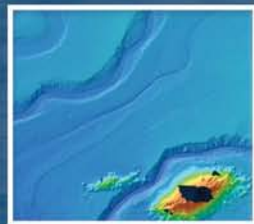
UNH/NOAA Joint Hydrographic Center
Performance and Progress Report
2018



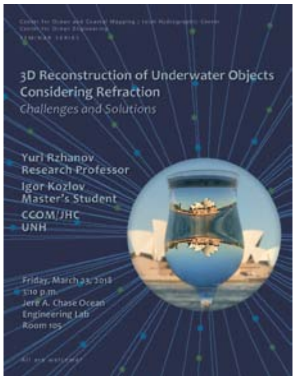


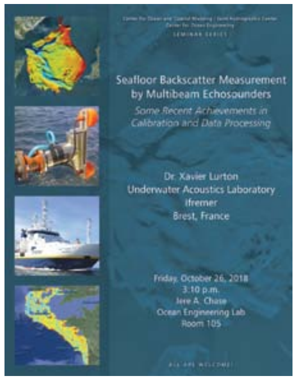


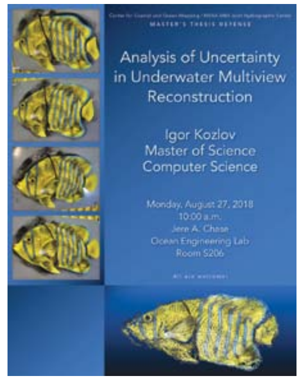
NOAA Grant No: NA15NOS4000200
Project Title: Joint Hydrographic Center

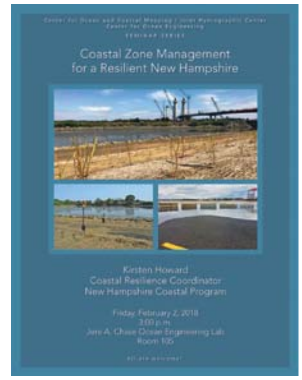
Principal Investigator: Larry A. Mayer

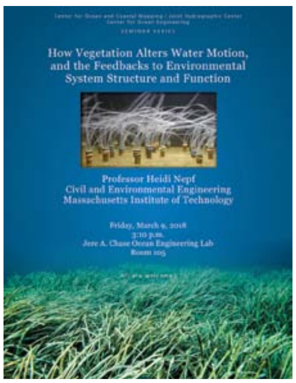
Reporting Period: 01/01/2018–12/31/2018

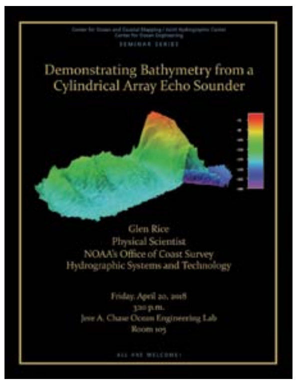


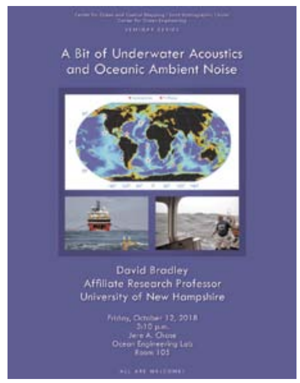


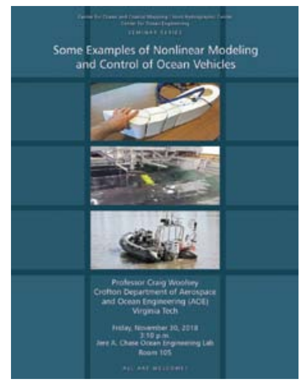


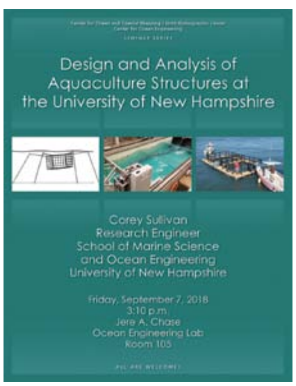


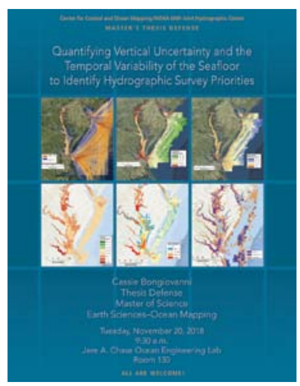


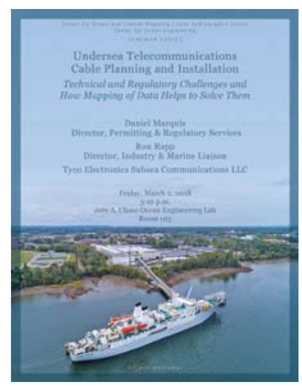


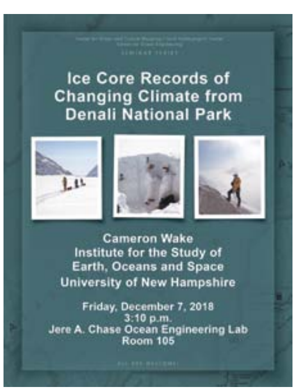


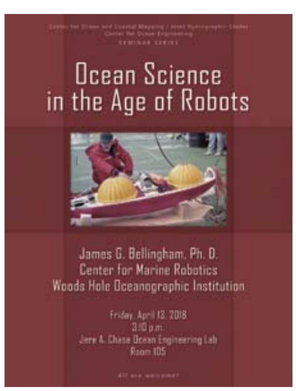


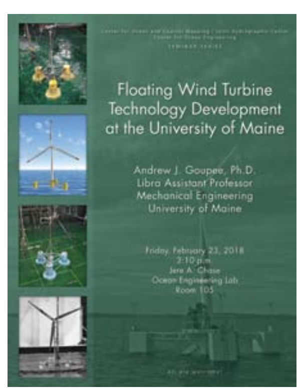


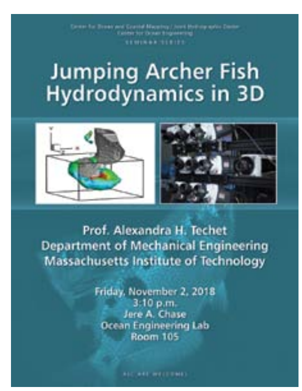












Flyers from the 2018 JHC/CCOM - UNH Dept. of Ocean Engineering Seminar Series.

