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UNH/NOAA Joint Hydrographic Center 2021 Performance and Progress Report Executive Summary

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NOAA-UNH Joint Hydrographic Center (JHC/CCOM)

UNH/NOAA Joint Hydrographic Center

2021 Performance and Progress Report

Executive Summary

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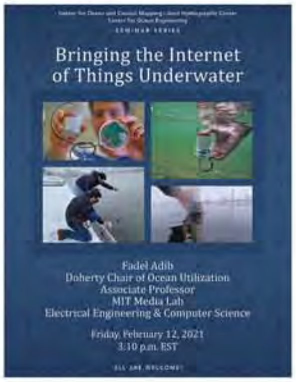
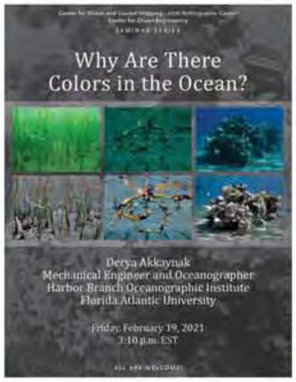
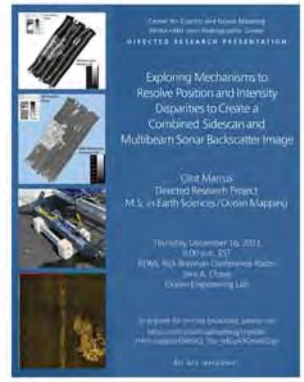
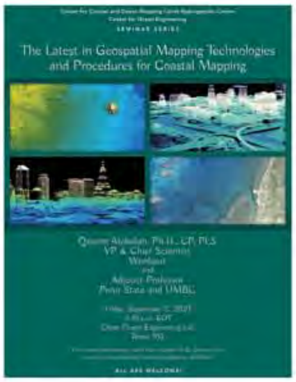
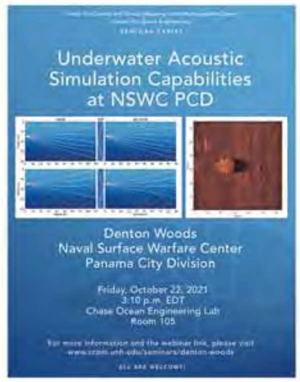
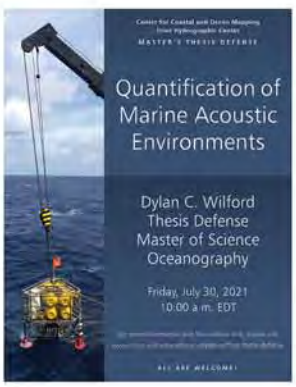


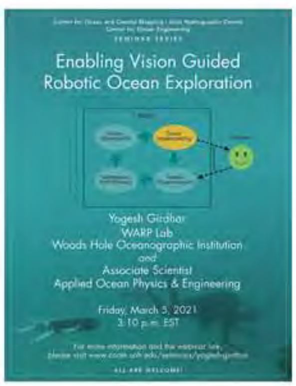


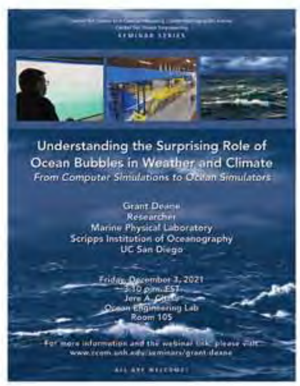


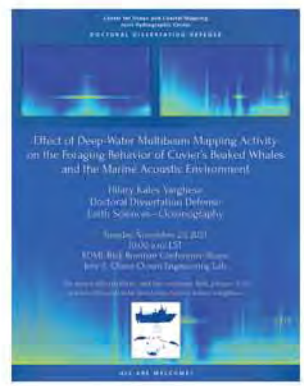


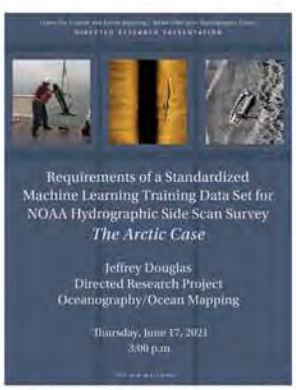


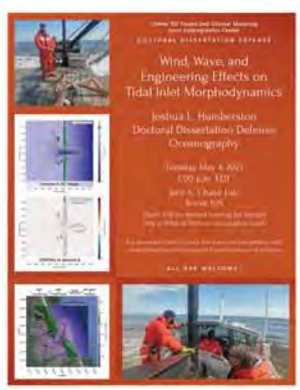












Flyers from the 2021 JHC/CCOM – UNH Dept. of Ocean Engineering Seminar Series.

The NOAA-UNH Joint Hydrographic Center (JHC/CCOM) was founded twenty-one 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 are doing 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 next generation of CUBE, CHRT (CUBE with Hierarchical Resolution Techniques) which supports the newly evolving concept of variable resolution grids, is currently being introduced to the hydrographic community and the innovative approach that CUBE and CHRT offer are now being applied to high-density topobathy lidar data.

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 Reflectance-Based Approach 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 with 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 in the field and speeds 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 were 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 aboard the ship said that the seafloor data provided by Center software was "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, 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. When

[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.

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 few years, a new generation of multibeam sonars has been developed (in part, as 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 and expand them to provide details of subtle, but critical oceanographic phenomena. The initial water-column studies funded by this grant have led to many new opportunities including follow-up work that has been 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. In the past few years, we have demonstrated the ability of both multibeam and broad-band single beam echo sounders to image fine-scale oceanographic structure 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). Most 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.

The value of our visualization, water-column mapping, and data fusion capabilities have 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 have developed 4D (space and time) visualization tools to monitor the underwater behavior of whales as well as to notify vessels of the presence 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, data visualization, our ASV/USV 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 until December 2025. This document summarizes the highlights of this NOAA-funded effort during calendar year 2021, which represents the final efforts on the previous grant (extended through a no-cost extension due to the COVID-19 pandemic) and the first year of the current grant. Detailed progress reports from this and previous grants can be found at our website http://ccom.unh.edu/reports.

Highlights from Our 2021 Program

This report represents the progress on the sixth year of effort on NOAA award number NA15NOS4000200 through its no-cost extension and the first year of effort on NOAA award number NA20NOS4000196. The progress of the Center of the period from 1 January 2021 to 31 December 2021 will be presented collectively, without explicit breakdown between those tasks supported by one grant or the other. This breakdown of effort is presented through NOAA's formal web-based Research Performance Progress Reporting (RPPR) process.

The overall objectives for the new and previous grants are quite consistent with each other thus the framework for presentation of results in this report will be that of the new grant. The Notice of Funding Opportunity (NOFO) 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:

Advance Technology to Map U.S. Waters

DATA ACQUISITION

a. 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.

b. 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.

c. 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.

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

DATA VALUE

a. 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.

b. 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.

c. 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.

RESOURCES OF THE CONTINENTAL SHELF

a. 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.

b. 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.

c. 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.

Advance Technology for Digital Navigation Services

a. 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.

b. 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.

c. 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.

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

e. 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.

f. 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

a. 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.

b. 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.

c. 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.

d. 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.

As mentioned above, the programmatic priorities and research requirements are consistent with those prescribed under earlier grants and much of the research being conducted under the new (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 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 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 are modified due to changes in personnel. Inasmuch as these tasks represent the beginning of a new grant cycle, there are no modifications to report at this time.

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 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 that 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 also developed a series of assessment tools and best-practices guidelines that are 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.

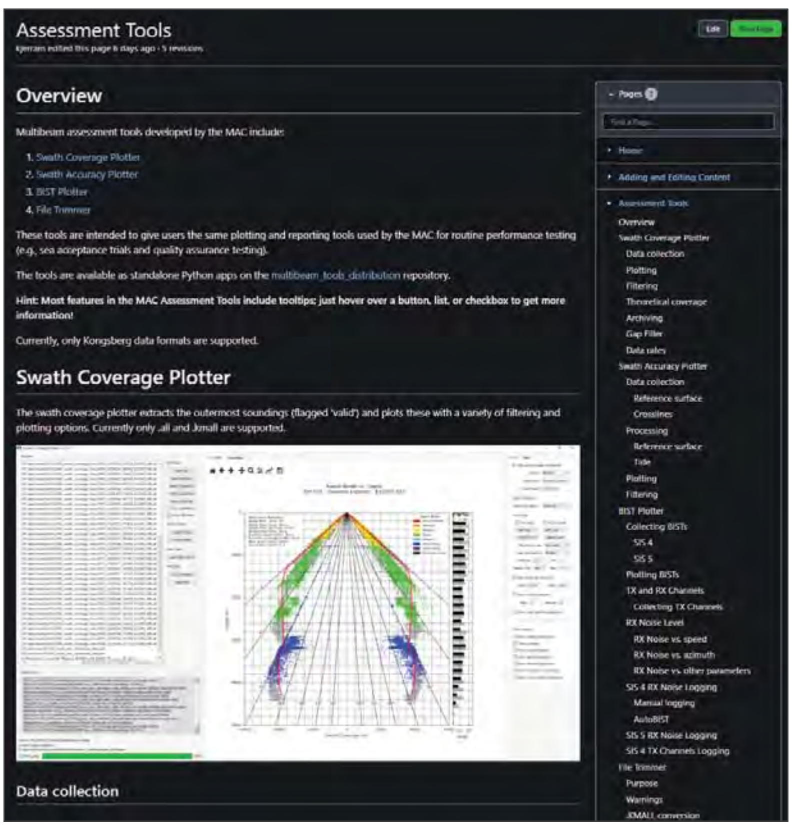


Figure ES-2. Assessment Tools documentation on the new Ocean Mapping Community Wiki (https://github.com/oceanmapping/community/wiki). GitHub was selected for its widespread adoption in the scientific community, simple interface for wiki collaboration, and ease of linking to other code repositories (e.g., Assessment Tools, Ocean Data Tools).

Sound Speed Manager

Acoustic sensors in modern surveys require an accurate environmental characterization of the water column. The quality of the sound speed profile used 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, which are used to estimate the gain settings in acoustic sensors and compensate the backscatter records.

Since 2016, researchers from the Center 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, along with the conversion to formats in use by hydrographic acquisition packages. SSM has now reached a high level of maturity, with a global user base of more than 6,500 users (Figure ES-3) spanning 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.

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.

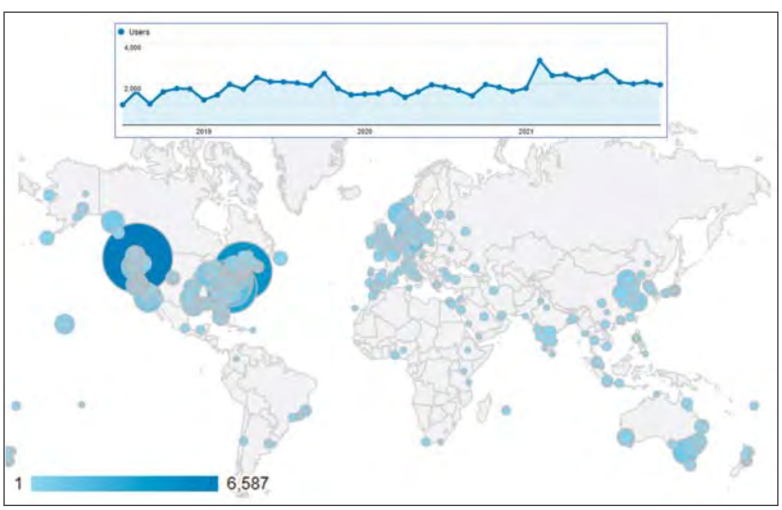


Figure ES-3. Number of monthly unique users (top pane) and map showing their geographical distribution (source: Google Analytics).

The facility is commonly 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 2021, operations at the acoustic tank were still impacted by the COVID-19 pandemic. Some operations considered essential research were allowed after safety protocols were established including: beam pattern, impedance, and TVR of prototype systems from Edgetech, calibration of an iXblue SeapiX sonar, acoustic recording of scuba gear used for internal research by Mitre Corporation, and evaluations of MSI parametric and acoustic communications transducers.

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 echo sounders (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 echo sounders is typically uncalibrated, limiting its usability to qualitative data products and comparison of one data set to another. Multibeam echo sounder 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 past year we worked with OCS to analyze backscatter data collected annually from launches on the NOAA Ships *Rainier* and *Fairweather* over a well-defined 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-4 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.

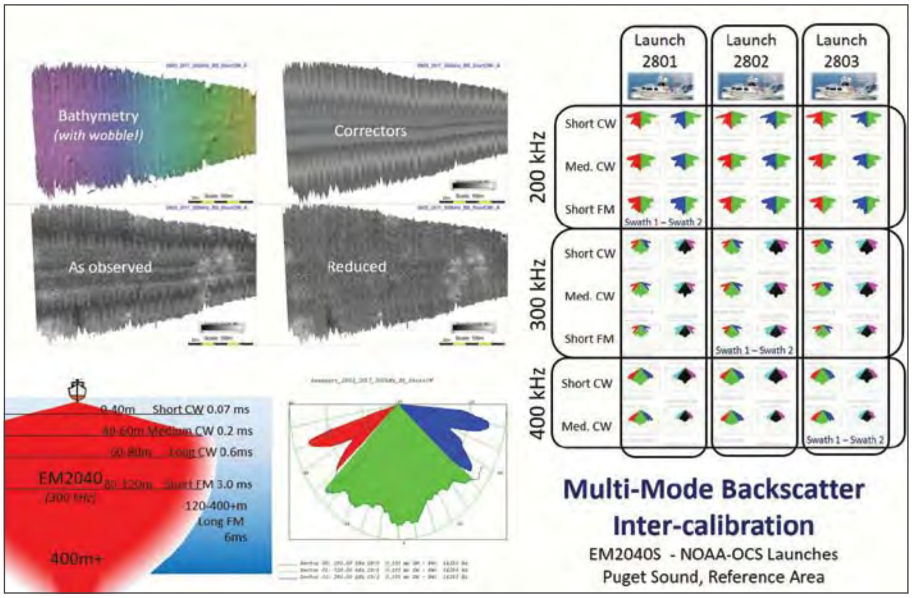


Figure ES-4. Extracted relative beam pattern for the multi-sector EM2040. For each sonar (three NOAA launches tested), as they operate in dual swath mode, there is a unique pair of patterns for the first and second swath, and that pair is unique for each pulse length/type and center frequency.

We have also continued our efforts to find efficient ways of providing absolute backscatter calibration for seafloor mapping multibeam sonars including tank-based calibration using a standard reference sphere which takes many days to complete versus the use of an extended chain link target which can be accomplished in just a few hours (Figure ES-5).

Substrate Change

While we strive towards a goal of calibrating backscatter systems so that they can be used to better characterize the seafloor, the fundamental question arises of how representative an instantaneous measure of backscatter is over longer periods.

The results showed large static offsets between the methodologies (as much as 3dB) pointing to the difficult and sensitive procedure of backscatter calibration and processing. The methods should produce similar results and the difference has potential implications when attempting to calibrate MBES using calibrated split-beam systems. Future research into how to best account for the ensonified surface/volume and physical scattering characteristics between the extended target and target spheres will provide insight into why the two methods produced different results and how best to account for them.

