UNH/NOAA Joint Hydrographic Center
Performance and Progress Report
2019 Executive Summary

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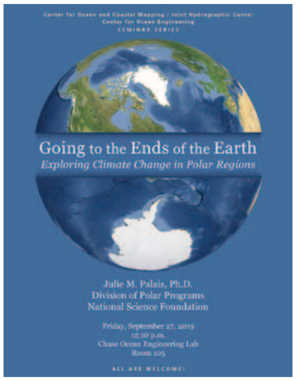
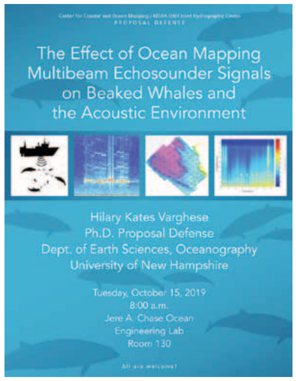
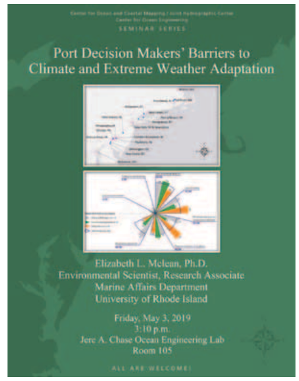
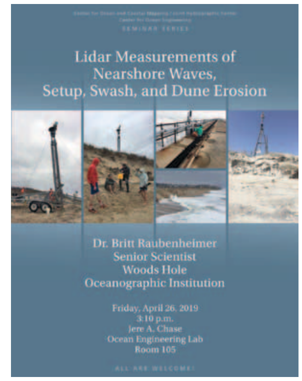
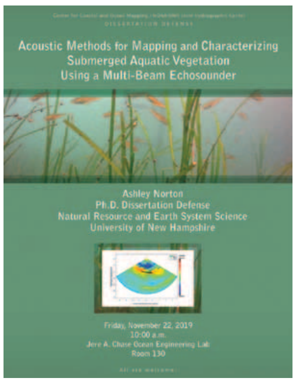
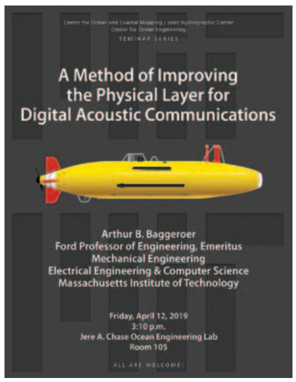


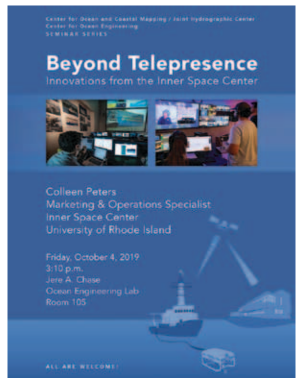


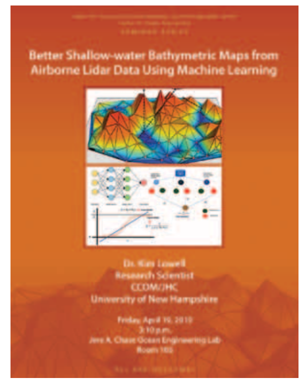


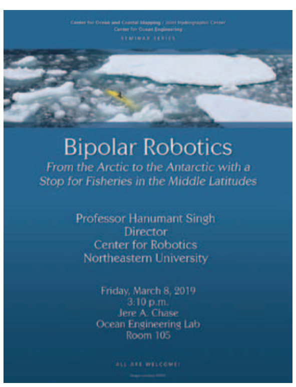


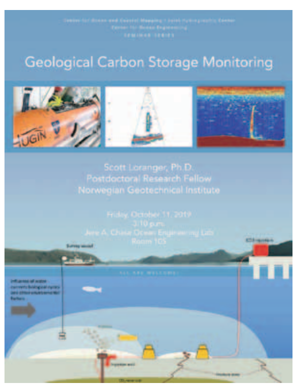


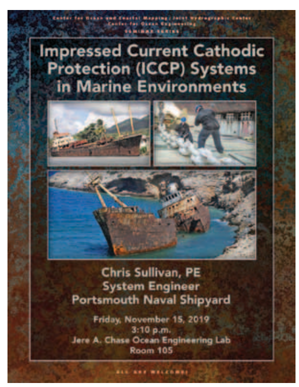


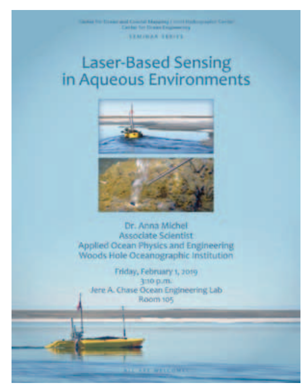


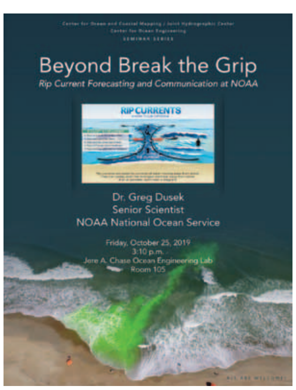


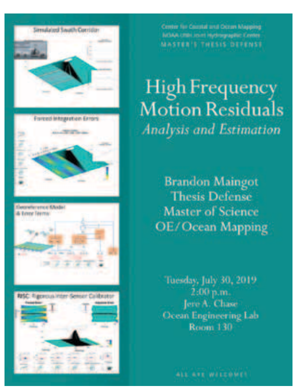


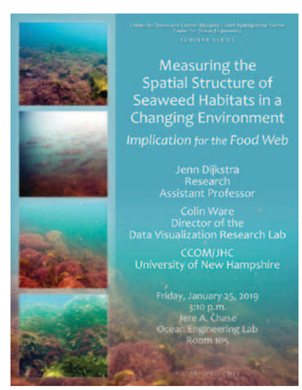












Flyers from the 2019 JHC/CCOM–UNH Dept. of Ocean Engineering Seminar Series.

The NOAA-UNH Joint Hydrographic Center (JHC/CCOM) was founded twenty 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 (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—and our establishment of an Integrated Ocean and Coastal Mapping (IOCM) Processing Center at UNH to support NOAA and others in delivering the required products of this new legislation. 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 has never before 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 hydrographic community.

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. There has been tremendous interest in this software throughout 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 message from a member of the Biogeography Team 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 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 was opportunistically processed for seabed characterization in support of essential fish habitat (EFH) and also in support of safety of navigation, including submission for charts and identification of a Danger to Navigation. Seafloor mapping data from the ME70 was used by fisheries scientists to identify optimal sites for fish-traps during a red snapper survey. Scientists 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 was also called upon to help with an international disaster—the mysterious loss of Air Malaysia Flight MH370. As part of our GEBCO/Nippon Foundation Bathymetric Training Program, researchers and students in the Center are compiling all available bathymetric data from the Indian Ocean. When MH370 was lost, the Government of Australia and several major media outlets came to the Center for the best available representations of the seafloor in the vicinity of the crash. The data we provided were used during the search and were displayed both on TV and in print media.

[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.

In the last few years, a new generation of multibeam sonars has been developed (in part as a result 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 Dept. 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 aide 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 Surface Vehicles (ASVs) as platforms for hydrographic and other mapping surveys and are looking closely at the capabilities and limitations of Airborne Laser Bathymetry (lidar) and Satellite-Derived Bathymetry (SDB) in shallow-water coastal mapping applications. To further address the critical very-shallow-water regimes we are also looking at the use of small personal watercraft and aerial imagery as tools to measure bathymetry in that difficult zone between zero and ten meters water depth. 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.

The value of our visualization, water-column mapping, and Chart of the Future 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 American 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."*

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, and the Chart of the Future 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 1 January 2016 until December 2020. This document summarizes the highlights of this NOAA-funded effort during calendar year 2019; detailed progress reports for each of the individual grants can be found at our website http://ccom.unh.edu/reports.

Highlights from Our 2019 Program

Our efforts in 2019 represent the fourth year of our work in response to a Federal Funding Opportunity (FFO) that defined four programmatic priorities:

Innovate Hydrography

Transform Charting and Change Navigation

Explore and Map the Continental Shelf

Develop and Advance Hydrographic and Nautical Charting Expertise

Under these, 14 specific research requirements were prescribed (our short name for each research requirement follows the description, highlighted in bold):

Innovate Hydrography

1. Improvement in the effectiveness, efficiency, and data quality of acoustic and lidar bathymetry systems, their associated vertical and horizontal positioning and orientation systems, and other sensor technology for hydrographic surveying and ocean and coastal mapping, including autonomous data acquisition systems and technology for unmanned vehicles, vessels of opportunity, and trusted partner organizations. **Data Collection**

2. 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, and data supporting the identification and mapping of fixed and transient features of the seafloor and in the water column. **Data Processing**

3. Adaption and improvement of hydrographic survey and ocean mapping technologies for improved coastal resilience and the location, characterization, and management of critical marine habitat and coastal and continental shelf marine resources. **Tools for Seafloor Characterization, Habitat, and Resources**

4. Development of improved tools and processes for assessment and efficient application to nautical charts and other hydrographic and ocean and coastal mapping products of data from both authoritative and non-traditional sources. **Third Party and Non-traditional Data**

Transform Charting and Change Navigation

1. Development of improved methods for managing hydrographic data and transforming hydrographic data and data in enterprise GIS databases to electronic navigational charts and other operational navigation products. New approaches for the application of GIS and spatial data technology to hydrographic, ocean, and coastal mapping, and nautical charting processes and products. **Chart Adequacy and Computer-Assisted Cartography**

2. Development of innovative approaches and concepts for electronic navigation charts and for other tools and techniques supporting marine navigation situational awareness, such as prototypes that are real-time and predictive, are comprehensive of all navigation information (e.g., charts, bathymetry, models, currents, wind, vessel traffic, etc.), and support the decision process (e.g., under-keel clearance management). **Comprehensive Charts and Decision Aids**

3. Improvement in the visualization, presentation, and display of hydrographic and ocean and coastal mapping data, including four-dimensional high-resolution visualization, real-time display of mapping data, and mapping and charting products for marine navigation as well as coastal and ocean resource management and coastal resilience. **Visualization**

Explore and Map the Continental Shelf

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

2. Development of new technologies and approaches for integrated ocean and coastal mapping, including technology for creating new products for non-traditional applications and uses of ocean and coastal mapping. **Ocean Exploration Technologies and IOCM**

3. Improvements in technology for integration of ocean mapping with other deep ocean and littoral zone technologies such as remotely operated vehicles and telepresence-enhanced exploration missions at sea. **Telepresence and ROVs**

Develop and Advance Hydrographic and Nautical Charting Expertise

1. 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. **Education**

2. Development, evaluation, and dissemination of improved models and visualizations for describing and delineating the propagation and levels of sound from acoustic devices including echo sounders, and for modeling the exposure of marine animals to propagated echo sounder energy. **Acoustic Propagation and Marine Mammals**

3. 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. **Publications and R2O**

4. Public education and outreach to convey the aims and enhance the application of hydrography, nautical charting, and ocean and coastal mapping to safe and efficient marine navigation and coastal resilience. **Outreach**

To address the four programmatic priorities and 14 research requirements, the Center divided the research requirements into themes and sub-themes and responded with 60 individual research tasks, each with an identified investigator or group of investigators as the lead. As our research progresses and evolves, the boundaries between the themes, programmatic priorities, research requirements, and tasks, sometimes become blurred. For example, from an initial focus on sonar sensors, we have expanded our efforts to include lidar and satellite imagery. Our data-processing tools are finding application in habitat characterization, mid-water mapping, and IOCM efforts. The data-fusion and visualization projects are also blending with our seafloor characterization, habitat, and Chart of the Future efforts as we begin to define new sets of "non-traditional" products. This blending is a natural (and desirable) evolution that slowly evolves the nature of the programs and the details of our efforts. This evolution is constantly being reviewed by Center management and the Program Manager, and tasks are adjusted as they are completed, merged, or are modified due to changes in personnel (e.g., the loss of Shachak Pe'eri from the Center faculty when he became a NOAA employee and moved to Silver Spring, or the loss of David Mosher due to his election to the Committee on the Limits of the Continental Shelf). This process is essential to allow innovation to flourish under the cooperative agreement.

As we complete the fourth year of effort, the updated tasks are presented in Figure ES-1. Note that when tasks are closed out, merged or completed, we have chosen not to renumber the other tasks so that there is continuity of reporting throughout the duration of the grant.

This executive summary offers only an overview of some of the Center's 2019 efforts through the presentation of a subset of ongoing tasks within the context of the four major programmatic priorities; the complete progress report with descriptions of all efforts and the Center's facilities can be found at http://ccom.unh.edu/reports.

PROGRAMMATIC PRIORITIES	RESEARCH REQUIREMENTS	THEMES	SUB-THEMES	PROJECTS	POC	REF. #	2019 TRL
INNOVATE HYDROGRAPHY	DATA COLLECTION	SENSOR CALIBRATION AND SONAR DESIGN	SONAR	Tank Calibrations	Lanzoni	1	3
				PMBS Evaluation	Schmidt	2	4
				Circular Array Bathymetric Sonar	Weber	3	3
				Synthetic Aperture Sonar	Weber and Lyons	4	2
			LIDAR	Lidar Simulator	Eren	5	3
			SOUND SPEED	~~Distributed Temperature Sensing~~	Eren	~~6~~	
		SENSOR INTEGRATION and REAL-TIME QA/QC		Deterministic Error Analysis/Integration Error	Hughes Clarke	7	4
				Data Performance Monitoring	Calder	8	3
				Auto Patch Test Tools	Calder	9	2
		INNOVATIVE PLATFORMS	AUVs	~~Nav Processing and Boot Camp~~	~~Schmidt~~	~~10~~	3
			ASVs	Add-on Sensors and Hydro Applications	Schmidt	11	2
		TRUSTED PARTNER DATA		Trusted Hardware	Calder	12	4
	DATA PROCESSING	ALGORITHMS and PROCESSING		CHRT and Expanded Processing Methods	Calder	13	5
				Multi-Detect Processing	Weber and Calder	14	5
				Data Quality and Survey Validation Tools	Calder	15	4
				Phase Measuring Bathymetric Sonar Processing	Schmidt	16	2
				Automatic Processing for Topo-Bathymetric LIDAR	Calder	17	4
		FIXED AND TRANSIENT	SEAFLOOR	Hydro-significant Object Detection	Calder and Masetti	18	4
		WATERCOLUM AND	WATER COLUMN	Watercolumn Target Detection	Weber	19	6
	SEAFLOOR CHARACTIZATION, HABITAT and RESOURCES	COASTAL AND CONTINENTAL SHELF RESOURCES		Mapping Gas and Leaky Pipelines in Watercolumn	Weber	20	7
				Tools for Identification of Marine Mineral Deposits	Ward	21	2
		SEAFLOOR CHARACTERIZATION	SONAR	GeoCoder/ARA	Masetti	22	4
				~~Singlebeam Characterization~~	~~Lippmann~~	~~23~~	1
				Multi-frequency Seafloor Backscatter	Hughes Clarke and Weber	24	4
			LIDAR and IMAGERY	Lidar Waveform Extraction	Parrish	25	2
			CRITICAL MARINE HABITAT	~~Object Based Image Analysis~~	~~J. Dijkstra~~	~~26~~	
				Video Mosaics and Segmentation Techniques	Rzhanov	27	5
				Margin-wide Habitat Analysis	Mayer and J.Dijkstra	28	1
			COASTAL RESILIENCE and CHANGE DETECTION	~~Shoreline Change~~	Eren	~~29~~	2
				Seabed Change	Hughes Clarke	30	2
				Change in Benthic Habitat and Restoration	J. Dijkstra	31	7
				Marine Coastal Decision Support Tools	Butkiewicz and Vis Lab	32	2
				Temporal Stability of the Seafloor	Lippmann	33	2
	THIRD PARTY and NON-TRADITIONAL DATA	THIRD PARTY DATA		Assessment of Quality of 3rd Party Data	Calder	34	3
		NON-TRADITIONAL DATA SOURCES	ALB	Assessment of ALB data	Eren	35	1
			SDB	~~Development of Techniques for Satellite Derived Bathymetry~~	Eren	~~36~~	
TRANSORM CHARTING AND NAVIGATION	CHART ADEQUACY and COMPUTER-ASSISTED CARTOGRAPHY			Managing Hydrographic Data and Automated Cartography	Calder and Kastrisios	37	3
				Chart Adequacy and Re-survey Priorities	Calder, Kastrisios, and Masetti	38	3
				Hydrographic Data Manipulation Interfaces	Calder, Hughes Clarke, Butkiewicz, and Ware	39	4
	COMPREHENSIVE CHARTS AND DECISION AIDS	INFORMATION SUPPORTING SITUATIONAL AWARENESS		Currents Waves and Weather	Ware, Sullivan, and Vis. Lab.	40	4
				Under-keel Clearance, Real-time and Predictive Decision Aids	Calder and Vis. Lab.	41	3
		CHARTS and DECISION AIDS		Ocean Flow Model Distribution and Accessibility	Sullivan	42	7
				Textual Nautical Information	Sullivan	43	7
				Augmented Reality Supporting Charting and Nav	Butkiewicz	44	4
	VISUALIZATION AND RESOURCE MANAGEMENT	GENERAL ENHANCEMENT OF VISUALIZATION		Tools for Visualizing Complex Ocean Data	Ware, Sullivan, and Vis. Lab.	45	4
				New interaction techniques	Butkiewicz	46	2
EXPLORE AND MAP THE EXTENDED CONTINENTAL SHELF	EXTENDED CONTINENTAL SHELF			Lead in Planning, Acquiring and Processing ECS	Gardner and Mayer	47	8
				Extended Continental Shelf Taskforce	Gardner and Mayer	48	8
				Best Approaches for Legacy Data: Delineation Techniques	Gardner and Mayer	49	5
	OCEAN EXPLORATION			ECS Data for Ecosystem Management	Mayer and J. Dijkstra	50	3
				Potential of MBES Data to Resolve Oceanographic Features	Weber, Mayer, and Hughes Clarke	51	2
	TELEPRESENCE AND ROVS			Immersive Live Views from ROV Feeds	Ware	52	2
HYDROGRAPHIC EXPERTISE	EDUCATION			Revisit Education Program	Hughes Clarke, Kastrisios and S. Dijkstra	53	N/A
	ACOUSTIC PROPAGATION AND MARINE MAMMALS			Modelling Radiation Patterns of MBES	Weber and Lurton	54	6
				Web-based Tools for MBES Propagation	Johnson and Arsenault	55	2
				Impact of Sonars on Marine Mammals	Miksis-Olds	56	3
	PUBLICATIONS AND R2O			Continue Publication and R2O Transitions	Mayer	57	N/A
	OUTREACH			Expand Outreach and STEM Activiites	Hicks-Johnson and Mitchell	58	N/A
DATA MANAGEMENT	EXTENDED DATA MANAGEMENT PRACTICE			Data Sharing, ISO19115 Metadata	Johnson	59	4
				Enhanced Web Services for Data Management	Johnson	60	6

Figure ES-1. Current breakdown of Programmatic Priorities and Research Requirements of FFO into individual projects or tasks.

Programmatic Priority 1: Innovate Hydrography

Data Collection

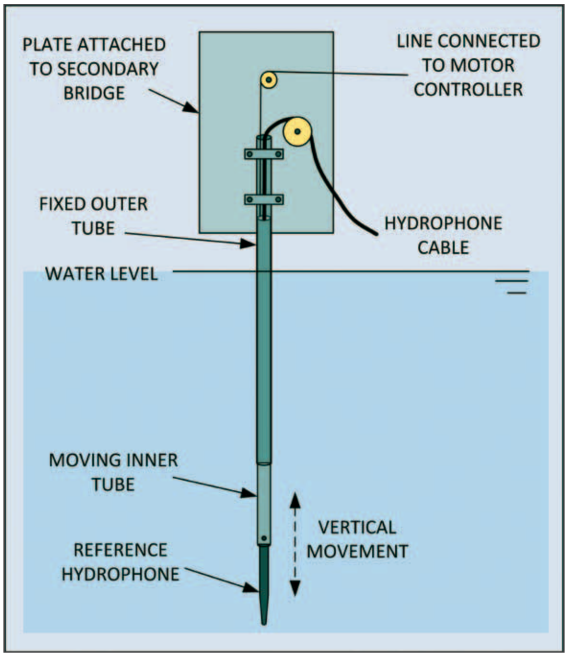


Figure ES-2. Vertical position control of reference hydrophone.

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, it is equipped with state-of-the-art test and calibration facilities. Upgrades to the facility include continuous monitoring of temperature and sound speed, a computer-controlled standard-target positioning system (z-direction; Figure ES-2), and the capability for performing automated 2D beam-pattern measurements. The facility is regularly used by Center researchers for now-routine measurements of beam pattern, driving-point impedance, transmitting voltage response (TVR), and receive sensitivity (RS).

Among the systems calibrated this year were Reson T50-P and Simrad ES70, ES120 and ES200 sonars. Standard tank calibration procedures and our newly developed (and much less time consuming) extended target method were compared and evaluated for the T50-P. After calibration, the T50-P was brought to our "NEWBEX" offshore backscatter reference line to compare the efficacy of in-tank calibrations to field calibrations (Figure ES-3).