The NOAA-UNH Joint Hydrographic Center (JHC/CCOM) was founded nineteen 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 already 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."*

Beyond GeoCoder, our efforts to support the IOCM concept of "map once, use many times" are also coming to fruition. In 2011, software developed by Center researchers was 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. In 2012, seafloor mapping data from the ME70 was used by fisheries scientists to identify optimal sites for fish-traps during a red snapper survey. Scientists on board ship said that the seafloor data provided by Center software was "invaluable in helping accomplish our trapping objectives on this trip." In 2013, tools developed for producing bathymetry and other products from fisheries sonars were installed on NOAA fisheries vessels and operators trained in their use. One of our industrial partners is now providing fully supported commercial-grade versions of these tools, and they are being installed on NOAA fisheries vessels. All of these (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 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.

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

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

to our efforts to map submerged oil and gas seeps and monitor the integrity of the Macondo 252 wellhead as part of the national response to the Deepwater Horizon oil spill. The Center's seep-mapping efforts continue to be of national and international interest as we begin to use them to help quantify the flux of methane into the ocean and atmosphere. The initial water-column studies funded by this grant have led to many new opportunities including follow-up work that has been funded by the National Science Foundation, the Office of Naval Research, the Dept. of Energy, and the Sloan Foundation.

Most recently, the Center has leveraged the tools and techniques that we had to quickly develop to find oil and gas in the water column during the Deepwater Horizon disaster to develop several exciting new research programs that have had important spin-offs 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), internal waves, turbulence, and the depth of the mixed layer (the thermocline). 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 2018; detailed progress reports for each of the individual grants can be found at our website, http://ccom.unh.edu/reports.

Highlights from Our 2018 Program

Our efforts in 2018 represent the third 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, merge, 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 third 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 2018 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. #
INNOVATE HYDROGRAPHY	DATA COLLECTION	SENSOR CALIBRATION AND SONAR DESIGN	SONAR	Tank Calibrations	Lanzoni	1
				PMBS Evaulation	Schmidt	2
				Circular Array Bathymetric Sonar	Weber	3
				Synthetic Aperture Sonar	Weber and Lyons	4
			LIDAR	Lidar Simulator	Eren	5
			SOUND SPEED	Distributed Temperature Sensing	Eren	6
		SENSOR INTEGRATION and REAL-TIME QA/QC		Deterministic Error Analysis/Integration Error	Hughes Clarke	7
				Data Performance Monitoring	Calder	8
				Auto Patch Test Tools	Calder	9
		INNOVATIVE PLATFORMS	AUVs	Nav Processing and Boot Camp	Schmidt	10
			ASVs	Add-on Sensors and Hydro Applications	Schmidt	11
		TRUSTED PARTNER DATA		Trusted Hardware	Calder	12
	DATA PROCESSING	ALGORITHMS and PROCESSING		CHRT and Expanded Processing Methods	Calder	13
				Multi-Detect Processing	Weber and Calder	14
				Data Quality and Survey Validation Tools	Calder	15
				Phase Measuring Bathymetric Sonar Processing	Schmidt	16
				Automatic Processing for Topo-Bathymetric LIDAR	Calder	17
		FIXED AND TRANSIENT WATERCOLUM AND SEAFLOOR	SEAFLOOR	Hydro-significant Object Detection	Calder and Masetti	18
			WATER COLUMN	Watercolumn Target Detection	Weber	19
	SEAFLOOR CHARACTIZATION, HABITAT and RESOURCES	COASTAL AND CONTINENTAL SHELF RESOURCES		Mapping Gas and Leaky Pipelines in Watercolumn	Weber	20
				Identification of Marine Mineral Deposits	Ward	21
		SEAFLOOR CHARACTERIZATION	SONAR	GeoCoder/ARA	Masetti	22
				Singlebeam Characterization	Lippmann	23
				Multi-frequency Seafloor Backscatter	Hughes Clarke and Weber	24
			LIDAR and IMAGERY	Lidar Waveform Extraction	Eren and Parrish	25
			CRITICAL MARINE HABITAT	Object Based Image Analysis	J. Dijkstra	26
				Video Mosaics and Segmentation Techniques	Rzhanov	27
				Margin-wide Habitat Analysis	Mayer, J.Dijkstra, and Mosher	28
			COASTAL RESILIENCE and CHANGE DETECTION	Shoreline Change	Eren	29
				Seabed Change	Hughes Clarke	30
				Change in Benthic Habitat and Restoration	J. Dijkstra	31
				Marine Coastal Decision Support Tools	Butkiewicz and Vis Lab	32
				Temporal Stability of the Seafloor	Mayer	33
	THIRD PARTY and NON-TRADITIONAL DATA	THIRD PARTY DATA		Assessment of Quality of 3rd Party Data	Calder	34
		NON-TRADITIONAL DATA SOURCES	ALB	Assessment of ALB data	Eren	35
			SDB	Development of Techniques for Satellite Derived	Eren	36
TRANSORM CHARTING AND NAVIGATION	CHART ADEQUACY and COMPUTER-ASSISTED CARTOGRAPHY			Managing Hydrographic Data and Automated	Calder and Kastrisios	37
				Chart Adequacy and Re-survey Priorities	Calder, Kastrisios, and Masetti	38
				Hydrographic Data Manipulation Interfaces	Calder, Hughes Clarke, Butkiewicz, Ware	39
	COMPREHENSIVE CHARTS AND DECISION AIDS	INFORMATION SUPPORTING SITUATIONAL AWARENESS		Currents Waves and Weather	Ware, Sullivan, and Vis. Lab.	40
				Under-keel Clearance, Real-time and Predictive	Calder and Vis. Lab.	41
		CHARTS and DECISION AIDS		Ocean Flow Model Distribution and Accessibility	Sullivan	42
				Textual Nautical Information	Sullivan	43
				Augmented Reality Supporting Charting and Nav	Butkiewicz	44
	VISUALIZATION AND RESOURCE MANAGEMENT	GENERAL ENHANCEMENT OF VISUALIZATION		Tools for Visualizing Complex Ocean Data	Ware, Sullivan, and Vis. Lab.	45
				New interaction techniques	Butkiewicz	46
EXPLORE AND MAP THE EXTENDED CONTINENTAL SHELF	EXTENDED CONTINENTAL SHELF			Lead in Planning, Acquiring and Processing ECS	Gardner, Mosher, and Mayer	47
				Extended Continental Shelf Taskforce	Mosher, Gardner, and Mayer	48
				Best Approaches for Legacy Data: Delineation	Mosher, Gardner, and Mayer	49
	OCEAN EXPLORATION			ECS Data for Ecosystem Management	Mayer, Mosher, and J. Dijkstra	50
				Potential of MBES Data to Resolve Oceanographic	Weber, Mayer, and Hughes Clarke	51
	TELEPRESENCE AND ROVS			Immersive Live Views from ROV Feeds	Ware	52
HYDROGRAPHIC EXPERTISE	EDUCATION			Revisit Education Program	Hughes Clarke and S. Dijkstra	53
	ACOUSTIC PROPAGATION AND MARINE MAMMALS			Modelling Radiation Patterns of MBES	Weber and Lurton	54
				Web-based Tools for MBES Propagation	Johnson and Arsenault	55
				Impact of Sonars on Marine Mammals	Miksis-Olds	56
	PUBLICATIONS AND R2O			Continue Publication and R2O Transitions	Mayer	57
	OUTREACH			Expand Outreach and STEM Activiites	Hicks-Johnson and Mitchell	58
DATA MANAGEMENT	EXTENDED DATA MANAGEMENT PRACTICE			Data Sharing, ISO19115 Metadata	Johnson and Chadwick	59
				Enhanced Web Services for Data Management	Johnson	60