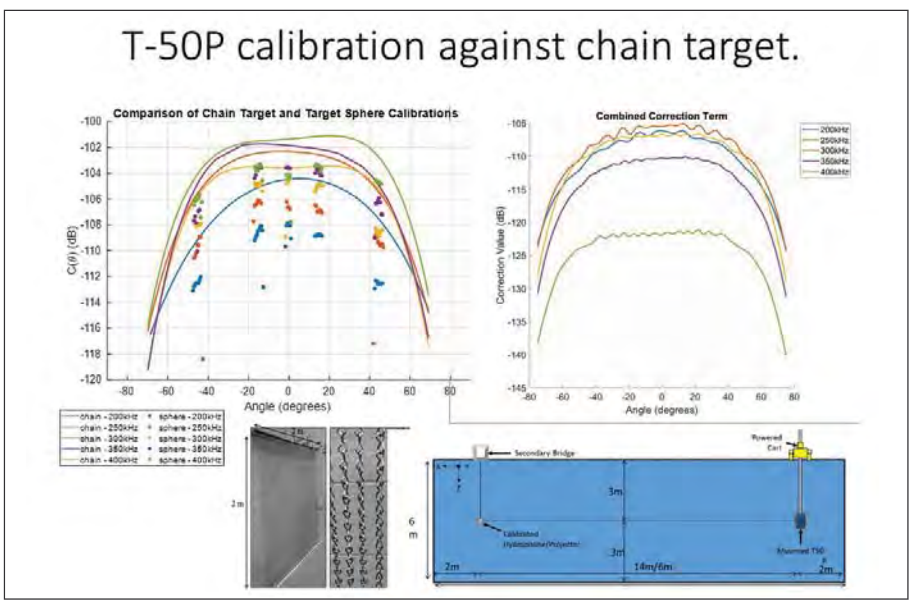


Figure ES-5. Reson T-50 tank based calibration results utilizing chain targets. Results for frequencies from 200-400 kHz, and comparison of chain target with conventional sphere target.

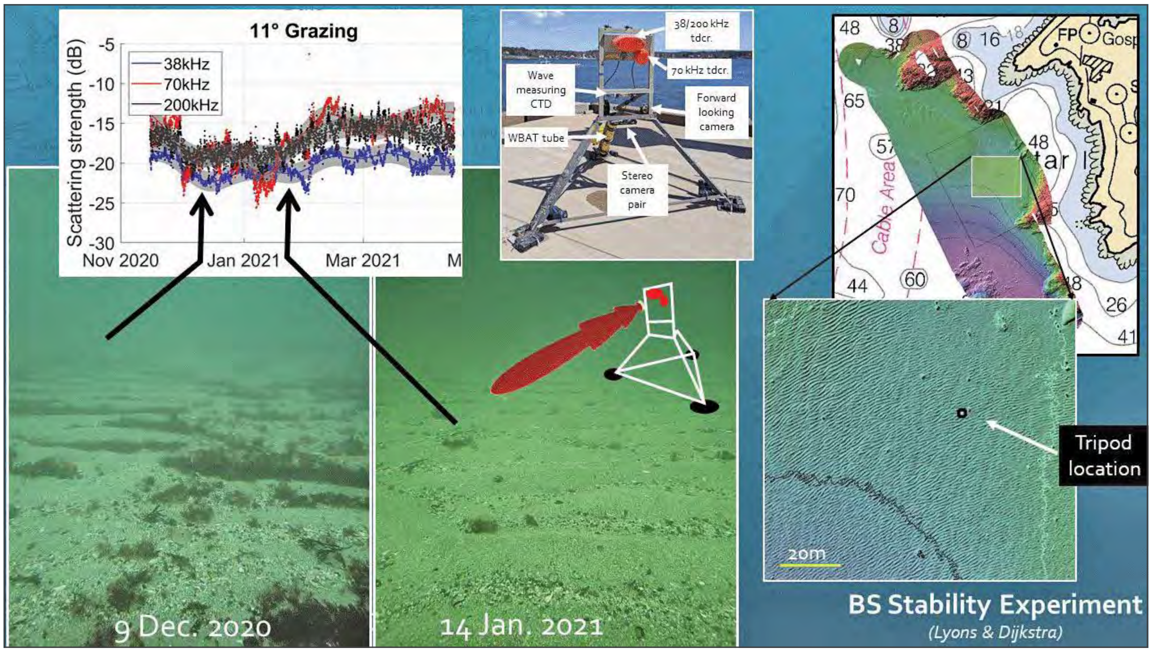


Figure ES-6. First results of Star Island time series. The site is monitored for all of backscatter strength, optical characteristics (divers) and morphologic change (repeat multibeam surveys).

To address this issue, we have designed a series of experiments that build on experience gained through ONR-funded work that compares long-time series of in-situ backscatter data, with repeated multibeam sonar data and camera and divers' observations (Figure ES-6).

Data for this project were collected offshore of Star Island, Isles of Shoals, New Hampshire, on 27 October–12 November 2020, 15 November 2020–14 April 2021, and 15 July–15 November 2021. Temperature and salinity measurements were made every hour during the acoustic transmit period and photos were taken for both qualitative 'context' using a forward-looking camera and for quantitative roughness estimates using a stereo camera set up. Preliminary results of scattering strength over a temporal scale of months showed daily variation of up to 10 dB, likely related to storm events changing seafloor properties (e.g., roughness, surface sediment composition, plant material). More variability is seen at lower grazing angles, below about 15 degrees. Distributions of scattering strength over 30-day intervals at 8 degrees grazing angle showed shifts in scattering strength of 3 to 6 dB.

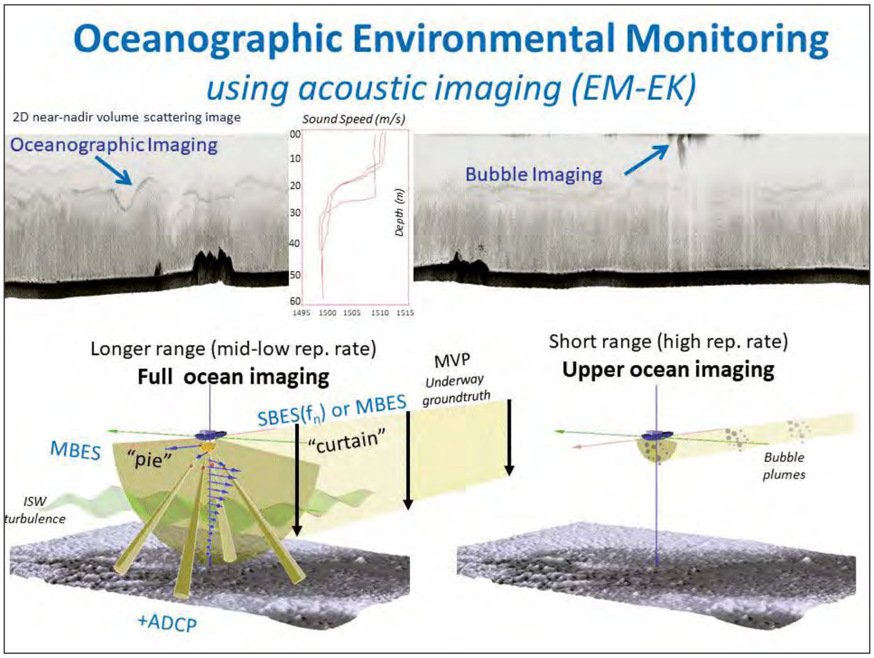


Figure ES-7. Differing geometries and scales of multibeam water column data to address full or just upper ocean phenomena. And the acquisition of complementary aiding information including ADCP and MVP.

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 who collect hydrographic data can adapt their surveys or sampling programs to minimize the impact of these phenomena (Figure ES-7).

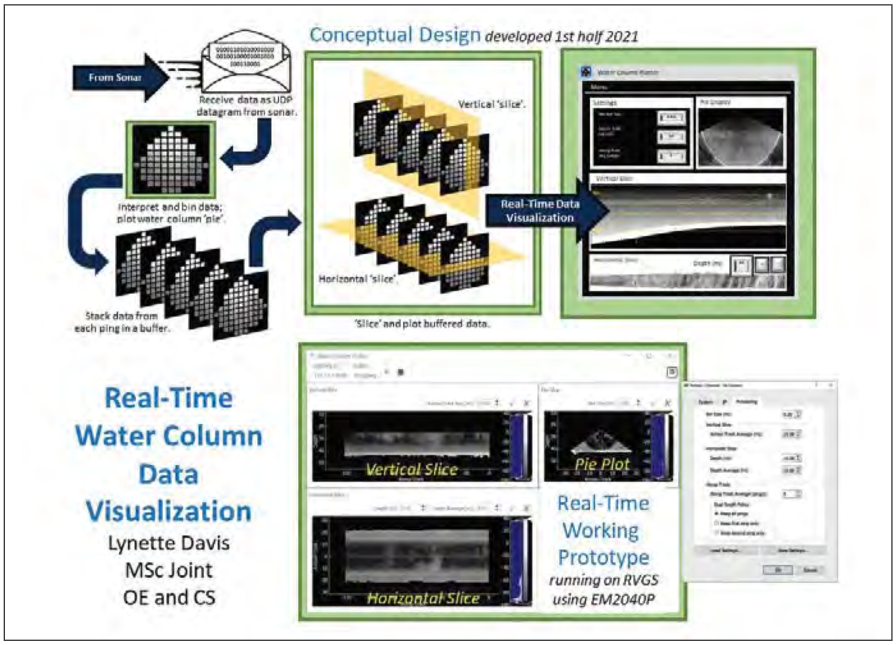


Figure ES-8. The conceptual design and working prototype developed by Lynette Davis for real-time water column visualization.

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. The tool implements parallel processing to utilize multiple computer cores and increase efficiency; however, further investigation and development is required to ensure that the tool can accommodate the heavy data loads associated with fast, shallow-water ping rates (Figure ES-8).

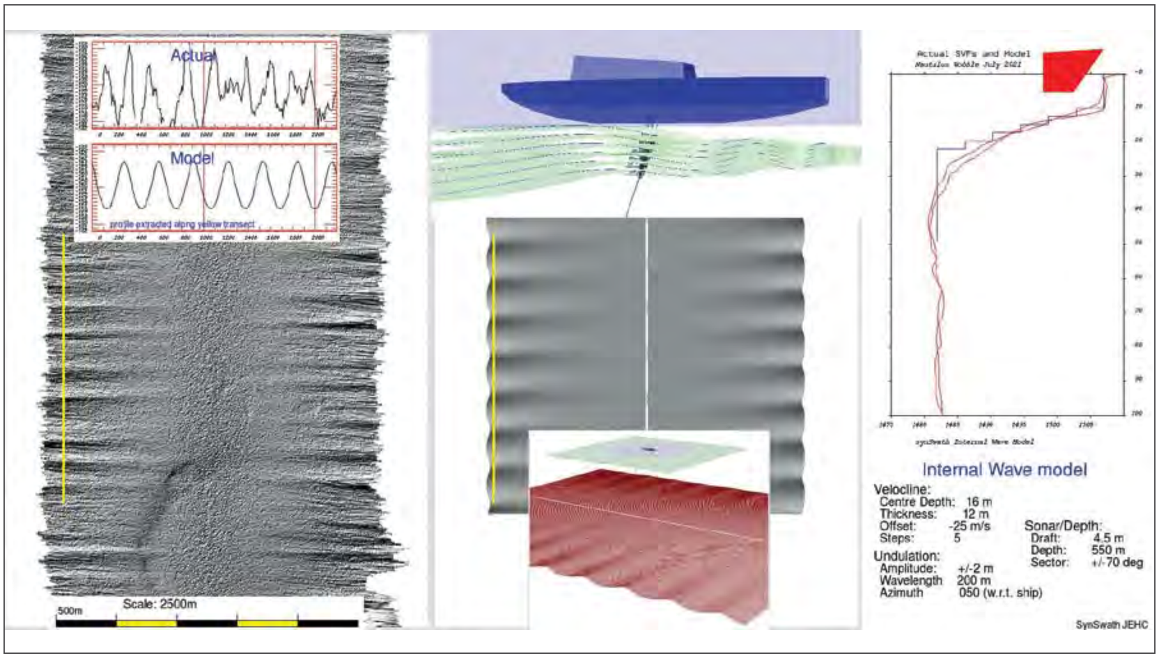


Figure ES-9. Output of the syn-Swath model looking at the refraction-related distortions of bathymetry due to ray tracing through an undulating velocline. The magnitude, wavelength, orientation and sound speed gradient can be varied to try to reproduce the field result. The left figure shows the observed data from the R/V *Nautilus*, the central figure is the model result.

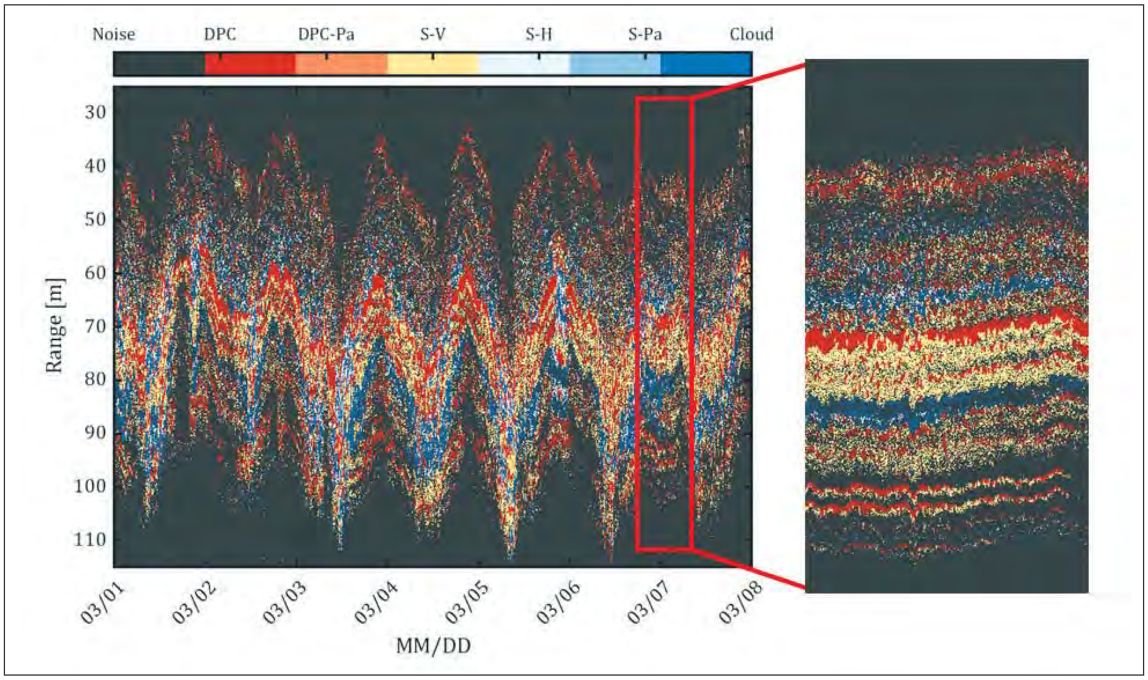


Figure ES-10. Plume morphology classification map of the identified morphology types in the acoustic record between 1-7 March 2020. DPC: Discrete plume column. DPC – Pa: Discrete plume column parallel to the SBES transducer face. S – V: Plume screen intersecting in the vertical direction of the SBES beam. S – H: Plume screen intersecting in the horizontal direction of the SBES beam. S – Pa: Plume screen intersecting parallel to the SBES face. Cloud: Diffuse plume cloud.

Such a tool allows the field operator rapid access to volume sections as an aid to environmental assessment. With training and familiarization, such scrolling displays would significantly aid the hydrographer in making near-real time decisions on the need to update sound speed measurements.