Synthetic Aperture Sonar

Leveraging efforts supported by the Office of Naval Research, Tony Lyons is looking into the applicability of synthetic aperture sonar for automatic object identification, seafloor characterization, and understanding oceanographic conditions. This year, Lyons took part in technical evaluations of the Kraken KATFISH SAS system on board the NOAA Ship *Okeanos Explorer* (Figure ES-4). An advantage of SAS system is the very high resolution achievable over a

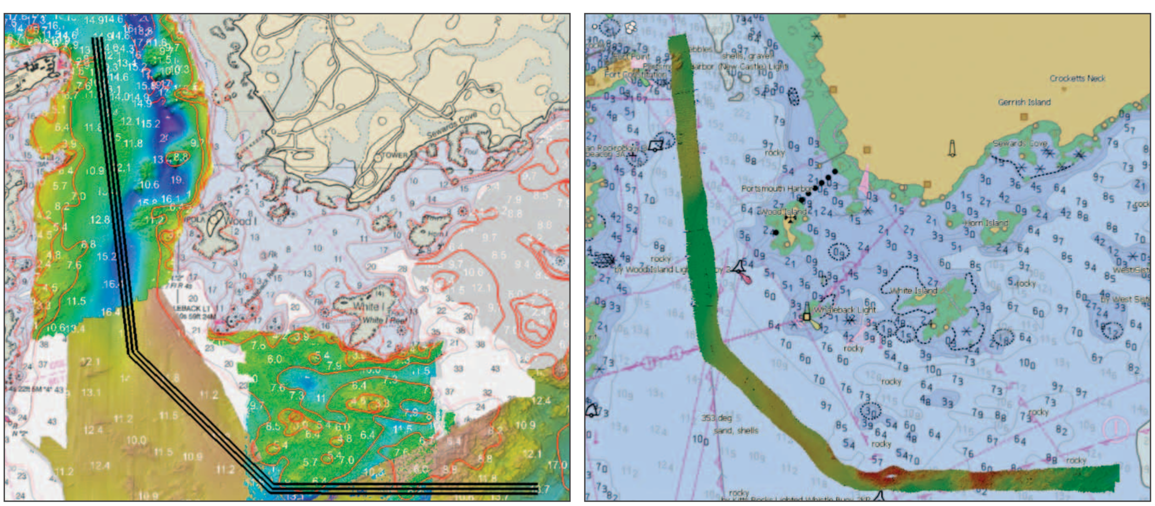


Figure ES-3. Left: Line plan for the 2019 NEWBEX project. Lines have been overlain on top of existing high-resolution bathymetry for the region. Right: Collected bathymetry at 300 kHz.

320 m swath (160 m on each side for the Kraken). The KATFISH can be run at faster speeds than an AUV-mounted SAS system owing to its long receive array (180 cm). Lines were regularly run at 6 knots during the technology demonstration and images were produced with tow speeds as fast as 8 knots.

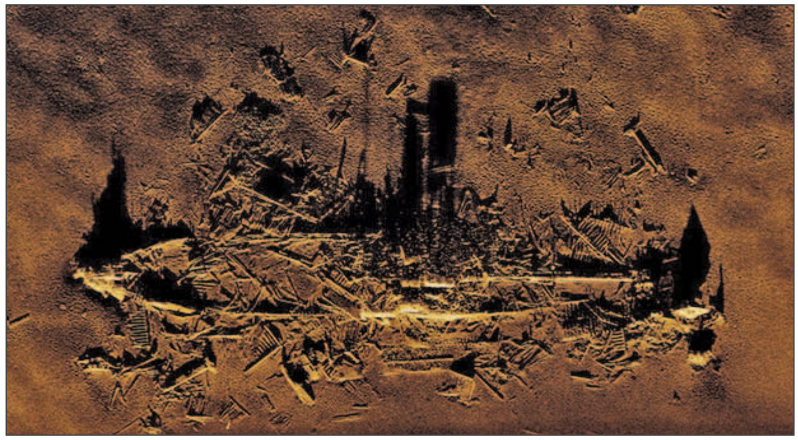


Figure ES-4. Synthetic aperture sonar image collected over a shipwreck site off Virginia using the KATFISH towed SAS system.

Use of Autonomous Surface Vessels for Hydrography

In our efforts to explore approaches to increasing operational survey efficiency and the quality of hydrographic survey data, the Center has embarked on a major research effort focused on evaluating the promise of autonomous surface vehicles (ASVs) for seafloor survey, and to add capability and practical functionality to these vehicles with respect to hydrographic applications. In support of this effort, the Center has acquired, through purchase, donation, or loan, several ASVs. The Bathymetric Explorer and Navigator (BEN) a C-Worker 4 model vehicle, was the result of collabor-ative design efforts between the Center and ASV Global LLC beginning in 2015. BEN was delivered in 2016. Teledyne Oceansciences donated a Z-boat ASV to the Center by in 2016, and Seafloor Systems donated an Echoboat in early 2018. A Hydronaulix EMILY boat, donated by NOAA, is in the process of a refit and, most recently—through the Center's industrial partnership program—the Center has acquired access to a new iXblue DriX ASV (Figure ES-5).

Figure ES-5. The Center's fleet of Autonomous Surface Vessels.

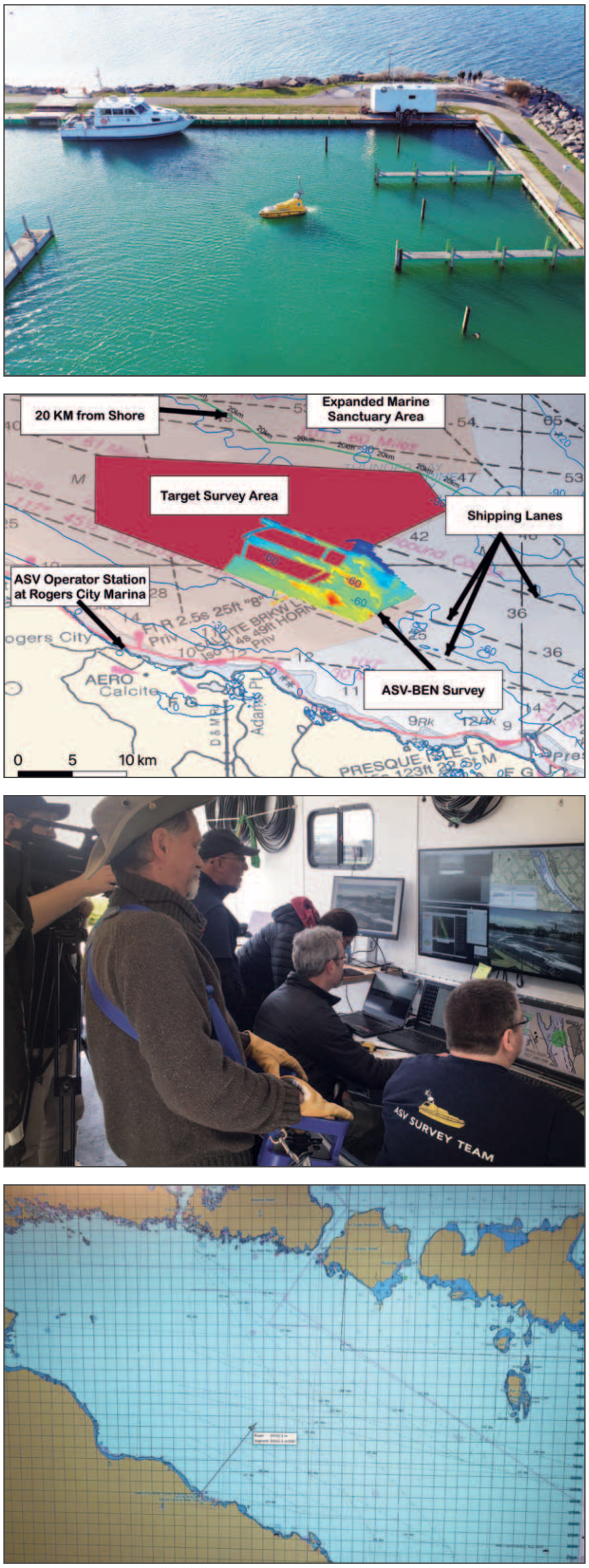


Figure ES-6. From Top: The ASV Shore Command Center, mapping data collected in Lake Huron, operating ASV-BEN in Lake Huron during the Thunder Bay expedition, and test of telemetry range of broadband radio (here at 20 km range).

These various vehicles provide platforms for in- and off-shore seafloor survey work, product test and evaluation for these industrial partners, and ready vehicles for new algorithm and sensor development at the Center. BEN is an off-shore-capable vessel, powered by a 30 h.p. diesel jet drive, is 4 m in length, has a 20-hour endurance at 5.5 knots, and a 1 kW electrical payload capacity. The Z-boat, Echoboat, and EMILY vehicles are coastal or in-shore, two-man portable, battery-powered systems with endurances of 3-6 hours at a nominal 3 knots (sensor electrical payload dependent). The DriX is an ocean-capable vessel, with a unique carbon fiber hull, giving it a maximum speed exceeding 13 knots and endurance exceeding five days at 8 knots.

ASV operations in 2019 focused on collaborative expeditions using BEN with the Ocean Exploration Trust and the National Marine Sanctuaries Program and testing of the DriX and sea trials on the NOAA Ship *Thomas Jefferson*. Expeditions were undertaken to Thunder Bay National Marine Sanctuary (May), American Samoan National Marine Sanctuary (July–August), and in the vicinity of Nikumaroro Island (August). Intensive testing of the DriX took place in September and October. Details of these events and the ongoing research and engineering involved are provided in the full progress report.

Operations at Thunder Bay National Marine Sanctuary featured the first use of a shore-based command center (Figure ES-6, top) equipped with an antenna mast system, AIS, long-range Marine Broadband radio, and a PZT camera with 30x zoom that could automatically track the vehicle. The radio was able to communicate to a maximum of 24 km with typical ranges on the order of 15 km (Figure ES-6, bottom). As part of the trials, numerous hardware and software upgrades were made to the ASV including path following algorithms, sonar upgrades, and the installation of a new lidar to support situational awareness. Research continues into the development of a real-time neural network for the automatic identification and classification of targets (based on cameras, lidar, radar, and other available sensors).

In support of the American Samoa National Marine Sanctuary, the ASV surveyed Pago Pago Harbor and Aunu'u Island, then proceeded to survey around Nikumaroro Island in support of the Ocean Exploration Trust's work (Figure ES-7). During these operations, the Center also developed approaches for using aerial drone imagery to fill the survey gap beyond the surf break.

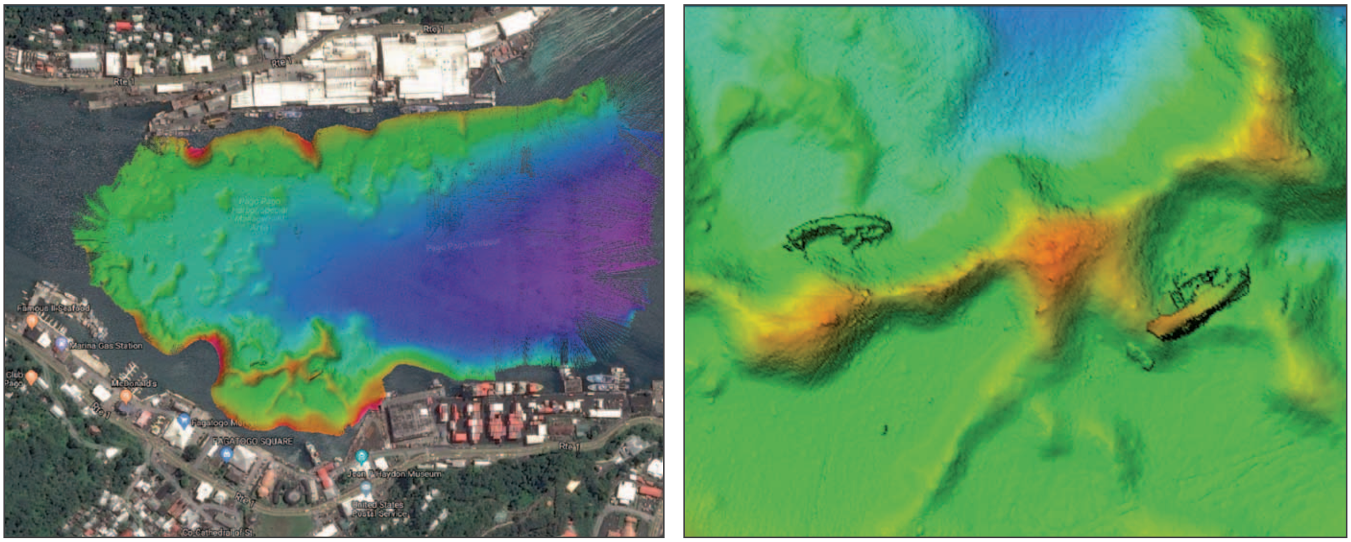


Figure ES-7. ASV Survey highlights from Pago Pago Harbor, American Samoa.

In the autumn and winter of 2019, Val Schmidt and the ASV team devoted their efforts to working with industrial partner iXBlue to ready their DriX ASV for NOAA field trials. The DriX is unique for an ASV since it can match or even exceed the survey speeds of a large ship with equivalent data quality and multi-day endurance.

In October, the Center facilitated DriX trials aboard the NOAA Ship *Thomas Jefferson*. Efforts focused on adaptating of the ship's davit to accept the DriX and the Delivery System (DDS), establishing an ASV operations center aboard the ship, and several days of testing and developing recovery methods for various failures at sea (Figure ES-8). Integration paths of DriX-collected data were established with the ship's acquisition systems, and operational survey models were evaluated. The Center provided draft handling and deployment procedures for the ship and an operational guideline for DriX operations for NOAA ships for future operations.

Deterministic Error Analysis and Data Performance Monitoring

Included in the broad category of "Data Collection" is our research into the causes—at acquisition—of many of the artifacts that degrade the data that we

Figure ES-8. Trials of the DriX ASV aboard the NOAA Ship *Thomas Jefferson*.

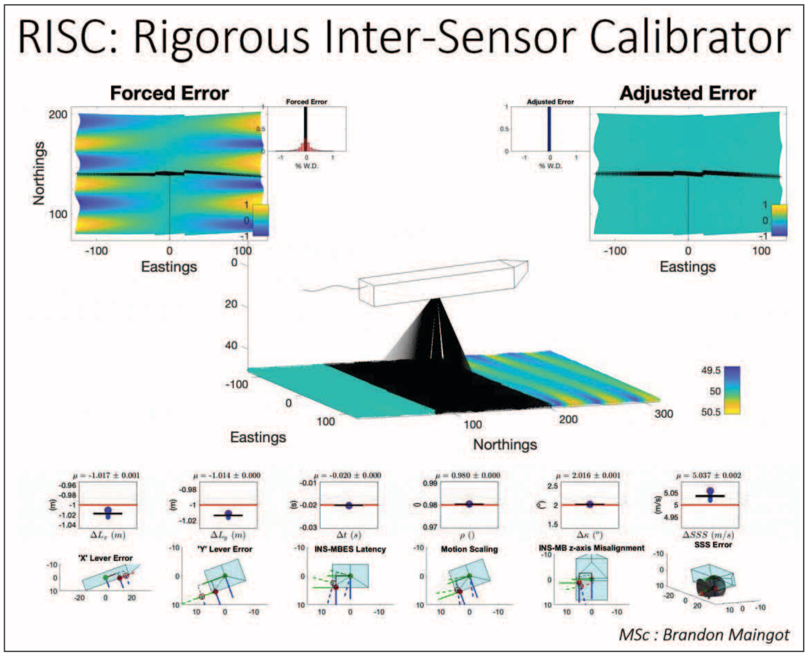


Figure ES-9. Input wobbled seafloor (top-left), the selection of the swath corridor (center), the resulting local and asymptotic estimation of the six integration errors (bottom), and finally the resulting de-wobbled surface (top right).

collect, and the development of a suite of tools to help recognize and hopefully mitigate these problems. With the ever-improving accuracy of the component sensors in an integrated multibeam system, the resultant residual errors have come to be dominated by the integration rather than the sensors themselves. Identifying the driving factors behind the residual errors (known as wobbles) requires an understanding of the way they become manifest. In this reporting period, modeling tools were developed to better undertake wobble analysis, focusing on the following areas:

Improved Wobble Extraction

To address these and other "wobble" issues, John Hughes Clarke and graduate student Brandon Maingot are developing improved methods for extracting the motion-derived depth residuals in a dataset. Maingot has developed a full simulator for a multi-sector sonar acquiring data under controlled dynamic conditions that collects bottom tracking information over undulating seafloor topography. The acquired data is then deliberately re-integrated using erroneous parameters to create a "wobbled" seafloor. This then provides the input, equivalent to a real system, in which the errors are perfectly known so that an approach can be developed and tested to see how close to the truth an inversion estimate will get.

The challenge of any field analysis tool is predicting how the data should look in the absence of the integration problem. To do that, an estimate of the seafloor "truth" must be established. Maingot's approach follows earlier methods in assuming that the underlying seafloor does not have short wavelength roughness with a length scale corresponding to the projected motion. This is done by fitting a quadratic surface to a short section of the swath corridor. Using that surface "truth," the mismatch of each of the soundings to that quadratic estimate is used as the input into a least squares minimization approach (Figure ES-9). This is termed the Rigorous Inter-Sensor Calibrator (RISC). Short period coherent undulations in bottom tracking remain one of the prime concerns in OCS hydrographic data quality control. With the widespread adoption of multi-sector systems by the

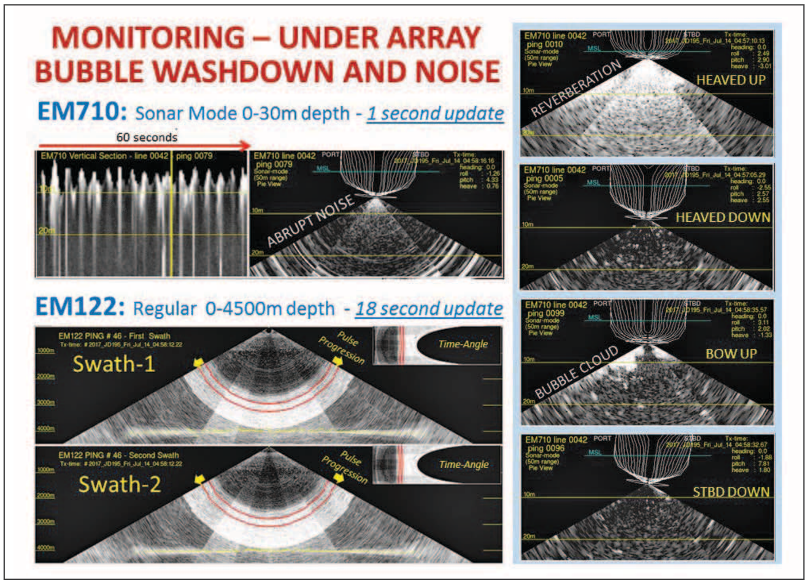


Figure ES-10. Simultaneous monitoring of near-array scattering and its effect on multi-sector deep water multibeam performance. Top-left shows a 60-second curtain of volume scattering within 30 m of the surface, together with instantaneous across track view of the scattering field. Bottom-left shows an 18-second ping cycle of an EM122, highlighting the one-second period during which the near array image above was collected. On the right are stills from an animation showing the second-by-second evolution of the scattering field immediately under the hull during a single EM122 ping cycle.

OCS fleet, there is a pressing need for operational tools that can automatically assess integration errors.

Bubble Washdown

Even with perfect integration of motion, if there are periodic external noise and sound blockage events due to bubbles close to the transducers generated by wave activity, this will overprint onto the data. Hughes Clarke has been investigating this issue by using a shallow water multibeam sonar set to "sonar mode" to image the volume scattering field within a few 10s to 100s of meters below the hull and allow the visualization of near surface bubble clouds (Figure ES-10). With the gradual revitalization of the NOAA fleet, the ability to monitor the second-by-second performance of the under-hull environment will aid in the design and placement of transducers as well as provide a monitoring tool to help in operational survey decisions.

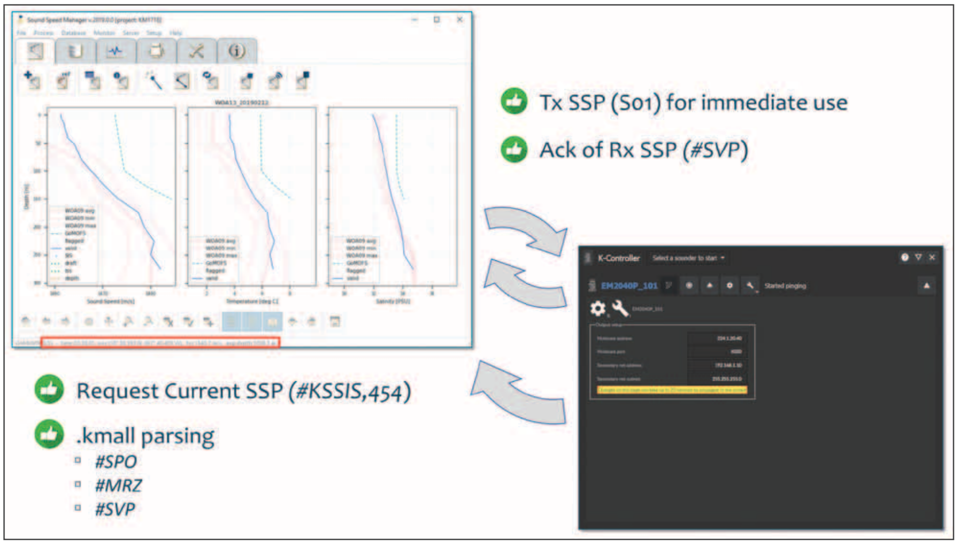


Figure ES-11. Summary of the current interactions for the experimental support of the Kongsberg K-Controller. SSM is able to transmit the enhanced sound speed profile data to K-Controller for immediate use, check its reception, retrieve the current profile, and parse the information-rich .kmall datagrams broadcast through UDP protocol packets.