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

State-of-the-Art Sonar Calibration Facility

We continue to work closely with NOAA and the manufacturers of sonar and lidar systems to better understand and calibrate the behavior of the sensors used to make the hydrographic and other measurements used for ocean mapping. Many of these take advantage of our unique acoustic test tank facility—the largest of its kind in New England and now equipped with state-of-the-art test and calibration facilities. Upgrades to the facility include continuous monitoring of temperature and sound speed, a computer-controlled standard-target positioning system, and the capability for performing automated 2D beam-pattern measurements. The facility is routinely used by Center researchers for the now-routine measurements of beam pattern, driving-point impedance, transmitting voltage response (TVR), and receive sensitivity (RS). Among the systems calibrated this year were an Edgetech DW216 transducer, Imagenix DeltaT, Nortek ADCP, Acoustic Zooplankton Fish Profilers, hydrophones from Mitre Corporation, and a new prototype Edgetech projector.

We have put tremendous effort into developing techniques for the calibration of sonar in our acoustic tanks, but the reality is that it is difficult and time-consuming to bring a sonar to such a calibration facility. Thus, we are working to develop innovative approaches to calibrating sonars in the field, including the use of an extended surface target for field calibration of high-frequency multi-beam echo-sounders and the development of "standard line" or "reference surface approaches for field calibration. Finally, we are developing approaches for absolute field calibration of multibeam sonars mounted on small boats (like NOAA launches). Our efforts are focused on an approach where a standard sphere is suspended in the water column from monofilament lines connected to remote-controlled thrusted buoys that move continuously to position the acoustic target throughout the entire swath of the MBES sonar systems. The thrusters on the buoys are radio controlled from the vessel while wireless radio transceivers provide real-time location of the buoys with a precision of 10 cm at ranges of up to 300 m (Figure ES-2). There is an emphasis on making the buoys small, hand deployable, and easy to carry on survey launches.

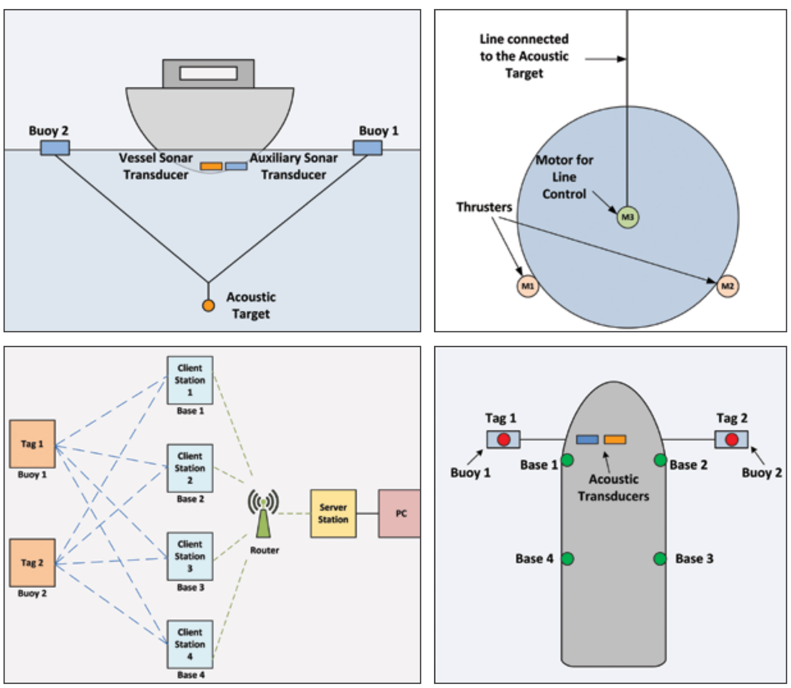


Figure ES-2. Target positioning mechanism using remote-controlled buoys. Top right: Buoy module; Bottom left: Real time location of tagged buoys using radio transceivers diagram; Bottom right: Location system setup on vessel.

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. In the example shown in Figure ES-3, coherence between multiple looks at an object is used to help discriminate man-made objects (even buried and partially buried) from background clutter. A component of this study is to understand the optimal processing parameters needed to extract manmade objects for the SAS data sets.

