure-from-Motion (SfM) is fast becoming a common method for monitoring seafloor change, particularly in coral reefscapes. The 3D models generated by the SfM process can be used for measuring the size of organisms and the rugosity of habitats, as input for artificial intelligence analysis, and for viewing in virtual reality. Values of rugosity are often singularly calculated at the model scale, yet many of the changes that occur in coral reefs, or other habitats dominated by habitat-forming species of interest, occur at smaller scales. In this progress report period, the project team (Beregovyi, Butkiewicz, and Jenn Dijkstra) developed new spatial analysis methods that fully capture rugosity within complex 3D scenes, using SfM models of coral reefs and intertidal landscapes as input. This method was implemented in a rugosity calculator tool that gives users the ability to choose the scale at which to measure rugosity.

Many of the current methods used to calculate rugosity rely on either 1D, line-based measurements, or 2D projections onto a single reference plane. These methods do not capture the full range of rugosity that occurs in complex habitats, as they cannot properly handle truly 3D scenes with holes and overlapping surfaces. To solve this, a number of different methods were explored. The first method expanded upon the 2D method by using multiple reference planes, which were generated using various polygonal mesh simplification techniques (Figure 23-7, Top). However, this method proved to have flaws that resulted in inconsistent results. The second method divides the model into a 3D voxel grid (based on the desired analysis scale), and for each cell a reference plane is calculated (Figure 23-7, Bottom). The calculations are run multiple times with a jittered grid, to smooth the results and suppress outliers resulting from edge cases. This solution eliminates the inconsistencies of the previous method and allows users to adjust cell size and thus, have more control over the scale of the measurement.

Experimentation with different methods for calculating reference planes for individual cells led to further improvements. For example, while a traditional approach of using the average normal of triangles in cell works well for most 2.5D "draped sheet" surfaces, such as those commonly generated from sonar, more complex 3D SfM models present many edge cases that result in poorly-fit reference planes and extremely unrealistic rugosity values. Ultimately, a rugosity-minimizing plane fitting approach was found to produce the most consistent results, with minimal extreme outliers.

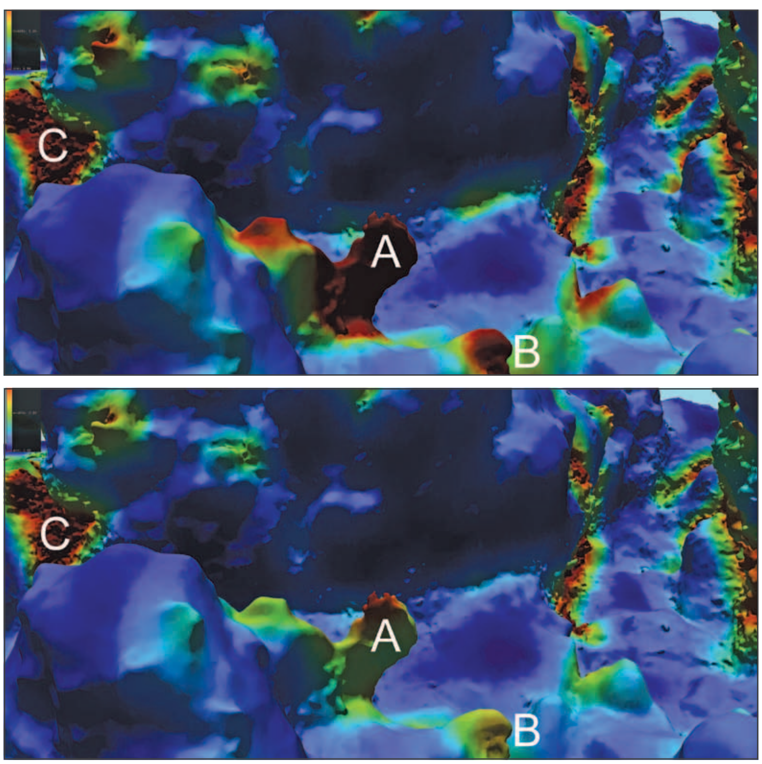


Figure 23-7. Comparison of two reference plane selection algorithms, (above) traditional--average surface normal, (below) our rugosity minimizing technique. Note the suppression of unrealistically-high rugosity values on otherwise-smooth protrusions (A, B), and preservation of truly-high rugosity values for rough regions (C).

In addition to creating a robust 3D rugosity calculator tool that functions at multiple scales, the project team worked to improve efficiency by optimizing the algorithm, adding multithreading and improving user features. Work is ongoing to expand this to support the visualization of annotations (e.g. of different species) provided either by human experts or AI/ML, and permit these annotations to be used to further refine rugosity analysis, e.g. to see rugosity contribution by substrate type, or see how rugosity influences species distribution. Further work is also focused on analyzing input models to estimate optimal parameters for what scale rugosity calculations should be performed at, as well as to provide users with guidance for making fair comparisons between different models.

Task 24: Volunteer Bathymetric Observations

JHC Participants: Brian Calder, Christos Kastrisios, Brian Miles, Patrick Debroisse, and Juliane Affonso

NOAA Participants: Jennifer Jencks and Georgiana Zelenak (NOAA NCEI/DCDB)

Other Participants: Helen Snaith and Pauline Weatherall (British Oceanographic Data Center/Seabed 2030 Global Center), Chris Parrish (Oregon State University)

Under the Data Acquisition component of the Advancing Technologies Programmatic Priority we have discussed our efforts to build a suite of inexpensive, yet authoritative data collection systems for volunteer bathymetric observations (Task 15). In this Task we explore approaches on evaluating data from volunteer and other non-traditional (i.e., non hydrographic agency) sources. With tightening budgets, there is more emphasis than ever on using all available sources of information on the bathymetry and non-bathymetric chartable objects to aid in the assessment, maintenance, and update of charts or other navigational products. While logical and fiscally prudent, this approach begs a number of difficult questions, particularly with respect to quality, reliability, and liability.

In previous reporting periods, the Center has examined components of this problem, for example through satellite-derived bathymetry (SDB) and volunteered bathymetric information (VBI). In the current reporting period, we have continued to develop techniques for volunteer observer reputation assessment, and to extend these to the assessment of the reputation of data using similar techniques, which has implications for database ageing and resurvey policy. We have also continued to develop VBI processing software with a number of international partners. Finally, we have investigated the use of a piecewise-linear model for SDB and the implications for this in reconstruction of bathymetry from satellite imagery.

Project: Observer and Data Reputation

A significant problem with the volunteer data model is that observers are, essentially, unreliable narrators in the sense that, contrary to typical data processing problems in hydrography, the data biases (deterministic uncertainty) may be considerably higher than the data variance (stochastic uncertainty), which is usually the primary concern. In practice, this means that the depths available from VBI observers might be significantly shoaler (or deeper) than the true depth in a way that is difficult to ascertain from the data itself. Combining data like this is also problematic, since most estimation techniques assume that any biases have been removed before combination.

The commonly cited alternative to using the depth data directly is to suggest that the data might be used indirectly for change detection and resurvey assessment. That is, although the depths might be unreliable, repeated indications of difference between the authoritative data and VBI data might indicate that resurvey is required. While this line of reasoning is plausible, it is also subjective: how much evidence is required from the VBI data to declare that an intervention is required?

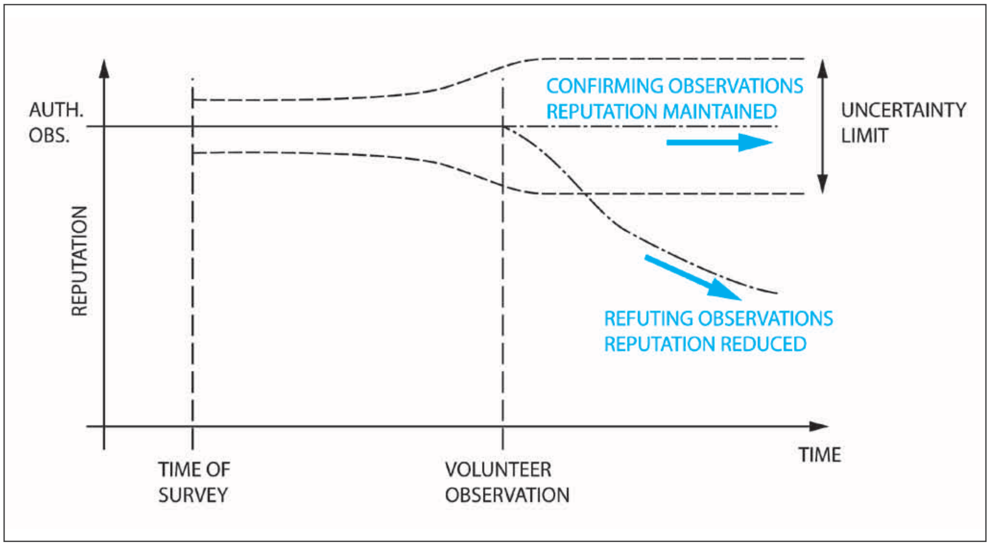


Figure 24-1. Illustration of the principle of data reputation. Data reputation is set to that of the observer at the time of survey, and then continues (with increasing uncertainty – dashed lines) until a new observation is made. Confirming observations maintain reputation; refuting observations reduce it.

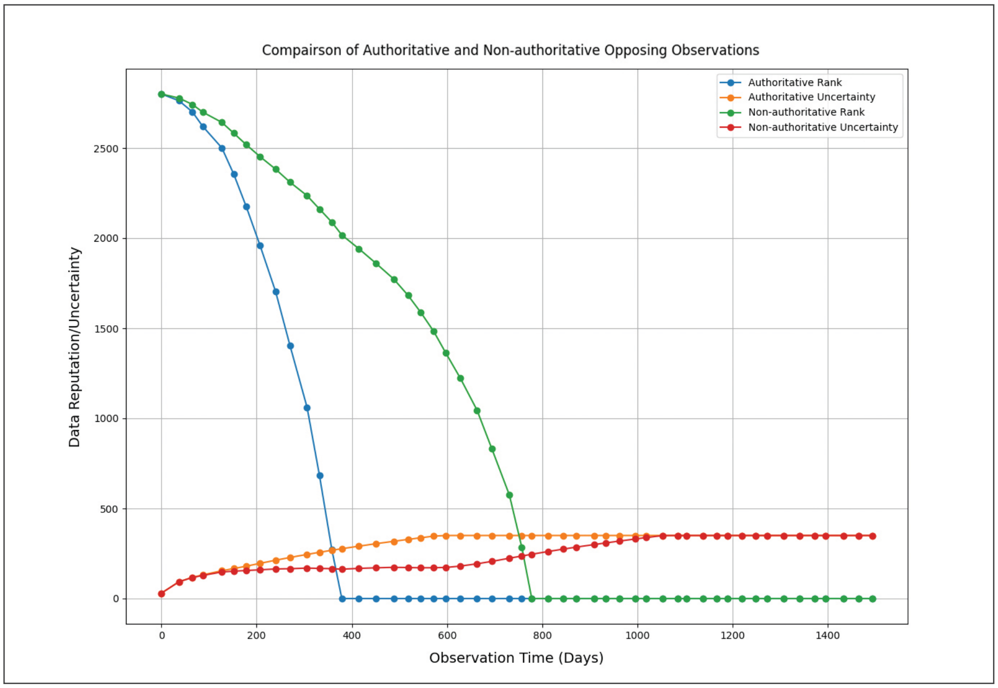


Figure 24-2. Example of data reputation aging based on new observations from volunteer (or other) data collection. Initially authoritative data (reputation above 2500) loses reputation as contradictory depths of expected difference 5m are observed. For a good observer (blue line reputation, orange line uncertainty), the reputation falls faster than for a mediocre observer (green line reputation, red line uncertainty).

Using this line of reasoning, we have previously proposed methods to develop a reputation assessment for VBI observers, ranking them by their ability to match, after correction for estimated vertical offsets, authoritative data on a consistent basis. The higher the reputation, the more likely it is that a depth measurement that contradicts the chart (outside of calibration processing) should be believed; the lower the reputation, the more evidence would be required (i.e., more contrary observations) before the chart would be modified, or an investigation would be considered.

In the current reporting period, Brian Calder and Brian Miles have extended this idea to reputation for data, assuming a transitive property between the observer and the observed. That is, each observation of depth inherits the reputation of its observer (including an uncertainty) at the time of observation, but thereafter maintains its own reputation, Figure 24-1. New observations that confirm the archival depth improve the archive's reputation as well as the observers; observations that refute the archival depth reduce the archive's reputation in line with the observer's reputation, and that of the archive at that point. As an extension, the uncertainty of the archive depth should also increase with time between observations, reflecting the potential for the seafloor to change away from that observed originally. Ultimately, archival depths with reputations that fall below a certain level would be considered unreliable and removed from the archive, giving a principled way to age out old data.

Figure 24-2 shows an example using simulated data for clarity. Here, an initially authoritative data point (i.e., with reputation above about 2800 and uncertainty approximately 30) is modified by continued observations with mean difference 5m from the reference depth. For a good observer (blue line reputation, orange line uncertainty), the reputation drops quickly because the algorithm believes that the observer is typically correct in its observations of depth, and therefore gives strong evidence that the archival data may be out of date. For a mediocre observer (green line reputation, red line uncertainty), the decay of reputation is slower, although just as final. For any given threshold of reputation at which the archival data might be considered obsolete (i.e., any horizontal line in Figure 24-2), the good observer will time out the archival data faster, and the number of observations required to reach that level answers the previously posed question of how many observations are required for a given observer's depths to be believed. In essence, this calibrates the techniques being proposed.

The implications of this proposed technique are not only to identify when sufficient information has been received to trigger remediation for a given chart, but to provide a technique to determine when data should be removed from the archives in general. This could be used, for example, to improve estimates of temporal decay for resurvey priority decisions, among other uses. Therefore, in addition to finalizing the previous reported conversion of the implementing code to Python so that it can be deployed more readily in the cloud (e.g., in conjunction with the WIBL cloud-segment processing code, Task 15 and below) and be more readily testable, in the current reporting period, Calder, Miles, and NOAA graduate student Patrick Debroisse have investigated how to automatically scrape information from both the IHO Data Center for Digital Bathymetry (DCDB) and OCS National Bathymetric Source (NBS) to feed these types of computations in a putative cloud-based deployment.

A program has been produced and is in the refinement and testing phase that handles both the data discovery and data management automatically. This open-source Python program (csb-python) allows for potential deployment in existing hydrographic tool packages while also allowing for individual customization by future users. The program provides the user options for local download of data or direct communication with the original data stored in Amazon Web Service (AWS) S3 buckets. Further, the program can initiate the reputation calculations outlined previously.

As a proof of concept, the NBS was chosen as the authoritative source for comparison against VBI data from the DCDB. While these data sources are heterogeneous both in content and metadata, geographic location can be used for data discovery and to ensure colocation. The program (Figure 24-3) can search either database using specific chart numbers (for NBS), specific vessel names (for DCDB), or by geographic area. The user chooses which database to search first and then the program searches the second by geographic area based on data discovered from the first. Depending upon the needs of the user, the result is either locally downloaded files organized and stored by the program, or text files containing S3 URLs to the desired data in its AWS S3 bucket. These datasets are then provided to the reputation calculator for comparison. Final presentation of the data discovery portions of the csb-python program is expected early in 2023.

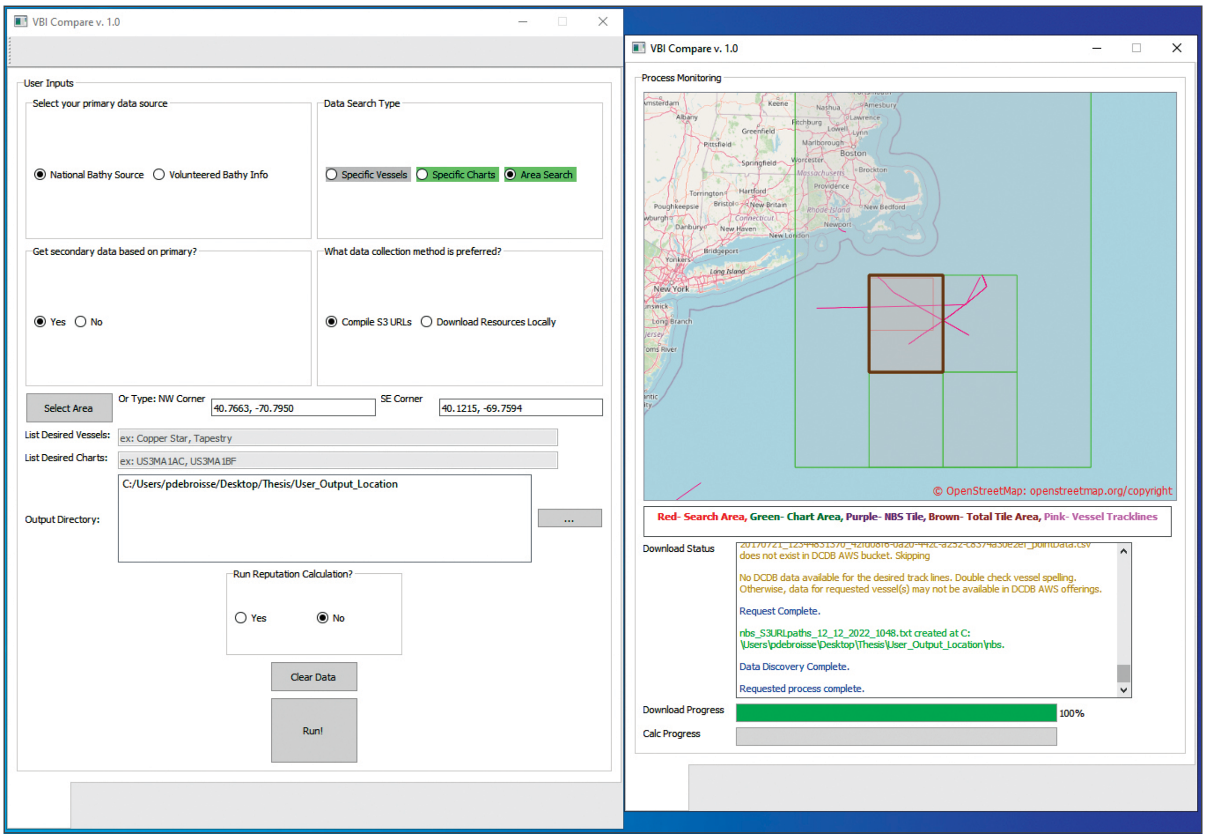


Figure 24-3. Example of data queries for volunteer data and authoritative reference depth in the vicinity of Long Island and Nantucket.

Project: Cloud-based Processing for Volunteer Bathymetry Observations

As part of the Center's work on data acquisition for volunteer observers (Task 15), we have developed a cloud-based processing scheme for VBI collected by our Wireless Inexpensive Bathymetry Logger (WIBL) system which transfers the logger data into an Amazon Web Services (AWS) Simple Storage Service (S3) object-based store, from whence it is processed using a series of AWS Lambda serverless applications. The goal for this system, in addition to immediate support of the WIBL technology demonstrator, is to provide a freely available example implementation of a cloud-based processing system that can be adopted for other users, and other loggers, and to form the basis for integration of other VBI processing development as described in the previous project. The source code for all the core processing system is available under an open-source license in a public repository.

In the previous reporting period, Calder cooperated with the Seabed 2030 Global Centre (Helen Snaith) to provide an implementation of the WIBL processing chain for use with other loggers, especially the TeamSurv and Yacht Devices NMEA loggers, which have no data processing chain of their own. This allowed the GAC to become an IHO Trusted Node and provide data to DCDB for any volunteers that do not have their own Trusted Node.

In the current reporting period, this effort has continued. As field trials in Palau, South Africa, and Greenland start to produce more data, and as more individual volunteers start to collect data, this project has been a valuable source of exceptions, bug-fixes, and test cases to allow the WIBL cloud-segment code to become both more capable and more robust.

In addition, Calder has begun the transition of the Trusted Community Bathymetry (TCB) processing chain from research MATLAB to Python so that it can be deployed in the cloud, and mixed more readily with other code, as described above, to provide value-added services for hybrid TCB/WIBL deployments (see Task 15). This effort was slowed by the unexpected departure of a graduate student but will continue in the next reporting period so that a more modern, stable code base is available to assess TCB observations and form the basis for cross-calibration in hybrid deployments.

Project: A Geographic Segmentation Approach for Satellite-Derived Bathymetry

Safety of navigation depends on our knowledge of seabed and its features, so any improvements in deriving bathymetry for nautical chart updating are of major importance. Due to the limited available resources, it often takes years for hydrographic offices to re-survey an area. There are cases where charts have been compiled with data collected over a hundred years ago.

Satellite derived bathymetry (SDB) from multispectral remote sensing has shown potential as a supplement to traditional surveys, particularly for mapping remote and shallow areas, due to its reduced cost and the absence of navigational risks in very shallow and unsurveyed areas. SDB has received significant attention since the 1970s and multiple algorithms have been developed. The ability to retrieve bathymetric information from satellite imagery is based on the observed radiance as a function of wavelength and depth. The two most used band-ratio optimization approaches use either a log-difference to derive bathymetry (Dierssen model) or the division between the observed radiance log values of two bands (Stumpf model). Linear regression is applied to transform imagery values into depths.

A main concern with SDB is that the accuracy of the method is not adequate for many coastal applications, including nautical charting. One of the reasons may be that the conventional approaches assume that bottom type and water clarity are constant within the entire image, and consequently a single (global) and linear model can be used. Researchers have investigated the use of a nonlinear model with the aim to improve the accuracy of the derived bathymetry (extended Dierssen model).

To address the spatial heterogeneity within a scene and with the aim to increase the accuracy and coverage of estimated depths, graduate student Juliane Affonso, under the supervision of Christos Kastrisios, Christopher Parrish (Oregon State University), and Brian Calder, investigated the use of multi-temporal, non-linear techniques, and the segmentation of the scene, both horizontally and vertically, into smaller spatial units. The idea of the spatial segmentation assumes that the magnitude of spatial heterogeneity is smaller (and possibly non-existent) in small regions, therefore we divide the image scene into smaller spatial units and calibrate the model within each segment. The individual models use the same algorithm but varying model parameters.

In the previous reporting period, the research team evaluated the performance of the extended nonlinear model in the Dry Tortugas, Florida. The system is solved with linear regression, but since the model is not linear, the final solution represents an approximated solution to the observation, and instead of two control points at least four points are required for the extended n model solution.

The preliminary results showed that the added parameters result in better depth estimates compared to the traditional models.

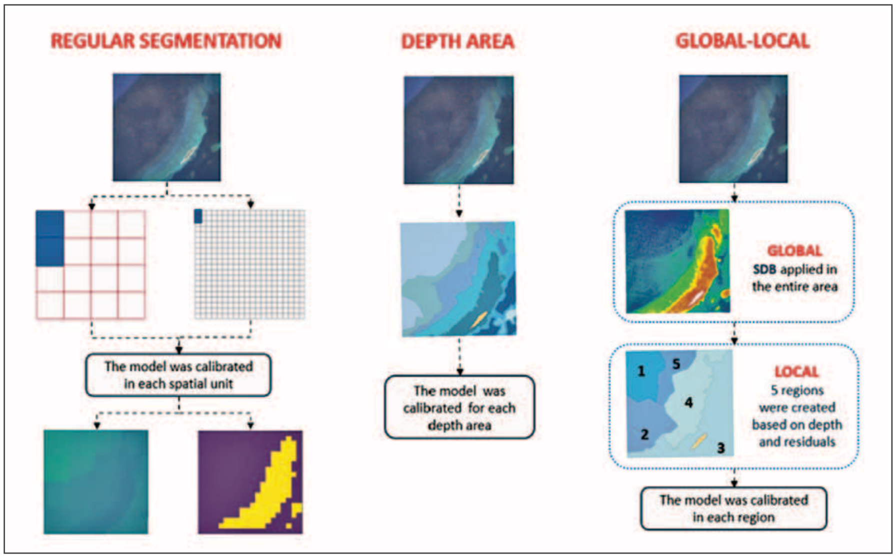


Figure 24-4. The horizontal segmentation workflow.

In the current reporting period, the research team further evaluated the extended model and subsequently focused on the investigation of the spatial segmentation of the scene using six different segmentation approaches:

1. Horizontal Segmentation (Figure 24-4)

   Either regular (square cells at 30 or 150 pixels in length with a model in each, using 150 pixels if the 30-pixel model does not converge), or irregular, either global-local (i.e., starting with a single model then generating regional models for areas with significant residuals between the global model and reference depths), or depth areas (i.e., a model every 5m in depth with small areas being treated with larger ones in the same range if they do not have sufficient reference depths).

2. Vertical segmentation (Figure 24-5)

   The vertical segmentation approach applies a piecewise regression to the band-ratio/depth to improve the accuracy in depths below the effective optical depth and to attempt the extraction of bathymetry beyond this point. To accomplish the vertical segmentation, the dataset was divided by depth, beginning with depth ranges of 5 m which progressively decrease to 1 m, and, given that enough control points exist, a model is calibrated for each subset of training data points. Based on the resulting RMSE, the best range selection provides the final bathymetry estimation.

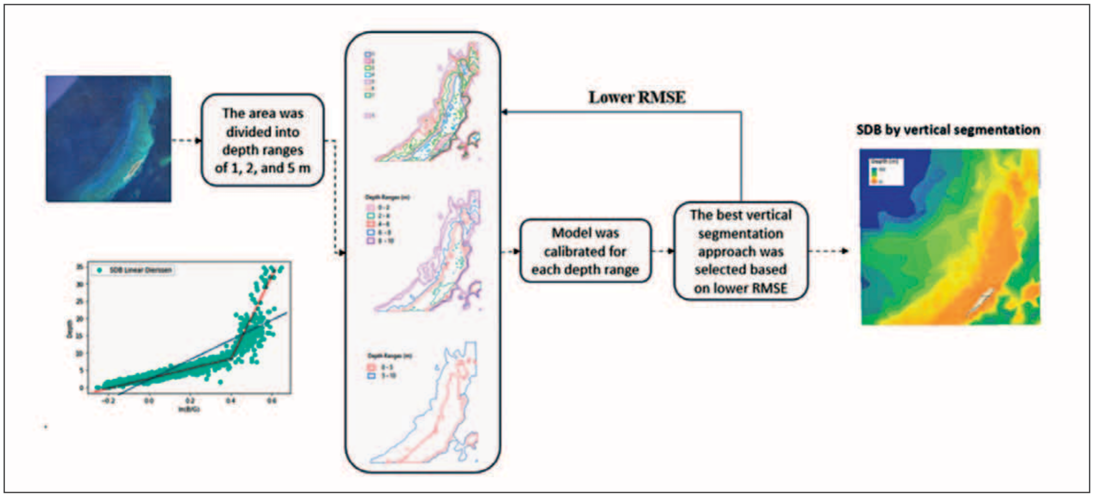


Figure 24-5. The vertical segmentation workflow.

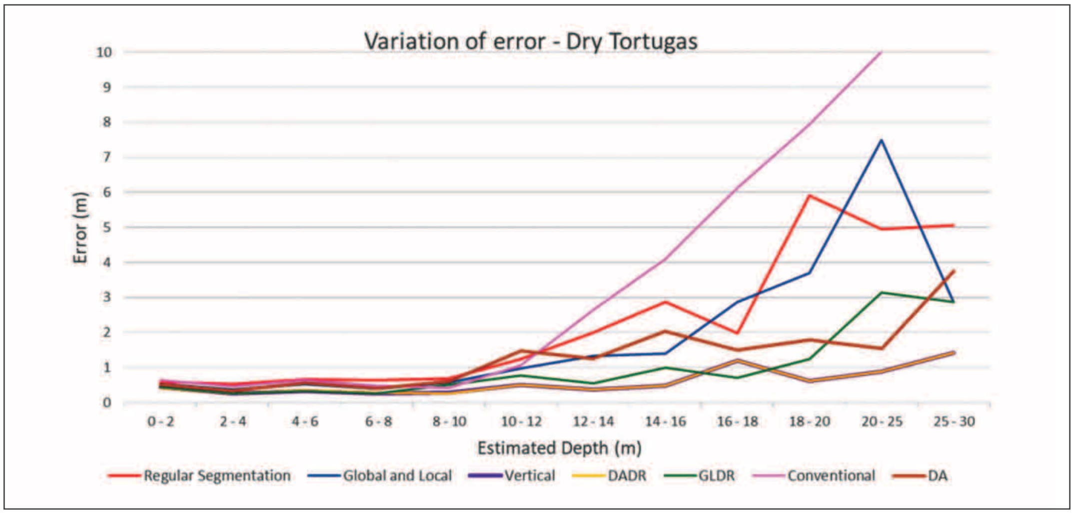


Figure 24-6. Performance of geographic models and conventional SDB approach in Dry Tortugas. The error variation is represented in depth ranges of 2 m.

3. Merged Segmentation

Merged segmentation combines the horizontal and vertical segmentation methods. With the two irregular horizontal segmentations, regions are divided into 1 m depth ranges.

The methods were evaluated at Loggerhead Key, west of Key West between the Gulf of Mexico and the Atlantic Ocean, and St. Thomas East End Reserve (STEER), U.S. Virgin Islands. In both sites, the use of the extended model improved the accuracy compared to the traditional, simplified model. In terms of the geographic approaches, all the investigated methods more accurately estimated depth compared to the conventional band-ratio algorithms. Furthermore, the results suggest that the vertical segmentation of the scene (Vertical and DADR in Figure 24-6) allows for inferring bathymetry beyond the effective optical depth (10 m in the areas considered) which is the limit for depth estimation with conventional approaches, thus increasing the coverage of the estimated SDB. Among all approaches, the vertical and DADR methods performed the best.

The geographic models provided significant improvements in depth estimation, but a few limitations and concerns exist. First, there is increased need for control points compared to the global models due to the greater number of spatial units for which a model must be calibrated. Furthermore, the geographic models consist of multiple steps compared to the conventional method, with a subsequent increase in processing time. Lastly, all vertical approaches (5 m, 2 m, 1 m) performed better than the global methods, and particularly that of the 1 m, but the segmentation results in discontinuities between the individual linear regression models of each depth range (Figure 24-7). It is part of future work to investigate whether the vertical segmentation approach indeed results in a substantial accuracy increase, as this work demonstrated, as well as the optimal bin size for improving accuracy and coverage without overtraining the model and losing its predictive capabilities.

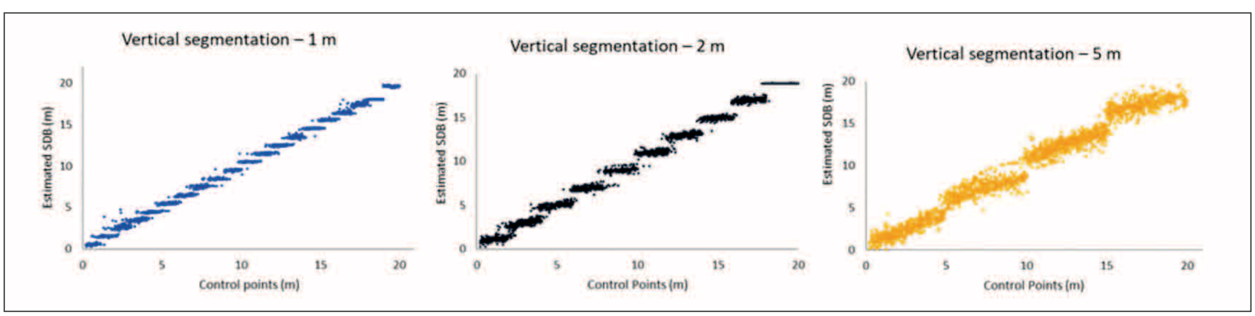


Figure 24-7. The quantized appearance in different depth ranges – 1m depth range (left), 2m (center), and 5m (right).

Task 25: Alternative Uses for ICESat-2 and Other Laser Altimeter Data

JHC Participants: Brian Calder, Kim Lowell, and Yuri Rzhanov

Other Participant: Chris Parrish (Oregon State University)

Satellite laser altimeter systems, such as the ICESat-2 ATLAS system, are typically used for measurement of surface phenomena, such as ice free-board, but prior research has demonstrated that they can successfully be used to determine water depth in some areas, at least in shallow, clear water. While the data density and accuracy are not necessarily what might be expected from airborne lidar systems, the ubiquity of the data and ongoing collection campaign make for an interesting dataset that may provide insight into other hydrographically significant features. For example, measurements of water height may provide insight into non-astronomical water level changes in coastal areas, with application to tidal modelling and hydrodynamic modelling, while approximate measurements of depth referred to the ellipsoid might possibly be used to provide reference depths for calibration of volunteer bathymetric information or imagery-based satellite derived bathymetry in remote regions.

A core component is reliable bathymetry derived from the ICESat-2 system. Therefore, in the current reporting period we focused on methods for reliable assessment of ICESat-2 data, and preliminary investigation of how to assess bathymetry points from the remaining data.

Project: ICESat-2 for Shallow Water Bathymetry

The current effort in this project also links to Tasks 26 (Ocean Mapping Data Analytics) and eventually will be more closely linked to Task 29 (Management of Living Marine Resources from ECS and ICESat-2). This work is discussed more in the narrative for Task 26.

The long-term outcome of this project targets two goals: 1) mapping bathymetry for remote areas and 2) monitoring benthic habitat (Task 29). Effort on this project is enhanced by the efforts of Chris Parrish at Oregon State University, and active participation by Center personnel in the ICESat-2 bathymetric working group chaired by Parrish that also includes other experts in the field such as Lori Magruder and her team at the University of Texas at Austin.

The near-term goal of the project is to enable (quasi-) automated extraction of bathymetry from ICESat-2 data and couple such data with remotely sensed imagery using satellite-derived bathymetry (SDB) techniques to produce area-based depth maps.

"ICESat-2 data" in reality, comprise some 20 "products" resulting from five levels of NASA processing. The most commonly used for bathymetry is "ATL03 Geolocated Photons" (Level 2 processing)—the x, y, and z coordinates of "photon events" (PEs) that are georeferenced laser returns. Other products such as "ATL06 Land Ice Height" (Level 3A) result from NASA processing of ATL03; such products facilitate achieving the primary ICESat-2 mission goal of cryosphere

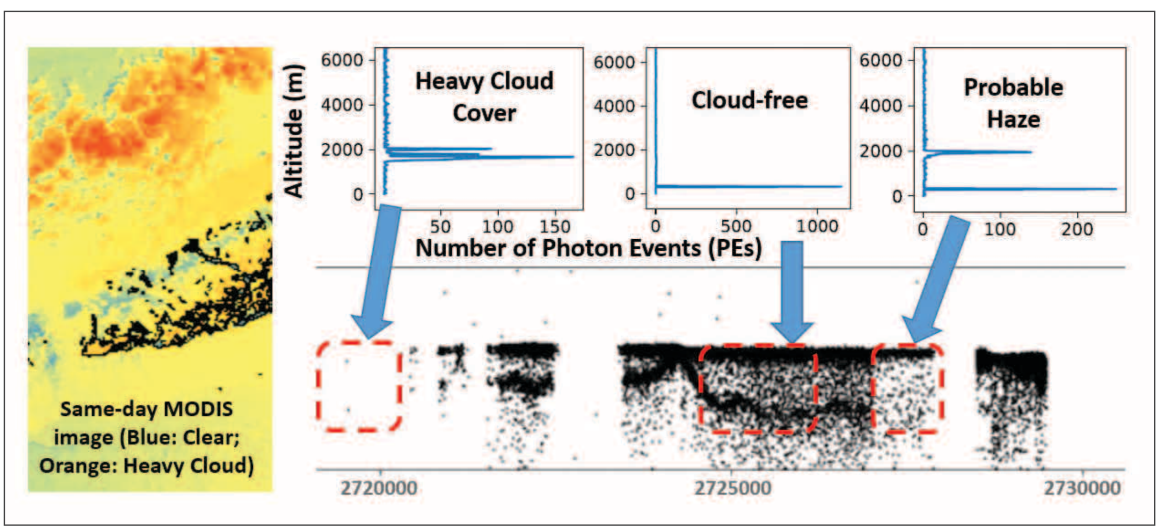


Figure 25-1. Example of ATL02 atmospheric histograms compared to same day MODIS image (250 m pixels) for a partly cloudy area in the Florida Keys.

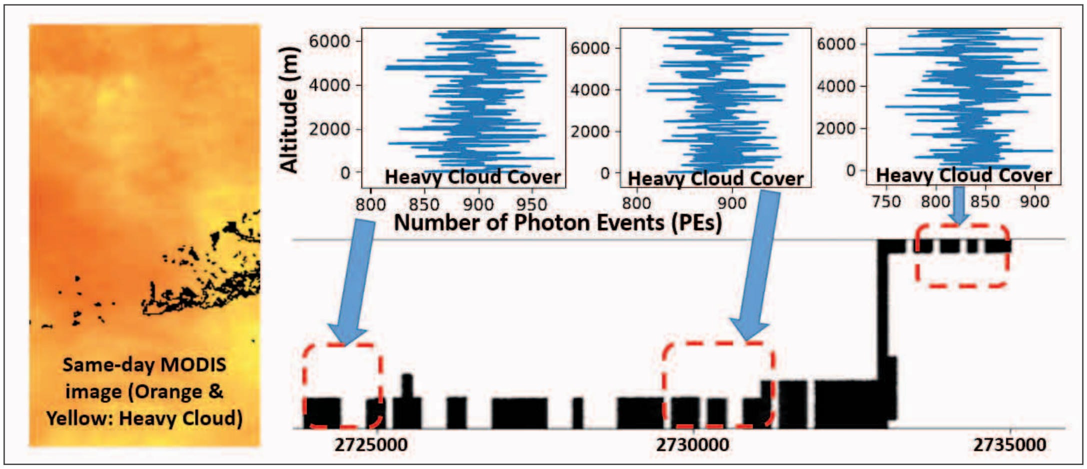


Figure 25-2. Example of ATL02 atmospheric histograms compared to same day MODIS image (250 m pixels) for an area completely covered by heavy clouds in the Florida Keys.

monitoring. However, the utility of other products to contribute to mapping shallow water bathymetry has been, and will continue to be, explored.

One type of data that has been found to be useful are "atmospheric histograms" (AHs) that are part of ATL02 ("Science Unit Converted Telemetry"–Level 1 processing). It has become clear that emerging bathymetry extraction algorithms will benefit greatly by first eliminating areas along ICESat-2 tracks that are unlikely to contain bathymetric PEs due to clouds or haze. The AHs are essentially vertical frequency histograms of PEs for voxels that are 30 m high, 540 m long, and the width of an ICESat-2 track (nominally 1 m); AHs extend from 300 m below sea level (10 voxels) to 14 km above sea level (457 voxels). By comparing AHs for three MODIS images for the Florida Keys acquired the same day as the corresponding ICESat-2 track, it is apparent that the AHs contain information that can be used algorithmically to eliminate from consideration areas that are unlikely to contain bathymetry. Figures 25-1 and 25-2 provide examples.

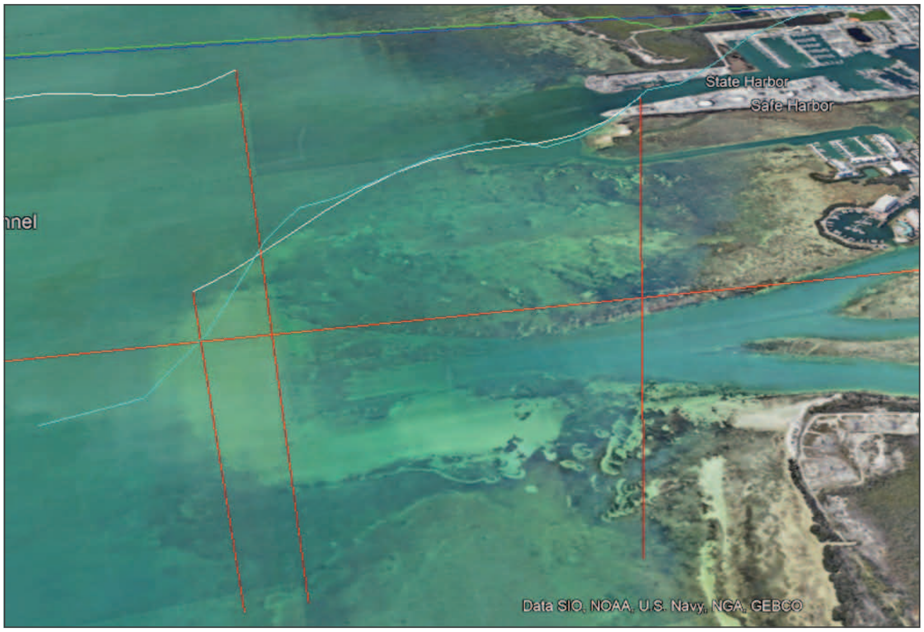


Figure 25-3. Example of bathymetry derived from ICESat-2 (cyan line) and NOAA airborne Lidar (white line). The green line at the top is ocean surface, the red horizontal line is 5m depth, and the bottom of the red vertical lines indicate the location of the track on the Earth's surface.

Following from this work is a re-consideration of the "confidence" associated with each PE that is a component of ATL03. Information in the ICESat-2 product documentation implies that "confidence" represents the likelihood that a PE is one of five land covers of interest, e.g., sea ice, inland water. However, examination of the ATL02 AHs relative to data in ATL04 (Normalized Backscatter Profiles; Level 2 processing produced using ATL02 and ATL03 as inputs) indicate that "confidence" may be of use since it provides an indication that a PE is "signal" rather than noise. "Signal" in this case appears to mean the PE has been returned from the Earth's surface rather than the atmosphere.

A fundamental issue also examined is the depth correspondence between (NOAA) airborne Lidar and what can be visually extracted from ICESat-2 tracks. In Figure 25-1 near UTM Northing 2725000, it appears that there is a clear trace of bathymetry PEs below the water surface. This was extracted from the ICESat-2 track, and the same area was extracted from NOAA airborne Lidar data from 2016. A GoogleEarth™ visualization was developed to examine differences between airborne Lidar depth and ICESat-2 depth for selected segments of ICESat-2 tracks. Figure 25-3 provides visual evidence that bathymetry from NOAA airborne Lidar data accords with subsurface ICESat-2 tracks assumed to represent bathymetry.

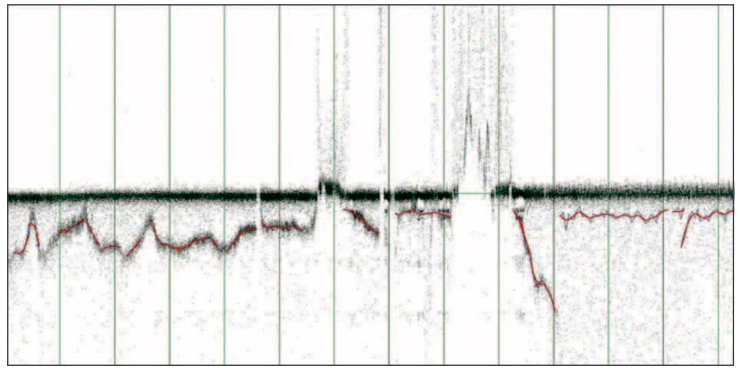


Figure 25-4. Example of bathymetry detected by the algorithm described in the text. Black dots are individual photon events (PEs), tiny lines "under" the red lines are potential bathymetric measurement (PBM) clusters, and the red lines are P-splines fit through the clusters and represent extracted bathymetry.

Development of an algorithm for fully automatic extraction of PEs reflected from the seafloor has begun. This is currently a multi-step algorithm as follows:

1. Identify the level of the ocean surface. Notably this is not constant along, for example, ~10 km of the ICESat-2 track. It has been shown to be affected by tide and/or wind, and water level may vary on opposite sides of land, even if neither side is inland water, i.e., not open to the ocean. Ocean surface PEs are defined as those that are within a 0.2 m standard deviation of the mean depth/altitude having the greatest frequency.
2. Extract subsurface PEs that may be bathymetry. First, the deepest 5% of PEs and/or those with a depth greater than 25 m are assumed to be noise. The standard deviation of the remaining PEs is calculated. Sub-surface PEs are those within three standard deviations of the ocean surface level determined in Step 1.
3. The track being examined is divided into 50 m segments. Given the ~15m geolocation uncertainty, all PEs in a segment are assumed to have the same geolocation. For each segment, a vertical histogram is constructed using the PEs retained in Step 2. The depth of each PE in a segment is represented by a Gaussian distribution and the depth is calculated as the sum of Gaussian contributions of all PEs in the segment. This approach provides for obtaining a smooth curve without plateaus although more complex distributions of PEs lead to multi-peak histograms. Peaks that are higher than half the height of the highest peak are designated "potential bathymetric measurements" (PBMs).
4. Reduce the number of PBMs. For each PBM, the neighbors in a "compressed vicinity," (i.e., a locally determined neighborhood), are identified and used to produce a single histogram. In doing so, to separate noise (PEs having "too few" neighbors) from signal (PEs in densely populated

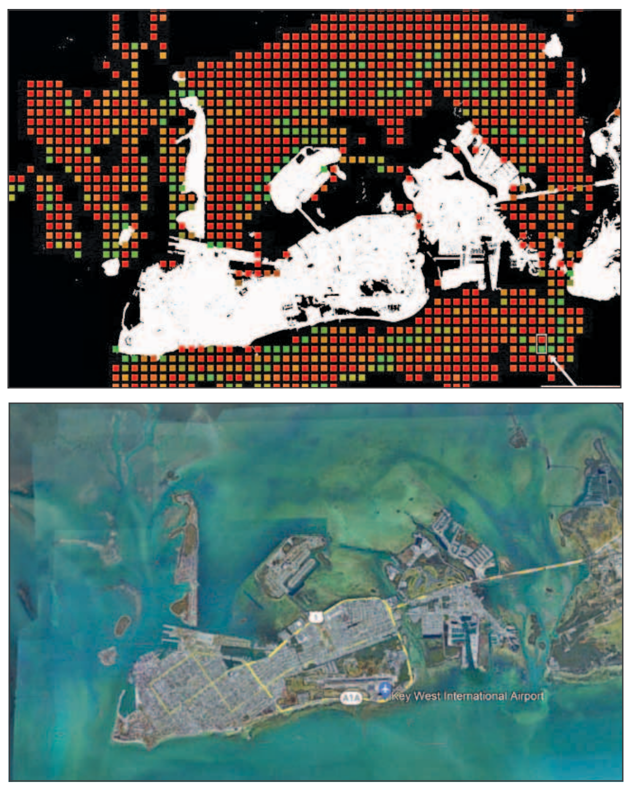


Figure 25-5. a. Best R2 values from four satellite derived bathymetry (SDB) models for 200 m-by-200 m cells fitted using Sentinel-2 imagery and ocean depths from airborne Lidar. Bright green indicates ideal correlation; bright red indicates no correlation. b. GoogleEarth™ image of the area.

vicinities) the algorithm proposed by Otsu, which is essentially a clustering technique for one-dimensional data, is applied.

5. Check retained PBMs for horizontal contiguity. If the distance between two neighboring (along track) PBMs is larger than two segment lengths (100 m), the PBMs are considered to belong to different clusters, i.e., connected sequences of PBMs.
6. Eliminate PBMs clusters that are contiguous to fewer than five segments.
7. Fit a penalized B-spline through the PBMs in each cluster of segments. These splines are considered to be local bathymetric trends. Their values are subtracted from the original PBMs that define the clusters and the standard deviation of differences calculated. If the standard deviation exceeds a value of ~0.25 m, the cluster is eliminated.

Figure 25-4 shows the outcome of applying this algorithm to an area where bathymetric PEs clearly appear to be present. While this algorithm has shown promising results, issues such as the existence of multiple hypotheses of PBM clusters have yet to be addressed. Moreover, it is common in such work to evaluate algorithm performance based on true positives, (i.e., bathymetric PEs correctly identified as bathymetric PEs). A more rigorous evaluation method must be developed that also consider the detection accuracy of false positives, false negatives, and true negatives.

Our intent is to use such automatically derived ICESat-2 bathymetry as input to satellite derived bathymetry (SDB) methods to produce "shore-to-shore" depth charts. For benchmarking, SDB techniques have been applied to a data source with more reliable depth estimates—NOAA's airborne Lidar acquired in 2016 for the Florida Keys. A cloud-free August 2021 Sentinel-2 image (10 m pixels) was acquired for an area approximately 20 km-by-10 km (Figure 25-5(b)). The area was divided into 200 m-by-200 m cells and separate SDB models fitted for each using the natural logarithm of the ratio of blue and green band values (Dierssen's model), the ratio of natural logarithms of blue and green band values (Stumpf's model); the same models were fitted by substituting the Sentinel-2 red band values for green which has been reported as superior for shallow areas (depth less that 1-2 m).

Figure 25-5(a) shows R^2 values (correlations) for individual cells. It is surprising (and disturbing) that in most cases the relationship between Sentinel-2 imagery and airborne Lidar depth is weak, which is contrary to what has been reported by others. Reasons for this result are being explored and include image selection, natural temporal depth changes, storm/hurricane impacts, and SDB model specification.

Given the results shown in Figure 25-5, "combined-data" models for two pairs of adjacent 200 m-by-200 m cells have been produced. The pairs selected have one "green" cell (high correlation SDB model) adjacent to a "red" cell (low correlation SDB model). Figure 25-6 shows the relationships between the Sentinel-2 imagery and airborne Lidar depth examined. For the example in Figure 25-6(a), there is no discernible difference in the models for the individual cells were the same, (i.e., there is not a clear distinction between the point clouds for the different cells, but the global correlation is low (R^2 is 0.11). Conversely, in the example in Figure 25-6(b) two distinct point clouds are apparent, but the model for the combined point clouds shows high correlation (R^2 is 0.84).

Work will continue on understanding SDB variability in an effort to understand how ICESat-2 data can best be used for shallow-water bathymetric mapping.

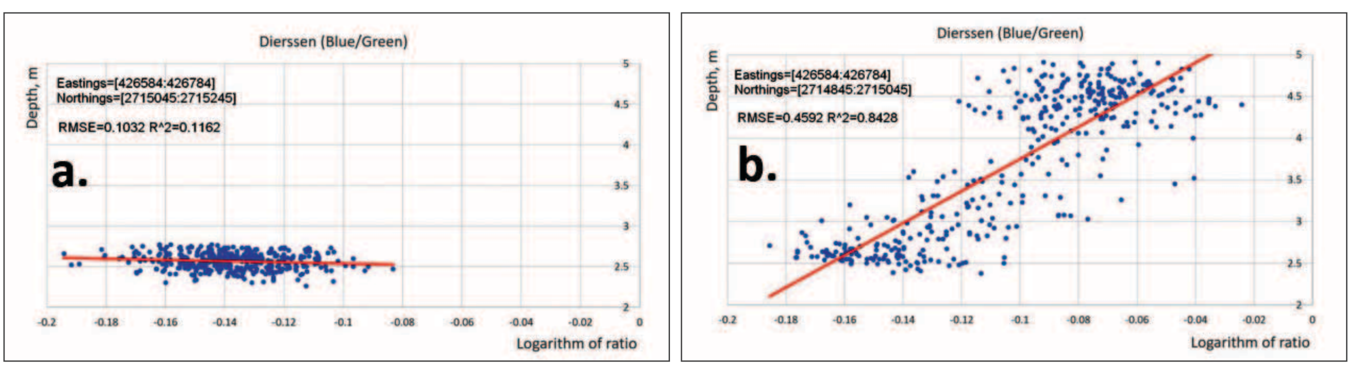


Figure 25-6. Two examples of Dierssen's satellite-derived-bathy-metry (SDB) model fitted for two adjacent 200 m-by-200 m cells.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: DATA VALUE

NOFO Requirement 7

Application of artificial intelligence, cloud services, and machine learning to the processing and analysis of hydrographic and coastal and ocean mapping data from both established and emerging sources, as well as to data from associated systems such as water level and current sensors, and from regional and global precise positioning networks.

JHC/CCOM responded to NOFO requirement 7 in one task:

Task 26: Ocean Mapping Data Analytics

Task 26: Ocean Mapping Data Analytics

JHC Participants: Kim Lowell, Brian Calder, Jenn Dijkstra, Jen Miksis-Olds, and Yuri Rzhanov

The Ocean Mapping Data Analytics (OMDA) task was created to address the growing need for research that applies a variety of analytical techniques, (e.g., artificial intelligence (AI), machine learning (ML), text analysis, visualization), across a range of JHC activities. Led by Kim Lowell, the OMDA task was created to have a dual focus. The primary focus continues to be the automated extraction of bathymetric soundings from lidar point clouds that was Lowell's nearly sole focus from 2018 when he joined JHC to the end of the prior JHC grant in 2020. The secondary focus is the contribution to the various activities across JHC that have identified a potential need for Data Analytics approaches.

Given this structure, detailed reporting of progress in the OMDA task is presented through its application in other Tasks described in this progress report. These are identified here and a brief summary of progress during the current reporting period is provided. In the current reporting period, three primary activities have been pursued; they are described in more detail in the specific tasks.

OMDA Project: Task 16: (Bathymetry Data Processing)

The goal of this effort is to provide an airborne Lidar processing flow that is more rapid and decreases manual input while maintaining the accuracy of existing NOAA processing. A major focus of the current reporting period has been a meta-analysis of the uncertainty associated with a machine-learning (ML)-based approach developed in CHRT (CHRT-ML 2.0) that merges CHRT output and ML outlier analysis and clustering techniques. An important innovation developed during this reporting period is that instead of evaluating CHRT-ML 2.0 solely relative to its ability to match NOAA's Bathy/NotBathy classification of Lidar soundings, it can now also be evaluated relative to its ability to produce the same depth charts as NOAA at multiple spatial scales. This evaluation addresses both the statistical and spatial patterns of depth disagreement between CHRT-ML 2.0 and NOAA.

Not reported in the narrative for Task 16 has been an in-depth exploration of statistically sound methods of evaluating more than a single data set (lidar tile in this case) against more than two "models" using more than a single evaluation metric. This has turned out to be a major gap in Data Analytics (DA) research. The conventional task in DA is to determine which model in a set of models is the best for a single database using a single accuracy metric such as root-mean-square-error (RMSE) or global classification accuracy. Conventionally, if more than two models are being considered, the model evaluation is reduced to a complete set of pairwise model comparisons and a cumbersome interpretation of the results. This approach is unsatisfactory for the examination of CHRT-ML uncertainty because the alternative central question asked is: What is the best classification method across multiple data sets (lidar tiles) using multiple accuracy metrics? Multiple pairwise comparisons are inappropriate for answering such a question. Progress has been made on developing an efficient and comprehensive evaluation methodology; such work will continue in the next reporting period.

The final major innovation has been the implementation of a semi-automated method of eliminating land (i.e., above-sea-level) areas from Lidar tiles prior to CHRT-ML processing. Implicit in CHRT-ML methodology is that there are no more than three major depth levels on a lidar tile—the ocean surface, a sub-surface layer such as a coral reef, and a deeper area such as dredged or natural channels.