Sound Speed Manager (HydrOffice)

We continue to focus on developing a suite of tools to monitor data in real-time, or to provide better support for data collection and quality monitoring. Our goal is to significantly reduce the time and effort needed for downstream processing, or to at least provide better assurance that no potentially problematic issues exist in the data before the survey vessel leaves the area. A major component of this effort is the building of tools in collaboration with NOAA's Hydrographic Systems Technology Branch (HSTB) so that they can be directly implemented by NOAA's field programs through the HydrOffice tool kit, and NOAA Pydro. Included in this tool kit is the Sound Speed Manager, a merger of a previous Center tool and NOAA's "Velocipy" tool. Sound Speed Manager manages sound speed profiles and greatly simplifies their processing and storage. This year, we saw numerous improvements to the user interface, systems supported, database capabilities and other functionalities, including interfacing with the new Kongsberg K-Controller and .kmall data format (Figure ES-11). Sound Speed Manager is now in wide use across NOAA, UNOLS, and other hydrographic agencies and scientific institutions (Figure ES-12). It has also been distributed through the U.S. University-National Oceanographic Laboratory System (UNOLS) fleet by Paul Johnson and Kevin Jerram, acting on behalf of the National Science Foundation (NSF)-funded Multibeam Advisory Committee (MAC).

SmartMap (HydrOffice)

Spatial and temporal variability in sound speed is often the single largest contributor to errors in hydrographic surveys. In order to help users better understand the sound speed variability in the area they will be, or are working in, Center researchers have been developing The Sea Mapper's Acoustic Ray Tracing Monitor and Planning (SmartMap) tool to provide a means to evaluate the impact of oceanographic temporal and spatial variability on hydrographic

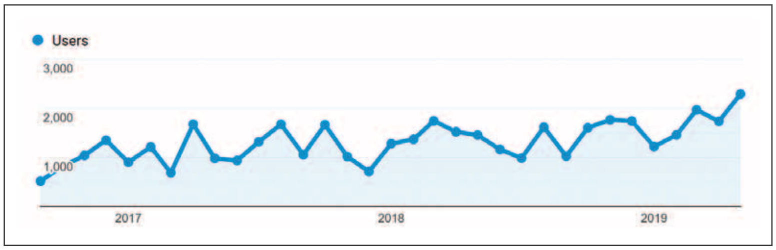


Figure ES-12. Accesses of HydrOffice online resources. The number of unique users has been steadily increasing since its initial launch in 2016.

surveys. The tool highlights areas where particularly high or low variability in the sound speed is expected, allowing the surveyor to assess how often to take profiles, where to take them, or even (in extreme circumstances) conclude that there is no rate at which SSPs can practicably be taken that will capture the variability of an area (with the implication that surveying at a different time is the more appropriate solution). Predictions used to be made based on the Global Real-time Operational Forecast System (RTOFS), and the World Ocean Atlas 2013 for climatology; this past year, experimental prediction products based on the Gulf of Maine Operational Forecast System (GoMOFS) data were added as alternatives (Figure ES-13). Such products provide better spatio-temporal coverage, and the evaluation of the potential application of high-resolution models to hydrographic problems has recently started. We also started the development of "ForeCast," an algorithm that uses the predicted spatio-temporal variability provided by an oceanographic forecast modeling system to inform the user when and where sound speed casts are required to maintain a certain level of uncertainty in the bathymetric data.

Trusted Community Bathymetry

Finally, under the rubric of Data Collection, we include efforts to evaluate the usefulness of crowd sourced, volunteered, or, more appropriately, trusted community bathymetry. Recognizing the reticence of many hydrographic agencies to ingest into the charting process data from uncontrolled sources, we are exploring a system where the data from a volunteer—or at least non-professional—observer is captured using a system that provides sufficient auxiliary information to ensure that the data does meet the requirements of a hydrographic office. That is, instead of trusting to the "wisdom of the crowd" for data quality, attempting to wring out valid data from uncontrolled observations, or trying to establish a

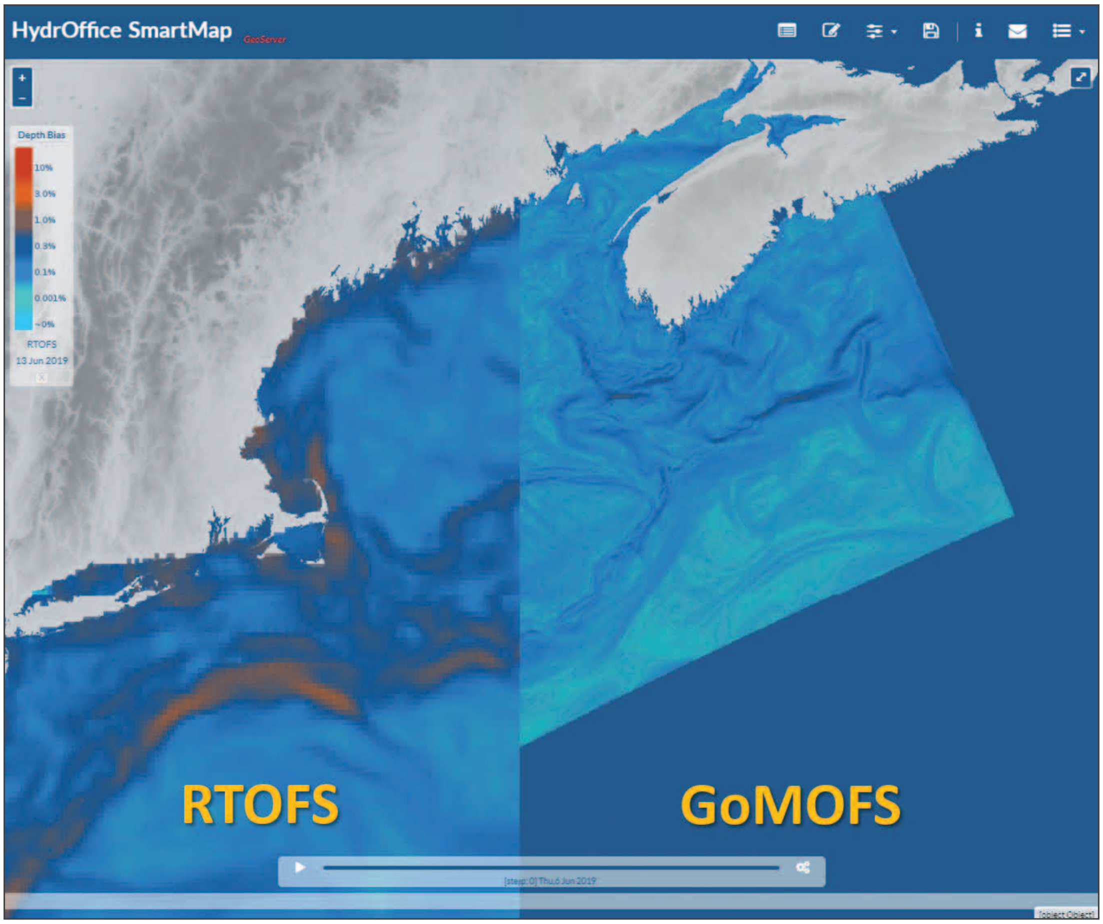


Figure ES-13. Comparison of the spatial resolution between the GoMOFS predictions (on the right) and the Global RTOFS one (on the left).

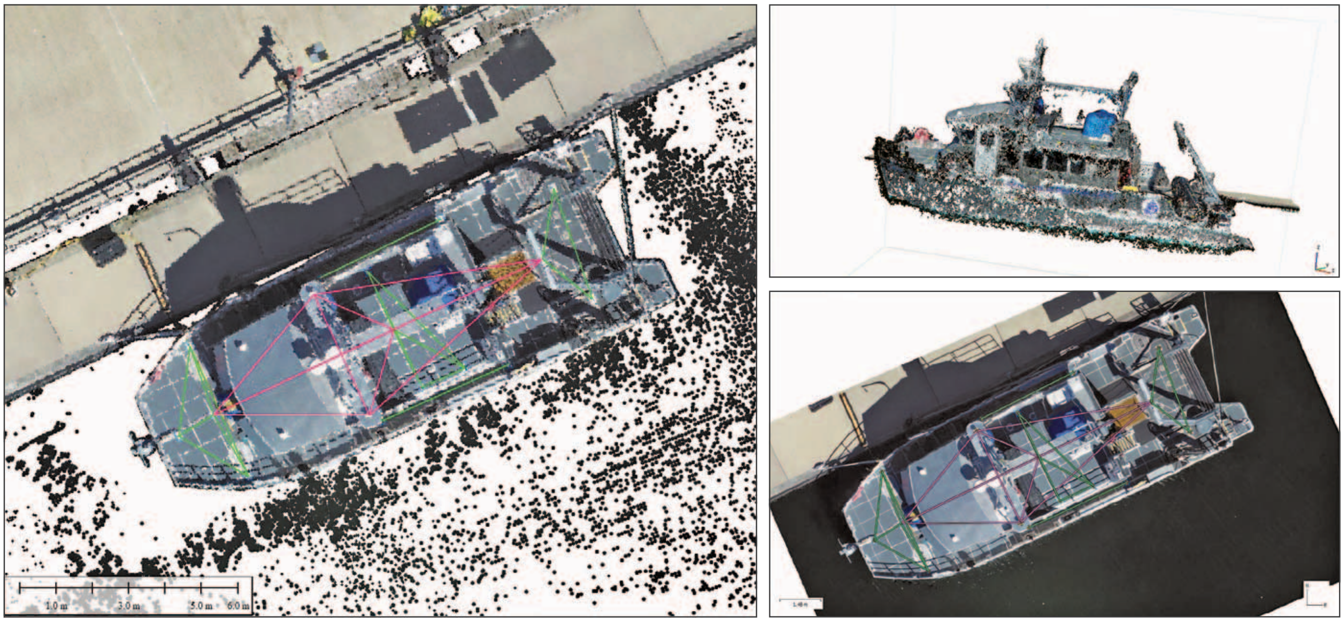


Figure ES-14. Left: Point-cloud for the R/V *Gulf Surveyor* constructed using aerial LiDAR from a DJI Matrice UAV at multiple altitudes. Note the lines joining survey monuments (purple) and Secchi targets (green), which are measured in the point cloud to assess the technique. Upper-right: Point cloud created using Structure from Motion (SfM) techniques from drone photogrammetry. Lower-right: Orthomosaic of the R/V *Gulf Surveyor* corresponding to the point-cloud on left. Note the lines joining survey monuments (purple) and Secchi targets (green), which are measured in the orthomosaic to assess the technique.

trusted observer qualification, we consider the question, "what if the observing system was the trusted component?"

Brian Calder, Semme Dijkstra, and Dan Tauriello have been collaborating with Kenneth Himschoot and Andrew Schofield (SeaID) on the development of such a Trusted Community Bathymetry (TCB) system, including hardware, firmware, software, and processing techniques. The aim is to develop a hardware system that can interface with the navigational echosounder of a volunteer ship as a source of depth information, while capturing sufficient GNSS information to allow it to establish depth to the ellipsoid and auto-calibrate for offsets, with sufficiently low uncertainty that the depths generated can be qualified for use in charting applications. Originally, the proposed plan for this task was to develop such a system independently; but collaborating with SeaID, who already produce data loggers of this type and strongly interact with the International Hydrographic Organization's Crowd-sourced Bathymetry Working Group, is a more efficient route to the same objective.

Testing of the development system during the last reporting period demonstrated that the prototype system can resolve soundings with respect to the ellipsoid with uncertainties on the order of 15-30 cm (95%), well within IHO S.44 Order 1 total vertical uncertainty (TVU) for the depth considered. In this reporting period, work focused on testing the prototype with a new, cheaper antenna made by Harxon Corporation, which is the intended "production" antenna for the system (being significantly cheaper), while research focused on extensions of the system for auxiliary sensors and observer ship horizontal offset calibration. Included in this effort is the development of demonstrator system and concept of operations for the use of low-cost recreational sidescan sonar for Trusted Community Bathymetry and efforts to find ways to quickly find the horizontal offsets between a vessel's GNSS antenna and the ship's echosounder (critical to providing accurate bathymetry from a Trusted Community Bathymetric system). To address this last topic, Calder and graduate student Casey O'Heran have been experimenting with the use of photogrammetry and lidar from aerial drones to produce these offsets (Figure ES-14), achieving centimetric errors against ground-truth offset estimates. Such techniques may provide a quick and inexpensive means to determine horizontal offsets on any vessel to the level of accuracy needed to produce qualified bathymetric data.

Data Processing: Bathymetry - Sonar

Next Generation Automated Processing Approaches – CHRT

In concert with our efforts to better understand the behavior and limitations of the sensors we use to collect hydrographic data, we are also developing a suite of processing tools aimed at improving the efficiency of producing the end-products we desire and, just important, at quantifying the uncertainty associated with the measurements we make. These efforts, led by Brian Calder, are now directed to further development of the next generation of the CUBE approach to bathymetric data processing—an algorithm called CHRT (CUBE with Hierarchical Resolution Techniques). The CHRT algorithm was developed to provide support for data-adaptive, variable resolution gridded output. This technique allows the estimation resolution to change within the area of interest, and the estimator to match the data density available. The technology also provides for large-scale estimation, simplification of the required user parameters, and a more robust testing environment, while still retaining the core estimation technology from the previously-verified CUBE algorithm. CHRT is being developed in conjunction with the Center's Industrial Partners who are pursing commercial implementations.

Although the core CHRT algorithm is complete in principle and has been licensed to Center Industrial Partners for implementation, modifications—some significant—continue to be made as the research progresses. In the current reporting period, we assisted a number of Industrial Partners with parameter configurations, and provided tools to assist with survey edge effects to NOAA for implementation in HydrOffice/Pydro.

One key to many NOAA hydrographic activities (and data specifications) is an accurate estimate of the density of data collected in a given area. An evolution in CHRT is the implementation of a "level of aggregation" algorithm to estimate data resolution. In the original implementation, data density was estimated by computing the area insonified by the sounder over a coarse resolution grid, the cells of which were then piecewise replaced with higher resolution grids over which the final depth estimation was computed. This approach is appropriate for swath-based data but is not well-suited to single-beam, mixed data sets, or most lidar data. To address this issue, Calder has now implemented a fine-to-coarse approach, estimating the level at which high-resolution cells need to be aggregated in order to ensure that the data density is enough to reliably estimate depth. This "level of aggregation" approach works with all data types, is computationally efficient, and has the added benefit of directly addressing the critical question of survey "completeness" (Figure ES-15).

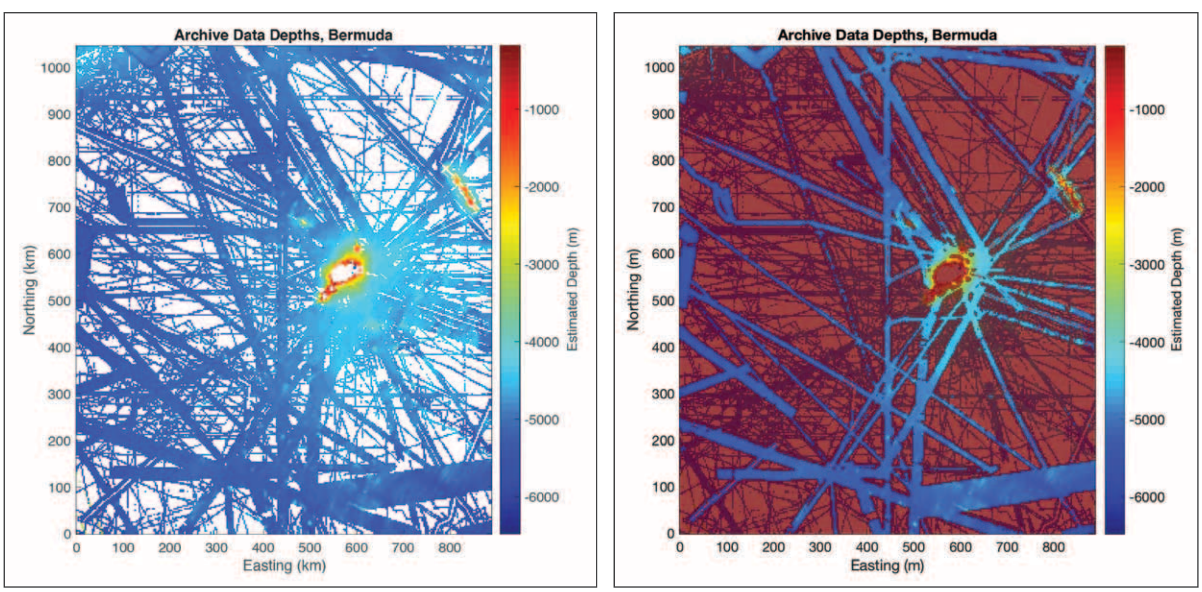


Figure ES-15. Estimated depth (a) and "complete" coverage (b). Depth is the primary low-resolution CHRT estimate from raw observations at 3,125 m cell resolution; areas with semi-transparent red tint are considered "incomplete" given the assumptions of five observations for estimation stability and 20% noise.

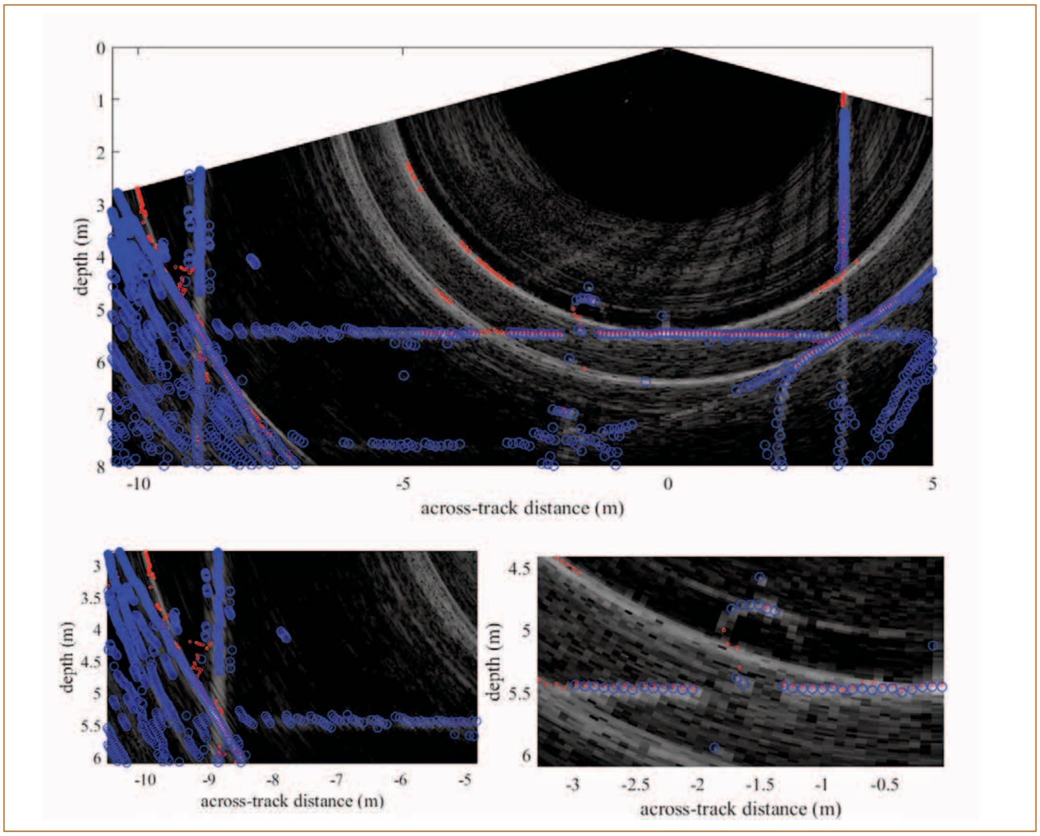


Figure ES-16. A single ping of Reson T50P data from the Chase Lab engineering tank. The backscatter intensity is shown in grayscale. Reson standard bottom detections are shown as red dots. Our multidetect algorithithm results are shown as blue circles. The pipe is apparent on the tank bottom at an across-track distance of -1.5 m, and in the insert on the lower right.

Multidetect Processing

The ability to make multiple detects in each beam of a multibeam sonar offers the promise of improved MBES performance for scenarios where hydrographic targets of interest are not constrained to a single surface (e.g., shipwrecks or submerged structures), where strong targets mask weak ones (e.g., specular reflections from pipelines), and for a variety of other applications where targets of interest are not on the seabed (e.g., fish schools or gas seeps). At least two manufacturers (Kongsberg and Reson) now offer multidetect capability that is integrated with their normal bottom detection routines, although it appears that the approaches are not yet optimized (Figure ES-16). To address this issue, Tom Weber developed an improved multidetect approach that includes a sequenced sidelobe rejection, amplitude threshold application, despeckling, and clustering. Initial results indicate an improvement over the existing approaches even in the difficult situation of a PVC pipe (Figure ES-16).