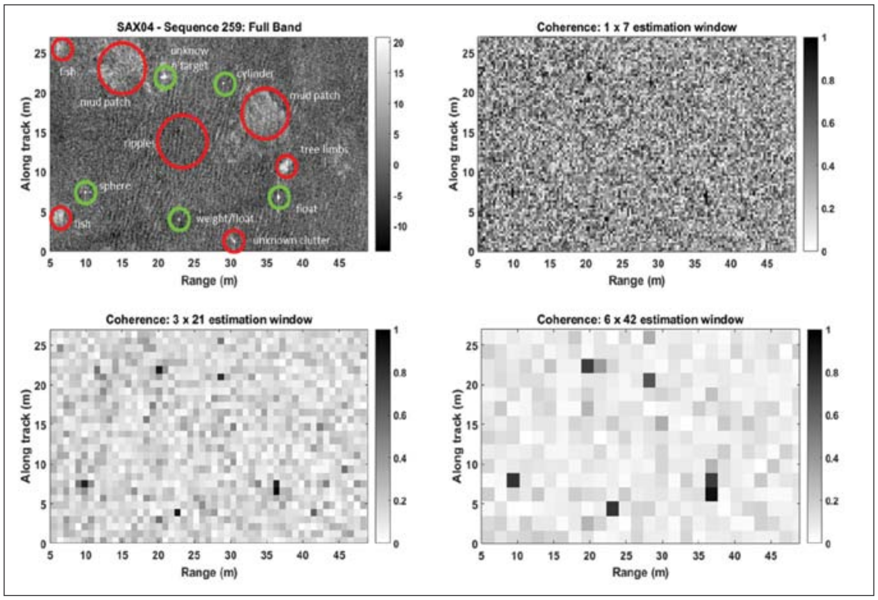


Figure ES-3. 30-50 kHz SAX04 rail-SAS intensity image (top left) includes buried, partially buried and proud targets on rippled sand (circled in green) and clutter objects (circled in red). Coherence estimated between a pair of sub-band images formed from the same 30 – 50 kHz dataset for variously-sized coherence estimation windows. The background coherence decreases as estimation bias decreases with larger window sizes.

Lidar Simulator and Understanding Uncertainty in Lidar Measurements

We have long recognized that one of the greatest challenges presented to the hydrographic community is the need to map very shallow coastal regions where multibeam echo sounding systems become less efficient. Airborne bathymetric lidar systems offer the possibility to rapidly collect bathymetric (and other) data in these very shallow regions, but there remains great uncertainty about the accuracy and resolution of these systems. Additionally, lidar (both bathymetric and terrestrial) offer the opportunity to extract other critical information about the coastal zone including seafloor characterization, habitat, and shoreline mapping data. We have thus invested heavily in lidar-based research on data processing approaches and a better understanding of the sensors themselves.

Large uncertainty remains as to the influence of the water column, surface wave conditions, and bottom type on an incident Airborne Laser Bathymetry (ALB) pulse. Unless these uncertainties can be quantified, the usefulness of ALB for hydrographic purposes will remain in question.

To address these questions, Firat Eren has continued to develop the Lidar Simulator—a device designed to emulate features of an ALB system in the laboratory. The simulator system includes a transmitter unit and a modular planar optical detector array as the receiver unit. The detector array is used to characterize the laser beam footprint and analyze waveform time series (Figure ES-4) in both horizontal (water surface measurements) and vertical (water column measurements) configurations.

Figure ES-4. Experimental setup at the UNH's Chase Ocean Engineering Lab with the optical detector array and the industrial fan that generated capillary waves.

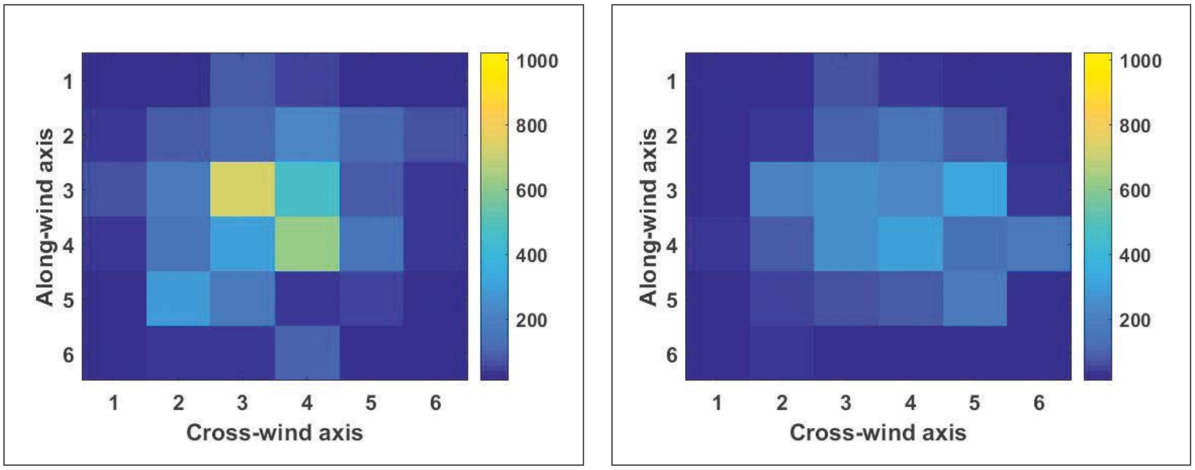


Figure ES-5. Optical detector array imageries sampled at two consecutive time steps from the optical detector array that is submerged into the water column.

Using this system, we are investigating the effect of variations in the water surface, the water column, and the bottom substrate, on the returned laser pulse in an ALB system (Figure ES-5).

In concert with these lab-based experiments, we are taking a theoretical look at the same problem in an attempt to characterize aqueous uncertainties associated with an Airborne Lidar Bathymetric measurement. These uncertainties start from the time the laser beam hits the water surface and end when the laser beam travels back through the water column to the receivers in the air. It includes the uncertainties contributed by the water surface, the water column, and the seafloor. Travel of the laser beam through the air is straightforward to model using standard geomatics approaches. However, the aqueous portion involves the complex interactions of the laser pulse with the instantaneous water surface, as well as the radiometric transfer interactions within the water column, which are difficult to model analytically. We are therefore using our empirical data to verify models, as well as applying Monte Carlo ray tracing to the primary factors that contribute to the uncertainty of the computed position of the lidar seafloor return, the water surface (Figure ES-6).