Knowledge and display of environmental conditions can offer important insights into the cause of artifacts or distortions in collected data sets. The example in Figure ES-9 shows a situation that was initially assumed to be a result of imperfect sensor integration but could not be explained adequately as the period was too long. Subsequent analyses of the logged midwater data revealed a matching internal wave packet of the same dimension passing under the gondola at the instant of the anomaly. Using XBT casts acquired within a few hours of the event, a very shallow thermocline is revealed that starts only 5m below the gondola. Using the observed sound speed gradient and the measured along-track wavelength, modeling revealed that the seafloor anomalies could be explained by an internal wave train oriented 50 degrees to the track of the vessel.

Water Column Mapping

In parallel with our efforts to image water column phenomena and better understand their impact on the quality of hydrographic data, we are also exploring the ability of our sonar systems to extract important and quantitative information about these mid-water phenomena, be they biological, physical or chemical. We continue to work both on creating and refining algorithms for the detection and classification of water column targets, as well as pushing the capabilities of multibeam and split-beam echo sounders in a variety of engineering and science areas.

Recently, a plume morphology classification algorithm, based on examining the coherence between quadrants of a split-beam echo sounder, has been developed by graduate student Alex Padilla. This algorithm is designed to classify the morphology of gas bubble plumes (e.g., discrete columns, bubble screens, diffuse bubble clouds), which is required information when estimating gas flux and flow rates (Figure ES-10). Padilla's work describing both this morphology classification algorithm and the acoustic theory needed to convert echoes from these different types of plumes into flow and flux rates has been focused on data collected on Platform Holly, an oil platform off the California coasts that sits in the natural Coal Oil Point seep field.

Subbottom Mapping

In the latest NOAA grant, the Center was called upon, for the first time, to explore research into approaches for collecting subbottom acoustic data. While the acquisition of new subbottom data in support of these efforts has not yet started, the Center has begun to look at existing data in order to locate appropriate reference sites in the Western Gulf of Maine to support these research efforts.

We have also been able to extract very useful subbottom imagery from existing NOAA NMFS data sets collected for fisheries purposes. In particular, we have shown that 18 and 38 kHz echo sounders used for fisheries surveys in the water column can provide up to 30 m of subbottom penetration and a useful indication of subbottom structure (Figure ES-11).

Operation and Deployment of Uncrewed Surface Vessels

Even a casual perusal of trade magazines, conferences, and the 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 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. It was delivered in 2016. Teledyne Oceanscience 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-OECI), the Center has purchased a DriX USV from iXblue, Inc.

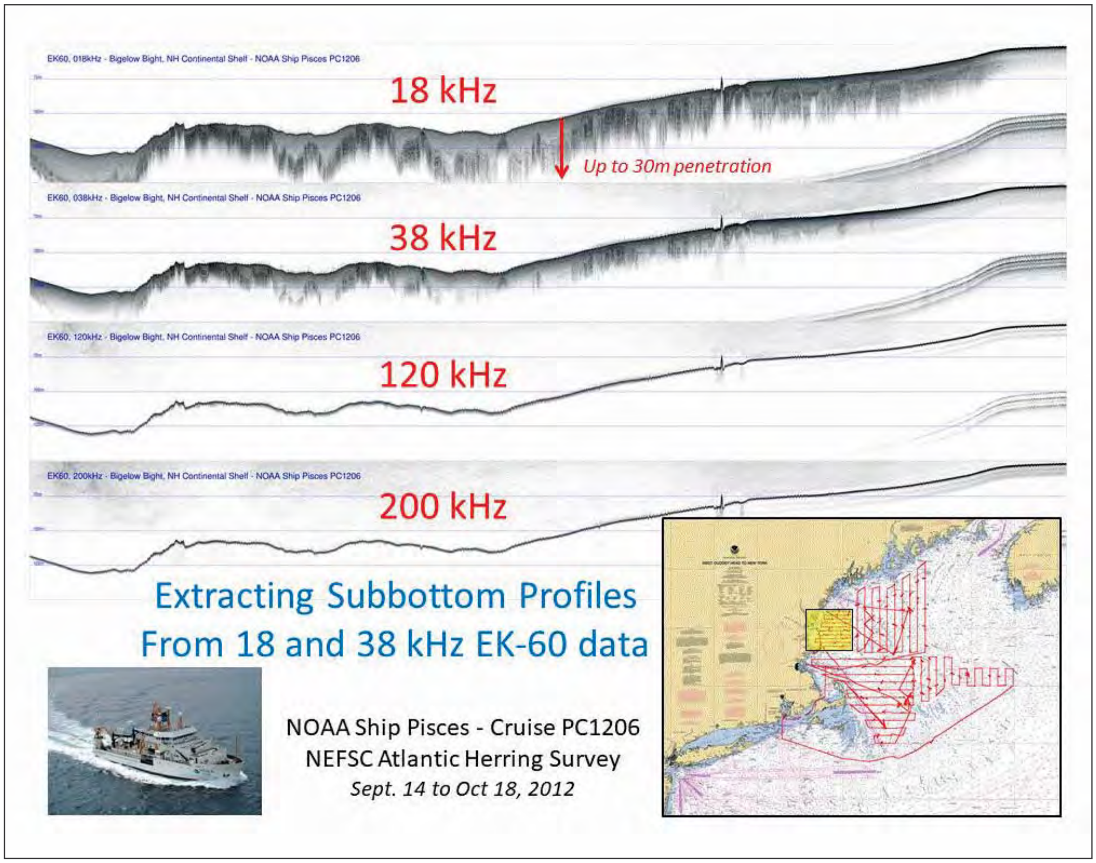


Figure ES-11. NMFS FSV EK-60 echo traces from their standard four center frequencies (18, 38, 120, 200 kHz). Note the extent of subbottom penetration achievable in soft sediments from the lower frequency systems.

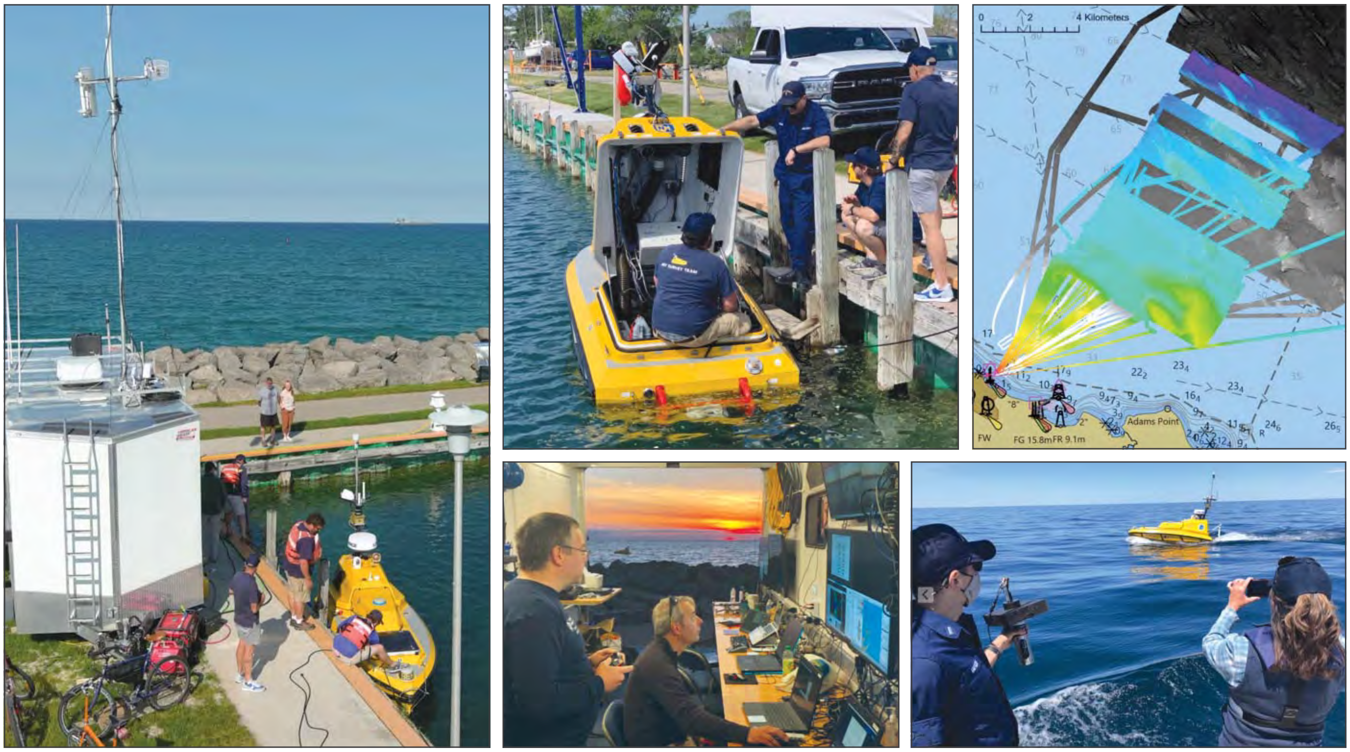


Figure ES-12. From the left and proceeding counterclockwise, images depict ASV-BEN and the Center's shore-based control van, early morning survey operations during a partial solar eclipse, wireless transfer of a CTD cast from a NOAA launch during survey operations, 2021 survey coverage along with previous coverage, the Center's ASV Engineers conducting training with NOAA Office of Coast Survey personnel.

The marine autonomy group within the Center focuses on the practical use of robotic systems for marine science and in particular seafloor survey. Practical autonomy is defined here as the engineering of systems and processes that make 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.

Building on five years of operating experience from both shipboard and shore-based operations in the Pacific, Atlantic and Arctic Oceans and the Great Lakes, the Center published "Hydrographic Survey with Autonomous Surface Vehicles: A Best Practices Guide" (International Hydrographic Review, vol. 24, pp. 189–201, Nov. 2020). Among other guidance, the document advocates use of a "Green-Amber-Red" risk assessment scoring system similar to NOAA's small boat program, and careful adherence to the COLREGS "Navigation Rules - Amalgamated," particularly Rules 5 (Lookout), 6 (Safe Speed), 7 (Risk of Collision), and 8 (Action to Avoid Collision). The guide also places an emphasis on careful assessment to augment robotic systems with human operators where the operating environment is complex and those systems fall short.

In June 2021, the Center's USV Team deployed to Thunder Bay National Marine Sanctuary in collaboration with the Ocean Exploration Trust and the Sanctuary. Mapping objectives for this mission included continuing the swath mapping coverage of the newly expanded Sanctuary and identification and characterization of the many archeological sites there (Figure ES-12).

In addition to the Center's USV team, four people from NOAA Office of Coast Survey, and Navigational

Response Team personnel joined the effort. NOAA staff were provided hands-on training, and were slotted into the USV watch rotation as USV pilots "under instruction." In addition, Clint Marcus, Coast Survey Physical Scientist, and graduate student at the Center, provided survey and data processing support for the expedition receiving class credit in lieu of taking the Center's summer Hydrographic Field Course.

Field events like this one provide critical learning opportunities to field test new systems and configurations and test new operational models. Many new hardware and software innovations were developed and tested during these operations including a number of advances in "Project 11," our ROS-based open-source back seat driver for uncrewed systems, integration of a Doppler marine radar system, development of a prototype CTD winch for BEN, integration of a loud-hailer system, improved telemetry systems, and directional WiFi antennas with automated azimuthal tracking of the ASV.

We have also greatly enhanced and put into practice the CCOM Autonomous Mission Planner (CAMP), developed to provide a simple, intuitive, efficient, and safe USV operator interface -- something that we have not found in commercially provided systems. Numerous improvements to CAMP have been developed this year, many born out of lessons learned during the June 2021 Thunder Bay Expedition. These include multi-color radar overlay of our new Halo 20+ dual-radar system, the ability to display AIS contacts observed by AIS receivers both on the USV and on the operator's vessel, the ability to simulate an AIS contact's position forward in time and display this graphically, and a new display mode that centers on the USV. CAMP now has the ability to append mission elements into a queue so they are run sequentially, and the ability to drag-and-drop them for quicker mission planning. New buttons in CAMP now allow the operator to start/stop pinging and data logging for Kongsberg systems running SIS 4 or SIS 5 for manual sonar operation when necessary (and increment data files at the end of survey lines). CAMP also has a new "docking mode" for joystick operation that limits the maximum thrust command for increased safety. We have also tested operation of multiple instances of CAMP during operations, to provide a passive observing station for mission operations; we have also tested handing off control of the USV from an operator on shore to another operator on a survey launch thereby greatly enhancing the range of operation from a shore-station (Figure ES-13). This kind of flexibility will be critical to our future developments for multiple vehicle operations. Many more details of improvements in CAMP and Project 11 can be found in the full progress report.

Camera Systems for Marine Situational Awareness

To provide improved situational awareness for remote USV operators, the Center has experimented with the use of a single 360° camera (QooCam 8K Enterprise) in a rainproof housing mounted on the USV. This camera has two extreme wide-angle lenses, performs stitching internally, and streams the resulting ultra-high resolution (8K) 360° video over an Ethernet connection. We have now developed

Figure ES-13. ASV BEN being chaperoned by Stephanie Gandulla (NOAA Sanctuaries) and a remote piloting team aboard NOAA Launch 301. In this mode, the coverage can be doubled and the launch used to extend the telemetry range achievable from shore.

Figure ES-14. (top) Original 360° video frame, and location of example region; (middle) example region visual quality using packing; (bottom) example region visual quality using traditional scaling. The video size is the same in each.

an approach to provide motion compensation to stabilize the 360° video, and to experiment with different approaches for transmitting the 360° video at variable resolutions, depending on what users were actively looking at, and where higher resolutions were needed (Figure ES-14).

Path Planning for Ocean Mapping

The Center's work in marine robotics has made clear that successful vehicle autonomy during survey operations requires continuous assessment of safe navigation trajectories. Figure ES-15 shows an example of this work in which the algorithm has found a clear path around a central obstacle avoiding a slowly moving vessel on its other side. The approach used, is an implementation of the Real-Time BIT* for Path Coverage (RBPC) algorithm. RBPC is unique in that it plans safe trajectories for a vessel in the presence of moving obstacles, while also optimizing the selection of paths to most efficiently achieve the mapping mission.

Data Acquisition for Volunteer/ Trusted Partner Systems

Continuing along the programmatic component of "Data Acquisition," the Center has also explored the potential value and approaches to the collection of "volunteer/trusted partner" systems as a source of bathymetric data for cartographic purposes. We take this approach because of the general reluctance of hydrographic agencies to accept crowd-sourced, third party, or "volunteered" data. The alternative that we are exploring is to develop an inexpensive system that can be used by the non-professional but which provides sufficient auxiliary information to ensure that the data does meet the requirements of a hydrographic office.