Not removing above-sea-level areas adds the possibility of a fourth major depth level which CHRT-ML has insufficient flexibility to address. The method developed applies thresholding to the Normalized Difference Vegetation Index (NDVI) calculated for Sentinel-2 images (10 m pixels) and an analysis of contiguous tiles to eliminate above-sea-level areas from individual tiles prior to processing. (A visual example is provided in the narrative for Task 16.)

While refinements of CHRT-ML 2.0 will continue, particularly for the uncertainty analysis, all necessary components of an operational workflow now exist (Figure 26-1).

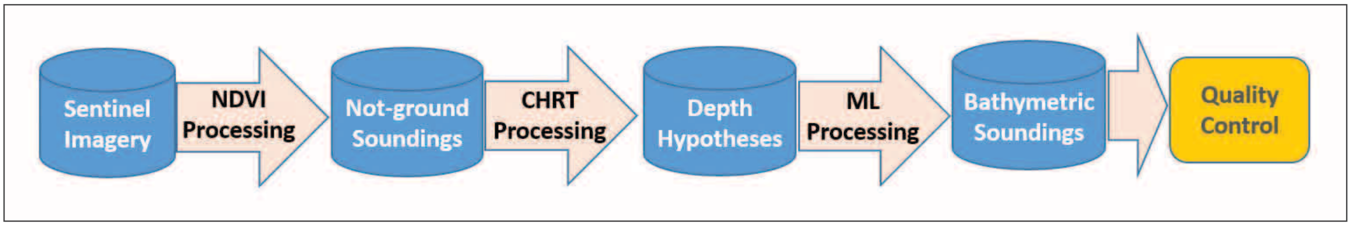


Figure 26-1. OceanMappingDataAnalytics-1. CHRT-ML 2.0 simplified workflow.

OMDA Project 2: **Task 24 and Task 29: Alternative Uses of ICESat-2 Data and Other Laser Altimeter Data and Management of Living Marine Resources from ECS and ICESat-2**

The activities for this project are described in detail in the narrative for Task 24. This project's ultimate goal is also related to Task 29 although in the current reporting period the connection to Task 29 is implicit rather than explicit. Plans for a more explicit connection in the next reporting period are in place.

"ICESat-2 data" comprise a vast resource whose size and associated documentation make it challenging to work with. Coupled with the reality that the ICESat-2 mission was launched to improve global monitoring of the cryosphere, understanding the data available that may improve the extraction of shallow-water bathymetry from ICESat-2 requires considerable effort. It also complicates attainment of the joint-goal of Tasks 24, 26, and 29 for (nearly) fully automated bathymetric mapping using ICESat-2 data.

The most-used ICESat-2 dataset for mapping bathymetry is product ATL03 ("Geolocated Photons"). In this OMDA project (described in more detail in Task 24), two complementary major efforts that operate at different spatial scales have been undertaken to extract bathymetric "photon events" (PEs), (i.e., lidar returns or soundings), from the PEs that comprise ATL03. One is developing a method to use the atmospheric histograms (AHs) of product ATL02 ("Science Unit Converted Telemetry") to identify lengths of ICESat-2 tracks that are so cloud-affected as to be unlikely to contain bathymetric PEs. The second strives to automatically extract bathymetric PEs from the lengths that are not eliminated in the preceding step. Currently under refinement is a 3-dimensional density-based algorithm to achieve this.

The preceding work has also led to varying levels of exploration of a number of topics related to this work such as effective use of repeated overpasses of ICESat-2, depth accuracy variability among images used to fit satellite-derived-bathymetry (SDB) models for an area using ICESat-2 track-based data, and seasonal trends in information content of ICESat-2 data. This work will continue in the next reporting period. It is further anticipated that work will begin on sampling/statistical issues associated with benthic habitat monitoring using ICESat-2 that is collected along very narrow transects with a repeat cycle of 91 days with geographically inexact repetition.

OMDA Project 3: **Task 31: Delivery of Bathymetric Data Services from Enterprise Data Bases**

Work has been initiated on examining and characterizing uncertainty associated with conventional NOAA practices of interpolation ("gap filling"). G. Rice of NOAA has made available a gap-free database for an area near the Isles of Shoals (Maine/New Hampshire). This is being sampled in various ways to represent realistic sonar data collection scenarios, (e.g., greater/lesser distances between survey lines, non-parallel survey lines). The data from the different scenarios are being spatially interpolated to produce seamless surfaces. Because the data set is spatially complete, the error for each sounding can be determined. Subsequently, the uncertainty will be characterized using information that can be obtained from the generating database and interpolated surfaces, (e.g., slope, rugosity, distance and relative directions from "neighboring" points). The overarching goal of this work is to facilitate survey planning efficiency by being able to anticipate the magnitude of interpolation errors that will result from different survey plans considered.

To examine this, a change point analysis was undertaken. The form of change point analysis here uses boot-strapping to identify when in a time-series the most substantial change(s) occurred, the magnitude of each change, and whether or not each change identified is statistically significant. Data for 2019 and 2020 were obtained from three of the seven ADEON hydrophones located closest to major shipping lanes. Weekly median sound levels were calculated for both years for six frequencies, weeks were matched for the two years (e.g., Week 1 for 2019 with Week 1 for 2020), and their medians differenced; a negative difference indicates that 2020 was quieter than 2019. *A priori,* it was expected that if there was a COVID-related decrease in shipping noise, four sound level change points would be observed:

1. a sharp drop of unknown magnitude in 2020 near Week 10 (mid-March),
2. a gradual increase and possible return to normal (zero difference between 2019 and 2020) between about weeks 20 (mid-May) and 26 (end of June),
3. a sharp drop of unknown magnitude near week 35 (early September) associated with the dual 2019 Dorian-Humberto hurricane event, and
4. a relatively sharp post-hurricane return to normal (zero difference) near week 37 (mid- to late-September).

A change point analysis model reflecting this expectation was formulated and fitted. Results (Figure 26-1) indicated that the actual change in soundscape levels did not match the "COVID expected" change. The dots indicate the change, statistical significance of change, or both.

The conclusion from this work is that there was no observable COVID-related change in the deepwater soundscape examined including for the frequencies (63 Hz and 125 Hz) that might be most expected to be impacted.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: RESOURCES OF THE CONTINENTAL SHELF

NOFO Requirement 8

Advancements in planning, acquisition, and interpretation of continental shelf, slope, and rise seafloor mapping data, particularly for the purpose of delimiting the U.S. Extended Continental Shelf and mapping the resources of the seabed.

JHC/CCOM responded to NOFO requirement 8 in one task:

Task 27: Support of U.S. ECS Efforts

Task 27: Support of U.S. ECS Efforts

JHC Participants: Larry Mayer, Paul Johnson, Jim Gardner, Juliet Kinney, and Brian Calder

NOAA Collaborators: Andy Armstrong (OCS) Elliot Lim (NCEI), Meredith Westington, (NOS), and Jennifer Jencks (NCEI)

Other Collaborators: Brian van Pay (State Dept), Kevin Baumert (State Dept.), and Project Team

Recognition that the implementation of the United Nations Convention on the Law of the Sea (UNCLOS) Article 76 could confer sovereign rights to resources over large areas of the seabed beyond the current U.S. 200 nautical mile (nmi) Exclusive Economic Zone (EEZ) focused interest in the potential for U.S. accession to the Law of the Sea Treaty. In this context, Congress, through NOAA, funded the Center to evaluate the content and completeness of the nation's existing bathymetric and geophysical data holdings in areas surrounding the nation's EEZ with an emphasis on determining the usefulness of existing data to substantiate the extension of sovereign rights over the resource of the seafloor and subsurface beyond the present 200 nmi EEZ limit into the UNCLOS-defined Extended Continental Shelf (ECS). This report was submitted to Congress on 31 May 2002.

Following up on the recommendations made in the above report, the Center was funded (through NOAA) to collect new multibeam sonar (MBES) data in support of a potential ECS claim under UNCLOS Article

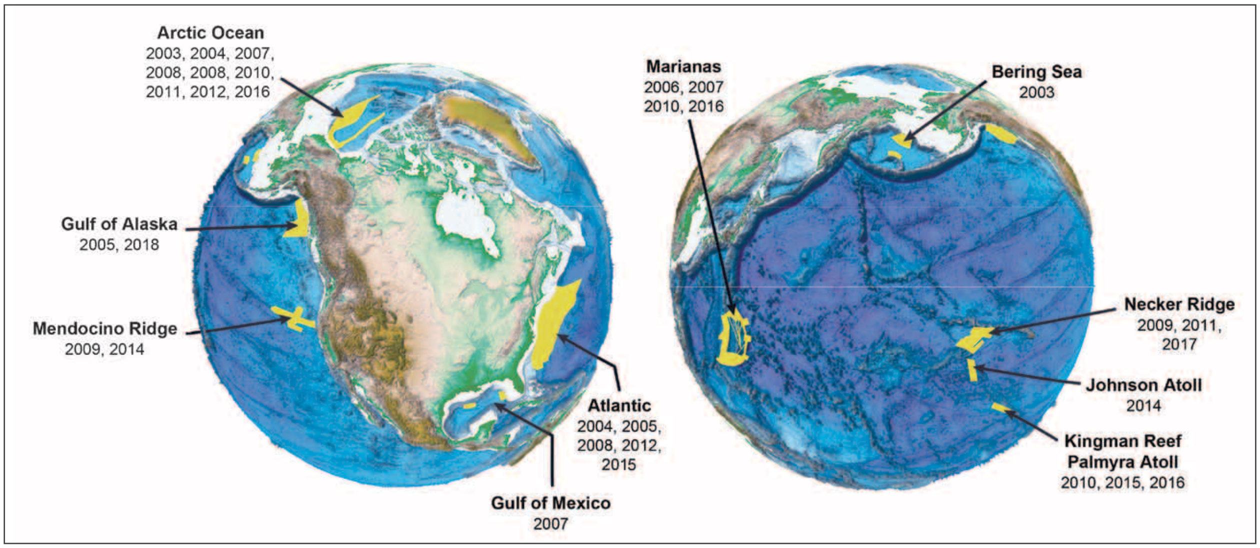


Figure 27-1. Locations of ECS multibeam sonar surveys conducted by the Center.

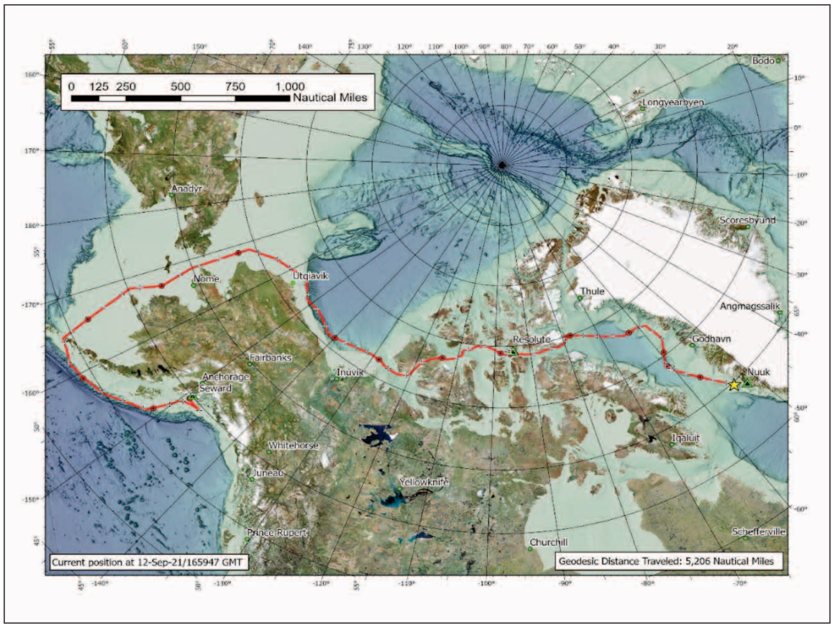


Figure 27-2. USCG Icebreaker *Healy* transit of the Northwest Passage in summer of 2021. While not undertaken for ECS purposes, ECS-relevant data were collected during transit through Canada Basin.

76. Mapping efforts started in 2003 and since then the Center has collected more than 3.1 million square kilometers of new high-resolution multibeam sonar data on 35 dedicated cruises that include nine in the Arctic, five in the Atlantic, one in the Gulf of Mexico, one in the Bering Sea, three in the Gulf of Alaska, three in the Necker Ridge area off Hawaii, three off Kingman Reef and Palmyra Atoll in the central Pacific, five in the Marianas region of the western Pacific and two on Mendocino Fracture Zone in the eastern Pacific (Figure 27-1). In 2021, the Center led another expedition on USCG Icebreaker *Healy* to the Arctic as it transited the Northwest Passage (Figure 27-2). While this cruise was not undertaken or funded for ECS purposes, we were able to collect useful data to supplement the U.S. ECS database in the Canadian Basin.

Summaries of each of these cruises can be found in previous annual reports and detailed descriptions and access to the data and derivative products can be found at http://www.ccom.unh.edu/law_of_the_sea.html. The raw data and derived grids are archived at NOAA's National Center for Environmental Information (NCEI) in Boulder, CO and other public repositories within months of data collection and provide a wealth of information for scientific studies for years to come.

Dr. James Gardner formally retired in 2021, ending a 50+ year career in marine geology. He is now, however, an Emeritus Professor and continues to participate in scholarly activity related to our ECS activities and is currently working on scientific manuscripts based on analysis of ECS data sets.

Numerous ECS conference calls, video-conferences, and meetings occurred throughout the year including monthly ECS Working Group conference calls to review overall ECS progress. These scheduled calls are supported by unscheduled phone calls and videoconferences to discuss specific regional details. Several key virtual meetings were held this year including regular reviews of the status of the U.S. submission and several emergency meetings to discuss Russian and Canadian updates to their submissions.

As the ECS task force finalizes the documentation for the submission by the U.S. for an extended continental shelf beyond 200 nmi, Mayer and Armstrong have spent much time reviewing draft U.S. submissions written by the ECS Project Office. Feedback was provided on each of these documents to the Project Office. Additionally, Paul Johnson and Juliet Kinney have been working closely with the Program Office and NCEI to ensure that all data collected by the Center of the past 20 years are fully available and appropriately attributed in the Program Office and NCEI databases. The Center team has been working with NCEI staff (Jencks, Zelnak, and Meyer) to validate the National Archive's data holdings for the Extended Continental Shelf surveys. This undertaking includes confirming that each raw file (bathymetry, backscatter, and water column) that was acquired during each of the ECS surveys was properly delivered from the Center's data stores to the National Archive. Following this verification, a Cruise level metadata record is generated in the ISO19115-2 format which documents relevant survey information such as acquisition systems, survey dates, spatial data bounds, processing information, chief scientist, contact information, etc. Also generated as part of the review process are gridded bathymetry and backscatter data products (with metadata) for each survey using the cleaned and processed data that has been submitted to the ECS program office. Through the last year, the Center and NCEI had finalized the Arctic region data and have almost wrapped up the Atlantic region data.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: RESOURCES OF THE CONTINENTAL SHELF

NOFO Requirement 9

Adaption and improvement of hydrographic survey and ocean mapping technologies, including the development of potential new approaches and technologies, in support of mapping the Exclusive Economic Zone and of "Blue Economy" activities in U.S. waters such as offshore mineral and resource exploration, renewable energy development, coastal hazard planning, and the responsible management of U.S. living marine resources.

JHC/CCOM responded to NOFO requirement 9 in three tasks:

Task 28: Offshore Mineral/Marine Resources

Task 29: Management of Living Marine Resources from ECS including use of ICESat-2

Task 30: Improvement in Change Detection

Task 28: Offshore Mineral/Marine Resources

JHC Participants: Larry Ward, John Hughes Clarke, Paul Johnson, Michael Bogonko, Rachel Morrison

Locating and exploiting marine minerals in complex continental shelf environments that are characterized by a wide range of sediment types and numerous physiographic features (geoforms) such as outcropping bedrock, reef structures, or eroding glacial deposits is often difficult. For example, continental shelves found in paraglacial environments (previously glaciated) are common in the U.S., dominating much of New England, the Pacific Northwest, and Alaska. Glaciated environments on land typically have abundant sand and gravel resources and historically have been a major source of aggregates. Unfortunately, land resources are becoming depleted, creating the need to find and utilize new sources. Continental shelves found in paraglacial environments likely have abundant sand and gravel resources that are associated with marine-modified glacial deposits. However, paraglacial continental shelves are extremely complex with respect to seafloor morphology and sediment distribution, making identification of mineral resources far more difficult than in tectonically stable, unglaciated areas with wide shelves composed of homogeneous sediment deposits (e.g., southeastern U.S. Atlantic or Gulf of Mexico). Therefore, it is important to continue to advance our understanding of the relationships between aggregate deposits and seafloor physiographic features in or near previously glaciated systems.

Over the past decade marine mineral resource studies carried out by the Center verified that many sand and gravel deposits located on the western Gulf of Maine (WGOM) continental shelf originated as glacial features. On the adjacent upland, glacial deposits such as deltas or braided outwash are well mapped and are primary sources of aggregates that are extensively mined and utilized. However, unlike glacial deposits on land, the offshore sites are poorly mapped and have been exposed to the harsh marine environment including multiple sea-level transgressions and regressions (rise and fall), wave and tidal currents, and biologic modification (e.g., vegetated or bioturbated). Therefore, glacial deposits, which may contain sand and gravel resources, have been extensively eroded and the sediment redistributed making identification and evaluation more difficult. The present research program seeks to advance the understanding of the relationships between aggregate deposits and seafloor physiographic features in complex shelf environments. The work is focused on the WGOM which provides a variety of physiographic features or geoforms common to paraglacial environments around the world.

Previously, the Center developed high-resolution surficial geology maps depicting the bathymetry, major geoforms (physiographic features), and sediment distribution for the continental shelf off northern

Massachusetts and New Hampshire extending seaward to Jeffreys Ledge, covering an area of ~3,250 km^2 (see 2016 JHC Performance and Progress Report, Task 21). More recently, changes in sea level and resultant transgressions (landward movement) and regressions (seaward movement) of the ocean that impacted the study area over the last 13,000 years were mapped (Figure 28-1). The sea-level maps were developed by taking advantage of high-resolution MBES bathymetry and lidar topography compilations for the region produced by the Center, coupled with well vetted sea-level curves from the literature (see 2021 JHC Performance and Progress Report, Task 28). The result of this analysis shows that many of the glacial deposits that have been identified in areas of the shelf impacted by the transgressions and regression of the sea were extensively eroded and altered by the marine environment. Although a good understanding of the surficial geology has been developed from this work, very little is known about the subsurface sediment composition and three-dimensional geometry of the deposits. Addressing these gaps are goals of Task 28 that will be initiated in the next reporting period.

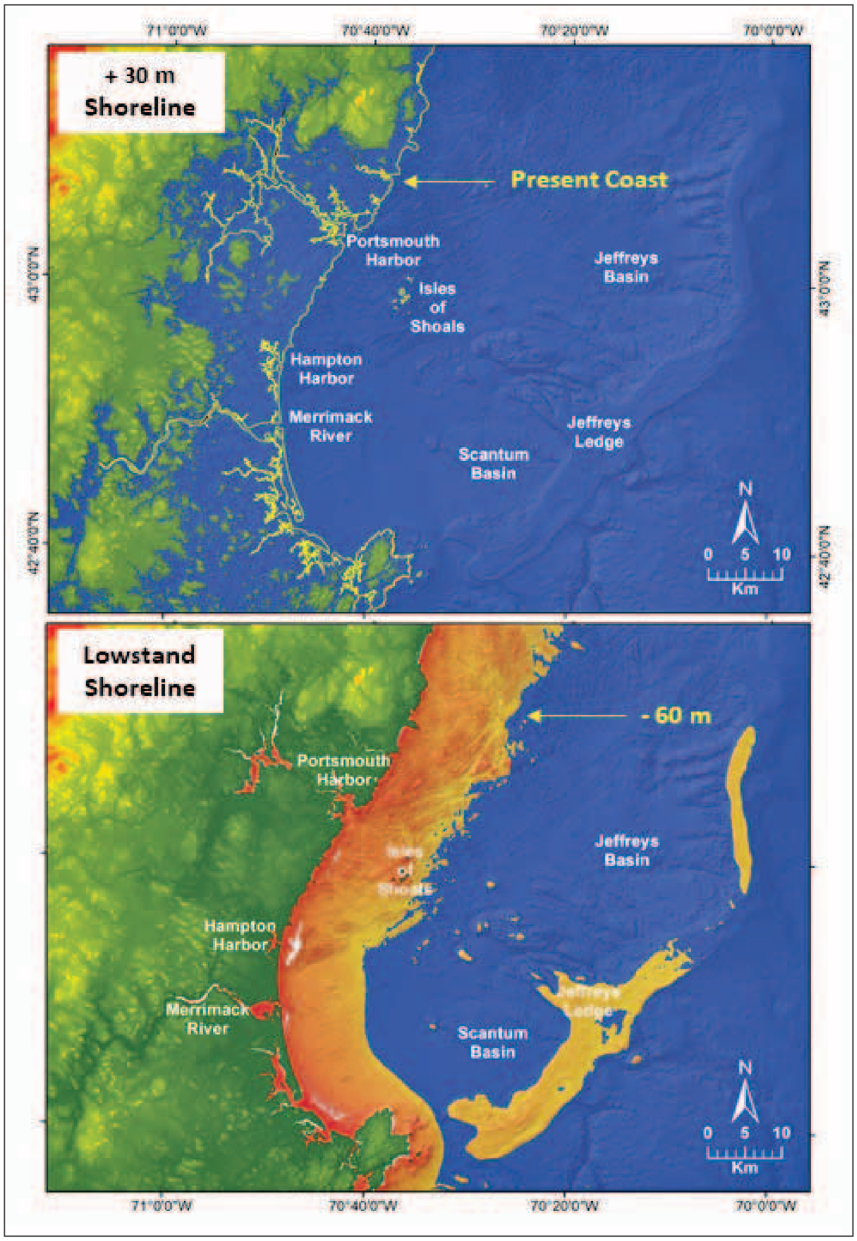


Figure 28-1. Changes in the location of the shoreline showing inundation of the upland ~13,000 years before present (ybp) (top figure) and exposure of the inner continental shelf ~12,500 ybp (lower figure) in the western Gulf of Maine (WGOM). Dark blue shows the ocean and shoreline. Positions of the shoreline determined from the compilation of high-resolution lidar for the upland topography and multibeam echosounder surveys for the bathymetry, coupled with a well vetted sea level curve for the WGOM from the literature. Note the extent of inundation of the ocean resulting in the deposition of marine deposits. Also note the exposure of the inner shelf resulting in significant erosion and redistribution of the sediment deposits.

During the present reporting period, a major field campaign was conducted directed at providing ground truth to support two priorities to further the understanding of the relationships between marine modified glacial deposits and marine mineral deposits including: 1) the establishment of Reference Sites for testing subbottom seismic systems to be used for studying the three-dimensional structure of aggregate deposits, and (2) the enhancement and expansion of the WGOM high-resolution surficial geology maps developed by the Center. The 2022 field campaign was conducted using the Center's RV *Gulf Surveyor*. In total, 135 stations were occupied, 129 sediment samples were collected, and seafloor video was taken at 70 of the stations (Figure 28-2). This large database will be processed and analyzed during the next reporting period.

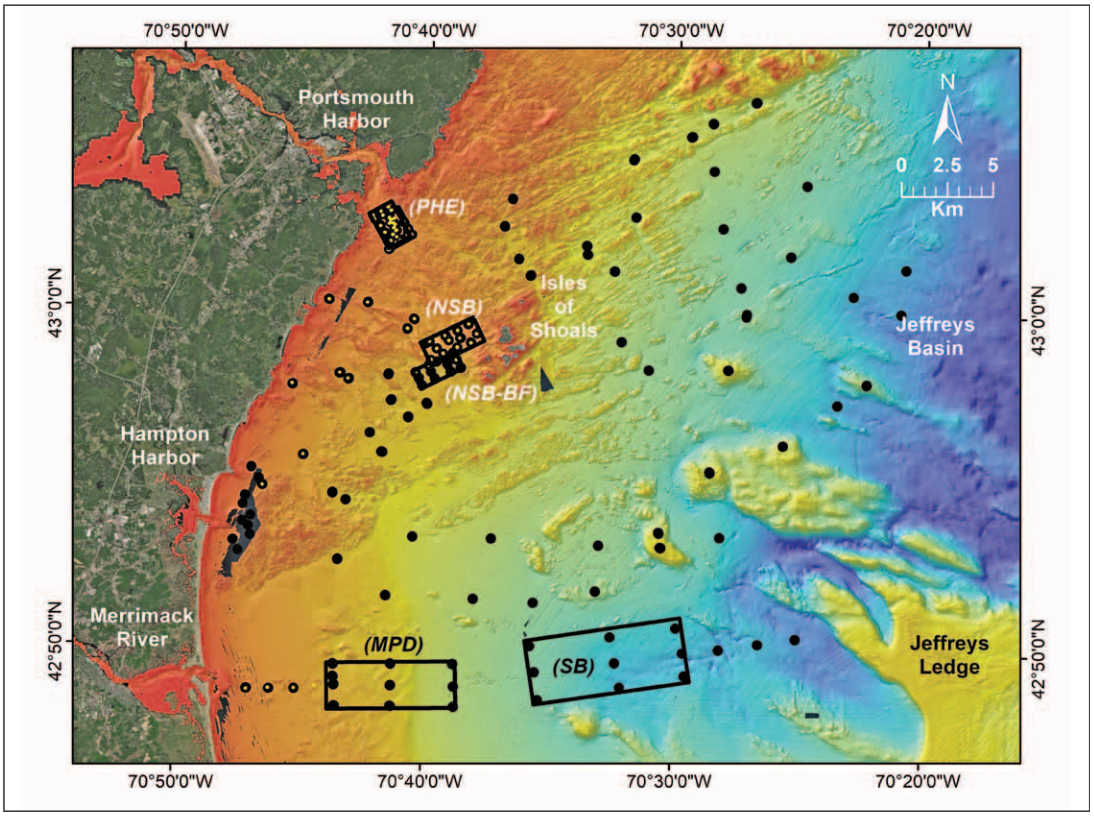


Figure 28-2. Location map for the sampling stations occupied during the 2022 field campaign. Black dots show the locations where bottom sediment samples were collected. Yellow dots represent locations where seafloor video was taken. The black rectangles show the locations of Reference Sites established for testing subbottom seismic and other acoustic systems.

The Reference Sites are located off New Hampshire and northern Massachusetts and will be used to assess the performance and compare several different types and brands of subbottom seismic systems (Task 8). The goal is to assess preferable SBP systems and configurations for mapping marine mineral resources and the shallow seismic stratigraphy of paraglacial environments. In addition to the sediment sampling and seafloor videography obtained during the 2022 field campaign, archived analog subbottom seismic records located within each Reference Site were analyzed in SonarWiz 7 V 7.06.04 and reviewed to assess the presence and strength of subsurface reflectors. Exceptionally strong reflectors important to this study were identified in all the Reference Sites including layered shoal deposits, subsurface bedrock, glaciomarine sediment, deltaic deposits, erosional unconformities (ravinement surfaces), gas, and pockmarks. This is discussed in more detail in Task 8.

Enhancement and expansion of the high-resolution surficial geology maps of the WGOM was initiated during the present reporting period. The maps have gaps in coverage where field verification is needed.

The database obtained by the 2022 field campaign will be used to verify seafloor classifications in previously mapped areas but are lacking sufficient ground truth. The database will also allow the maps to expand into adjacent unmapped areas that are relevant to the study of marine mineral resources (e.g., Merrimack Embayment) or are important to the region (e.g., Jeffreys Basin and Scantum Basin).

The surficial geology maps have proven to be very valuable for identifying potential marine mineral deposits associated with glacial features that warrant further study. In addition, the surficial geology maps, along with the high-resolution bathymetry compilations, have value outside of the Center. For example, expertise gained from the surficial geology maps provided valuable input by the Center to the development of the Gulf of Maine Seascape maps funded and coordinated by NOAA Office of Coastal Management. It should be noted that the development of the Seascape maps heavily utilized BRESS which was developed by the Center and is now operational (see 2017 JHC Performance and Progress Report, Task 22).

Task 29: Management of Living Marine Resources from ECS Including Use of ICESat-2

JHC Participants: Jenn Dijkstra, Kristen Mello-Rafter, Glenna Dyson, Anne Hartwell, Kim Lowell

NOAA Collaborators: Matthew Sharr (NOAA OCS)

Other Collaborators: Chris Parrish (Oregon State University), Selina Lambert (OSU), Chase Simpson (OSU), Erich Bartels and Ian Combs (Mote Marine Laboratory), and Matthew Tyler (UNH)

Coastal regions are the powerful engines to our economy, providing billions of dollars in goods and services to the U.S economy. Hydrographic survey data and other marine mapping and charting data have tremendous potential to benefit NOAA marine resource management initiatives, in keeping with Integrated Ocean and Coastal Mapping (IOCM) best practices. Accurate seafloor characterization and multi-temporal data of marine living resources observed on the continental shelf are particularly valuable for assessing the efficacy of various restoration practices, and monitoring change at spatial extents and timescales that are relevant to management.

Project: Multi-Modal Mapping for Change Detection on Coral Reefs

Obtaining accurate bathymetric data on the repeat cycles necessary for coral reef restoration site monitoring is nearly impossible using only single-source data. Hence, methods of combining data from a wide range of platforms and sensors, ranging from satellites to uncrewed aircraft systems (UAS), autonomous surface vehicles (ASVs), and diver collected underwater imagery are of interest. Specifically, the project team, led by Jenn Dijkstra and Chris Parrish and in collaboration with Mote Marine Laboratory are working to advance the use of these various platforms for seafloor mapping, supporting NOAA's Office of Coast Survey (OCS) Strategic Plan FY2020-2024, Goals 2.1.1, 3.5.1 and 3.5.2 and NOAA's Blue Economic Strategic Plan FY 2021-2024 to "Assess, Restore and Protect America's Coral Reef Systems."

A particular area of focus for this task is optimization of system subcomponents and acquisition settings for simultaneous mapping of bathymetry and ben-

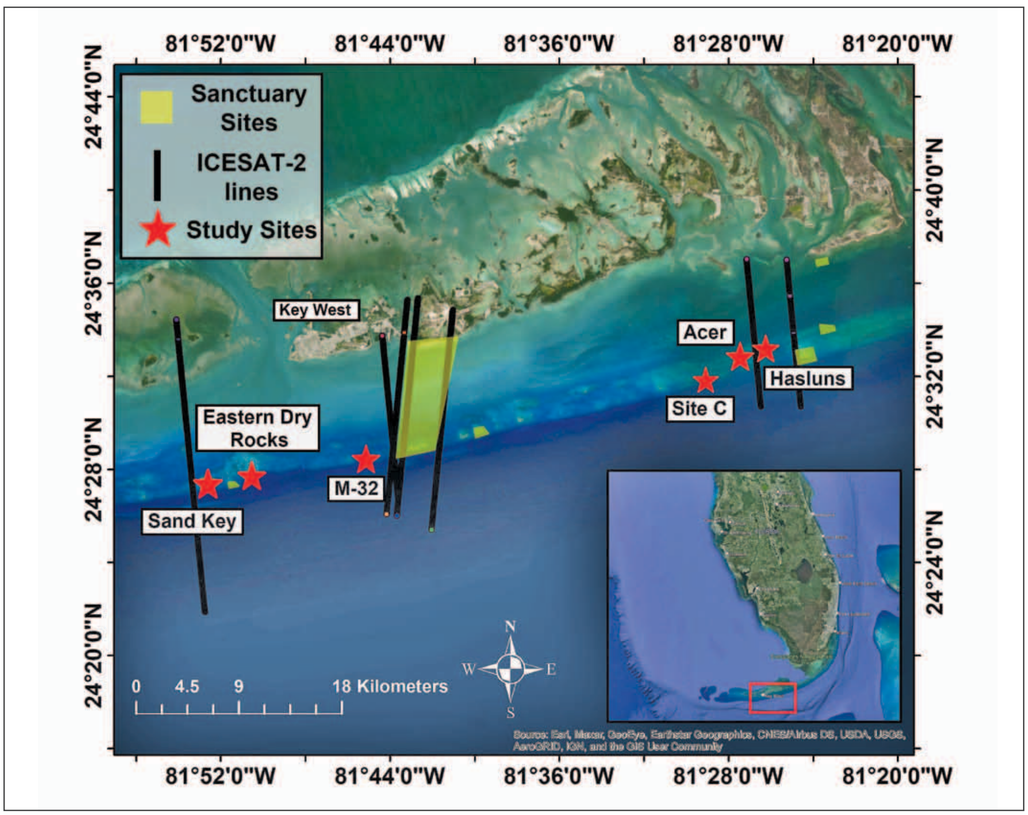


Figure 29-1. Coral reef study sites in the lower Florida Keys.

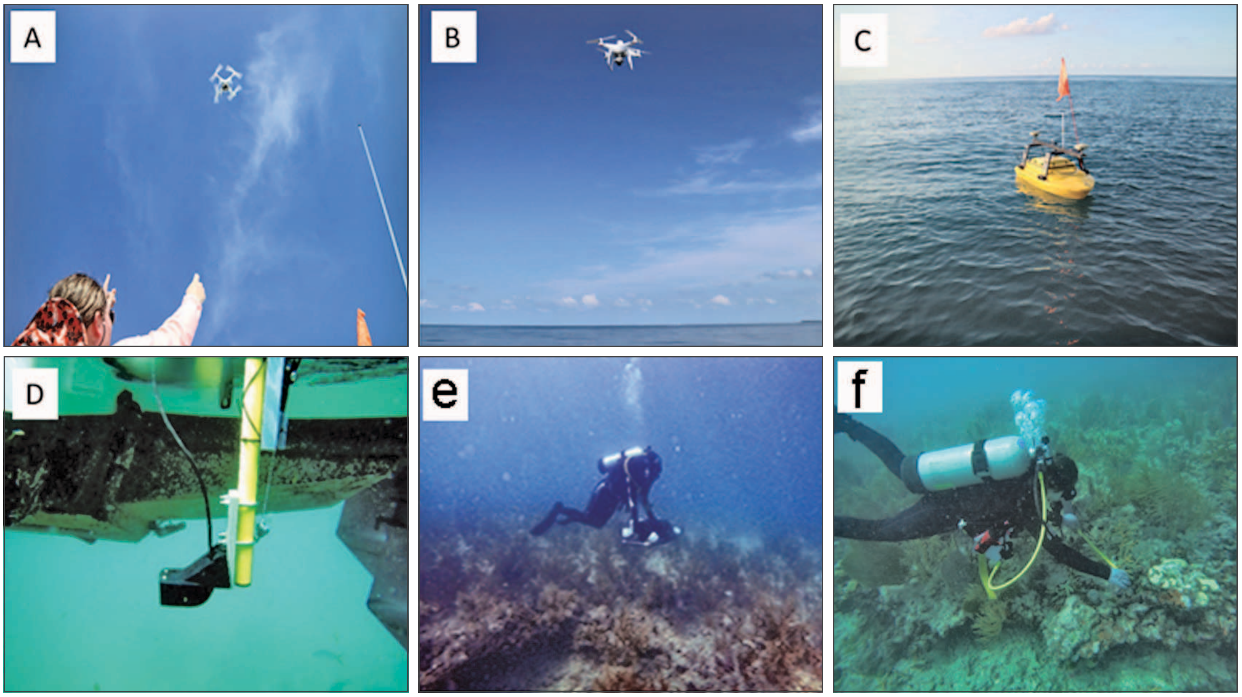


Figure 29-2. A) and B) UAS imagery collection (Ph.D. student Selina Lambert is shown hand launching the UAS); C) Seafloor Systems EchoBoat MBES data collection; D) SBES data collection from the dive boat; E) In situ stereo-imagery collection (Jenn Dijkstra); and F) Coral measurements (M.S. student Glenna Dyson is shown measuring a restored staghorn coral).

thic habitat. The project team is investigating camera polarization filters, GNSS and image processing techniques, and imagery acquisition optimized for shallow (< 10 m) reef mapping. Additionally, operational procedures have been designed to enable an ASV and UAS to be easily deployed from a small boat, enabling efficient, flexible operations.

In June 2022, the team collected MBES data from a Seafloor Systems EchoBoat (Figure 29-2C) with a PicoMB-120 and integrated Applanix POS system for the three eastern Florida Keys sites: Hasluns, Acer 17-18, and Site C (Figure 29-1). Additional single beam echosounder data were collected with a SonarMite MilSpec (Figure 29-2) for all six project sites. A UAS (Figure 29-2) equipped with a 20-MP camera and carrier-phase recording, multi-frequency GNSS was used to acquire imagery for all six sites, including some which were collected multiple times, under varying water clarity conditions. Finally underwater imagery and coral measurements were collected at all six coral reef study sites (Figure 29-2).

The MBES trajectories were processed in POSPac by OSU graduate student, LT Matt Sharr (NOAA), and the MBES and sound velocity casts were processed in QPS Qimera to generate reduced soundings and bathymetric surfaces (Figure 29-3).

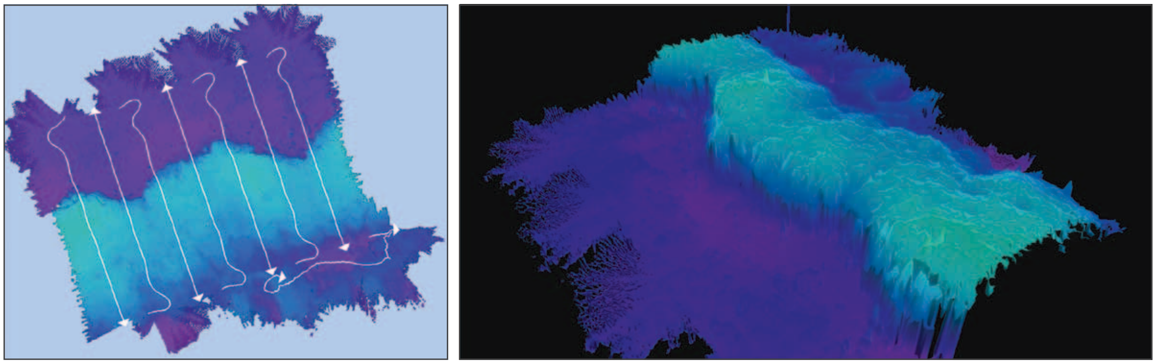


Figure 29-3. Processed ASV MBES data for Florida Keys Site C.

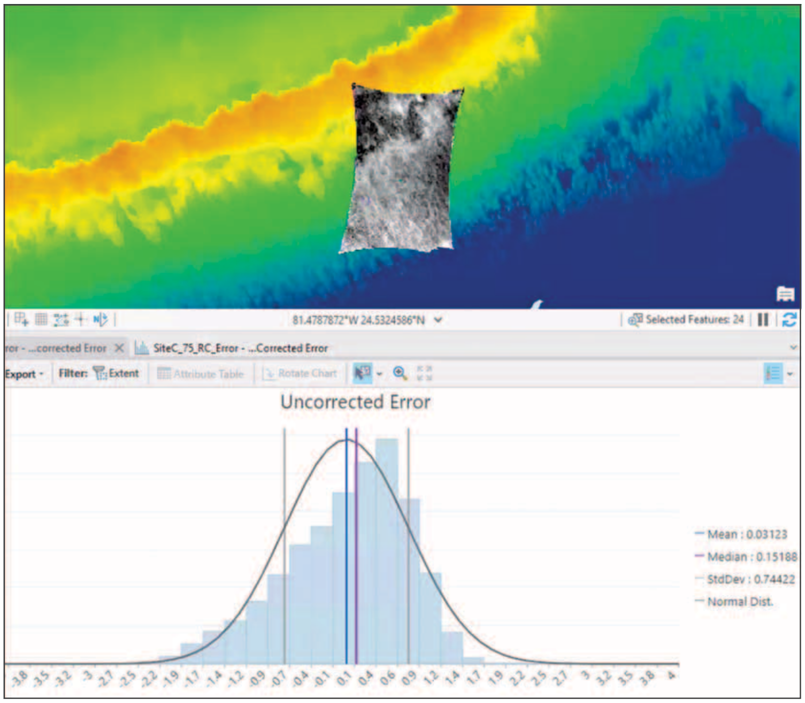


Figure 29-4. Geometric correction strategy for SDB. Top: geometrically-corrected bathymetric grid from UAS imagery overlaid on coarser-resolution bathymetric lidar data. Bottom: error analysis before and after geometric correction.

These will be integrated with point clouds from the underwater diver imagery processed using structure from motion (SfM) photogrammetry software to assist in georeferencing the underwater imagery through a cloud-to-cloud co-registration process. The SBES data are also anticipated to assist with georeferencing of the SfM point clouds generated from the underwater imagery, and to enable investigation of the ability to assess coral reef change over time at multiple spatial resolutions.

The UAS imagery from the Florida Keys are simultaneously being used to compare with the underwater SfM and in the research of PhDPh.D. student, Selina Lambert to generate and test a geometric correction for satellite derived bathymetry (SDB). Preliminary results of this work have shown statistically significant accuracy improvements in SDB generated from low-altitude, wide field-of-view (FOV) sensors, such as airplanes and UAS by applying the geometric correction (Figure 29-4). A journal publication on this work is in preparation, and the results will simultaneously be submitted to the IHO Hydrographic Surveys Working Group (HSWG) SBD Project Team.

Additionally, these results and the source code will be delivered to NOAA NGS's Remote Sensing Division (RSD) for evaluation for use in NOAA's Sat-Bathy tool (Parrish and Imahori, 2022).

In related work, OSU graduate student, LT Matt Sharr (NOAA), is investigating automatic segmentation of true and false bathymetry in SDB. The motivation for this research is that SDB algorithms output a value for every pixel in the scene, but these values do not necessarily represent bathymetry: a given pixel could be land, a cloud, a boat, or an optically-deep area. Machine learning models using a range of spectral and surface features (e.g., rugosity, slope, aspect, etc.) have been trained on multiple sites and are showing promise for prediction of true vs. false bathymetry in SDB grids (Figure 29-5). The resulting algorithms and source code are anticipated to be used in NOAA's SatBathy tool (Figure 29-6).

The team is also using SfM photogrammetry software to generate bathymetry from the stereo imagery collected with the UAS and *in situ* imagery. This process complements the SDB procedures, as bathymetry from stereophotogrammetry generally works well in areas of high-texture seafloor, such as reefs (Figure 29-7), while SDB algorithms often perform better over areas of homogeneous seafloor (Slocum et al., 2020).

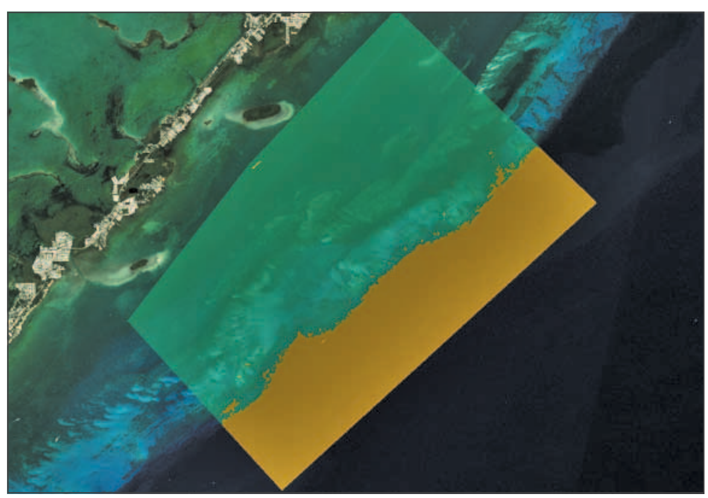


Figure 29-5. SDB bathymetric grid used for auto-segmentation of true vs. false bathymetry.

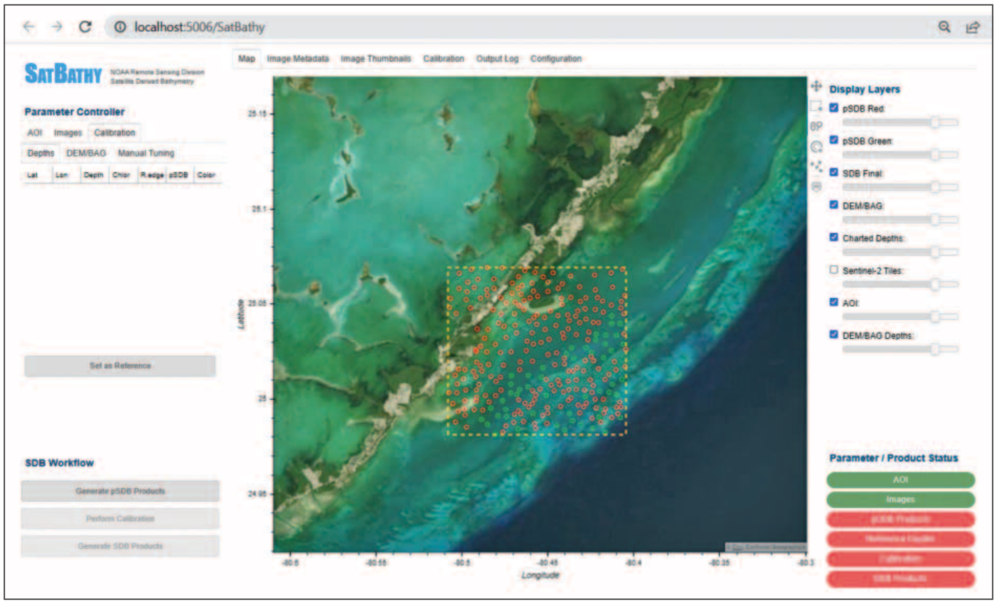


Figure 29-6. The true-false bathymetry segmentation algorithm and SDB geometric correction algorithm will be submitted to NOAA NGS for evaluation for possible inclusion in the NOAA SatBathy tool.

Use of the imagery-based bathymetric mapping techniques together can improve both accuracy and coverage. However, because most commercial SfM software does not account for the refraction of light at the air-water interface, an additional refraction correction step is needed for the UAS imagery, after generating the SfM point clouds.

Image mapping efforts were also leveraged by Jenn Dijkstra and master's student Glenna Dyson to improve stereo-image acquisition, compare post-processed images collected from two different stereo-camera rigs and validate coral measurements within 3D models against in situ measurements. While collecting data, one of the JHC cameras malfunctioned. This was fortuitous as Mote Marine Lab has a stereo-camera rig that uses different cameras, camera settings and data collection is also slightly different. Mote's cameras are Nikon D750 DSLRs with a wide-angle fixed 20 mm lens and dome port and the JHC stereo-camera rig has Canon 70Ds with a wide-angle fixed 20 mm lens and dome port. Images collected using the Canon 70Ds were manually taken by the user while images collected using the Nikon D750s were automatically taken every second.

Identical image processing methods were used to create 3D models of each of the six sites. Models constructed using images collected by the NIKON D750s had a greater number of points above the model than models constructed using images collected by the

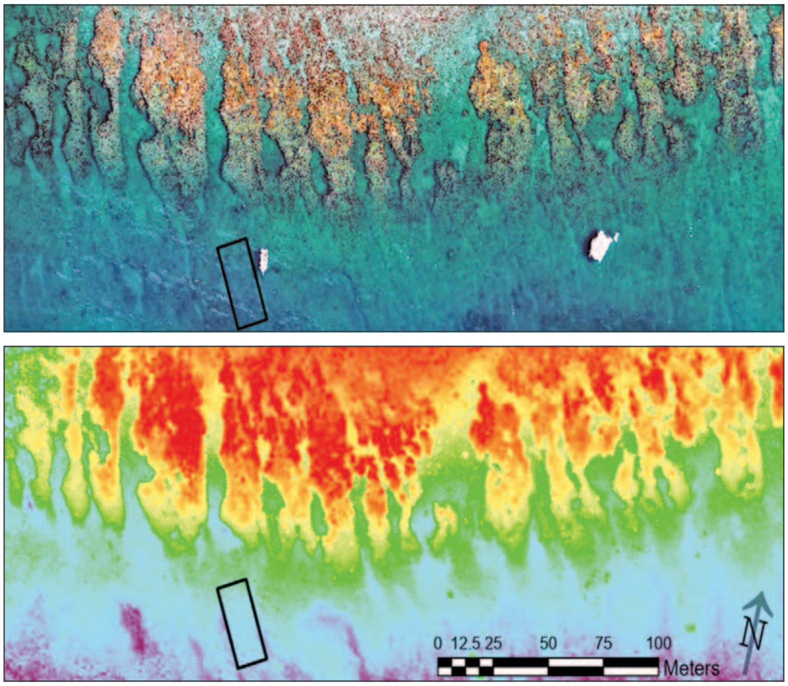


Figure 29-7. Outputs of structure from motion (SfM) photogrammetry software applied to the UAS imagery for the Sand Key site: top: orthomosaic; bottom: bathymetric DEM.

Cannon D70s. By automatically taking photos every second, the user does not have the ability to check if the images are in focus. Multiple blurry images can result in poorly rectified points in the final model causing the entire model to appear "blurry" and/or cause the program to "eliminate" areas from the final model or orthomosaic.

To measure change in seafloor properties using orthomosaics or models created by Jenn Dijkstra, it will be important to establish accuracies of constructed imagery and terrain models. Widths of three to six corals from each site were measured and compared to the width of corals in quality controlled orthomosaics by master student Dyson (Figure 29-8). An attempt was made to measure coral heights in each model. However, this proved to be difficult as the measured height from the model depended on the user's ability to see the point of attachment of the coral to the seafloor.

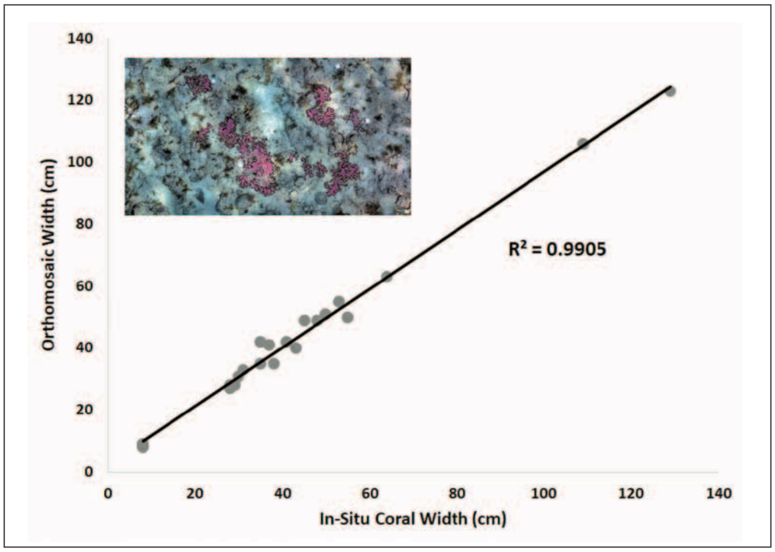


Figure 29-8. Relationship between in-situ coral width and coral width measured in the quality controlled orthomosaics.

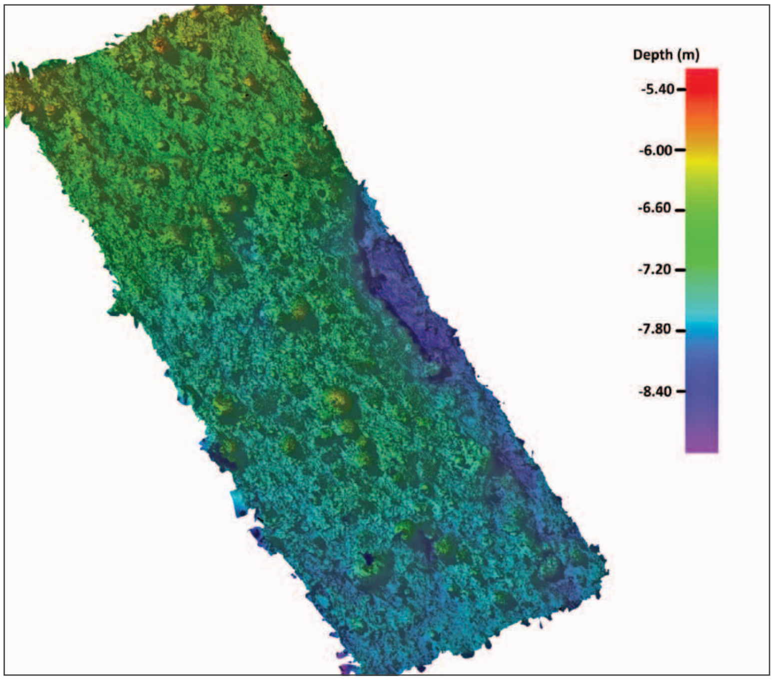


Figure 29-9. Digital Elevation Model of a coral reef created from SfM.

Digital Elevation Models (DEMs) created from the SfM models were used to extract bathymetry surrounding identified corals (Figure 29-9). Depth, slope, curvature and roughness were then determined from the extracted bathymetry surrounding corals. Spatially distinct sites and within site characteristics will be used as input to a mixed model examining the influence of bathymetric characteristics on coral growth and disease.

Project: **Predicting Seaweed Habitat Types Around the Isles of Shoals Using Supervised Machine Learning Classification**

Identifying seafloor characteristics that can used to detect areas of declining marine living resources is critical for their management. In temperate zones, kelp forests are ecologically significant and support a wide variety of species of commercial importance. Due to anthropogenic activities, kelp forests are declining, yet there is evidence that pockets of healthy kelp forests exist. This project leverages ground-truth data and high-resolution bathymetric data sets collected over a decade by previous JHC-sponsored projects in combination with satellite imagery to identify areas of kelp forests.

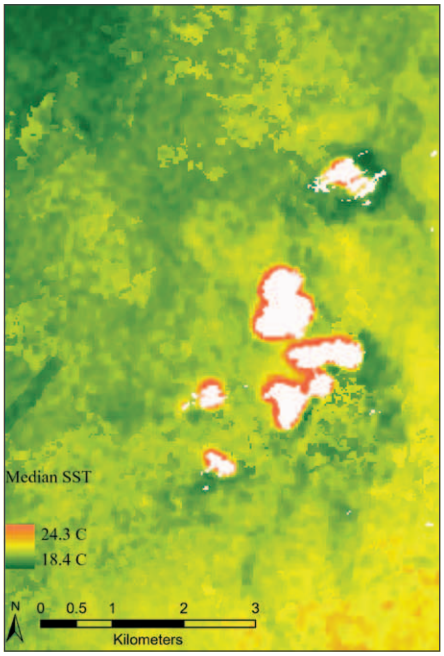


Figure 29-10. Map of median summer temperatures around the Isles of Shoals extracted from Landsat 8/9 thermal sensors using Google Earth Engine.