Streamlining the NOAA Hydrographic Processing Workflow – HydrOffice

We continue to work closely with the NOAA Office of Coast Survey (OCS) to identify challenges and needs that face those doing hydrographic processing—both in the field and in the office—using current NOAA tools. Since 2015, the Center has collaborated with NOAA HSTB personnel to develop a suite of analysis tools designed specifically to address quality control of problems discovered in the NOAA hydrographic workflow. Built within the HydrOffice tool-support framework (https://www.hydroffice.org), the resulting QC Tools were released in June 2016, and have since been enthusiastically adopted by NOAA field units and processing branches. Yearly updates and edits to NOAA's Hydrographic Survey Specifications and Deliverables are now made with an eye toward automation, anticipating implementation via QC Tools.

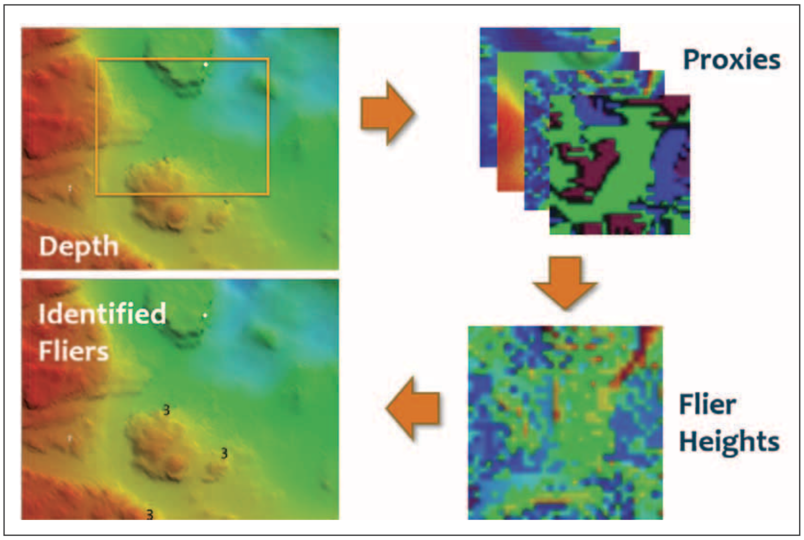


Figure ES-17. Structure of the Anomaly Detector algorithm. This calculates localized flier heights using grid-derived proxies, potentially resulting in fewer false positives and missed fliers.

In the current reporting period, Giuseppe Masetti, Tyanne Faulkes (NOAA PHB), and Brian Calder, in collaboration with Julia Wallace (NOAA AHB), and NOAA HSTB personnel, continued to develop the toolset, including improvements in "Flier Finder" to accommodate variable resolution grids and using grid-derived proxies (Figure ES-17). The application, which aggregates a number of tools within a single GUI, is available through NOAA Pydro (which delivers software to the NOAA hydrographic units) and through the HydrOffice website for non-NOAA users. A number of mapping agencies, NOAA contractors, and other professionals have adopted some of these tools as part of their processing workflow.

QC Tools is in active use in the field, making it a valuable source of feedback and suggestions. Before the beginning of the 2019 field season, a customer satisfaction survey was conducted among NOAA Office of Coast Survey users. Of 39 NOAA respondents, about 75% use QC Tools almost every single working day. This provided evidence that the application is judged to be valuable to the QC Tools community and offered important input for future improvements.

Chart Adequacy (CA) Tools in HydrOffice

In addition to QC tools, HydrOffice also addresses the issue of Chart Adequacy (CA) which includes the timely and accurate identification of change detection for areas depicted on nautical charts. Currently, this is typically approached through manual or semi-automated processes, based on best practices developed over the years that require a substantial level of effort and human experience (i.e., to visually compare the chart with the newly collected data or to analyze the result of intermediate products). In the current reporting period, Giuseppe Masetti and Christos Kastrisios, in collaboration with Tyanne Faulkes (NOAA PHB), have continued the development of CA Tools, an application begun in 2018 aiming to act as a container of tools to automate this chart-adequacy task by comparing current Electronic Navigational Charts (ENCs) with newly acquired survey data sets. These tools include the Chart Comparison tool that aims to automate the change identification process and reduce its subjectivity. During the current reporting period, a tool for sounding selection from bathymetric grids using a moving window and point-additive algorithm (Figure ES-18) has been added, improving the algorithm.

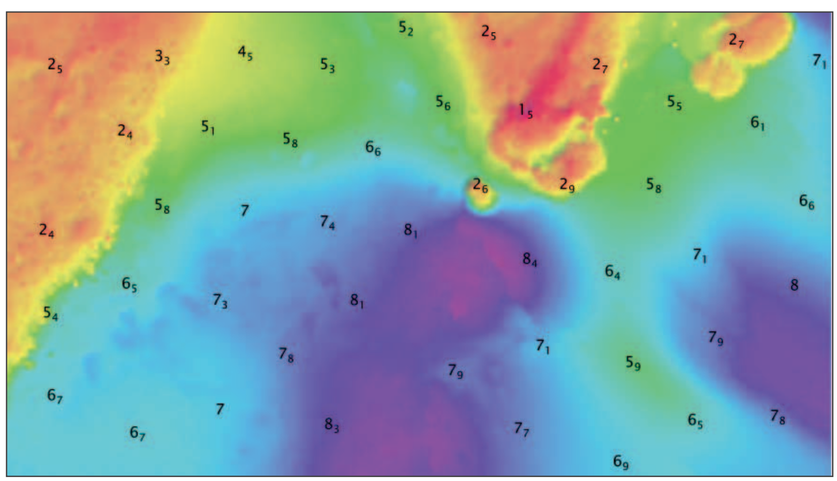


Figure ES-18. Example of output soundings created using the "point-additive" algorithm provided by the Sounding Selection tool recently introduce in CA Tools. The algorithm can take as parameter a user-defined search radius (in meters) or can automatically retrieve the compilation scale from an ENC (if provided).

Data Processing: Bathymetry - Lidar

We have long recognized that one of the greatest challenges facing the hydrographic community is the need to map very shallow coastal regions where multibeam echo sounding systems become less efficient. New-generation topographic-bathymetric (topobathy) lidar systems have the potential to radically change the way that lidar data is used for hydrographic mapping. Specifically, they generate relatively dense data (compared to traditional airborne bathymetric lidars) resulting in improved data and product resolution, better compatibility with modern data processing methods, and the potential to fill in detail in the shallow regions where acoustic systems are least efficient. Routine ingestion of topobathy data into the hydrographic charting pipeline is problematic. In addition to large volumes of data being generated, which makes processing time-consuming and many tools ineffective, the topobathy data lacks a robust total propagated uncertainty model that accounts for the aircraft trajectory and laser beam ranging uncertainties as well as the behavior of the laser beam in response to waves and the water column.

In conjunction with NOAA's Remote Sensing Division (RSD) and colleagues at Oregon State University (OSU), the Center is developing tools to understand and predict the sensor uncertainty of typical topobathy lidar systems, and adaptations of current-generation data processing tools to the lidar data processing problem.

A Total Propagated Uncertainty (TPU) model for lidars flown by RSD, among others, (cBLUE—Comprehensive Bathymetric Lidar Uncertainty Estimator) was developed and delivered to NOAA/NGS in 2018. Additional lidar training, including cBLUE training, was conducted by Chris Parrish at NOAA RSD in 2019. As the models and concepts of TPU are now starting to be supported within the bathymetric lidar community, standardization and validation of models, and best practices, is seen to be very important with respect to vendor and client adoption. OSU and the Center are, therefore, helping to support development and documentation of best practices through stakeholder meetings and interaction with the American Society for Photogrammetry and Remote Sensing (Figure ES-19).

The volume of data generated by modern topobathy lidar systems is immense. Any particular flight could entail collection of perhaps three billion observations (at the lowest capture rate available), which are recorded as several hundred gigabytes of digital records. Brian Calder and Kim Lowell have begun to adapt the CHRT processing approach to the topobathy lidar and have demonstrated that it was possible to extend the basic algorithm with a new "level

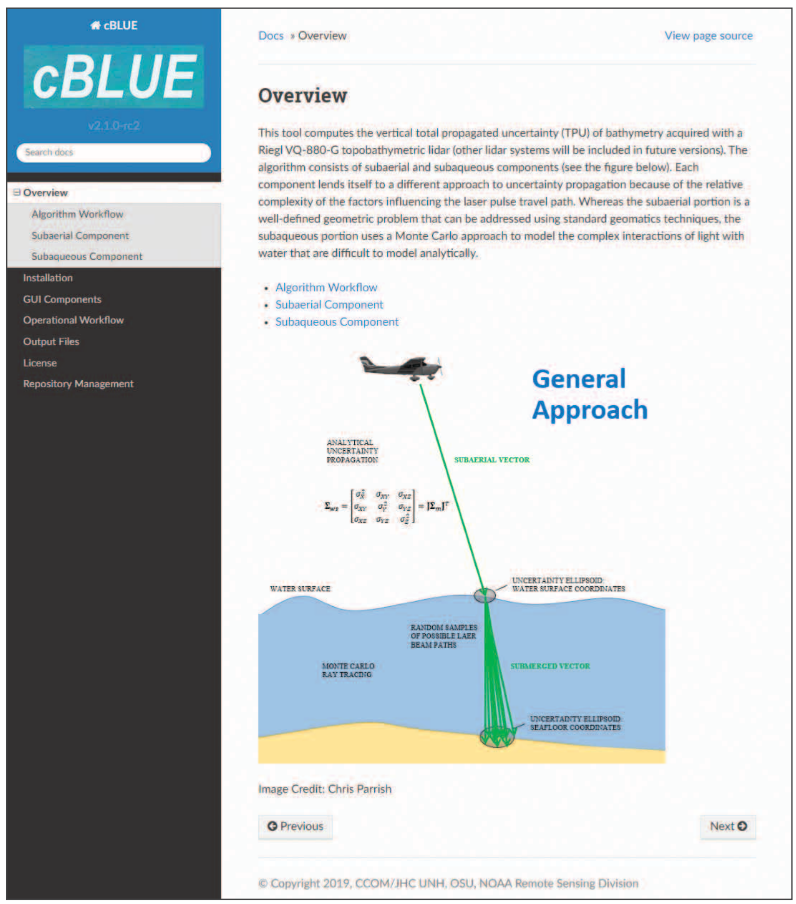


Figure ES-19. Documentation of the cBLUE tool in the GitHub repository. A great deal of effort has gone into carefully documenting both the tool itself and its operational use.

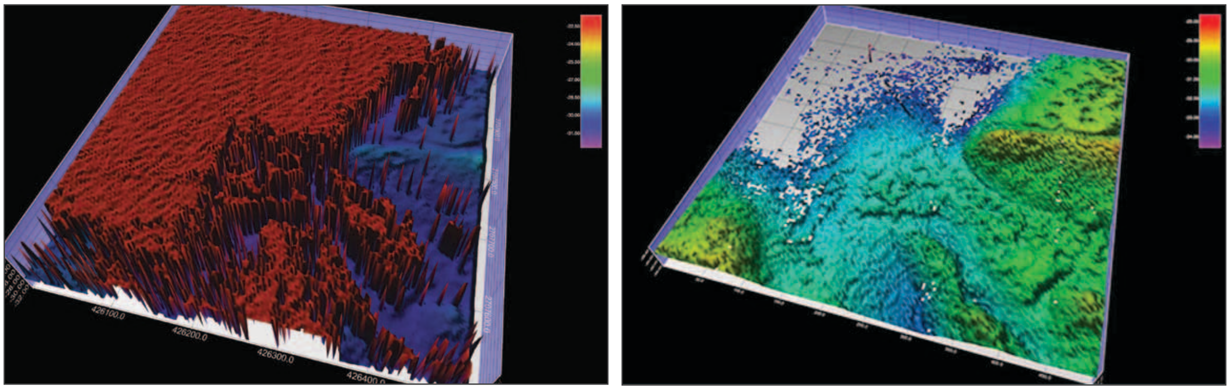


Figure ES-20. Example of depth reconstruction using acoustic-inspired selection rules (left), and the (revised) VQ-HMM approach (right), based on raw (unclassified) LAS files. The noise points in the "standard" selection method (left) are mis-selected reconstructions caused by the density of noise, or lack of actual data, at the estimation points; red points are reconstructions due to surface noise. The VQ-HMM method (right) pre-filters hypotheses and opts to not reconstruct if there are none which resemble the training set's idea of a seafloor hypothesis.

of aggregation" approach to resolution determination and machine learning based methods (specifically a vector-quantized Hidden Markov Model) to provide clean first-pass estimates of depth from raw data, Figure ES-20. In addition to being objective, this approach significantly reduces the user interaction time, and provides an acoustic-compatible workflow for lidar. The machine learning approach being developed seeks to assign to each return an *a priori* probability of being bathymetry—*p(Bathy)*—that is incorporated into the disambiguation rules of CHRT. This "certainty index" will ultimately be used within CHRT to influence the decision about which hypothesis for a grid point is considered most likely.

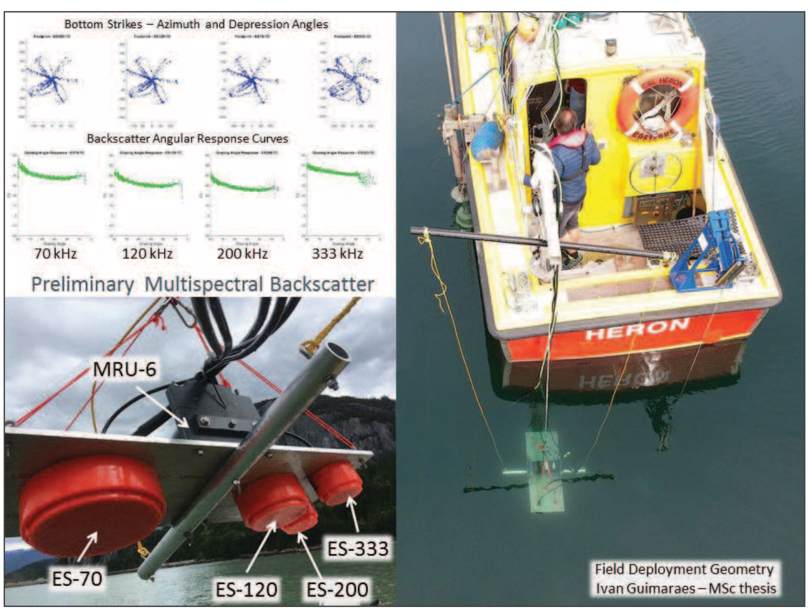


Figure ES-21. Apparatus to collect backscatter data at four frequencies over a range of angles.

Processing Backscatter Data

Seafloor Backscatter

Along with bathymetry data, our sonar systems also collect backscatter (amplitude) data. Previous progress reports have discussed many of our efforts to understand and quantify the sources of uncertainty in backscatter. We continue to develop techniques to appropriately correct backscatter for instrumental and environmental factors, including the development of approaches to correct for sector beam pattern artifacts, and to correct backscatter mosaics from dropouts due to bubble wash beneath the transducers. Once these corrections are applied, the backscatter data are much more suitable for quantitative analyses that may lead to the long-sought goal of remote characterization of the seafloor.

With an ever-growing array of multibeam sonars operating at different frequencies (and individual systems, displaying greater bandwidth), John Hughes Clarke has been exploring ways to exploit the frequency dependence of seafloor scattering. He has addressed this by looking at inter-frequency offsets and/or changes in the shape of the angular response curves for various sediment types. To that end, new tools and procedures are being developed to allow the user to extract the angular response for site-specific areas at a range of both frequencies and angles (Figure ES-21). This multi-spectral and multi-angular approach offers an exciting new dimension to seafloor characterization.

Results from these experiments, as well as field work being done at Sequim Bay, WA in collaboration with the University of Washington's Applied Physics Lab, will provide input into the evolution of a new generation of physics-based inversion models. These models, developed by University of Washington, are being incorporated into a new open-source approach to backscatter processing called OpenBST. OpenBST is a new effort begun at the lab in response to community concerns about inconsistencies in the results of commercial backscatter processing algorithms. This effort, done in collaboration with the vendors of the software packages, seeks to develop community-vetted open-source backscatter processing algorithms that can then be used by vendors to benchmark their approaches (Figure ES-22).

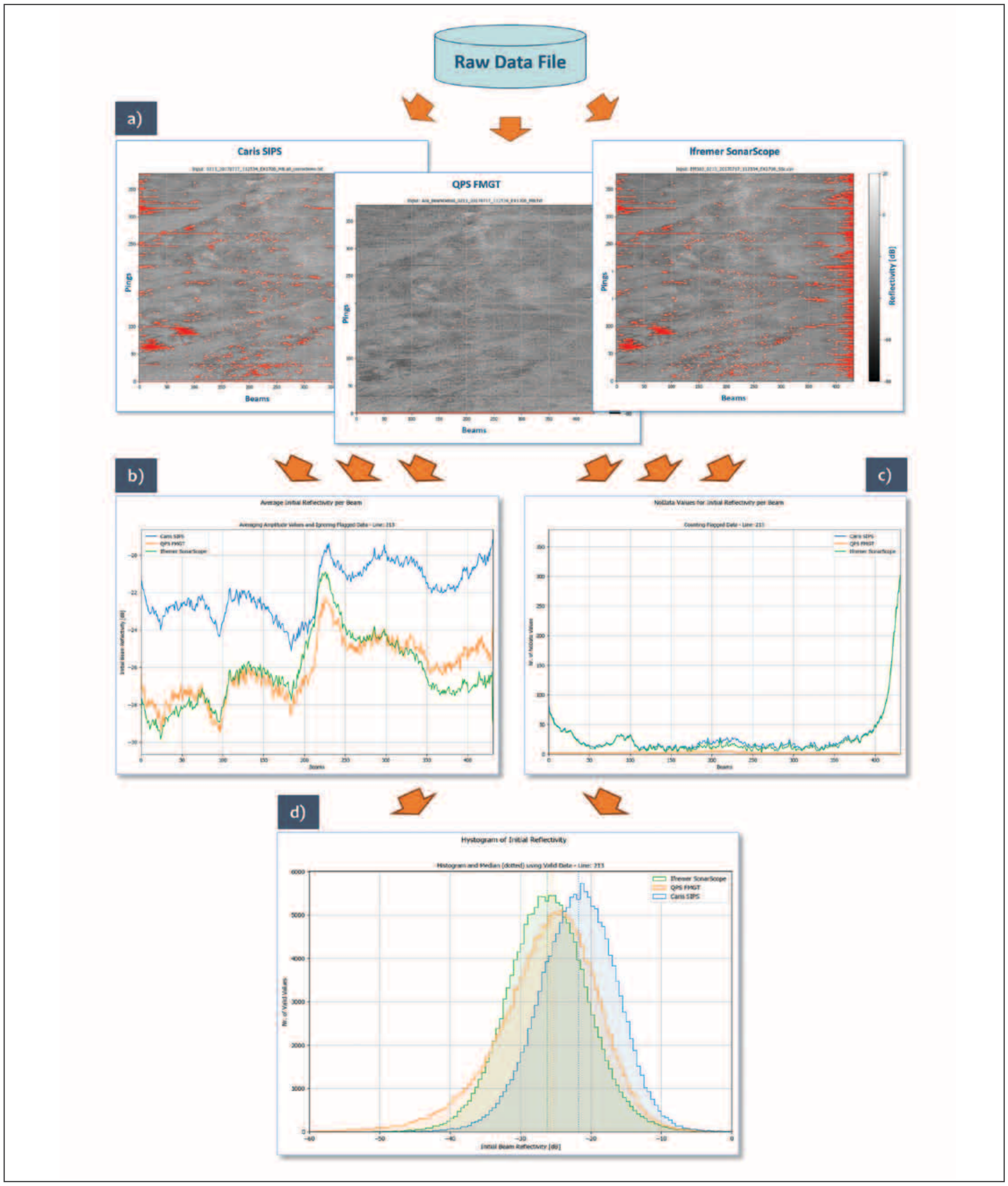


Figure ES-22. Pane a) shows the initial reflectivity values calculated by three software packages (and retrieved from the same raw data file) in a ping-beam geometry. Pane b) plots, for each package, the average value per beam across the whole survey line. Similarly, Pane c) displays the number of no data values per beam. Finally, Pane d) compares the resulting histograms for the three software packages highlighting how the resulting statistical characteristics starts to diverge since the very first processing step.