To this end the Center has developed a Trusted Community Bathymetry (TCB) system, including hardware, firmware, software, and processing techniques. The aim is to develop a hardware system that can interface to the navigational echo sounder of a volunteer ship as a source of depth information, but capture sufficient GNSS information to allow it to establish depth to the ellipsoid, and auto-calibrate for vertical offsets, with sufficiently low uncertainty that the depths generated can be qualified for use in charting applications. Initial versions of the system were

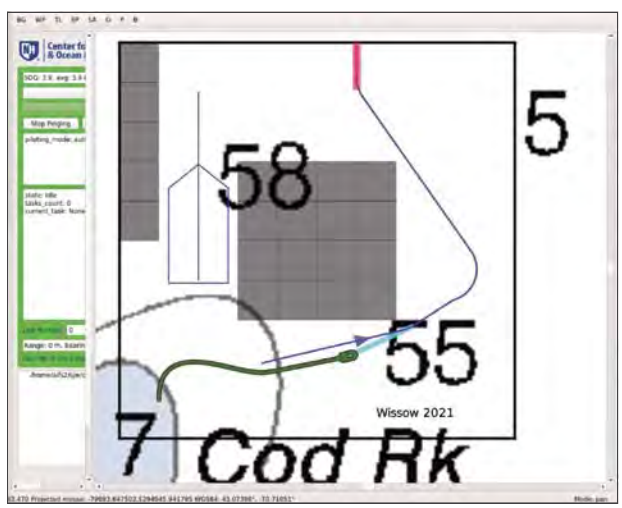


Figure ES-15. An intermediate solution of the BIT* algorithm in a test scenario.

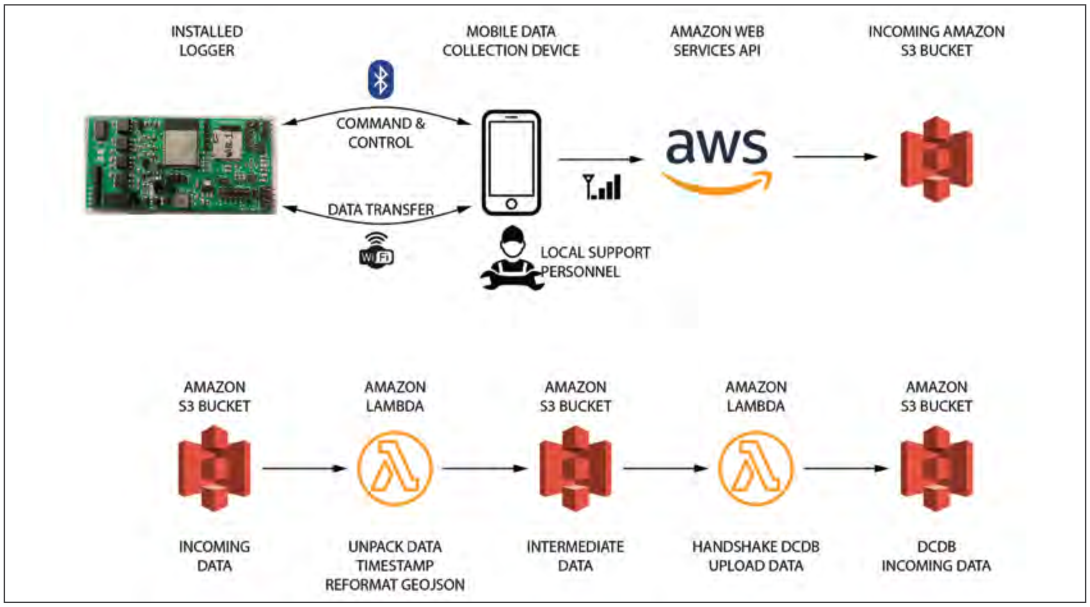


Figure ES-16. WIBL processing segments and basic concept of operations diagram. At upper left is WIBL v 2.3 PCB, fully assembled. The system can be powered from a nominal 12V power supply and dissipates ~1.3W when running at full speed with WiFi enabled.

in the $1000-2000 range, too expensive for mass distribution efforts over the past year have however led to the development of the Wireless Inexpensive Bathymetric Logger (WIBL).

WIBL consists of four segments: hardware, firmware, mobile, and cloud (Figure ES-16). By providing a standardized method for data upload, processing, and submission to the IHO international archive at the Data Center for Digital Bathymetry, the project aims to minimize effort for volunteers and the local sponsoring entity, encouraging more uptake of local clones of the project. At the core of the system is a low cost data logger for NMEA 0183 and NMEA 2000 networks. The estimated cost for the fully functional logger, capable of recording NMEA 0183, NMEA 2000, and IMU data simultaneously, is approximately $10 in batches of 50. Auxiliary costs for a box, connectors, etc., would also be expected for field units, perhaps doubling this estimate. Lower costs for larger batches would also be expected, and the overall cost could be reduced by only populating the board for either NMEA 0183 or NMEA 2000 if required.

WIBL loggers were field tested by Calder during the current reporting period during the USCGC *Healy* expedition through the Northwest Passage demonstrating collection over an extended period and production data processing and upload to DCDB and by a volunteer observer in San Diego, CA demonstrating that installation and operation by a motivated volunteer is possible (Figure ES-17). New versions of the WIBL hardware and firmware are now being developed.

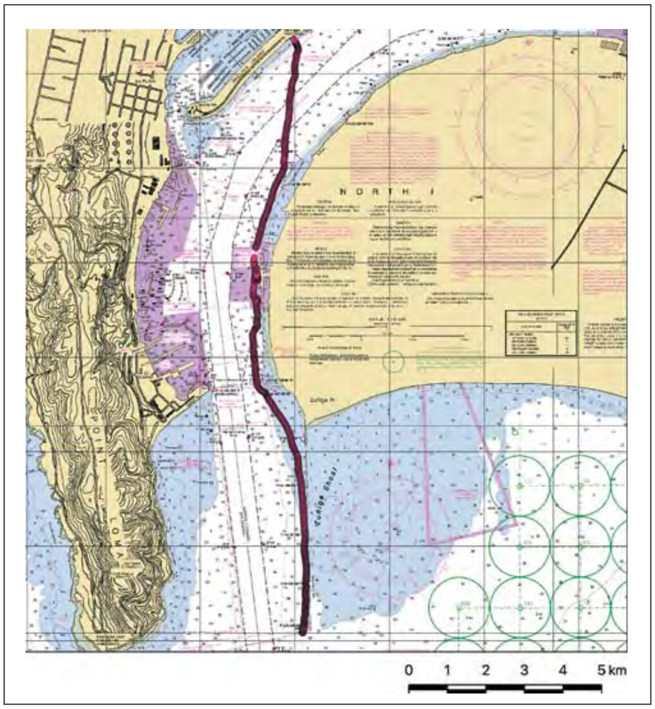


Figure ES-17. Data collected with WIBL in San Diego, CA on a small boat by a local volunteer. Data courtesy of Laura Trethewey.

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 of large-scale, high-density, shallow-water hydrographic datasets is still a challenging task. Over the years, the Center has pioneered a number of techniques to improve 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.

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 currently being developed in conjunction with several of the Center's Industrial Partners who are pursing commercial implementations.

February 2023 will mark the twentieth anniversary of the formal release of the CUBE source code for Industrial Partner development. CUBE was the first-generation bathymetric processing code developed at the Center to tackle the problem of high-resolution, high-density multibeam bathymetry data. Given the age of the software, and upcoming anniversary, it is the Center's intent to provide an open-source licensed version of the original CUBE source code while still offering commercial license terms for any Industrial Partner organizations who would prefer them. Among other things, this will allow for interaction with NOAA partners at Hydrographic Systems and Technology Branch (Eric Younkin) for development of a demonstration CUBE in Python, and integration with the developing Kluster processing system.

Volunteer Bathymetric Observations

Along with our effort to increase the efficiency and accuracy of the processing of professionally collected multibeam sonar data, we also have been exploring approaches to assuring the quality, and reliability of volunteer bathymetric data. This work involves estimating observer reputation (or credibility) through comparison of volunteer bathymetric (VB) data against authoritative databases after bias estimation and removal steps have been applied to the VB data. In the current reporting period, prototype algorithms have been converted to Python

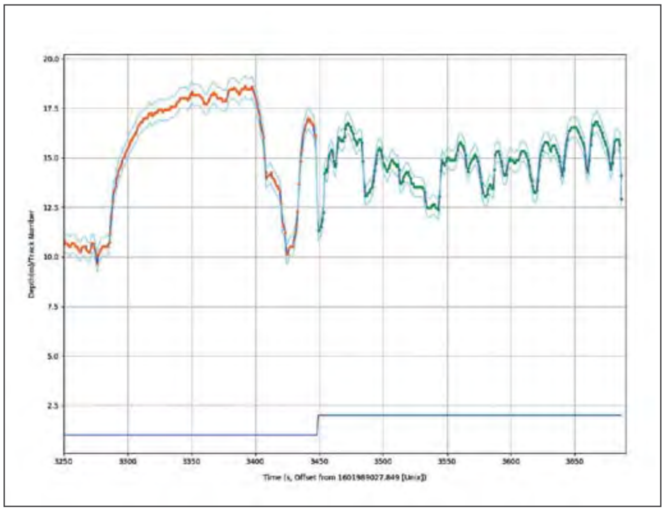


Figure ES-18. Example VBI time series data tracking using a dynamic linear model. The original data (dark blue) is modeled by a series of tracking models (orange and green dots), with associated uncertainty (cyan curve); the tracking model changepoint is shown in the lower step function.

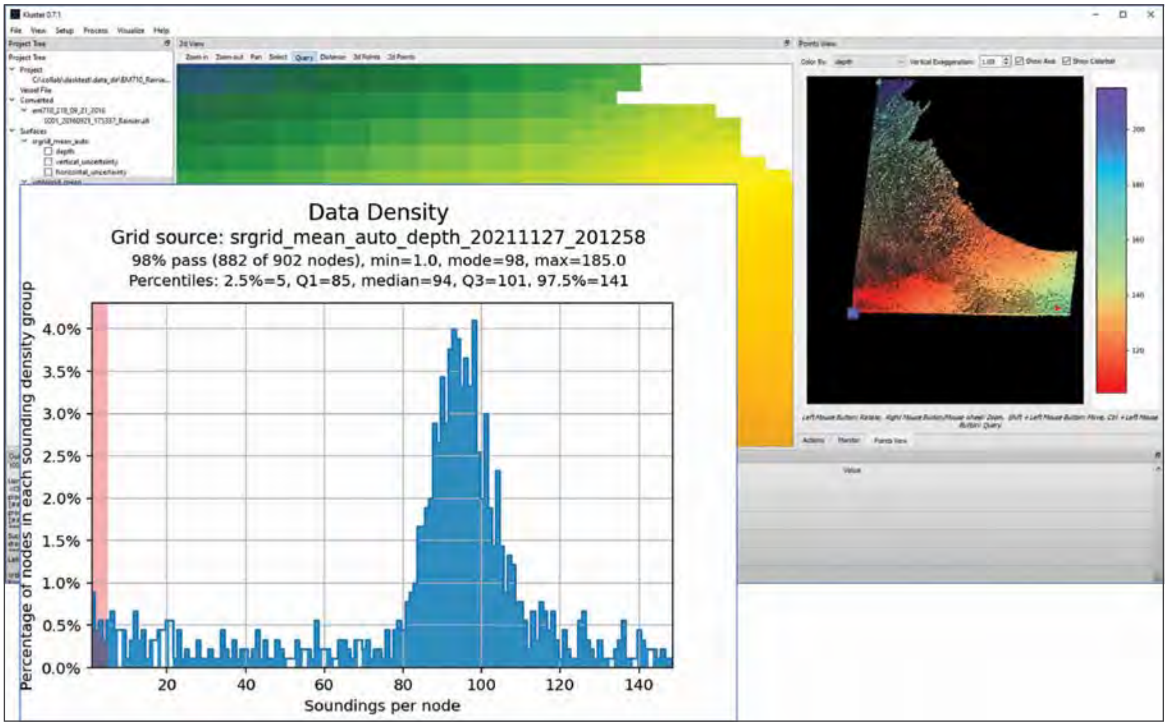


Figure ES-19. Example of QC Tools integration with Kluster. The density layer stored in a Kluster's BathyGrid is used to feed the QC Tools' Grid QA algorithm. Among other information, the resulting 'Data Density' plot provides the critical percentage of valid grid node passing the HSSD-required data density test.

to provide better collaboration opportunities and allow for cloud-based processing. In addition techniques to handle time series VB data (which will typically be single beam soundings as opposed to dense multibeam data), characterizing the depth response and thereby identifying non-consistent behaviors, have been investigated. For example, if an algorithm can learn the characteristics of the current bathymetric environment as a function of time, deviations from the general properties (e.g., a sudden change in bottom texture, or an unexpected vertical offset) could be used to identify less reliable data. As with current multibeam techniques, this could cause the data to be identified to a human operator for remediation or, since this is volunteer data, simply have the data culled from the database as "suspect" (Figure ES-18).

Advanced Quality Assurance/Control Tools

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 their transition to operations through both HydrOffice and Pydro toolsets. These 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. Most notable among these efforts has been the development of QC Tools—a suite of analysis tools designed specifically to address quality control steps in the NOAA hydrographic workflow within the HydrOffice tool support framework. In the current reporting period, the BAG Checks algorithm was implemented, tested, and added to QC Tools. QC Tools was updated to ensure that data fulfill NOAA 2021 HSSD requirements and, in collaboration with Eric Younkin (NOAA HSTB), QT Tools were integrated with Kluster, an open-source hydrographic processing application that is currently in its incubation phase). The main result of this work has been the added support in QC Tools of Kluster's BathyGrid format to provide Kluster users with a seamless operation of the QC Tools on the new platform (Figure ES-19).

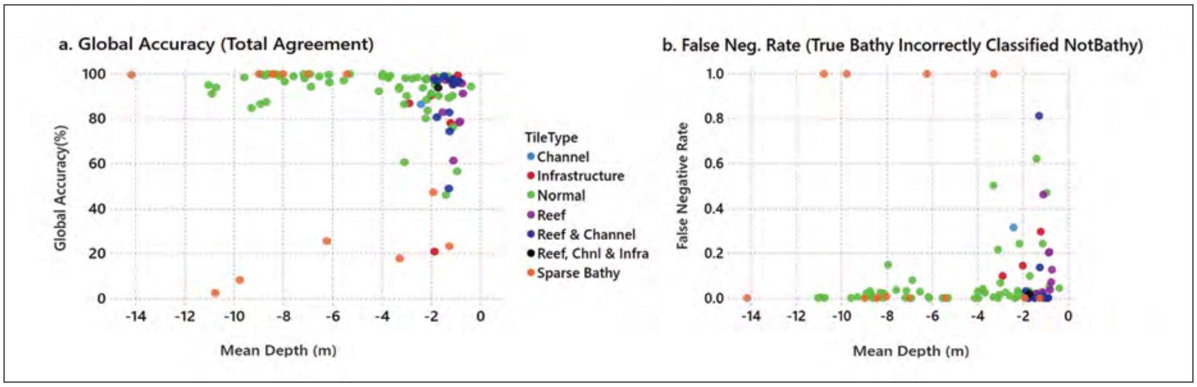


Figure ES-20. Global classification accuracy and false negative rates for 103 tiles.

Automated Data Processing for Topobathy LiDAR Data

With the development of topobathy lidar representing a fundamental change in the density of lidar data (compared with traditional bathymetric lidars), the processing approaches developed for multibeam sonar data using CHRT may find application in topobathy lidar data. The overarching goal of this work 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* data set. The adopted approach couples CHRT with machine learning (ML) to process individual 500 m x 500 m NOAA lidar tiles. In the current reporting period, a second-generation algorithm (CHRT-ML 2.0) has been developed and found to perform reasonably well though analyses in regions where bathy soundings are sparse/rare remain difficult (Figure ES-20). However, this is associated with the depth-related limits of light penetration rather than methodological flaws inherent in CHRT-ML 2.0.

Backscatter Data Processing

OpenBST

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 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. In the current reporting period, the project has been restructured to use a graphical user interface, which will permit the user to navigate the backscatter workflow and provide a number of comparison tools to facilitate investigation of the underlying data.