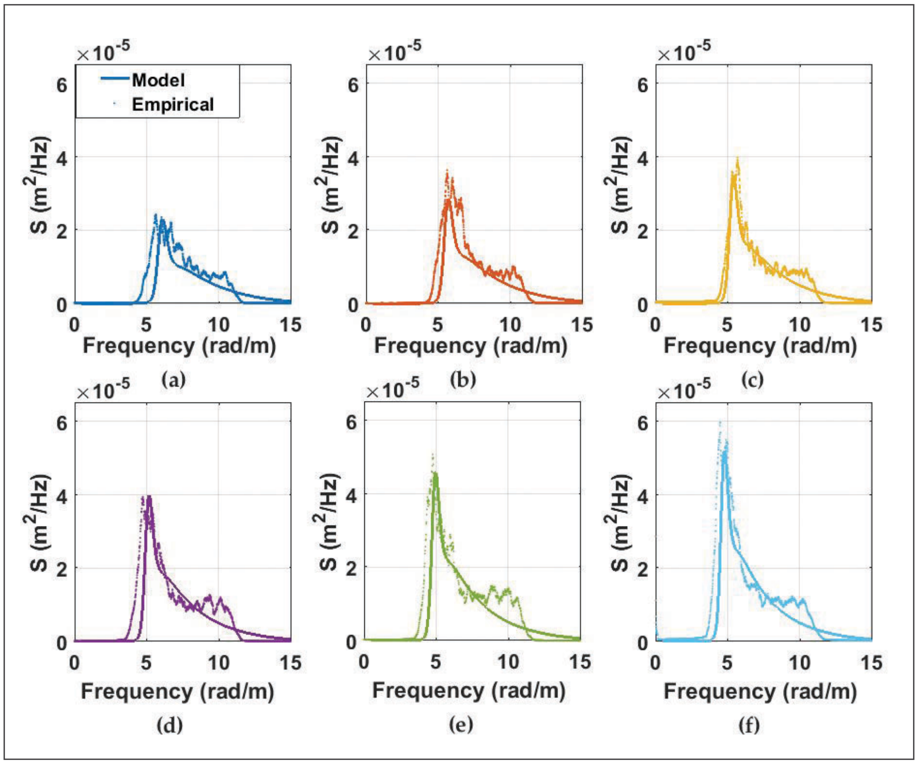


Figure ES-6. Experimental and model-derived wave spectrum. Distance from the fan: (a) 3.5 m; (b) 4.5 m; (c) 5.5 m; (d) 6.5 m; (e) 7.5 m and (f) 8.5 m.

The theoretical and empirical studies conducted in conjunction with our colleagues at Oregon State

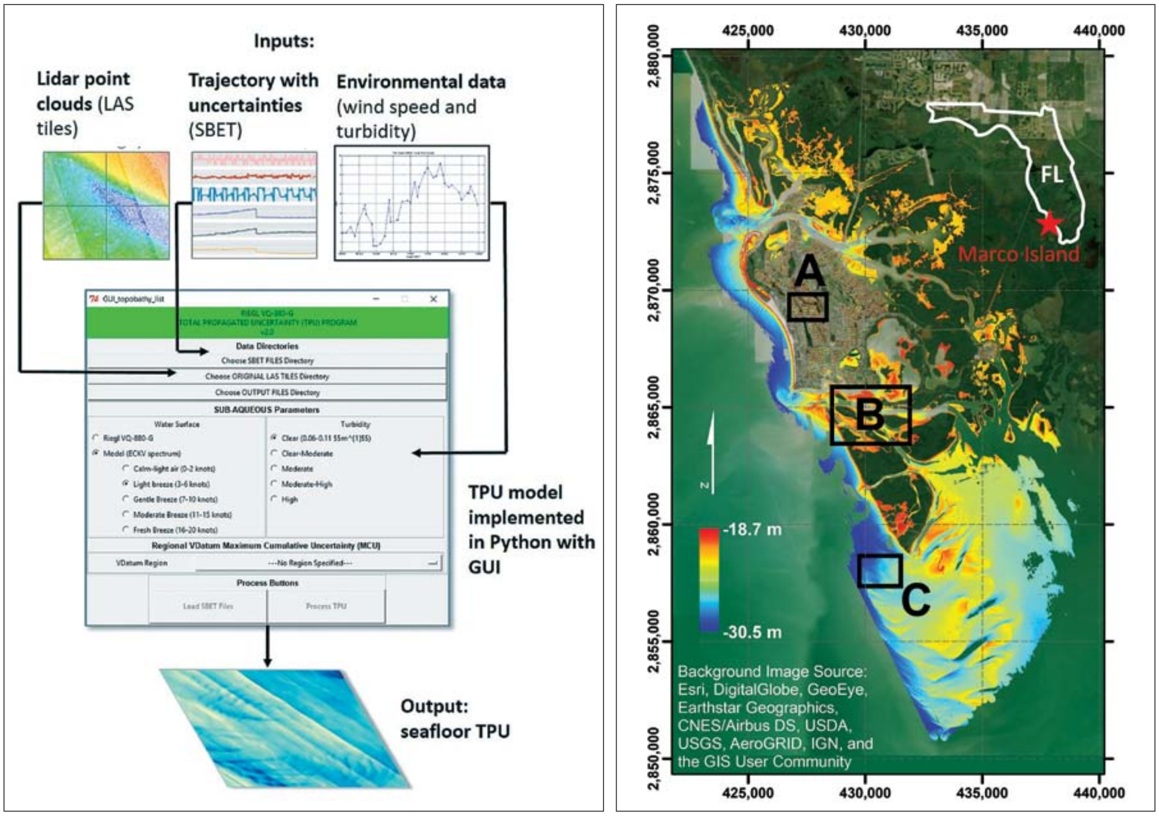


Figure ES-7. Left: Overview of cBLUE software, including inputs and output. Right: Topobathy lidar data collected by Riegl VQ-880-G system in Southwest Florida on May, 2016. The areas squared in A, B and C denote the residential area, shallow bathymetry and sand waves, respectively.