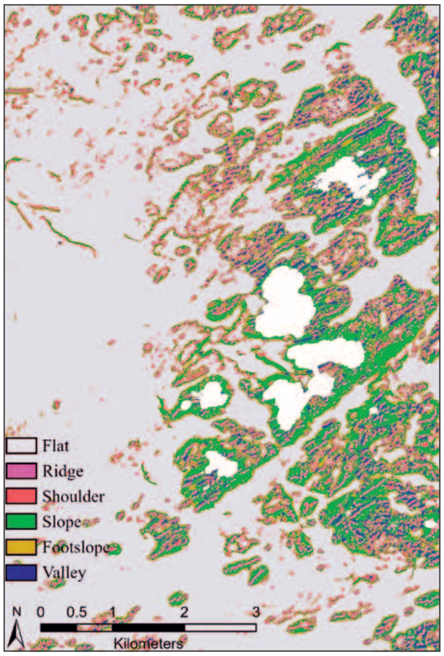


Figure 29-11. Flat (grey), ridges (pink), valleys (blue) and green (slope), footslope (tan).

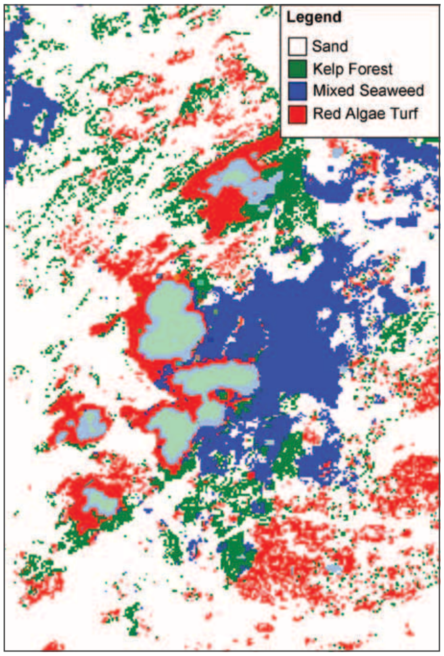


Figure 29-12. Random forest supervised classification of macroalgae habitat types surrounding the Isles of Shoals. Light blue indicates areas of insufficient data.

In previous reports, Dijkstra's graduate student Tyler explored the use of the Seaweed Enhancing Index (SEI) produced from the Landsat 8 and 9 imagery to identify and locate submerged kelp beds with mixed results. In this progress report period, Jenn Dijkstra and Tyler worked on study design and practices for macroalge habitat classification. Landsat imagery was classified into four categories, bare substrate, kelp, mixed and red filamentous macroalgae, and then divided into training and validation data. Ground-truthed imagery was also classified into the same four categories. Rasters of the mean, median, standard deviation and range of sea surface temperatures for the period of 2014-2022 were produced in Google Earth Engine (Figure 29-10). Geomorphic landform classification rasters of the area surrounding the Isles of Shoals were created from existing 4 m resolution bathymetry using the Bathymetry- and Reflectivity-based Estimator for Seafloor Segmentation (Figure 29-11; BRESS; Masetti et al., 2018). These rasters were then down sampled to match the 30 meter resolution of the Landsat imagery. Geomorphic and temperature rasters were uploaded into Google Earth Engine, where Random Forest supervised classification was used to generate a raster predicting macroalgae habitat types across the extent of the imagery (Figure 29-12). To determine the accuracy of the model, a confusion matrix was then generated for both training and validation datasets.

Project: Mapping of Physical and Biological Features on Discharge Outcrops in Ridge Flank Hydrothermal Systems

The goal of this study is to build on previous methods for fine-scale habitat mapping developed at the Center and to explore species composition and distribution in conditions that reflect predictions of climate change driven deep-sea warming in the coming decades. This study integrates high quality multibeam sonar bathymetry, ROV observations, and environmental data from Ridge Flank Hydrothermal Systems (RFHS) to characterize geomorphology and marine habitats. Study locations are in the eastern Pacific and include two outcrops in the NOAA sanctuary Davidson Seamount Management Zone (DSMZ) and a third outcrop in the equatorial Pacific, Dorado Outcrop. These three outcrops were selected for their similar environmental conditions and periodic venting of low temperature fluid absent of significant chemical alteration relative to ambient seawater.

In this progress report period, Ph.D. student Anne Hartwell characterized the biology and substrate of vent and non-vent zones in the DSMZ (Figures 29-13). Jenn Dijkstra and Hartwell worked together to statistically compare biological communities across vent and non-vent zones, and indicator species of the two zone types were identified. Though communities were found to be similar between vent and no-vent zone areas, species richness was significantly different. These results are in the process of being prepared for submission for peer-reviewed publication.

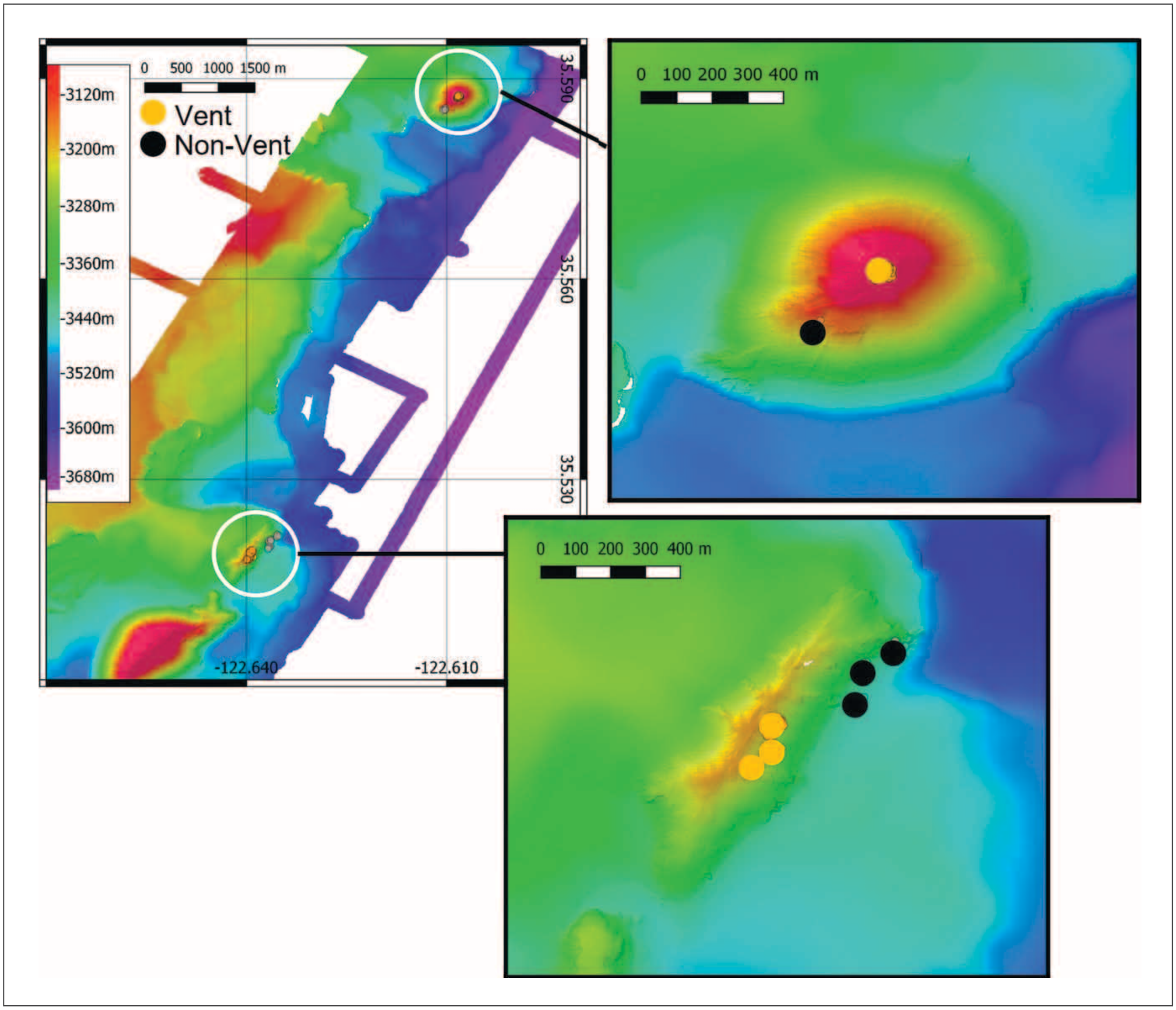


Figure 29-13. Distribution of Vent and Non-Vent zones at DSMZ. Orange circles represent vent zones. Temperature anomolies measured by the ROV were greater than or equal to 0.01°C above background. Black circles represent the locations of non-vent zones.

Task 30: Improvements in Change Detection

JHC Participants: John Hughes Clarke, Jenn Dijkstra, Anthony Lyons, Daniel Leite, and Kaan Cav

Other Collaborators: Ian Church (Ocean Mapping Group, UNB), Lars Anderson and Kjell Nielson (Kongsberg Maritime), and Gwynn Lintern and Cooper Stacey (Geological Survey of Canada)

Additonal Funding Sources: Kongsberg, ONR

As every mariner knows, seabed morphology can change, especially in areas of strong currents and unconsolidated sediment such as river mouths and shallow tidal and/or storm driven seas. As part of NOAA's mandate to both maintain chart veracity and to monitor dynamic seabed environments, change monitoring is therefore a fundamental requirement. Separating real change from residual biases or intermittent bottom tracking errors in the survey data, however, is a major limiting factor in confidently identifying such change. This is the survey challenge that this task addresses.

As an additional component beyond the bathymetric changes, we are now also examining the potential variability of seabed backscatter strength. This complements Task 3 which is specifically aimed at providing an absolute calibration of backscatter strength measurement made by multibeam sonars. In the long term, the hope is that the US continental shelf can be adequately characterized, and multibeam-derived backscatter strength measurements are expected to be a major tool to achieve that. The missing aspect, however, is how stable the seabed composition is. Those same natural and anthropogenic processes that impact bathymetry have the potential to also alter the substrate. In this reporting period progress has been made in methods for detecting substrate and morphological seabed change.

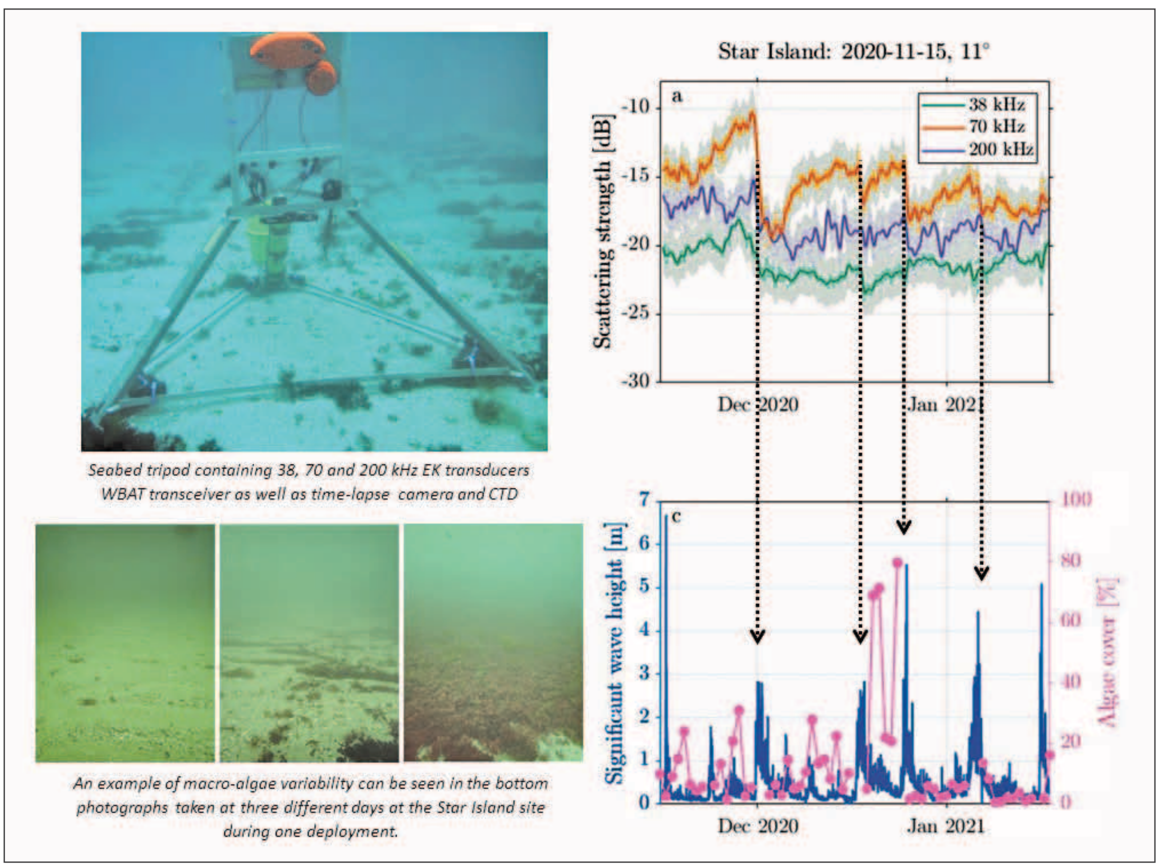


Figure 30-1. A two month time series of bottom backscatter strength observations at three frequencies (38, 70 and 200 kHz) during the winter storm period. The abrupt changes (up to 10 dB) are clearly associated with storm wave events. That change, however, is strongly frequency dependent with the largest changes seen at 70 kHz and much more subdued change at 200 kHz.

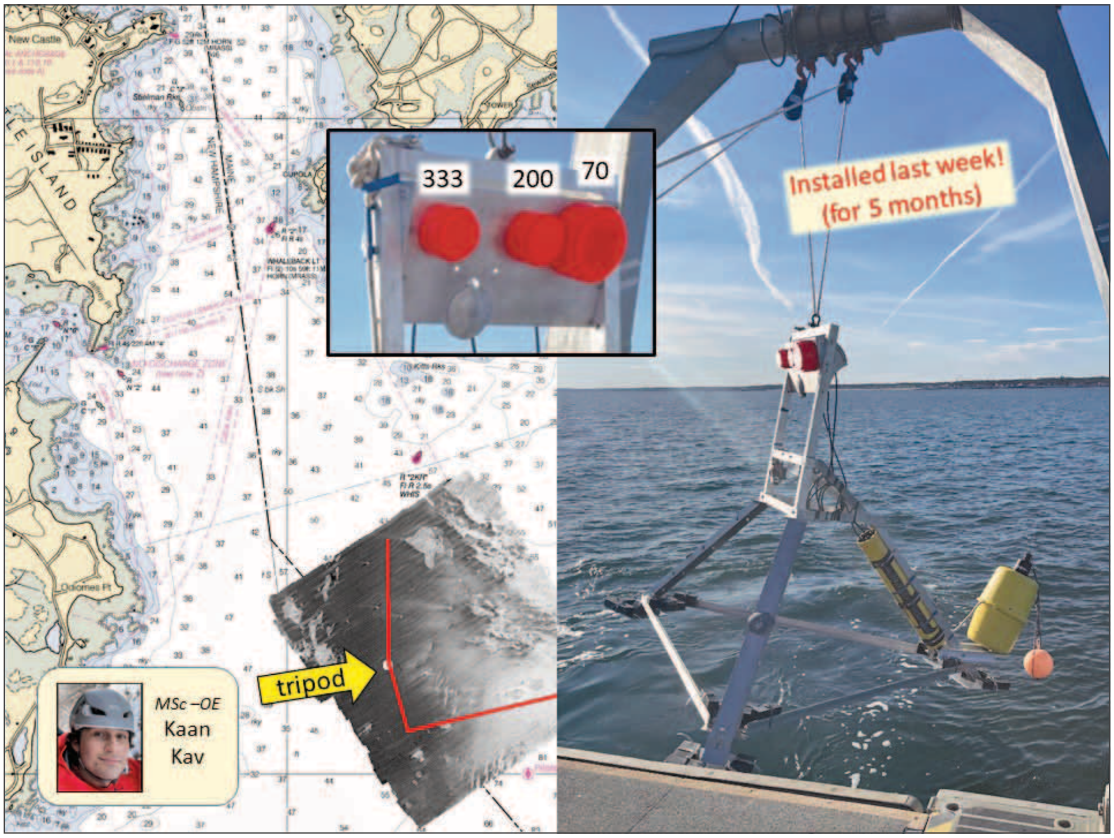


Figure 30-2. Backdrop shows the location of the "sedimented area," a mobile inner shelf sand sheet with gradational sediment coverage. Foreground shows the new tripod with 3x ES transducers, WBAT transceiver, camera, CTD and acoustic release. This was installed in late November 2022.

Substrate Change

In this reporting period an experiment design was implemented to address backscatter variability. It builds strongly on experience derived through parallel work funded through an ONR Task Force Ocean project (PI Lyons). To better assess the backscatter strength variability on the New Hampshire inner continental shelf, Lyons's 2020-2021 deployment was further analyzed to better understand the factors driving the changes (Figure 30-1).

These data reveal that the major shifts in the backscatter strength occur in the wake of major storm events. Based on these results a more convenient location was chosen that could serve simultaneously to address research under this Task (30) as well as Tasks 2 (integration), 3 (backscatter calibration), 4 (environmental monitoring), and 8 (subbottom profiling). A broad sand sheet in the Piscataqua estuary approaches was selected. A second tripod (Figure 30-2) was fabricated and has just (in November) been installed to cover the 2022-2023 winter period.

The tripod allows high temporal resolution in monitoring seabed change, but cannot address the issue of spatial variability. For example, it only examines a single corridor about 15 m long on a fixed azimuth. Are changes seen in that small footprint, however, representative of changes over a larger area? To address the spatial variability, the same test area (located in Figure 30-2) has now been regionally surveyed seven times at about two-month intervals from November 2021 until December 21, 2022. Those surveys have been conducted using the same EM2040P multibeam utilizing a single mode (300 kHz, Short CW) with a fixed angular sector (+/-70°). Survey line orientation is switched by 90 degrees every time so that any systematic biases in bathymetry or backscatter are immediately apparent in inter-survey difference calculations.

Inter-survey apparent changes in the bottom backscatter strength maps are presented in Figure 30-3. To minimize the spatial variation due to changing

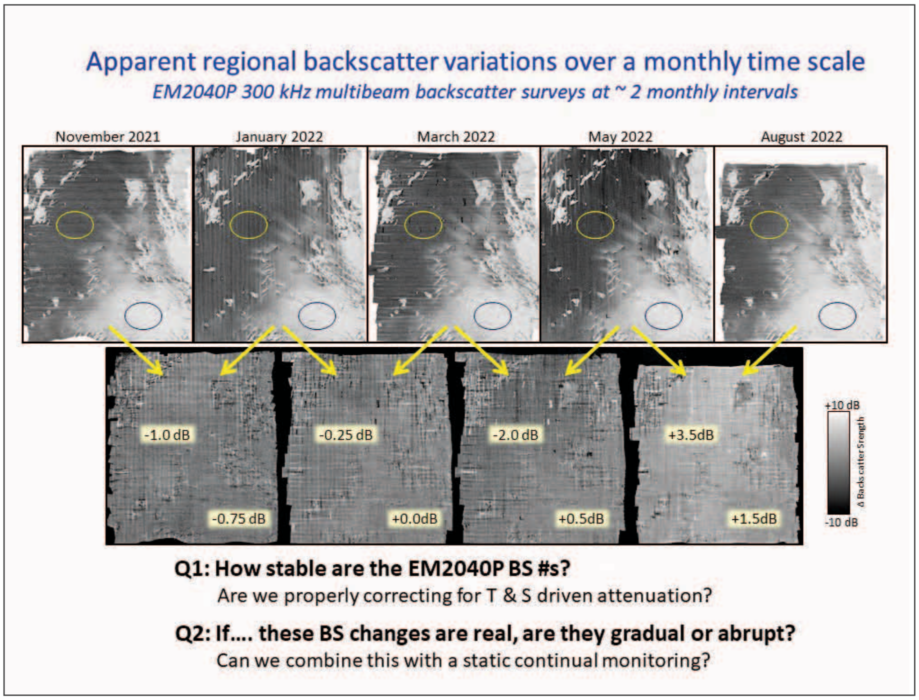


Figure 30-3. top: 300 kHz backscatter strength mosaics showing the first 5 of the bi-monthly surveys (local mean ARC has been removed from the data to attempt a grazing-angle free image). Bottom: inter-survey differences. The lassoed areas represent two homogenous regions (high and low backscatter) and the #s in the lower figure indicate the average change over two months in grazing-angle-normalized backscatter strength in these regions.

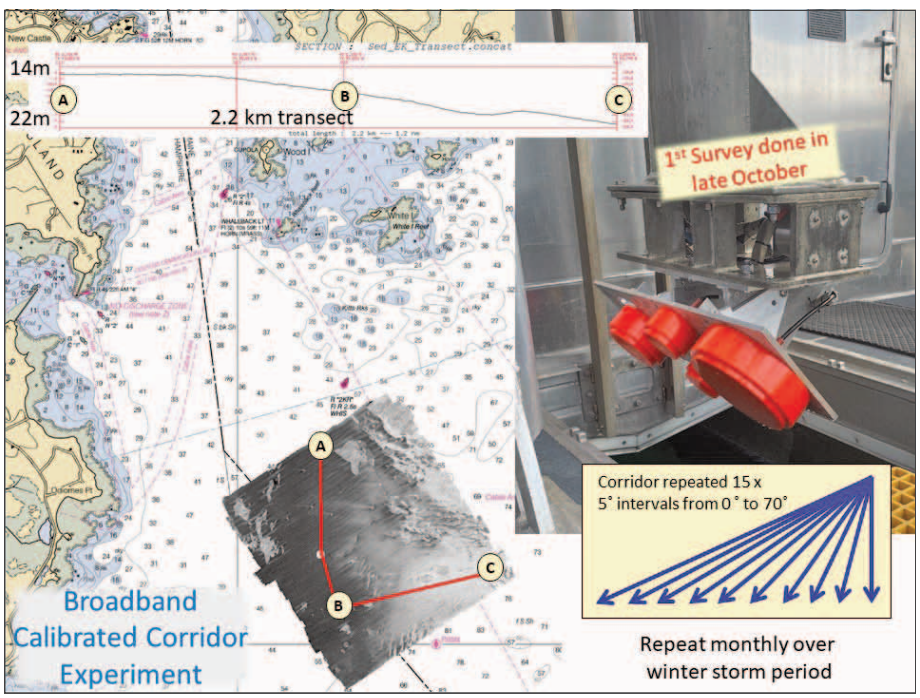


Figure 30-4. Transect that is run 15 times to derive broadband seabed backscatter strength measurements. Profile indicates the depths over the 2.2 km transect. Photo shows the 4 EK transducers (70-120-200-333 kHz) mounted on a tiltable plate on the RVGS strut.

grazing angles, the local apparent angular response curve (ARC) has been derived and used to flatten it. This process requires spatial averaging and produces artifacts wherever the seabed type (specifically the shape of the ARC) is changing rapidly. Thus, a faint "tartan" pattern can be discerned, particularly in heterogeneous regions. Nevertheless, in the areas which are regionally homogenous, one can extract average back-scatter strength estimates and look at the mean change over the two-month intervals.

The results in Figure 30-3 suggest a drop of about 2 dB toward the end of the winter wave period, followed by a ~3.5 dB rise through the storm-free summer period. Note that we do not have the temporal resolution to know when exactly in the two-month window these changes (if real) occurred. However, going forward into the 2022-2023 winter, we will now have the static tripod sitting in the middle of the homogenous area to give us higher local temporal discrimination. These bi-monthly surveys are scheduled to be continued until the summer of 2023.

There is still a significant resolution step between high temporal measurements in just a local area and the regional but low temporal results. To fill that gap, an additional experiment has been designed and just been implemented. It involved utilizing the 4 EK transducer configuration previously used for Task 3, mounted on the strut of the R/V *Gulf Surveyor* (Figure 30-4).

The mounting frame, designed by Michael Smith and fabricated by Paul Lavoie can be shifted in 5 degree increments. It can be installed on the end of the R/V *Gulf Surveyor* retractable RAM (Figure 30-4). A representative transect has been selected crossing the sediment area (A-B-C, Figure 30-4). That transect will be run periodically (planned for about monthly) 15 times so that calibrated backscatter strength value over the full ARC can be derived.

The first survey was done in late October prior to the tripod deployment. Combined with the regional EM2040P MBES backscatter surveys and the point source tripod measurements, the hope is to investigate both the temporal and spatial variability of seabed backscatter strength measurement over a typical wave-dominated mobile inner shelf sand sheet. The EK aspect of this is part of the M.S. thesis of Kaan Cav, and the EM2040P backscatter part of this forms a subset of the M.S. thesis of Daniel Leite.

Morphological Change

As well as seabed backscatter strength variations, the bathymetry of the region discussed above is known to change temporally as the sand sheet moves around. This is most apparent on the margins of the sheet, where the location and definition of the boundary of the sand against boulder and rocky terrain has previously been noted to change significantly. The same EM2040P experiment described above can be similarly used to assess that change. The bi-monthly EM2040P multibeam bathymetry surveyed may be differentiated in the same manner.

Preliminary bathymetric change results suggest that, even when seen through significant systematic biases, the inter-survey depth difference maps (Figure 30-5) suggest that the broad positive ridge in the sand sheet grew by about 10-15 cm from January to March, and then deflated about the same amount from March to May. Such results, however, are close to or below the typical total-propagated vertical uncertainty inherent in the data. A much more detailed analysis of these surveys (continuing until summer 2023) will form the main part of the ESCI M.S. thesis of Daniel Leite.

Other Seabed Change Experiments

While the focus of the Task 30 efforts this year have been primarily on the inner shelf "sedimented area" off the New Hampshire coast, through external funding, the center has also played a major role in

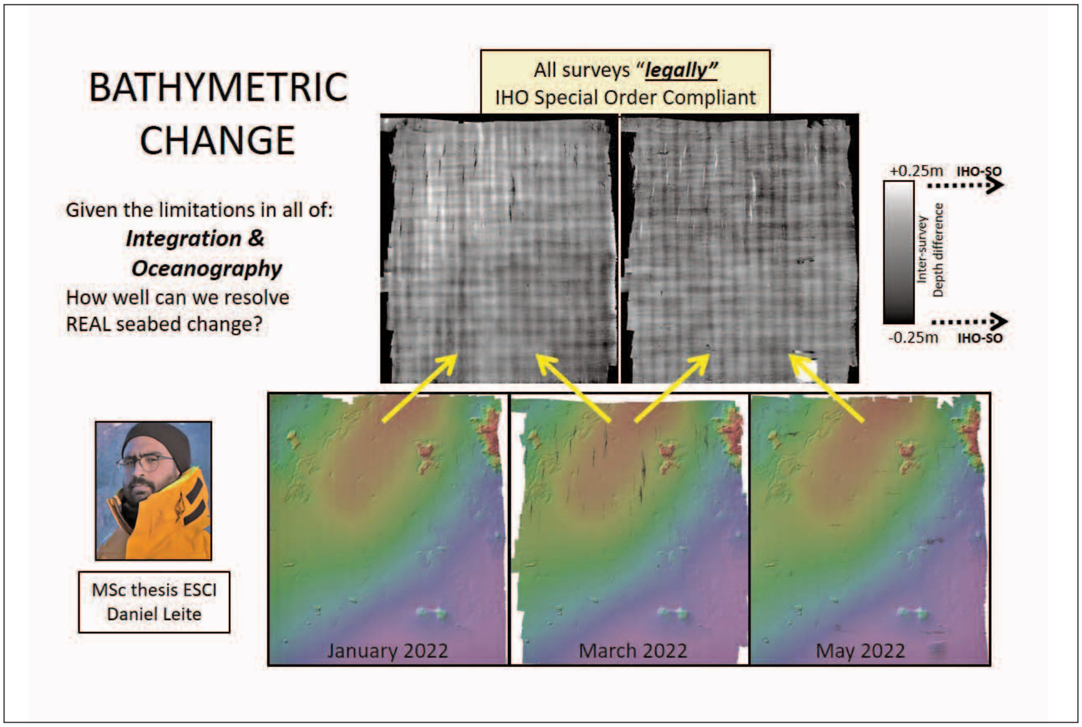


Figure 30-5. Bi-monthly bathymetric change. Lower: bathymetric surveys, upper: inter-survey difference map. The rectilinear grid represents the systematic biases due to changing sound speed in the area.

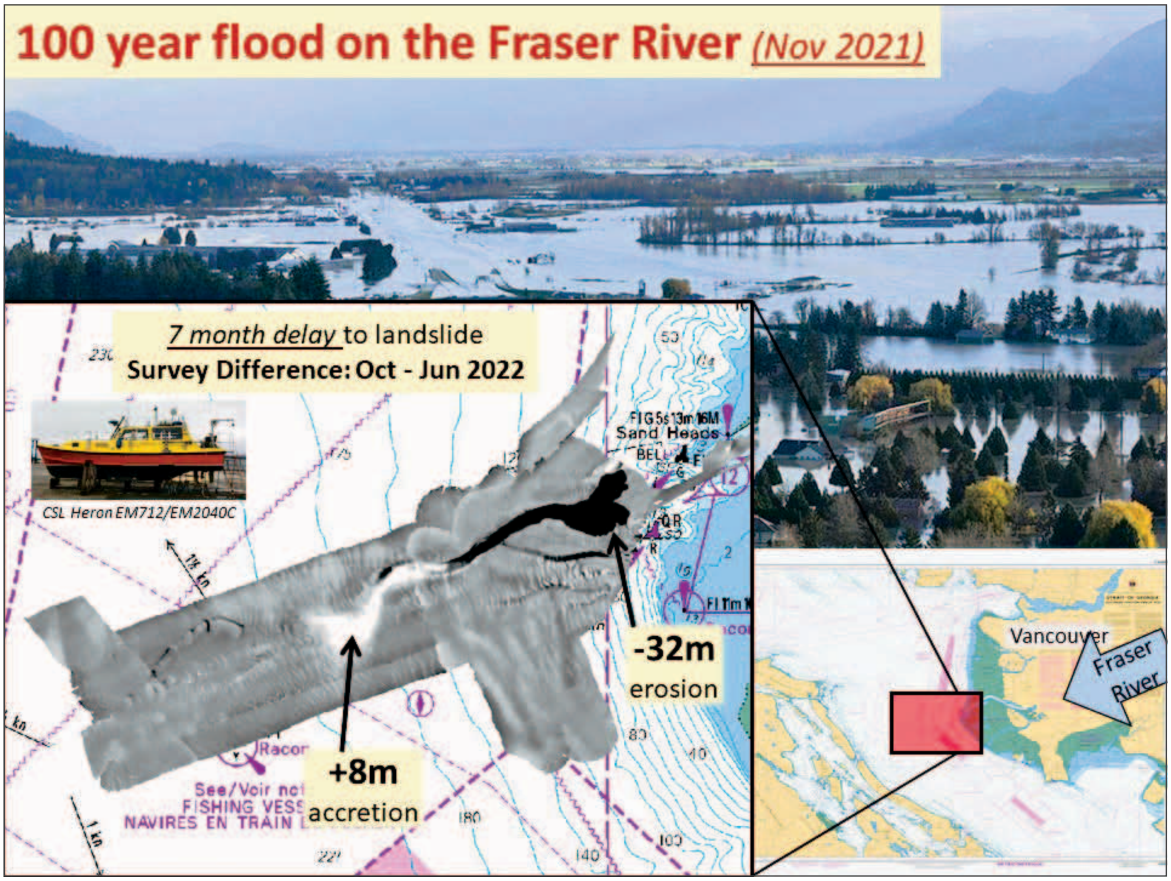


Figure 30-6. Backdrop shows the flooded lower Fraser River valley. Foreground shows a seabed change map from differencing multibeam surveys in June and October of 2022. A massive deepening of the Fraser canyon head occurred and a large deposit appeared on the lower slope as well as evidence of much more widespread reactivation of old scour features. These scour features had not previously been active in the last 20 years of annual monitoring.

a parallel, much longer duration, seabed change experiment being carried out in collaboration with the Geological Survey of Canada and the Canadian Hydrographic Service, in fjord deltas in British Columbia. These experiments, which have been ongoing for over two decades on the Squamish and Fraser deltas, are pertinent to both this task and Task 4 (environmental monitoring). While changes off New Hampshire are due to winter storm wave activity, changes off British Columbia are mainly associated with estuarine oceanography and river plume dynamics. The most notable result of the 2022 field season utilizing the CSL *Heron* was being able to monitor the response of the Fraser prodelta to the 100-year flood in the Fraser River watershed (that affected northern Washington State too) that took place in November 2021. Such cataclysmic floods are predicted to be more common with climate change.

The standing hypothesis was that massive delta front changes would be linked directly to major river discharge events and that associated mass wasting events could trigger local tsunamis. The *Heron*, however, surveyed immediately after the December 2021 event and demonstrated that, initially, only regional accretion had occurred. Subsequent surveys in May, June, July, September, and October (by both the *Heron* and CCGS *Vector*) illustrated that only after seven months did the prodelta finally collapse and, when it did, the change evolved subsequently. The bathymetric change (Figure 30-6) reveals the single largest change seen on the delta front in the entire 20 years of monitoring. Yet despite the impressive volume of sediment that has been remobilized, the adjacent tide gauges have not been observed to pick up any hazardous sea surface events.

Programmatic Priority 1

ADVANCE TECHNOLOGY TO MAP U.S. WATERS

Component: RESOURCES OF THE CONTINENTAL SHELF

NOFO Requirement 10

New approaches to the delivery of bathymetric services, including, among others, elevation models, depth comparisons and synoptic changes, model boundary conditions, and representative depths from enterprise database such as the National Bathymetric Source and national geophysical archives.

JHC/CCOM responded to NOFO requirement 10 with one task:

Task 31: Delivery of Bathymetric Services from Enterprise Databases

Task 31: Delivery of Bathymetric Services from Enterprise Databases

JHC Participants: Brian Calder and Christos Kastrisios, Paul Johnson, Brian Miles, Kim Lowell, and Elias Adediran

NOAA Collaborator: Glen Rice (NBS) and Noel Dyer (MCD)

Other Collaborators: Leila de Floriani (University of Maryland)

Databases are now ubiquitously used for hydrographic data storage and management, including gridded bathymetric data in the National Bathymetric Source, and vector cartographic data in the National Charting System. While significant improvements have been made in scale and completeness of these databases, services constructed on top of them have often not been as developed. These services are, however, essential if we are to take advantage of the effort involved in compiling the databases in the first place. Our research in this area therefore revolves around methods to use databases to provide hydrographic or cartographic products, ideally fully automatically.

Project: Accessibility of Large Compiled Grid Datasets (NBS)

The National Bathymetric Source (NBS), under development at NOAA's Office of Coast Survey provides a continuously updated, resolved estimate of bathymetry for all national hydrographic holdings. In addition to the internal database, NBS provides a publicly available abstract known as BlueTopo. Access to this dataset can be complex, however, and therefore in the current reporting period Paul Johnson, working with Glen Rice from NOAA's Office of Coast Survey, has begun exploring the possibility of delivering web accessible data services of the BlueTopo dataset.[5] The BlueTopo dataset, being produced by Rice's group at Coast Survey, is currently composed of 3,535 individual 3-Band GeoTIFFs (as of December 2022) with Elevation in Band 1, Contributors (with a raster attribute table) in Band 2, and Uncertainty in Band 3. The current dataset covers the North-East portion of the United States, the South Atlantic region of the U.S., the Gulf of Mexico, and Puerto Rico (Figure 31-1). An initial goal of this undertaking was to assess the ease of BlueTopo data tile transfers, data preparation and staging for serving, and the creation of publicly available web services hosted through the Center's ESRI GIS Enterprise Portal server[6]

During the late fall of 2022, Johnson, working with Python scripts[7] developed by Rice and his team, first tested the ability of different generations of the scripts to initiate the download of a small region covered by BlueTopo tiles from an AWS S3 bucket where they were stored, and then transitioned to testing the capability of downloading the full tile dataset, and finally moved on to testing the ability to download only tiles with changes or that were new from the last data transfer. Johnson, working with Rice and his team, then tested the ability of the scripts to create a compilation of the tiles for the eventual visualization using the Center's ESRI GIS Enterprise Portal. As of December 2022, the scripts developed by Rice worked perfectly to cover each of the tasks listed above.

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5 https://www.nauticalcharts.noaa.gov/data/bluetopo.html
6 https://gis.ccom.unh.edu/
7 https://github.com/noaa-ocs-hydrography/BlueTopo

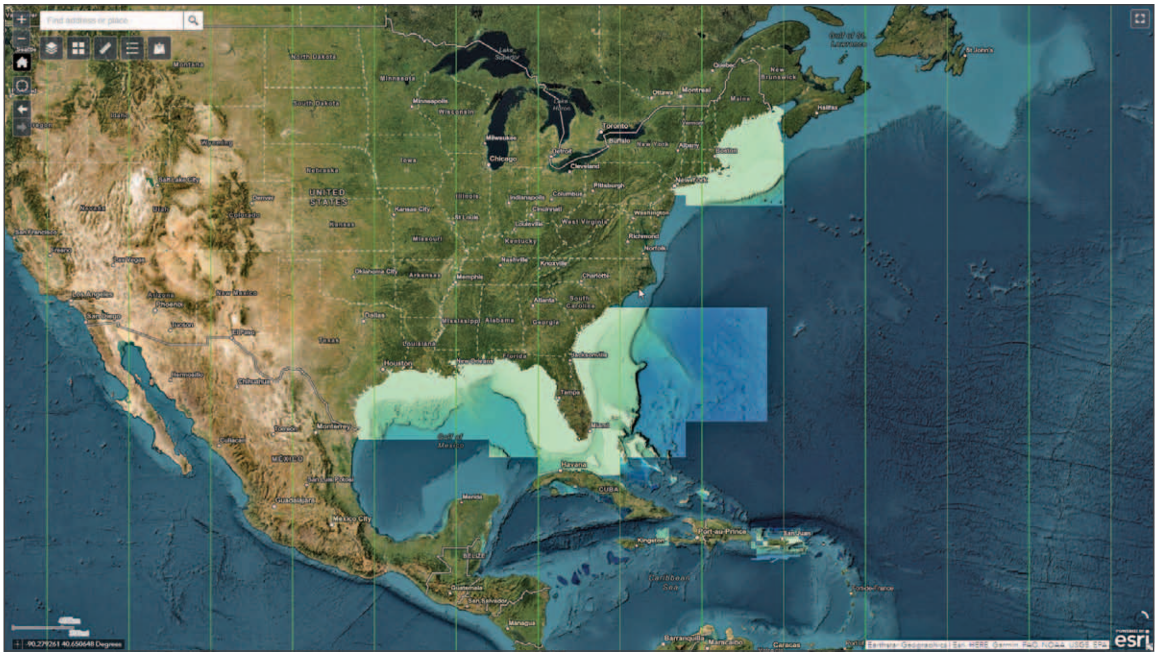


Figure 31-1. Visualization of the BlueTopo Elevation layer using the Center's GIS Portal to show the current geographic bounds of the dataset.

To publish the BlueTopo compilation for data visualization and interaction, Johnson devised a method that would allow for easy publishing of web services from the final output of the Coast Survey Python scripts. The scripts generated a directory structure of tile GeoTIFFs which were "mosaiced" together by the UTM zone using a virtual raster format known as a GDAL VRT.[8] The VRT format, which is an ASCII text file, allows for the creation of a virtual dataset that can be constructed out of multiple files, in this case the downloaded BlueTopo GeoTIFF files. Ideally, the publishing method for the compilation to create the web services on the Center's portal will not require any manual interaction with the VRTs generated by the Python scripts and will not require the generation of derivative products by outside programs for the Portal to work with the compilation. If this method can be achieved, it would allow the BlueTopo dataset to be updated as frequently as desired with no real work on the publication and serving portion of the project. Johnson currently has an early prototype of a webapp which interacts with published services from the GIS portal currently running, which allows users to interact with and assess the Elevation, Contributors, and Uncertainty bands of the dataset.[9] In the next reporting period, further improvements to the methods of publishing the web services and the means of interacting with the layers will be implemented, as the current method requires the server to parse the full VRT of the data set at initial load which requires a significant length of time.

Project: Open Navigation Surface Bathymetric Attributed Grid

Since its inception in 2003, the Center has played a role in the Open Navigation Surface Working Group (ONSWG) and the Bathymetric Attributed Grid (BAG) file format defined through their efforts. The development of the BAG format was successful enough to be adopted by the IHO as standard S-102 (gridded bathymetry), and ongoing development of new approaches and facilities, for example the metadata layer required by the National Bathymetric Source (Figure 31-2(c)), have been reported in previous Center progress reports.

The software developed by the ONSWG to demonstrate the principles of the BAG format was started in 2003 and has been in continuous development since; consequently, it has built up a considerable

[8] https://gdal.org/drivers/raster/vrt.html
[9] https://gis.ccom.unh.edu/portal/apps/webappviewer/index.html?id=5a2c1ba5c6d340c888d5357284586e6d

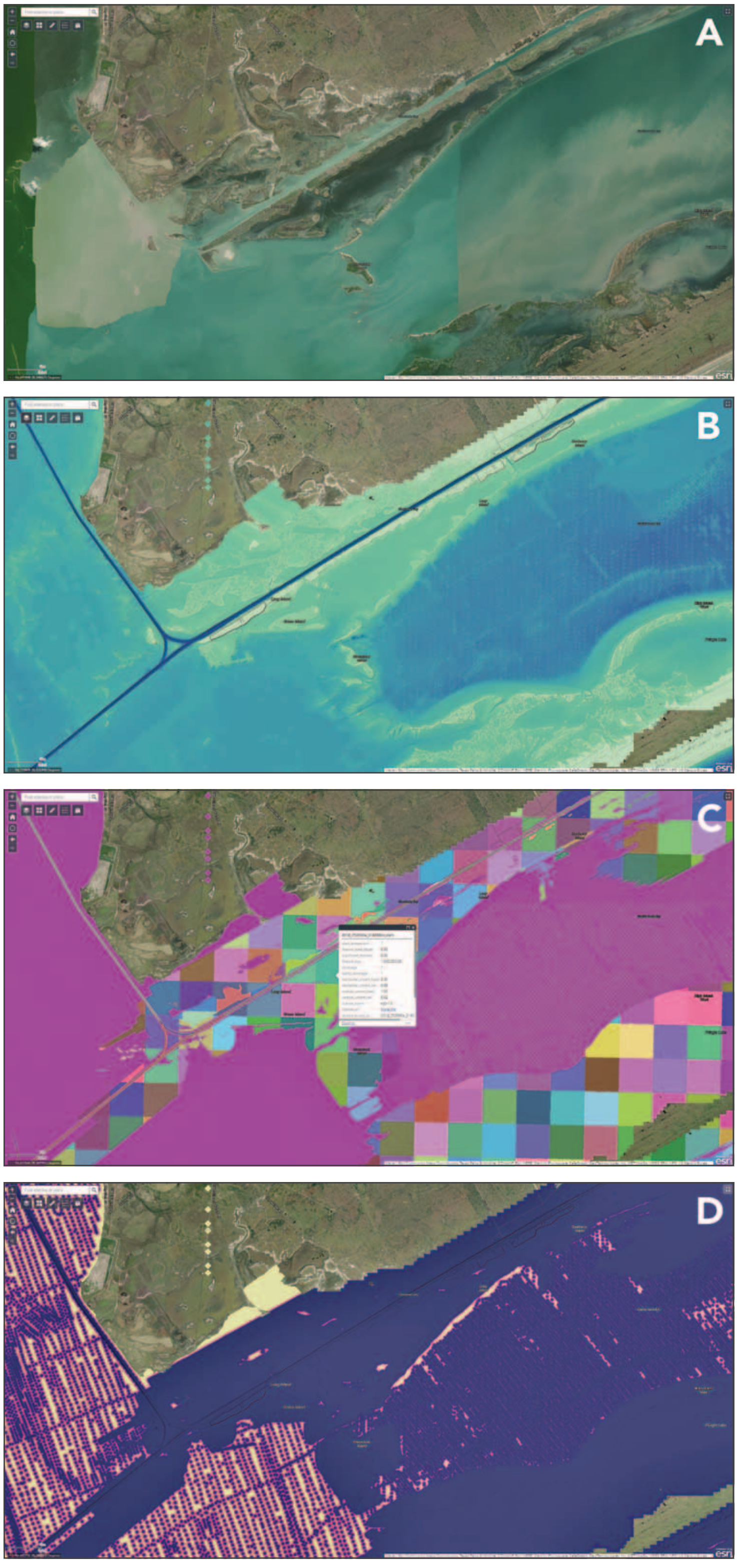


Figure 31-2. Web services for the BlueTopo dataset hosted through the Center's GIS Portal. A. ESRI imagery layer served through the Center's webapp, B. Elevation with Hillshade, C. BlueTopo contributor's layer with interactive pop-ups, and D. BlueTopo uncertainty.

technical debt. The current version is a mixture of C and C++ code, has poor documentation that is frequently out of date, allows no foreign language bindings (e.g., Python), and has neither regression tests nor modern software engineering facilities such as continuous integration, test coverage estimation, etc. A modernization of the library and associated API was therefore long overdue. Previous work sponsored by NOAA Office of Coast Survey attempted to rectify this, but a funding shortfall led to the project being left at an advanced, but incomplete stage.

In the current reporting period, Brian Miles and Glen Rice have worked closely together to generate a repository pull request for the new API. Miles led the programming effort and project management, with Rice acting as guide from the user level. Efforts included adding Python bindings, adding support for the NBS metadata layer, cleaning up tests, adding code coverage metrics, fixing automated continuous integration/delivery build systems, updating the documentation (so that it is automatically built and distributed to a website on each commit), and packaging the code for review and merge to the main codebase. The efforts were briefed to the ONSWG at their meeting at the Canadian Hydrographic Conference in June and made available for review (with the working group's blessing) in November 2022. The formal review period closed on 8 December 2022, and the code will be reviewed and merged early in 2023 before the next ONSWG meeting at U.S. Hydro in March 2023.

In addition, Brian Calder initiated, and Rice led, a sub-working group to develop new recommendations for managing coordinate reference systems (CRS) in BAG files. The original metadata structure for BAG files provided a mechanism for reporting the projected coordinate system in use for the specific data, but modern methods for datum specification and transformation have made this method obsolete. Rice successfully chaired the sub-working group to develop a new set of recommendations; the results will be presented to the next ONSWG meeting at U.S. Hydro in March 2023 for formal adoption.

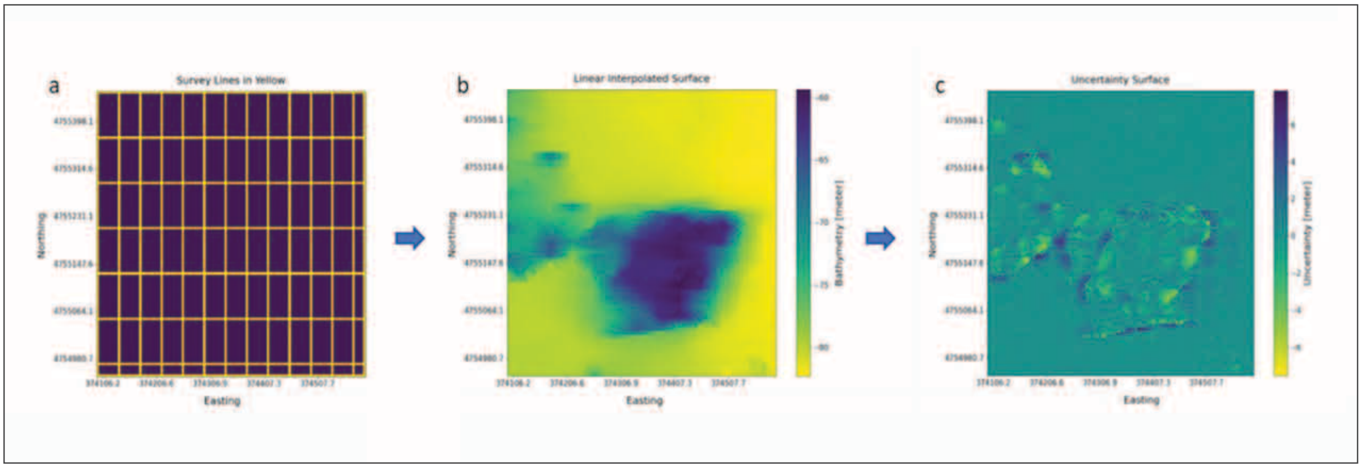


Figure 31-3. Example of interpolation with uncertainty surface: a. Survey lines. b. Depth surface produced by interpolation of survey line data. c. Associated uncertainty surface.

Project: Interpolation of Multi-Source and Quality Bathymetric Data for a Seamless Navigation Surface

With about 75% of the world's ocean unmapped, interpolation across large distances is typically required among sparse bathymetric datasets/measurements to fill the data gaps and create a model of the seafloor. The increasingly widespread use of interpolation-based digital bathymetric models generally makes little provision for accompanying estimates of model-inherent uncertainty. Yet the uncertainty associated with bathymetry is clearly important generally, but particularly for nautical charting and navigational safety. The research in this project is motivated by the current lack of methods/techniques to produce realistic estimates of uncertainty from interpolated datasets in operational settings with eventual benefits flowing to users of nautical charts.

During this reporting period, research was begun focused on estimating the uncertainty in interpolated bathymetric datasets and characterizing these uncertainties using machine learning (ML). The existing approach is shown in Figure 31-3a (survey lines) and Figure 31-3b (interpolated depth surface); Figure 31-3c shows a (preliminary) uncertainty surface generated by this project that will be the focus of the analysis in this research. Characterizing such uncertainty surfaces across a range of interpolation scenarios will facilitate the determination of an optimal spatial interpolator for filling bathymetric gaps. It will also provide for the evaluation of survey plan alternatives to identify the optimal plan for cost and accuracy. An optimal spatial interpolator in this context is one that meets requirements for a specific application while providing the best estimate of uncertainty in operational settings.

Currently, graduate student Elias Adediran, under the supervision of Kim Lowell and Christos Kastrisios, is evaluating the performance of deterministic and stochastic interpolation techniques statistically and spatially on different testbeds in the United States. ML techniques such as multivariate regression, neural networks, and extreme gradient boosting are being used to model the relationship between interpolation uncertainty and various independent ancillary variables such as dataset characteristics, spatial density, and terrain characteristics derivable from raw data and interpolated surfaces. These models will also be used to investigate the effect of each variable on the interpolation uncertainty so that a spatially explicit *a priori* estimate of uncertainty can be part of survey planning.

Beyond the broader impact of better hydrographic charts and knowledge of associated uncertainty, the findings of this work are expected to help the hydrographic community confidently choose a situation-specific optimal interpolation method and improve NOAA data-driven projects such as the National Bathymetric Source.

Project: **Hydrographic Sounding Selection**

Contemporary bathymetric data collection systems perform measurements at sub-meter resolution to support safe navigation as well as for other scientific uses and applications. For nautical charting, these high-resolution datasets must be generalized in accordance with different data formats, compilation guidelines, and chart symbology. Algorithms that can provide consistent results while reducing production time and costs are increasingly valuable; particularly in nautical cartography, where updates to bathymetry and locations of dangers to navigation need to be disseminated as quickly as possible. The process of generalizing source bathymetry data is known as sounding selection and can be separated into hydrographic and cartographic selection. Hydrographic sounding selection involves generalizing bathymetric datasets to produce a shoal-biased and dense, yet manageable, subset of soundings that can support the subsequent cartographic selection. Traditionally, hydrographic sounding selection was in the form of a sheet of paper, known as a smooth-sheet. The smooth-sheet was a manual shoal-bias selection from the source data, where the physical dimensions of the paper and label sizes limited the quantity of soundings that could be included. With digital cartographic production systems, hydrographic sounding selections are stored in a digital format, namely point clouds. Currently, automated algorithms for hydrographic soundings selection rely on radius- and grid-based approaches, but their outputs normally contain a dense set of soundings with a significant number of cartographic constraint violations, thus increasing the burden and cost of the subsequent, mostly manual, cartographic sounding selection. Existing algorithms rely on simple distance metrics but are intrinsically limited in that they do not consider portrayal of soundings on ECDIS screens. They also require user-defined input parameters, which can significantly affect the results depending on the selected values.

Christos Kastrisios, Noel Dyer from NOAA MCD, and Leila de Floriani from the University of Maryland at College Park have been working on the development of a comprehensive sounding selection algorithm for use in nautical charting. The effort is divided into Hydrographic (presented here) and Cartographic sounding selections (discussed in Task 33).

For Hydrographic Selection, the research team has focused on the generalization of the source, high-resolution point cloud to a shoal-biased subset that contains the maximum density of soundings that could be portrayed at the scale of the product. To achieve this, in the previous reporting periods the research team proposed a label-based generalization approach that accounts for the physical dimensions of the symbolized soundings on the ECDIS screen. The process consists of two phases: a shoal-biased selection of soundings within the complex polygon footprint of each shallow sounding, and the elimination of nearby soundings within legibility polygons to ensure that output soundings do not overplot. The proposed label-based

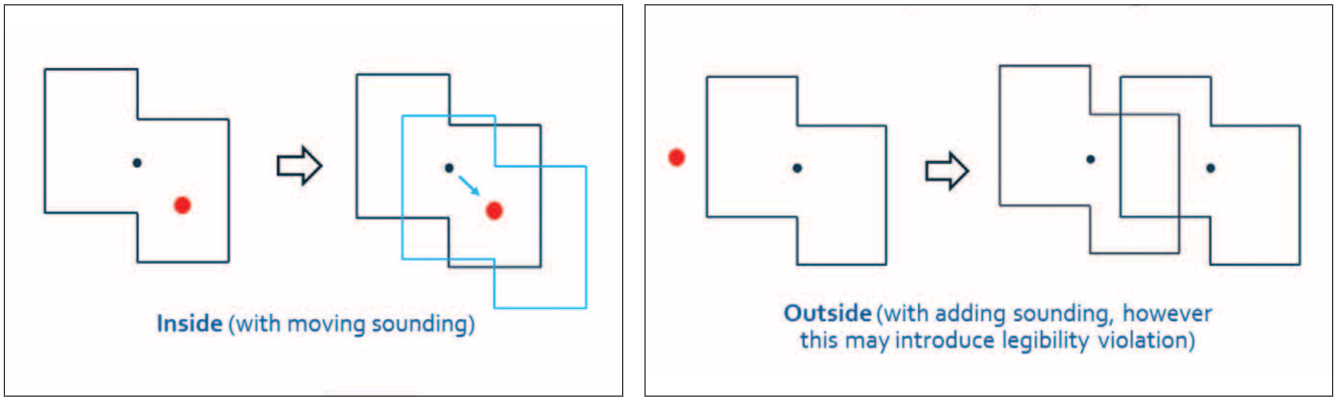


Figure 31-4. The Safety Violations Correction approach.