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 (i.e., 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.

Table ES-1. Root mean squares errors of the estimated depths from February 2017 with respect to depth ranges.

Method	Model	Brands	Depth Range	RMSE
Linear	Stumpf	B/G	0 – 15	0.88
Linear	Dierssen	B/G	0 – 15	0.65
Non-Linear	Dierssen	B/G	0 – 15	0.53
Non-Linear	Dierssen	B/G	0 – 15 (5 m depth range)	0.35

Multi-temporal and Non-Linear Satellite Derived Bathymetry

Satellite derived bathymetry (SDB) from multispectral remote sensing has shown potential as a supplement to traditional surveys in charting shallow areas with low cost. The ability to retrieve bathymetric information from SDB is based on the observed radiance as a function of wavelength and depth. One of the main concerns with SDB is that the accuracy of the method is not adequate for many coastal applications, including nautical charting. In the current reporting period, we have investigated the use of multi-temporal, non-linear techniques for improving the accuracy of the derived bathymetry from satellite images. The accuracy of the empirical SDB techniques was assessed by calculating the root mean square differences between ENC validation depths and SDB estimated water depths. Table ES-1 shows the results for the linear and the nonlinear models and the reduction in error when data are divided into 5 m depth ranges. Further investigations of approaches to increase the accuracy are underway.

ICESat-II for Shallow Water Bathymetry

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.

A new research area at the Center, we have focused our initial efforts on familiarization with ICESat-2 data—primarily its collection, processing, output products, and data dictionaries—and initial evaluation of potential methods for automated extraction of bathymetry and reliable assessment of ICESat-2 data (Figure ES-21).

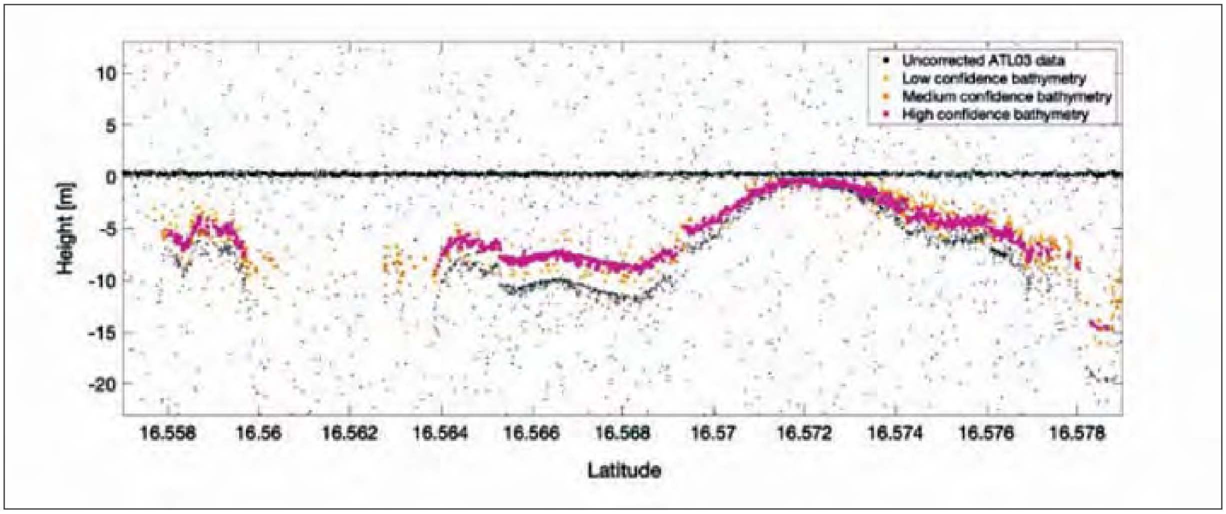


Figure ES-21. Typical ICESst-2 data selected for processing in various publications. (Data processed by median-based algorithm of Ranndal et al. 2021).

Enhanced Underwater 3D Reconstruction

The sonars that we use to map the seafloor offer an acoustic representation of the seafloor (based on travel time and intensity of the sonar return) but never with the fidelity that can be provided by optical imaging systems (with the tradeoff being propagation distances). In those cases where we seek to truly understand the nature of the seafloor at high-resolution, we call upon optical imaging and thus the Center is also exploring approaches to high-fidelity 3D reconstruction of seafloor scenes using Structure from Motion (SfM) photogrammetric techniques. For this reporting period, the project team has been developing workflows for 3D model construction of larger, highly rugose seaweed dominated habitats. Seaweeds are soft bodied and sway with water movement, making 3D model reconstruction difficult as images taken consecutively may appear different because the seaweed, particularly kelp, may be in a different location within the image. For this reason, the method of image collection for seaweeds is slightly different than for coral reefs, and images used to create the model require more manual alignment in post processing.

Ocean Mapping Data Analytics: Artificial Intelligence, Machine Learning and Other Techniques

With the growing awareness of the important role that artificial intelligence (AI) and machine learning (ML) and other powerful analytical techniques can play in the analysis and processing of ocean mapping data, the Center has started a new effort we call Ocean Mapping Data Analytics (OMDA) to address the growing need for research that applies a variety of analytical techniques—artificial intelligence (AI), machine learning (ML), text analysis, visualization—across a range of Center activities. Under the supervision of Kim Lowell, OMDA is being applied to a number of ongoing Center projects including bathymetric data and topobathy lidar data processing, (CHRT-ML), enhanced underwater 3D reconstruction where machine learning has been used to identify and segment corals, the evaluation of ICESat-2 data, and in our soundscape work where advanced data analytics have been used to quantitatively characterize soundscapes, to evaluate changes in behavior of marine mammals in response to echo sounders, and opportunistically, looking at the impact of the COVID pandemic on ocean noise levels.

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 echo sounder (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 of new high-resolution multibeam sonar data on 35 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,

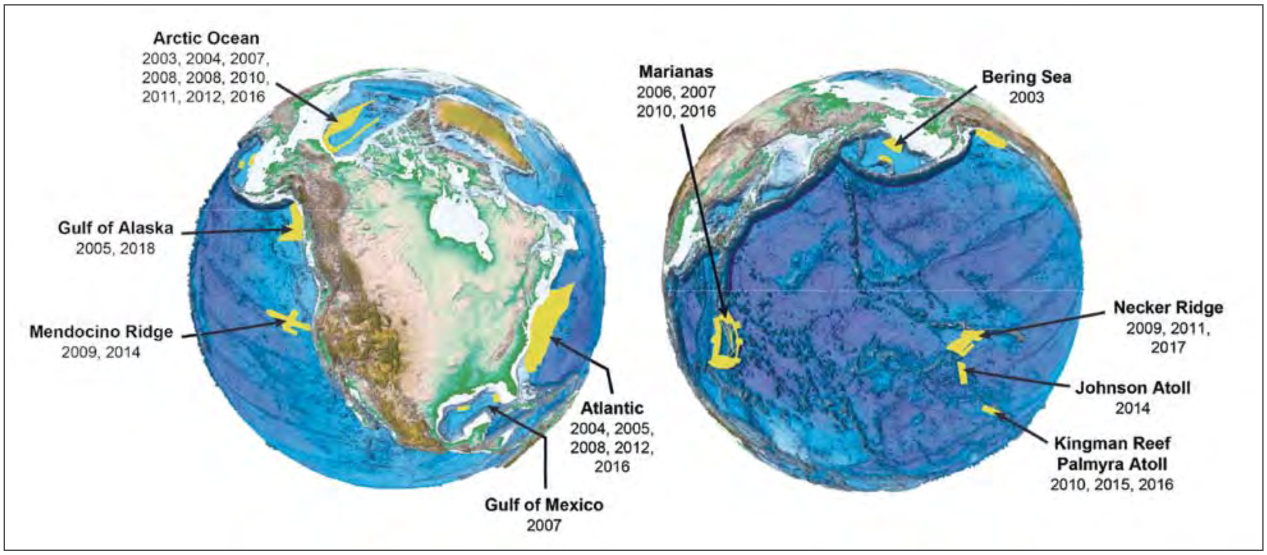


Figure ES-22. Summary of Law of the Sea multibeam sonar surveys mapped by the Center. Total areas mapped represents more than 3.1 million square kilometers since 2003.

five in the Marianas region of the western Pacific and two on Mendocino Fracture Zone in the eastern Pacific (Figure ES-22). 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.

Current year activities focused on writing technical papers describing results from ECS cruises, continued support of the ECS Project Office with the provision of data sets and analyses, continuing update of the Center's ECS website including a transfer to ArcGIS Pro and an enter-prise online GIS solution (https://maps.ccom.unh.edu/portal/home/), and on participation in numerous ECS conference calls, videoconferences, and meetings including several key virtual meetings to review U.S. submissions with former and current CLCS commissioners. Additionally, Paul Johnson has been working closely with the Project 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 Project Office and NCEI databases. Finally, the Center participated in a transit of the USCG Icebreaker *Healy* through the Northwest Passage in August/Sept 2021. While this cruise was not a dedicated cruise in support of ECS activities, several data sets were collected in the Canada Basin that will add to the ECS database (Figure ES-23).

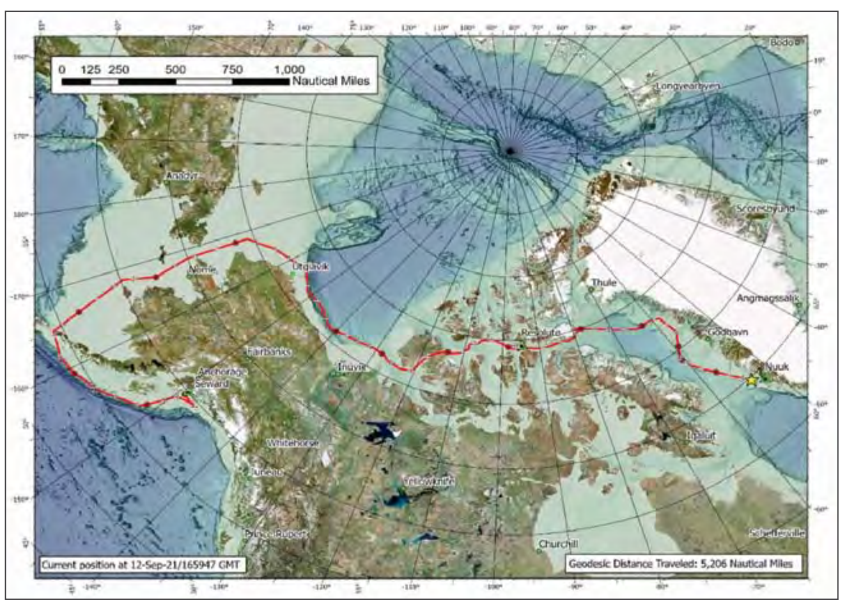


Figure ES-23. USCG Icebreaker *Healy* transit of the Northwest Passage in summer of 2021. While not undertaken for ECS purposes, ECS-relevant data were collected during transit through Canada Basin.

Mapping Biological, Geological, and Environmental Conditions of Critical Marine Habitats in the U.S. Northwestern Atlantic Margin Canyons and Seamounts

With the winding down of new data collection for ECS we are now focusing on demonstrating the "value-added" of the more than 3.1 million square kilometers of high-resolution multibeam bathymetry and backscatter that have been collected. Our initial focus has been on evaluating the data from the U.S. Atlantic margin and determining if data that is useful for ecosystem-based management (EBM) can be extracted from it. The goal is to interpret the ECS data using novel classification approaches developed at the Center, in combination with existing ground-truth data, to gain insights into predicted substrate types of the seafloor and to characterize the geomorphic features of the seafloor consistent with the Coastal and Marine Ecological Classification Standard (CMECS).

Using ECS and OER data from Gosnold Seamount, the Atlantic Margin Canyons, and the New England Seamount Zone, we demonstrated that the interpretation of the morphology using our BRESS seafloor characterization approach produces a consistent and reproducible habitat classification for ROV tracks and for large regions. Key benefits of the study's semi-automated approach included high speed classification of terrain over very large areas and complex terrain, reduced subjectivity of delineation relative to manual interpretation of landforms, transparency and reproducibility of the methods, and the ability to apply the same methods to large regions with consistent results. The approaches developed through these studies have provided a model of how to consistently classify ecological marine units using CMECS as an organizing framework across large potential ECS regions nationally or globally.

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. Studies carried out by the Center have verified that many sand and gravel deposits on the western Gulf of Maine (WGOM) continental shelf originated as glacial features. We are now focusing on advancing the understanding of the relationships between aggregate deposits and seafloor physiographic features in complex shelf environments with initial focus on glacial features in paraglacial environments in the WGOM. To support these efforts, an ArcGIS project was developed that depicts sea-level movements over the last ~13,000 years using high-resolution bathymetry grids for the WGOM developed previously by the Center, a well-vetted relative sea level curve for the WGOM from the literature, and a new, high-resolution topographic map of the adjacent upland based on recent lidar

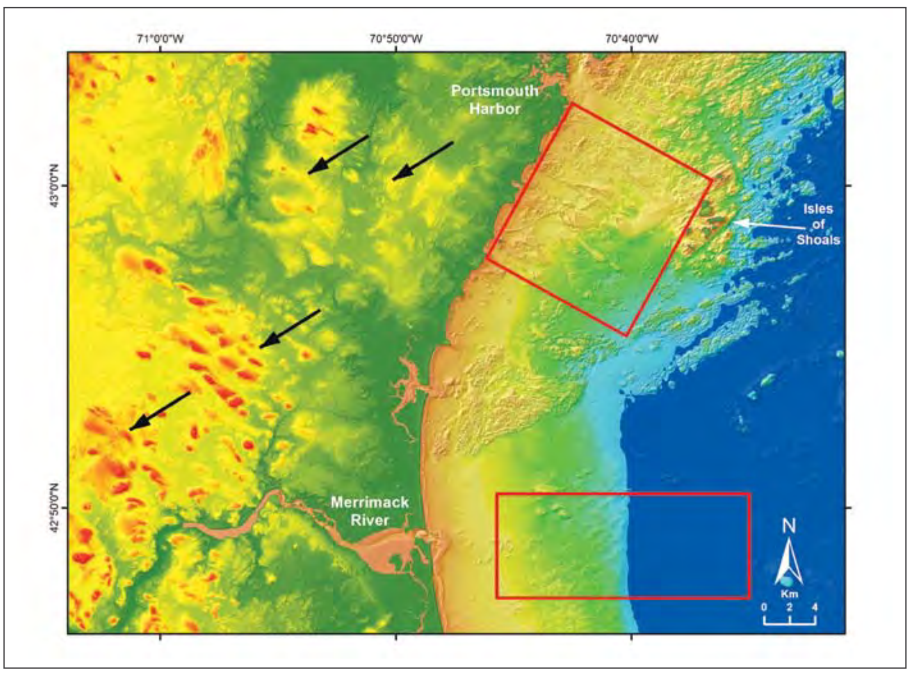


Figure ES-24. Topographic and bathymetric map of the NH and northern MA coastal upland and inner shelf. The western edge of the dark blue in the bathymetry is the location of the sea level lowstand at -60 m at ~12,500 years before present. The upper red box outlines multiple marine-modified glacial features (e.g., drumlins, outwash, and eskers). The lower red box outlines the location of the Merrimack River paleodelta. Both locations have proven sand and gravel resources. The black arrows on land show drumlins and other glacial features that are analogous to the offshore glacial features in the upper red box.