University described above have contributed to this year's debut, and adoption by the Remote Sensing Division of the National Geodetic Survey, of the Comprehensive Bathymetric Lidar Uncertainty Estimator (cBLUE) software package for calculating the Total Propagated Uncertainty (TPU) for topo-bathymetric lidar. cBLUE takes a number of input data sets and parameters, which are readily available in existing topographic-bathymetric processing workflows, computes per-pulse uncertainty estimates for seafloor points, and outputs uncertainty metadata, summary statistics, and point clouds with per-point uncertainty attributes, which can be used in generating total propagated uncertainty surfaces (Figure ES-7 left). The current version of the software has been developed for and tested on data from the Riegl VQ-880-G lidar system operated by NGS, although extension to other lidar systems is possible, and, in fact, is currently underway.

The first fully-operational version of cBLUE was evaluated by NOAA/NGS in January 2018. It was tested on a southwest Florida project (Figure ES-7 right), using Riegl VQ-880-G data. A comparison of computed TPU values was made against empirically-determined seafloor elevation uncertainties, based on the quantified spread in lidar-derived seafloor elevations within a number of flat seafloor patches in a range of depths. The results indicate that cBLUE is providing realistic, if slightly conservative, estimates of TPU.

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 adding 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 collaborative design efforts between the

Figure ES-8. The Center's fleet of Autonomous Surface Vessels.

Center and ASV Global LLC beginning in 2015 and delivered in 2016. Teledyne Oceansciences donated a Z-boat ASV, also 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. Most recently, through the Center's industrial partnership program, the Center acquired access to a new iXblue DriX ASV (Figure ES-8).

These various vehicles provide platforms for in- and off-shore seafloor survey work, product test and evaluation for the associated 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,

Figure ES-9. The Center's new mobile lab provides protective transport for ASVs, as well as a comfortable field work space for engineers, scientists, and students.

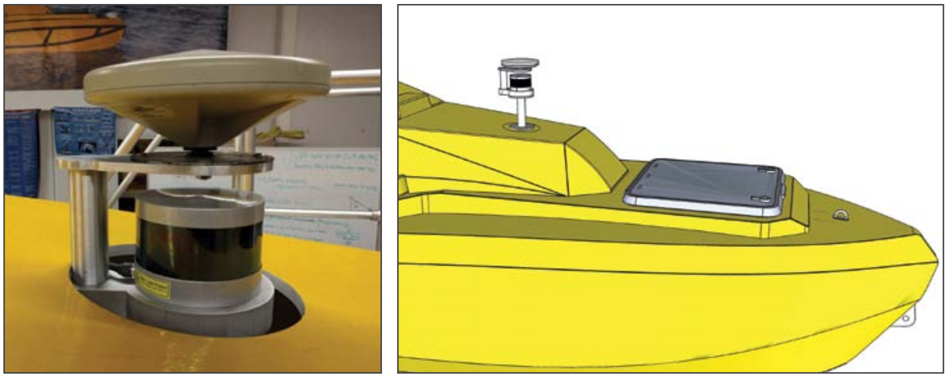


Figure ES-10. A mount designed for the Velodyne-16 Lidar for the C-Worker 4 ASV. The placement, optional standoff, and its aluminum fabrication, provide rigidity with respect to the vessel's attitude and positioning system while maintaining a good field of view for object detection and avoidance.

Davis began development of a robotic state machine for marine vehicles. In addition to all of this, the group deployed BEN aboard the NOAA Ship *Fairweather* in the Arctic and Ocean Exploration Ship the E/V *Nautilus* off the Channel Islands. At the very end of the year, we received the new DriX ASV and conducted preliminary sea trials off the New Hampshire coast. Details of all of these efforts can be found in the full progress report; highlights of few of them are described below.

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 and electrical payload dependent). The DriX is an ocean-capable vessel with a unique carbon fiber hull. Its maximum speed exceeds 13 knots and endurance exceeds five days at 8 knots.

This past year was a remarkably busy and productive year for the ASV group with the acquisition and outfitting of a new mobile lab (Figure ES-9), the testing of high-density LiOH battery systems for the small ASVs, field trials of Silvus radio telemetry systems for operation with NOAA vessels, and the design and manufacture of skegs for BEN to improve line driving. Numerous other engineering enhancements were made to BEN including design and field trial of a new Velodyne Hi-Res lidar for obstacle avoidance and shoreline mapping (Figure ES-10), design of a new sensor/antenna mount, integration of an engine room FLIR camera to better monitor engine conditions and overheating (Figure ES-11), and modifications to the antenna mast for shipping. In addition, many software enhancements were made to "Project 11," the Center's marine robotics framework, and the "CCOM Autonomous Mission Planner," which provides survey planning tools for our entire fleet of autonomous systems. Sam Reed finalized his thesis work on nautical chart-based path planning, Coral Moreno began her graduate work on robotic perception at sea, and Lynette

The "Project 11" Marine Robotics Framework

To provide a research and development environment for increased autonomy and functionality for our vehicles, a marine robotics framework, dubbed "Project 11," is being developed by Arsenault, Schmidt, and others, and is based on the widely popular Robotic Operating System (ROS). It is designed to be portable and work with the various autonomous vehicles in the Center's fleet. Line following capability

Figure ES-11. A thermal image taken from the C-Worker 4's new engine room FLIR camera is shown. The engine is secured in this image, but the unit allows operators to easily monitor critical drive-train temperatures during operation in the event of fouling or other failure.