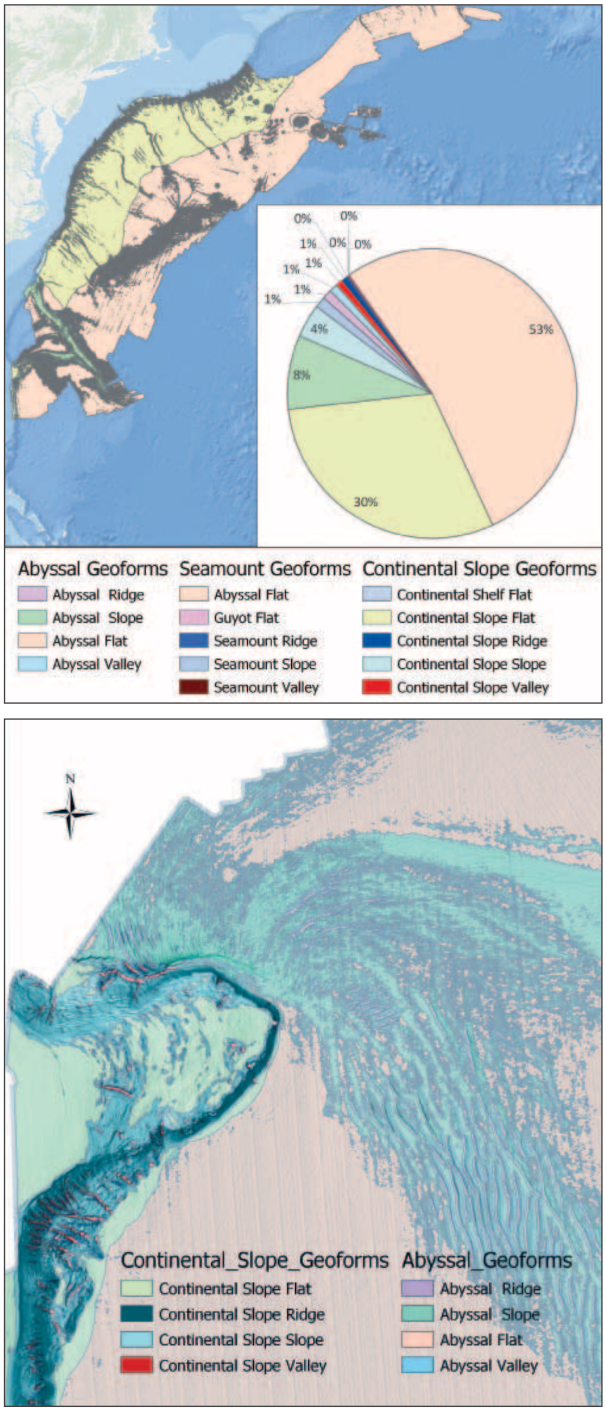


Figure ES-23. Top: CMECS geoform classifications for the entire Atlantic Margin region. Bottom: CMECS geoform classes for a portion of the study area highlighting Blake Escarpment, Blake Spur, and Blake Ridge. The figure provides mapped landforms in both the continental shelf and abyssal portions of the area. The massive bedform features in the right corner of the figure are striking, with crest-to-crest distances between 2000-3000 meters. The significant features of the terrain are well represented in the geoform unit polygons derived from the landforms generated via the automatic delineation algorithm in BRESS.

Seafloor Characterization and Habitat Mapping

Our efforts to produce more quantitative and consistent backscatter data stem from the great potential of backscatter to be used for the remote characterization of the seafloor and the determination of benthic habitat. To address this issue, Giuseppe Masetti and others have developed an approach to seafloor characterization that first evaluates the context of the area, attempting to take full advantage of both bathymetric and backscatter data to create a bathymetry- and reflectivity-based estimator for seafloor segmentation (BRESS). The initial phase of the algorithm performs a segmentation of the bathymetry surface through the identification of contiguous regions of similar morphology, for example valleys or edges. The backscatter for these regions is then analyzed to derive final seafloor segments by merging or splitting the regions based on their statistical similarity. The output of BRESS is a collection of homogeneous, non-overlapping seafloor segments, each of which has a set of physically-meaningful attributes that can be used for task-specific analysis (e.g., habitat mapping, backscatter model inversion, or change detection).

This past year, BRESS has been applied to a bathymetric synthesis generated from all available high-quality data from the U.S. Atlantic Margin canyons collected as part of the U.S. Extended Continental Shelf Project. This effort used the automatic segmentation capabilities of BRESS to identify landform features from the bathymetry of the region, then used ArcGIS Pro to translate these results into complete coverage geomorphology maps of the region utilizing the Coastal and Marine Ecological Classification Standard (CMECS) to produce broad scale geomorphology maps as a key component of marine habitat characterization in support of ecosystem-based management (Figure ES-23). These data are being ground-truthed through the quantitative evaluation of ROV video data collected by the NOAA vessel of exploration, Okeanos Explorer (Figure ES-24).

The high-resolution imagery that we use to ground-truth our acoustic data provides a precise view of seafloor environments and allows insight into important biological and physical metrics that gives indication regarding the health and well-being of seafloor habitats. With current technology, it is possible to collect and store large amounts of digital imagery data. The annotation of this data however, is an expensive and time consuming task which is almost

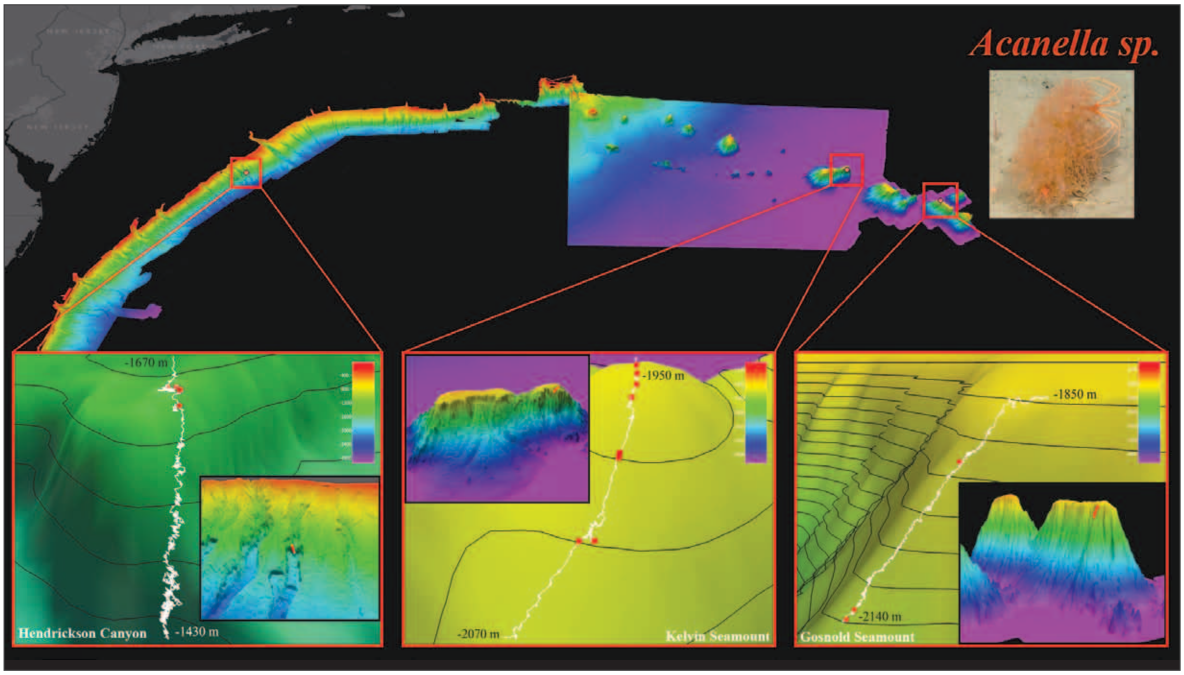


Figure ES-24. ROV tracks showing the distribution of bamboo corals collected in Hendrickson Canyon, Kelvin and Gosnold Seamounts.

always preformed manually by a trained expert. In an attempt to reduce the amount of time required to annotate data, we are exploring methods that use computer vision and deep learning algorithms to assist in the autonomous annotation of imagery data. We have tested and refined our methods on still images of underwater video footage of coral reef patches collected from the Florida Keys, and have generated highly representative samples of each taxonomic class category, limiting the overall annotations needed to be done manually before training an image classifier capable of providing autonomous annotations on the remainder of the dataset. Once the deep semantic segmentation model was trained, it was applied to the still images used for 3D reconstruction of coral reef patches, providing a 3D assessment of the spatial distribution of different taxa within a patch reef (Figure ES-25).

Building on our expertise in scientific data visualization we have been exploring the use of virtual reality-based 3D reconstructions of seafloor imagery, including coral habitats, which includes advanced interaction techniques, and interactive analysis tools.

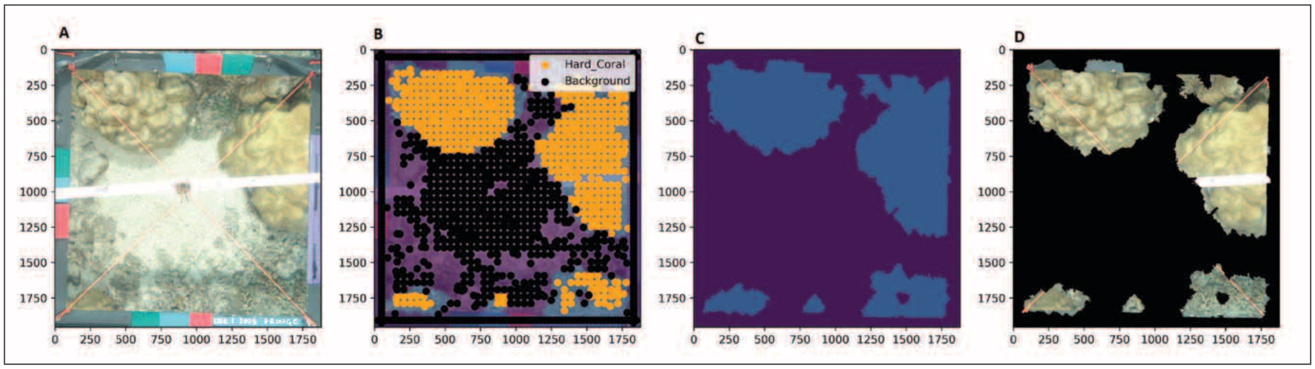


Figure ES-25. Process of generating masks for each class category and its use as training data for the deep semantic segmentation algorithm: (A) sample image from the MLC (2000x2000 pixels) dataset; (B) image with more labelled points by trained artificial intelligence that act as autonomous annotator; (C) groupings of pixels belonging to the same class category created by a SLIC algorithm; (D) masked class images.

The system developed provides an immersive 3D environment through a Vive VR headset, which contains a 3D reconstruction of seafloor features built using "structure from motion" techniques based on diver video and still imagery. The VR environment is free-area tracked, meaning that the user can simply physically walk around the feature (e.g., a coral head) to shift viewpoint, and contains two hand-held controllers that allow the user to shift zoom, manipulate the environment, and summon menus and interaction tools to, for example, measure interstitial dimensions within the feature (Figure ES-26). Additionally, due to careful selection of a cross-platform toolkit, the same visualization could be implemented for other environments, including web, and mobile systems, making it a potential outreach modality. We are currently working on combining this work with that on seafloor and target characterization so that the 3D environment can be used to provide ground-truth to train the classification algorithms, and the results of the classification can be displayed in the 3D environment for further analysis and insight.

Processing Backscatter Data

Water Column

The sonars we use to map the seafloor can also collect acoustic data from the water column. Building on work done in response to the Deep Water Horizon spill, the Center has pioneered techniques to capture, process, and visualize water column acoustic data, particularly with respect to the location and quantification of gas and oil seeps. As these tools evolve, we seek to push the limits of quantitative midwater mapping, developing tools to measure flux of gas and identify the nature (oil, water, gas, etc.) of mid-water targets. This past year has presented a number of opportunities to collect water column data and further our development of processing and visualization approaches. One of the foci for water column target detection was a research cruise in New Zealand on the R/V Tangeroa. The cruise involved the use of a large suite of acoustic echo sounding equipment for quantitatively assessing both the seafloor and the water column, including several broadband

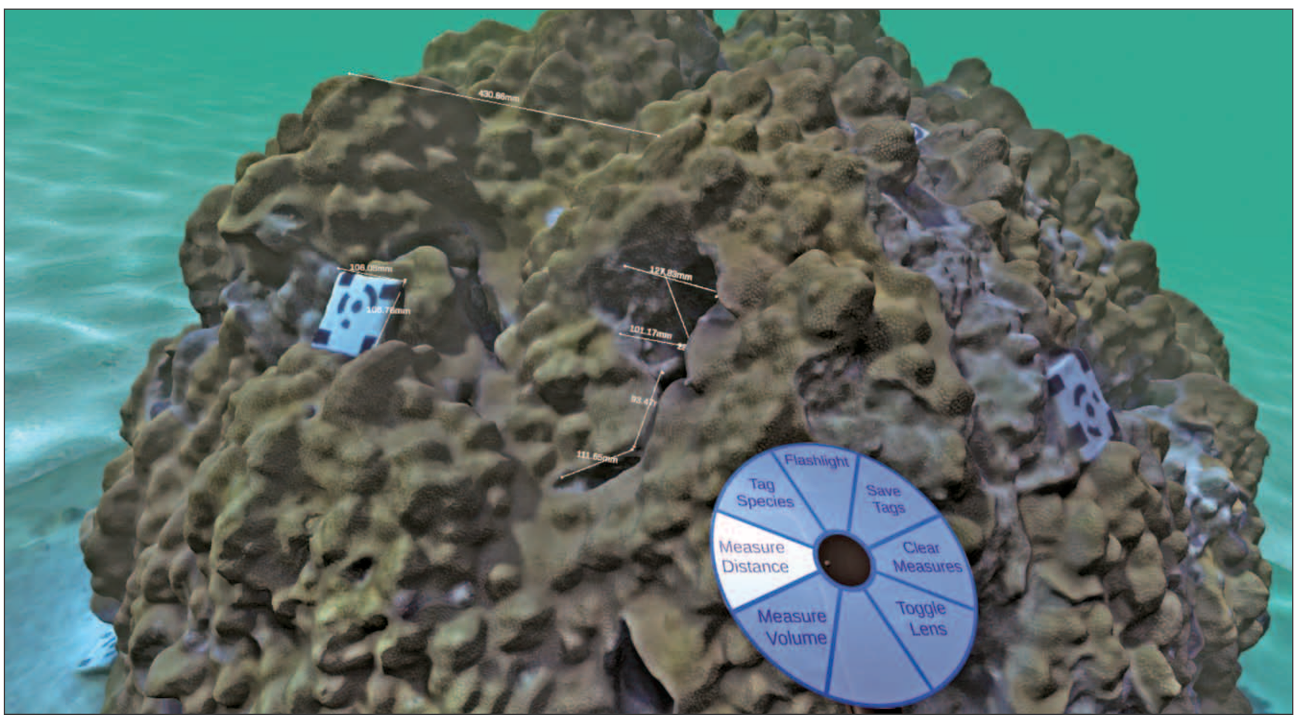


Figure ES-26. Screenshot from the updated CoralVis VR software, showing a high-fidelity coral model (generated by Jordan Pierce and Jennifer Dijkstra) and 3D measurements (white lines/text) made using tools accessed via the radial-menu (blue disc) attached to the handheld controller.

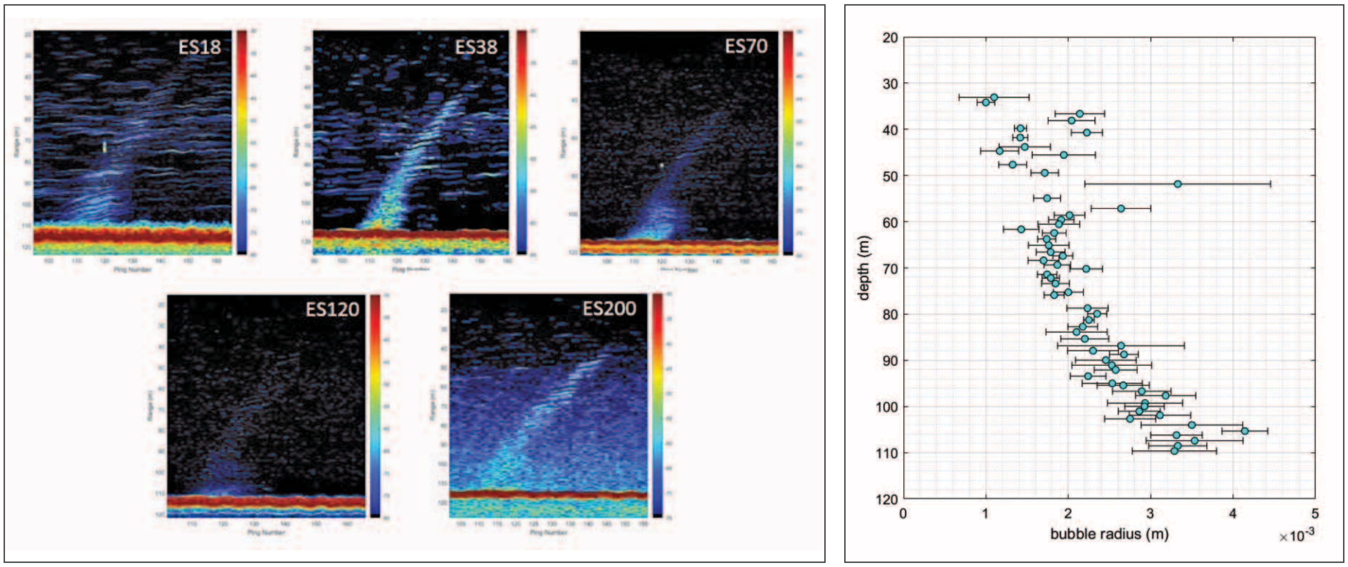


Figure ES-27. Left: Echograms showing the bubble stream as viewed at different frequencies. Right: Derived bubble radii from a single ES200 pass.

split-beam echo sounders operating at frequencies ranging from 15-25 kHz, a 30 kHz EM302, and a 200 kHz EM2040. Ground truth data were collected using a camera tow-sled and water sampling. The Center contributed a synthetic gas bubble generator, developed by former student Kevin Rychert, which was used to test detection limits and to perform cross-calibrations between different systems. Graduate student Liz Weidner analyzed bubble generator data collected as part of a dedicated experiment aimed at calibrating multibeam water-column backscatter measurements with the pan & tilt system (PTS) split-beam echosounder system (Figure ES-27 Left). Individual bubbles were sampled at the point of maximum acoustic response and the bubble range, electrical phase angle, peak acoustic intensity, and vessel motion were extracted. Bubble radii for each detection were then computed through comparison to acoustic scattering models, providing bubble size as a function of water depth (Figure ES-27 Right).

The techniques we have been developing to quantitatively monitor oil and gas flow acoustically, has been applied to the question of leak rates at wrecked and leaking oil wells of the Taylor Energy site in the Gulf of Mexico. As part of his thesis work under the supervision of Tom Weber, Scott Loranger was able to estimate the total flux of oil associated with the lower portion of the plume to be in the range of 150-350 barrels per day, assuming the entire lower portion of the plume is oil. These estimates were in reasonable agreement with later ground-truth measurements (Figure ES-28).

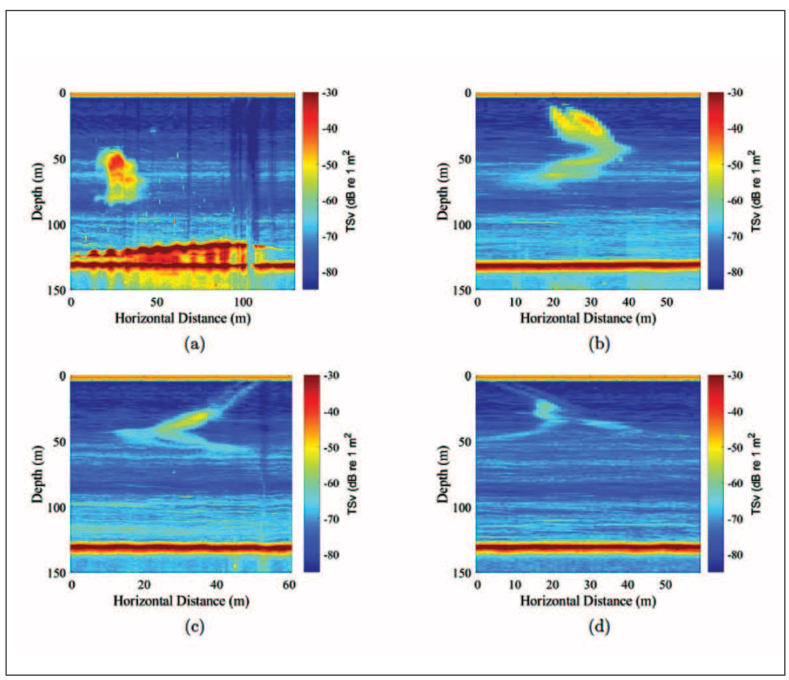


Figure ES-28. From Scott Loranger's thesis: Echograms for cross sectional passes downstream of the Taylor seep origin. Echogram (a) is the closest to the origin (58 m), followed by (b) (115 m), then (c) (187 m), and (d) (235 m).