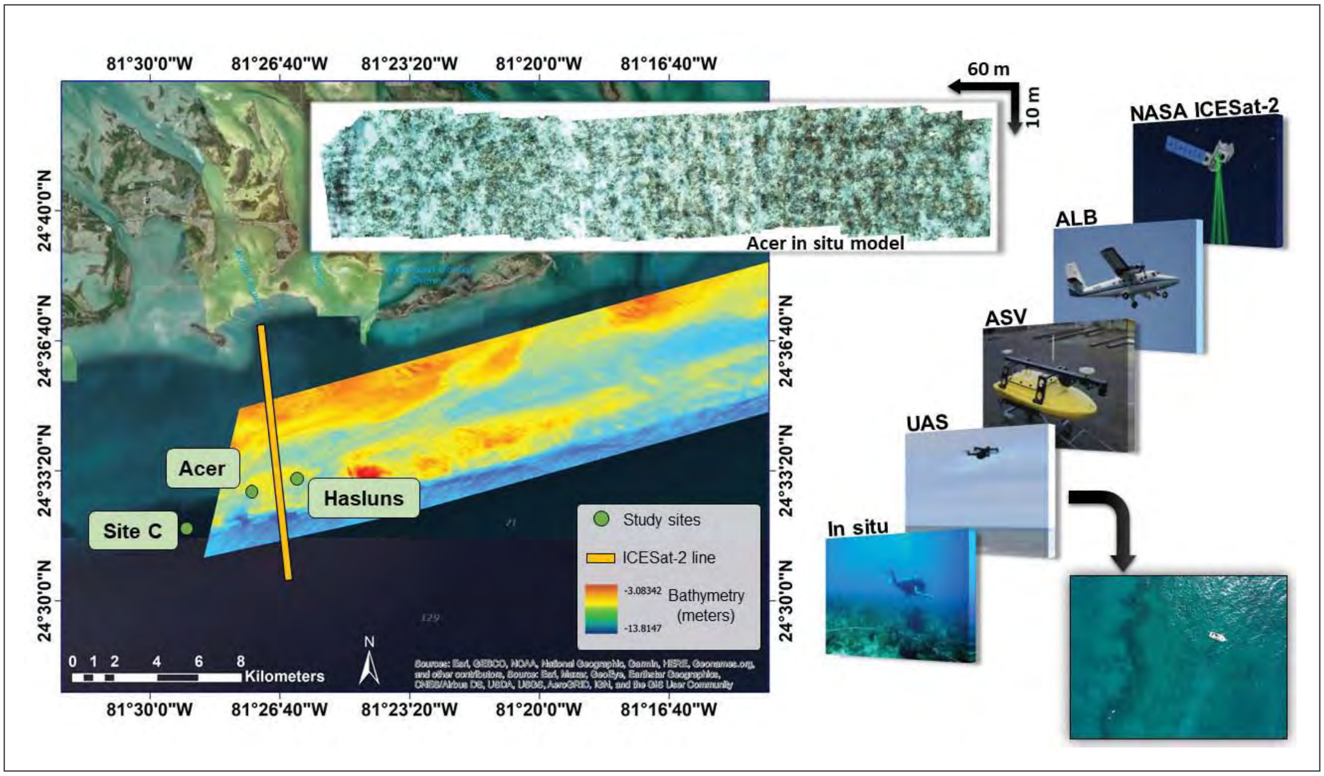


Figure ES-25. Sites in the Florida Keys (green dots), bathymetry, ICESat-2 track (yellow) and 3D model of Acer reef. Systems used to acquire data in the Florida Keys in summer 2021 were the HyDrone Autonomous Surface Vehicle (ASV), Skydio 2 uncrewed aircraft system (UAS), and an underwater stereo-camera rig. Bathymetry was generated from ICESat-2 aided satellite derived bathymetry (SDB) following procedures developed in previous work of our project team.

surveys (produced for this study). The ArcGIS project and associated maps allow various sea level scenarios to be explored from a lowstand depth at -60 m to the probable maximum marine inundation (+50 to +60 m) and facilitates assessing the submergence and exposure history of inner shelf and nearshore deposits (Figure ES-24). This information will be used in conjunction with high-resolution bathymetry and subbottom seismic studies to assess the origin and characteristics of sand and gravel bodies in the WGOM.

Multi-Modal Mapping for Change Detection on Coral Reefs

Included in the research requirements of the "Resources of the Continental Shelf" component of Programmatic Priority 1 is the development of ocean mapping technologies that support the responsible management of U.S. living marine resources. Among these, coral reefs are an important habitat and resource and thus the Center has explored approaches for mapping coral reefs and evaluating the efficacy of various restoration practices and monitoring change at spatial extents and timescales that are relevant to management. A multi-modal approach is being taken using data from satellites, uncrewed aircraft systems (UAS), autonomous surface vehicles (ASVs), and diver-collected underwater imagery. We have partnered with Mote Marine Laboratory to study priority coral sites of varying bathymetric rugosities, slopes, and cover types (coral, seagrass, macroalgae) in the Florida Keys (Figure ES-25).

In this reporting period, the project team conducted field operations in the Florida Keys field sites using a Skydio 2 UAS Seafloor Systems, HyDrone equipped with an Ohmex SonarMite single beam echo sounder and an underwater stereo-camera rig consisting of two DSLR Canon cameras. Additionally, the project team is investigating satellite-based bathymetric mapping techniques developed in related studies for generating lower spatial resolution but higher temporal resolution bathymetric grids for the project area.

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

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. Included among these are efforts to automate hydrographic sounding selection—the process of generalizing bathymetric datasets to produce a shoal-biased and dense, yet manageable, subset of soundings that can support the subsequent cartographic selection. The approach taken has been a label-based generalization approach that accounts for the physical dimensions of the symbolized soundings (Figure ES-26).

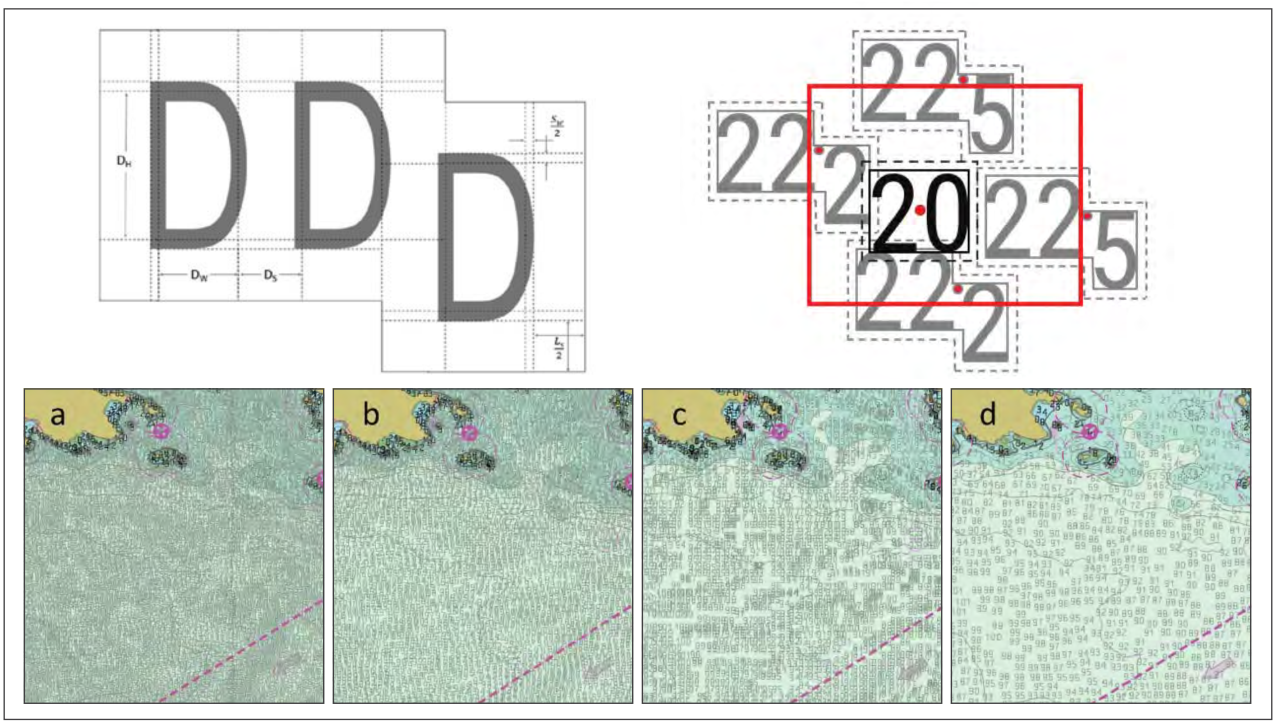


Figure ES-26. Upper: label-based generalization consists of removing deep soundings directly inside the sounding label footprint (left) to enforce shoal-bias, while the second component removes soundings whose labels overlap with shallower sounding labels. This is achieved by using a legibility rectangle (in red on right) calculated specifically for the label footprint of the target sounding (in black), labels of potential neighbors (in grey on right), and a label separation value (selected based on human perception factors) to maintain legibility among soundings. In the example illustrated above (right), the 22.2 m soundings are within the legibility rectangle and will be eliminated because, when rendered at scale, they overlap with the 20 m target label. Conversely, the 22.5 m soundings are marginally outside the legibility rectangle, and, as such, are retained in the generalized dataset. Lower: Sounding label distributions of generalization approaches for the Strait of Juan de Fuca dataset: a) fixed radius; b) variable radius; c) grid-based; and d) label-based.

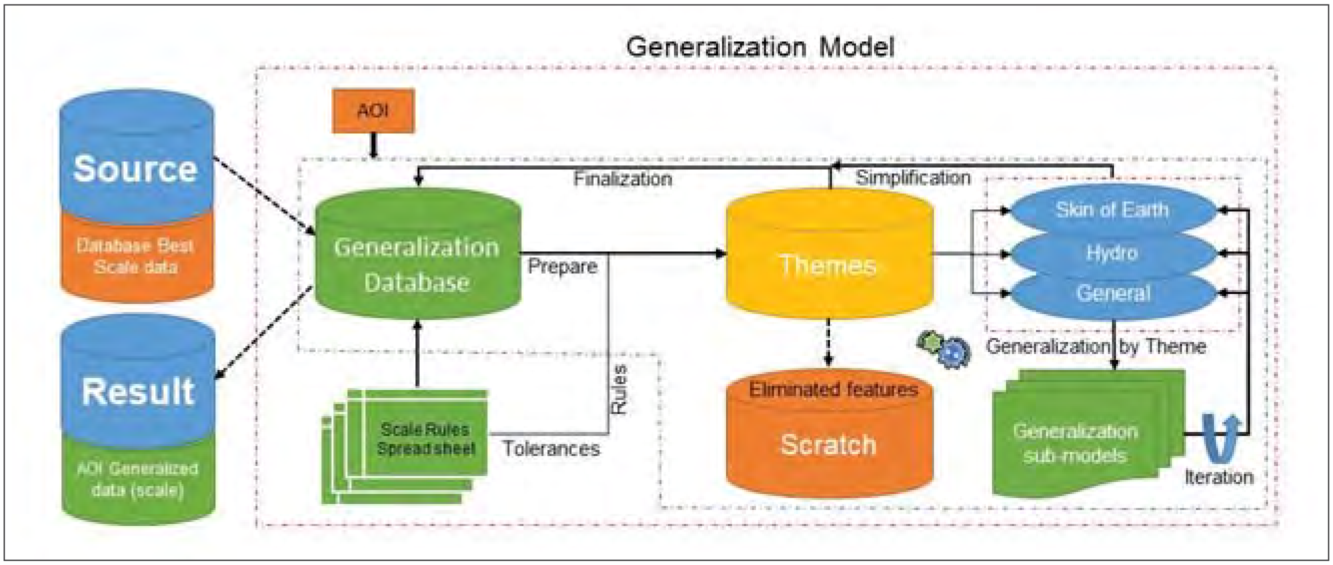


Figure ES-27. The preliminary nautical generalization model.

Managing and Transforming Data to Navigation Products: Computer Cartography

The development of enterprise bathymetric databases also requires the concurrent development of automated cartographic tools, yet still many of the chart compilation processes remain manual and time-consuming. The focus of this research effort is to explore approaches for computer-based cartography that will emulate both the aesthetic and safety-based considerations of a human cartographer. Included in our efforts are approaches to cartographic sounding selection (as opposed to hydrographic sounding selection discussed above), sounding selection verification methods, data quality polygon simplification, and approaches for the automated compilation of ENCs (Figure ES-27).

Innovative Approaches to Support Precision Navigation

It is essential that the mariner understand the uncertainty associated with the information displayed on a chart or ECDIS, but the legibility and utility of the current methods are limited, and thus we have focused on developing new visualization and integration methods of bathymetric data quality in ECDIS in support of decision making on board. Our research has considered how different visual variables might be used to meet the requirements and proposes the use of a sequence of textures created by combining two or more visual variables. Two coding schemes were developed: one consisting of lines and one consisting of clusters of dots (with the fundamental principle that the number of lines or dots represent the data quality). Adopting ideas previously expressed in the maritime community, three more color-based coding schemes were developed—one with opaque color fills, one of transparent color fills, and, in the effort to overcome the obscuring issue of opaque colors and the blending issues of transparent colors, one of see-through color textures (Figure ES-28). The initial result of a survey of mariners indicates that texture solutions are preferred.

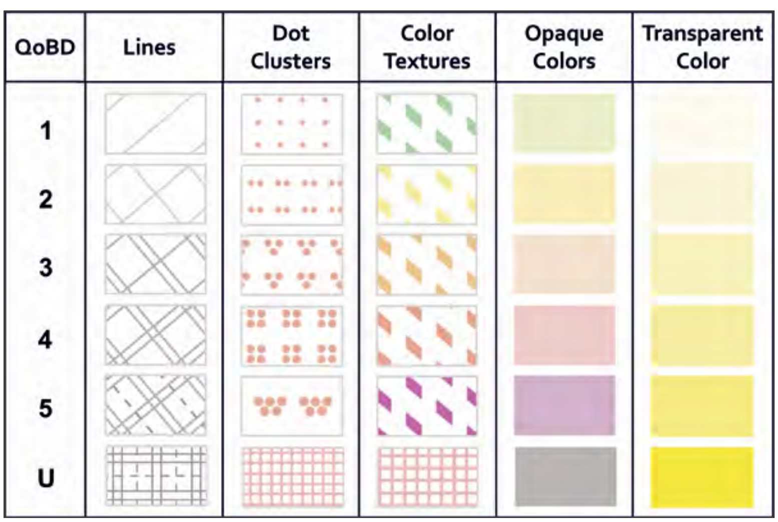


Figure ES-28. The developed five coding schemes for the visualization of the QoBD categories on ECDIS displays.

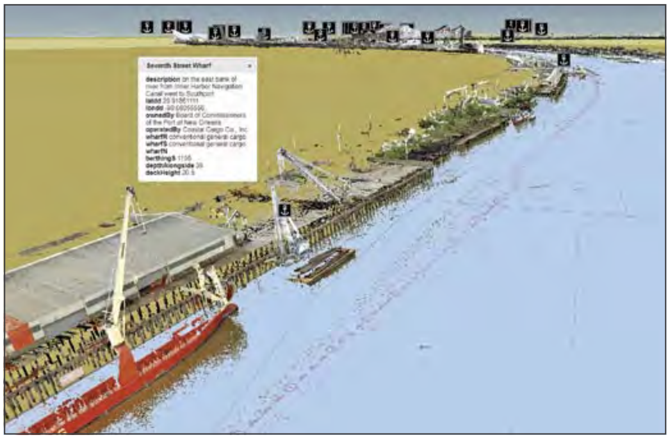


Figure ES-29. Example view of S-131 marine harbor infrastructure features, with color lidar data revealing crane locations and sizes along a wharf.