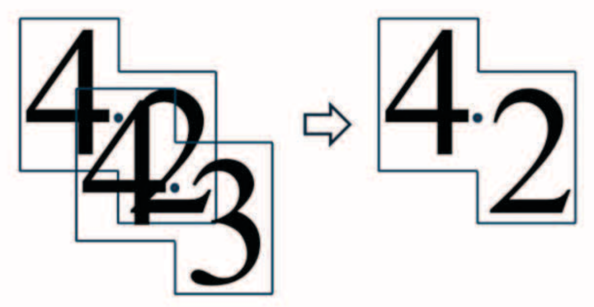


Figure 31-5. The Legibility Violations Correction approach. A deeper sounding is removed only if the action does not introduce a safety violation.

algorithm was compared to a fixed size radius, a variable size radius, and a grid-based data thinning algorithm applied in four geographic regions with different survey characteristics. The label-based algorithm consistently resulted in the least number of soundings in the four evaluation areas that may better serve the subsequent Cartographic Sounding Selection and resulted in the least number of safety violations and zero legibility violations across all datasets. The fact that this is achieved with the least number of soundings makes the introduction of new safety violations in the cartographic process less likely compared to the other approaches due to that the resulting label-based hydrographic selection requires the least amount of generalization for cartography compared to the other approaches.

In the current reporting period, the research team worked on making improvements to the proposed algorithm with the aim of deriving a set of soundings free of safety violations, as well as making the tool operational within NOAA/MCD. To eliminate the remaining safety violations, the research team incorporated an iterative process that consists of a Safety Violations Correction and a Legibility Violations Correction phase. For the Safety Violations Correction, the derived dataset is compared to the source information and when a safety violation is detected the algorithm fixes it. The fixing approach depends on whether the violation is within the label footprint ("Inside" violation) or outside of it ("Outside") as illustrated in Figure 31-4. For the former, the initially selected sounding is moved to/substituted by another sounding within the footprint. For the latter, the violation (flagged sounding) is added to the dataset.

The additional soundings included in the output introduce legibility violations. The Legibility Violations Correction phase aims to remove legibility violations when this action does not introduce safety violation. That is, a legibility violation is identified, the deeper sounding is selected, and the output without it assessed for safety. If no safety violation is introduced, the deeper sounding is removed (Figure 31-5). The result of the above iterative process is a Hydrographic Sounding Selection free of safety violations but with legibility violations which, however, are expected to be addressed in the subsequent cartographic selection process.

An automated tool was developed from this research and was made available on a git hub repository (https://github.com/NoelDyer/Sounding-Selection) while it was also made available along with the other NOAA MCD production tools for use by MCD cartographers.

Programmatic Priority 2

ADVANCE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES

NOFO Requirement 11

Development of innovative approaches and concepts for electronic navigation charts and for other tools and techniques supporting precision navigation such as chart display systems, portable pilot units and prototypes that are real-time and predictive, are comprehensive of all navigation information water levels, charts, bathymetry, models, currents, wind, vessel traffic, etc.), and support the decision process (e.g., efficient voyage management and underkeel, overhead, and lateral clearance management) in navigation scenarios.

JHC/CCOM responded to NOFO requirement 11 with one task:

Task 32: Innovative Approaches to Support Precision Navigation

Task 32: Innovative Approaches to Support Precision Navigation

JHC Participants: Tom Butkiewicz, Christos Kastrisios, Colin Ware, Andrew Stevens, Brian Calder, Briana Sullivan, Kindrat Beregovyi, Ilya Atkin, Lee Alexander

Other Collaborator: Rogier Broekman (Royal Netherlands Navy Hydrographic Service)

Project: Interactive Air Gap Visualizations

To aid precision navigation and safe passage of larger vessels, NOAA has been installing air gap sensors on bridges crossing important, high traffic waterways, such as the Mississippi River. These sensors report the distance to the water below, and this value is adjusted by a known offset to reflect the air gap at a specific reference point on the bridge, often the "low steel" point of the main span over the navigation channel. Currently, only a single air gap value at the reference point is provided to pilots via the NOAA PORTS website, as shown in Figure 32-1.

Butkiewicz and Atkin have developed an interactive web visualization that can replace these static air gap diagrams with a dynamic visualization that provides air gap values anywhere under a bridge.

These visualizations were created from lidar scans collected as part of the Lower Mississippi River Precision Navigation Project. Lidar scans of the bridges and their surroundings are first cleaned using The Center's VR point cloud editor (See Task 39). The "Cross Section" tool in the open-source application

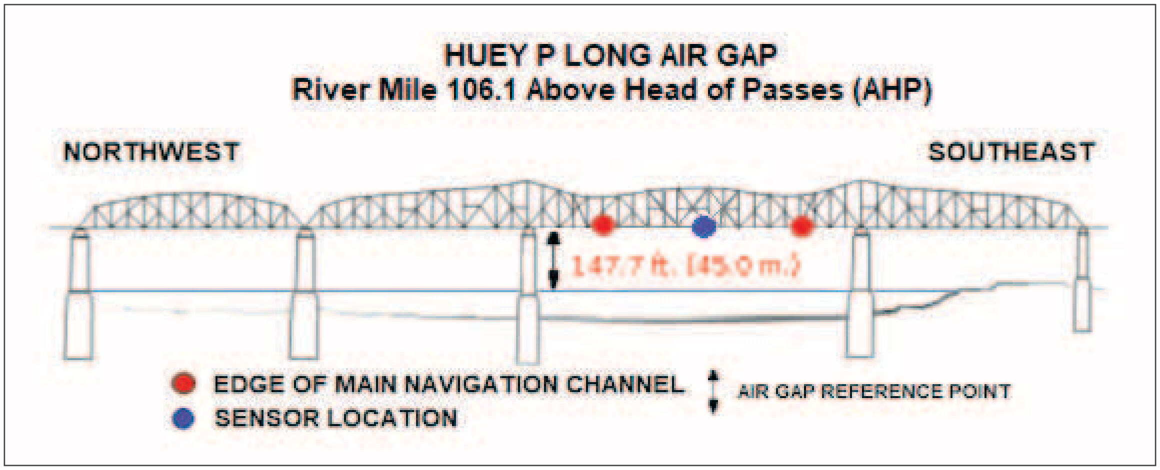


Figure 32-1. Example of an air gap diagram used on PORTS website, providing a single air gap value at the reference point.

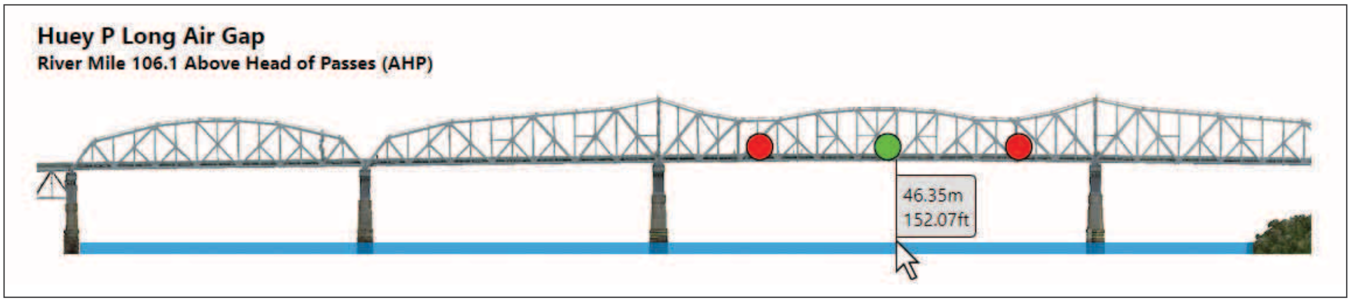


Figure 32-2. Example of the new dynamic air gap visualization, which can show air gap values anywhere under any span of the bridge.

CloudCompare is then used crop and 'flatten' the points in the direction that a ship passing underneath would travel. Finally, an under-bridge contour line is generated, which tightly fits below all the points. This line, which extends from one end of the bridge to the other, encodes the lowest points that would be encountered when passing under the bridge at any location. Because these scans are highly detailed (tens of millions of points per bridge), this contour line captures virtually every object hanging down from the bridge, such as lights or cables.

An orthogonally projected image of the point cloud is used as the visual reference in the visualization. For some datasets, this produces a high-quality color image (e.g., Figure 32-2). For datasets pieced together from multiple scans, colors may not be consistent enough to be aesthetically pleasing, and some lidar scans do not contain color information. In these cases, the point cloud image is reduced to a silhouette of the bridge and its surroundings, which can then be manually colored in a photo editor as needed to aid recognition of objects/landmarks. Red and green markers are added to these images to clearly indicate where the red/green navigation lights are located. Because the visualization is dynamically drawn, users can easily switch the viewing direction between upstream and downstream, so that it matches their view as they approach.

The visualization pulls the current air gap value from NOAA PORTS, and uses it to set the waterline relative to the bridge. By default, it draws an indicator of the air gap at the same reference location as

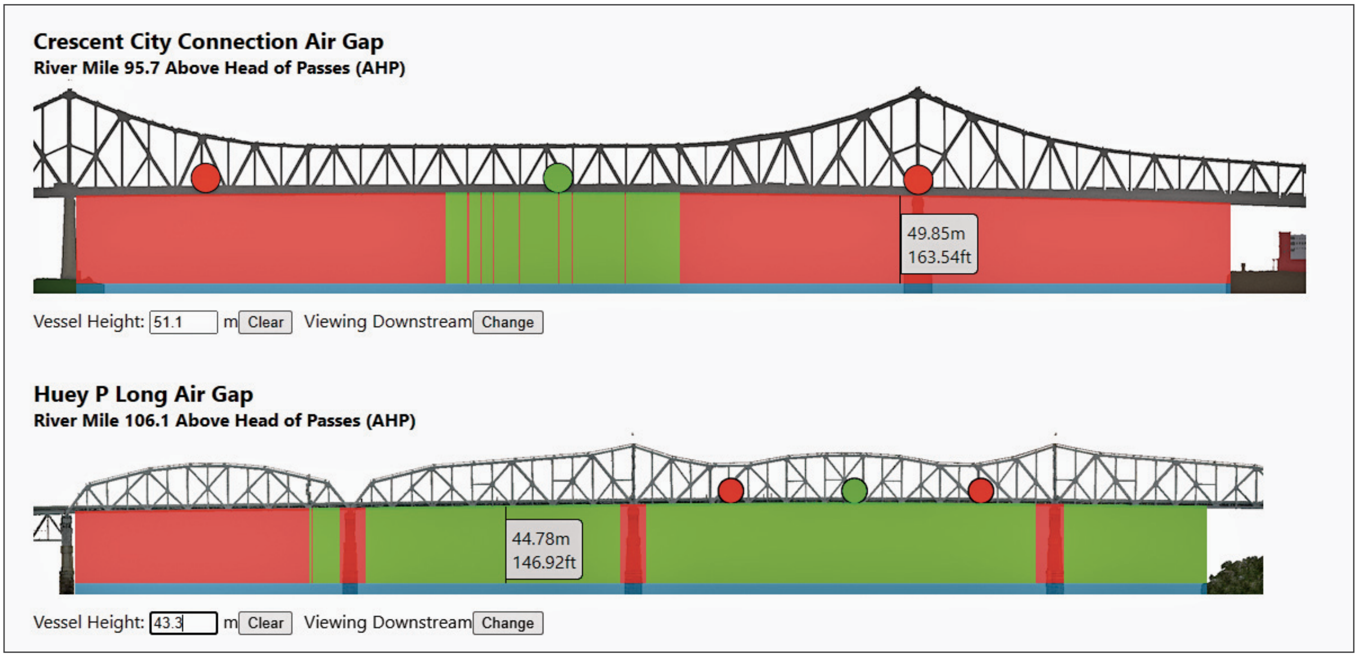


Figure 32-3. Color coded information about where there is, and is not, sufficient vertical clearance to permit safe passage, based on user-provided vessel height. (top) identifying areas where there is more clearance than the reference point. (bottom) assessing clearance under secondary spans.

currently displayed on the static PORTS diagrams. However, when a user moves their desktop mouse (or finger if on mobile device) over the visualization, this air gap indicator moves to indicate the air gap at any location, under any span. These values are calculated in real time by using the under-bridge contour line, the current air gap value from PORTS, and the known height of the reference point.

Users can also enter a value for their vessel's required vertical clearance. With this value, the visualization is able to color code the areas under the bridge to indicate where there is, and is not, sufficient air gap to allow safe passage. As shown in Figure 32-3 (top) this can allow for a pilot to identify locations where the air gap is slightly higher than the reference location, and (bottom) to assess clearance under secondary spans not over the main navigational channel. Such a tool could potentially have helped prevent the $6.7 million 2018 allision with the Sunshine Bridge by a crane barge passing under a secondary span that had an inaccurately charted vertical clearance.

In addition to bridges, this technique could be applied to other overhead obstacles as well. For example, power lines crossing a waterway can pose an interesting challenge: Unlike bridges, which often curve upward towards their center, power lines sag downward, presenting a lower air gap in the center of the waterway, sometimes forcing pilots to carefully balance between underkeel clearance and air gap clearance.

Project: Web-based 3D Visualization of Next Generation S-100 Datasets

The Visualization Lab previously presented a web-based 3D visualization interface for viewing large point clouds on top of imagery from NOAA's ENCs web service. During this reporting period, the interface was further expanded to incorporate other datasets relevant to the Lower Mississippi River Precision Navigation Project. Over 80 miles of the 230 miles of shoreline lidar data displayed on the site have now been fully cleaned using The Center's VR Point Cloud Editor (See Task 39). Because this dataset covers such a wide area, and spans multiple UTM coordinate system zones, it has revealed some shortcomings with the point cloud rendering code that was being used, Potree. To avoid these issues, and simplify the interface, current plans are to move away from Potree, and instead use the 3D Tiles data format supported by Cesium, which is used for most of the other geospatial visualization aspects of this interface.

Development continued on integrating S-100 precision navigation data from textual sources, primarily the S-131 Marine Harbour Infrastructure database that Sullivan digitized from Coast Pilot. Improvements were made to how the interface presents these feature collections at different scales (e.g., feature clustering) and how and when it displays features that are not easily mapped to a single location (e.g., a sidebar panel shows any features applying to the onscreen area). New icons were developed for many of these features (see Task 37, Figure 37-3). A substantial new feature is the streamline based visualization of S-111 Surface Current data, which is pulled from NOAA's NGOFS2 flow model. This involved the creation of several backend scripts to transform the NGOFS2 model output into streamline geometry files that can be easily displayed by web interfaces such as Cesium.

NGOFS2 model output files are transformed to be compatible with The Center's S-111 Streamline

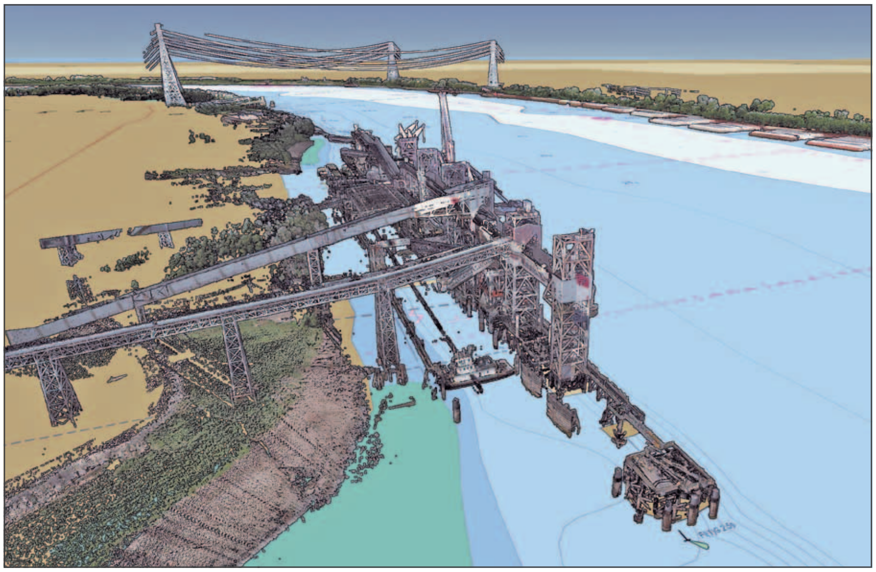


Figure 32-4. Example of the additional details of shoreline infrastructure that are provided by Mississippi River shoreline lidar points drawn over an ENC.

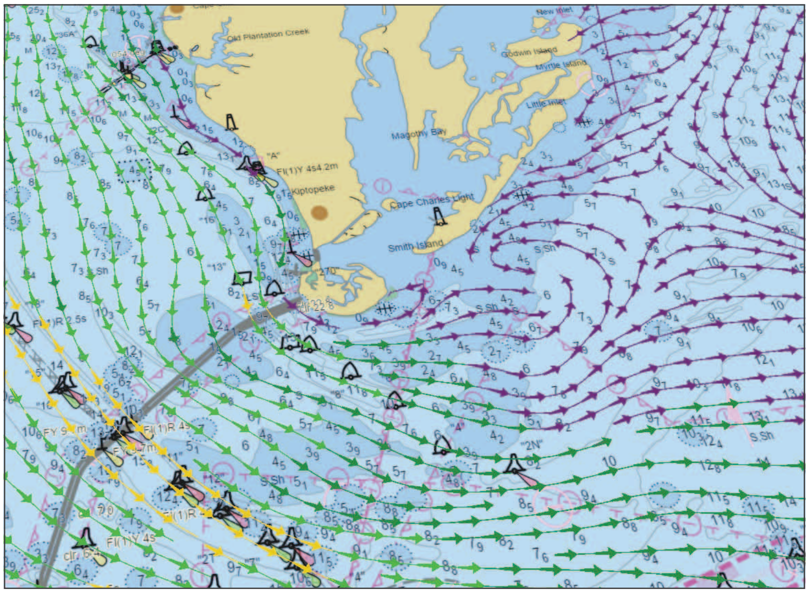


Figure 32-5. Cesium based 3D web map showing tiled S-111 Surface Current streamlines of CBOFS2 model output, drawn over NOAA ENC tiles.

library, originally developed by Roland Arsenault. This library was improved with multithreading for faster processing and modified to support more source file types beyond S-111 compliant H5 files. The streamline geometry output from the library is then broken up into multiple levels of GeoJSON tiles. A site component for Cesium was created to display these GeoJSON tiles, and has been used to experimentally display other sources of current data. Streamline presentation is generally in line with the IHO S-111 standard, though colors were modified to provide more contrast over the ECDIS base map (Figure 32-5). It is hoped that, because this technique removes most of the calculation burden from the client browser, this new method for dissemination of streamline geometry will promote adoption of these perceptually-superior streamline techniques over more commonly-encountered, but less effective, grids of arrows.

High resolution S-102 bathymetry from the Lower Mississippi River Precision Navigation Project was added, which can be used either as a color-coded 2D base layer, or as a 3D surface. Users can also now upload a 3D model of their vessel, which can be moved around to check clearances to objects or see how it would align with port infrastructure. Future work may include integrating data from air gap sensors and river gauges to create a dynamic water surface along the river, which combined with input ship draft values, would allow for in-browser calculation of air gap clearance and underkeel clearance (Figure 35-6).

Additional details about this project can be found in a paper entitled "Web-based Visualization of Integrated Next-Generation S-100 Hydrographic Datasets," which was published in IEEE/MTS OCEANS 2022.

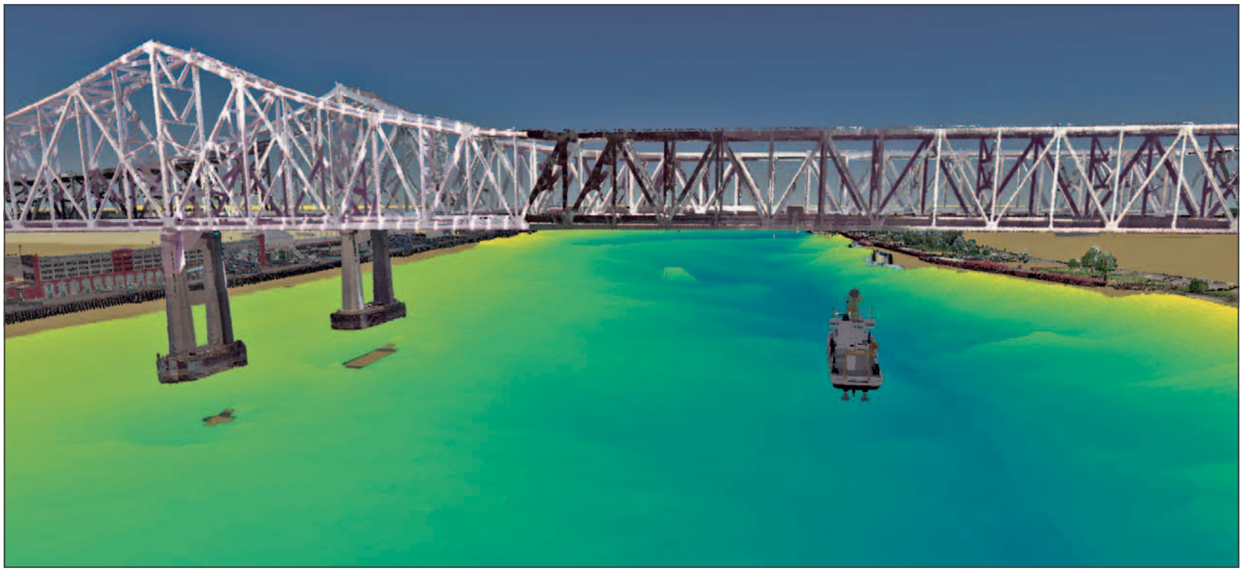


Figure 32-6. High-resolution S-102 bathymetry as a 3D surface, with user-uploaded 3D model of ship.

Figure 32-7. The visualization lab's semi-immersive tiled display running a head-tracked bridge simulator with accessory monitor that can display ECDIS (reflecting virtual ship's position/orientation) and augmented camera feeds generated from a virtual camera.

Project: **Evaluating Augmented Camera Feeds for Marine Navigation**

Multiple companies in the marine navigation industry are now offering systems advertised as "augmented reality," however, most of these would be more accurately described as augmented camera feeds. Whereas true AR uses a head-mounted display to superimpose digital content onto the user's real-world view, these systems overlay navigational information onto the video feed coming from a fixed camera, and then display this augmented video on a standard monitor somewhere on the bridge. The Center has previously demonstrated the performance and safety benefits of AR heads-up display of navigational information. For augmented camera feeds, as long as the perspective of the mariner and the camera are roughly the same (e.g. both at center of bridge, looking forward), there should be minimal cognitive load in terms of spatial transformations required when compared to a track-up ECDIS presentation (based on the Center's previous studies into handheld perspective displays). However, it is unknown how closely this approximates the benefits of head-coupled AR, where no spatial transformations are required.

To answer the questions "Are these augmented camera feed systems good enough? Or do we really need heads-up displays?", the visualization lab has been preparing to run a new experiment to identify the performance differences between these two methods of providing navigational information to mariners. Whereas previously, the lab ran its AR studies using a VR headset, simulations are now displayed on a wide-format semi-immersive tiled display, which provides much higher resolution (~50 megapixel) and allows the use of multiple accessory displays for ECDIS, augmented camera feeds, etc. A small tracking device worn by the user permits head-coupled perspective, i.e., the imagery updates naturally as they move around the room, simulating the effect of looking out bridge windows. This allows for tasks where users must walk back and forth between fixed displays (e.g. ECDIS) and side windows to view parts of the scene not visible from in front of the fixed display.

A new Unity plugin was developed that makes it easy to create "CAVE" style, head-tracked virtual environments across multiple displays. A calibration application was developed that only requires the user to simply point a stick (with a tracker attached) at the corners of each display. Virtual cameras then render separate imagery with the correct head-coupled perspective for each display.

Multiple accessory displays can be added, running on their own computers. The simulation streams the virtual ship's position and orientation over the network in a standard format, allowing the use of regular ECDIS software. Another virtual camera in the simulation renders video frames that can then be augmented with navigational information and streamed over the network to an accessory monitor, simulating the functionality of current industry "AR" systems (Figure 35-7).

Project: Visualization and Integration of Bathymetric Data Quality on ENCs

Nautical charts are compiled from geospatial information of varying quality, collected at different times, using various techniques. In maritime navigation, failure to take chart data quality into account can be one of the factors leading to maritime accidents, e.g., the cases of Nova Cura, Pazifik, and Stellar Banner. The first approach of the hydrographic community for informing mariners about the data quality on charts was with a description in the title of the chart, which with time took the form of a chart inset either with the use of the source diagram or with the more complex reliability diagram. In the early 1990s, the hydrographic community introduced the Category of Zones of Confidence (CATZOC) for use on paper and the newly introduced Electronic Navigational Charts (ENCs). The Quality of Bathymetric Data (QoBD) is the newest development for use in the S-100 series of standards. In QoBD, the five ZOC alphanumeric categories of assessed data A1, A2, B, C, and D are renamed to 1, 2, 3, 4, and 5, respectively. One more category "O" (Oceanic) is provided for the areas where water depth is deeper than 200m and, thus, does not pose a threat to surface navigation. The horizontal and vertical uncertainties and the seabed coverage criteria for each category remain unchanged, while an attribute for the temporal variation of the seabed is added. Despite these changes, however, the legibility and utility of the current methods are limited, and therefore the aim of this research project is the development of new visualization and integration methods of bathymetric data quality in ECDIS in support of decision making on board.

CATZOC/QoBD may be used at any stage of passage, but in the planning phase of the voyage, the normal process is for the prudent mariner to plot the planned route and then check for features along the intended route that may pose a threat for the vessel. For each identified bathymetric feature, the mariner accounts for the horizontal and vertical uncertainty and, where necessary, the route is appropriately modified. Tools that use CATZOC to identify areas of danger can, however, be problematic. Because of the portrayal method, in some cases, dangers can be missed, and in others false dangers can cause needless alerts. Improving portrayal is therefore a priority.

In the previous reporting periods, Christos Kastrisios, Colin Ware, Brian Calder, and Tom Butkiewicz, in collaboration with Lee Alexander and Rogier Broekman, reviewed the deficiencies of the current CATZOC symbology and integration in route planning and execution. Subsequently, the research team studied recent research into the portrayal of bathymetric data uncertainty and set the requirements that the new visualization method should satisfy to be effective for the application. Accordingly, Kastrisios and Ware considered how different visual variables might be used to meet the requirements and proposed the use of a sequence of textures created by combining two or more visual variables.

Two countable textures schemes were developed: one consisting of lines (Lines) and one consisting of clusters of dots (Dot-Clusters) with the fundamental principle being that the number of lines or dots represent the QoBD. Adopting ideas previously expressed in the hydrographic community, two other, color-based, coding schemes were developed, one with opaque color fills (Opaque-Colors) and one of transparent color fills (Transparent-Color). To overcome the obscuring issue of Opaque-Colors and the blending issues of Transparent-Color, we developed a see-through color textures (Color-Textures) scheme (Figure 32-8).

In collaboration with the UNH Survey Center, we developed and conducted an online survey and in-lab experiment for the evaluation of the five coding schemes. The survey was disseminated to the maritime and hydrographic communities with the support of three US Maritime Academies as well as through LinkedIn and Facebook relevant groups. Participants were asked to evaluate the five coding schemes in 16 subjective questions using a 0-6 Likert scale and one objective question where they were called to identify the QoBD category that covers one of the survey evaluation areas. As reported in the 2021 annual report, the two proposed schemes of Lines and Dot-Clusters were the preferred coding schemes among survey participants. Together they received 70.9% of best rankings in Day-bright and 60.5% in Dusk mode. Lines received the most positive ratings overall. It was the only coding scheme with mean ratings over three in all four evaluation areas, and the only with mean ratings over three in the combined questions against the five requirements, while it was participants' first choice in both Day-Bright and Dusk modes rankings. Dot Clusters was the second-best coding scheme in participants' rankings followed by Opaque-Colors (OC). Transparent-Color (TC) and Color-Textures (CT) performed generally worse than the other three schemes.

In the survey study discussed above, the results showed that the texture solutions were preferred, but only on average. Although most of the participants clearly preferred textures, many strongly preferred color. Subjective ratings of coding schemes may be biased, and mariners are not trained in critical evaluation of symbology; many of them rated opaque colors highly on the criterion of not interfering with other chart information, even though the opaque colors completely obscured color coded depth areas. This suggested the need for more objective metrics. Accordingly, we carried out an experiment to provide an objective evaluation of how quickly and accurately the alternative codes could be read and how easily codes could be remembered and used in the absence of a key.

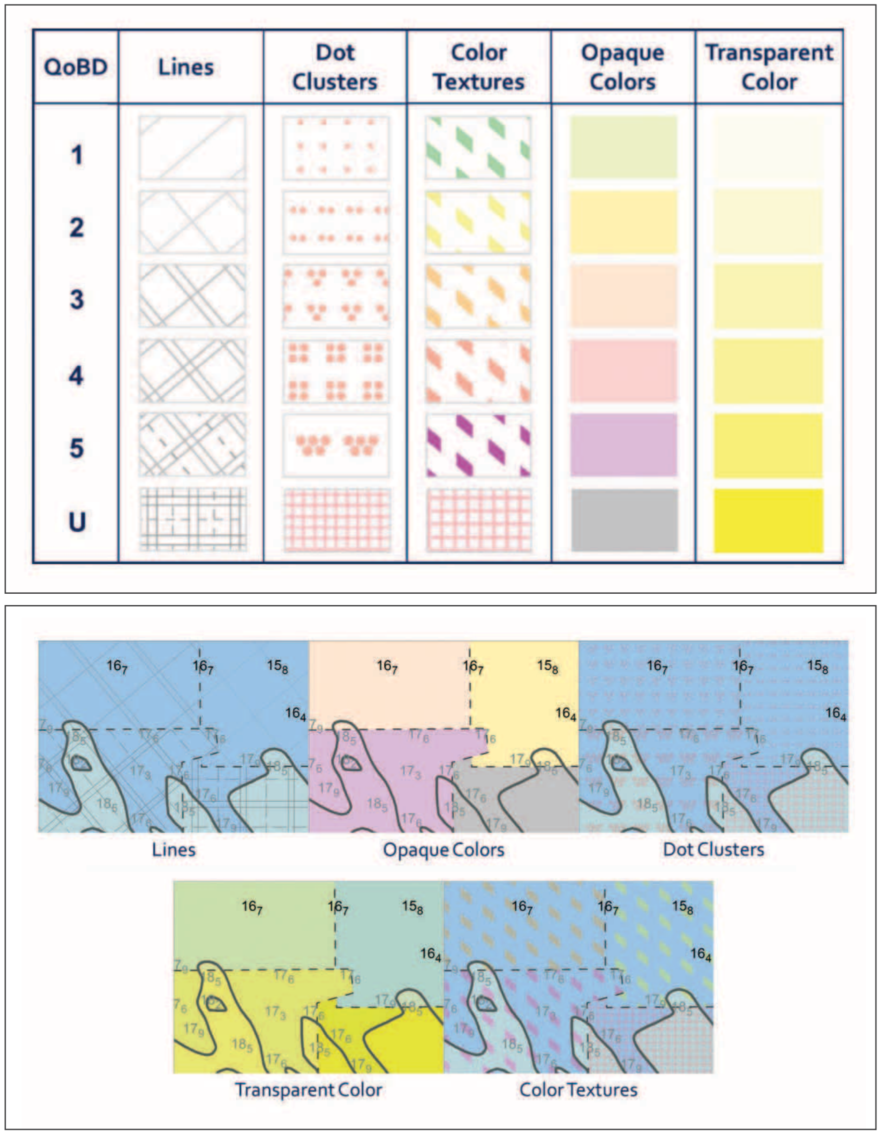


Figure 32-8. Top: the tested coding schemes. Bottom: coding schemes over a chart section.

For the in-lab experiment, synthetic chart generation software was used to create chart-like displays, based on random parameters, as the background for ZOC coded overlays for each trial (Figure 32-8). Participants were required to respond as quickly as possible by entering the ZOC/QoBD category under the cursor as a number on the keyboard. Two experiments were carried out: one with and one without the key/legend present on the synthetic chart display. Both response times and errors were measured. Overall, the Dot-Clusters produced the fastest response times and the lowest error rates, followed by Lines and Opaque-Colors. The Transparent-Color coding scheme yielded the slowest response times with very high error rates and clearly would not be suitable.

In the current reporting period, the research team published the results of the survey and the experiment and presented them at IHO relevant working groups (WG) meetings (i.e., Data Quality WG, Nautical Cartography WG, and S-101 Project Team meetings). The two proposed countable textures have been well received by the community, and the S-101 project team has decided to further test them in an S-100 ECDIS in simulators and at sea. Toward this, the research team is investigating methods to translate the two textures into an appropriate format for use with ECDIS as well as fine tuning them so that they become part of the S-100 IHO Portrayal registry.

Programmatic Priority 2

ADVANCE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES

NOFO Requirement 12

Development of improved methods for managing hydrographic data and transforming hydrographic data and data in enterprise databases to electronic navigational charts and other operational navigation products, particularly in the context of the new S-100 framework and family of associated data standards.

JHC/CCOM responded to NOFO 12 requirement with one task:

Task 33: Managing and Transforming Data to Navigation Products: Computer Cartography

Task 33: Managing and Transforming Data to Navigation Products: Computer Cartography

JHC Participants: Christos Kastrisios, Brian Calder, Giuseppe Masetti, Tamer Nada

NOAA Collaborators: Noel Dyer, Christie Ence, Brian Martinez, Daniel Morrow, Sean Legeer, and Kathryn O'Neill (MCD), Peter Holmberg (PHB), Glen Rice and Katrina Wyllie (HSTB)

Other Collaborators: Leila de Floriani (University of Maryland), Stelios Contarinis (National Technical University of Athens, Greece), Jose Cordero (Spanish Hydrographic Office), Craig Greene and Amber Bethell (ESRI), Edward Hands (Kartverket, Norway), Morgane Gaumet (SHOM), Wu Lingzhi (China Maritime Safety Administration), and members of the IHO DQWG

Over the years, nautical chart creation evolved from a hand-drawn, manual process, to a computer assisted, semi-automated process. This has unquestionable advantages, especially relating to the access and transformation of data from enterprise databases and the ability to more rapidly update and disseminate information to the end user. However, notwithstanding the technological advances, many of the tasks in chart compilation remain manual, time consuming, and prone to human error. One of the main issues is the limited availability of algorithms that meet the nautical cartography constraints (and most importantly that of safety) while appropriately reducing the complexity of the source information for the scale of the product. A shared deficiency of generalization algorithms is that they are unaware of the other relevant information on the chart. For instance, for the sounding selection task, only an algorithm that is cognizant of other charted features (e.g., wrecks, buoys, depth curves) may yield acceptable outputs. As a result, cartographers perform generalization tasks in a software environment using techniques that often require the rendering and visualization of large amount of data, straining current computational approaches and creating considerable delays and frustration. Unquestionably, chart compilation, as with any other mapping product, is a largely subjective process, and subject to interpretable guidelines, which is why products from two compilers, two production branches, or two Hydrographic Offices often look and feel very different to the end-user. A more objective and uniform result may be achieved with generalization algorithms that contain contextual knowledge of cartographic practice and can consistently apply this informed rule-base system to the chart.

The projects described below are stepping-stones toward the overarching goal for automating the chart compilation process, as it was demonstrated by the participation of a Center-led team to a recent international mapping competition (see "Speed Mapping Challenge" Project).

Project: Cartographic Sounding Selection

Nautical charts are relied upon to be as accurate and up-to-date as possible. The processing of the high-resolution data for nautical chart production includes tedious and repetitive data generalization tasks that decrease the efficiency of the process. One of the most crucial and time-consuming generalization tasks (and bottleneck in the ENC creation/update process) in nautical cartography is sounding selection, i.e., picking the spot depths, that, along with the other charted information, are used to illustrate the seafloor and its characteristic features on the chart. Ideally, that task should be accomplished with the least number of soundings necessary while satisfying the application's constraints. Doing this efficiently is difficult, and therefore the aim is to develop an appropriate algorithm for nautical chart production. Existing algorithms are limited in that they do not account for information present in contemporary bathymetric surveys such as data uncertainty, operate strictly in the Digital Landscape Model (DLM)-space and disregard the Digital Cartographic Model produced on ECDIS display (which is what mariners use to navigate), do not consider other chart features, focus on the less navigationally relevant cartographic constraints (e.g., morphology), and do not validate the selection output against product constraints (and, particularly that of safety). As a result, the sounding selection remains largely a semi-manual process, as previous Center research has shown.

Christos Kastrisios, Noel Dyer from NOAA MCD, and Leila de Floriani from the University of Maryland at College Park have been working on the development of a comprehensive sounding selection algorithm for use in nautical charting. The effort is divided into Hydrographic (discussed in Task 31) and Cartographic sounding selections (presented here).

In previous reporting periods, the research team developed a workflow that uses the reduced density dataset from the Hydrographic Sounding Selection (Task 31) as the input which is converted to a bathymetric surface model through a Delaunay triangulation for the selection of prime and supporting soundings. Prime soundings are the most critical to navigation, as they illustrate both dangers (shallow) and sea-route (deep) soundings. Supporting soundings are used to complement prime soundings as well as to support navigation through challenging areas. Prime and supporting soundings correspond to the critical points of a bathymetric surface model, where shallow soundings are local maxima, deep soundings are local minima, and supporting soundings are saddle points of the modelled seafloor. The benefits of extracting the critical points from the label-based hydrographic selection dataset is that the latter implicitly defines the search neighborhood as a function of the scale of the product and not by a user-defined search distance, which is a known problem in the surface critical point extraction (i.e., how the neighborhood is defined).

Once the prime and supporting soundings selection is complete, the algorithm performs the background soundings selection. Traditionally, these soundings have been primarily used to fill gaps between prime and supporting soundings for interpolating depths between widely spaced depth contours, which usually follow aesthetic-based criteria for their selection. In this work, however, the research team is incorporating a data- and product-driven approach that prevails over aesthetics, although the latter plays a crucial role in the process. Toward this, the density of hydrographic selection soundings is reduced with a variable radius generalization followed by a selection based on the CATZOC depth uncertainty tolerance, to achieve a balance between aesthetic and quantitative approaches. For the CATZOC-based enhancement procedure, adopted by the surface-test developed by previous JHC research, the surface created from the reduced density dataset (after the prime, supporting, and background soundings selection) is compared to the source dataset. When the difference between the source and interpolated depth exceeds the CATZOC tolerance in the area, the sounding is added to the selection and the surface is recalculated with the new selection. The process is repeated until none of the generated triangles contain soundings that are outside of the expected depth tolerance. Surveys with CATZOC D and U do not have a quantified depth uncertainty range, thus a modified background selection process is implemented. More precisely, the implemented approach is similar to that for the other ZOC categories in that the goal is to identify soundings that significantly deviate from their expected value. However, since uncertainty tolerance is not available, each triangle is only assessed once and the sounding with the highest difference is added to generalized soundings dataset. This step is subject to change according to the end-user (cartographer) needs; for instance, a user-defined depth tolerance or number of iterations may be implemented.

In this reporting period the research team continued the effort for a chart ready sounding selection with making various improvements to the initial approach for a methodology that leverages both the DLM and DCM spaces to make generalization decisions. This includes the incorporation of the label-based hydrographic selection as an integral part of the process where, instead of the sequential process for safety and legibility violations correction (as described in Task 31), only safety violations are fixed while any remaining legibility violations are corrected later in the cartographic selection process. Furthermore, other chart features carrying bathymetric information (surrounding soundings, depth contours, dredged areas, wrecks, rocks, and obstructions) have been incorporated for building the surface model of the seabed and the extraction of the critical points of it. Due to the incorporation of other chart features, the taxonomy of soundings was also updated to meet cartographic needs (e.g., with the inclusion of the "least depths" defined in NOAA nautical chart manual). Improvements have also been made for removing edges without appropriate connectivity (e.g., crossing land areas) with using a constrained Delaunay triangulation. For the Fill sounding selection, contrary to other works that propose specific distance values, a product-driven approach has been incorporated that determines the starting and ending radius lengths from the soundings present on the existing same scale ENCs in the area. This aims to account for the variability of geographic configurations which require different distributions of soundings and, as such, universal values for every waterway do not really exist (Figure 33-1) (e.g., a river vs open sea). However, the thinning radius parameter can be modified to meet other applications' requirements, where necessary.

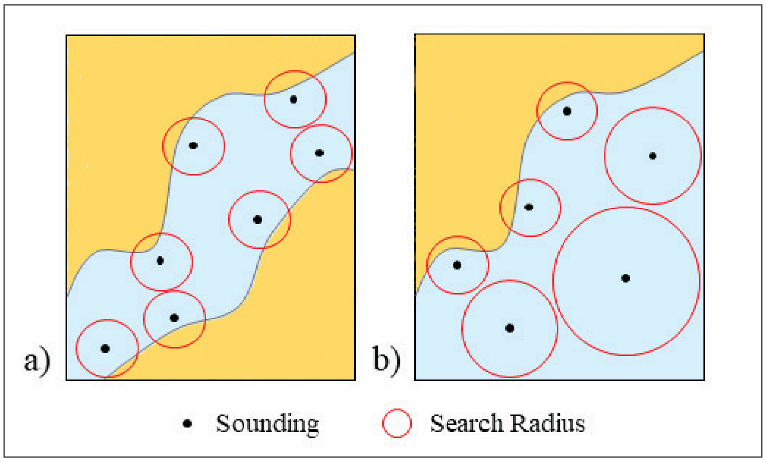


Figure 33-1. Example of use of different radii for the selection of fill soundings in different geographic configurations.

Lastly, for the fill soundings, besides a surface-test based selection, a triangle-test based selection has also been made available (which can be selected, e.g., if the CATZOC area does not provide quantitative information about the data uncertainty).

The improvements made in this reporting period bring us closer to deriving the final chart soundings directly from the National Bathymetric Source (NBS) in support of the MCD rescheming project. An example of derived soundings from the NBS in Mobile, AL is illustrated in Figure 33-2.

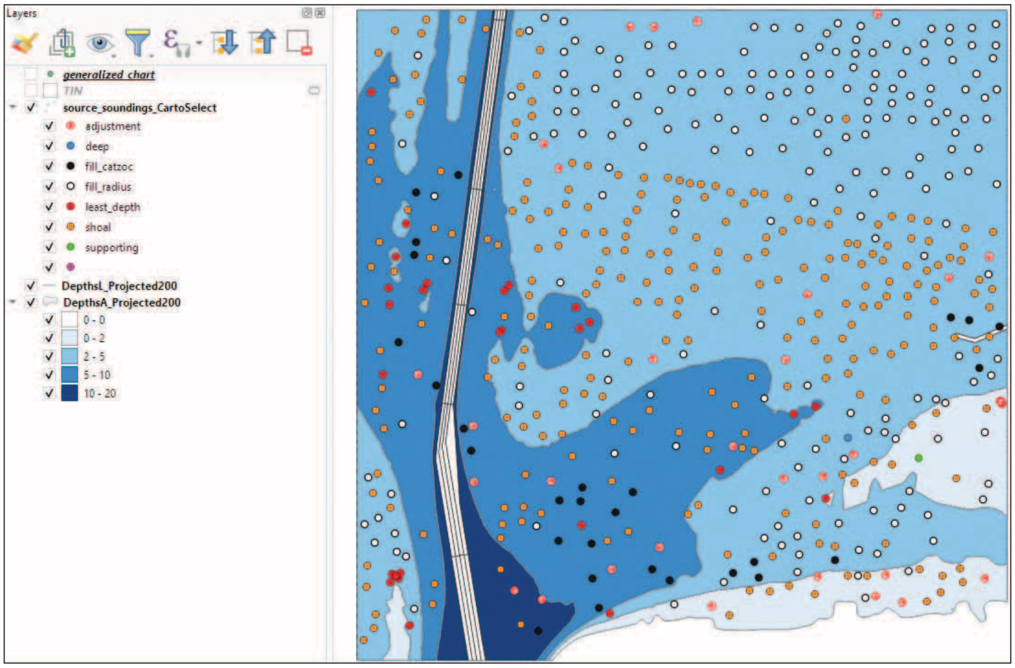


Figure 33-2. Preliminary sounding selection in Mobile, AL.

Project: **Sounding Selection Verification Methods**

Depth curves and soundings, which are used for the representation of submarine relief, are two of the most important features on nautical charts. They are derived from more detailed datasets, either survey data and/or larger scale charts, through generalization (see, e.g., Task 31 Hydrographic Sounding Selection project). The generalization process is a continuous compromise among the chart legibility, topology, morphology, and safety constraints as they are often incompatible with each other. Once depth curves are created, the cartographer, following established cartographic practice rules, selects the soundings that will be charted. The selection (as well as depth curves compilation) is performed either fully manually and/or with using one of the existing software solutions. The initial selection is then evaluated and corrected where necessary to meet the fundamental constraint of safety, i.e., that the expected water depth based on the charted bathymetric information does not appear, at any location, deeper than the source information. According to the IHO S-4 Chart Specifications, the "shoal-biased pattern" of selection for the charted soundings is achieved through the "triangular method of selection," and more specifically through two tests, known as the Triangle and Edge Tests. For the triangle test the cartographer verifies that no actual (source) sounding exists within a triangle of selected soundings which is shallower than the least depth of the triangulated soundings. Likewise, for the edge test, no source sounding may exist between two adjacent selected soundings shallower than the least of the two selected soundings forming an edge of the triangle.

In previous reporting periods, Christos Kastrisios, Brian Calder, and Giuseppe Masetti, in collaboration with Pete Holmberg (NOAA PHB) and Brian Martinez (NOAA MCD), developed an algorithmic implementation of the triangle test with increased performance near and within depth curves and coastlines, and the first automated implementation of the edge test described in the literature. The work showed the significance of the edge test in the validation process, as it identifies discrepancies that the triangle test fails to detect. The research work documented individual limitations of the two tests and revealed a fundamental "intrinsic" limitation that prevents the construction of a fully automated solution based solely on them. The fundamental limitation is considered "intrinsic" because it is the result of the definition of the two tests as described in the IHO S-4 publication and is thus independent of any particular implementation. Due to this limitation, a sounding may pass both the triangle and edges tests and yet deviate significantly from the expected depth in the area based on the charted bathymetric information.

As a solution, a new surface-based test was proposed, investigated, and developed, termed the Nautical Surface Test (NST), or "surface-test" (ST) for short. This method accounts for the configuration of the seabed at the appropriate charting resolution and captures the relevant discrepancies between the source and the selected bathymetric information for charting. Unlike the triangle and edge test where source information is compared against a distant but shallower depth value within the triangle or edge, the surface test compares source soundings to the "expected" depth at the exact location of the source soundings. For each source sounding, the surface test interpolates the charted bathymetric information and compares the calculated value to the actual depth of the source sounding. If the former is greater (meaning that the depth at this location appears deeper than the measured depth), the source sounding is flagged. Another important advantage of the surface test over the triangle and edge tests is that a tolerance can be used, which helps to distinguish the significant from insignificant detection. On the contrary, use of a tolerance value with the traditional two tests would make them behave unpredictably.

The research effort has led to a toolset consisting of the triangle, edge, and surface tests that was made available to NOAA/OCS Marine Chart Division cartographers for evaluation. To facilitate the use of the tools, Christos Kastrisios compiled the supportive documentation that provides problem background information, details the algorithm and the use of the tools, and explains errors and warnings. Many improvements were made to the tools in the previous reporting periods, such as optimization and bug fixes. Other improvements included: IHO S4 and S52 truncation, coordinate system outputs, utilized CATZOC tolerance, improved triangles selection in dredged areas and sliver triangles outside coverage polygon, flexibility in spatial queries due to the use of NAD83 as WGS84 coordinates, validation of coverage polygon and the single scale of Nautical Dataset inputs, new selection of Errors and Warnings, new export layer with pre-defined color-coded labels, and others.

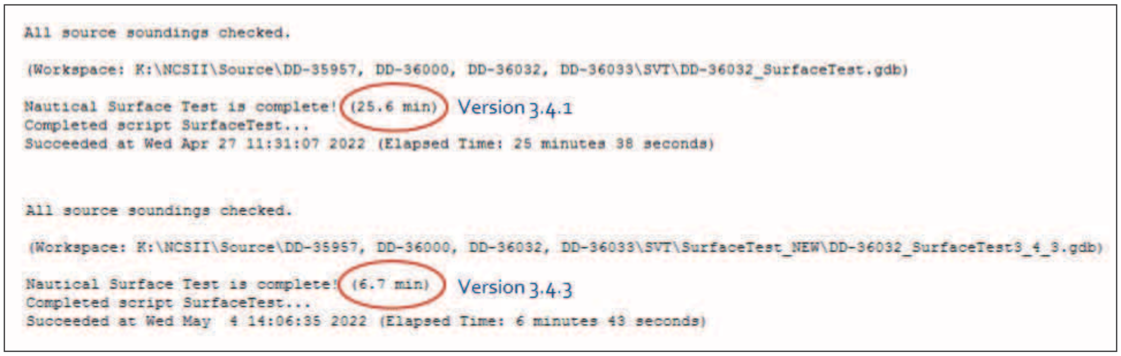


Figure 33-3. Example of the reduced run time of the surface test tool after the enhancements made in this reporting period.

In the current reporting period, Christos Kastrisios, Brian Martinez, and Kathryn O'Neill continued testing and making improvements to the tools based on user feedback/requirements, and more specifically speed enhancements (Figure 33-3) and internal validation of inputs to ensure that NIS data may not be used and modified by the tools. With the support of MCD/FADS the tools became operational and are now available to all MCD cartographers along with the other NOAA production tools (Figure 33-4).

Project: Change Detection

As explained in the introduction to this Task, regardless of the many research efforts, nautical chart compilation remains a time-consuming process requiring much human interaction. Cartographers perform most generalization tasks manually or semi-manually. For a manual sounding selection, the cartographer first selects the least depths, critical, controlling, and supporting soundings, and subsequently the other soundings necessary for the representation of the seabed morphology on the chart. When a chart already exists in the area, the cartographer often uses the distribution of soundings on the existing chart as a guiding subset for the selection of the additional soundings. The initial selection is then typically evaluated and corrected where necessary to meet the prime constraint of safety. Identifying the representative soundings for a safe selection from a high-resolution point cloud (Figure 33-5) is a challenging, if not impossible, task.

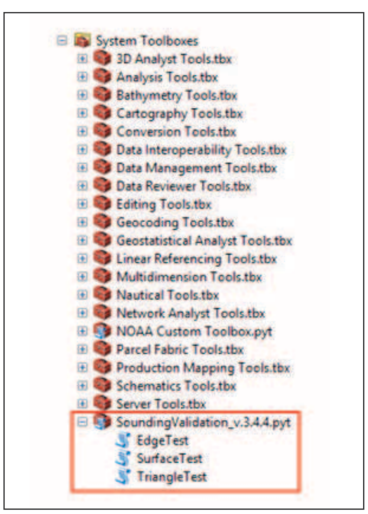


Figure 33-4. The Sounding Validation Toolbox along with the other NOAA Production tools.

The Hydrographic Sounding Selection and the Cartographic Sounding Selection projects aim to automate the task. However, this is a very difficult task and bringing research-to-operations may take years (as our experience with the Sounding Selection Verification Methods project has shown). This is because the charting authorities must verify that the new algorithms meet their needs and requirements, while testing and adapting tools to make them compatible to the existing production systems also require time and effort.

As an interim measure, Christos Kastrisios, Daniel Morrow, and Brian Martinez from MCD investigate the development of a change detection tool to support the sounding selection task. In detail, the tool compares the Nautical Surface model, i.e., a model of the seabed constructed by the bathymetric features on the existing chart, to the seabed surface of the new survey (or the Nautical Surface of the larger scale chart). Inputs are the Nautical dataset, Source soundings, AOI polygon, Depth field, depth interpolation method, and the required depth precision (default "full"). The output is a color-coded layer of the source soundings that aims to illustrate how depth has changed and to attract cartographer's attention. Figure 33-6 illustrates such a preliminary output of the tool.

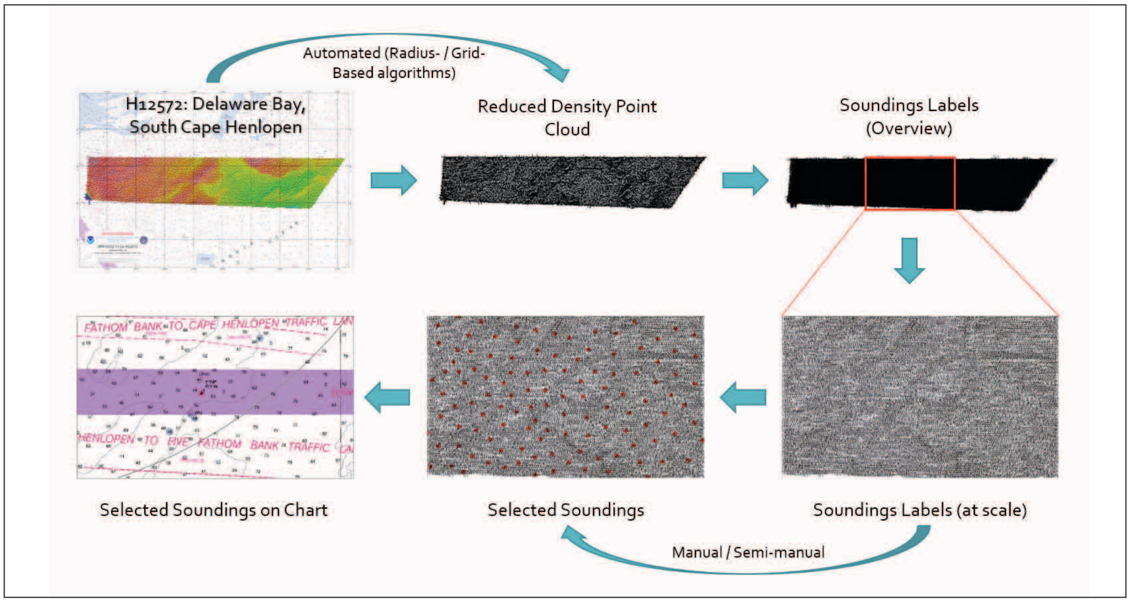


Figure 33-5. Survey sounding datasets are extremely dense for the (mostly manual) cartographic sounding selection.

Project: **Survey-to-CATZOC**

Combining different datasets requires appropriate data quality elements while meta-quality information (CATZOC/QoBD) should be made available to mariners so they can assess a safe route planning and execution of voyage. However, datasets provided by adjacent Hydrographic Offices may differ in the methods incorporated. The IHO Data Quality Working Group (DQWG) was established to provide guidance to hydrographic offices to ensure a harmonized implementation of data quality aspects. At DQWG16 a dedicated sub-WG was created to draft guidelines and recommendations to Hydrographic Offices based on best practices to allocate CATZOC/QoBD values from survey data in application of the new S-44 Standard for Hydrographic Surveying. The work of the Sub-WG aims to provide tools to assess the self-consistency and explain the differences of datasets produced by one or adjacent Hydrographic Offices. The target publication will describe the process from data capture to data storage and validation and standardize/define the components and structures of data quality measures for allocating the descriptive quality indicators (CATZOC/QoBD) on charts.