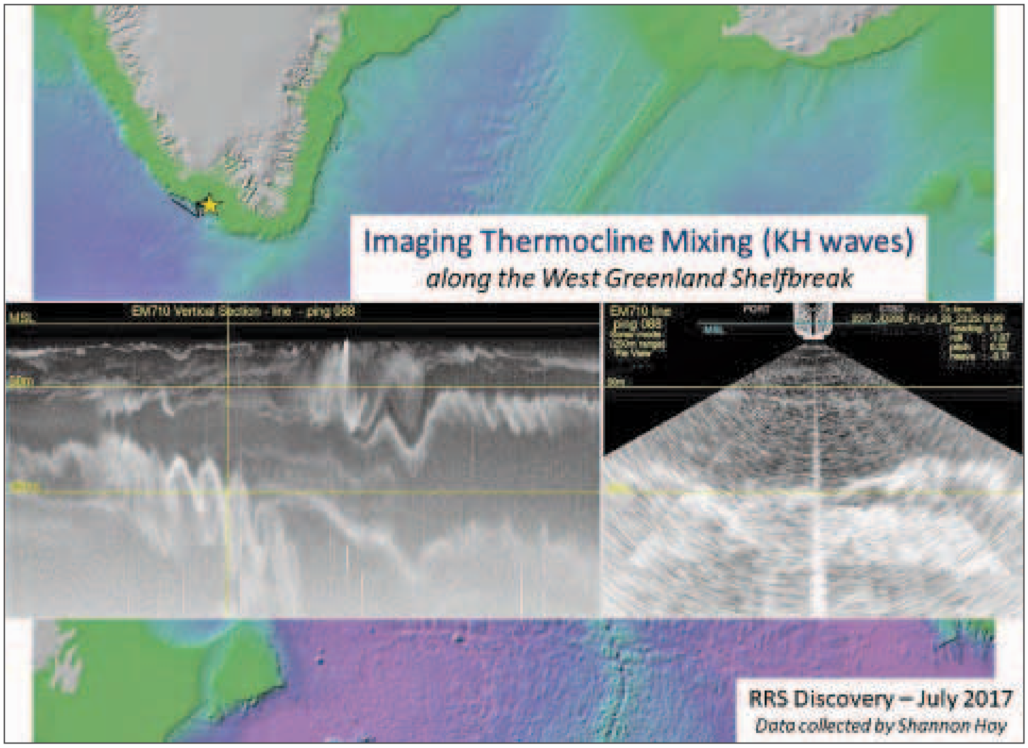


Figure ES-29. Sections of Kelvin-Helmholtz waves developed in the thermocline, acquired using an EM710 in sonar mode (250m range) while operating an EM122 in slope depth water off the West Greenland Continental Shelf (RRV Discovery).

One of most exciting aspects of our water-column work has been the demonstration that both multibeam and broadband single beam sonar can show oceanographic features with remarkable detail. This was previously demonstrated in the high Arctic where our sonars were able to discern very small impedance contrasts that represented small thermohaline steps and the thermocline. This past year, John Hughes Clarke and Shannon Hoy demonstrated the feasibility of mapping Kelvin-Helmholtz waves using an EM710 in sonar mode with a 250m range in the Labrador Sea (Figure ES-29). Additionally, Liz Weidner has been able to track the oxygen minimum zone in the Baltic Sea with a broadband echosounder (Figure ES-30).

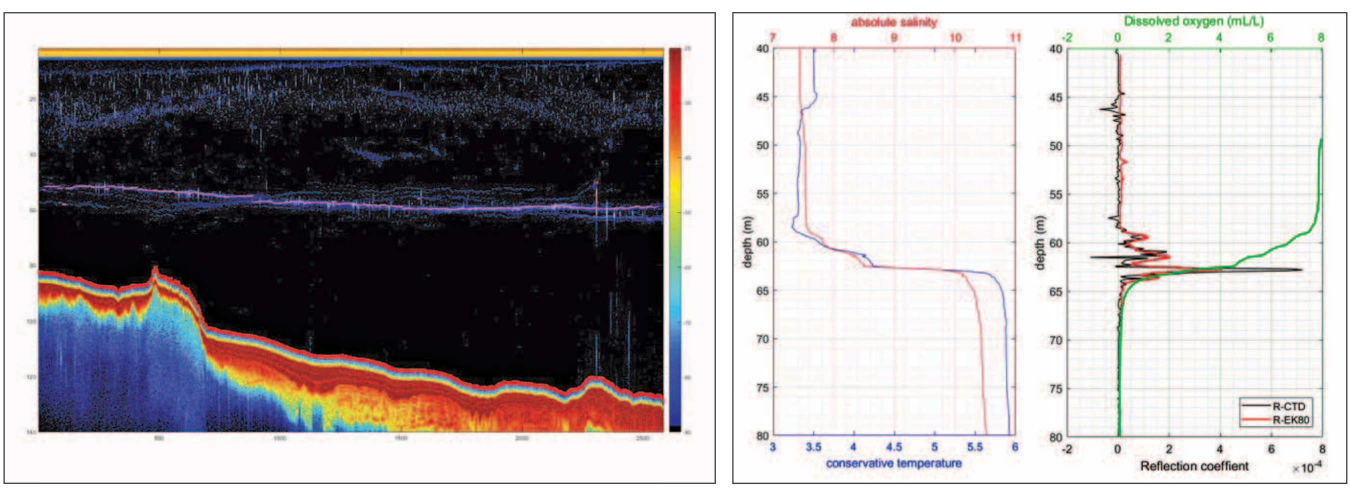


Figure ES-30. Left: Echogram of the tracked oxygen minimum location along transect in the Baltic. Right: Reflection coefficient calculated at CTD site through oxygen minimum zone. The black reflection coefficient profile corresponds to the CTD estimate and the red to the acoustic estimate; green line is dissolved oxygen.

Programmatic Priority 2: Transform Charting and Navigation

Chart Adequacy and Computer Aided Cartography

Managing Hydrographic Data and Automated Cartography

A long-term goal of many hydrographic agencies is to automatically construct cartographic products from a single-source database populated with a consistent representation of all available data at the highest possible resolution; in many cases, the goal is to populate with gridded data products. Such an approach has the potential to radically improve the throughput of data to the end user, with more robust, quantitative, methods, and to improve the ability to manipulate chart data much closer to the point of use. Our efforts under the second programmatic priority have been focused on various aspects of meeting this goal, including exploring more robust approaches for sounding selection verification (Figure ES-31), developing automated techniques to ensure vertical continuity on charts, approaches to the visualizing uncertainty on Electronic Nautical Charts (ENCs; Figure ES-32), for the automatic compilation of ENCs, and automated approaches to generalizing nautical charts.

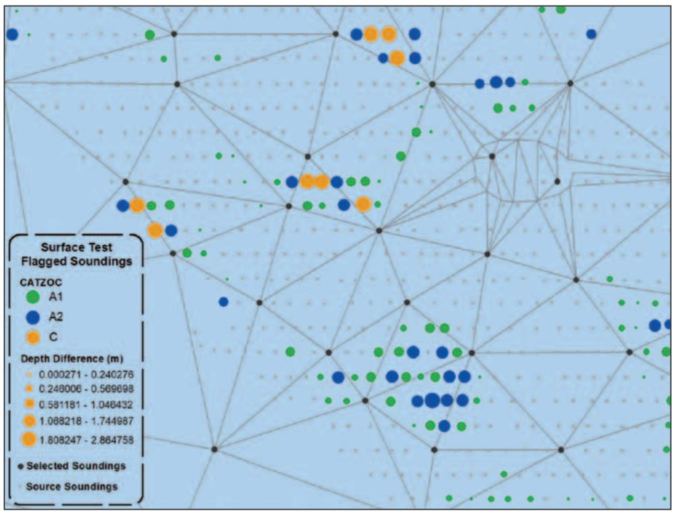


Figure ES-31. Soundings flagged by a newly developed toolset that includes triangle, edge, and surface tests now being tested by MCD.

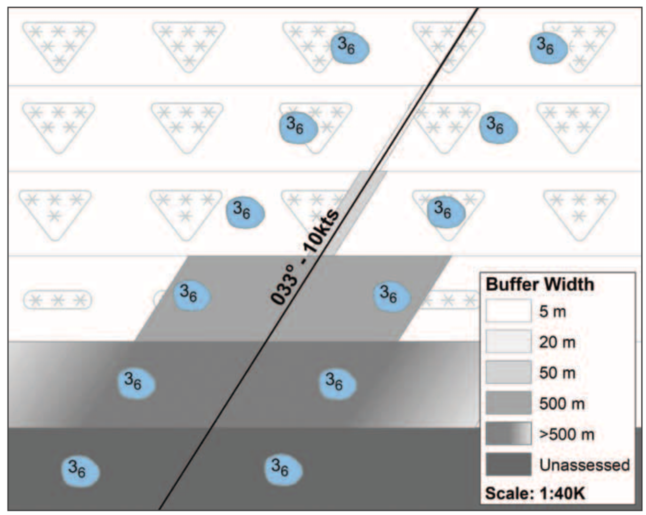


Figure ES-32. A proposed approach to visualizing dangers along proposed route. Zone width is set equal to the horizontal uncertainty in the area.

Immersive 3D Data Cleaning

No matter how comprehensive and effective automated processing tools become, there will likely always be some data that need to be examined and manipulated by hand by a human operator. As part of the ongoing effort to explore new interfaces for hydrographic data manipulation, therefore, Tom Butkiewicz and graduate student Andrew Stevens are creating an immersive 3D, wide-area tracked, sonar data cleaning tool. The system developed relies on an HTC Vive virtual reality (VR) system, which consists of a head-mounted display (HMD), two hand-held six-degree-of-freedom (6DOF) controllers, and a laser-based wide-area tracking system which accurately and rapidly calculates the positions of all of these components in a 5×5m tracked space.

To evaluate the viability of using an immersive system on a moving vessel, we conducted an informal evaluation in a seasickness-inducing simulator (Figure ES-33), and found that adding a virtual horizon and moving the surroundings in our virtual environment to match vessel motion, greatly reduced the potential for motion sickness, indicating that the use of immer-sive VR technologies aboard underway ships may be feasible. Experiments comparing cleaning performance between the Center's novel VR interface and a generic desktop monitor and mouse/keyboard based interface representative of traditional software packages showed a clear advantage when using the VR interface with regard to completion time, while errors were generally equivalent between the interfaces.

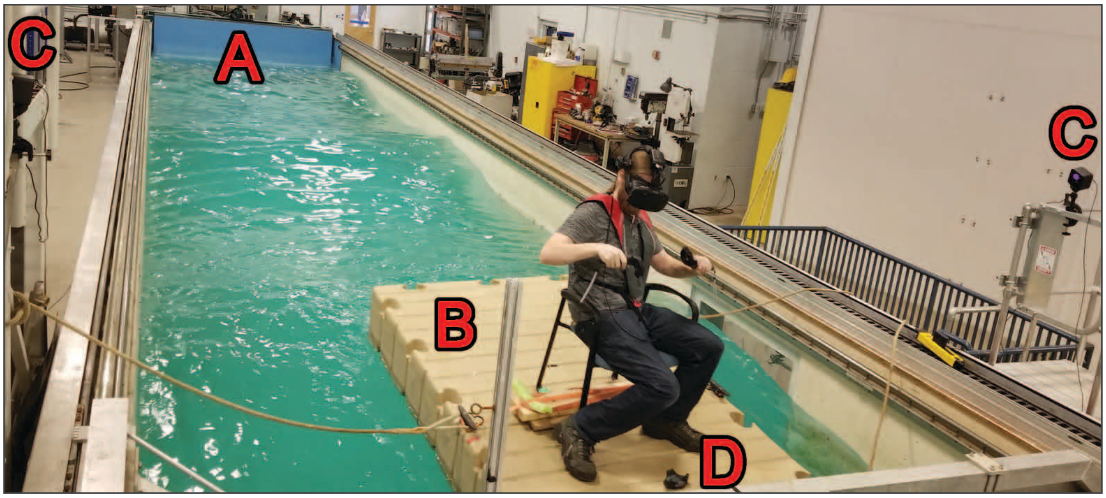


Figure ES-33. Nauseagenic testing setup. The paddle (A) at the end of the tank creates waves which induce motion on the floating platform (B). The tracking cubes (C) on the sides of the tank provide a fixed reference space, while a tracking device (D) provides the platform's pose, which is used to compensate the visuals in the virtual environment to match the felt motion, reducing motion sickness.

However, because users can be reluctant to use immersive interfaces and wear head mounted displays for long periods of time, we have also developed a desktop monitor based, non-immersive version of our editing software (Figure ES-34). While users do not get the same depth perception and head coupling benefits, the handheld six-degree-of-freedom controllers are still a better interface than a mouse for the inherently 3D task, which preserves much of the benefits our immersive system presents over traditional interfaces. We have also added support for lidar point cloud editing.

Figure ES-34. Interactive point cloud editor being used on a standard 2D desktop monitor, where the 6DOF handheld controllers can be used to "reach into the screen" and edit, manipulate, reposition, and scale data similar to the immersive mode.

Comprehensive Charts and Decision Aids

Digital Coast Pilot – Chart Update Mashup

The Sailing Directions (SD)/Coast Pilot (CP), a textual aid to marine navigators, has traditionally been a product distributed in print or as PDFs—forms unable to take full advantage of the detailed georeferenced data it includes. One of our goals as we explore the "chart of the future" is to be able to use supplementary data for the electronic nautical chart (ENC) to augment and add value to the mariner's experience. The IHO is in the process of creating standards for ECDIS/ENC called S-100 (replacing the old S-57 standard). The IHO Nautical Information Provisions Working Group (NIPWG) is responsible for the Nautical Textual Information (NTI) contained within the Coast Pilot. Working to support the mandate of NIPWG, we are investigating how to parse the unstructured NTI into structured data models so that this data can be used in electronic chart displays. We are also investigating how well-structured/machine-readable information can best be displayed in an interactive display and are looking for other ways in which it can be used to support the mariner. Briana Sullivan has developed a web-based, interactive test-bed (iCPilot) for evaluating new approaches for presenting NTI (Figure ES-35).

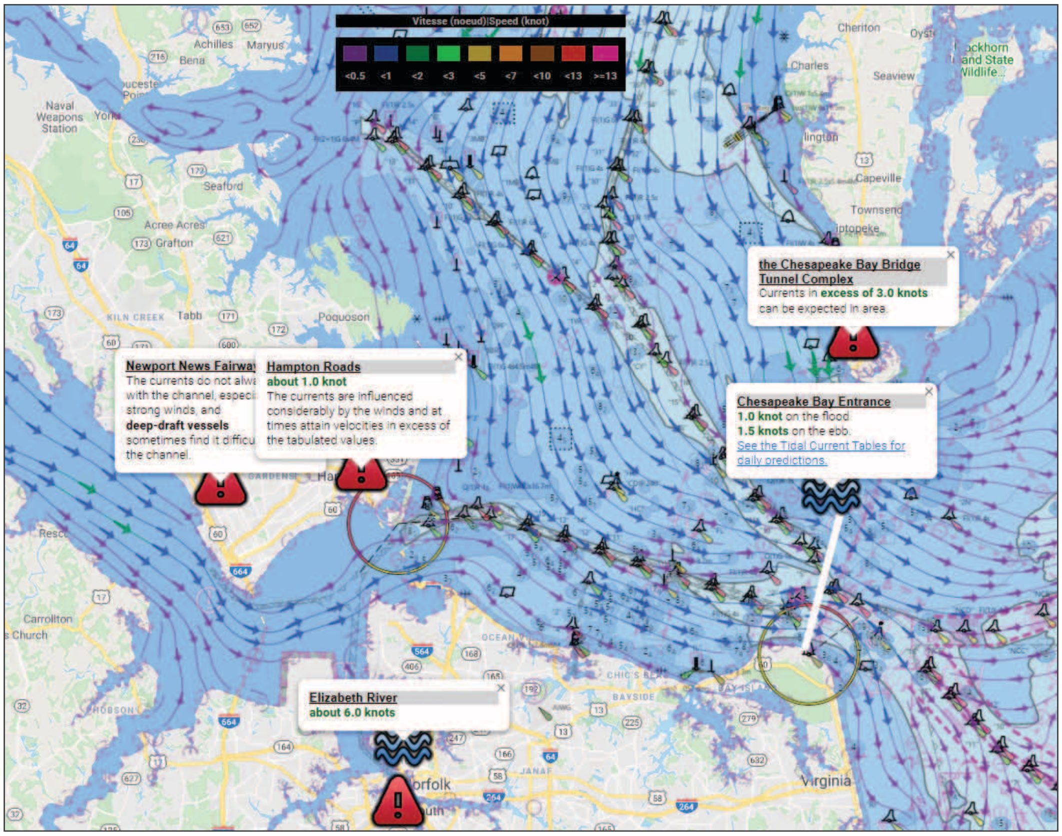


Figure ES-35. ICPilot prototype showing S-111 surface current data in conjunction with related Coast Pilot textual data.

Augmented Reality for Marine Navigation

In concert with our activities to extend and enhance current charts and navigational support tools (like the Coast Pilot), we are exploring how new developments in interactive data visualization—including augmented and virtual reality—may play a role in the future of marine navigation. Augmented Reality (AR), which is the superimposition of digital content directly over a user's real-world view, is an emerging technology that may have great potential for aiding safe marine navigation.

Tom Butkiewicz has continued to develop a dynamic and flexible bridge simulation for experimenting with a range of possible AR devices and information overlays across different times-of-day, visibility, and sea-state/weather. This simulation allow for safe evaluation in a more diverse set of conditions than are available on our research vessel. The project's goals include identifying what technical specifications are required for future AR devices to be useful for navigation, what information is most beneficial to display, and what types of visual representations are best for conveying that information. Butkiewicz has completed a physical interface for piloting the virtual boat. The controls include a full-size ship's wheel that provides realistic force feedback and a throttle. These are mounted to a portable platform with an integrated tracker which keeps the virtual bridge's controls and real controls perfectly aligned so that one can always reach out and grab them within the simulator (Figure ES-36).

Using these controls, we have conducted a number of studies focused on understanding the effects of field-of-view on the usefulness of the AR overlays for marine navigation tasks, including the use of an eye-tracker that can accurately detect what participants are looking at 120 times per second. While participants navigated the course, we used the eye-tracker to record how often they looked up at the ECDIS, which is a useful metric for understanding the effects of field-of-view on situational awareness. The results of the study indicated great potential for AR to aid in safe marine navigation by keeping mariner's eyes on the water.

Figure ES-36. Upper: Simulated augmented reality overlay of nautical chart information. Lower: The virtual bridge and AR simulator. Lower Left: The physical controls used to pilot the boat. Above Right: The virtual ECDIS display above the bridge windows, showing a track-up OpenCPN chart with the same trackline and waypoint. Below Right: The view from the virtual bridge within the field-of-view study environment, showing ship traffic and AR trackline to next waypoint.

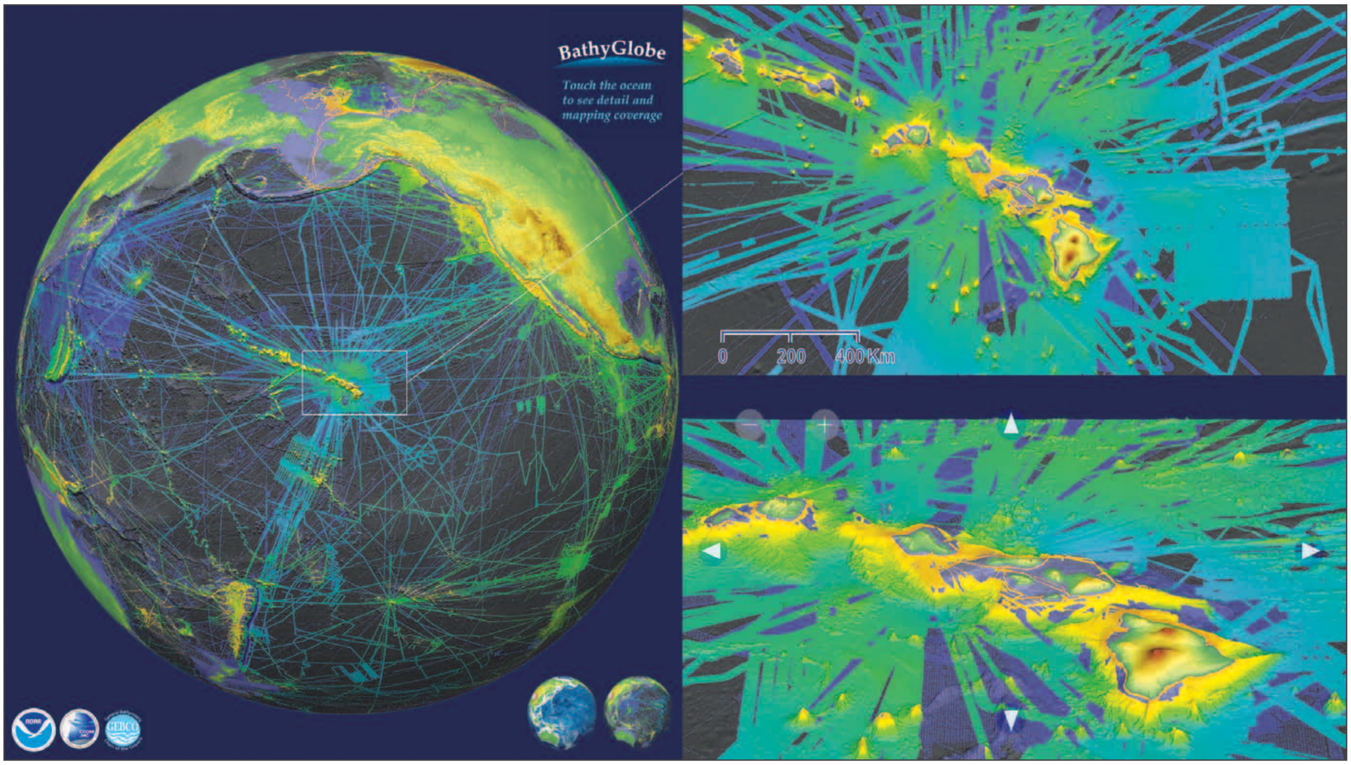


Figure ES-37. BathyGlobe, showing the newest GEBCO 2019 data with a colormap designed to emphasize areas with multibeam coverage.