Figure ES-30. 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.

Web-based Visualization of Massive 3D Coastal Data

In further support of precision navigation, we have also explored web-based 3D fusion and display of very high-resolution coastal data sets. The challenge here is to manage and manipulate these massive data sets that include bathymetry and coastal lidar clouds, and often contain a hundred million points per mile of waterway. Using a NOAA-provided data set from a 230-mile segment of the lower Mississippi River coming into the Port of New Orleans, we developed a modification to the software used on NOAA's Data Access Viewer that allows the streaming of chart imagery from NOAA's ENC web service, and the fused display of the electronic chart underneath the lidar point cloud data to provide context. In addition, we have added the ability to display S-131 harbor infrastructure information (Figure ES-29).

Augmented Reality for Navigation

Furthering our efforts to explore innovative approaches for using high-resolution 3D data sets in support of precision navigation, we are also exploring the use of augmented reality (AR) for navigation support. Augmented reality (AR) is a technology that superimposes digital information directly on top of a user's real-world view and holds tremendous potential for a range of ocean mapping applications, including enhanced navigation, immersive exploration of 3D scenes, and new approaches to collaborative data editing. Previous work in the Center's VisLab demonstrated that available AR glasses were limited in practice because of poor light levels and limited field of view. This past year, the lab received a new type of AR glasses (Nreal) that appears to resolve many of these issues (Figure ES-30). Efforts are now underway to incorporate these glasses into the lab's testing and research program. In further support of these efforts, the VisLab has developed an approach for bringing high-density bathymetric and lidar data sets (including NOAA BAG files) into the widely used Unity graphics engine.

Figure ES-31. A portion of the current landing page of the Center's Data Portal (https://maps.ccom.unh.edu) where users can find highlights of some web services developed from research and activities conducted at the Center.

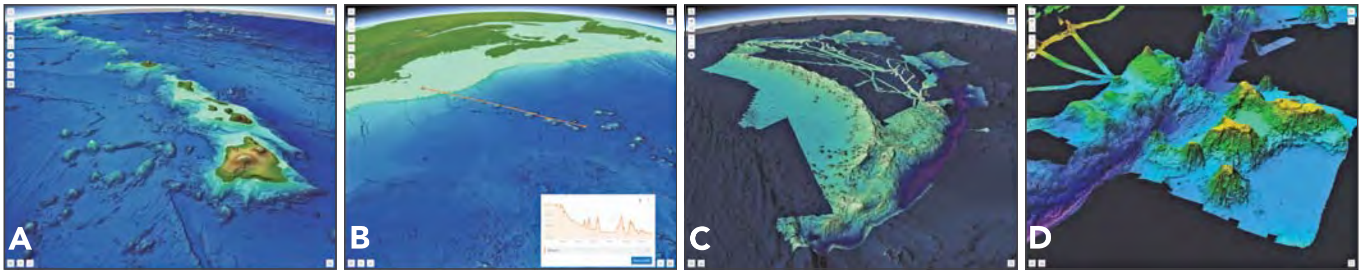


Figure ES-32. Visualizations of large datasets using the Center's GIS portal. A) GEBCO 2021 grid with a 5x vertical exaggeration (https://bit.ly/3rRjawD). B) GEBCO 2021 grid with a 1x vertical exaggeration showing an interactive profiling tool (https://bit.ly/3pLH9uF). C) & D) Marianas extended continental shelf bathymetry with a 5x vertical exaggeration (https://bit.ly/3yAfFMd).

Enhanced Web Services for Data Management: Enterprise Geospatial Platform

The Center has maintained an online data access portal using different technologies since 2011. The most recent iteration is an ESRI Enterprise framework consisting of a GIS Server, Data store, and Portal running on a well provisioned server (dual 8-core Xeon E5-2630 CPUs, 128 GB of RAM, and 3.6 TBs of RAID storage) providing access to a wide variety of services, including maps, images, grids, and feature layers for a broad range of areas including extended continental shelf mapping, local (to the Center) hydrographic and geologic mapping, and global bathymetric syntheses (ES-31).

Among the specialized services developed at the Center are web-based global data quality assessment tools which allow the visual review of large gridded data sets (including on a sphere—Figure ES-32) by providing access controls to the data and databases hosting the review layers, and has an easy-to-use form to fill out metadata that describes problems with the data. This interface was used successfully to review the GEBCO 2021 release and a pre-release of SRTM+V2.3.

BathyGlobe and GapFiller

The BathyGlobe application has been 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 two years, a spinoff of BathyGlobe—GapFiller—has been developed that allows for interactive planning of survey routes over existing data sets so as to optimize filling gaps in coverage during a voyage. In the current reporting period, GapFiller has been upgraded with a much more robust, image-processing-based algorithm for identifying gaps and optimizing overlap and coverage. Additionally, an "Arctic" version of GapFiller was developed that uses a polar stereographic projection (and was successfully used for planning the transit of USCG Icebreaker *Healy* through the Northwest Passage and is now actively being used by hydrographers in Greenland). Currently, a Global GapFiller is being developed that allows smooth transition between polar and sub-polar regions (Figure ES-33).

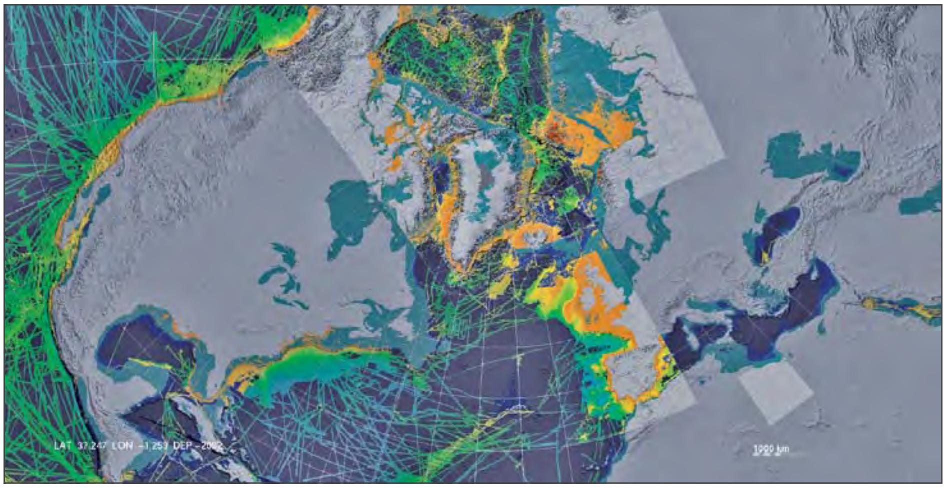


Figure ES-33. Global GapFiller provides a unified view in a locally defined stereographic projection based on both IBCAO and GEBCO data.

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 echo sounders to the ocean soundscape (particularly the impact of multibeam sonars on marine mammals), as well our educational and outreach programs.

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

The impact of scientific acoustic systems on the marine environment has come under close scrutiny of late. To better understand the potential impact of these systems, the Center is conducting research to measure the radiation patterns of common scientific acoustic systems, including multibeam echo sounders (MBES), sidescan sonars and subbottom profilers (SBP). Since 2017, the Center has been conducting research into the radiation patterns of deep-water MBESs. The results of the SCORE 2017, AUTEC 2018, and SCORE 2019 experiments provided some of the first measured far-field transmit radiation patterns of Kongsberg EM122 and EM302 deep-water MBESs. The results highlighted the complex radiation patterns of these systems, as well as identified a technical issue within the systems which resulted in numerous, high source-level grating lobes within the transmit patterns. Based on many meetings between Center representatives and the sonar manufacturer, the source of the technical issue was identified, and in 2021, the grating lobes in the EM122 and EM302 were reported to be resolved by the manufacturer; this was verified by field trials conducted in June and July 2021 (Figure ES-34).

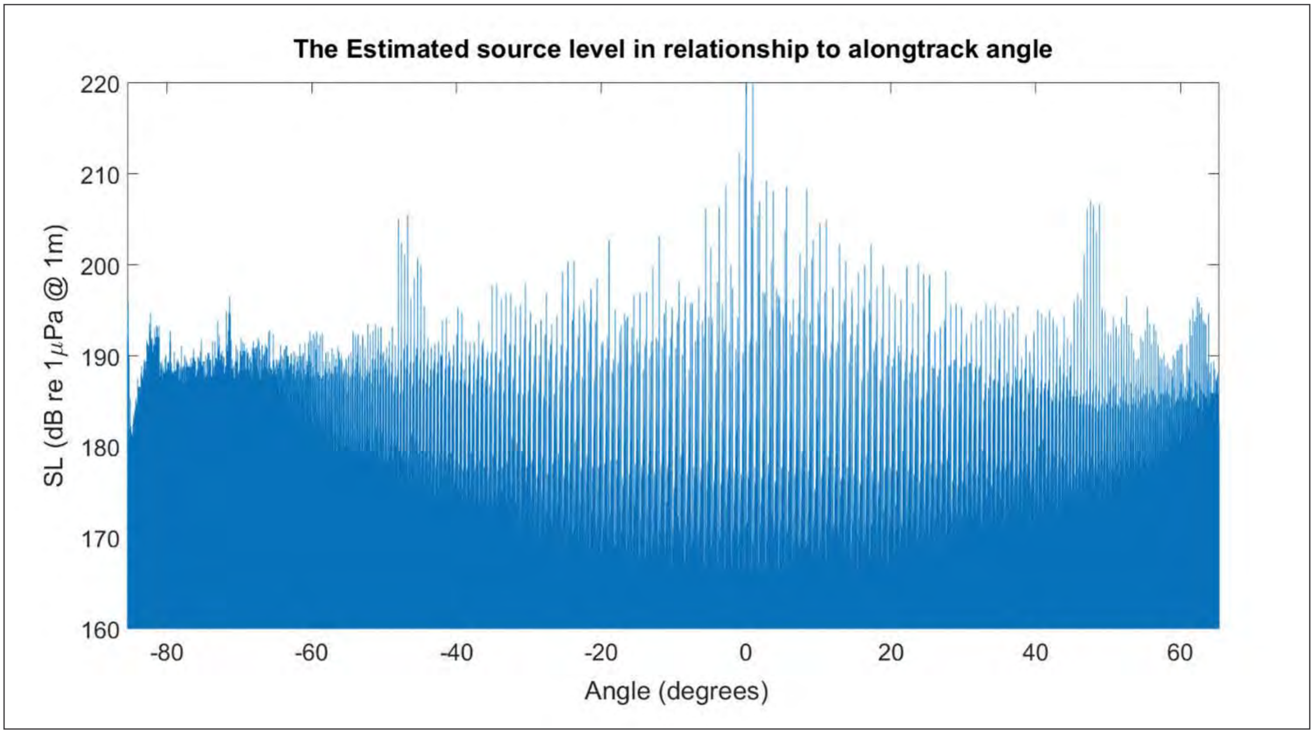


Figure ES-34. Plot of estimated source level of EM302 on R/V *Sally Ride* relative to along track angle. Large grating lobes found in earlier studies (see previous progress reports) are now gone.

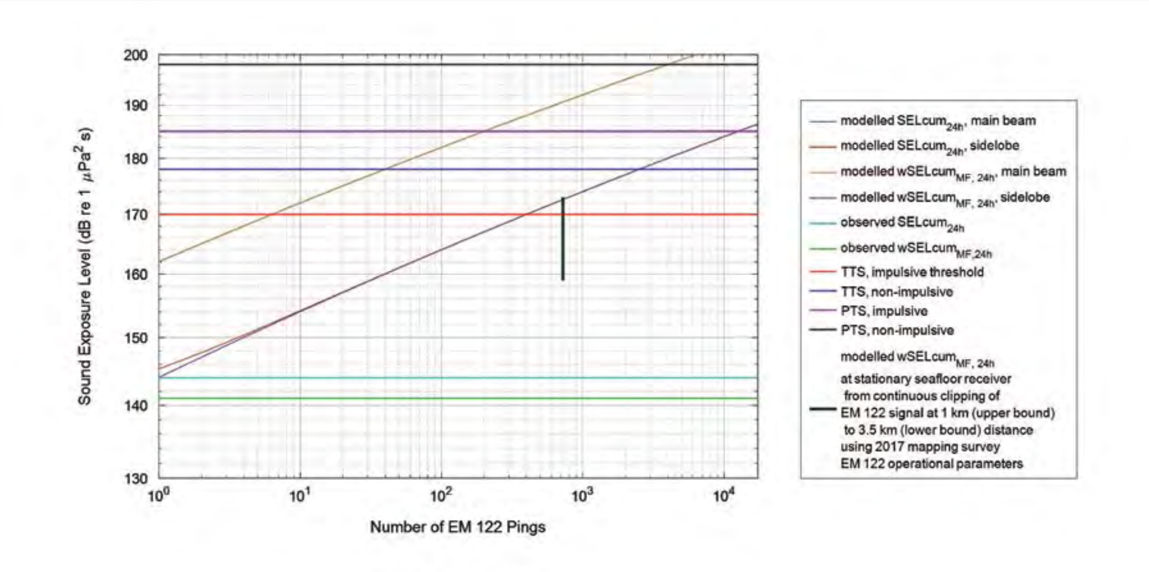


Figure ES-35. Modelled SELcum24h plotted as a function of the number of pings—from no pings (far left) up to 24 hours of pinging with the operational parameters of the 2017 mapping survey (far right)—received on a stationary bottom-mounted hydrophone from 1 km away for various permutations of the following assumptions: whether the clipped signal received was from the main beam, a sidelobe, weighted or unweighted conditions using SELmod equation. Realistic scenario results using SELmod2 equation, plotted as a single green horizontal line. The lower bound represents the scenario for if clipping occurred from sidelobe transmissions received at a constant distance of 3.5 km from the stationary receiver for one hour, in addition to three main beam transmissions received from a distance of 1 km. The upper bound represents clipping that may have occurred from sidelobe transmissions at a distance 1 km from the stationary receiver for one hour in addition to 3 main beam transmissions received from a distance of 1 km.

MBES Contribution to Local Soundscape

Using the sound levels measured at the Navy ranges, a comprehensive soundscape study was undertaken that provided both temporal and spatial information through amplitude and frequency-based sound level analyses applied to characterize the acoustic environment. A summary of the results of the worst-case scenario exposure modelling compared to both observed values, non-weighted injury thresholds, and weighted injury thresholds is provided in Figure ES-35, where sound exposure level (SEL) variant SELmod is shown as a function of the number of EM 122 pulses. Observed and modelled 24 hour cumulative sound exposure levels (SELcum24) did not exceed regulatory thresholds for a non-impulsive sound. The upper bound of the range of modelled SELcum24, accounting for clipping at a stationary seafloor receiver exceeded the impulsive threshold for TTS (temporary threshold shift—a temporary reduction in hearing sensitivity of marine mammal caused by exposure to intense sound) by up to 3 dB. This is an extremely conservative estimate in that it does not consider the mobility of a marine mammal receiver, and depending on the operating mode of the MBES, the signals can be considered impulsive or non-impulsive. Further analysis of frequency correlation difference matrices between periods of MBES activity and non-activity conservatively indicate that the MBES contributed to the acoustical energy field only within the frequency band of the echo sounder and at a finite distance around the survey vessel (<17 km).