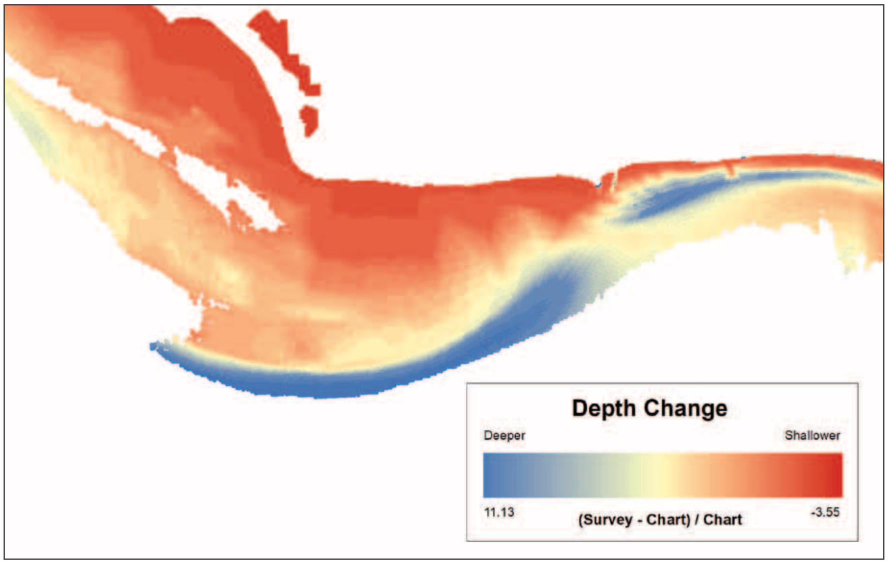


Figure 33-6. Example of bathymetry change to facilitate sounding selection.

In the previous reporting period, Christos Kastrisios in collaboration with Edward Hands from Kartverket, Norway (DQWG Chair) compiled a document with information on data capture, storage, generalization, quality components, quality evaluation, and current HOs practices on allocating CATZOC/QoBD on charts to serve as the working draft of the Sub-WG toward the new publication.

In the current reporting period, updates were made to the draft publication in collaboration with the other Sub-WG members mostly with the aim to simplify the text and finalize the cross-reference tables. Table 33-1 is a sample table that summarizes the minimum required survey order for the target ZOC/QoBD category.

Table 33-1. Minimum required Survey Order for each ZOC/QoBD category.

Criterion / ZOC/QoBD	Data Assessment	Features Detected	Least Depth	Seafloor Coverage	Depth Accuracy	Position Accuracy
A1 / 1	Assessed	1a	1a	1a	1b (d<145m)	1b
A2 / 2	Assessed	1a	1a	1a	2	1b (d<300m)
B / 3	Assessed	2	2	2	2	2 (d<300m)
C / 4	Assessed	2	2	2	2	2
D / 5	Assessed	2	2	2	2	2
U / U	Unassessed	-	-	-	-	-
- / Oceanic	Assessed	2	2	2	2	2

Furthermore, Christos Kastrisios with Morgane Gaumet from SHOM developed a spreadsheet with matrices that map survey data quality components to the respective CATZOC / QoBD DQ components. Figure 33-7 illustrates how the achieved horizontal uncertainty for different survey coefficients corresponds to the CATZOC/QoBD (example is for 60 m depth). The goal is to perform the evaluation and characterization of depths and aggregate them for generating the CATZOC polygons for S-57 ENCs, as well as a sanity check prior sending an S-101 ENC for validation by the Regional ENC Centers (i.e., that the calculated QoBD in ECDIS based on the populated DQ indicators is as intended by the compiler).

Hoorizontal	(see S-44 7.6 Matrix)							
a/b(%)	0.1	0.25	0.5	1	2	5	10	20
0.05	0.11	0.2	0.35	0.65	1.25	3.05	6.05	12.05
0.1	0.16	0.25	0.4	0.7	1.3	3.1	6.1	12.1
0.35	0.41	0.5	0.65	0.95	1.55	3.35	6.35	12.35
0.5	0.56	0.65	0.8	1.1	1.7	3.5	6.5	12.5
1	1.06	1.15	1.3	1.6	2.2	4	7	13
2	2.06	2.15	2.3	2.6	3.2	5	8	14
5	5.06	5.15	5.3	5.6	6.2	8	11	17
10	10.06	10.15	10.3	10.6	11.2	13	16	22
15	15.06	15.15	15.3	15.6	16.2	18	21	27
20	20.06	20.15	20.3	20.6	21.2	23	26	32
50	50.06	50.15	50.3	50.6	51.2	53	56	62
100	100.06	100.15	100.3	100.6	101.2	103	106	112
200	200.06	200.15	200.3	200.6	201.2	203	206	212
500	500.06	500.15	500.3	500.6	501.2	503	506	512

maximum depth of survey

60 60

CATZOC/QoBD	A1 / 1	A2 / 2	B / 3	C / 4	D / 5
horizontal	8	20	50	500	
vertical	1.1	2.2	2.2	5	

Figure 33-7. Mapping the calculated horizontal uncertainty of a 60m sounding to a ZOC/QoBD category for the different survey coefficients.

Project: Cross-check of Data Quality Chapters of S-1xx Product Specifications

Geospatial data may vary in quality in accuracy, precision, completeness, and consistency in space, time, and theme. Geospatial data quality allows producers to evaluate and report how well a dataset meets the criteria set forth in the product specification and users to assess fitness for use for a particular application. Working with data quality includes understanding the data quality concepts, defining data quality conformance levels in data product specifications based on product requirements, specifying quality aspects in application schemas, evaluating, and reporting. The IHO Data Quality Working Group (DQWG) provides guidance on data quality aspects to hydrographic offices to ensure harmonized implementation. In 2021 DQWG Meeting, a sub-WG was formed and tasked to perform a cross-check of the existing S-1xx Product Specifications and their respective data-quality chapters to the data quality aspects described in IHO S-97 (IHO Guidelines for Creating S-100 Product Specifications).

In this reporting period, Christos Kastrisios and Wu Lingzhi (China Maritime Safety Administration and current DQWG Chair) performed a comparison that identified various discrepancies between the S-1xx Product Specifications and IHO S-97, as well as inconsistencies among them. The detailed findings were reported to HSSC at the 2022 meeting (a summary is outlined in Table 33-2). The research team is working toward the development of a template for the DQ chapter of S-1xx Product Specifications to ensure harmonization across product specifications.

Table 33-2: Summary of the DQ elements cross-check.

Recommandations	S-101	S-102	S-111	S-121	S-122	S-123	S-127	S-129
1. Completeness	N	Y	Y	Y	N	N	Y	N
2. Conceptual consistency	N	Y	N	N	N	N	Y	N
3. Domain consistency	N	Y	N	Y	N	N	Y	N
4. Format consistency	N	Y	N	Y	N	N	Y	N
5. Topological consistency	N	N/A	N/A	Y	N	N	Y	N
6. Positional Accuracy	N	Y	Y	Y	N	N	Y	N
7. Thematic Accuracy	N	Y	Y	Y	N	N	Y	N
8. Temporal Quality	N	Y	N	Y	N	N	Y	N
9. Aggregation	N	N	Y	N	N	N	Y	N
10. Introduction to DQ	N	N	Y	N	N	Y	N	N

Project: Towards Automated Compilation of ENCs

Nautical chart compilation is a time-consuming process requiring much human interaction. Regardless of the many research efforts, cartographers are required to perform most generalization tasks manually or semi-manually. Furthermore, while many database-methods are now used and there are good support tools, current approach necessitates the maintenance and storage of digital product objects as first-class entities, i.e., objects that must be maintained for a significant length of time independent of their initial source data. This implies a significant effort to update, check consistency, maintain, and distribute data, all which can heavily impact the efficiency of the workflow.

A fully automated solution could generate products on demand, at the right scale, at the point of use, and directly from a seamless database, such as a National Bathymetric Source, inclusive of the necessary chart features. Such a solution could support

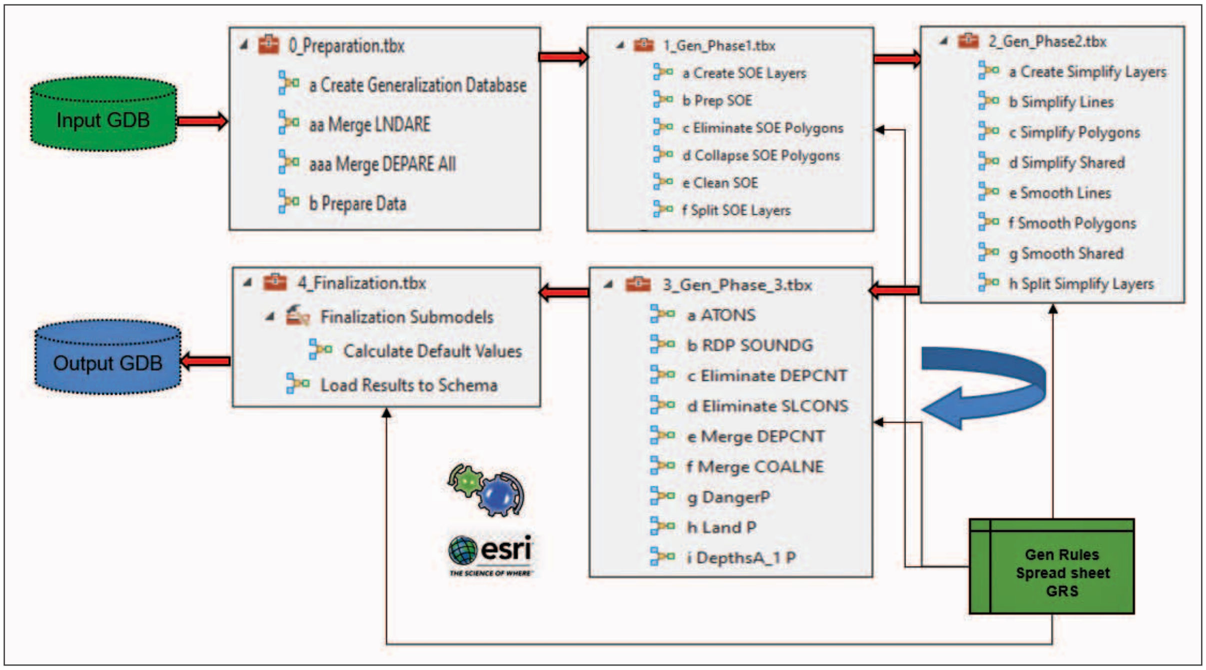


Figure 33-8. The Automated Nautical Generalization model phases.

rapid chart update and the Precision Navigation application while generating products dedicated to specific vessel characteristics that could be updated as new information becomes available. However, such a solution is still far from reality, in part due to the limited availability of algorithms that perform consistently while respecting the safety concerns and other requirements of the final product. Furthermore, it remains uncertain whether algorithms can fully substitute the human thought process and the subjective decisions often involved in map compilation.

This research aims to assess the viability of, and contribute to, the holistic ideal solution of a fully automated nautical chart production. Toward this goal, this research attempts to translate cartographic practice and theory into algorithmic building blocks that can iterate and cooperate to find the appropriate chart representation for any given area, any scale, optimized according to set criteria.

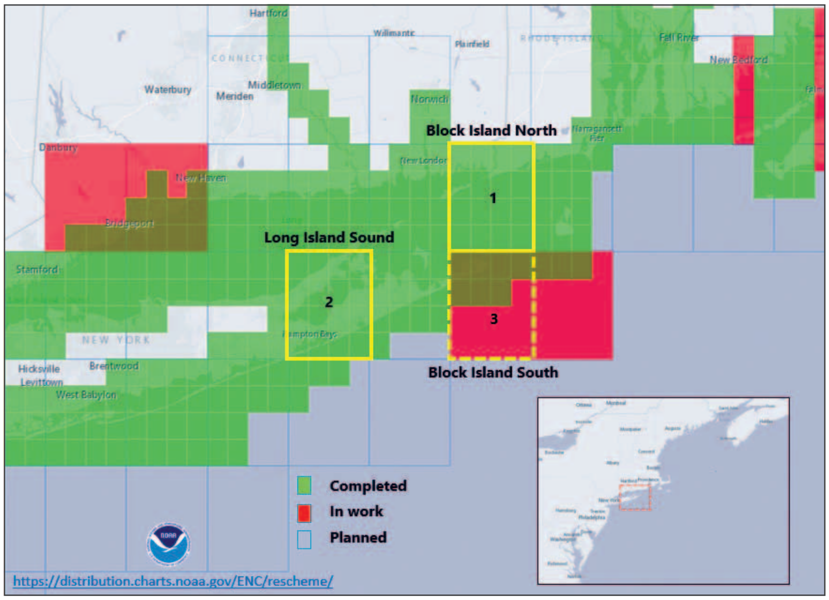


Figure 33-9. The Study Area ENCs—Long Island Sound, NY, USA (Green: completed cells, Red: in work, Grey: planned, Yellow: 16 band 5 cells study case, Dashed Yellow: mixed bands (5&4) case).

In the previous reporting periods, Tamer Nada, under the supervision of Brian Calder and Christos Kastrisios, and in collaboration with Christie Ence from MCD, Craig Greene and Amber Bethell from ESRI, investigated previous research efforts toward automated map production, reviewed the available relevant nautical cartographic standards and specifications, and extracted and categorized the nautical chart generalization guidelines. The extracted guidelines were subsequently translated into rules and defined as conditions to be respected during the generalization process. A template was developed that defines the properties of those constraints, feature class to which they apply, geometry type, a hierarchy level, as well as a simple pseudo code for each condition. Using the template and the guidelines, a Generalization Rules Spreadsheet (GRS) was developed that contains information about the selected feature classes, tolerances that will be used for each scale, hierarchy levels and operations that need to be applied on each feature within each theme. Lastly, an Automated Nautical Generalization model (ANG) was developed in the ESRI environment. The ANG utilizes the GRS to drive the generalization to the desired output scale, using generalization tools available with ArcGIS Pro.

In the current reporting period, the ANG model was organized in five main phases or sub-models (Figure 33-8); each phase consists of various generalization tools that are used to automate the process. These sub-models were developed in ArcGIS Pro and contain the necessary generalization tools either in Python scripts or model builder format.

Following the NOAA's new ENC coverage scheme, the ANG model was tested in three different areas in the greater New York Long Island area (Figure 33-9) that represent different real-world scenarios (e.g., with and without edge matching inconsistency, cells of different bands), to generalize band 5 to band 4 data.

The model output in all scenarios showed no topological violations. Figure 33-10 illustrates the model results in the case with a couple of edge matching inconsistent cells (i.e., New York, Long Island Sound area), where the 16 band 5 ENC features (scale 1:20 k) were generalized to one Band

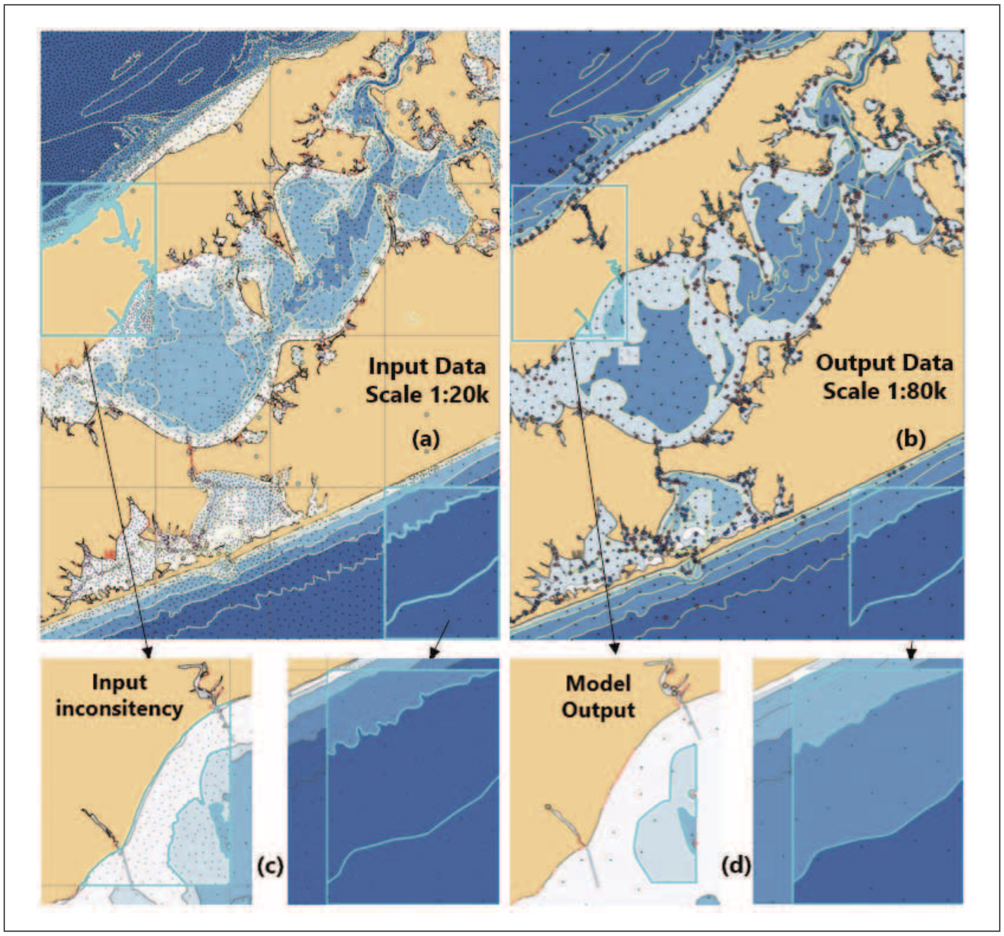


Figure 33-10. The study area—Long Island Sound, NY, USA (a) Pre-generalization data, (b) Post-generalization data, (c) Input inconsistency cells, (d) Inconsistency model output.

4 cell (scale 1:80 k). However, for the two highlighted cells with edge matching issues, the model treated and generalized them separately as it couldn't identify their spatial connection.

While free of topological errors output, the model output did demonstrate safety violations of the generalized depth areas and contours. This is due to the fact that the generalization tools available in ArcPro do not, generally, respect the safety constraint. Since safety is of utmost importance in nautical charting, as a first step to remedy this deficiency, a tool was developed that detects depth contours' safety violations. The tool is composed of three main stages as shown in Figure 33-11 (a). The output of this safety validation tool (Figure 33-11d and e) is the safety violation polygons sorted in an attribute table by area and perimeter.

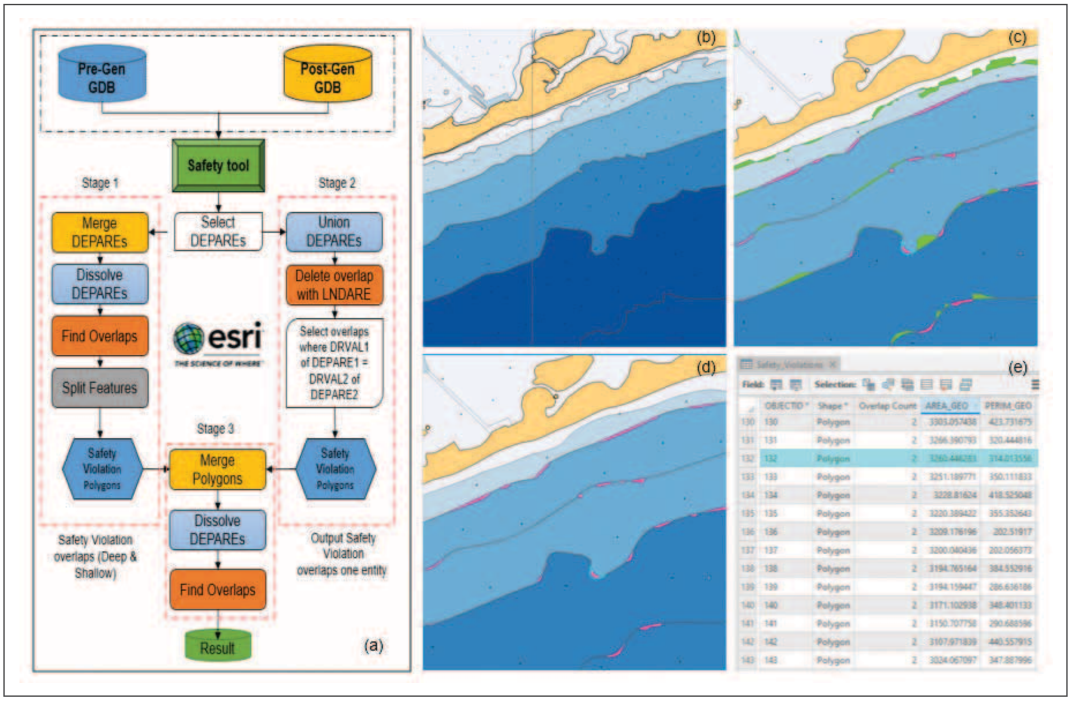


Figure 33-11. (a) Safety Validation tool flowchart with three main stages (b) Model Input (c) Model Output with safe generalization-green and unsafe-red (d) Safety violations polygons (e) Geo-table with safety violations area and perimeter.

Project: Speed Mapping Challenge

The benefits of, and the acquired expertise from, the Center efforts to automate individual generalization tasks (i.e., Task 33: Cartographic Sounding Selection, Sounding Selection Verification Methods, Data Quality Polygon Simplification, Task 31: Hydrographic Sounding Selection, Task 24: Satellite Derived Bathymetry), to model the chart compilation workflow and generalize ENC Skin-of-the-Earth (SOE) features with no topological errors (Task 33: Towards Automated Compilation of ENCs), to shed light and gain knowledge on the capabilities of free and open software for geospatial applications (Task 34: Free and Open Software for Ocean Mapping), to build innovative chart symbology (Task 32: Visualization and Integration of Bathymetric Data Quality on ENCs, Task 37: CartoSemiotics), as well as the national and international collaborations the Center has built (Figure 33-12), were demonstrated at a recent international competition organized by the Canadian Hydrographic Service, the Canadian Hydrographic Association, and the Canadian Ocean Mapping Research and Education Network. The scope of the "Speed Mapping Challenge" was to prototype a cartographic production chain using open data and free software.

The work by Christos Kastrisios, Tamer Nada, Noel Dyer, Stelios Contarinis, and Jose Cordero won the first prize, ranked first unanimously by all judges. The SEGU-United Team (SEGU stands for the nationalities of the Team members, i.e., Spain, Egypt, Greece, and USA) developed a semi-automated methodology workflow building upon the research efforts and the expertise of the team members. To achieve the goals of the competition, the Team accessed open data sources (e.g., Canadian Vector CanVec, NCEI, Sentinel Hub EO, Open Street Map, and Google Earth) to acquire bathymetry in unsurveyed areas, enrich database with conspicuous and other important chart features (e.g., churches, chimneys, piers, lights, buoys, buildings), and to separate natural from man-made shorelines. Accordingly, the Team used open-source software for querying and accessing data (e.g., Overpass Turbo), as well as processing and visualizing data (e.g., QGIS, LBHSS Label-Based Hydrographic Sounding Selection, HydrOffice, MapBox, Python Libraries). Where no available free software solution was identified, or could not be utilized (e.g., due to a requirement for .000 files), the team developed/improved custom scripts/tools in the Python programming language.

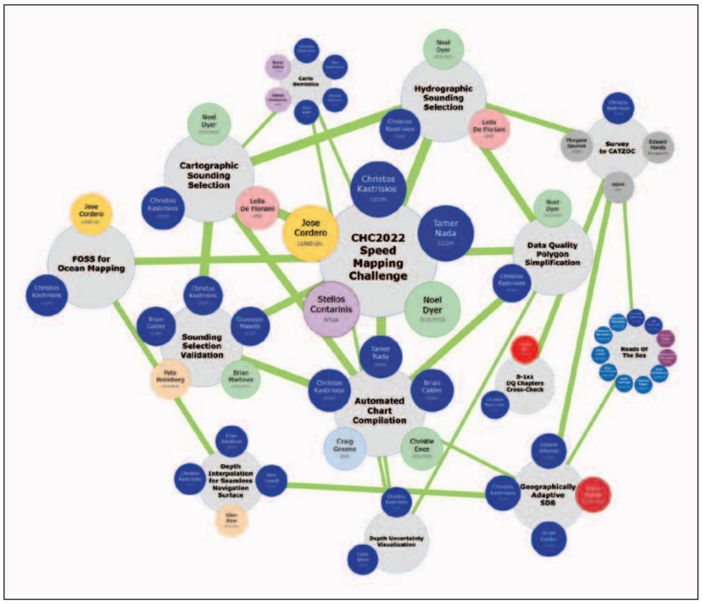


Figure 33-12. The constellation of research projects for chart compilation.

The competition was an opportunity for the Team to apply research, identify deficiencies, make improvements, and test cartographic concepts on complete datasets into the greater context of chart compilation. This includes workflows/algorithms for generalizing shorelines without topology errors, sounding selection, validation of results, and visualization. Throughout the process the Team considered the accuracy of the map (i.e., safe contours and safe sounding selection), the topology (e.g., gaps and overlaps of SOE features), the legibility of the map (e.g., avoid soundings overlaps), and the flexibility and robustness of the methodology. The latter was demonstrated with the selection of two test areas with different characteristics that pose different challenges. In detail, source bathymetry in Thunder Bay was roughly half full seabed coverage with the other half being spot soundings, while the seabed was relatively smooth/evenly sloped with land being on the one side only. Bathymetry in Ottawa River consisted of survey lines with a few intertidal areas and an unsurveyed area, with water areas being surrounded by land and with the presence of two islands in the study area. The produced "chart-like" maps in Thunder Bay and Ottawa River areas are illustrated in Figure 33-13.

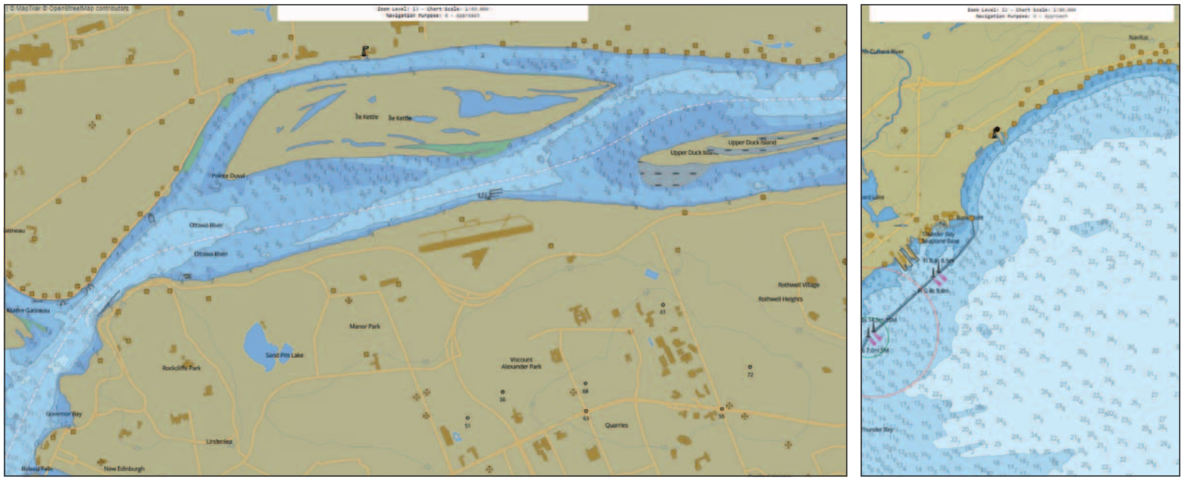


Figure 33-13. Left: Thunder Bay screen capture using our custom map service. Right: Ottawa River Nautical screen capture using our custom map service.

Programmatic Priority 2

ADVANCE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES

NOFO Requirement 13

Development of new approaches for the application of spatial data technology and cartographic science to hydrographic, ocean and coastal mapping, precision navigation, and nautical charting processes and products.

JHC/CCOM responded to NOFO requirement 13 with one task:

Task 34: Spatial Data Technology in the Context of Charting and Ocean Mapping

Task 34: Spatial Data Technology in the Context of Charting and Ocean Mapping

JHC Participants: Christos Kastrisios, Paul Johnson, Larry Ward, Michael Bogonko, and IT Staff

Other Collaborators: Jose Cordero (Spanish Hydrographic Office)

Project: Free and Open-Source Software for Ocean Mapping

The hydrospatial community has advanced the use of Free and Open-Source Software (FOSS) in the ocean mapping workflow by developing new solutions and adopting tools originally developed for other applications. These specialized tools allow users to conduct common tasks in hydrography without the need for commercial software, but, most importantly, to perform tasks for which no proprietary solutions exist. Besides the above tools, there is a plethora of additional FOSS for geospatial applications (FOSS4G) that could be used in ocean mapping. There is often documentation for these tools, however, a comprehensive study of their capabilities and performance in ocean mapping is not available. It is not surprising that the use of FOSS4G within hydrographic offices remains limited. To fill this gap, we are conducting a project that aims to investigate the functionalities of the available FOSS4G and raise awareness about the potential benefits of their use in the domain.

This project aims to discover the FOSS4G that may be used in ocean mapping (hereinafter, Free and Open-Source Software for Ocean Mapping (FOSSOM)), evaluate their features, compare their performance against commercial software, to identify if and how they can complement the latter, and, lastly, investigate the viability of a workflow based on FOSSOM. In the previous reporting periods, Christos Kastrisios, in collaboration with Jose Cordero from Instituto Hidrografico (Spanish Hydrographic Office), conducted an online discovery of the available tools by marine research centers, ocean related academic institutions, hydrographic offices, regional mapping initiatives, the Open Source Geospatial Foundation, and popular repositories and research supporting websites, such as GitHub and ResearchGate; a total of 110 relevant software packages of potential FOSSOM were identified. This list of potential FOSSOM was filtered out according to factors such as the level of complexity, maturity, popularity, operating system, and functionalities of the software. After the initial selection process, 28 different pieces of software were left for further evaluation.

Subsequently, as reported in the JHC 2021 Progress Report, Jose Cordero tested the selected software in a mapping mission near the Canary Islands (Spain), as a part of mapping the Spanish Exclusive Economic Zone (EEZ). FOSSOM was used to optimize survey design, troubleshoot and evaluate multibeam systems performance, generate derived products, and enhance data visualization and dissemination. The testing during the above survey campaign demonstrated that FOSSOM can be an effective complement to the commercial software used onboard, however, no single FOSSOM can fully substitute any of the leading commercial software used in the hydrographic profession.

In the current reporting period, the research team focused on further testing FOSSOM in a deep-water survey and adding FOSSOM in hydrography education and capacity building. As a continuation of the software testing in real deep-water survey, more experimentations were conducted aboard R/V *Hesperides* during the 2022 Spanish EEZ mapping campaign near the Balearic Archipelago in the Mediterranean. The workflow for leveraging the use of FOSSOM complementing commercial software was improved, bringing in new tools such as Iskaffe (the Geological Survey of Norway) to help assess the quality of the seafloor backscatter data acquired by multibeam echosounders.

Regarding the education and capacity building aspects of the effort, open-source hydrographic tools were extensively used for the teaching of the multibeam subject within the FIG/IHO Cat A course at the Spanish Hydrographic Schools. Particularly, "Kluster," the hydrographic processing package to produce accessible bathymetry products by NOAA OCS, was successfully utilized to help explain how a multibeam system works. Two in-person workshops on FOSSOM were offered to the Spanish scientific marine community in Spain at IHM facilities. M.S. and Ph.D. students from the University of Cadiz as well as scientists and technicians from the Spanish National Science Council participated in the event.

In addition, and with the occasion of the winter meeting of the THSOA Latin America chapter, an invited presentation on FOSSOM was given to attendees from 11 Spanish and Portuguese speaking countries, demonstrating the interest of the community to open-source software. An online workshop on the use of "Kluster" is scheduled for January 2023. A GitHub repository with a short description of and the link to each FOSSOM has been made available online (https://github.com/monocilindro/Awesome-Hydrospatial#hydrographic-data-processing).

Project: Enhanced Web Services for Data Management – Enterprise Geospatial Platform

The Center has maintained an online data access portal using different technologies since 2011. During the summer of 2022, Paul Johnson and the IT team installed a new server to host the primary GIS portal. The new server is a significant upgrade over the previous server which has been providing services for the Center for the last four years. The latest server has dual Intel Xeon Gold 5320 CPUs, each having 26 cores. These CPUs are paired with 256 GB of RAM, dual 1 TB SSDs running in a RAID 1 configuration for operating system, and 14 TBs of storage, also in a RAID configuration. Following installation, Johnson loaded the most recent version (11) of ESRI's Enterprise software on the server and configured the system to be both a Portal and Image Server. The operational system went online in August of 2022 and Johnson has been loading services on it since. The current plan is to have the new server, http://bit.ly/3FuS2c0l (Figure 34-1), host new content and services, while the previous server, http://bit.ly/3HOJcZl, act as a development server and as a host for collaborative services.

To showcase some of the capabilities of the new GIS portal, the very popular Western Gulf of Maine, Long Island, and Southern New England (WGOM-LI-SNE) web services, image services, web maps, and web apps were the first services migrated to the new GIS portal. This compilation incorporates all publicly available bathymetry and backscatter, tracks contributing source to the synthesis using survey domains with embedded metadata. Each of these data layers are now available through the Data Portal's REST interface, http://bit.ly/3v61Idr, and through a newly built web application, http://bit.ly/3G2Rrjc (Figure 34-2), which also allows for users to interact with each of these layers.

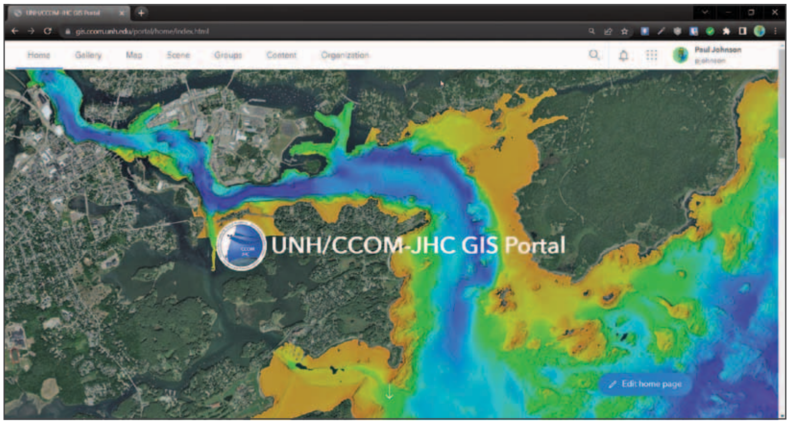


Figure 34-1. A portion of the current landing page of the Center's Data Portal (http://bit.ly/3FuS2c0l) where users can find highlights of some web services developed from research and activities conducted at the Center.

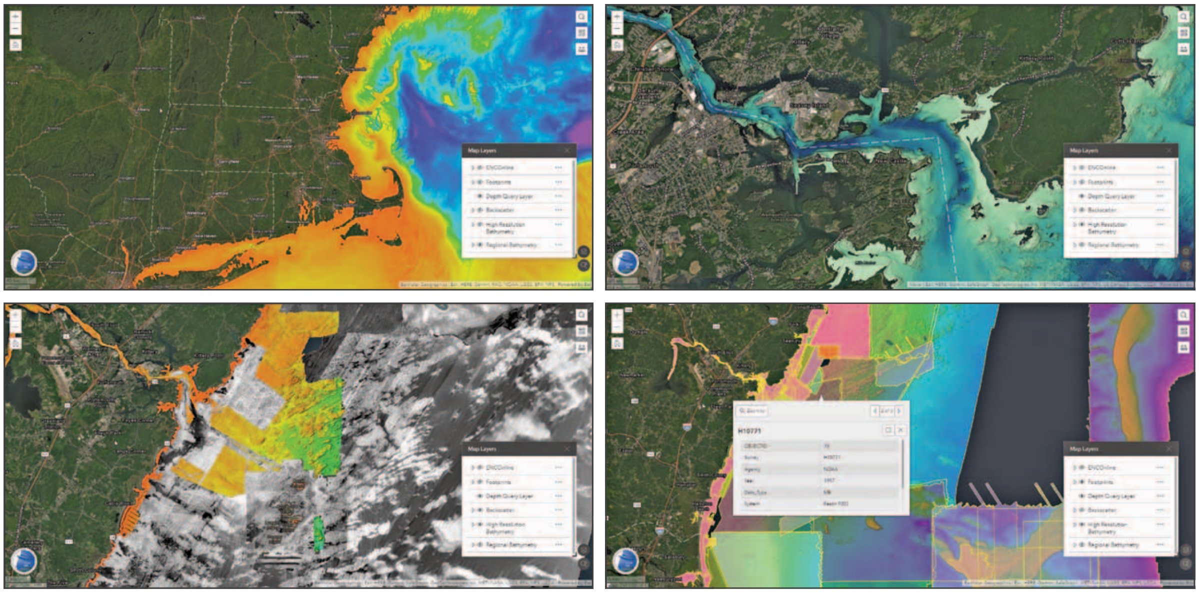


Figure 34-2. Examples of different datasets available through the Western Gulf of Maine, Long Island, and Southern New England Compilation (http://bit.ly/3G2Rrjc). Upper-Left: Regional shaded-relief bathymetry with a color palette that dynamically adjusts. Upper-Right: High resolution bathymetry with a blue-green color palette. Lower-Left: Backscatter compilation overlaid on the regional bathymetric data. Lower-Right: Survey domains with embedded metadata tracking the source of each dataset contributing to the compilation.

Project: High-Resolution Bathymetry, Surficial Geology Maps, and Interactive Databases: Continental Shelf from Coastal New Hampshire to Jeffreys Ledge

Paul Johnson, Larry Ward, and Michael Bogonko finalized and published an interactive web application in 2021 for the bathymetry, backscatter, and surficial geology of the New Hampshire shelf. With the new server in place, Johnson set about remaking the web application for these datasets with the now improved capabilities provided by the server in both designing and implementing web applications. The application for the New Hampshire shelf is now available from the Center's new portal at http://bit.ly/3V6iJtl (Figure 34-3). The new interface significantly speeds up the access to the bathymetry and backscatter layers and has also improved the ability to interact with the vector layers and their associated information by displaying embedded raster data within an information window. Johnson plans to continue making improvements to this web application during the spring of 2023.

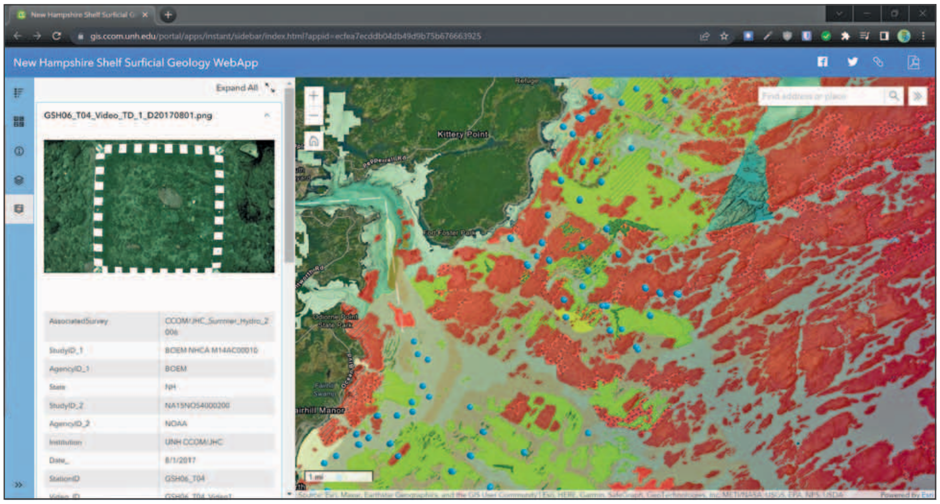


Figure 34-3. Screen shot from the New Hampshire Shelf Surficial Geology web application (http://bit.ly/3V6iJtl).

Project: **Large Dataset Visualization and Data Assessment Tools for the Web**

During the summer of 2022, Johnson tested the capabilities of the new GIS server with the GEBCO 2022 grid. This dataset is fairly large, measuring 43,200 rows x 86,400 columns (3,732,480,000 elevation values), and makes an ideal dataset to test server capabilities. Johnson, working on progress made during 2021, loaded the bathymetry, elevation, type identified layer, and the indirect measurement mask into the new server and from them generated a new web application (Figure 34-4).

The new services and application have much better performance and capabilities than those available on the previous GIS server. The new configuration has an elevation layer available through the Image Server of the portal, and has tiled services for the bathymetry, elevation, TID, and mask. This configuration allows the server to very rapidly visualize the entire globe from any location and also allows for visualization of a rotating globe with no manual intervention.

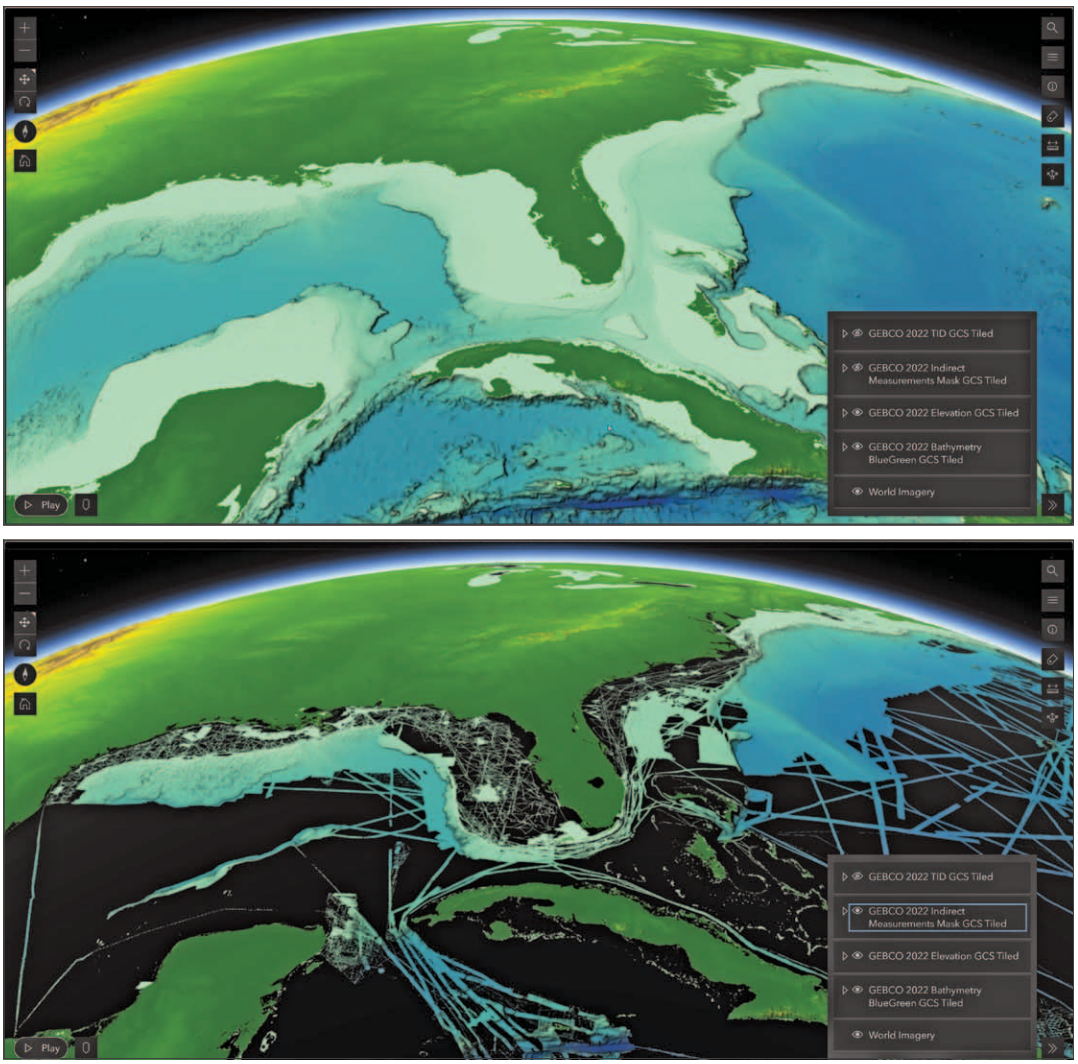


Figure 34-4. Visualizations of the GEBCO 2022 datasets (http://bit.ly/3YwNNFz) using the Center's new GIS portal. Upper image shows the bathymetry and elevations with a 5x vertical exaggeration. Lower image shows the same area with areas of indirect measurements masked.

 Technology for Digital Navigation

Programmatic Priority 2

ADVANCE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES

NOFO Requirement 14

Application of hydrodynamic model output to the improvement and development of data products and services for safe and efficient marine navigation.

JHC/CCOM responded to NOFO requirement 14 with one task:

Task 35: Application of Hydrodynamic Models to Navigation Products

Task 35: Application of Hydrodynamic Models to Navigation

JHC/CCOM Participants: Tom Butkiewicz, Ilya Atkin, Jang-Geun Choi (OE)

Project: High-resolution Situational Flow Visualization

The Center has integrated large-scale flow models into precision navigation visualizations, for example in Task 32, the NGOFS2 model is used to provide surface current streamlines along the Mississippi River. However, these models generally do not provide fine-scale details that are practically useful for precision navigation scenarios. The visualization lab is looking at using individual, finer-scale hydrodynamic models to provide situational flow visualizations for specific locations of interest.

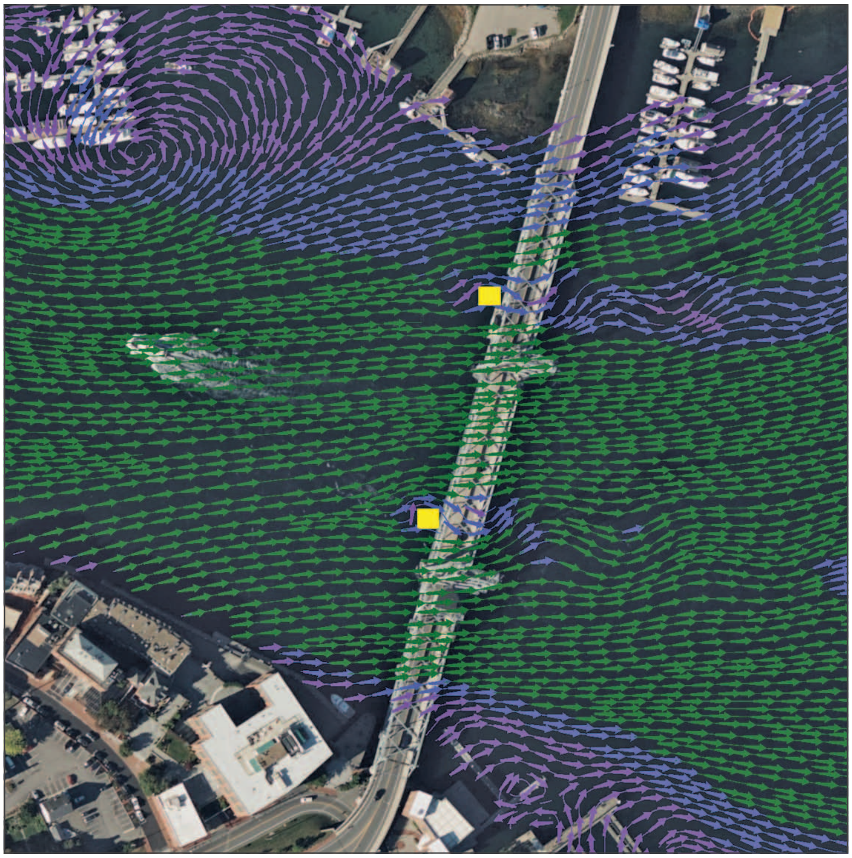


Figure 35-1. Web based streamline visualization of surface currents in Piscataqua tidal model, showing flow patterns around (roughly-simulated) bridge pilings (yellow squares).

As proof of concept, a hydrodynamic model developed by UNH OE post doc Jang-Geun Choi was imported into the web-based visualization interface described in Task 32. As shown in Figure 35-1, this tidal flow model of the Piscataqua River can provide higher resolution depictions of flow patterns around individual bridge pilings. It is proposed that, for specific areas of interest on rivers, such as tight turns or obstacles like bridge pilings, limited-scope hydrodynamic models be created, using the high resolution bathymetry available, and run for the range of likely flow rates. A visualization interface could then pull the current flow rate from a nearby gauge and display the flow data from the appropriate model run.

Programmatic Priority 2

ADVANCE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES

NOFO Requirement 15

Improvement in the visualization, presentation, and display of hydrographic and ocean and coastal mapping data, vessel data, and other navigational support information such as water levels, currents, wind, and data model outputs for marine navigation. This would include real-time display of mapping data and four-dimensional high-resolution visualization of hydrodynamic model output (water level, currents, temperature, and salinity) with associated model uncertainty and incorporate intelligent machine analysis and filtering of data and information to support precision marine navigation.

JHC/CCOM responded to NOFO requirement 15 with six tasks:

Task 36: Tools for Visualizing Complex Ocean Data Sets

Task 37: General Semiotics

Task 38: Artificial Intelligence and Machine Learning for Analysis and Filtering (work not started)

Task 39: Hydrographic Data Manipulation Tools

Task 40: Real-time Display of Ocean Mapping Data

Task 41: BathyGlobe

Task 36: Tools for Visualizing Complex Ocean Data Sets

JHC Participants: Tom Butkiewicz, Andrew Stevens, Kindrat Beregovyi, Colin Ware

Project: Applications of the Unity Graphics Engine

The Visualization Lab has consistently sought ways to make the tools and approaches they develop accessible to the broadest possible community. In previous years, in support of this effort, the Visualization Lab has developed a set of plugins and scripts for the Unity engine to enable loading, viewing, and interacting with hydrographic and geospatial datasets. They form a Hydrographic Toolkit for Unity, and they are freely available on the 'Tools' section of the Visualization Lab's website. They have also developed a BAG (Bathymetric Attributed Grid) Loader plugin for Unity which leveraged the built-in terrain system to achieve good performance for real-time viewing of high-resolution bathymetry, a point cloud plugin for Unity, and a Unity script that adds 3D flight capabilities to project. These tools have been described in previous progress reports. There were no active projects categorized under this task during this reporting period. However, work on transforming OFS model output into S-111 surface currents streamline geometry tiles for web-based visualization is described within Task 32, "Web-based 3D Visualization of Next Generation S-100 Datasets."

Task 37: General Semiotics

JHC Participant: Christos Kastrisios, Tom Butkiewicz, Briana Sullivan

NOAA Collaborators: Christie Ence, Colby Harmon, and Megan Bartlett (NOAA MCD)

Other Collaborators: Stelios Contarinis and Byron Nakos (National Technical University of Athens, Greece)

Project: CartoSemiotics

The new S-1xx product specifications being developed by IHO Working Groups (WGs) enrich navigation related information on Electronic Chart Display and Information Systems (ECDIS). However, many of them do not yet have defined symbology, e.g., the S-122 Marine Protected Areas (MPAs), S-126 Marine Physical Environment

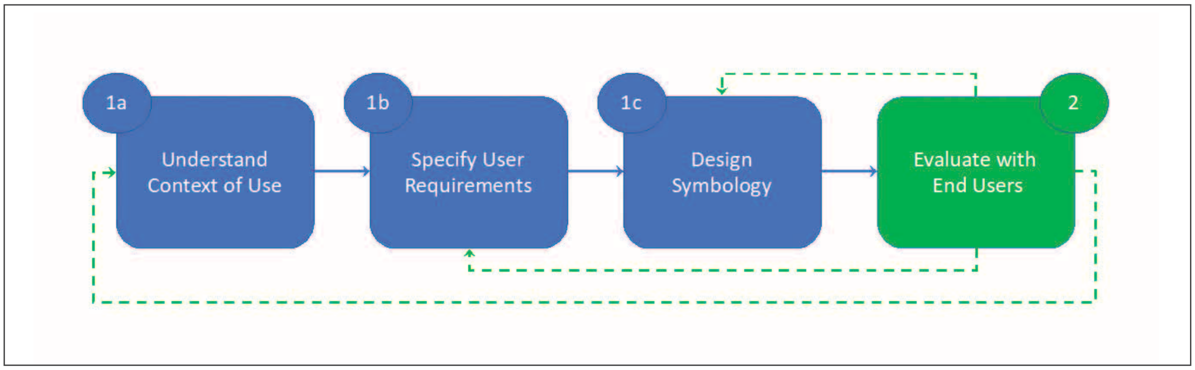


Figure 37-1. User Centered Design Methodology.

(under development), S-127 Marine Traffic Management, and S-131 Marine Harbour Infrastructure (under development). Therefore, as S-122 Edition 1.0.0 explains, implementers are allowed to select the technique and style of representation that they believe is most suited to their requirements, but they should plan for future versions that may contain a portrayal catalogue by making adequate preparations in the system.

Symbology is an essential part of the cartographic profession as it helps humans to decode mapped real-world features. For example, intuitive, easily understood, symbology can support the effective management of MPAs by ECDIS users and the various Coastal Zone Management and Marine Spatial Planning stakeholders. Therefore, Christos Kastrisios and Thomas Butkiewicz, in collaboration with Stelios Contarinis and Byron Nakos from the National Technical University of Athens, and Christie Ence, Colby Harmon, and Megan Bartlett from MCD, are working on the development of new symbology for the S-1xx Product Specifications following a user-centered design (Figure 37-1). The first, broad, phase of this effort comprises the understanding of context of use, user requirements, and symbology design. The second phase focuses on making improvements to the initially developed symbology based on feedback by stakeholders and user surveys.

The nautical chart is a product highly regulated by various IHO publications, such as the Publication S-4 Regulations for International (INT) Charts and Chart Specifications that provides guidelines for every aspect of chart compilation, including chart construction, utilized units, use of color, requirements for the representation of topography, hydrography and aids to navigation, generalization guidelines for various chart features, text, chart maintenance, etc. This high level of standardization, on the one hand, answers many of the research questions with respect to context and user requirements, but, on the other hand, takes away some flexibility from symbology design (e.g., due to specific colors being reserved for specific uses).

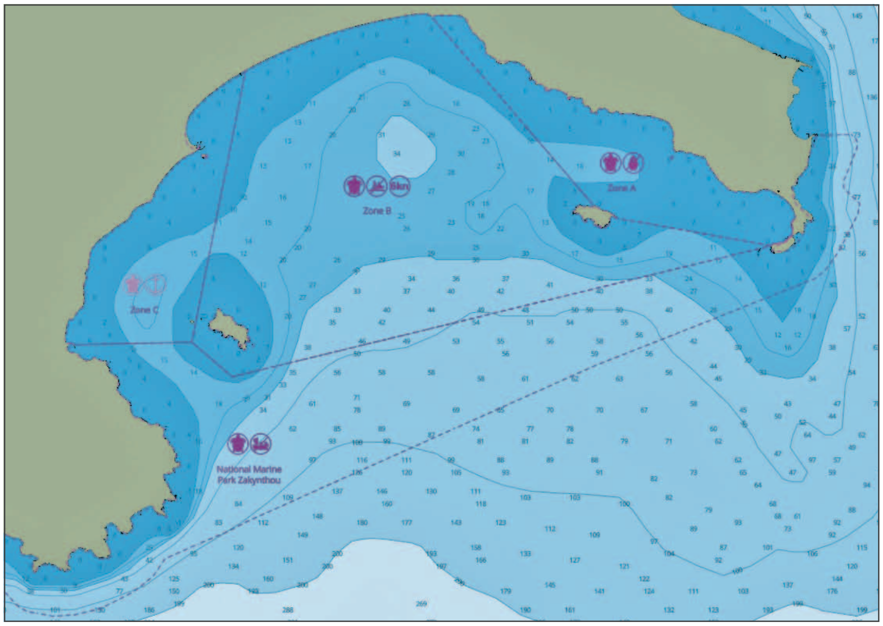


Figure 37-2. The Monachus Turtle MPA Charting Testbed in Zakynthos, Greece.