Digital Bathymetric Globe (BathyGlobe)

Within the context of our visualization activities, Colin Ware has initiated the "BathyGlobe" project, a new effort focused on developing an optimal display for global bathymetric data. One of its goals is to provide support for the Seabed 2030 initiative to heighten awareness of the extent to which the seabed has and has not been mapped. The BathyGlobe presents the actual scaled coverage of existing bathymetric data on an interactive globe display, clearly demonstrating how little of the world's ocean has real bathymetric data. Numerous enhancements have been added to the BathyGlobe including, the ingestion of the newest GEBCO 2019 grid and enhanced color maps and 3D viewing (Figure ES-37). In concert with these efforts, Ware is also working on optimized gridding algorithms for multi-resolution global bathymetric data sets.

Programmatic Priority 3: Explore and Map the Continental Shelf

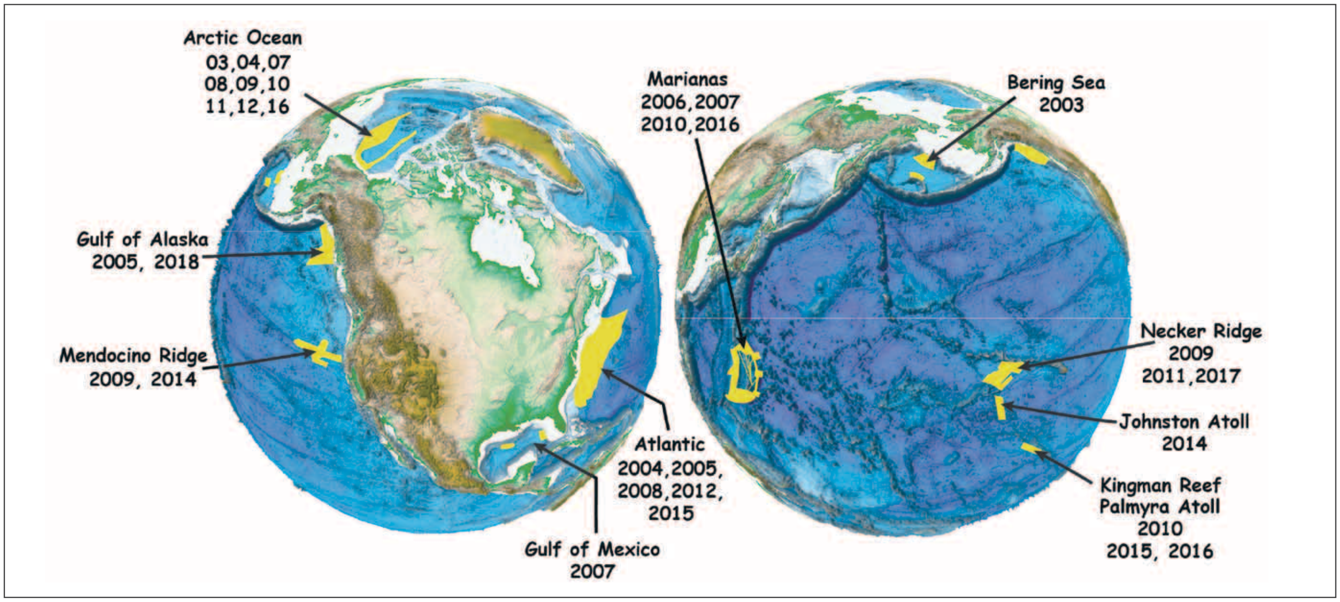


Figure ES-38. Summary of Law of the Sea multibeam sonar surveys mapped by the Center. Total areas mapped represents more than 3.1 million square kilometers since 2003.

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 sub-surface 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.

Figure ES-39. Home page of the Center's GIS portal.

Following up on the recommendations made in the study, the Center was funded (through NOAA) to collect new multibeam sonar (MBES) data in support of a potential ECS claim under UNCLOS Article 76. Mapping efforts began in 2003. Since then, the Center has collected more than 3.1 million square kilometers of new high-resolution multibeam sonar data during 35 cruises—nine in the Arctic, five in the Atlantic, one in the Gulf of Mexico, one in the Bering Sea, three in the Gulf of Alaska, three in the Necker Ridge area off Hawaii, three off Kingman Reef and Palmyra Atoll in the central Pacific, five in the Marianas region of the western Pacific, and two on Mendocino

Fracture Zone in the eastern Pacific (Figure ES-38). 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 Center for Environmental Information (NCEI) in Boulder, CO and other public repositories within months of data collection and provide a wealth of information for scientific studies for years to come.

Current year activities focused on writing up ECS results and revising and updating the Center's ECS website including a transfer to ArcGIS Pro and an enterprise online GIS solution **https://maps.ccom.unh.edu/portal/home/** (Figure ES-39). This has allowed a range of new visualization and interactive features including color palettes based on dynamic range, real-time calculation of single and multiple hill-shades, real-time calculation of contours and many enhanced query activities. (Figures ES 40 and 41).

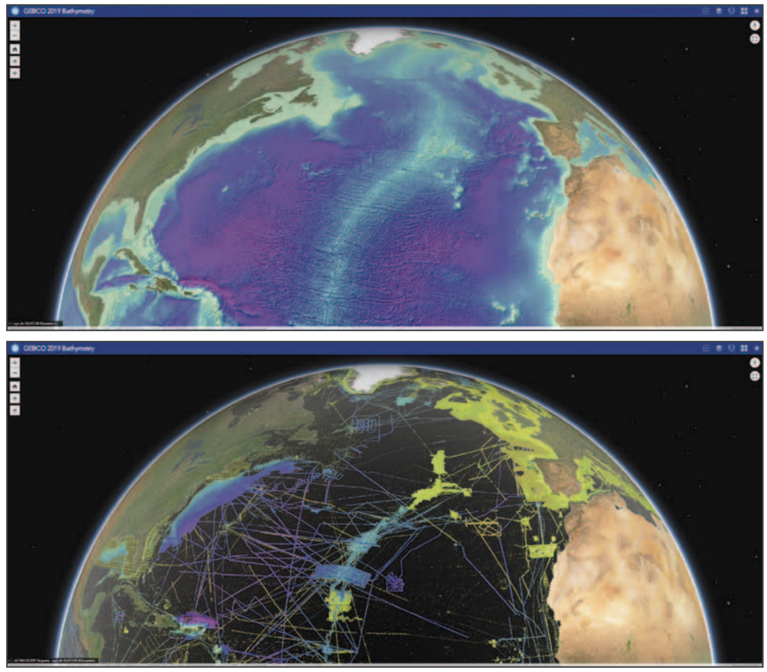


Figure ES-40. Top: The GEBCO 2019 bathymetry grid. Bottom: The same grid with areas containing interpolated values set to black and areas composed of pre-generated grids as yellow.

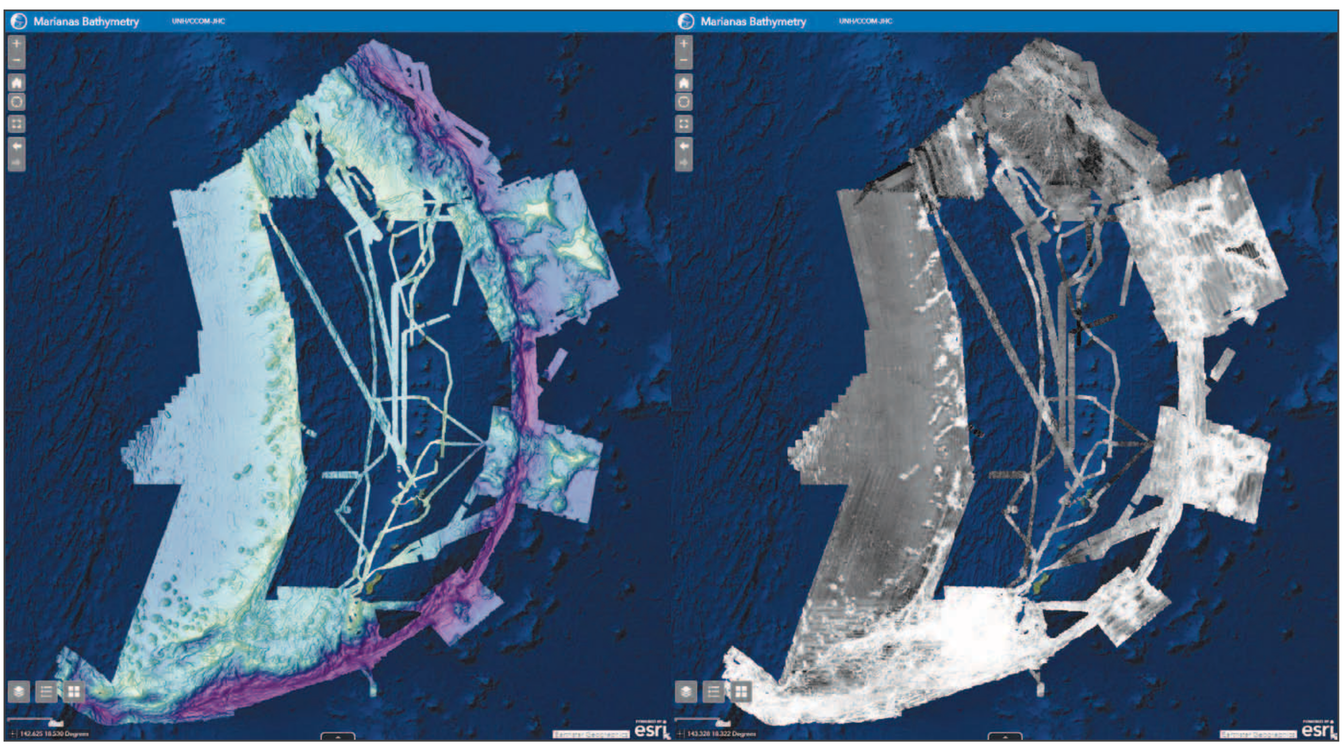


Figure ES-41. Primary bathymetry and backscatter syntheses for the Marianas region from ECS data and other sources.

Programmatic Priority 4: Develop and Advance Hydrographic and Nautical Charting Expertise

Acoustic Propagation and Marine Mammals

An important goal of the Center is to adequately model, and validate at sea, the radiated field from multibeam echo sounders (MBES) so that we may provide the best available information to those interested in investigating potential impacts of radiated sound on the environment. In support of this goal, Center researchers have organized and undertaken several cruises to Navy calibration ranges designed specifically to help characterize the ensonification patterns of deep water multibeam sonars. The first of these cruises was conducted in early 2018 at the Southern California Offshore Range (SCORE), located in the San Nicholas Basin off San Clemente Island, CA using a 12 kHz EM122 on the R/V *Sally Ride*, followed by a second experiment at the AUTEC range in the Bahamas using a 30kHz, EM302 on the NOAA Ship *Okeanos Explorer*, and a third back at the SCORE range in early 2019. In the latter two experiments, we deployed custom-designed moorings (Figure ES-42) in addition to the Navy hydrophones.

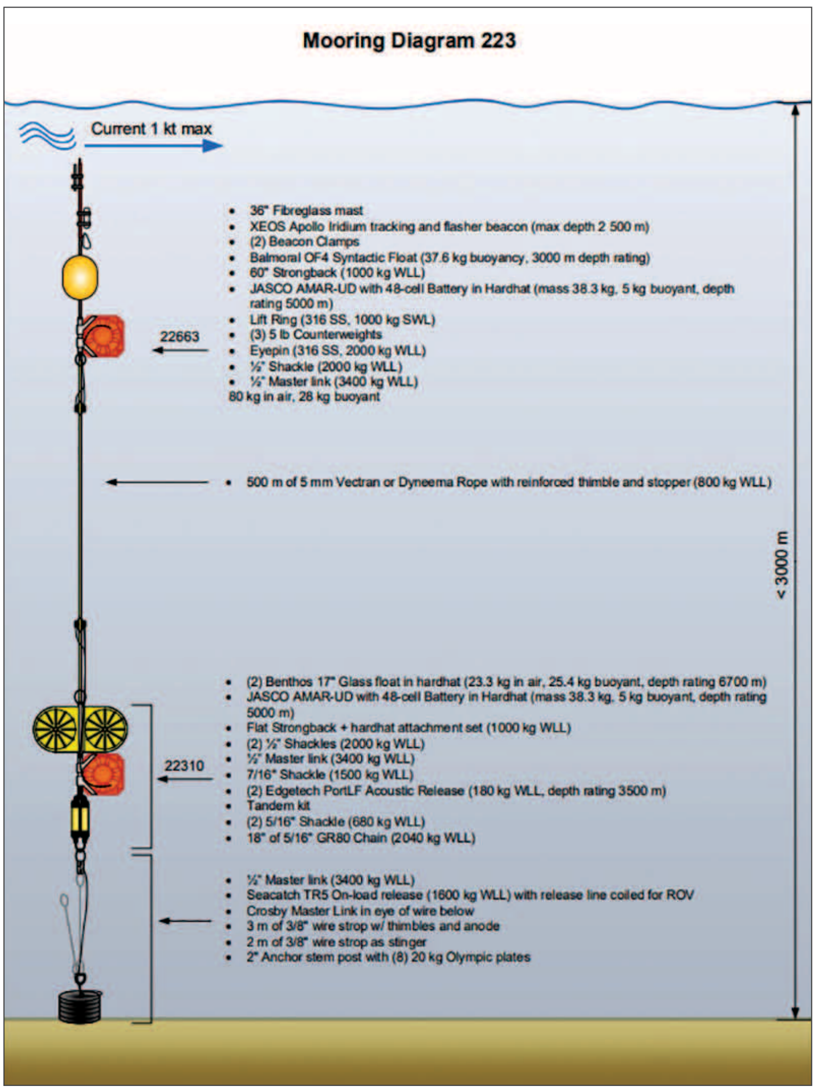


Figure ES-42. Diagram of mooring supplied by JASCO and deployed at both AUTEC in December 2018 and at SCORE in January 2019.

The results of these experiments have confirmed our initial results demonstrating some unexpected behaviors in the radiation patterns of the multibeams and have now allowed us to measure absolute source levels (Figure ES-43).

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).

Echolocation clicks are produced by Cuvier's beaked whales as they hunt for prey. The period of vocal activity during a foraging dive is referred to as the group vocal period (GVP). Group vocal periods were automatically detected using software that identified clicks, combining them into click trains based on species-specific characteristics. Closely associated click trains are grouped into GVPs on a per-hydrophone basis. GVP characteristics are then used as a proxy to assess the temporal distribution of foraging activity across six exposure periods with respect to multibeam activity at the range. These characteristics included the number of group vocal periods, the number of clicks in a GVP, and GVP duration. The exposure periods included: before the vessel was on the range (Before); while the vessel was on the range with the mapping sonar off (Control Survey); while the vessel was on the range and the mapping sonar was on (EM 122 Survey); while multiple acoustic sources were on (Other Active Acoustics); while the vessel was mapping off-range (Immediately After); and while the vessel was off the range and the sonar was off (After). A one-way analysis of variance test was conducted to compare each GVP characteristic across the exposure periods.

The results of both studies indicate that there is no clear change in foraging behavior of beaked whales at the Navy range in response to the EM 122 survey. For three of the four metrics, there was no change in foraging behavior across the exposure periods analyzed (Figure ES-44). The only significant difference observed in any of the GVP characteristics during the 2019 survey was in GVP duration. The GVP duration steadily shortened from the Before period through the Traditional Survey and then increased again After. 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.

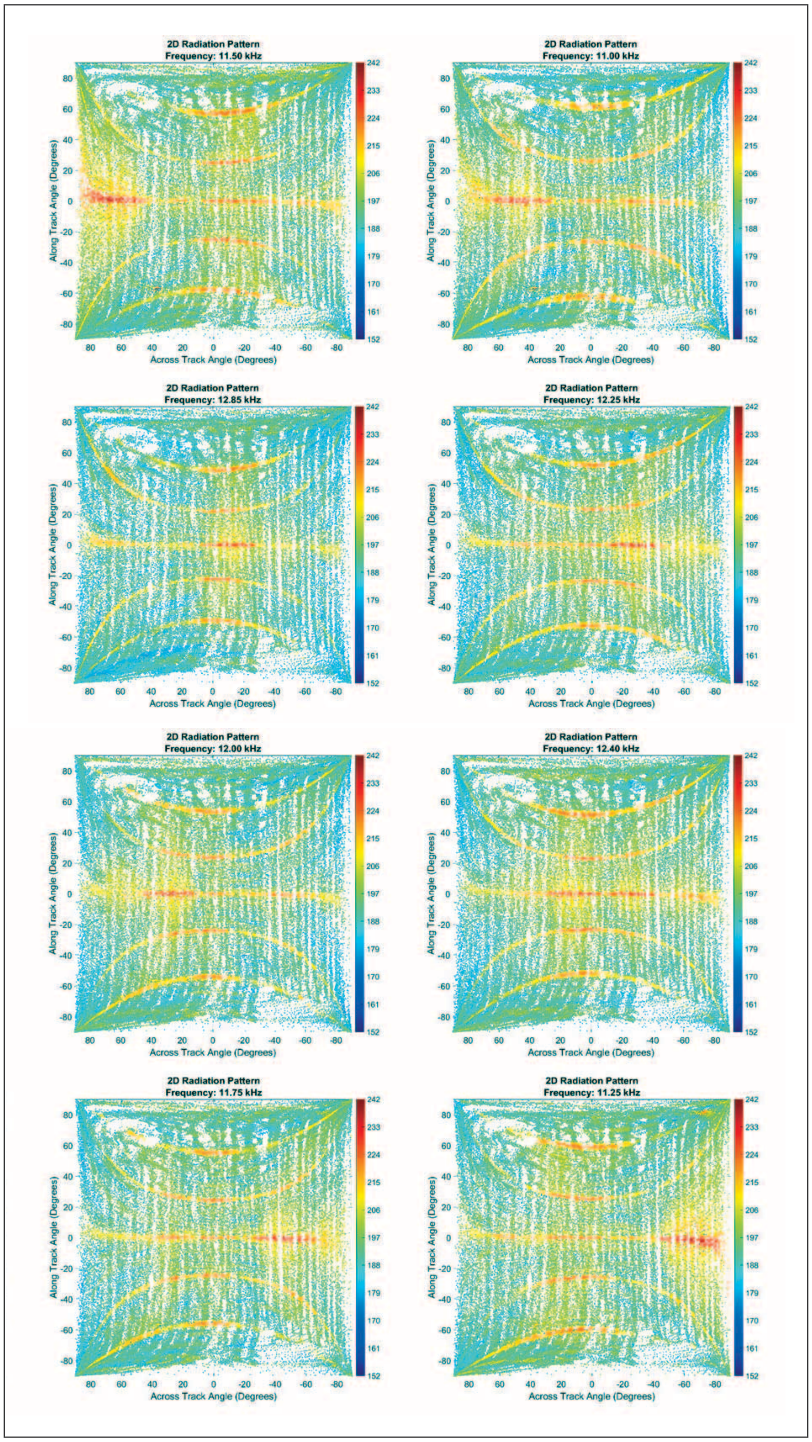


Figure ES-43. Baseline Radiation Pattern test results. Each plot is a top-down, 2D representation of the 3D transmit radiation pattern of a given sector. Data was plotted in the across versus along track and the color corresponds to the equivalent far field source level at 1m as measured by the hydrophone's.main beam response and ending after the second lobe generated on the aft end of the vessel. Data is presented in equivalent source level at 1m using an approximate transmission loss correction for the slant range. Black arrows point to the main beam and the additional lobes.

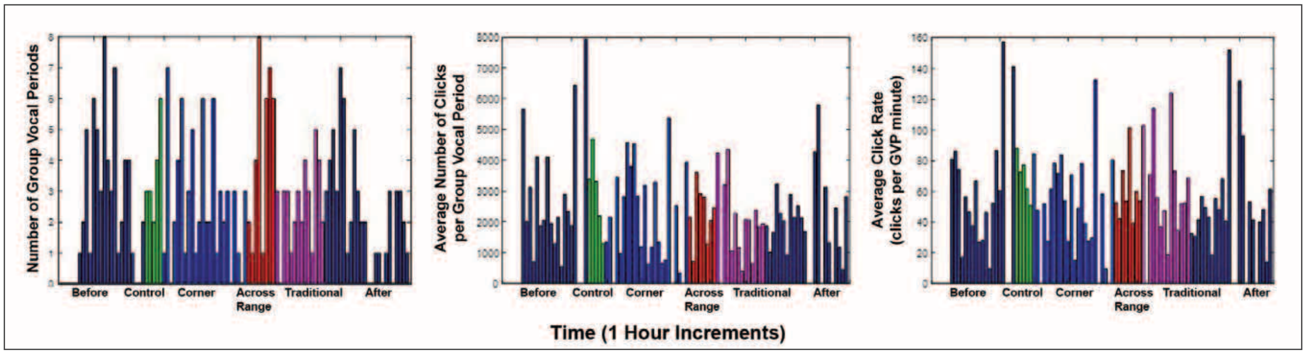


Figure ES-44. Bar graphs of the three GVP characteristics where no differences were found across exposure periods in the 2019 survey. Each graph shows the data binned into hour increments for each of the six exposure periods.

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 (DiMarzio et al. 2019). The results of this study are currently under review for an upcoming Journal of the *Acoustical Society of America's Special Issue* on "The Effects of Noise on Aquatic Life."