Impacts of Sonars on Marine Mammals

The experiments at the Navy hydrophone ranges also provided an opportunity to track the behavior of resident marine mammal populations whose vocalizations during foraging can be monitored on the Navy hydrophones during the operation of the multibeam sonars. We have now looked at the feeding behavior of Cuvier's beaked whales at the SCORE range for two periods of multibeam operation (2017 and 2019). The study design and analysis parallel studies done by researchers that examined the effect of mid-range naval sonars on Blainville's beaked whales foraging at the Atlantic Undersea Test and Evaluation Center (AUTEC).

As reported in previous progress reports (and now published in peer-reviewed journals), overall there was no widespread change in foraging behavior during the MBES survey that would suggest that the MBES activity impacts foraging at this coarse scale. In addition, the animals did not stop foraging and did not leave the range during the MBES survey. This is a significantly different response from that of beaked whales during Navy Mid-Frequency Active Sonar (MFAS) activity on the range, where the same species decreased foraging during MFAS activity.

Applying a Global-Local Comparison (GLC) method to the data demonstrated that the number of foraging events across analysis periods were similar within a given year, and strongly suggests that the level of detected foraging during either MBES survey did not change, and the foraging effort remained in the historically well-utilized foraging locations of Cuvier's beaked whales on the range. Both the GLC method development and beaked whale spatial analysis effort were published in a special issue in Frontiers in Marine Science on Before-After-Impact-Control Studies

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 46 graduate students enrolled in the Ocean Mapping program in 2021, including five GEBCO students, three NOAA Corps officers and three NOAA physical scientists (some as part-time). This past year, we graduated four M.S. and three Ph.D. students, while five GEBCO students received Certificates in Ocean Mapping.

We have continued our evolution to Python as the preferred programing language for ocean mapping courses and have further developed an E-learning course and Python-based lab modules and better aligned them with to coincide with the sequencing of the material taught in class. We have also worked to strengthen connections to the UNH undergraduate program including supporting undergraduate interns on the NOAA Ships *Fairweather* and *Thomas Jefferson* (Figure ES-36) and offering a newly developed "Introduction to Ocean Mapping" course explicitly for undergraduates. Making up for the inability to run our Hydrographic Field Program during the peak of COVID in the spring and summer of 2020, we ran an extra "Winter Hydro Field Program" in December with four brave GEBCO students who came back to UNH to design, implement and process data from a survey conducted in the dead of a New Hampshire winter.

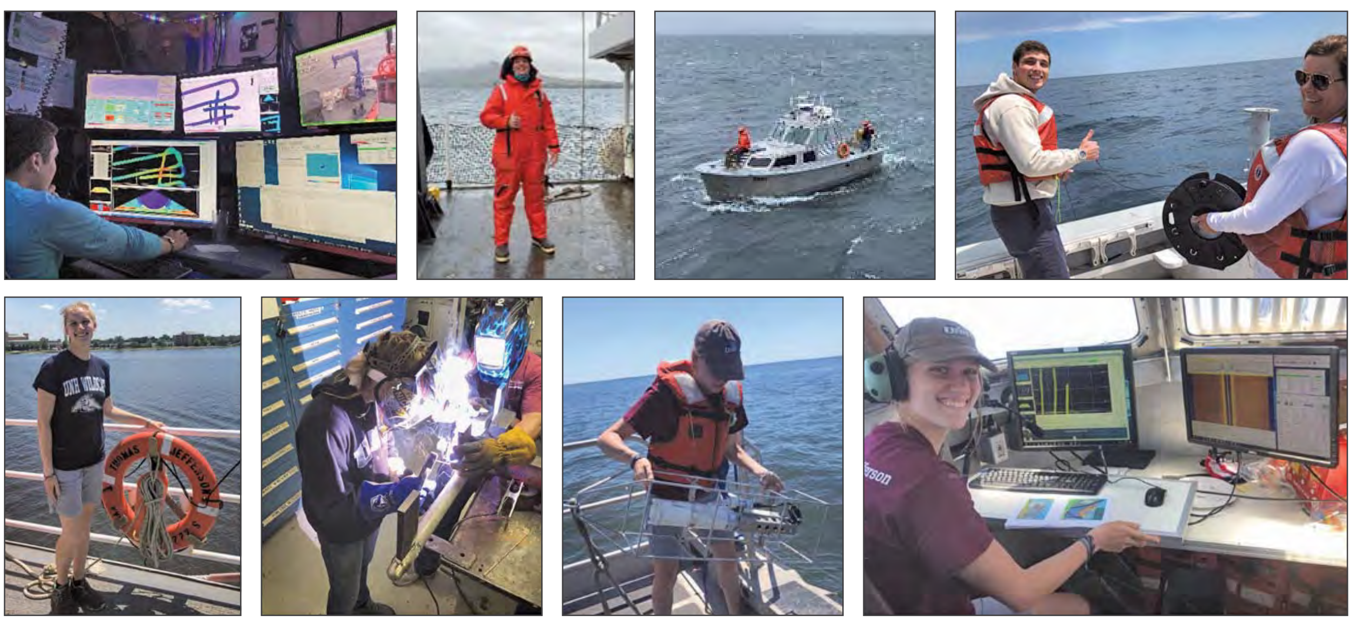


Figure ES-36. Photos showing Thomas Spiro (top row) and Natalie Cook (bottom row) conducting their summer 2021 mapping internships aboard the NOAA Ships *Fairweather* and *Thomas Jefferson*.

Nippon Foundation/ GEBCO Training Program

Since 2004, The Center has hosted, through international competition, The Nippon Foundation/GEBCO Training Program. One hundred and two scholars from 45 nations have completed the Graduate Certificate in Ocean Mapping from the University of New Hampshire as part of this program and funding has been received for Years 17 and 18. In 2019, a group of alumni from our program beat out twenty other teams to win the $4M Shell Ocean Discovery XPRIZE. The core GEBCO-NF Team was made up of fifteen alumni from the UNH Nippon Foundation/ GEBCO Training Program and was advised and mentored by selected GEBCO and industry experts. The prize was awarded at a gala ceremony hosted by the Prince Albert I Foundation on 31 May in Monaco (Figure ES-37). This alumni group has stayed in contact and are now active in supporting deep-sea mapping activities around the world.

Figure ES-38. The homepage of the Center's website.

Figure ES-37. Mr. Unno (Executive Director) and Mao Hasebe (Project Coordinator for the Ocean and Maritime Program and Strategy Team) of the Nippon Foundation with the GEBCO-Nippon Foundation Alumni Team members including Bjørn Jalving and Stian Michael Kristoffersen (Kongsberg Maritime) after the award ceremony in Monaco.

Outreach

We also 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 of our work. One of the primary methods of this communication is our website (Figure ES-38, http://ccom.unh.edu). In 2021, we had 114,215 views from 39,123 unique visits to the site from 182 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 also upgraded other aspects of our web presence including a Flickr photostream, Vimeo site, Twitter feed and a Facebook presence. Our Vimeo site has 141 videos that have been viewed a total of 55,000 times (2,456 in 2021). Our seminar series (38 seminars featured in 2021) is widely advertised and webcast, allowing NOAA employees and our industrial partners around the world to listen and participate in the seminars. Our seminars are recorded and uploaded to Vimeo.

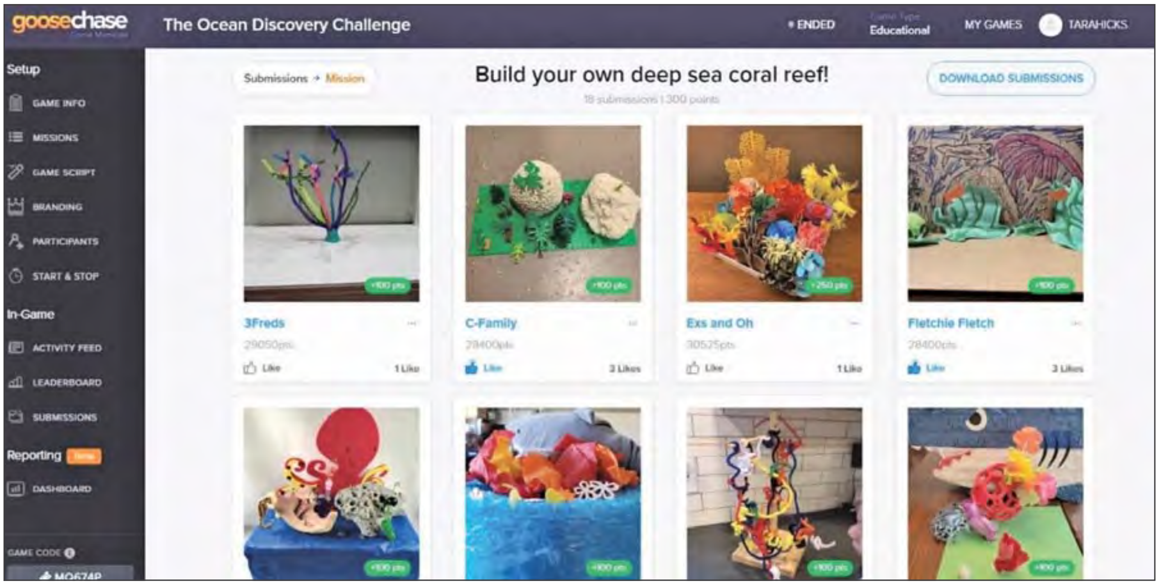


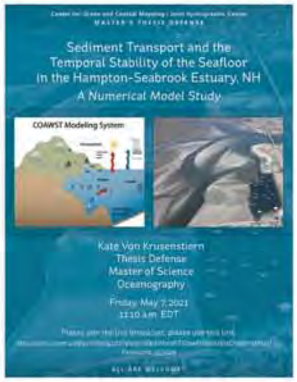
Figure ES-39. Example of some of the submissions from teams asking to build a deep sea coral reef. Some missions asked for text answers, and some for more creative answers, like these crafts, photos, or videos.

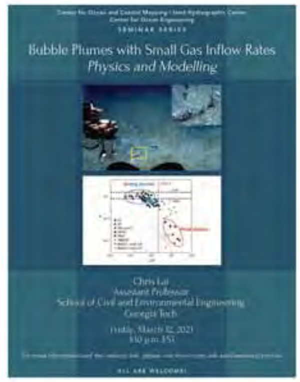
Along with our digital and social media presence, we also maintain an active "hands-on" outreach program of tours and activities for school children and the general public. Under the supervision of our full-time outreach coordinator, Tara Hicks Johnson, several large and specialized events are organized by the Center outreach team, including numerous SeaPerch ROV events and the annual UNH "Ocean Discovery Day." These, of course, were heavily impacted by the COVID pandemic, though we did have visits from 435 K-12 students under COVID protocols. The large (attracting thousands of people to the lab over a weekend) Ocean Discovery Day event was redone this year as a virtual "Ocean Discovery Day Challenge" that took participants on missions either online or in-person (Figure ES-39). We did, however, arrange with a local middle-school to do a virtual SeaPerch ROV build. Kits were distributed to the children and mentors led the build virtually (Figure ES-40). Students then took their ROVs to local ponds and rivers to test them.

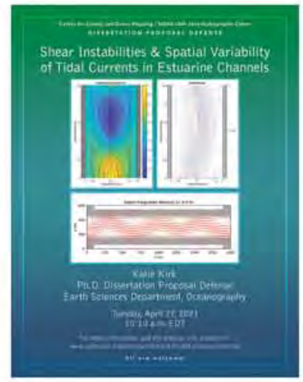
Center activities have also been featured in many international, national, and local media outlets this year including: *TechCrunch, Wired, Scientific American*, the BBC, *The Guardian, Eurasia News, Seapower Magazine, Seattle Times, Cision, Time, Physics Today, Bloomberg Opinion*, Al Jazeera, *Hydro International, Movs. World, Wonderful Engineering, The Alpena News, Star Advisor, Eureka Alert, The Mercury News, Monterey Herald*, and *The Union Leader*.

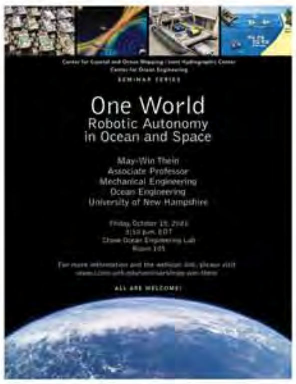
The highlights presented here represent only a fraction of the activities of the Joint Hydrographic Center in 2021; more detailed discussions of these and other activities, as well as a complete list of publications and presentations of the Center can be found in the full progress reports available at http://ccom.unh.edu/reports.

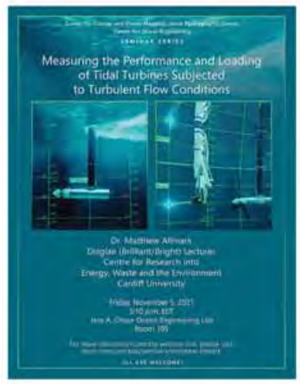
Figure ES-40. Showing off newly built SeaPerch to E/V *Nautilus* crew.

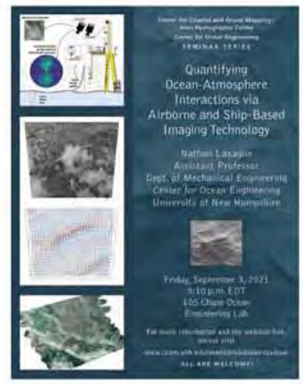


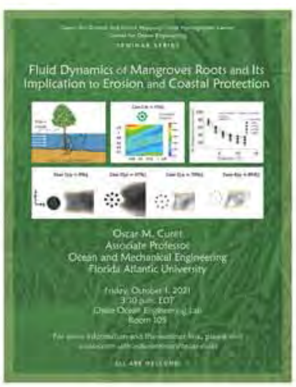


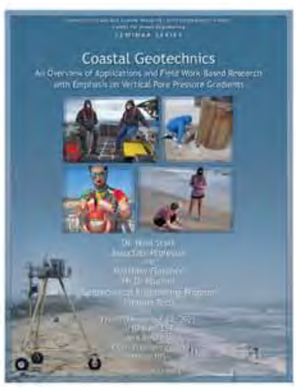


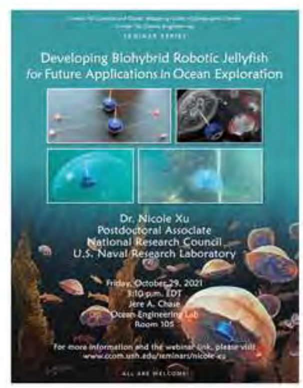


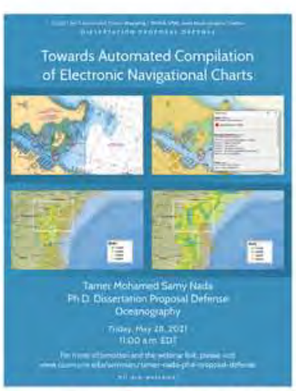


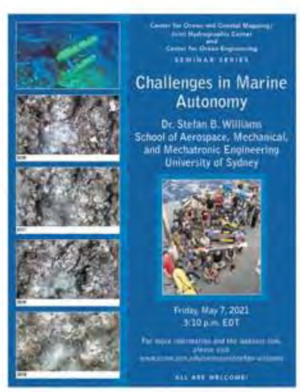












Flyers from the 2021 JHC/CCOM–UNH Dept. of Ocean Engineering Seminar Series.

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