Figure 37-3. Preliminary symbols for the new feature types in S-126, S-127, and S-131, built for 3D interactive web-based applications.

As reported in last progress report, in designing symbology for the S-122 MPAs, Christos Kastrisios, in collaboration with Stelios Contarinis and Byron Nakos from the National Technical University of Athens, worked on the development of symbology for the various S-122 MPA feature types, information types, and restrictions, reviewed use cases and the legal foundation for the protection of MPAs as well as existing mapping methods for the protection of marine mammals in the Mediterranean and other geographic regions. The research team developed icons representative of the MPA type (e.g., the species being endangered; historical or cultural submerged sites; vessels surveillance) and regulations (e.g., slow zones with specified speed limits in knots; permitted, prohibited, and restricted marine activities such as anchoring, small- and large-scale fishing, passage for various types of vessels; vessel traffic services), as well as the selection of symbol color, enclosing shape, and size. In terms of enclosing shape, various shapes are used in nautical charting, i.e., circles, triangles, squares, diamonds, and hexagons. To avoid confusion with existing chart symbols without an enclosing shape (see e.g., a generic anchorage symbol), as well as any quantitative comparison due to icons' size difference, a circular enclosing shape was used. In terms of color, magenta is the color on charts for dangers and other information. Magenta has the advantage of being one of the four ENC basic colors and is established as the color utilized to attract mariners' attention to important information. Therefore, for the preliminary symbols, saturated magenta was used to denote restricted and prohibited activities (thus informing mariners about the MPA becomes important) and less saturated magenta (magenta faint) for the less important (visually and navigationally), permitted activities.

In the current reporting period, the team reviewed the existing chart symbols for their physical size which showed that symbols with an enclosing shape vary from 6 to 12mm. Therefore, the size of the preliminary symbols was set to 9mm at chart scale. Furthermore, the team experimented with the use of green color in place of the magenta faint for the permitted activities. Two MPAs in Greece (Figure 37-2) were identified and used as test beds for further experimentation.

For the S-126, S-127, S-131, this reporting period Christos Kastrisios, Tom Butkiewicz, and Briana Sullivan, investigated the development of icons representative of the feature mapped, utilizing existing chart symbols where available/possible. The sample preliminary symbols are illustrated in Figure 37-3. In terms of the shape and color, the current bold black and white rectangular markers were purposefully designed to contrast with ENC basemap and overlayed lidar and other data in 3D web-based applications, so that they clearly stand out as interactive elements (see Task 32 Web-based 3D Visualization of Next Generation S-100 Datasets project).

As part of the second phase of the user-centered design, Christos Kastrisios, in collaboration with Christie Ence, Colby Harmon, and Megan Bartlett from MCD, developed a questionnaire for the students in the Nautical Cartography Category B program offered by MCD. The questionnaire aimed to evaluate the intuitiveness of the developed symbols for all four Product Specifications, as well as alternative symbols for the S-126, S-127, and S-131, and investigate different color combinations for the S-122 MPA symbology. The analysis of responses will be carried out and reported in the next reporting period along with symbology improvements based on the received feedback.

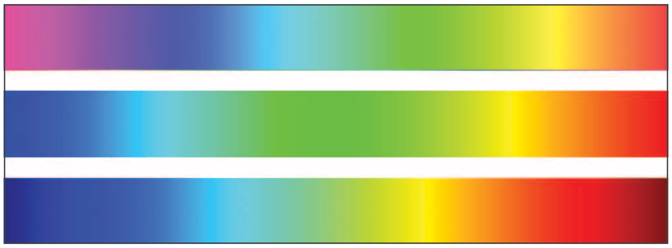


Figure 37-4. Three variants of the original rainbow colormap.

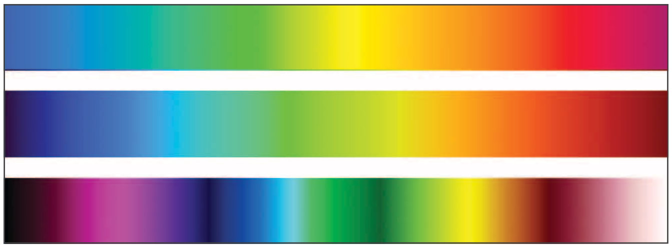


Figure 37-5. Three newer rainbow colormap variants.

Project: **Colormapping**

A paper entitled "The Rainbow Colormap Considered Harmful" published in 2007 has had a disproportionate impact on the data visualization community which now mostly eschews the use of rainbows. However, they are still extensively used by scientists. There are three basic arguments against the rainbow colormaps: 1) They are not monotonic in luminance, which can distort the shapes people infer from the data; 2) They are not perceptually uniform, which can distort the perception of data variation; 3) They partition the data into distinctly colored regions or bands, which create false divisions within the data. Empirical evidence is available to support all these positions.

There is also experimental evidence in support of rainbow colormaps. They have been repeatedly shown to be the most accurate in studies where a value must be read using a key. Being able to read a temperature value is essential for common visualizations like weather maps where people need to get an accurate estimate of the predicted temperature at specific locations. Other research shows that rainbow colormaps may draw attention to global structure within the data and enable people to better reason about relationships between data distributions.

The critiques levied against rainbows mostly have merit for the original rainbow which was (and is) a simple sequence of interpolations in the color space provided by red, green and blue colors produced in a dot pattern on computer monitors. [R+B →B→B+G→G→G+R→R]. Figure 37-4 shows three variants of the original rainbow colormap.

It is well known from color psychophysics that the ability of the brain to see smaller visual features in the environment depends mostly on variation in luminance, or more precisely in L* which is a metric of luminance scaled according to the response of the human visual system. The smaller the feature in the data, the less color (in the sense of hue and saturation) contributes to our abilities to detect those features relative to luminance. This correlation means that for a colormap to effectively show details in the data, it should have a lot of luminance variation. In other words, feature resolving power depends mostly, although not entirely, on luminance variation.

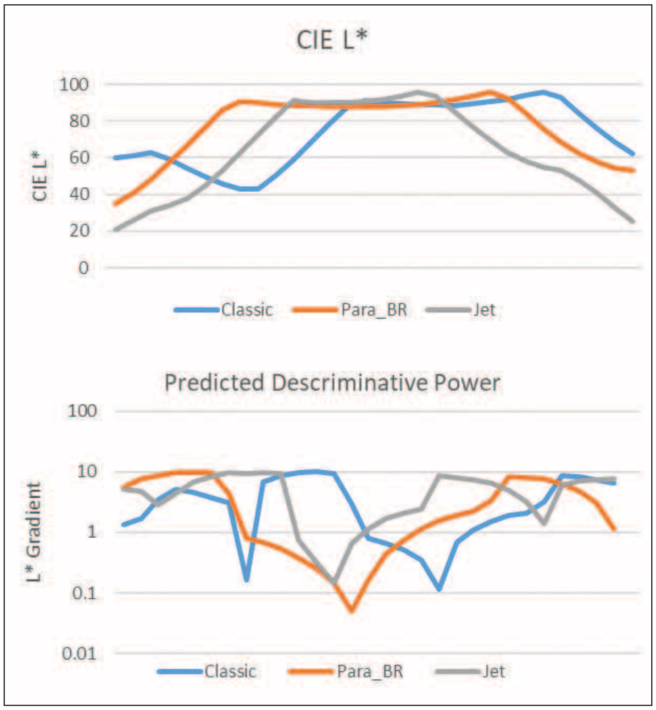


Figure 37-6.(above) the Luminance (L*) profiles of the colormaps shown in Figure 37-4. (below) The predicted feature resolving power of the colormaps along their lengths.

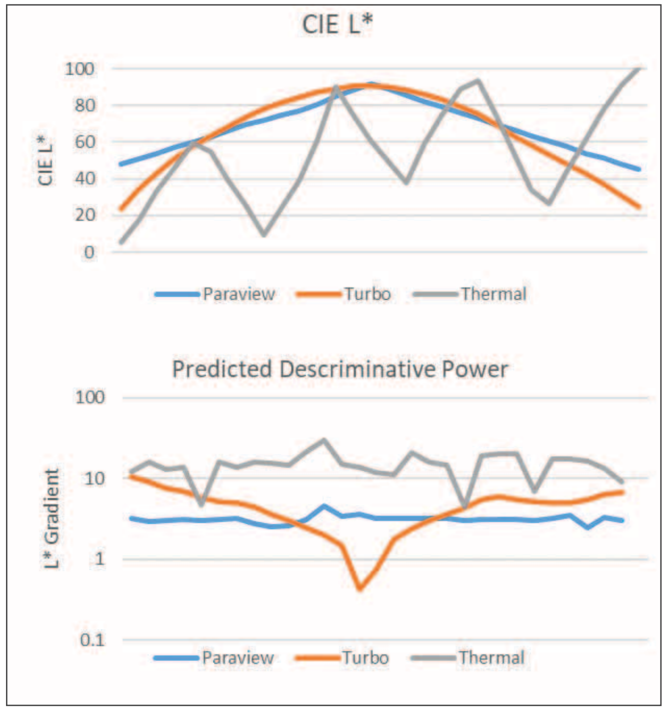


Figure 37-7. (above) the Luminance (L*) profiles of the colormaps shown in Figure 37-5. (below) The predicted feature resolving power of the colormaps along their lengths.

We can apply these ideas to understand tradeoffs in different rainbow colormap designs. CIE L* is a measure of perceived luminance often used to create and evaluate colormaps. The L* profiles of the colormaps shown in Figures 37-4 and 37-5 are shown in Figures 37-6 and 37-7. Furthermore, the *gradient* of L* at a particular point on a colormap is highly correlated with how well we can detect features in visualized data (hue and saturation also contribute to a limited degree). We can use L* gradient to show how the feature resolving power of a colormap varies along its length. Figure 37-6 shows that the classical HSV rainbows are extremely non-uniform in terms of how much data they communicate at different points, especially between cyan and green. However, by creating a diverging rainbow with a luminance peak in the center and linear (in L*) darkening to the left and right, as shown at the top in Figure 37-5. This rainbow has relatively uniform feature resolving characteristics as shown in Figure 37-7.

Designers can also increase the feature resolving power of a colormap by introducing a sawtooth pattern in the colormap's luminance profile. For example, the bottom colormap in Figure 37-5 traverses from light to dark (or the reverse) seven times, it has much greater feature resolving power than any monotonic colormap and is used in thermal imaging. However, the trade-offs of this design choice for broader applications are not yet well understood.

Ware with Maureen Stone (Tableau) and Danielle Szafir (UNC Chapel Hill), have submitted a paper to counter the bad press of rainbow colormaps and to argue that carefully designed rainbow colormaps have a place in data visualization.

Task 38: Artificial Intelligence and Machine Learning for Analysis and Filtering

JHC/CCOM Participants: Kim Lowell

Task 38 has been merged with Task 26 and is distributed throughout many other tasks.

Task 39: Hydrographic Data Manipulation Tools

JHC Participants: Andrew Stevens, Kindrat Beregovy, Tom Butkiewicz, Brian Miles

Project: VR Point Cloud Editor

Automated data processing tools continue to become more comprehensive and effective, but there will always be data that must be manually reviewed or edited by human operators. Human interaction cannot be accelerated with faster computers, making the efficiency of interaction an essential component of the overall efficiency of the data processing pipeline. By developing advanced interfaces using off-the-shelf virtual reality (VR) headsets and handheld 3D interaction devices, the Data Visualization Research Lab continues to improve the efficiency of editing 3D sonar and lidar point cloud data.

Previously, Butkiewicz and Stevens created a virtual reality point cloud cleaning application to view and edit sonar and lidar data. During this reporting period, the visualization lab has significantly improved this application with new features designed to serve NOAA's needs and has released it to the public as a free download via the Center's website. (https://ccom.unh.edu/vislab/tools/point_cloud_editor)

The tool was internally tested by cleaning over 80 miles of Mississippi River shoreline lidar scans collected as part of NOAA's Lower Mississippi River Precision Navigation Project. One of the new features this testing led to is the ability to quickly display reference maps. One of the challenges of editing these scans is that, in addition to noise, there are transient objects (e.g., boats) that are imaged by the scanner, but which do not belong in a final navigational product. These cannot be removed algorithmically and require subjective evaluation.

To aid in this decision making, users can move their thumb around the controller's touchpad to quickly view different reference map layers under the point cloud. This includes the latest ENC for the data area, which is automatically downloaded from NOAA OCS's ECDIS Display Service when a point cloud dataset is loaded. This ENC layer allows users to quickly determine if objects in the data are associated with permanent, charted features. For example, Figure 39-1 shows how the ENC reveals the charted mooring buoys that should be preserved, while the ship and mooring lines can be edited out.

Multiple satellite images are also automatically downloaded from different providers (e.g., ArcGIS and Google), and can be quickly scrolled through to get a clearer perspective of features captured in the data, and a sense of what an area looked at different times. This can be helpful, for example, in determining if a cluster of moored barges might be useful to maintain in the dataset as a visual reference. While the exact number of barges at a mooring location might vary daily, if similar clusters appear in multiple satellite photos, it can be assumed that there will usually be barges there. Figure 39-2 shows an example of this scenario.

To better serve the needs of NOAA's National Bathymetric Source Project, the editor was extended to support annotation and classification of points rather than just simple deletion. Because the traditional keyboard is not available in VR, voice recognition controls are used to indicate what feature types are to be annotated, as this is much faster than navigating long lists

Figure 39-1. Mississippi River lidar data in the editor, with an ENC reference map indicating the mooring buoys that should be preserved while editing out the ship and the mooring lines.

Figure 39-2. (left) view of lidar in editor, showing uncharted barge moorings, (middle, right) views of lidar with satellite photos reference maps from different times, showing there are usually barges moored here, though not always the same number of barges.

in clunky VR menus. Classification values and associated voice commands can be easily customized by users via a simple text file. (The editor currently uses a list of IHO S-57 feature types.)

NOAA NBS currently uses QGIS to process data. To better integrate the VR editor into their existing workflow, the Center is developing a QGIS plug-in that will allow users to quickly select point data in QGIS, send it to the VR editor, and have their edits show up back in QGIS. This avoids having to manually save and load files back and forth between the two applications.

Task 40: Real-time Display of Ocean Mapping Data—Augmented Reality ASV Telepresence

JHC Participants: Tom Butkiewicz, Thomas Donnelly, Roland Arsenault, and Val Schmidt

Project: Augmented Reality for ASV and ROV Teleoperation and Telepresence

Augmented reality (AR) is a technology that superimposes digital information directly on top of a user's real-world view. AR holds tremendous potential for a range of ocean mapping applications including enhanced navigation, immersive exploration of 3-D scenes and new approaches to collaborative data editing. The Center's Visualization Lab has previously evaluated first-generation commercial AR devices (e.g., Microsoft HoloLens and Magic Leap) and found significant limitations that made them impractical for marine use. However, the Center was able to research the potential of AR for marine navigation by creating a virtual reality bridge simulation that permitted experimentation with a wide range of possible AR devices and information overlays. Through user studies conducted in this simulator, the Center identified future hardware requirements and demonstrated AR's potential for aiding safe marine navigation (Figure 40-1). Recently, a number of companies have started developing their own AR marine navigation systems, though most are actually annotated video and not true AR. We are continuing to explore the pros and cons of these devices as well as design experiments to test the relative advantages or disadvantages of operating in an AR environment.

Two areas that we hope to apply this approach to are the remote operation of our uncrewed systems and the use of immersive telepresence for ROV exploration operations. For the uncrewed vehicle application to be viable we need to develop better image stitching and stabilization onboard the ASV (part of Tasks 9 and 10) and for the ROV we are waiting to receive appropriate ROV-based data sets.

Figure 40-1. Point cloud of the Crescent City Bridge as seen through the lens of the Nreal Light AR glasses. Point density had to be reduced to render at interactive speeds.

Task 41: BathyGlobe

JHC Participants: Colin Ware, Paul Johnson, Larry Mayer, and Kindrat Beregovyi

Other Collaborators: GEBCO/SB2030

The BathyGlobe application was first developed to display global bathymetry on a sphere in public spaces with the ability to scale to demonstrate the actual (very limited) area of seafloor covered by data. In the last three years, the effort has been re-directed to a spinoff from BathyGlobe—GapFiller—which has been developed to allow for interactive planning of survey routes over existing data sets to optimize filling gaps in coverage during a voyage.

In the current reporting period, the work has involved creating and distributing a new version based on GEBCO 2022 bathymetry, fixing bugs as they arise and distributing the package. BathyGlobe GapFiller has been packaged and is now downloadable from the CCOM VisLab website. A significant new feature is support for survey cost calculations. Sometimes a survey planner may have the option of contracting with different suppliers who have access to ships with different MBES systems. To compare costs with different systems for a polygonal area, the area should first be defined and saved. Following this the config file can be set with the parameters (day rate, speed, and extinction file) for each system and the polygon filled in the usual way. To compare survey costs for different MBES and ship day rates, parameters must be set for ship speed, the ship day rate as well as the name of a file specifying an MBES extinction curve in the config file. Given a polygonal planned survey area, GapFiller is used to simulate a survey filling the polygon with a specified degree of overlap, using the specified parameters. The costs are calculated when the Stats function is invoked.

Figure 41-1 shows an example where the costs for surveying three different areas with four different MBES systems using a standard ship day rate of $45,000, using a 20% overlap setting and surveying at 9 knots. Each of the areas was approximately 40,000 sq km. and their mean depths averaged approximately 1800 m, 3400 m and 5650 m respectively. The survey costs are given in dollars per square meter. The MBES extinction curves came from various sources: The EM122 and EM304 curves are empirical and come from a method develop by the Multibeam Advisory Committee (https://mac.unols.org). The EM302 curve is based on a hand fit to measurements made on the E/V Nautilus (L. Gee, personal comm). The EM124 curve is a theoretical curve provided in the Product Description document from the manufacturer – Kongsberg Maritime. There has been no attempt to standardize these results for such variables as bottom type and water temperature. Consequently, they are given as examples only and should not be used to provide support for an actual cost analysis. Ware, Mayer and Johnson have written and submitted a paper on GapFiller and its incorporated algorithms and submitted it for publication.

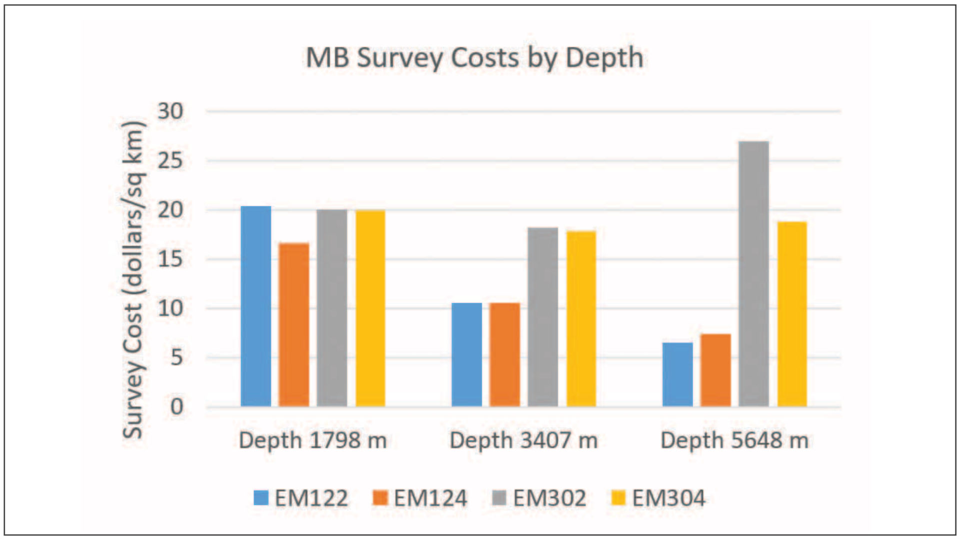


Figure 41-1. A comparison of the predicted costs for surveying three areas having different mean depths using different MBESs.

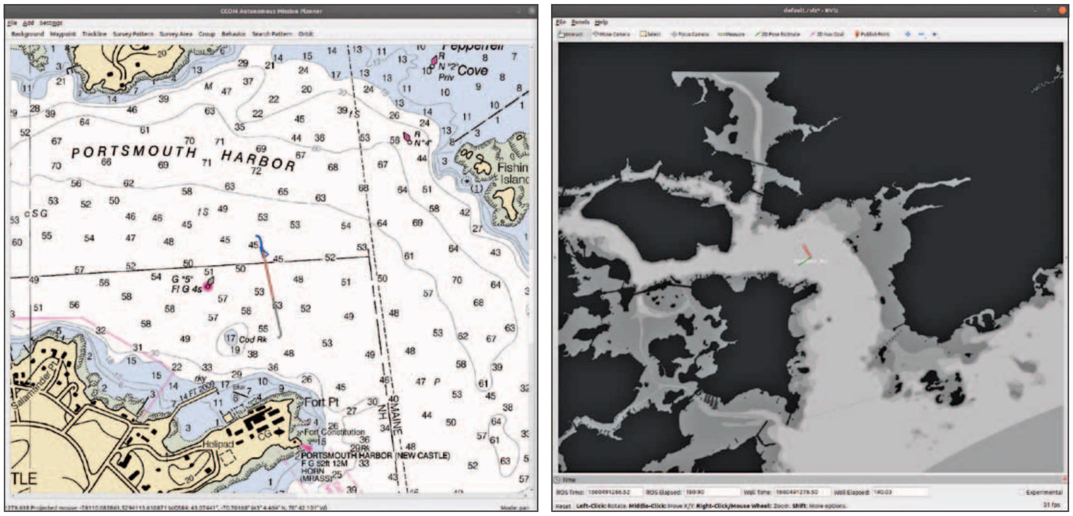


Figure 42-1. Left a Raster based nautical chart is shown for a portion of Portsmouth Harbor, while on the right, the navigational "occupancy grid" used for robot navigation is shown generated from the larger chart.

Programmatic Priority 2

ADVANCE TECHNOLOGY FOR DIGITAL NAVIGATION SERVICES

NOFO Requirement 16

Development of approaches for the autonomous interpretation and use of hydrographic and navigational information including oceanographic and hydrodynamic models, advanced systems such as minimally-staffed and unmanned vessels.

JHC/CCOM responded to NOFO requirement 16 with one task:

Task 42: Semantic Understanding of Nautical Charts for Autonomous Navigation

Task 42: Semantic Understanding of Nautical Charts for Autonomous Navigation

JHC/CCOM Participants: Val Schmidt, Roland Arsenault, Christos Kastrisios

Safety of navigation by uncrewed, autonomous vessels can be improved if the vessels' autonomous (AI) navigator can read and properly understand a nautical chart. Electronic Nautical Charts in S-57 or S-100 formats are easily obtained, and many libraries exist for reading them. But it is something altogether different to provide an AI navigator with a semantic understanding of the features on a chart, and to do so respecting the chart interpretation that ensures safety of navigation. This project is focused on investigating methods to provide proper semantic understanding of a nautical chart for autonomous vessels.

In previous work, graduate student Sam Reed and Schmidt developed a methodology to convert an S-57 chart to a raster map suitable for navigation by robotic vessels. The effort converted depth areas, contours, soundings and many charted features into a "cost map", upon which classical path planning algorithms can navigate.

In 2022, Arsenault, building in part on Reed's work, developed a similar methodology, converting a more limited set of features from an S-57 chart into an "occupancy grid", whose format is standardized within the larger academic Robotic Operating System framework that the Center uses for marine robotics. An example is shown in Figure 42-1, displaying both the original chart and the occupancy grid generated from it. Many academically developed robotic path planners can "plugin" to such an architecture, improving our ability to conduct research on robotic path planning for marine vehicles.

Programmatic Priority 3

DEVELOP AND ADVANCE MARINE GEOSPATIAL AND SOUNDSCAPE EXPERTISE

NOFO Requirement 17

Development, evaluation, and dissemination of improved models and visualizations for describing and delineating the propagation and levels of sound in the water from acoustic devices including echo sounders, and for modeling the exposure of marine animals to propagated echo sounder energy. Improvements in the understanding of the contribution and interaction of echo sounders and other ocean mapping-related acoustic devices to/with the overall, ocean and aquatic soundscape.

JHC/CCOM responded to NOFO requirement 17 with one task:

Task 43: Contribution of Echo Sounders to Ocean Soundscape

Task 43: Contribution of Echo Sounders to Ocean Soundscape

JHC Participants: Michael Smith, Jennifer Miksis-Olds, Xavier Lurton, and Carlo Lanzoni

Additional Funding Sources: ONR and NOPP (Miksis-Olds)

NOAA's effort to map and characterize the seafloor relies on a wide variety of active acoustic systems such as multibeam echosounders, wide-bandwidth single and split beam echosounders, and sub-bottom profilers among others. With the Presidential Memorandum on Ocean Mapping and the release of the Blue Economy Strategic Plan, activities in seafloor mapping and characterization are expected to increase, and likely so will the usage of active acoustic systems. With the expected increase comes the responsibility to ensure that these systems are used in a manner that protects marine life while preserving commerce, research, and exploration. Maintaining this balance requires knowledge of both the anthropogenic sound generated by commonly used scientific echosounders, and knowledge of the impact of these systems on the local soundscape. The soundscape, formally defined by IOS 18405, is the characterization of the ambient sound in terms of spatial, temporal, frequency attributes and the types of sources contributing to the sound field. By utilizing soundscape information, we can better understand environmental impacts on ocean dynamics, biodiversity and ecosystem health, and the risk of anthropogenic impacts on marine life. The Center currently conducts research into the modelling and measurement of scientific echosounder transmit radiation patterns, and practical analysis of their potential impact in soundscape studies.

Project: Sound Source Modeling of Scientific and Hydrographic Systems

MBES have unique design and transmission characteristics that presents challenges when attempting to model and regulate their impact. Historically, environmental regulations used simplified models of MBES which focused on the narrow main swath or transmit beam, when assessing these systems for potential for impact. However, modern systems feature widely varying operational characteristics such as pulse length, bandwidth and waveform that change in response to the survey environment. These dynamic parameters and complex transmit radiation patterns have made it difficult to accurately model and measure MBES systems. To better improve our understanding of the potential impact of these systems, the Center has conducted research on novel ways to measure deep-water MBES transmit radiation patterns and research to improve MBES modeling capabilities.

In June of 2022, Center researcher Michael Smith participated in the Joint Industry Program Acoustic Modeling workshop (JAM 2022). This invitation-only workshop is hosted by the Joint Industry Program (JIP), which funds research and events designed to improve understanding of the potential impact of acoustic systems used in the energy industrial sector on marine life. The workshop's focus was on the understanding and improvement of various source and propagation models used in impact assessment. The inclusion of MBES in this year's workshop presented a rare opportunity for the Center to present the results of the multi-year SCORE experiments to an interdisciplinary group of industry, bio-acousticians, and regulators.

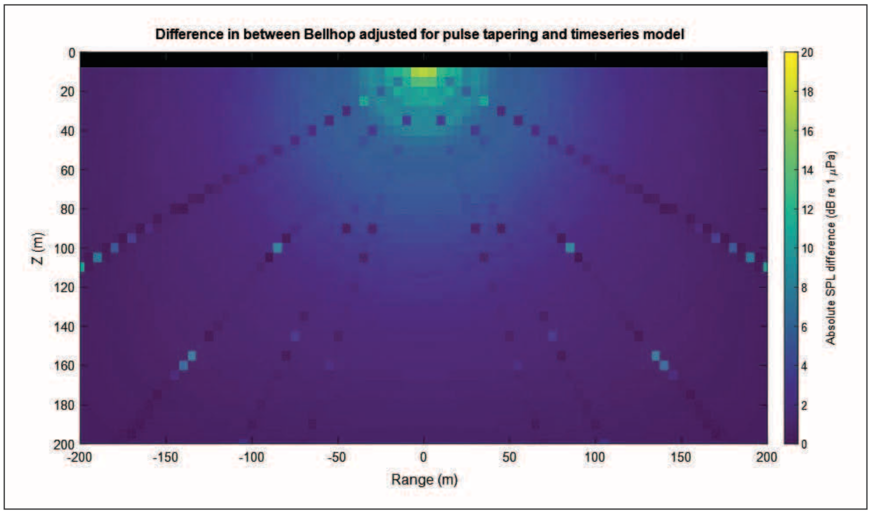


Figure 43-1. Difference plot of the SPL as computed by the BELLHOP model and the simulated time-series model for the central sector of a deep-water MBES. Note that the BELLHOP model overestimates the sound levels from 3 to 20dB in an annulus of approximately 100m around the system. Differences along radials are due to null misalignment between models and are not real, observable phenomena.

As part of the workshop, a MBES propagation modeling comparison study was started. The goal of the work is to demonstrate the importance of using accurate models of MBES transmit pattern as an input to modeling approaches. In the study, important metrics such as sound pressure level (SPL) and sound exposure level (SEL) were computed at ranges varying from close to the sonar, to ranges out to 30 km. Fundamental models such as a simulated time-series approach were contrasted against more commonly used models such as the Acoustic Toolbox's BELLHOP model. A major takeaway of the work has been the need to properly account for the nearfield of MBES, where the sound field generated by the many individual transducers that comprise the array does not coherently sum. The impact of the nearfield on metrics such as SPL, which is a measure of the maximal power or pressure exposure, can be seen in Figure 43-1. It demonstrates that models like BELLHOP, which use far-field radiation patterns, can overestimate the SPL by almost 20dB in ranges close to the system. This is important when using these models to develop safety zone radii which impact active operation in the field.

In addition, SEL which is a measure of the cumulative sound energy exposure, was modeled for a typical multibeam transect line in models with different levels of complexity. A sonar-equation model was used to calculate the SEL over the transect and considered all sectors, pings, and up to three multipath arrivals when calculating the SEL. This was compared to a modified BELLHOP model which estimated SEL only as a function of vessel speed, receiver range, and the full system radiation pattern. The BELLHOP model does not consider every ping in the transect but estimates the single strike SEL of the main transmit swath and modulates it by the number of potential ping exposures at a given field point. The model comparison can be seen in Figure 43-2.

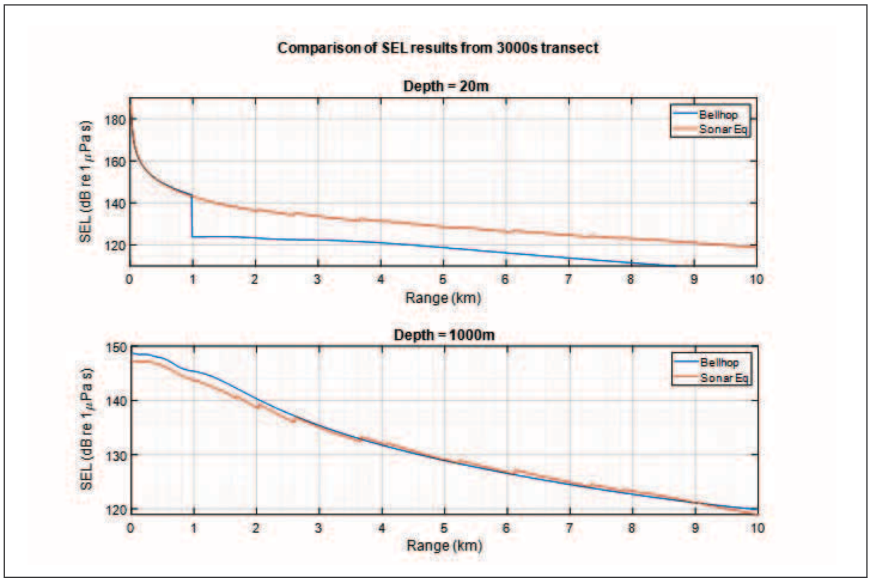


Figure 43-2. Comparison between sonar equation model in orange and BELLHOP model in blue at two ranges (top 20m, bottom 1000m). The Sonar equation model neglects refraction and as a result is only valid out to 1km at a 20m depth and is fully valid at 1000m depth. The close agreement between the two models demonstrates that main beam exposure dominates the cumulative SEL metric.

The results verify what has been suggested in earlier studies—that the maximum SEL is primarily attributed to the number of times a potential listener is exposed to the main beam. Figure 43-3 demonstrates the expected worst case SEL levels along the transect using the BELLHOP model. Overlain are typically accepted threshold level contours indicating ranges of safe operation radii. The radii conservatively suggest a 50 to 100 m safety zone for the system operating in full ocean depth (>1000 m).

Project: Passive Acoustics and Acoustics Training

Jennifer Miksis-Olds, research faculty member in our Center and the Director of a new UNH Center for Acoustics Research and Education (CARE) is contributing to our ocean mapping mission through multiple projects that broaden the scope of ocean bottom mapping to water column, habitat, and soundscape mapping, as well as aim to build a strong program for training in acoustics at UNH. For the most part, these efforts are funded by other sources, but still contribute to the overall aims and objectives of the Joint Hydrographic Center and, in particular, to Task 43.

Deepwater Atlantic Habitats II: Continued Atlantic Research and Exploration in Deepwater Ecosystems with Focus on Coral, Canyon and Seep Communities (DEEP SEARCH)—NOPP-funded

The overarching goal for this project is to augment the ability to predict the location of seafloor communities within a study area on the outer continental shelf (OCS) that is potentially sensitive to natural and anthropogenic disturbances. This area encompasses a variety of different habitat types, including canyons, hard-bottoms, cold-water coral mounds, methane seeps, and soft sediments. The UNH portion of the project is devoted to soundscape mapping and pattern analysis of cold-water coral habitats. Dylan Wilford completed his MS in 2021 using data from this project that directly aligns with Task 44 in the JHC grant. Details related to the methods and application of soundscape analyses can be found in Wilford (2021)[10] and Wilford et al. (2021).[11] New work conducted in 2022 applied the developed Soundscape Code to the assessment of two sandy habitats of the US east coast OCS, two deep-sea coral habitats along the US east coast of the OCS, and a shallow coral habitat on the Great Barrier Reef (Figures 43-4 and 43-5). The main message of this work was to convey that more than just amplitude metrics are required to fully characterize marine soundscapes.

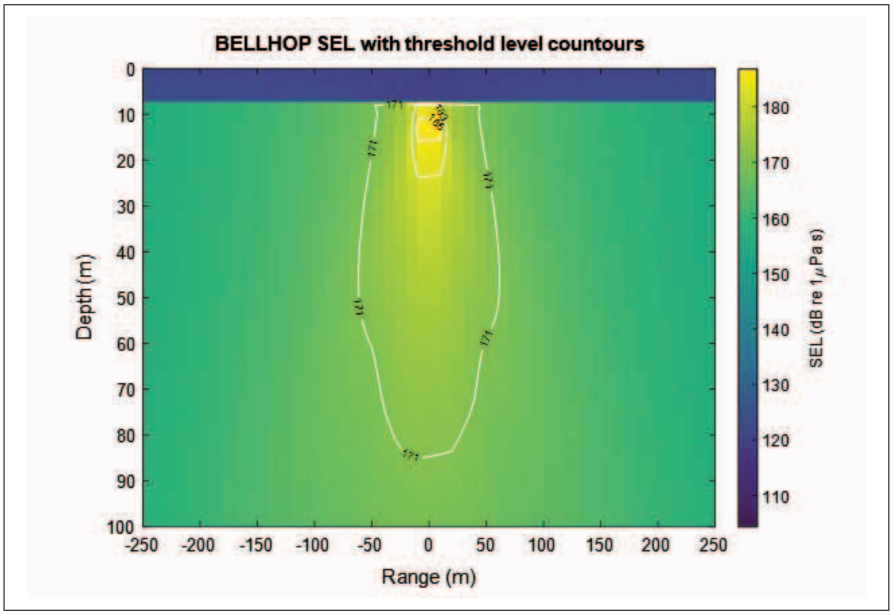


Figure 43-3. Cumulative SEL field for a 3000s transect during a simulated MBES survey. Contours corresponding to threshold levels from Southall et al. 2007 have been overlain to demonstrate the effective safety radii for various animal/exposure criteria.

Exploring the use and impact of sentinel indicators in ocean acoustics—ONR-funded

This effort is focused in the Gulf of Maine and aims to 1) conduct basic research that demonstrates the utility of acoustic technology and measurements as a sentinel indicator of environmental change; 2) conduct basic research that explores the relationship between non-

[10] Wilford, DC (2021). Quantification of Marine Acoustic Environments. MS Thesis. University of New Hampshire.

[11] Wilford, DC, Miksis-Olds, JL, Martin, SB, Howard, DR, Lowell, K, Lyons, AP, Smith, MJ. (2021). Quantitative Soundscape Analysis to Understand Multidimensional Features. Frontiers in Marine Science, 8: 672336. doi:10.3389/fmars.2021.672336

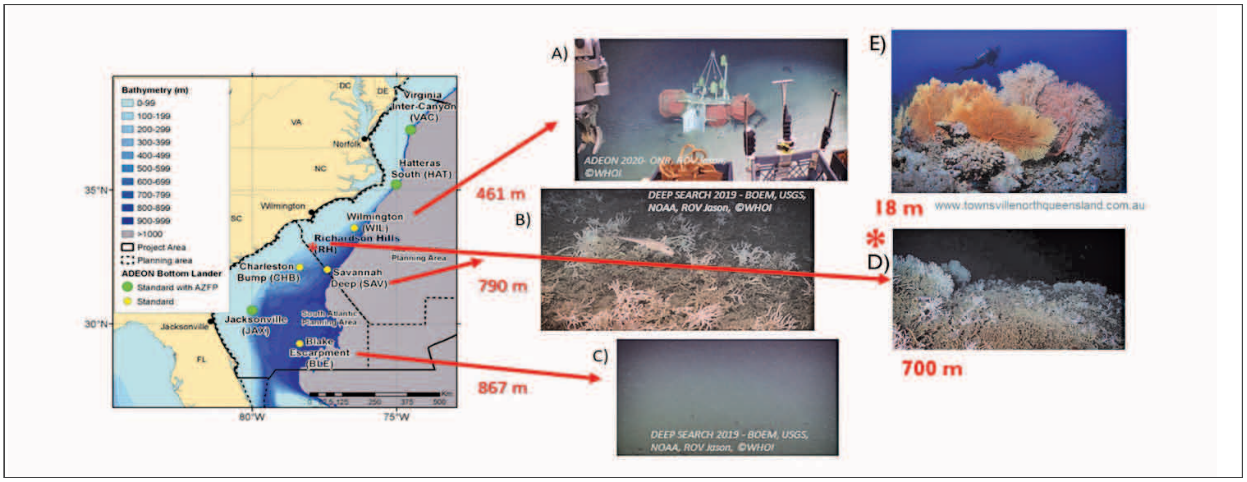


Figure 43-4. Locations, depth, and bottom habitat of the 5 locations in the soundscape comparison analysis. A-D are located on the US east coast OCS in water depths greater than 450m. Locations A (WIL) and C (BLE) are sandy bottom habitats. Locations B (SAV) and D (RH) are deep cold water coral habitats, and location E (Great Barrier Reef) is a shallow warm water coral habitat.

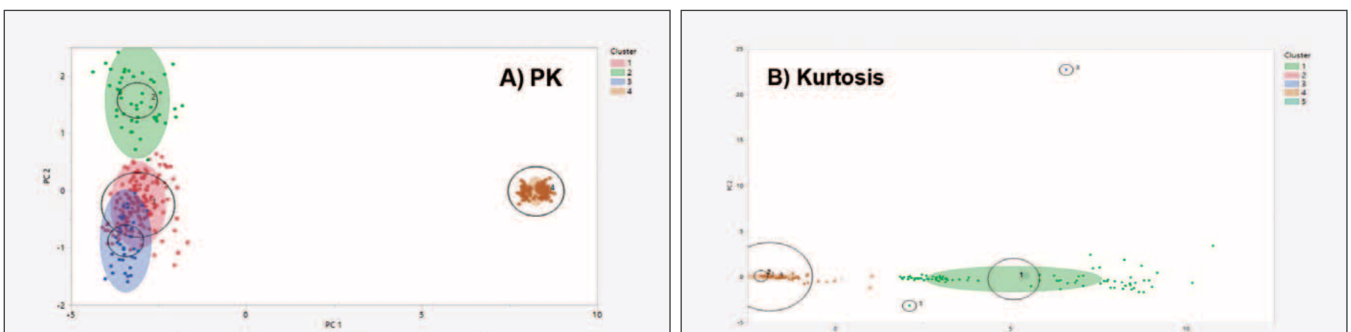
acoustic sentinel indicators that impact acoustic measurements; and 3) develop a framework that relates sentinel indicators to factors impacting sonar performance prediction (Figure 43-6).

Acoustic and Environmental Observation Network in the NW Atlantic (AEON)—ONR-funded

The goal of the AEON is to establish an acoustic observation network that complements existing physical and biogeochemical oceanographic observations with acoustic measurements at key locations where the effects of the Labrador and Gulf Stream currents are projected to impact the Gulf of Maine and possibly other shelf regions in the NW Atlantic. Five acoustic bottom landers are currently deployed in the Gulf of Maine with support from this project (https://eos.unh.edu/aeon).

Building a Comprehensive Training Program for Developing and Sustaining the Ocean Acoustics Workforce 2021-2024—ONR-funded

Education in ocean acoustics is critical at all levels and necessitates programs that create a pipeline of personnel with the specialized acoustics training necessary to meet current and future national workforce needs. Education and training programs serving traditional students through formal university degrees and programs, as well as distance education and professional development opportunities, including certificates, micro-credentials, and digital badges which



	Site ID				
Cluster	BLE	GBR	RH	SAV	WIL
1	67	0	0	29	68
2	1	0	48	0	0
3	0	0	0	39	0
4	0	96	0	0	0

	Site ID				
Cluster	BLE	GBR	RH	SAV	WIL
1	0	83	0	0	0
2	1	0	0	0	0
3	0	13	0	0	0
4	67	0	46	68	68
5	0	0	2	0	0

Figure 43-5. Cluster analyses for A) peak sound pressure level (PK) and B) kurtosis impulsiveness measures of the Soundscape Code 1-min values over one month at each location identified in Figure 1. Shaded regions indicate where 50% of the observations in the cluster fall. Shading is the 50% portion of all points within a specific cluster, whereas the color of shading and points denotes cluster number.

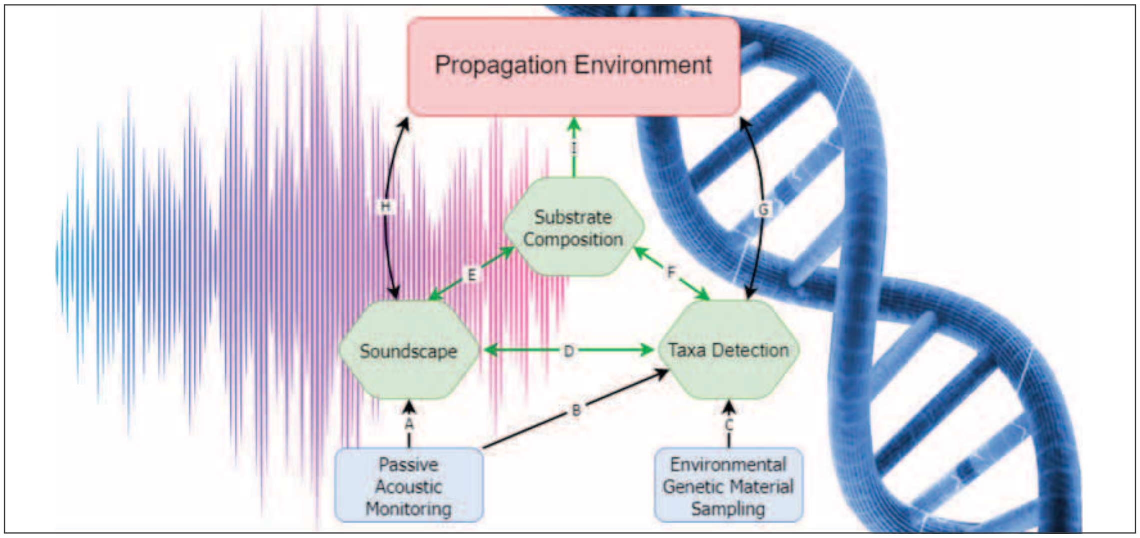


Figure 43-6. Framework relating passive acoustic monitoring and environmental genetic sampling to the acoustic environment. Arrows indicate interactions between observation techniques and environmental components.

provide flexibility to non-traditional students, will ensure the workforce remains adequately trained as new research and technology advance. This effort has a three-component education infrastructure designed to improve ocean acoustics training at the University of New Hampshire (UNH), in the Northeast region, and the nation to serve the entirety of those requiring training. The three components are specifically designed to serve: 1) residential university students seeking formal degrees and graduate certificates, 2) non-residential students seeking formal degrees and graduate certificates, and 3) non-traditional students, in particular naval personnel, seeking professional development opportunities in ocean acoustics. The development of distance education capabilities directly supporting the ocean acoustics curriculum will benefit all these populations through access to courses and inclusions of technical practitioners in class cohorts. Investment in ocean acoustic education is the emphasis of the current effort, however, other complementary UNH programs of interest in, e.g., mechanical engineering, ocean engineering, ocean mapping, oceanography, and marine robotics, will also be advanced which will impact naval and NOAA workforce needs.

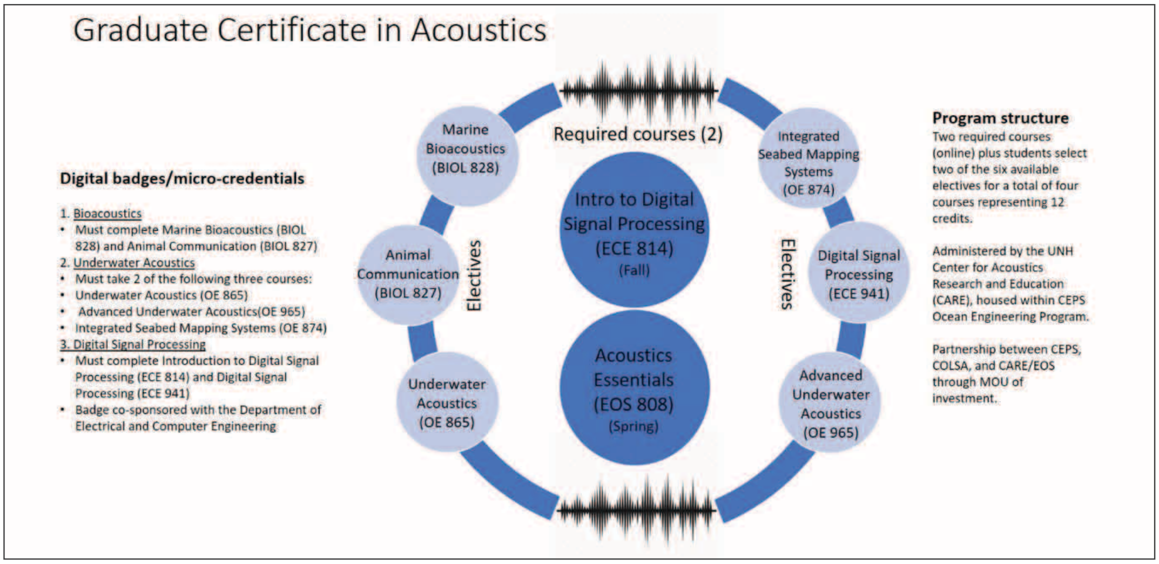


Figure 43-7. UNH Graduate Certificate in Acoustics program. This is a 4-course program with 2 required courses and 2 electives. The three digital badge/micro-credential topics are listed on the left-hand side of the figure.

At present, a new Graduate Certificate in Acoustics and three acoustics-related micro-credentials have been developed and implemented in partnership with different University of New Hampshire (UNH) programs across campus (Figure 43-7). The Graduate Certificate in Acoustics program is appropriate for students with either a mathematical or applied science background, and the courses related to digital badging/micro-credential competencies can be pursued individually or in conjunction with the certificate or a UNH graduate degree (Figure 43-7).

A UNH digital badge represents a defined micro-credential which is simply a validated skill, achievement, or experience obtained from the successful completion of one or more courses or educational opportunities. The digital badge itself contains detailed information about the skill or experience which enables employers to ascertain what activities and/or assessments the learner completed. Sharing digital credentials is learner controlled and open across technology platforms including social media (e.g., LinkedIn), blogs, online portfolios, and others.

Cabled Acoustic Array in the Gulf of Maine—ONR-funded

Through ONR funding, a cabled ocean acoustic array, tied into the Shoals Marine Laboratory, will be installed in the coastal waters of the Gulf of Maine (Figure 43-8) providing a real-time system that extends the 5-node network of offshore acoustic landers of the Acoustic and Environmental Observation Network in the NW Atlantic (AEON) and providing a permanent southern terminus whose data links the coastal and slope waters. The cabled array will complement existing oceanographic monitoring infrastructure allowing studies to be performed that may reveal significant connections between coastal measurements and the overall Gulf of Maine environment. The cabled system is being designed to synoptically collect acoustic, oceanographic, and biogeochemical measurements, while also remaining flexible enough in design to incorporate new sensors in the future. Acoustic signals, as opposed to visual and chemical signals, can propagate long distances in the ocean and provide the most long ranging means for marine life and humans to gain information about the environment. Acoustic measurements are the key to providing connectivity between the autonomous slope-water platforms and the coastal cabled system. Measurements made with this ocean asset will serve as a baseline for pattern and trend analyses of changing environmental conditions in an area of high productivity, human use, and species diversity.

The cabled system will be located at the Shoals Marine Laboratory (SML) on Appledore Island and is expected to be operational by late 2024/early 2025. Partnership with SML will enable student training including the effects of the observatory on SML's green grid as part of the Sustainability Engineering Internship Program, and training engineering students in marine system instrumentation design and maintenance. The UNH data manager and data visualization team will develop an infrastructure to provide public access to the data, and data products, while also archiving the passive acoustic data at the National Centers for Environmental Information. Public data access will permit researchers at all levels to advance their understanding of ocean acoustics and oceanographic processes. It is anticipated that ocean modelers will use the data to study fluctuating Gulf of Maine environmental parameters that affect the ecosystem from phytoplankton growth to right whale feeding and moderate climate including winter Nor'easter storms and summer hurricanes. Data from this system will provide insights that will aid the Navy and NOAA in appropriately responding to and proactively predicting how long-term environmental changes will impact operations in the Western Atlantic Ocean. *Data from this system will directly benefit NOAA and Task 43 in that it will be capable of recording the acoustic signatures of many operational and new ocean mapping systems within the context of the greater local soundscape variation.*

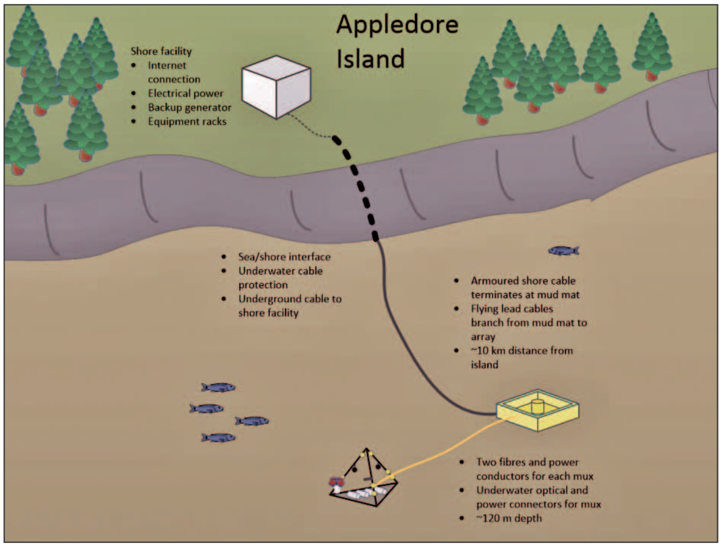


Figure 43-8. Schematic of the cabled array system to the Shoals Marine Laboratory on Appledore Island.

Programmatic Priority 3

DEVELOP AND ADVANCE MARINE GEOSPATIAL AND SOUNDSCAPE EXPERTISE

NOFO Requirement 18

Development, maintenance, and delivery of advanced curricula and short courses in hydrographic and ocean mapping science and engineering at the graduate education level—leveraging to the maximum extent the proposed research program, and interacting with national and international professional bodies—to bring the latest innovations and standards into the graduate educational experience for both full-time education and continuing professional development.

JHC/CCOM responded to NOFO requirement 18 with one task:

Task 44: Curriculum Development

Task 44: Curriculum Development

JHC Participants: Semme Dijkstra, John Hughes Clarke, Brian Calder, Larry Mayer, Larry Ward, Rochelle Wigley, Giuseppe Masetti, Juliet Kinney, Elizabeth Reed-Weidner

NOAA Collaborators: Andy Armstrong and John Kelley

In addition to our research efforts, education and outreach are also fundamental components of our program. Our educational objectives are to produce a highly trained cadre of students who are critical thinkers able to fill positions in government, industry, and academia and become leaders in the development of new approaches to ocean mapping. We had 41 graduate students enrolled in the Ocean Mapping program in 2022, including six GEBCO students, four NOAA Corps officers and one NOAA physical scientist (some as part-time). This past year, we graduated four Masters' and one Ph.D. student while five GEBCO students received Certificates in Ocean Mapping.

FIG/IHO/ICA Category A Accreditation

The content, sequence, and delivery of the ocean mapping training at CCOM is continuously being updated to represent current developments. Careful attention is paid to ensure that the FIG/IHO/ICA Category A course standards continue to be met. The curriculum in Ocean Mapping offered through CCOM is one of the key components of the NOAA grant. NOAA staff are routinely assigned to UNH for graduate and diploma-based training. Maintaining Category A accreditation is an essential part of ensuring the quality of the educational program.

Lasting COVID-19 Impacts

With COVID-19 going from a pandemic to an endemic phase, the presentation of lectures and materials has been normalized. Classes and labs are fully back to in-person gatherings. Because of COVID-19 however, some permanent changes have been made in the curriculum, prime among them is the availability of pre-recorded lectures. Many of the classes are now taught with the expectation that the students watch a pre-recorded lecture, which is then recapped and discussed in detail during the class period. Also, for many of the courses, office hours are now offered online which has the significant advantage that the students can share their screens, allowing the instructor to directly address issues while other students follow along.