An added benefit to the work at the ranges has been the ability to assess the contribution of multibeam sonar to the local acoustic environment (soundscape). Jen Miksis-Olds and graduate student Hilary Kates-Varghese have used differences in frequency correlation plots to successfully separate the contribution of the multibeam signal from background vessel-related noise, a critical component in assessing animal response to MBES surveys (Figure ES-45).

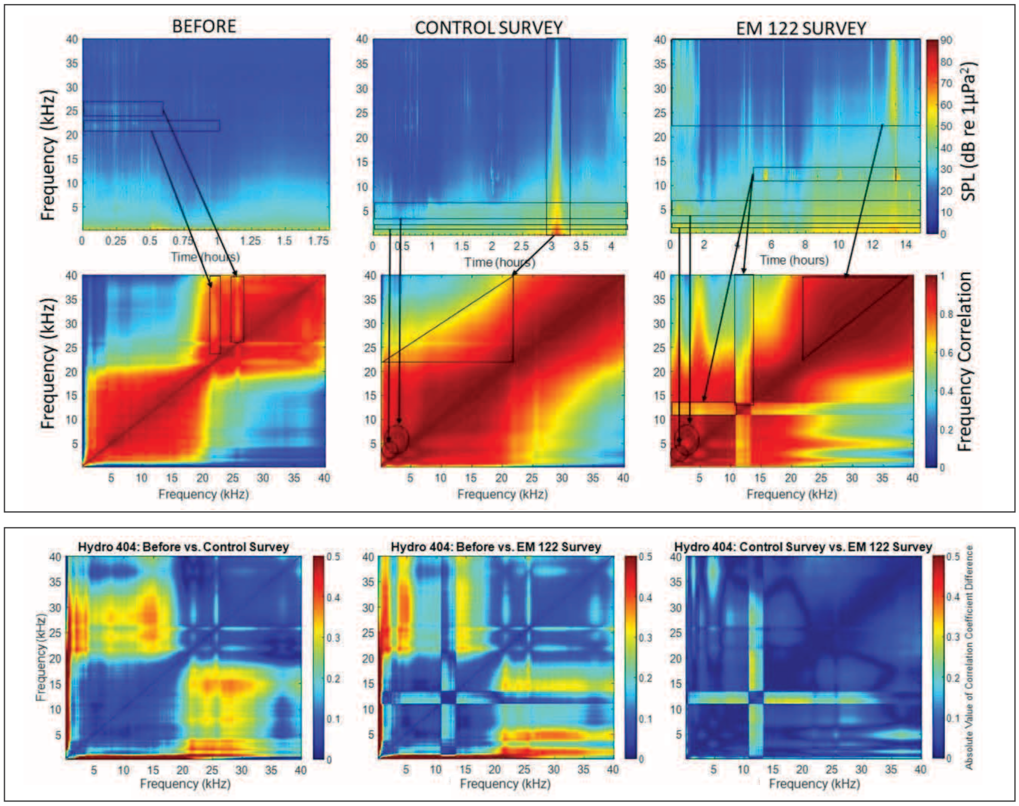


Figure ES-45. Upper Two Frames: Frequency correlation plots for the three time periods on hydrophone 404 (bottom row) in comparison to respective spectrograms (top row). Black boxes and arrows indicate how the content of the two plots relate. Lower Frame: Frequency correlation difference plots, comparing each pair of time periods on hydrophone 404 and showing separation of multibeam signal (right box) from ship-noise (middle box).

Education and Outreach

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—critical thinkers able to fill positions in government, industry, and academia, and become leaders in the development of new approaches to ocean mapping. Thirty-seven students were enrolled in the Ocean Mapping program in 2019, including six GEBCO students, one NOAA Corps officer, and three NOAA physical scientists (as part-time Ph.D. students). This year, we graduated two master's and three Ph.D. students, while six GEBCO students received Certificates in Ocean Mapping.

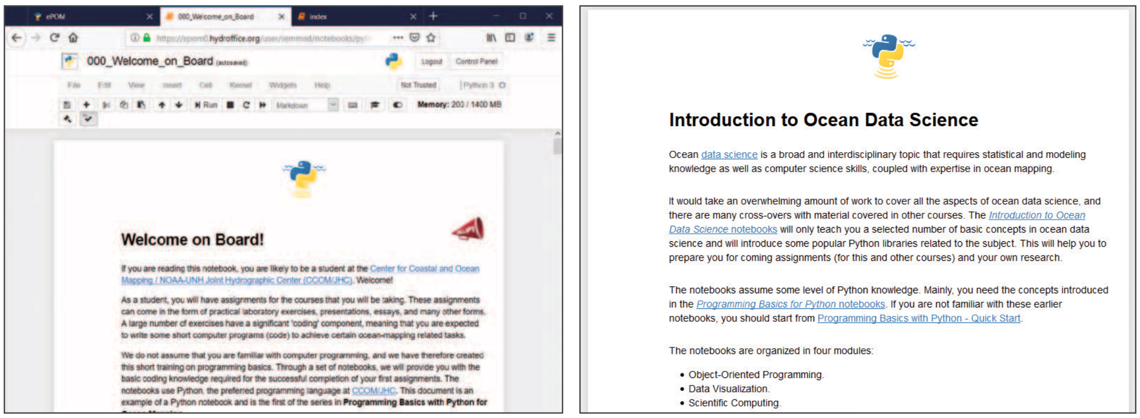


Figure ES-46. Left: The ePOM welcome notebook. Right: Introduction to Ocean Data Science is organized in four modules.

This year, in response to discussions with NOAA OCS, we converted to Python as the preferred programing language for ocean mapping courses and introduced a new E-learning course that will ensure a minimum common level of programing skills among the incoming students (Figure ES-46). In addition, we developed a second Python-based toolkit—Introduction to Ocean Data Science—which provides a series of Python-based lab exercises that are directly tied to our introductory Integrated Seabed Mapping Systems and Geodesy and Positioning for Ocean Mapping courses (Figure ES-46).

Through international competition, the Center has hosted the Nippon Foundation/GEBCO Training Program since 2004. Ninety scholars from 40 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 15 and 16. 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 Alumni Team was made up of fifteen alumni from of 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-47).

Figure ES-47. 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.

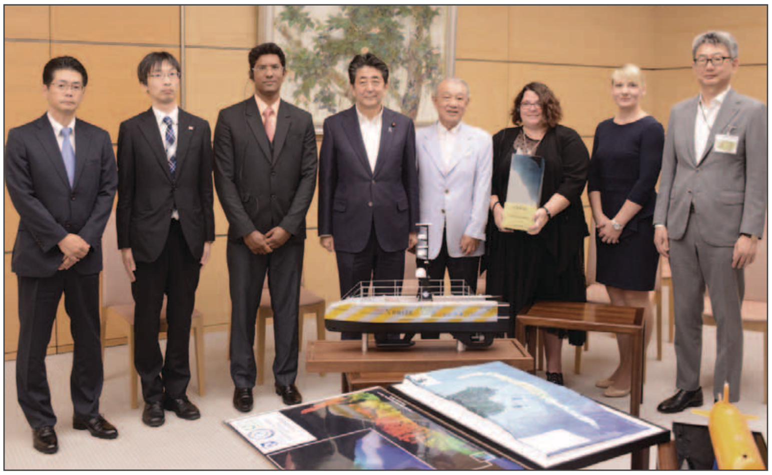


Figure ES-48. Left to right: Mr. Unno, Masanao Sumiyoshi, Sattiabaruth Seeboruth, Prime Minister Shinzo Abe, Mr. Sasakaw, Rochelle Wigley, Karolina Zwolak and Hisataka Hiragochi (Director General of National Ocean Policy Secretariat).

A subset of the team met with Japanese Prime Minister Shinzo Abe on 18 September 2019 to talk about the technology that they developed, and how their model of international scientific cooperation can help to map the gaps that still remain in our understanding of the ocean floor. Also present were Yohei Sasakawa, the Chairman of The Nippon Foundation, which backed the team's entry, and Mitsuyuki Unno, executive director of the Ocean Affairs division at The Nippon Foundation (Figure ES-48).

We recognize the interest that the public takes in our research 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, **http://ccom.unh.edu** (Figure ES-49). In 2019, there were 122,537 views from 32,380 unique visitors to the site from 191 different countries.

We also recognize the importance of engaging young people in our activities to ensure that we will have a steady stream of highly skilled workers in the field. To this end, we have upgraded other aspects of our web presence including a Flickr photostream, Vimeo site, Twitter feed and a Facebook presence. Our Flickr photostream currently has 2,621 photos and our 135 videos were viewed 4,627 times in 2019. Our seminar series (30 seminars featured in 2019) is widely advertised and webcast, allowing NOAA employees and our Industrial Partners around the world to listen and participate. Our seminars are also recorded and uploaded to Vimeo.

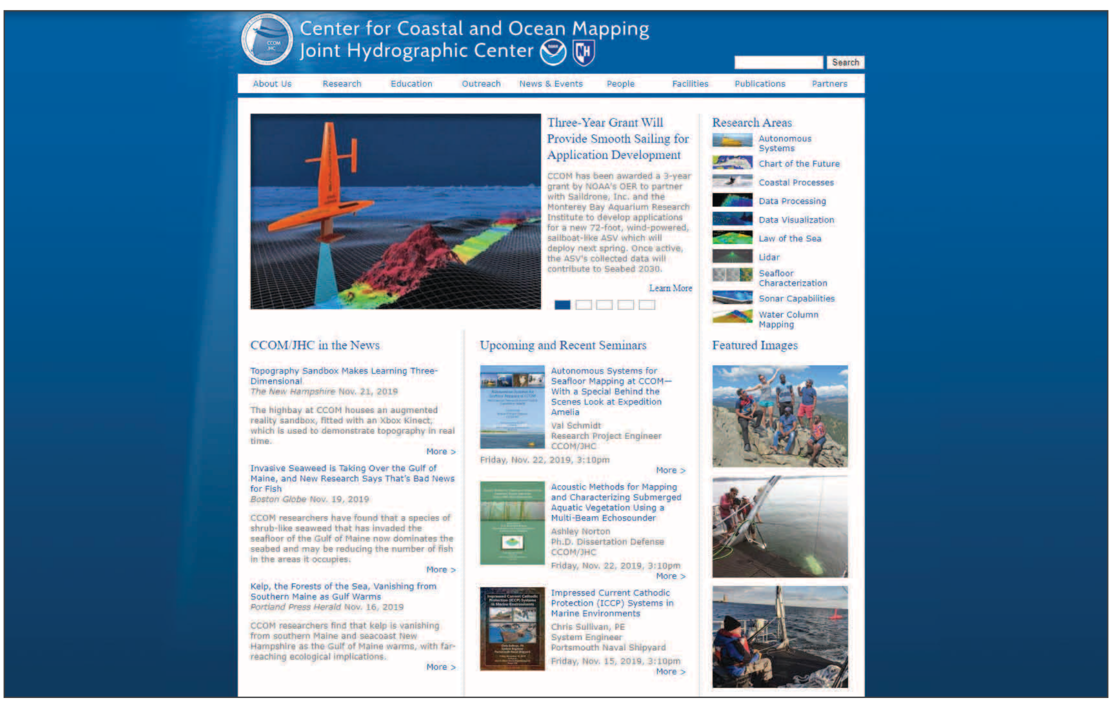


Figure ES-49. The homepage of the Center's website.

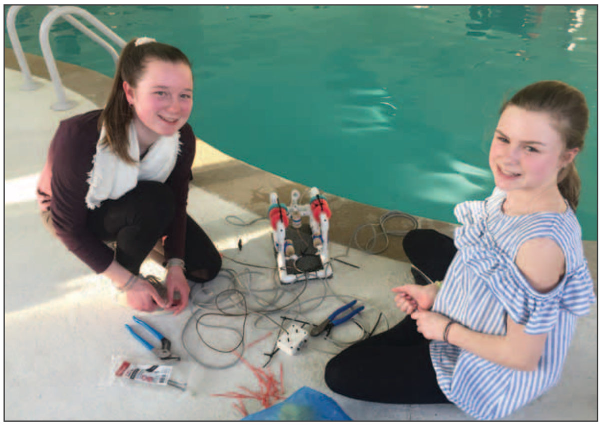
Along with our digital and social media presence, we maintain an active "hands-on" outreach program of tours and activities for school children and the general public. Under the supervision of our full-time outreach coordinator, Tara Hicks-Johnson, several large and specialized events were organized by the Center's outreach team, including numerous SeaPerch ROV events and the annual UNH "Ocean Discovery Days."

In the SeaPerch ROV events, coordinated with the Portsmouth Naval Shipyard (PNS), students build ROVs and then bring them to the Center to test them in our deep tank as well as tour the Center and the engineering facilities on campus. In its seventh year, fifty teams from New Hampshire, Maine, and Massachusetts schools, after-school programs, and community groups competed in this challenge, using ROVs that they built themselves (Figure ES-50). A SeaPerch is an underwater ROV made from simple materials such as PVC pipe, electric motors, and simple switches. While there is a basic SeaPerch ROV design, the children have the freedom to innovate and create new designs that might be better suited for their specific challenge.

This year's competition included challenges such as an obstacle course where pilots had to navigate their ROV through five submerged hoops, and a Challenge Course modeled after the Thailand cave rescue, where the ROV had to maneuver through hoops to deliver supplies and collect ROV parts. This year's winning teams represented the Seacoast at the SeaPerch Finals in College Park, Maryland, which was a wonderful opportunity for our local students to experience competition on a higher level. One of our high school teams came first place for the High School division, and a second high school team came in third for the Mission Course.

The Center hosted the National Marine Educators Association Annual Conference in July, bringing together more than 350 formal and informal marine educators from K-12 schools, public aquariums, non-profit NGOs, and government agencies came together for four days of learning, sharing, and networking.

Ocean Discovery Day is an annual two-day event held at UNH's Chase Ocean Engineering Laboratory, where the Center is located. On Friday, 18 October we hosted over 1,500 students from school groups and homeschool associations from all over New Hampshire, Maine, and Massachusetts who came to visit our facilities and learn about the exciting research happening here at the Center. Activities



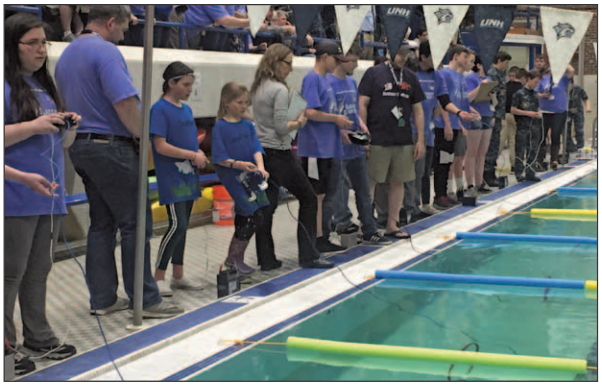


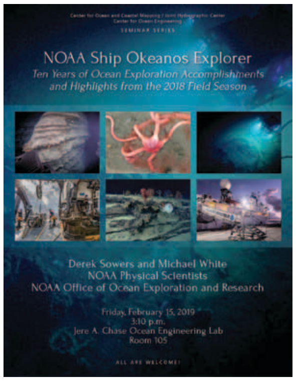
Figure ES-50. Student teams competing at the 2019 SeaPerch Challenge at UNH's Swasey Pool.

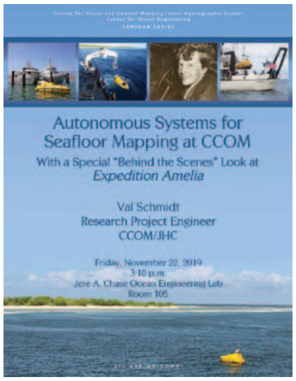
and demonstrations for all ages highlighted research on telepresence, ocean mapping, Autonomous Surface Vehicles (ASVs), ROVs, ocean engineering, coastal ecology, sounds of the ocean, and ocean visualization. The event was then opened to the public on Saturday, 19 October, when 800 more children and adults came to learn about the exciting research at the Center (Figure ES-51).

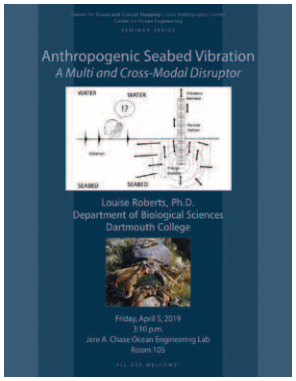
Center activities have also been featured in many international, national, and local media outlets this year including: the BBC, *Wired*, *Forbes*, *Science*, *Popular Mechancis*, *Bloomberg Businessweek*, *Hydro International*, *NewsWise*, *The Engineer*, *Business Telegraph*, *Digital Trends*, *Yale Environment 360*, *Philanthopy News Digest*, *Marine Technology News*, *National Marine Sanctuaries News*, *Arctic Today*, *Daily Beast*, *Tech Crunch*, *Ars Technica*, *Hakai Magazine*, *Union Leader*, *Foster's Daily Democrat*, *Concord Monitor*, *Seacoast Online*, *NH Business Review*, *Hellenic Shipping News*, *City Press*, *Science Daily*, *Boston Globe*, *Portland Press Herald*, *Maritime Executive*, *Workboat*, *Svierges Radio*, *Kristinstad Bladet*, *Alpena News*, *News 18*, NHPR, WCAX, and *Boston News 25*.

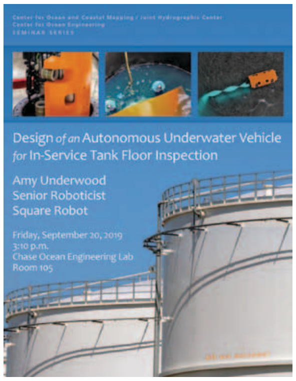
The highlights presented here represent only a fraction of the activities of the Joint Hydrographic Center in 2019. More detailed discussions of these and other activities, as well as a complete list of Center publications can be found in the full progress reports available at http://ccom.unh.edu/reports.

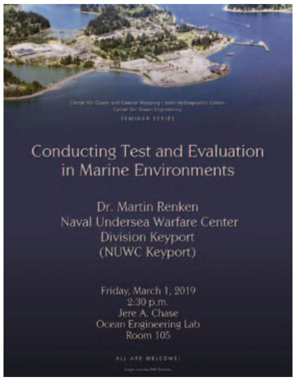
Figure ES-51. More than 1,500 students visited the Center during Ocean Discovery Day followed by another 800 visitors at the open house on the following day.

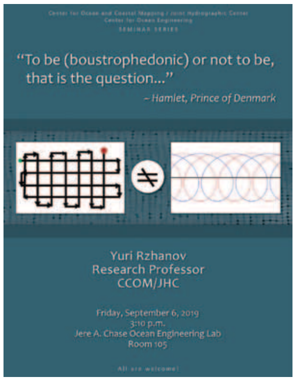


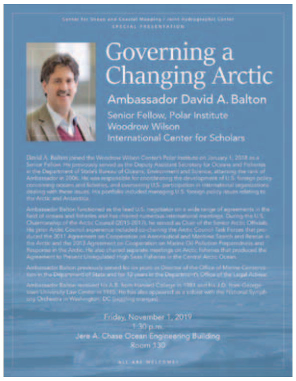


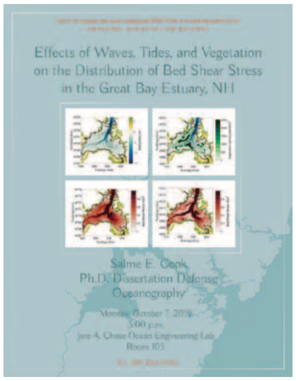


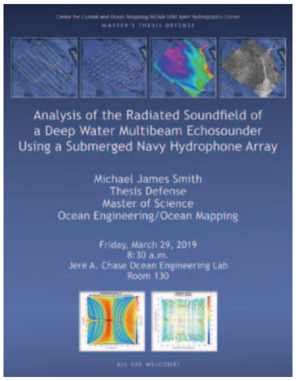


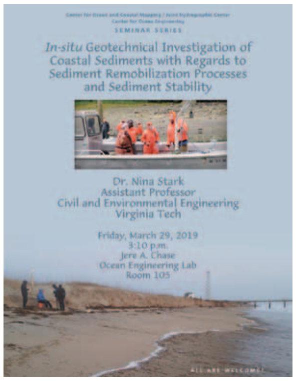


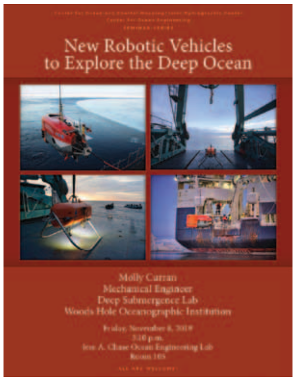


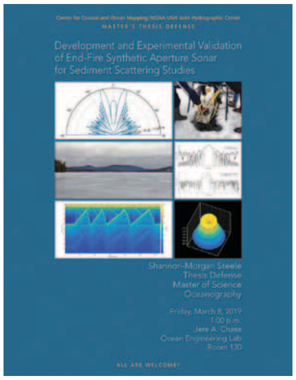


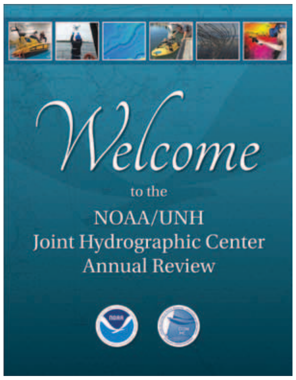












Welcome signs and flyers from the 2019 JHC/CCOM–UNH Dept. of Ocean Engineering. Seminar Series.

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