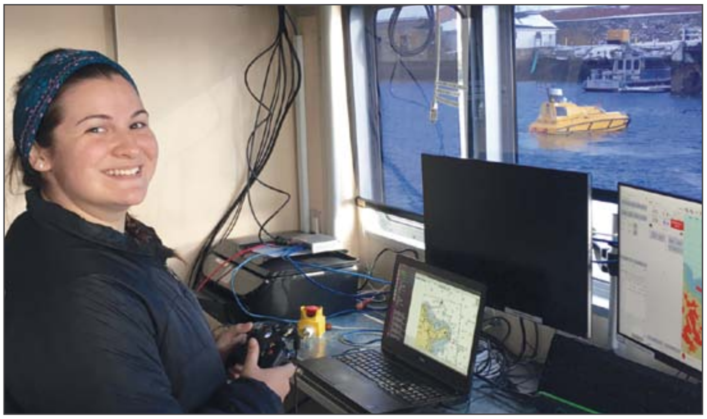


Figure ES-12. Olivia Dube, an Ocean Engineering undergraduate and ASV Group intern, testing an X-box controller for remote-piloted operation of the Center's C-Worker 4 ASV.

is handled by the MIT open-source package "MOOS IvP Helm" (for vessels that do not provide it natively) while ROS provides a middleware layer allowing the various nodes to publish and/or subscribe to data streams, and a framework for data logging and playback. A joystick controller has been integrated to allow manual piloting of a vehicle from an X-box controller (Figure ES-12).

Nautical Chart-Based Path Planning

Safe navigation of any autonomous vessel requires the ability to interpret a nautical chart. The goal of Reed's master's research is to utilize nautical charts to increase the autonomy of autonomous robotic vessels (ASVs) by giving an environmentally-aware mission plan and, if the ASV is taken off its desired path, to remain safe by adjusting its path to avoid known obstacles. In many cases, an obstacle can be avoided *a priori* utilizing chart information during mission planning (Figure ES-13), however, the vehicle must also have the ability to avoid obstacles in real time (Figure ES-14).

Robotic Perception and Deep Learning for Computer Vision at Sea

If ASVs are to operate safely and be truly autonomous, a means must be developed to increase the ASV's awareness of its environment so it can safely maneuver with minimal operator intervention. Graduate student Coral Moreno is laying the groundwork for a review of sensing systems that might be used by ASVs to identify obstacles on the surface and underwater—assessing their detection and classification capabilities, their limitations and uncertainties, and their ability to apply deep learning techniques to identify hazards to navigation and classify them as such (Figure ES-15).

ASV Operations

Arctic Ops on NOAA Ship *Fairweather*

The Center has been working to find opportunities to operate and evaluate BEN with the NOAA fleet. On 28 May, BEN and the ASV's field kit were loaded into a 40-foot container for shipment to Kodiak, Alaska, where it was subsequently loaded on board the *Fairweather* in preparation for a collaborative mapping event in the vicinity of Point Hope, AK in late July (Figure ES-16). Among the many challenges to operating BEN in collaboration with the *Fairweather* is the difference in their respective survey speeds. BEN's maximum speed is 5.5 knots, while the *Fairweather* can comfortably

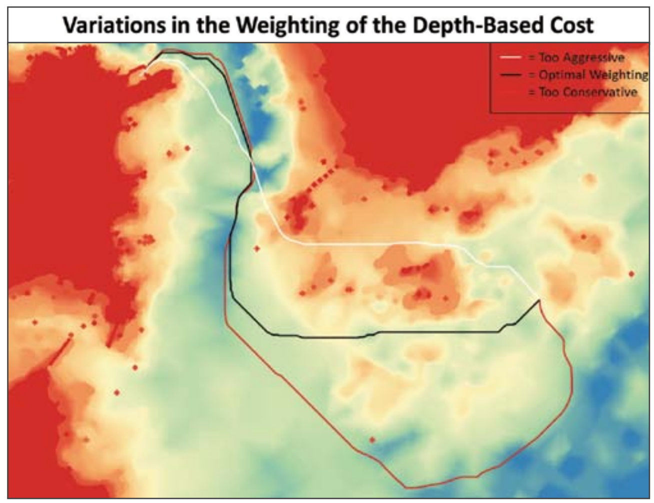


Figure ES-13. Here Nautical Chart based path planning. The charted depths and chart features have been generalized to indicate risk (red=increased risk) and three paths are illustrated whose risk toler-

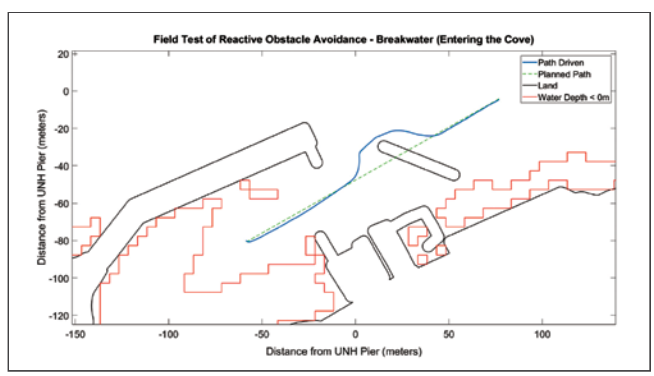


Figure ES-14. Sam Reed's reactive obstacle avoidance algorithm is illustrated with field data measured aboard the Center's Echoboat. The ASV deviates from the path planned purposefully across a charted floating breakwater as it is approached, safely resuming the path on the other side.