E-Learning Python for Ocean Mapping

Students at the Center need to have a minimum level of programing skills to successfully complete many of their assignments. In the academic year 2020–2021 it became clear that the contents of the ePOM modules prepares the students well in terms of content, but that the sequencing needed to be altered to better align with the other courses offered—thus the sequence of the curriculum involving Python is now:

Programming Basics with Python
Introduction to Python Programming
- *Online, pre-arrival at the Center*

Introduction to Ocean Data Science
Introduction to programming concepts used in the Ocean Mapping core curriculum
- *In-person, at the Center*
- *Part of the 'Ocean Mapping Tools' course*

Introduction to Integrated Development Environment (IDE) and Version Control
Introduction to IDE's such as PyCharm and Version Control Software such as GitHub
- *In-person, at the Center*
- *Part of the 'Ocean Mapping Tools' Course*

Addressing all the basic skills before the students encounter labs involving software creation has led to a significant improvement of student performance in the lab components, particularly for the Integrated Seabed Mapping Systems course. This trend was observed in the academic year 2020-2021 and has continued in 2021-2022. To keep abreast with technological development as well as better meet our students' needs two new ePOM servers were activated with a current CONDA Python 3.9 environment and with increased memory allocation per account—all incoming students have received accounts on the primary server ePOM3.hydroffice.org (ePOM2.hydroffice.org serves as a backup and development server).

Automated Grading Assistance for ePOM

Most of the time spent grading assignments offered through ePOM was on routine work that can be replaced by an automated approach. To reduce this time an automated grading tool was developed for the Geodesy course ePOM assignments. Based on the success of this tool for the Geodesy course a generalized version was developed to allow grading in all courses (Figure 44-1). Currently in testing is then a Jupyter Notebook grading system that may be used for any assignment provided through the ePOM server, rather than just the Geodesy assignments.

New Linear Algebra Module

One of the key math subjects that ocean mapping practitioners need to master is linear algebra. Linear algebra occurs in many of the math applications in ocean mapping, e.g., rigid body transformations, the method of the least squares, Kalman filtering, etc. In

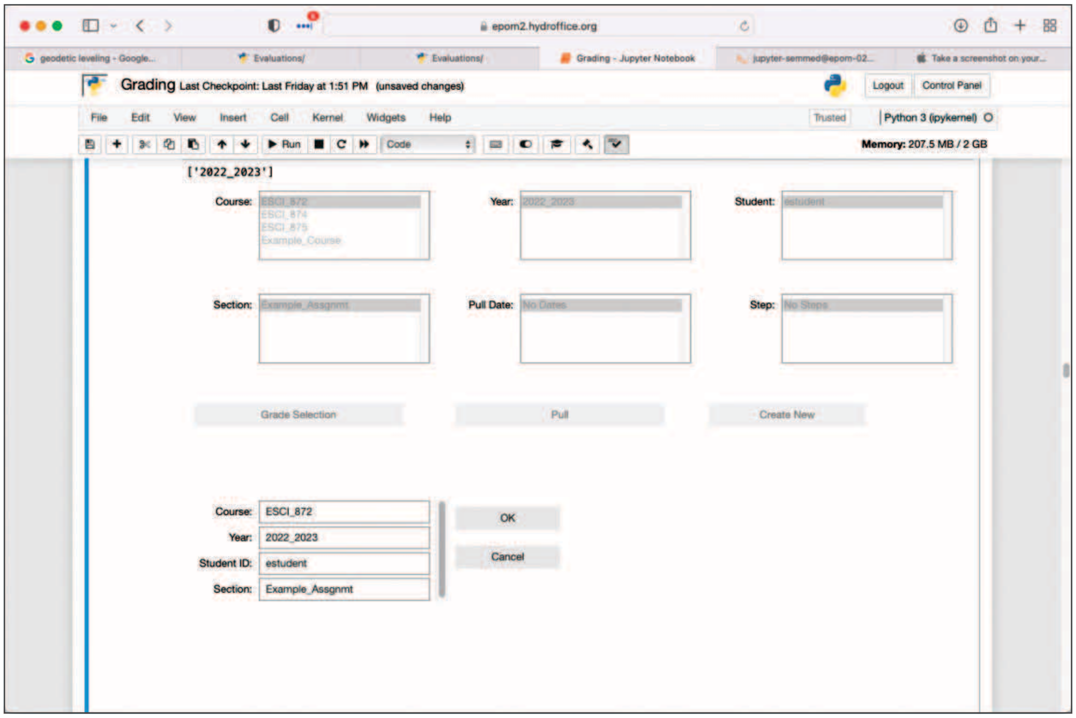


Fig 44-1 Generalized automatic grading tool for ePOM assignments.

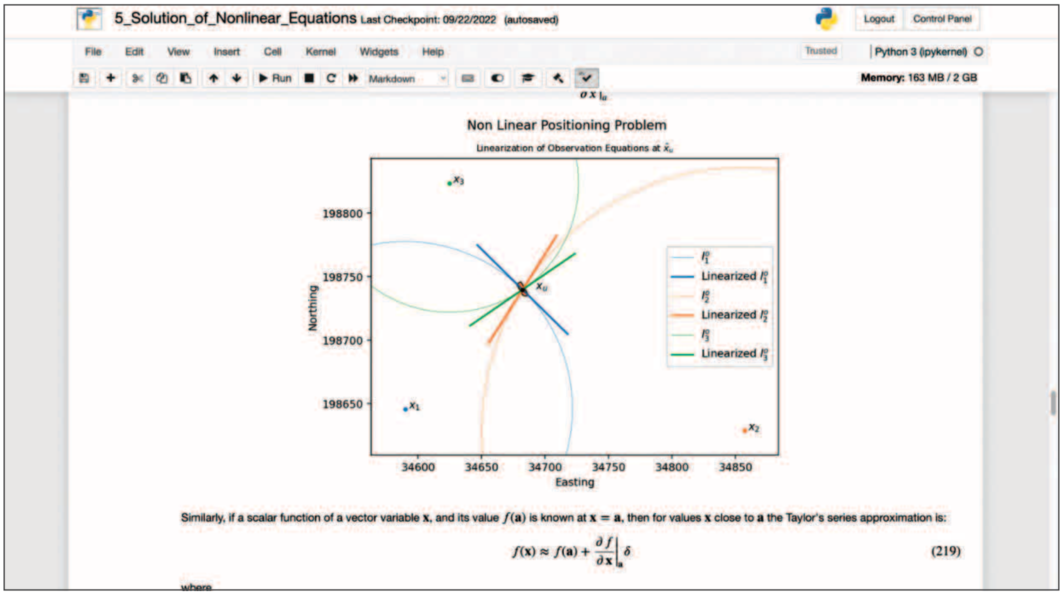


Fig 44-2. ePOM Linear Algebra module.

the context of this a new ePOM linear algebra module was developed by Dijkstra with a focus on ocean mapping applications (Figure 44-2). The module focuses on:

1. Matrix Algebra
2. Solution of Linear Equations
3. Linear Transformations
4. Solution of non-linear equations

Many examples are provided that are all ocean mapping-related. The writing of all text and code has been completed and the module will go into review in January 2023. The Pydro suite of software in use by the Office of Coast Survey is implemented in Python. The ePOM course materials are made available within Pydro enabling NOAA staff to learn programming skills consistent with the skills obtained by NOAA staff at the Center.

Course Updates

Introduction to Ocean Mapping

The content of the course remains largely unchanged; the course is now in its second year and has had significant positive feedback from its first iteration. This course introduces new students to the field of Ocean Mapping, increasing the size of the talent pool available for recruitment in NOAA and the private sector.

Applied Tools for Ocean Mapping (formerly "Integrated Seabed Mapping")

The course was changed to a half term course with classes offered every day, and a once weekly lab period. The labs involving programming were recreated to better prepare the students for the 'Integrated Seabed Mapping Systems' course. Given the success of achieving better alignment of the materials between the 'Applied Tools for Ocean Mapping' and 'Integrated Seabed Mapping Systems' this new format was kept for 2022.

Integrated Seabed Mapping Systems

John Hughes Clarke teaches the majority of the course, with significant contributions by Dijkstra (field and lab exercises and motion sensors). In 2021, the integrated Seabed Mapping class was offered for the seventh time. The content of the course remains largely unchanged, however in 2021 the format was changed significantly to provide better sequencing of the content of this course and the 'Ocean Mapping Tools' course. Due to the success of this format change this was also adopted for 2022. This course was developed to address the integration of multibeam systems, which remains a large concern for operational hydrographic surveys by OCS. Keeping this course abreast of current developments addresses this concern.

Advanced Topics in Ocean Mapping

The content of the course remains largely unchanged. Dijkstra teaches the majority of the course, with significant contributions by Armstrong (Tides), Calder (Digital Signal Processing), and Mayer (Seafloor Characterization and Law of the Sea). All labs implemented by Dijkstra saw minor revisions. The digital signal processing module, formerly part of 'Integrated Seabed Mapping Systems', was included in this course and presented by Calder.

Marine Geology and Geophysics for Hydrographic Surveyors

Marine Geology and Geophysics for Hydrographic Surveyors was taught for the fourth time with some minor alteration based on student feedback. The two-credit hour course was taught by Ward, Hughes Clarke and Wigley. The course provides students with an understanding of the concepts of geology and geophysics relevant to hydrographic surveying, while simultaneously reducing the required course load.

Oceanography for Hydrography

In January 2022 the oceanography course was presented for the fourth time. The course contents and presentation were left unchanged after the positive reception by the students of the first courses. The course has been taught by John Hughes Clarke in the J-term since January 2020. This course is offered to meet both the specific needs of the research program at CCOM and to address the more general hydrographic training desired by OCS for its staff and contractors.

Geodesy & Positioning for Ocean Mapping

For the academic year 2021-2022 the course contents remained largely unaltered. The majority of course materials is now offered in the form of Jupyter Notebooks. All grading of ePOM notebook assignments is now done with automated assistance.

Hydrographic Surveying Field Course (Summer Hydro)

This course was carried out in person. It marked the 3rd year of the involvement of Dan Tauriello as a second instructor, and the second of his in-person involvement with the students. This year, the course commenced with a week of software training provided by QPS. The practical work then consisted of a week of planning activities, five mobilization days, three weeks of data acquisition on R/V *Gulf Surveyor*, and two weeks of reporting. In addition, there was a day each assigned for the installation of a tide gauge and tying it in to benchmarks, a gauge to staff comparison, the installation of a GNSS base station, and a coast-line survey using aerial imagery obtained with a drone. This follows the model adopted in 2019, putting a greater emphasis on the integration and reporting stages.

The 2022 Summer Hydrographic Field Course brought the R/V *Gulf Surveyor*, nine JHC/CCOM students, and several technical staff under the supervision of Semme Dijkstra to the near shore waters off Hampton Beach, NH. The primary objective was to finish mapping of the Hampton Harbor entrance, an area that was not previously covered by any high-density survey technique. Each student was involved in the planning of the survey, execution of the survey, processing of the collected data and report writing. Activities included, among others, the creation of a budget, planning of patch tests, shore lining, data QA/QC procedures (cross line analysis, junctioning surveys), installation and verification of a tide gauge, the verification of the operation of a GNSS RTK base station, and the execution of an aerial beach shoreline survey using a drone.

Seventy-four kilometers of main scheme lines were collected, with an additional 7 kilometers of cross lines in water depths ranging from 1 m to 40 m below MLLW for a total areal coverage of 13 km^2. Additionally, 9 video stations were occupied at 8 of which grab samples were recovered. Finally, 0.4 km^2 of shoreline were mapped in high resolution using a drone (Figure 44-3).

Two parallel data acquisition streams were used with great success: one for routine data collection of data that will be processed and submitted to NOAA OCS and a second on which the students were allowed to alter the system settings and configurations allowing them to evaluate the impact of these on the collected data. This year the primary system was the Kongsberg EM2040p; the Edgetech 6205 was used as the secondary system.

Routine data acquisition was performed using QPS QINSy collecting sonar data from a Kongsberg 2040p multibeam. The data were processed using Qimera, FMGT, and POSPac. A comparison with Charts 13274, 13278 and 13282 was performed and in many locations observed depths were shallower than the charted depths. Additional data collection was performed using an Edgetech 6205 PDES system in the area of Salisbury, MA. For this survey the 6205 was mounted on the main mount of the *Gulf Surveyor*.

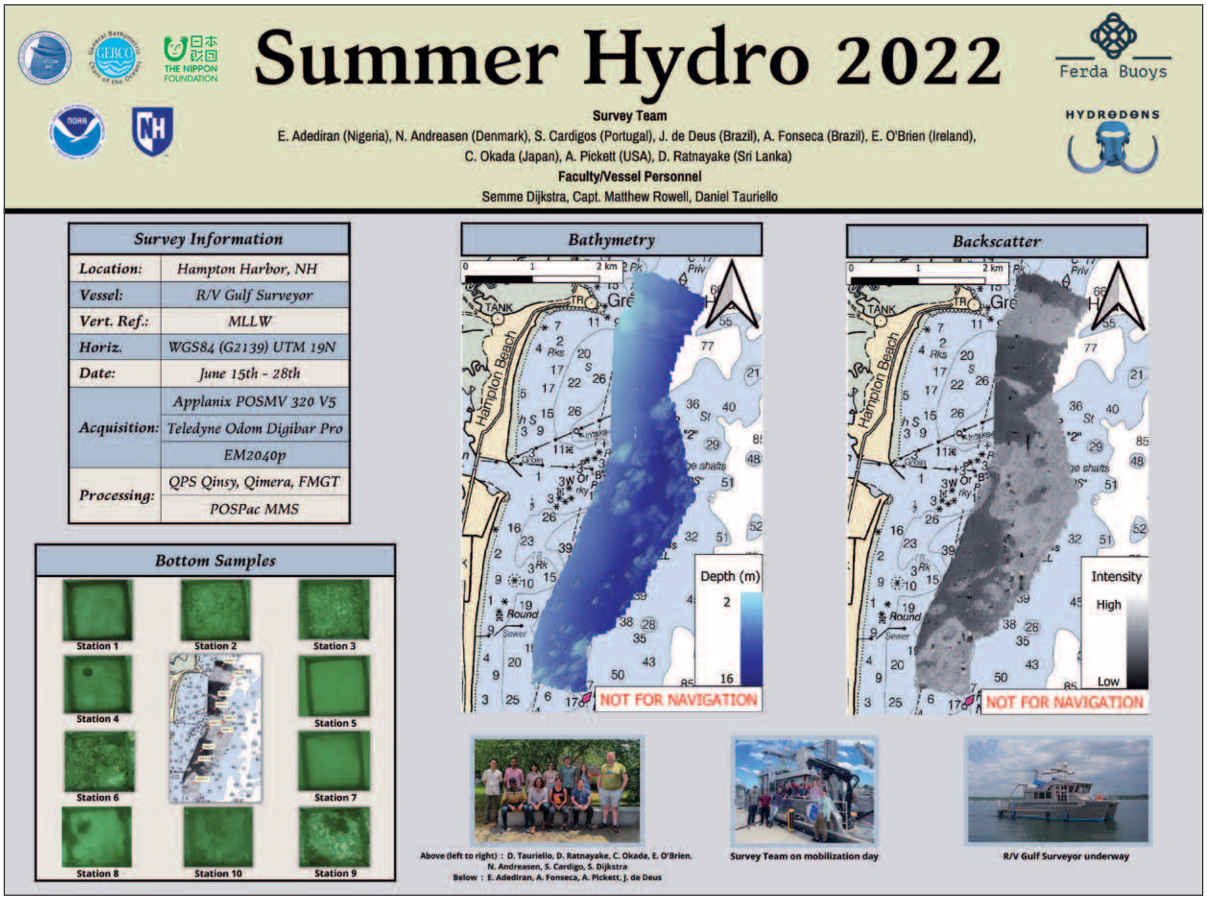


Figure 44-3 Poster representing the priority survey area near Hampton Beach, NH.

Project: **Nippon Foundation GEBCO Training Program**

JHC/CCOM Participants: Rochelle Wigley, Larry Mayer, and other JHC Faculty

Other Collaborators: Evert Flier (GEBCO), Robin Falconer (GEBCO), Nippon Foundation

The Center was selected to host the Nippon Foundation/GEBCO Bathymetric Training Program in 2004 through an international competition that included leading hydrographic education centers around the world. UNH was awarded $0.6 M from the General Bathymetric Chart of the Oceans (GEBCO) to create and host a one-year graduate level training program for seven international students. Fifty-seven students from thirty-two nations applied and, in just four months (through the tremendous cooperation of the UNH Graduate School and the Office of International Students and Scholars), seven students were selected, admitted, received visas and began their studies. This first class of seven students graduated (receiving a "Graduate Certificate in Ocean Mapping") in 2005. Eighteen classes, with one hundred and seven scholars from forty-four Coastal States, have since completed the Graduate Certificate in Ocean Mapping from the University of New Hampshire (Figure 44-4).

Funding for the 19th year of this Nippon Foundation/GEBCO training program was received from the Nippon Foundation in March 2021 and the selection process for the 19th class followed the guidelines of including input from the home organizations of prospective students as well as including input from alumni on applicants from their home countries. The Year 2021 class of seven (including a deferred applicant) were selected from 72 applications from 28 countries, attesting to the on-going demand for this course—so that we will have 113 students from 46 coastal states with the new class that started in the Fall of 2022. The Year 19 Nippon Foundation / GEBCO Training Program class only has six students as the seventh candidate could not obtain a visa due to COVID impacts at his embassy. The six students are from Australia, Ireland, Nigeria, Tanzania, Kenya and Morocco, with this class significantly building capacity in African coastal states.

One of the important aspects included in the Nippon Foundation/GEBCO training program at UNH is the network opportunities for students resulting from visits at NOAA's National Geophysical Data Center (NGDC) and co-located International Hydrographic Organization Data Center for Digital Bathymetry (IHO-DCDB) in Boulder, CO. Due to the current status of travel reflecting the COVID-19 pandemic, these annual visits have been postponed.

In addition, the visit(s) to an international laboratory and/or opportunity to take part in a deep-ocean cruise to round out the students training, to help them build networks and to deepen some of their newly-acquired theoretical knowledge. Two of the students, Nicki Andreasen and Dulap Ratnayake sailed as interns on the Lu'uaeaahikiikawawāapalaoa: Dual-Technology Seafloor Mapping expedition (NA142) as Watch Lead Mappers/Navigators from July 15 to August 8, 2022 (23 days of operation) on board the E/V *Nautilus*.

Sara Cardigos sailed on the DSSV *Pressure Drop* for the Japan I & II expeditions from 23 July to 21 September, 2022 as an intern and mapper. Chiaki Okado sailed with the NOAA Ship *Thomas Jefferson* as it surveyed in the Great Lakes. Chiaki was one of three women chosen to serve on NOAA vessels during the 2022 survey season as part of the Empowering Women in Hydrography project. Elaina O'Brien worked with Red Penguin Marine for her lab visit, both visiting their head office and working remotely as an intern, working on a cable burial risk assessment for a power cable project off the east coast of the UK. Both Chiaki Okada and Sara Cardigos worked with the Nippon Foundatio/GEBCO Seabed 2030 project team at Center for Coastal and Ocean Mapping as an introduction to their methodologies and approaches to data sourcing and processing.

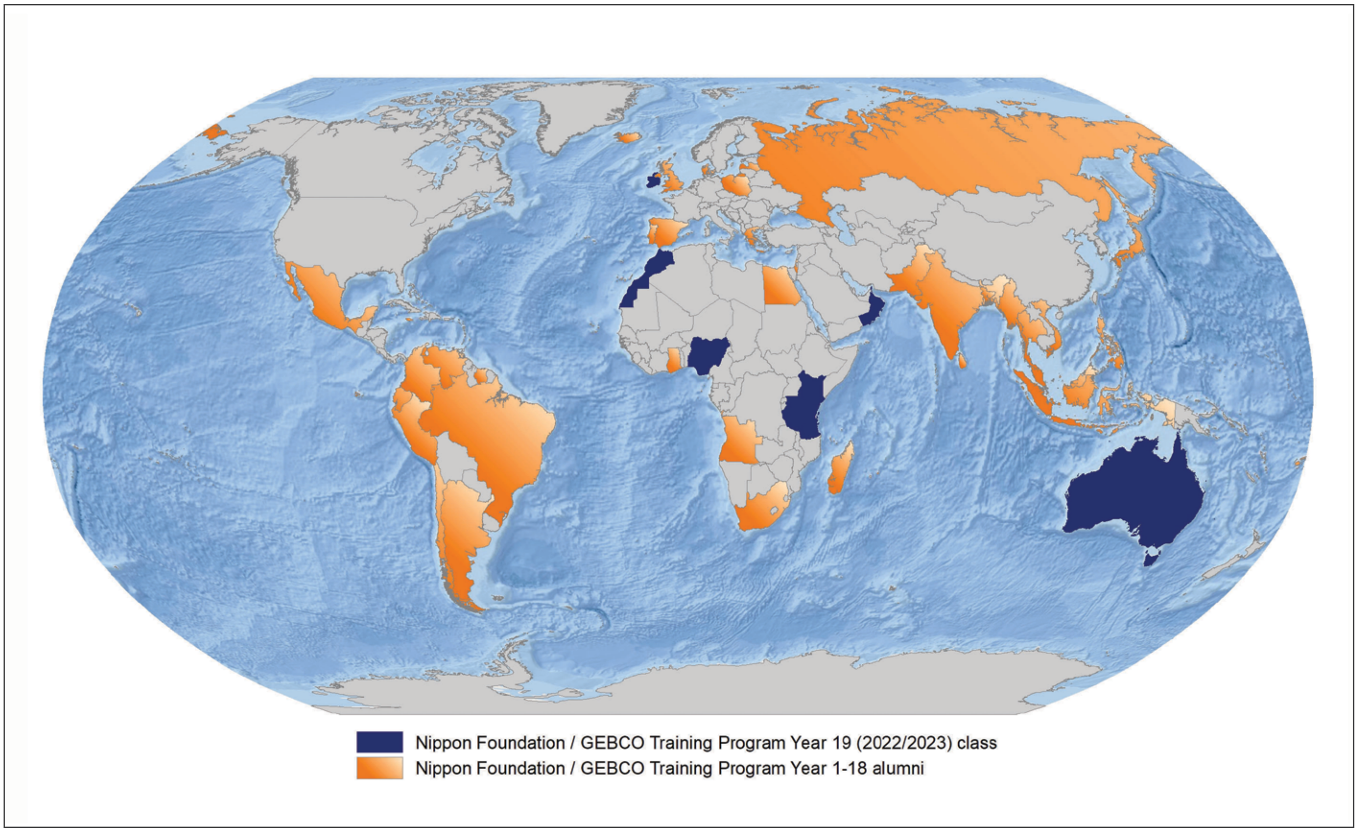


Figure 44-4. Distribution of Nippon Foundation GEBCO Training Program students.

Programmatic Priority 3

DEVELOP AND ADVANCE MARINE GEOSPATIAL AND SOUNDSCAPE EXPERTISE

NOFO Requirement 19

Effective delivery of research and development results through scientific and technical journals and forums and transition of research and development results to an operational status through direct and indirect mechanisms including partnerships with public and private entities.

JHC/CCOM responded to NOFO requirement 19 with one task:

Task 45: Delivery of Results: Publications and Presentations

Task 45: Delivery of Results: Publications and Presentations

JHC Participants: All

Members of the Center continue to actively publish their results in refereed and other journals, make numerous presentations and transition their research to NOAA and others. A complete list of Center publications, conference and other presentations, reports, and theses can be found in Appendices D and E. In addition, the Center has a very active Industrial Partner Program with more than 60 industrial partners. A full list of the current Industrial Partners can be found in Appendix C.

Programmatic Priority 3

DEVELOP AND ADVANCE MARINE GEOSPATIAL AND SOUNDSCAPE EXPERTISE

NOFO Requirement 20

Public education, visualization tools, and outreach to convey the aims and enhance the application of hydrography, nautical charting ocean coastal and Great Lakes mapping and related hydrodynamic models to safe and efficient marine navigation and coastal resilience.

JHC/CCOM responded to NOFO requirement 20 with one task:

Task 46: Outreach

Task 46: Outreach

JHC Participants: Tara Hicks Johnson and Colleen Mitchell

In addition to our research efforts, we recognize the interest that the public takes in our work and our responsibility to explain the importance of what we do to those who ultimately fund our work. We also recognize the importance of engaging young people in our activities to encourage a steady stream of highly skilled workers in the field. To this end, we have upgraded our web presence and expanded our outreach activities. Outreach Manager Tara Hicks Johnson joined our staff in 2011. She coordinates Center-related events, represents the Center on committees and at meetings, and is the friendly face the Center presents to the public. Graphic Designer Colleen Mitchell, who joined the Center in 2009, is responsible for the communications side of outreach, managing the Center's website and social media, and using her design skills to translate the Center's mission through print and digital mediums.

The Center continued to attract significant media attention during this reporting period, including articles in *Popular Science*, *National Geographic*, and the *New York Times*.

JHC/CCOM Media Coverage
January–December 2022

Jan. 7	Ocean Mapping Honor	*UNH Today*
Jan. 8	Accidental Implosion Yields New Measurement for Ocean's Deepest Point	*National Geographic*
Feb. 10	ThayerMahan Partners with University of New Hampshire Center for Coastal and Ocean Mapping	*Yahoo!*
Feb. 10	ThayerMahan Partners with University of New Hampshire Center for Coastal and Ocean Mapping	*Benzinga*
Feb. 22	ThayerMahan Joins Forces with UNH/NOAA Partnership	*Hydro International*
Mar. 23	Seatrec and Seabed 2030 Launch Project NEMO, the "Last Great Expedition" to Map Ocean's Most Remote Spot	*WebWire*
Apr. 14	NOAA's Ocean Exploration Cooperative Institute Takes Delivery of DriX Uncrewed Surface Vehicle	*Directions Magazine*
Apr. 17	NOAA's Ocean Exploration Takes Delivery of DriX USV	*Dark News*
Apr. 20	NOAA Takes Delivery of Uncrewed Surface Vehicle	*WorkBoat*
Apr. 20	Winds of Change	*UNH Today*
May 26	Engineers on E/V Nautilus Expedition Test 3 Remotely Operated Vehicles	*Hawai'i Public Radio*
Jun. 1	Cracking the Case of Arctic Sea Ice Breakup	*MIT News*
Jun. 2	UNH Researchers Develop Software to Monitor Ocean Soundscape Especially During COVID-19	*EurekaAlert!*
	Distributed Sensor Network May Reveal Physical Processes Contributing to Diminishing Sea Ice	*Science X Daily*
Jul. 27	Large Crew of UNH Scientists, Students Map Seafloor of Marine National Monument	*UNH Today*
Jul. 28	There Are Holes on the Ocean Floor. Scientists Don't Know Why	*New York Times*
Jul. 28	'The Holes Look Human Made': Eerie Discovery on the Ocean Floor Leaves Scientists Scratching Their Heads	*The Daily Caller*
Jul. 29	There Are Holes On The Ocean Floor Scientists Don't Know Why	*Weird Era News*
Aug. 5	UNH Scientists and Students on Monumental Ocean Mapping Expedition in Hawaii	*UNH Press Release*
Aug. 9	UNH Scientists and Students on Monumental Ocean Mapping Expedition in Hawaii	*Hillsborough Sun*
Aug. 14	UNH Scientists and Students on Monumental Ocean Mapping Expedition in Hawaii	*Union Leader*
Aug. 17	Significant Progress Made on Mapping Papahānaumokuākea Seafloor	Hawai'i Public Radio

Aug. 18	Interagency Public-Private Partnership Sends Uncrewed Saildrone to Explore Remote Alaskan Waters	*NOAA Ocean Exploration*
Aug. 22	SHIP REVIEW | DriX: Unmanned Vehicle to Support NOAA's Ocean Exploration Programs	*6Park News*
Aug. 22	Uncrewed Saildrone to Explore Remote Alaskan Waters	*Marine Technology News*
Sep. 13	Invasive Seaweed Threatens the Gulf of Maine	*Boston Chronicle, WCVB*
Sep. 14	The Centuries-Long Quest to Map the Seafloor's Hidden Secrets	*Popular Science*
Sep. 20	Shifting Sands	*UNH Today*
Oct. 31	A Career's Work Recognized	*UNH Today*
Nov. 3	UNH Research Shows COVID-19 Lockdown Did Not Lead to Quieter Offshore Ocean	*EurekaAlert!*
Nov. 3	Shipping Sounds	*UNH Today*
Nov. 3	Research Shows COVID-19 Lockdown Did Not Lead to Quieter Offshore Ocean	*Phys Org*
Nov. 15	Research Snapshot: Offshore Survival	*UNH Today*
Nov. 21	Lockdowns Didn't Reduce Ocean Sound Levels	*Deep Blue*
Dec. 17	The Deep Sea Discoveries and Sightings of 2022 are Fascinating	*Mashable*

Outreach Events

The facilities at the Center provide a wonderful opportunity to engage students and the public in the types of research that we do (Figure 46-1). With the continuation of the COVID-19 pandemic, the number of visits is smaller this year than pre-pandemic levels, but we have found ways to reach as many students and members of the public as possible. We have also supported outreach events held outdoors. In 2022, the Center provided individual outreach opportunities for these students and individuals from a number of schools and organizations (see list below):

January–December 2022

School or Community Group	Number of Students or Participants
Hollis Brookline School/SeaPerch and Tour	180
ME 441/477 Tour	30
UNH Manchester/ Krevia Academy SeaPerch Tour	50
Manchester School of Technology	35
UNH Summer Internship Students	20
UNH Keepers Campers	20
Portsmouth Middle School Tour	30
Stratham Memorial School	50
Oyster River Middle School SeaPerch	120

Figure 46-1. School and groups visit the Center, touring the ASV lab, the Visualization Lab, and the Great Bay interactive display.

Ocean Discovery Challenge

Due to ongoing covid concerns, Ocean Discovery Day was cancelled for 2022. We hope to return to our in-person event in the fall of 2023.

SeaPerch ROV

For a number of years, the Center has worked with the Portsmouth Naval Shipyard (PNSY) and the UNH Cooperative Extension to train and host participating schools, after school programs, and community groups who have built SeaPerch Remotely Operated Vehicles (ROVs) and wish to test them out in our facilities. Local schools have brought their students to the Center to test drive ROVs in our engineering tank and tour both our Center and the engineering facilities on campus. The interest in these ROVs was so great that PNSY and the Center started the Seacoast SeaPerch Regional Competition in 2012. We have continued to host SeaPerch builds and provide facilities to support participating student groups throughout this year.

We are thrilled to have been able to return to an in person regional competition this past April. Teams from New Hampshire, Maine and Massachusetts contended for the chance to compete at the International SeaPerch Competition which was held in Maryland in June (Figures 46-2 and 46-3).

Figure 46-2. Scenes from the 2022 Seacoast SeaPerch Regional Competition.

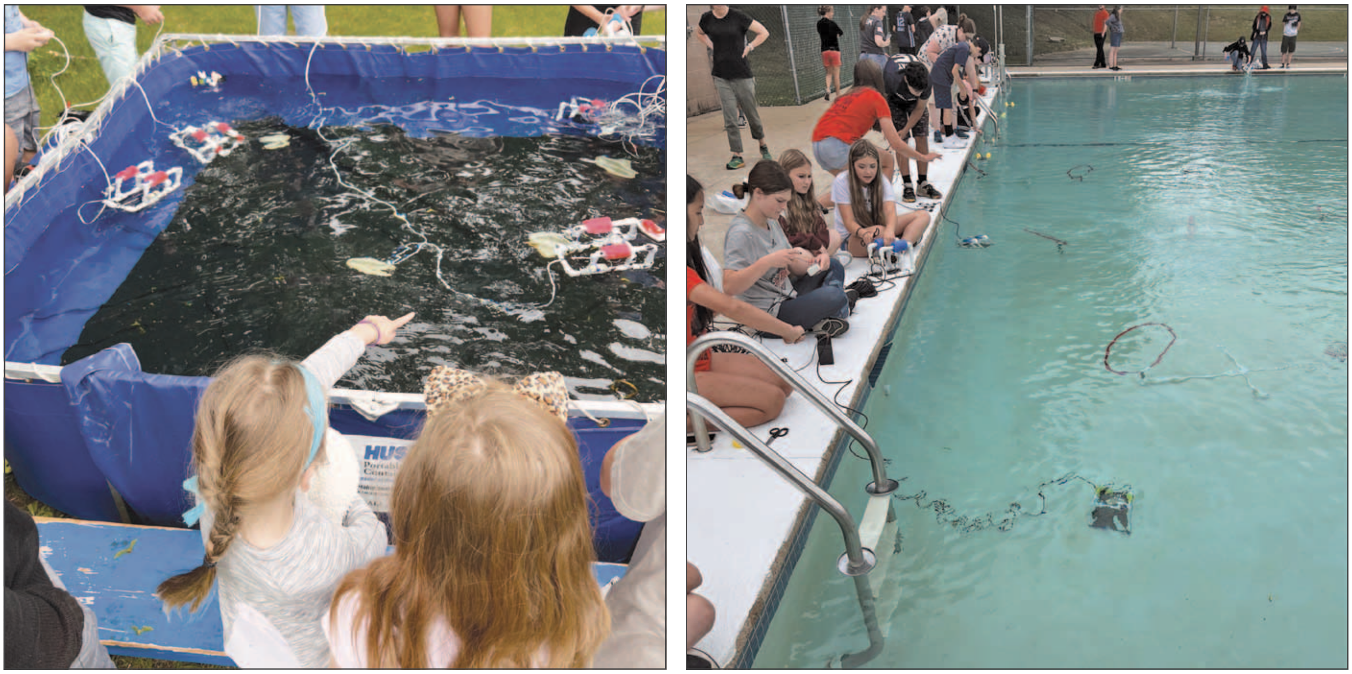


Figure 46-3. Some schools prefer to test SeaPerch outdoors, as seen with these builds with John Fuller School in North Conway (left) and Somersworth Middle School (right).

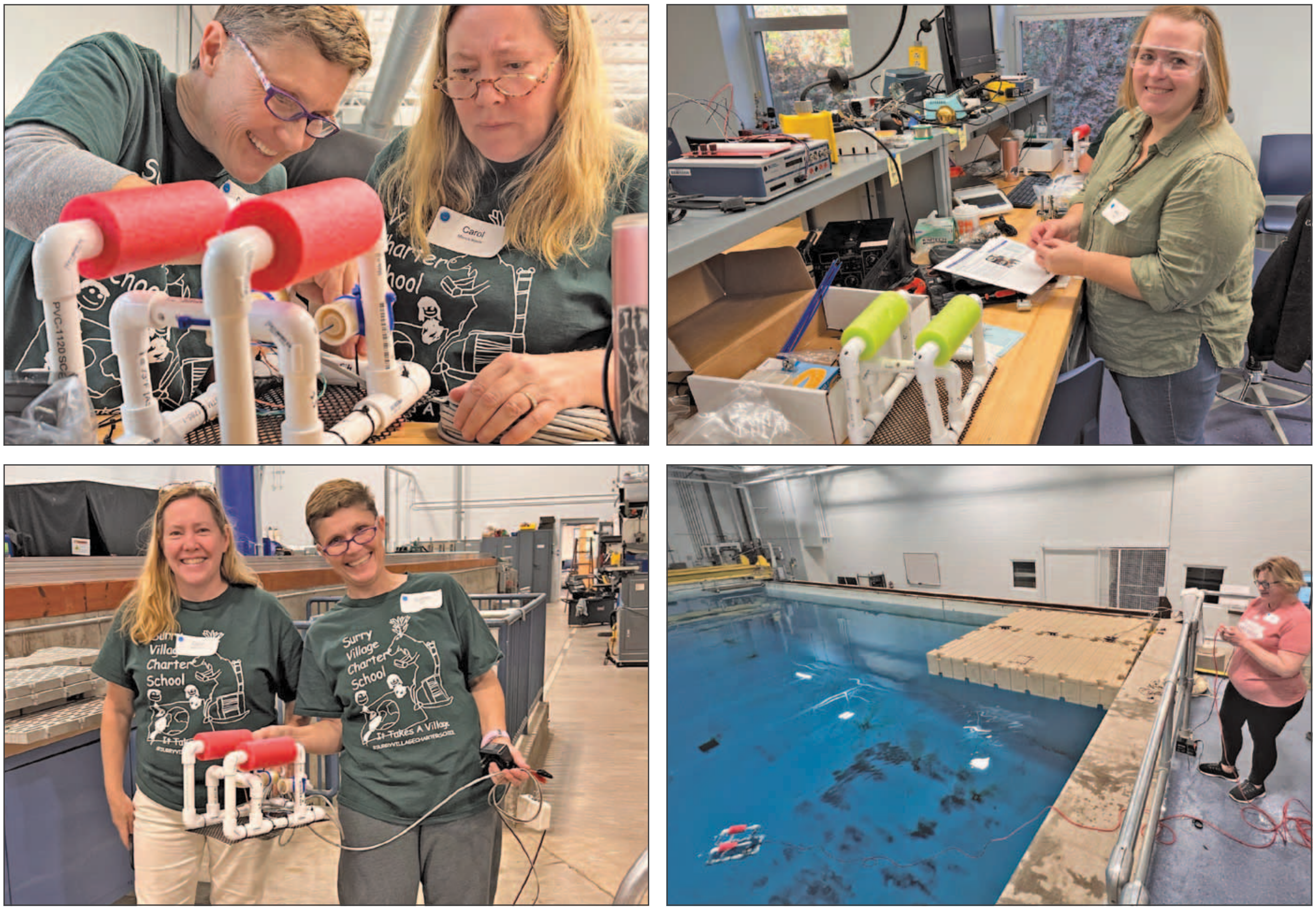


Figure 46-4. SeaPerch educator workshop in November 2022.

We also hosted a SeaPerch educator workshop, introducing and training 16 educators on how to build a SeaPerch ROV with their groups or classes. We host these once or twice a year and are available to any educator that wants to learn more about the program (Figure 46-4).

In other SeaPerch action, we had a testing tank at the Girl Scouts STEM Expo, sharing information with the scout leaders about how to introduce SeaPerch ROVs into their programs (Figure 46-5).

Figure 46-5. SeaPerch at the Girl Scout STEM Expo.

Other Activities

In addition to the major outreach events that we manage each year, we also participate in smaller events and support smaller groups. For example, the Center exhibited at the Canadian Hydrographic Meeting in Ottawa, Canada, and participated in the UNH booth at the Fall American Geophysical Union Meeting in Chicago, Illinois. Participating in these booths allowed us to showcase videos and materials related to our research and academic programs, and we are available to chat with interested researchers and prospective students. We also get to show off our visualization lab demonstrations (Figures 46-6 and 46-7

Figure 46-6. Recruiting graduate students and doing VR demonstrations at the Fall AGU Conference in Chicago, Illinois.

Figure 46-7. Center booth at the Canadian Hydrographic Conference (left, top and bottom) and discussing CCOM research at the SACNAS Diversity in STEM conference in San Juan, Puerto Rico (right, top and bottom).

Website and Other Digital Media

While the Center is dedicated to finding opportunities to expose local and regional young people to ocean science and engineering, we are also committed (and very excited!) to engage with our constituents around the world. With today's social media platforms and digital media, we have built a community with our industrial partners, our alumni, our ocean-going cohorts, and people working in ocean sciences in other countries.

Website

The JHC/CCOM website, (www.ccom.unh.edu) is the public face of the Center (Figure 46-9). The website is a vast repository of information about the Center's research, education programs, outreach, and facilities. It not only is regularly updated with new information, but it contains the history of the Center in its publications catalog, news archive, media resources, and progress reports.

The management of the website requires constant attention. Will Fessenden facilitates the backend—installing updates, troubleshooting problems, and assuring that the site is smoothly served up to the internet. Colleen Mitchell manages the content—overseeing publications, writing briefs and articles, and creating web-optimized images that serve to enhance and illuminate the Center's work. The homepage is frequently updated with announcements, publications, images, and videos. During this reporting period, 21 front page slides were featured, highlighting awards and honors, interviews, news articles, and outreach events.

The website received 117,673 page views from 43,215 unique visitors in 2022. The average visit lasted 1 minute and 35 seconds with an average of 2.07 pages visited. New visitors accounted for 90% of users.

The U.S. was the origin of 51.69% of visits, while the rest were spread all over the globe. In fact, we have had visits from 193 countries outside of the U.S., including such far flung locations as Peru, Morocco, and Switzerland. Nearly every ocean state in the world has accessed the Center's website. A plot offered by Google Analytics illustrating web access

Figure 46-8. The homepage of the Center's website.

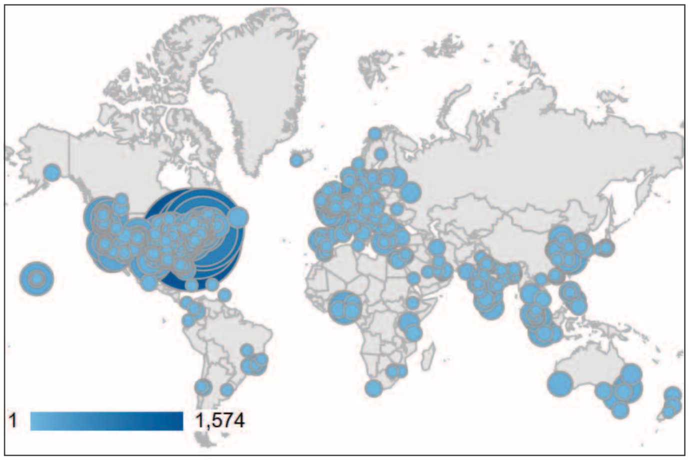


Figure 46-9. Google Analytics plot of Center website visitors by city.

	Page	Pageviews	% Pageviews
1.	/	12,678	11.06%
2.	/project/jeffreys-ledge	5,074	4.42%
3.	/people	4,512	3.93%
4.	/about-ccomjhc	1,867	1.63%
5.	/research	1,819	1.59%
6.	/project/bathymetry-globe	1,760	1.53%
7.	/theme/lidar	1,744	1.52%
8.	/education	1,428	1.25%
9.	/certification	1,173	1.02%
10.	/seaperch	1,168	1.02%

Figure 46-10. Google Analytics chart of Center website visitors' destinations.

by city shows that people from 6,175 cities around the world visited our website in 2022. Hovering over the marked cities on the Analytics website reveals the exact number of visitors, such as the 307 users in London, the 73 users in Perth, Australia, and the 24 users in Helsinki (Figure 46-9).

A report on page views shows that our homepage is the most popular landing page, followed by the Jeffreys Ledge project page, the People directory, the about CCOM JHC page, and the Research oversight page (Figure 46-10).

Social Media

Facebook

The Center's Facebook page (FIgure 46-11) currently has 2.3 K followers (www.facebook.com/ccomjhc).

Facebook's analysis algorithms are continually changing and no longer show data for the entire year. However, there is a new chart showing the age and gender breakdown of the Center's current followers. (Figure 46-12).

Stats are still available for posts in the last 90 days. We will now collect this data quarterly. The most popular post in the final quarter of 2022 was the announcement on November 19 that master's student Elias Adediran was selected to be part of the inaugural class of the Marine Technology Society (MTS) and IEEE Oceanic Engineering Society's (IEEE OES) Emerging Leaders in Marine Technology Program (EMERGE) (Figure 46-13, left). The post reached an audience of 1,845.

The second most popular post of the quarter was the October 12 announcement that Val Schmidt would be the

Figure 46.11. The Center's Facebook page.

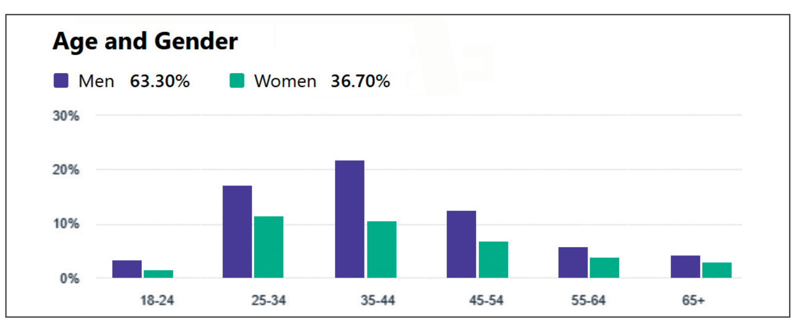


Figure 46-12. Chart showing the Center's Facebook audience breakdown by age and gender.

Ocean Seminar speaker of the week and would present, "Adventures on the High Sea: Marine Robotics at the Center for Coastal and Ocean Mapping," on October 14 (Figure 46-13, right). The post reached 1,154 people.

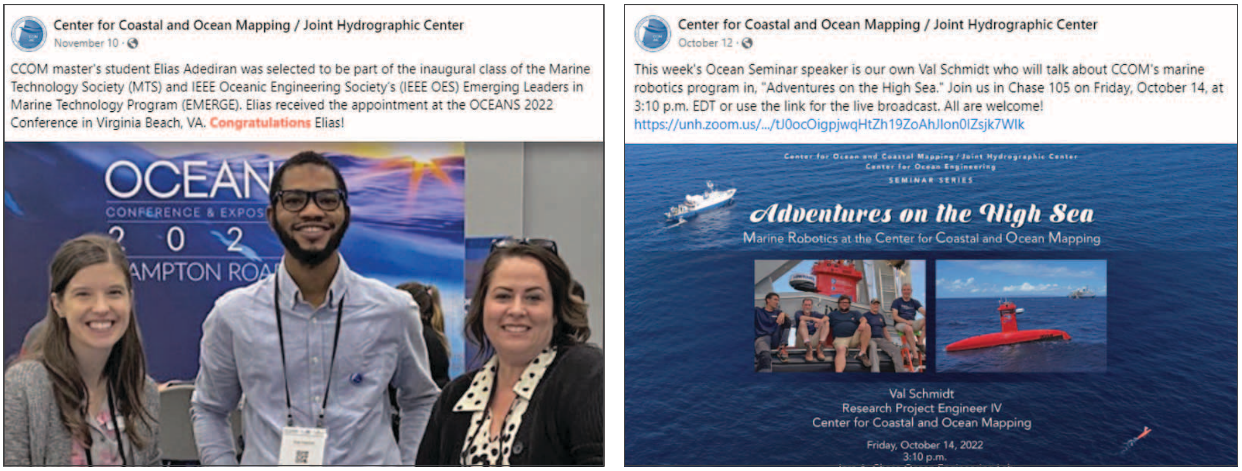


Figure 46-13. The two Facebook posts with the most exposure in the final quarter of 2022.

LinkedIn

Our LinkedIn page (www.linkedin.com/school/ccomjhc) (Figure 46-14) now has 2,448 followers. Likes and comments sometimes exceed those on our Facebook posts. Being able to tag individuals and organizations contributes greatly to how far our reach can go. We have also found LinkedIn to be an excellent place to post papers and scholarly articles which don't get much response on Facebook or Twitter.

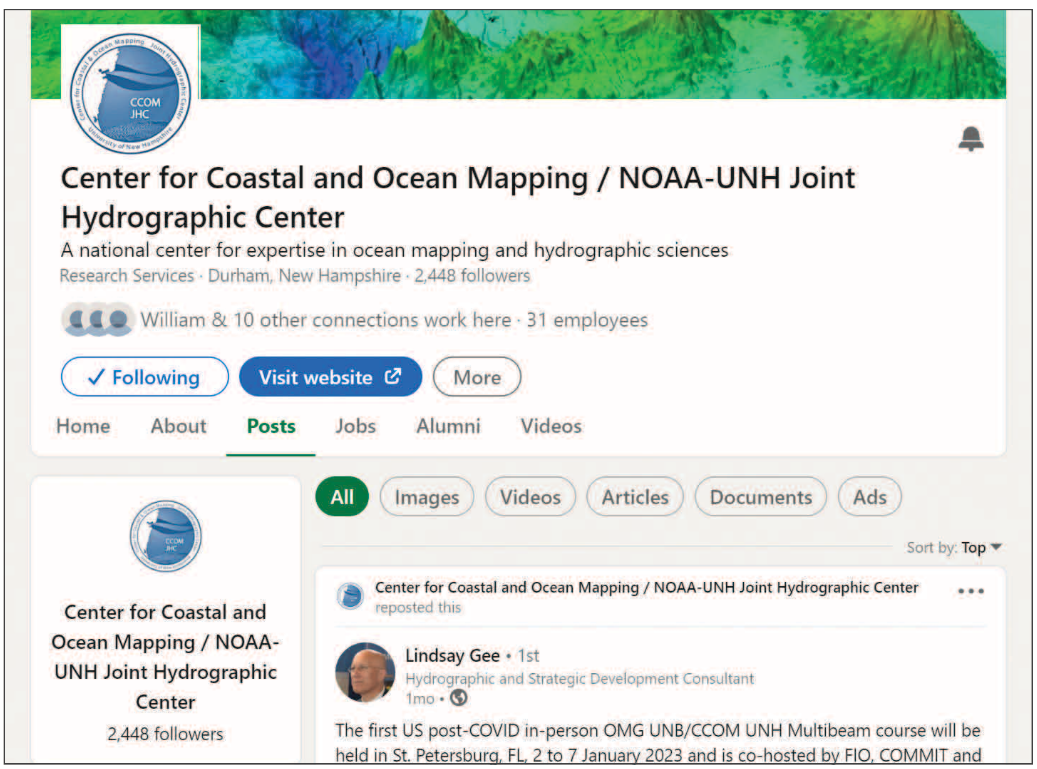


Figure 46.14. The Center's LinkedIn feed.

Vimeo

The Center's videos are hosted by Vimeo (vimeo.com/ccomjhc). There are currently 177 public videos in the Center's catalog (Figure 46-15). Our videos were played 1,883 times in 2022. While the U.S. is the origin of most plays, Center videos have been viewed all over the world.

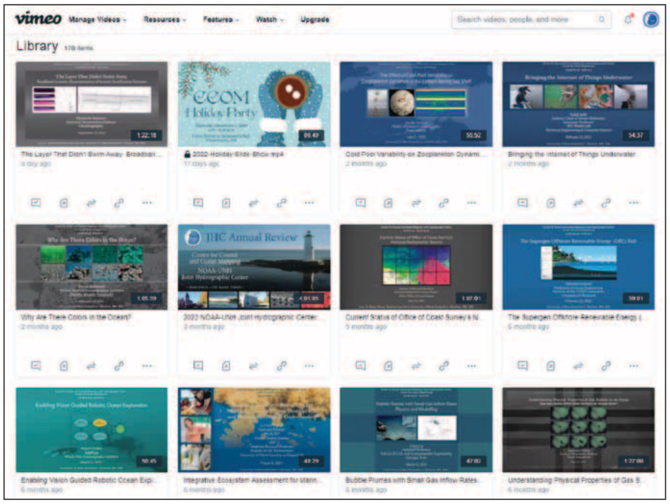


Figure 46-15. A sampling of the videos available in the Center's Vimeo catalog.

Figure 46-16. The Center's Twitter page.

Twitter

The Center is now following 69 groups or individuals in Twitter's ocean community, while 671 people or groups follow us (twitter.com/ccom_jhc). To date, we have tweeted 1,027 times to announce seminars and media coverage, and to amplify news stories about us from other source—such as UNH Research.

Seminar Series

Our seminar series featured 34 seminars in 2022. Four of these seminars were master's thesis defenses and two were doctoral dissertation defenses. The rest were given by Center researchers or experts from industry and academia. Ph.D. student Brandon Maingot and Ocean Engineering Ph.D. student Melissa Marry were the student seminar co-ordinators for the 2022 spring semester. CCOM master's student Airlie Pickett and Ocean Engineering Ph.D. student Zachary Moscicki took over for the fall semester.

Figure 46-17. A few of the 34 flyers produced for our 2022 seminar series.

Appendix A: Graduate Degrees in Ocean Mapping

The University of New Hampshire offers Ocean Mapping options leading to Master of Science and Doctor of Philosophy degrees in Ocean Engineering and in Earth Sciences. These interdisciplinary degree programs are provided through the Center and the respective academic departments of the College of Engineering and Physical Sciences. The University has been awarded recognition as a Category "A" hydrographic education program by the International Federation of Surveyors (FIG)/International Hydrographic Organization (IHO)/International Cartographic Association (ICA). Requirements for the Ph.D. in Earth Sciences and Engineering are described in the respective sections of the UNH Graduate School catalog. M.S. degree requirements are described below.

Course	MSOE Thesis	MSES Thesis	MSES Non-Thesis	Certificate
Integrated Seabed Mapping Systems	✓	✓	✓	✓
Advanced Topics in Ocean Mapping	✓	✓	✓	✓
Geodesy and Positioning for Ocean Mapping	✓	✓	✓	✓
Hydrographic Field Course	✓	✓	✓	✓
Geological Oceanography		✓	✓	
Introductory Physical Oceanography		✓	✓	
Ocean Measurements Lab	✓			
Ocean Seminar I	✓			
Ocean Seminar II	✓			
Underwater Acoustics	✓			
Mathematics for Geodesy		✓	✓	✓
Research Tools for Ocean Mapping		✓	✓	✓
Seminar in Earth Sciences		✓	✓	✓
Proposal Development		✓	✓	
Seamanship	✓	✓	✓	✓
Introduction to Physical Oceanography	✓			✓
Geological Oceanography for Hydrographic Surveyors	✓			✓
Approved Elective Credits	+3		+4	
Thesis	✓	✓		
3rd Party Training				
QPS (QIMERa, FMGT, Fledermaus)	✓	✓	✓	✓
Caris (HIPS/SIPS)	✓	✓	✓	✓
HYPACK (Hysweep)	✓	✓	✓	✓

MSOE: Master of Science in Ocean Engineering with Ocean Mapping option – includes thesis
MSES: Master of Science in Earth Sciences with Ocean Mapping option – includes thesis
MSES non-thesis: Master of Science in Earth Sciences with Ocean Mapping option – non-thesis
Certificate: Graduate Certificate in Ocean Mapping – non-thesis

Table A.1 The Ocean Mapping (OM) graduate curricula offered through the Center. Black tick marks indicate the courses required for the various degrees. The red tick marks indicate the additional training required to meet Category A requirements.

Master of Science in Ocean Engineering

Ocean Mapping Option

Core Requirements		Instructor	Credit Hours
OE 810	Ocean Measurements Lab	Lippmann	4
OE 874	Integrated Seabed Mapping Systems	Dijkstra/Hughes Clarke/Calder	4
OE 875	Advanced Topics in Ocean Mapping	Dijkstra/Mayer/Armstrong	4
OE 871	Geodesy and Positioning for Ocean Mapping	Dijkstra	4
OE 865	Underwater Acoustics	Weber	3
OE 972	Hydrographic Field Course	Dijkstra	4
OE 990	Ocean Seminar I	Mayer	1
OE 991	Ocean Seminar II	Mayer	1
OE 899	Thesis		6

At Least Three Additional Credits from the Electives Below

OE 854	Ocean Waves and Tides	Swift	4
OE 857	Coastal Engineering and Processes	Foster	3
OE 864	Spectral Analysis of Geophysical Time Series Data	Lippmann	4
OE 895	Special Topics	Staff	1-4
ECE 814	Introduction to Digital Signal Processing	Smith	4
ESCI 858	Introduction to Physical Oceanography	Pringle	3
ESCI 896	Special Topics	Staff	1-4

Where a course of equivalent content has been successfully completed as an undergraduate, an approved elective may be substituted.

Master of Science in Earth Sciences

Ocean Mapping Option

Core Requirements		Instructor	Credit Hours
ESCI 858	Introductory Physical Oceanography	Pringle	3
OE 859	Geological Oceanography	Johnson	4
OE 871	Geodesy and Positioning for Ocean Mapping	Dijkstra	4
OE 872	Applied Tools for Ocean Mapping	Dijkstra	2
OE 874	Integrated Seabed Mapping Systems	Dijkstra/Hughes Clarke/Calder	4
OE 875	Advanced Topics in Ocean Mapping	Dijkstra	4
OE 972	Hydrographic Field Course	Dijkstra	4
MATH 831	Mathematics for Geodesy	Wineberg	3
ESCI 997	Seminar in Earth Sciences	Hughes Clarke	1
ESCI 998	Proposal Development	Palace	1
ESCI 899	Master's Thesis		1-6

Additional elective courses must be taken to meet graduate credit requirements (with approval).

Master of Science in Earth Sciences (Non-Thesis Option)

Ocean Mapping Option

Core Requirements		Instructor	Credit Hours
ESCI 858	Introductory Physical Oceanography	Pringle	3
OE 859	Geological Oceanography	Johnson	4
OE 871	Geodesy and Positioning for Ocean Mapping	Dijkstra	4
OE 872	Applied Tools for Ocean Mapping	Dijkstra	2
OE 874	Integrated Seabed Mapping Systems	Dijkstra/Hughes Clarke/Calder	4
OE 875	Advanced Topics in Ocean Mapping	Dijkstra	4
OE 972	Hydrographic Field Course	Dijkstra	4
MATH 831	Mathematics for Geodesy	Wineberg	3
ESCI 997	Seminar in Earth Sciences	Hughes Clarke	1
ESCI 998	Proposal Development	Palace	1
ESCI 898	Directed Research		2

Additional elective courses must be taken to meet graduate credit requirements (with approval).

Where a course of equivalent content has been successfully completed as an undergraduate, an approved elective may be substituted.

Graduate Certificate in Ocean Mapping

Core Requirements		Instructor	Credit Hours
OE 871	Geodesy and Positioning for Ocean Mapping	Dijkstra	3
OE 872	Applied Tools for Ocean Mapping	Dijkstra	2
MATH 831	Mathematics for Geodesy	Wineberg	3
OE 874	Integrated Seabed Mapping Systems	Dijkstra/Hughes Clarke/Calder	4
OE 875	Advanced Topics in Ocean Mapping	Dijkstra	4
OE 972	Hydrographic Field Course	Dijkstra	4
OE 677	Seamanship and Marine Weather	Armstrong	2
ESCI 896.2	Physical Oceanography for Hydrographers	Hughes Clarke	2
ESCI 896.4	Geological Oceanography for Hydrographers	Hughes Clarke/Wigley/Ward	2

Additional elective courses must be taken to meet graduate credit requirements (with approval).

Where a course of equivalent content has been successfully completed as an undergraduate, an approved elective may be substituted.

Graduate Students: Academic Year 2022

Student	Program	Advisor/Mentor
Elias Adediran*	M.S. OE Ocean Mapping	K. Lowell/C. Kastrisios
Juliane Affonso	M.S. ES Ocean Mapping	C. Kastrisios
Kindrat Beregovyi*	Ph.D. Computer Science	T. Butkiewicz
R. Miguel, Candido	M.S. ES Ocean Mapping	J. Hughes Clarke
Kaan Cav*	M.S. OE Ocean Mapping	J. Hughes Clarke
Lynette Davis	M.S. ES Ocean Mapping	J. Hughes Clarke
Patrick Debroisse (NOAA)	M.S. OE Ocean Mapping	A. Armstrong
Massimo DiStefano	Ph.D. ES Ocean Mapping	L. Mayer
Glenna Dyson*	M.S. ES Oceanography	J. Dijkstra
Jenna Ehnot*	M.S. OE Ocean Mapping	L. Mayer
Adriano Fonseca*	Ph.D. Ocean Engineering	B. Calder
Joshua Girgis*	M.S. Ocean Engineering	J. Dijkstra
Andrea Granger*	M.S. ES Ocean Mapping	K. Lowell
Anne Hartwell	Ph.D. Oceanography	J. Dijkstra
Erin Heffron	M.S. ES Ocean Mapping	L. Mayer
Shannon Hoy (NOAA)*~	M.S. ES Ocean Mapping	A. Armstrong
Ti-Yao Hsu	Cert. OE Ocean Mapping	C. Kastrisios/B. Calder
Sally Jarmusz*	M.S. ES Ocean Mapping	B. Calder/L. Mayer
Katherine Kirk	Ph.D. ES Oceanography	T. Lippmann
Nicholas La Manna*	M.S. OE Ocean Mapping	A. Lyons
Daniel Leite*	M.S. ES Ocean Mapping	J. Hughes Clarke
Brandon Maingot*	Ph.D. OE Ocean Engineering	J. Hughes Clarke
Howie Meyers (NOAA)	M.S. ES Ocean Mapping	A. Armstrong
Grant Milne	Ph.D. Marine Biology	J. Miksis-Olds
Garret Mitchell	M.S. ES Ocean Mapping	L. Mayer
Coral Moreno*	M.S. OE Ocean Mapping	L. Mayer
Tamer Nada*	Ph.D. Oceanography	B. Calder/C. Kastrisios
Alexandra Padilla	Ph.D. Ocean Engineering	T. Weber
Airlie Pickett (NOAA)	M.S. OE Ocean Mapping	A. Armstrong
Indra Prasetyawan	Ph.D. ES Oceanography	J. Hughes Clarke
Elizabeth Reed-Weidner*	Ph.D. ES Ocean Mapping	L. Mayer
Joao Silva de Deus	M.S. ES Ocean Mapping	J. Hughes Clarke
Dan Tauriello	M.S. OE Ocean Mapping	B.Calder
Kevin Tennyson (NOAA)	M.S. OE Ocean Mapping	A. Armstrong
Aditi Tripathy	M.S. Ocean Engineering	J. Miksis-Olds/A. Lyons

* Funded by NOAA/JHC Source
~ Part-time

GEBCO Students: 2022-2023

Student	Institution	Country
Luke FitzGerald	University of Limerick	Ireland
Rebecca Formanek	Hydrographic and Cadastral Survey	Australia
Fadhili Mustafa Malesa	University of Da es Salaam	Tanzania
Daina Mathai	Kenya Marine and Fisheries Research Institute	Kenya
Jihad Rachid	Hassan II University of Casablanca	Morocco
Ekechukwu Uzoeshi	Nigerian Navy Hydrographic Office Lagos	Nigeria

Appendix B: Field Programs

OXR220220109 R/V *OceanXplorer* EM304/EM712 Quality Assessment Testing, January 9–16. Johnson and Jerram visited the R/V *OceanXplorer* for externally funded testing of the vessel's EM304, EM712, and Seapath systems during an opportunistic science system shakedown off Gibraltar. The planning, data collection, analyses, and follow-up with OceanX and Kongsberg have informed similar support that Johnson and Jerram provide for the Center and partners. (Paul Johnson, Kevin Jerram)

NA132 E/V *Nautilus* 2022 Shakedown and DriX-8 Integration, February 17–March 14. NOAA OECI-Funded expedition, focused in initial integration of the DriX-8 USV aboard the E/V *Nautilus*, plus a 10-day shakedown cruise. (Larry Mayer, Kenneth G. Fairbarn, Andy McLeod, Avery Munoz, Val E. Schmidt)

SKQ202203S R/V *Sikuliaq* EM302/EM710 Quality Assurance Testing, February 25. In early 2022, the Multibeam Advisory Committee (MAC) planned a series of calibrations at proven sites off Oregon for the EM302 and EM710 systems aboard R/V *Sikuliaq*. The vessel completed data collection in late February and the MAC provided remote data analysis and reporting to support field season readiness. The report for this field program is available on the MAC website. (Paul Johnson, Kevin Jerram)

NA136 E/V *Nautilus* 2022 Shakedown Cruise, March 1–10. Planned and led the Kongsberg EM302 multibeam quality assessment testing. (Paul Johnson)

NA139 OECI 2022 Tech Challenge, April 29–May 24. OECI-Funded "Tech Challenge Cruise" focused on multi-robot operations in collaboration with other OECI partners—WHOI and the Ocean Exploration Trust. (Larry Mayer, Andy McLeod, Roland Arsenault, Val E. Schmidt)

WGOM 2022 Field Campaign, May 17–November 4. The 2022 Field Campaign included 13 one-day cruises on the R/V *Gulf Surveyor* in the WGOM to collect bottom sediment samples and seafloor video. (Michael Bogonko, Matthew Rowell, Daniel Tauriello, Larry Ward)

HLY22TA USCGC *Healy* EM122 Quality Assurance Testing, May 21–23. The Multibeam Advisory Committee (MAC) planned a series of quality assessment tests at proven sites off Washington for opportunistic testing of the EM122 aboard USCGC *Healy*. The vessel completed data collection in late May and the MAC provided remote data analysis to assess field season readiness. The report for this field program will be available on the MAC website after final documentation of post-QAT settings. (Paul Johnson, Kevin Jerram)

KM 2022 Gear Trials R/V *Kilo Moana* EM122/EM710 Quality Assurance Testing, May 22. In early 2022, the Multibeam Advisory Committee (MAC) planned a series of patch tests at proven sites off Oahu for opportunistic testing of the EM122 and EM710 aboard R/V *Kilo Moana*, following factory calibration and reinstallation of the POS MV IMU. Additional, alternative sites were developed to accommodate the vessel's planned transits to Station Aloha. The MAC provided remote data analysis and reporting to support field season readiness. The report for this field program will be available on the MAC website following the addition of recent data collection. (Paul Johnson, Kevin Jerram)

OE 972 Hydrographic Field Course, R/V *Gulf Surveyor,* May 23–August 28. The class completed a multibeam, phase differencing sidescan, and towed sidescan survey in multiple regions along the New Hampshire seacoast. (Semme J. Dijkstra, Matthew Rowell, Daniel Tauriello, Airlie Pickett, Adriano Fonseca)

R/V *Gulf Surveyor*, June 6. Scoped out diveable sites for Task 30—Improvements in Change Detection. (Kristen L. Mello, Jenn Dijkstra)

Coral Reef Mapping Study, R/V *Lady Lynne,* June 17–July 1. Along with Chris Parrish and his team, collected single beam, multibeam, UAS and in situ stereo-imagery from six coral restoration sites. This included two NOAA sanctuary sites and one Mission Iconic Reef site. (Kristen L. Mello, Jenn Dijkstra)

Mapping Seaweeds, July 5–August 19. Mapped seaweed habitats at the Isles of Shoals using our stereo-camera. (Kristen L. Mello, Jenn Dijkstra)

EX2205 Voyage to the Ridge 2, NOAA Ship *Okeanos Explorer*, July 9–30. A combined mapping and remotely operated vehicle (ROV) expedition to the Mid-Atlantic Ridge and Azores Plateau (Norfolk, VA to Horta, Faial, Azores). Operations during this 22-day expedition included the completion of ten successful ROV exploration dives in the vicinity of the Azores and the Mid-Atlantic Ridge north of the Azores. Derek Sowers was Expedition Coordinator. (Shannon Hoy, Derek Sowers)

Onslow Bay, NOAA Ship *Ferdinand Hassler*, July 10–23. Augmented as Officer of the Deck. (Patrick Debroisse)

Mapping Kelp Habitats, R/V *Gulf Surveyor*, July 11–21. Tested our new camera lens and collected stereo-imagery of seaweed communities (Kristen L. Mello, Jenn Dijkstra)

DriX 12 SAT, R/V *Gulf Surveyor*, August 4–16. Schmidt and McLeod. With help from interns, Ehnot and Cook, facilitated a combined training and Sea Acceptance Test event completed by iXblue for NOAA. This included several days of assembly and familiarization, followed by several days of deployment at sea, and followed by several days of logistics to disassemble and pack the gear for shipment. (Andy McLeod, Jenna Ehnot, Val E. Schmidt)

DriX 12 Aboard the NOAA Ship *Thomas Jefferson*, August 25–September 12. Provided technical support, operational guidance and training to the crew during the integration and operational testing of NOAA's DriX-12 ASV, in preparation for two weeks of scheduled survey effort. They also provided a mobile work space with the Center's mobile ASV lab and designed and installed a temporary painter boom to facilitate DriX deployments. (Andy McLeod, Avery Munoz, Val E. Schmidt)

DriX-12 Training for NOAA, October 12–20. Provided logistical support to aid in readyment and deployment of the DriX-12 to support a six-day DriX Supervisor Training for NOAA Fisheries Personnel. However, when a death in the family prevented the iXblue instructor from completing the event, the Center's team—drawing from their own training event and more than 30 operational days at sea this year—stepped up and provided the training. (Andy McLeod, Kenneth G. Fairbarn, Avery Munoz, Val E. Schmidt)

Mapping System Configuration Review, R/V *Marcus G. Langseth*, October 25–December 7. The Multibeam Advisory Committee (MAC) provided a comprehensive review of mapping system geometry and configuration for the R/V *Marcus G. Langseth* in consultation with technicians and managers at Lamont-Doherty Earth Observatory (LDEO). The MAC and LDEO have developed a detailed plan for updating all mapping system configurations to reflect the most recent vessel survey in a unified mapping reference frame, followed by calibrations and other quality assurance testing during the next available window for data collection. (Paul Johnson, Kevin Jerram)

BEN Engineering, November 29–December 14. Basic engineering test and evaluation of the *BEN ASV,* who had not been deployed operationally for more than a year. Included testing new software infrastructures, a robotic mast for directional antennas and validation of basic functionality of all systems. (Andy McLeod, Kenneth G. Fairbarn, Avery Munoz, Jenna Ehnot, Val E. Schmidt)

Mapping System Configuration Review, R/V *Tarajoq*, December 2. Jerram worked remotely with technical personnel at Greenland Institute of Natural Resources to review mapping system configurations and address data quality challenges experienced during multibeam calibrations. Updates were applied to reflect the most recent vessel survey in a unified mapping system reference frame and correct the positioning errors experienced during initial testing. (Kevin Jerram)

Appendix C: Partnerships and Ancillary Programs

One of the goals of the Joint Hydrographic Center is, through its partner organization the Center for Coastal and Ocean Mapping, to establish collaborative arrangements with private sector and other government organizations. Our involvement with Tyco has been instrumental in the University securing a $5 million endowment; $1 million of this endowment has been earmarked for support of post-doctoral fellows at the Center for Coastal and Ocean Mapping. Industrial Partner Kongsberg Maritime has also provided $1 million to support the research of John Hughes Clarke. Our interaction with the private sector has been formalized into an industrial partner program that is continually growing.

Industry Partners 2022

- Acoustic Imaging Pty, Ltd.
- AML Oceanographic
- Arete Associates, Inc.
- BeamworX
- Bedrock Ocean Exploration PBC
- Chance Maritime Technologies (CMT)
- CIDCO
- Clearwater Seafoods Limited
- David Evans and Associates
- Earth Analytic, Inc.
- EdgeTech
- EIVA Marine Survey Solutions
- Environmental Systems Research Institute (ESRI)
- Euclideon International Pty, Ltd.
- Farsounder, Inc.
- Fugro USA Marine, Inc.
- Huntington Ingalls Industries
- HydroOctave Consulting, Inc.
- IIC Technologies
- iXblue
- Jasco Applied Sciences (Canada) Ltd.
- Kongsberg Underwater Technology (KUTI)
- Leidos
- Mitcham Industries, Inc.
- NLA International
- Norbit SubSea
- Ocean Exploration Trust
- Ocean High Technology Institute, Inc.
- Ocean Power Technologies, Inc.
- Quality Positioning Services B.V.
- Saildrone, Inc.
- SBG Systems
- Sea ID Ltd.
- Sea Machines Robotics
- Seafloor Systems
- SevenCs
- SubCom (TYCO)
- SubSeaSail LLC
- Substructure
- TCarta
- Teledyne CARIS
- Teledyne Marine
- Teledyne OceanScience
- Teledyne Reson, A.S.
- Terradepth
- Tetra Tech, Inc.
- ThayerMahan Inc.
- Woolpert, Inc.

In addition, grants are in place with:

- Department of Commerce, NOAA
- Department of Defense, Office of Naval Research
- Department of the Interior, BOEM
- Department of the Interior
- Exxon Corp
- International Association of Oil & Gas Producers
- Kongsberg Maritime
- Massachusetts Institute of Technology
- MSI Transducers Corp (from U.S. Dept. of Defense, ONR)
- National Science Foundation
- Nature Conservancy
- NH Department of Environmental Services, U.S. DOC (NOAA)
- Nippon Foundation/GEBCO
- Ocean Exploration Trust
- Regional Association for Research on Gulf of Maine
- Schmidt Marine Technology Partners
- Stockholm University (from GEBCO-Nippon Foundation)
- TDI Brooks (from U.S. Dept. of Interior)
- TE Connectivity
- TYCO
- University of California at Santa Barbara (from CA State Lands Commission)
- University of New Hampshire ADVANCE Collaborative
- University of Rhode Island (from U.S. Dept. of Commerce, NOAA)
- Virginia Polytechnic Institute and State University (from U.S. Dept. of Defense, Navy)
- Wells National Estuarine Reserve (from U.S. Dept. of Commerce, NOAA)

The Center has also received support from other sources of approximately $4,580,361 for 2022 (see below).

2022 Project Title	PI	Sponsor	CY Award 2022	Total Award	Length
IT Support for NOAA Employees and Contractors at the Joint Hydrographic Center	Calder, B.	U.S. DOC, NOAA	57,821	115,642	2 years
Quantifying Long-Term Changes and Linkages in Marine Ecosystems Using Historic Observation Data of Gulf of Maine	Dijkstra, J.	Reg. Assn. for Research on Gulf of Maine		2,000	2 years
SOAR Monitoring	Dijkstra, J.	Nature Conservancy	15,823	15,823	6 months
Feasibility of Sustained Real-Time Turbidity Current Monitoring	Hughes Clarke, J.	Exxon Corp.		190,000	5 years
Improving Integrated Multibeam Survey Systems (Phase 2)	Hughes Clarke, J.	Kongsberg Maritime		1,050,000	5 years
Collaborative Research: Optimization of the Multibeam Sonar Systems of the U.S. Academic Fleet	Johnson, P.	National Science Foundation	145,193	838,835	5 years
Field Surveys in Support of Geotechnical Soil Characterization in Coastal NH	Lippmann, T.	Virginia Polytechnic Institute and State University (U.S. DOD, Navy)		47,000	2 years
Potential Impacts of Climate Change-Induced Changes in Temperature on the Coupling of Ovigerous Female Movements and Larval Recruitment Success of Lobsters in the Gulf of Maine	Lippmann, T.	Wells National Estuarine Reserve (U.S. DOC, NOAA)		44,563	4 years
UNH Oceanography Graduate Program	Lippmann, T.	TE Connectivity		10,000	5 years
Measuring and Modeling Temporal Changes in the Seafloor Scatter	Lyons, A.	U.S. DOD, Office of Naval Research		830,000	4 years
Continuing Studies of Multi-Look SAS Techniques for Target Detection and Classification	Lyons, A.	U.S. DOD, Office of Naval Research	134,000	390,000	3 years
DURIP-DEPSCoR Proposal (ONR Ocean Acoustics Program)	Lyons, A.	U.S. DOD, Office of Naval Research		352,205	2 years
Measuring and Modeling Internal Wave Properties and Their Effects on High Frequency Imaging Sonar	Lyons, A.	U.S. DOD, Office of Naval Research		436,626	3 years
Arctic Ice Experiments	Lyons, A.	Massachusetts Institute of Technology	76,970	87,500	2 years
Seabed 2030: Complete Mapping of the Ocean Floor by 2030	Mayer, L.	Stockholm University (Nippon Foundation/GEBCO)	54,135	230,770	5 years
Seabed 2030: Engagement and Development	Mayer, L.	GEBCO-Nippon Foundation	328,727	453,313	2 years
GEBCO Training Program Year 17	Mayer, L.	GEBCO-Nippon Foundation		705,369	3 years
GEBCO Training Program Year 18	Mayer, L.	GEBCO-Nippon Foundation		724,033	2 years
Saildrone Surveyor: Autonomous Mapping and Environmental Characterization Using Deep Ocean ASV	Mayer, L.	U.S. DOC, NOAA		999,852	4 years
Ocean Exploration Cooperative Institute (OECI)	Mayer, L.	Univ. of Rhode Island (U.S. DOC, NOAA)	2,734,990	8,158,842	4 years

Sustainable Seafloor Mapping-A Pilot Demonstration of Echosounder on Profiling Float Powered by Ocean Thermal Energy	Mayer, L.	Schmidt Marine Technology Partners		300,000	2 years
TYCO Fellowship	Mayer, L.	TYCO	53,038		in perpetuity
Monitoring for Shifts in Odontocete Range and Distribution	Miksis-Olds, J.	U.S. DOD, Office of Naval Research		800,000	6 years
SeaBASS 2018: BioAcoustic Summer School	Miksis-Olds, J.	U.S. DOC, NOAA		30,500	4 years
ADEON	Miksis-Olds, J.	U.S. DOI		6,092,513	6 years
Deep Water Atlantic Habitats	Miksis-Olds, J.	TDI Brooks (Department of the Interior)	67,524	383,911	5 years
Sound and Marine Life Joint Industry Program	Miksis-Olds, J.	International Assoc of Oil & Gas Producers		100,000	5 years
SCC-PG: Enhancing Community Engagement in Flood Mitigation Using Integrated Hydrodynamic Modeling and Multi-Scale Socio-Economic Risk Assessment	Miles, B.	University of Louisiana (NSF)	21,241	21,241	1 year
AUV-Based Acoustic Mapping and Characterization in Seafloor Hydrothermal Discharge	Reed-Weidner, E.	University of Washington (NOAA)	44,075	44,075	**1 year**
Volunteer Beach Profile Monitoring Program: Year 7	Ward, L.	NH DES (NOAA)	26,809	26,809	1 year
GEBCO Training Program Year 19	Wigley, R.	GEBCO-Nippon Foundation	820,015	820,015	1 year
		TOTALS	**4,580,361**	**24,301,437**	

Appendix D: Publications

Book Sections

Contarinis, S. and Kastrisios, C., "Marine Spatial Data Infrastructure," in The Geographic Information Science & Technology Body of Knowledge, 2022.

Kastrisios, C., Sullivan, B.M., Powell, J., and Baek, Y., "Hydrographic Geospatial Data Standards," in The Geographic Information Science & Technology Body of Knowledge, 2nd Quarter 2022.

Conference Abstracts

Affonso, J., Kastrisios, C., Parrish, C., and Calder, B.R., "A Geographically Adaptive Model for Satellite Derived Bathymetry," 2022 Canadian Hydrographic Conference, Ottawa, Canada, 2022.

Arsenault, R., "Mapping the Seafloor with ROS Using Project11," ROSCon 2022, Kyoto, Japan, 2022.

Arsenault, R. and Lindzey, L., "A ROS-Enabled Floating Hackathon: Coordinating Multiple Marine Robots," ROSCon 2022, Kyoto, Japan, 2022.

Cowan, K., Bernardini, A., Mercedes, A., Troupiotis-Kapeliaris, A., Zissis, D., Kastrisios, C., and Schmidt, V.E., "Toward a Readily Available Maritime Route Suggestion and Prediction System Using Historic 'Roads of the Sea'," Canadian Hydrographic Conference, Ottawa, Canada, 2022.

Dyer, N., Kastrisios, C., and De Floriani, L., "Towards an Automated Chart-Ready Cartographic Sounding Selection," Canadian Hydrographic Conference, Ottawa, Canada, 2022.

Lingzhi, W. and Kastrisios, C., "Cross Check of Data Quality Chapters of S-1xx Product Specifications," Canadian Hydrographic Conference, Ottawa, Canada, 2022.

Nada, T., Kastrisios, C., Calder, B.R., Christie, E., Greene, C., Bethell, A., and Hosuru, M., "The Nautical Cartographic Constraints and an Automated Generalization Model," Canadian Hydrographic Conference, Ottawa, Canada, 2022.

Contarinis, S., Kastrisios, C., and Nakos, B., "S-122 Portrayal and Integration Concepts and Services," Canadian Hydrographic Conference. Ottawa, Canada, 2022.

Sowers, D., Mayer, L.A., Masetti, G., Cordes, E., Gasbarro, R., Lobecker, E., Cantwell, K., Hoy, S., White, M., Candio, S., Malik, M.A., and Dornback, M., "Standardized Geomorphic Characterization of the Extensive Cold-Water Coral Mound Province of the Blake Plateau, USA," Ocean Sciences Meeting 2022.

Conference Poster

Schmidt, V.E., "A Solution to TSP for Survey Line Segments", North East Robotics Colloquium. Lowell, MA, 2022.

Conference Proceedings

Ware, C. and Kastrisios, C., "Evaluating Countable Texture Elements to Represent Bathymetric Uncertainty," EuroVis 2022, The Eurographics Association, Rome, Italy, 2022.

Kastrisios, C. and Ware, C., "Subjective and Objective Evaluation of Data Quality Visualization Methods on Navigational Charts," AutoCarto 2022. Redlands, CA, 2022.

Butkiewicz, T., Atkin, I., Sullivan, B. M., Kastrisios, C., Stevens, A. H., and Beregovyi, K., "Web-based Visualization of Integrated NextGeneration S-100 Hydrographic Datasets," Oceans 2022. Hampton Roads, VA, 2022.

Database

Weatherall, P., Bringensparr, C., Castro, C.F., Dorschel, B., Drennon, H., Ferrini, V.L., Harper, H.A., Hehemann, L., Jakobsson, M., Johnson, P., Kinney, J., Mackay, K., Maher, S.M., Martin, T.V., Mayer, L.A., McMichael-Phillips, J., Mohammad, R., Nitsche, F.O., Roperez, J., Sandwell, D.T., Snaith, H., Tozer, B., Viquerat, S., Warnke, F., and Yu, Y., "The GEBCO 2022 Grid - A Continuous Terrain Model of the Global Oceans and Land," NERC EDS British Oceanographic Data Centre NOC, 2022.

Journal Articles

Dorschel, B., Hehemann, L., Viquerat, S., Warnke, F., Dreutter, S., Tenberge, Y. Schulze, Accettella, D., An, L., Barrios, F.R., Bazhenova, E., Black, J., Bohoyo, F., Davey, C., De Santis, L., Jencks, J., Hogan, K., Jakobsson, M., Mayer, L.A., Ryzhov, I., et al., "The International Bathymetric Chart of the Southern Ocean Version 2," Sci Data, vol. 9(275), 2022.

Dyer, N., Kastrisios, C., and De Floriani, L., "Label-Based Generalization of Bathymetry Data for Hydrographic Sounding Selection," Cartography and Geographic Information Science. Taylor & Francis, 2022.

Eberhardt, A.L., Ward, L.G., Morrison, R.C., Costello, W.J., and Williams, C., "Connecting Science and Community: Volunteer Beach Profiling to Increase Coastal Resilience," Continental Shelf Research, vol. 242(5) 104733, 2022.

Gasborro, R., Sowers, D., Margolin, A., and Cordes, E., "Distribution and Predicted Climatic Refugia for a Reef-Building Cold-Water Coral on the Southeast US Margin," Global Change Biology, vol. 28(23). John Wiley and Sons Ltd., pp. 7108-7125, 2022.

Jakobsson, M., Mayer, L.A., et al., "The International Bathymetric Chart of the Southern Ocean Version 2," Scientific Data, vol. 9(1), Springer Nature, 2022.

Jakobsson, M. and Mayer, L.A., "Polar Region Bathymetry: Critical Knowledge for the Prediction of Global Sea Level Rise," Frontiers in Marine Science, 2022.

Kastrisios, C. and Ware, C., "Textures for Coding Bathymetric Data Quality Sectors on Electronic Navigational Chart Displays: Design and Evaluation," Cartography and Geographic Information Science, vol. 49(4), Taylor & Francis, 2022.

Lowell, K. and Calder, B.R., "Operational Performance of a Combined Density- and Clustering-based Approach to Extract Bathymetry Returns from LiDAR Point Clouds," International Journal of Applied Earth Observation and Geoinformation (Special Issue: Recent Advances in Geocomputation and GeoAI for Mapping), vol. 107, p. 102699, 2022.

Lyons, A.P., Olson, D.R., and Hansen, R.E., "Modeling the Effect of Random Roughness on Synthetic Aperture Sonar Image Statistics," Journal of the Acoustical Society of America, vol. 152, Acoustical Society of America, pp. 1363-1374, 2022.

Masetti, G., Andersen, O., Andreasen, N.R., Christiansen, P.S., Cole, M.A., Harris, J.P., Langdahl, K., Schwenger, L.M., and Sonne, I.B., "Denmark's Depth Model: Compilation of Bathymetric Data within the Danish Waters," Geomatics, vol. 2(4), pp. 486-498, 2022.

Masetti, G., Faulkes, T., Wilson, M.J., and Wallace, J., "Effective Automated Procedures for Hydrographic Data Review," Geomatics, vol. 2(3). MDPI, Basel, Switzerland, pp. 338-354, 2022.

Masetti, G., Dijkstra, S.J., Wigley, R., and Faulkes, T., "Introducing Programming to Ocean Mapping Students," International Hydrographic Review, vol. 28. International Hydrographic Office (IHO), Monaco, pp. 108-120, 2022.

Miksis-Olds, J., Martin, B., Lowell, K., Verlinden, C., and Heaney, K., "Minimal COVID-19 Quieting Measured in the Deep, Offshore Waters of the U.S. Outer Continental Shelf," Journal of the Acoustical Society of America Express

Letters, vol. 2(9), p. 090801, 2022.

Saeed, Z., Weidner, E., Johnson, B.A., and Mandel, T.L., "Buoyancy-Modified Entrainment in Plumes: Theoretical Predictions," Physics of Fluids, vol. 34(1), 2022.

Song, S., Santos, I.R., Yu, H., Wang, F., Burnett, W.C., Bianchi, T.S., Dong, J., Lian, E., Zhao, B., Mayer, L.A., Yao, Q., Yu, Z., and Xu, B., "A Global Assessment of the Mixed Layer in Coastal Sediments and Implications for Carbon Storage," Nature Communications, vol. 13(4903), 2022.

Spain, E., Lamarche, G., Lucieer, V., Watson, S., Ladroit, Y., Heffron, E., Pallentin, A., and Whittaker, J.M., "Acoustic Predictors of Active Fluid Expulsion From a Hydrothermal Vent Field, Offshore Taupā Volcanic Zone, New Zealand," Frontiers in Earth Science, vol. 9:785396, 2022.

Stasse, A., Meyer, K., Cheng, M.L.H., Bumbera, N., Van Volkom, K., Laferriere, A.M., Dijkstra, J.A., and Brown, B., "Temporal Dynamics of Eastern Oyster Larval Abundance in Great Bay Estuary, New Hampshire," Journal of Shellfish Research, vol. 403, pp. 401-408, 2022.

Reports

Kastrisios, C. and Ware, C., "Data Quality Indicators for Bathymetric Data on ECDIS Display," IHO Nautical Cartography Working Group (NCWG), Wollongong, Australia, 2022.

Kastrisios, C., Contarinis, S., Butkiewicz, T., Nakos, B., Sullivan, B. M., Harmon, C., Christie, E., and Bartlett, M., "Efforts for Developing Symbology for New S-1xx PS," IHO Nautical Cartography Working Group (NCWG), Wollongong, Australia, 2022.

Kastrisios, C. and Ware, C., "User Survey Results on Five Alternative QoBD Coding Schemes," International Hydrographic Organization, 2022.

Kastrisios, C. and Gaumet, M., "ZOC / QoBD Matrices," International Hydrographic Organization, 2022.

Master's Theses

Affonso, J., "A Geographic Segmentation Approach for Satellite Derived Bathymetry," University of New Hampshire, Durham, NH, 2022.

Cândido, M., "Implementing a Reference Backscatter Calibration Technique on a Multi-Sector Multibeam Echosounder," University of New Hampshire, Durham, NH, 2022.

Heffron, E., "Analysis of Acoustic Scattering Layers In and Around Petermann Fjord, Northwest Greenland," University of New Hampshire, Durham, NH, 2022.

Tripathy, A., "The Impact of Hurricanes on the Acoustic Detection of Cetaceans," University of New Hampshire, Durham, NH, 2022.

Doctoral Dissertations

Padilla, A.M., "Understanding Physical Properties of Gas Bubbles in the Ocean: How Does Reality Affect What We Think We Already Know?," University of New Hampshire, Durham, NH, 2022.

Weidner, E., "The Layer That Didn't Swim Away: Broadband Acoustic Characterization of Oceanic Stratification Structure," University of New Hampshire, Durham, NH, 2022.

Appendix E: Technical Presentations and Seminars

Jenn Dijkstra, Invited, January 19. Marine Community Response to Climate Change in the Gulf of Maine, Regional Invasive Species and Climate Change Symposium, Amherst, MA. Invited speaker and panelist.

Larry Mayer, Keynote, January 26. Using Bathymetry to Understand the Melting of the Greenland Icesheet, Geotalks, Virtual.

Larry Mayer, Invited, February 8. Experiences from Petermann and Ryder Glacier Expeditions, Swedish Polar Research Secretariat, GEOEO Meeting, Virtual, Sweden.

Larry Mayer, Invited, February 8. Update on U.S. Decade on Ocean Science, Ocean Sciences Meeting.

Brian Calder, Contributed, February 17. Estimating Volunteer and Authoritative Observer and Data Reputation, UK Hydrographic Society, International Conference on Remote Hydrography, Dublin, Ireland, Presentation was contributed by pre-recorded video for hybrid meeting.

Larry Mayer, Invited, February 28. From the President's Panel on Ocean Exploration to NOMEC—Can We Really Map and Characterize the US EEZ?, Ocean Sciences Meeting, Virtual.

Larry Mayer, Jenn Dijkstra, Contributed, February 28. Fine-Scale Mapping of Deep-Sea Habitat-Forming Species Densities Reveals Taxonomic Specific Environmental Drivers, Ocean Sciences Meeting, Zoom, NH. Presented a published paper.

Larry Mayer, Invited, March 2. Munk Medal Award Lecture, Can We Map the Entire World Ocean by 2030?, Ocean Sciences Meeting, Virtual.

Elizabeth Weidner, Contributed, March 3. Remote estimation of stratification strength in the Baltic Sea through broadband acoustic inversion, AGU Ocean Sciences, Ocean Sciences Meeting , Durham, NH. Virtual.

Brian Calder, Invited, March 9. Getting from "Why" to "Why Not": Normalising the Selection and Acceptance of Bathymetric Data Licenses, NOAA HSRP, HSRP Meeting, Silver Spring, MD. Meeting was held online.

Brian Calder, Invited, March 17. Supporting Volunteered Bathymetric Information: Encouraging, Understanding and Utilising Volunteer Effort, NGA, NGA Technical Seminar Series, Durham, NH. Meeting was held online.

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Larry Mayer, Invited, March 22. Frontier Mapping – HEALY Northwest Passage Expedition, Seabed 2030, Arctic/Antarctic/North Pacific Regional Center Meeting, Stockholm, Sweden.

Jenn Dijkstra, Invited, March 24. Invasive seaweeds in the Gulf of Maine: Predator-Prey Interactions, Active Retirement Association, Durham, NH.

Paul Johnson, Kevin Jerram, Contributed, March 31. Updates from the Field: MAC and Other Projects, Kongsberg Maritime, Kongsberg/UNH CCOM Annual Meeting, Durham, NH. Multibeam Advisory Committee updates, 'lessons learned,' and current topics for Kongsberg technical discussion stemming from recent field experiences with the U.S. Academic Research Fleet and other Center partners.

Lynette Davis, Contributed, March 31. Real-Time Water Column Data Visualization, Kongsberg Maritime, Kongsberg/UNH CCOM Annual Meeting, Durham, NH. Discussed master's project work of developing a software tool for real-time water column data visualization.

Larry Mayer, Brian Calder, Val E. Schmidt, Contributed, March 31. Autonomous Systems for Seafloor Mapping, Kongsberg-CCOM, Kongsberg/UNH CCOM Annual Meeting, Durham, NH. An overview of CCOM's robotic systems operations, challenges and successes related to Kongsberg gear.

Jenn Dijkstra, Invited, April 1. Gulf of Maine: An Invaded Ecosystem under Environmental Stress, Benthic Ecology Meeting, Honoring Larry Harris, Portsmouth, NH. Spoke about climate change and invasive species in the Gulf of Maine.

Larry Mayer, Invited, April 7. UNCLOS Article 76, The Arctic and Law of the Sea, Climate and Law of the Sea, Marine Scientific Research in the Arctic, Harvard University Law School, Cambridge, MA.

Larry Mayer, Invited, April 7. UNCLOS Article 76 and the Arctic, The Fletcher School, Tufts University, Medford, MA.

Larry Mayer, Invited, April 12. Diplomacy Forum on Statecraft in the Evolving Frontiers: Ocean, Arctic and Space, Meridian International Center, Meridian International Center, Washington, DC.

Val E. Schmidt, Invited, April 13. OECI Colloquium, NOAA Office of Ocean Exploration, Monthly Colloquium, Virtual. Presentation of major events and lessons learned during integration of DriX 8 aboard the E/V *Nautilus* during the 2022 Shakedown Cruise.

Larry Mayer, Invited, April 19. UNCLOS Article 76 and the Arctic, Yale Law School, New Haven, CT.

Larry Mayer, Invited, April 20. Ocean Exploration from Deep Water Horizon to the Arctic, RiverWoods, Durham, NH.

Larry Mayer, Invited, April 22. Cross-Cutting Themes for the U.S. Contributions to the Decade to UN Ocean Decade, Subcommittee on Oceans Science and Technology (OSTP), Washington, DC.

Larry Mayer, Val E. Schmidt, Invited, April 22. DriX-8 Lessons Learned, NOAA OMAO, Virtual. Presentation to Capt. Bill Mowitt and others of OMAO's Office of Un-crewed Systems, regarding lessons learned during the DriX-8 integration aboard the E/V *Nautilus*.

Larry Mayer, Invited, April 25. Cross-Cutting Themes for the U.S. Contributions to the Decade to UN Ocean Decade, National Science Foundation, Washington, DC.

Larry Mayer, Invited, April 27. Cross-Cutting Themes for the U.S. Contributions to the Decade to UN Ocean Decade, Bermuda to Bear Island Consortium (B2B), Virtual.

Brian Calder, Invited, May 11. Cloud-based Making Data Processing, Ocean Exploration Cooperative Institute, OECI Colloquium Series, Durham, NH. Meeting was held online.

Anthony Lyons, Nicholas LaManna, Contributed, May 23. Modeling the Effects of Internal Waves on Synthetic Aperture Sonar Resolution, Acoustical Society of America, ASA Denver 2022, Denver, CO.

Larry Mayer, Invited, May 26. Engineers on E/V *Nautilus* Expedition Test Three Remotely Operated Vehicles, Hawaii Public Radio, Honolulu, HI.

Alexandra Padilla, Contributed, May 27. Understanding Physical Properties of Gas Bubbles in the Ocean: How Does Reality Affect What We Think We Already Know?, University of New Hampshire, Thesis Dissertation, Durham, NH.

Brian Calder, Contributed, June 7. Wireless Inexpensive Bathymetry Logger, Canadian Hydrographic Organisation, Canadian Hydrographic Conference 2022, Gattineau, QC, Canada.

Larry Mayer, Keynote, June 7. We've Come a Long Way – Where are we Going?, Canadian Hydrographic Conference, Canadian Hydrographic Service, Ottawa, Canada.

Larry Mayer, Invited, June 8. Expanding Ocean Understanding, Capitol Hill Ocean Week, Washington, DC.

Larry Ward, Contributed, June 10. New Hampshire Volunteer Beach Monitoring Program (VBPMP) Results and Implications for Management, Maine Sea Grant, The Beaches Conference 2022, South Berwick, ME.

Michael Smith, Invited, June 13–18. Multibeam Echosounder Sound Source Evaluation, IOGP Sound and Marine Life Joint Industry Program, JIP Acoustic Modelling Workshop 2022, Cambridge, United Kingdom.

Larry Mayer, Invited, June 15. Onboard the Nautilus Ocean Exploration Trust, Wondros Podcast, https://www.youtube.com/watch?v=Djj2uboEyV4, Virtual.

Larry Mayer, Invited, June 16. Cross-Cutting Themes for the U.S. Contributions to the Decade to UN Ocean Decade, Subcommittee on Ocean Science and Technology and Associated Federal Agencies, Washington, DC.

Anthony Lyons, Nicholas LaManna, Contributed, June 23. Quantifying and Modeling the Effects of Internal Waves on Synthetic Aperture Sonar Resolution, Institute of Acoustics, ICUA 2022, Southampton, United Kingdom.

Jenn Dijkstra, Invited, July 3-4, 2022. Invasive Species in the Gulf of Maine, Marine Invasive Species Class, Shoals Marine Laboratory, ME. Gave a seminar and help to identify invertebrate and fish species

Paul Johnson, Larry Mayer, Juliet Kinney, Contributed, July 7, 2022. Arctic & North Pacific Ocean Regional Center 2022 North Pacific Update, NIWA New Zealand, 4th South and West Pacific Regional Mapping Community Meeting, Wellington, New Zealand, Remote Attendance and Presentation.

Jennifer Miksis-Olds, Invited, July 10-15, 2022. Ocean Sound: More than Just Amplitude, Effects of Noise on Aquatic Life, Effects of Noise on Aquatic Life, Berlin, Germany,

Larry Mayer, Invited, July 20, 2022. Deep-Water DriX, Ocean Exploration Cooperative Institute, OECI Colloquium, Online.

Larry Mayer, Invited, July 22, 2022. Cross-Cutting Themes for the U.S. Contributions to the Decade to UN Ocean Decade, National Academies of Science, Engineering, and Medicine, Washington, DC.

Larry Mayer, Andrew Stevens, Elizabeth Weidner, Invited, August 26, 2022. Ocean Research Presentation, UNH Board of Trustees, Board of Trustees Meeting–REEO Division, Durham, NH. Presentation of research efforts to the UNH Board of Trustees and coverage the graduate student experience at UNH.

Brian Calder, Contributed, August 31, 2022. CloudMap: Cloud-based Mapping Data Processing, NOAA OER, OECI Colloquium Series, Silver Spring, MD. Virtual colloquium presentation on the CloudMap project, mainly on performance metrics for cloud-based deployments of desktop MBES data processing software.

Larry Mayer, Invited, September 8, 2022. Autonomous Surface Vessel Activities at the Center for Coastal and Ocean Mapping, Office of Naval Research, Arlington, VA.

Larry Mayer, Invited, September 21, 2022. Update of Activities of the Joint Hydrographic Center, Hydrographic Services Review Panel, Honolulu, HI.

Andy McLeod, Contributed, October 8, 2022. Uncrewed Vehicle Panoramic Camera Array, UMass Amherst, Northeast Robotics Colloquium 2022, Amherst, MA.

Val E. Schmidt, Contributed, October 14, 2022. Adventure of the High Sea: Marine Robotics at the Center for Coastal and Ocean Mapping, The Center for Coastal and Ocean Mapping, Ocean Engineering Seminar, Durham, NH. Overview of recent field deployments of robotics systems owned and operated by the Center, new technologies we have been working on and ones we hope to develop in the future.

Roland Arsenault, Contributed, October 19–21, 2022. A ROS-Enabled Floating Hackathon: Coordinating Multiple Marine Robots, Open Robotics, ROSCon 2022, Kyoto, Japan.

Roland Arsenault, Contributed, October 19–21, 2022. Mapping the Seafloor with ROS Using Project11, Open Robotics, ROSCon 2022, Kyoto, Japan.

Michael Smith, Contributed, October 25, 2022. Acoustic backscatter research at the Center for Coastal and Ocean Mapping, Backscatter Working Group II, Backscatter Working Group II 2022, Halifax, NS, Canada. Presentation on the Center's current efforts and state-of-the-art in acoustic backscatter research. Presentation gave a broad overview of the various research topics conducted by Center faculty and research staff such as: backscatter calibration, seafloor stability, backscatter data processing, and more.

Rochelle Wigley, Contributed, October 26-28, 2022. The Nippon Foundation / GEBCO Training Program: A Capacity-Building Success–As Demonstrated by Their International Impact, Map the Gaps Symposium, Southampton, United Kingdom. Presented on the Nippon Foundation / GEBCO Training Program alumni involvement in Map the Gaps and some of the projects that they have been involved in and the impact on alumni of these Map the Gaps projects.

Kenneth G. Fairbarn, Contributed, November 1-3, 2022. Uncrewed Vessel Launch and Recovery, Lessons Learned, UNOLS, UNOLS RVTEC Meeting, Seattle, WA. Poster Presentation.

Paul Johnson, Shannon Hoy, Kevin Jerram, Invited, November 2-3, 2022. Multibeam Advisory Committee (MAC) 2022 RVTEC Update and Breakout Session, UNOLS Research Vessel Technical Enhancement Committee, UNOLS RVTEC Meeting, Seattle, WA. The NSF-funded Multibeam Advisory Committee discussed ship visits, remote support opportunities, lessons learned, and development of Python tools and related testing documentation over the last year. An overview of the Ocean Mapping Community Wiki (developed in collaboration with Shannon Hoy, NOAA) was presented with an invitation for attendees to become active contributors. A breakout session was hosted with more detailed examples of these topics and opportunities for discussion in smaller groups.

Rochelle Wigley, Contributed, November 9-10, 2022. Map the Gaps: Supporting a Diverse Global Ocean Discovery Community, Ocean, Weather, and Climate GIS Forum, Redlands, CA. Presented on the Nippon Foundation/ GEBCO Training Program alumni involvement in Map the Gaps and some of the projects that they have been involved in and the impact on alumni of these Map the Gaps projects.

Larry Mayer, Invited, November 16, 2022. From Deepwater Horizon to the Arctic: Exploring the Secrets of the Deep, University of New Brunswick, Dineen Lecture, Fredericton, NB, Canada.

Christos Kastrisios, Contributed, November 17, 2022. Efforts for Developing Symbology for New S-1xx Product Specifications, IHO Nautical Cartography WG Meeting, Online, Australia.

Brian Calder, Invited, November 17, 2022. A System Solution for Volunteer Bathymetry Collection, NOAA Office of Coast Survey (OCS), Alaska Coastal and Ocean Mapping Summit, Anchorage, AK. Presented on the WIBL project for volunteer bathymetric data collection and processing, and to participate in a panel discussion on this topic. Virtual participation.

Christos Kastrisios, Invited, November 24, 2022. Data Quality Indicators for bathymetric data on ECDIS display, S-101 Project Team, S-101 Project Team meeting, Online, New Zealand.

Brian Calder, Invited, December 1, 2022. Florida Coastal Mapping Program Summit 2022, Florida Institute of Oceanography, Florida Coastal Mapping Program Annual Summit, St. Petersburg, FL. Invited to take part in a round-table panel on volunteer bathymetric information ("crowdsourced bathymetry") initiatives and best practices; virtual attendance.

Val E. Schmidt, Invited, December 5, 2022. Multibeam Echosounders, Seafloor Mapping and Autonomous Systems, Michigan Technological University, Naval Systems Course, Houghton, MI. Introduced Michigan Tech students to the basics of multibeam echosounding and marine robotics.

Val E. Schmidt, Invited, December 5, 2022. Balancing Autonomy and Supervision: Lessons Learned from Seven Years of Robotic Vehicle Operations, Weekly Seminar Series, Great Lakes Research Center, Michigan Technological University, Houghton, MI. An overview of the Center's robotic vehicle operations since 2016 and lessons learned from having operated from many ships and from shore and in many areas around the world.

Jenn Dijkstra, Invited, December 6, 2022. Ocean Engineering Undergraduate Student Class (taught by Elizabeth Wiedner), University of New Hampshire, Durham, NH. Talk on the various habitat mapping methods for nearshore and deep-sea communities.

Elizabeth Weidner, Contributed, December 7, 2022. Broadband Acoustic Characterization of Scattering from a Rough Stratification Surface, Acoustical Society of America, 183rd Meeting of the Acoustical Society of America, Nashville, TN. Abstract: Presentation on the utility and limitations of broadband scientific echo sounders in characterizing the frequency-dependent scattering from stratification interfaces.

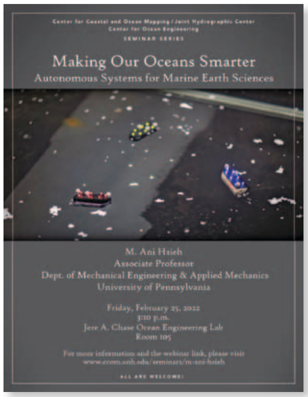
Jenn Dijkstra, Invited, December 12, 2022. Structure from Motion in Marine Environments, Russ Congalton Lab Meetings, Durham, NH. Overview of the SfM work in the Gulf of Maine, Florida Keys and intertidal

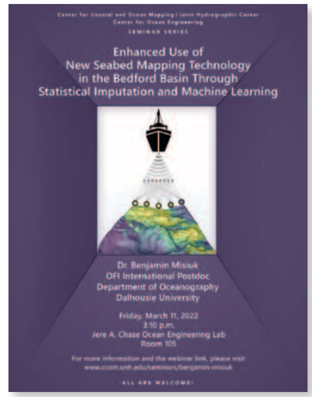
Shannon Hoy, Kevin Jerram, Invited, December 13, 2022. An Overview of the Ocean Mapping Community Wiki, NOAA, Survey Tech Training 2022, Seattle, WA. Overview of Multibeam Advisory Committee resources and common motivations across the UNOLS, NOAA, and other mapping organizations to create the Ocean Mapping Community Wiki. Various features of the wiki were demonstrated with an invitation to the audience to contribute their expertise and share hard-won lessons from the field.

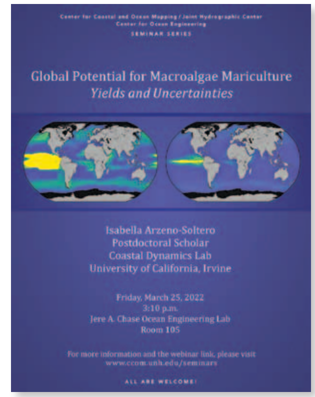
Larry Mayer, Invited, December 13, 2022. Expanding Scientific Operations in the Arctic: Technical Challenges, DARPA, DARPA FORWARD, San Diego, CA.

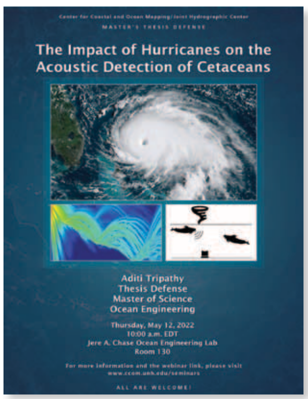
Larry Mayer, Invited, December 16, 2022. The Challenges of Mapping the Seafloor, American Geophysical Union College of Fellows Legacy Lecture, AGU Fall Meeting, Chicago, IL.

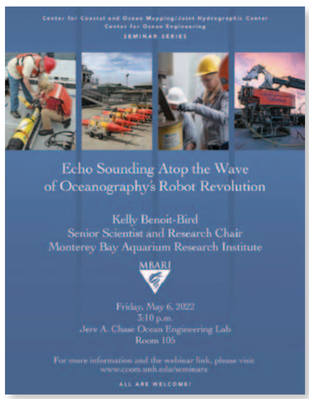
Larry Mayer, Invited, December 16, 2022. UNH-CCOM Uncrewed Vehicle Activities, IFREMER, Online.

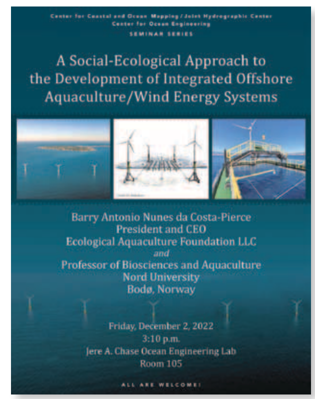


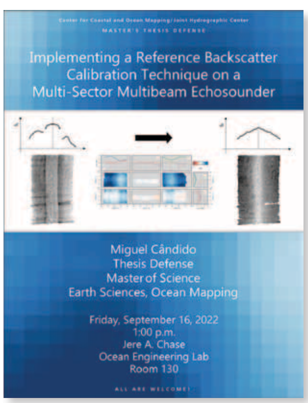


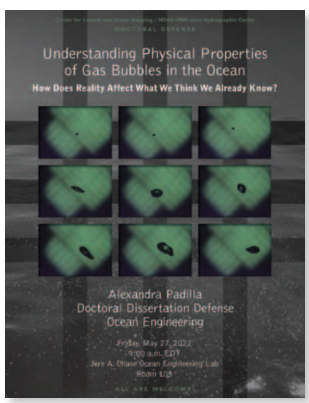


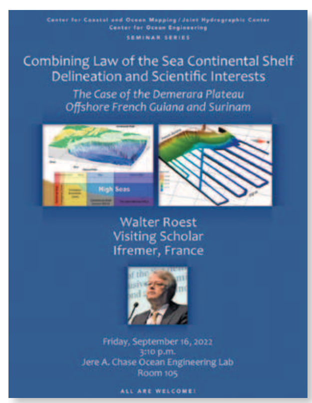


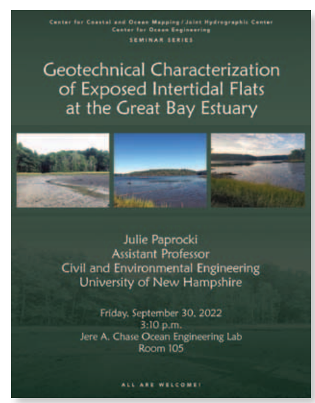


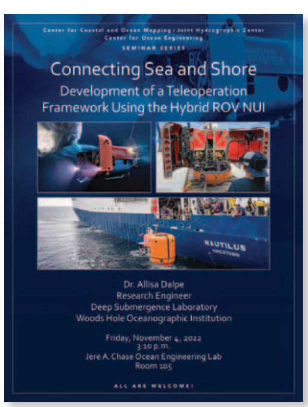


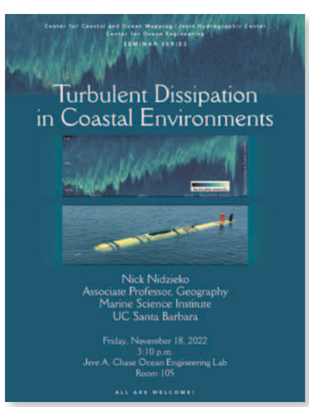


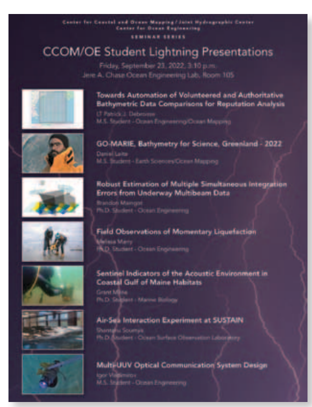












Flyers from the 2022 JHC/CCOM–UNH Dept. of Ocean Engineering Seminar Series.

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