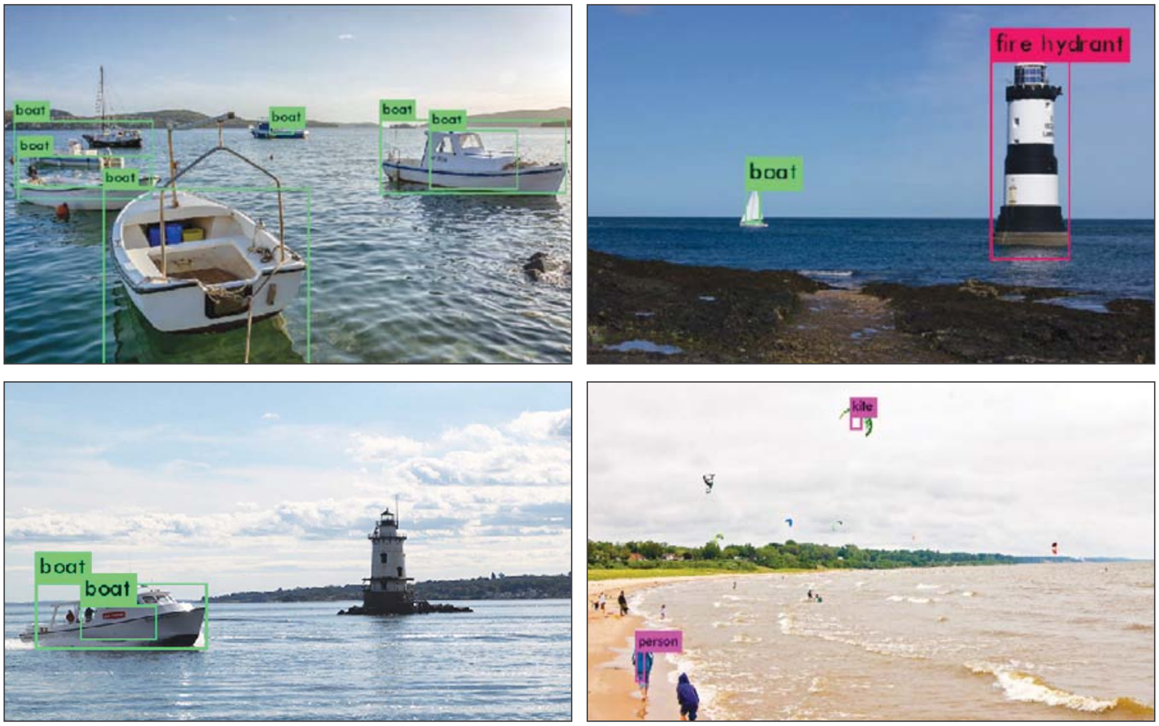


Figure ES-15. A pre-trained version of the "YOLO" algorithm is tested on images of objects in a marine environment to determine the suitability for object identification and classification.

survey at 10 knots, so tandem operation for long linear stretches with constant telemetry is not possible. Therefore, we developed survey geometries that would synchronize survey operations while keeping constant telemetry (Figure ES-17).

Operations Aboard the E/V *Nautilus* for "Submerged Shorelines of the California Borderland"

In November, BEN deployed aboard the E/V *Nautilus* to provide a shallow water mapping asset for ongoing exploration of submerged paleo-shorelines and underwater caves in the vicinity of the Channel Islands off

Figure ES-16. July and August deployment of BEN off the NOAA Ship *Fairweather*. (Photo courtesy Christina Belton, NOAA)

Figure ES-17. The overview image on the left shows combined survey coverage by NOAA and BEN (197 km^2) in the vicinity of Point Hope, AK. This overview map includes data collected over 21 survey days by NOAA launches and 6 survey days for BEN. The right image shows BEN's contribution alone (27 km^2)

the California coast. Operations aboard *Nautilus* again demonstrated the value of the ASV for high-resolution mapping in proximity to steep shorelines and other coastal obstacles. It also afforded us with opportunities to develop and field test new features in our software. These include the ability to automatically rotate sonar log files when the end of a survey line is reached, a new ROS node for the SEAPATH positioning system, the ability to display the operator's ship in proper dimensions with the mission planner GUI, and a new ROS node for Kongsberg sonar systems allowing real-time 3D display of sonar data within ROS tools.

Test and Evaluation of iXblue "DriX" ASV in New Castle, New Hampshire

In late November and December, the Center began a formal collaboration with iXblue. Through an industrial partnership agreement and with support from NOAA's Office of Marine and Aviation Operations, iXblue's "DriX" unmanned surface vehicle will be housed at UNH and provide for 20 days of operation each year. The DriX is a unique ASV whose hydrodynamic carbon fiber design provides for long endurance and high speeds. During these operations, tests were made of the DriX's survey capability as a function of vessel speed. Surveys were run at 8 knots, 10 knots, and 12 knots with a Kongsberg EM2040 (0.7x0.7 degree) system having "Dual Swath" and "High Density" features, without compromise of data quality (Figure ES-19).

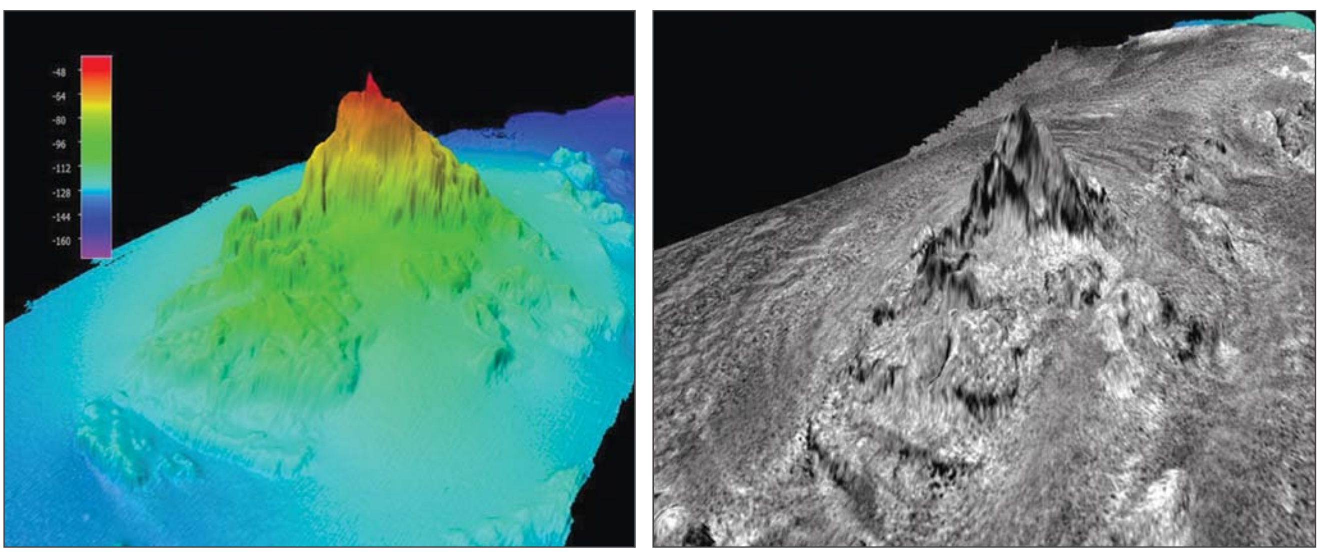


Figure ES-18. Perspective image of the "Matterhorn," a seafloor feature approximately 30 km northwest of Santa Barbara Island, California. 2X VE, facing east and colored by depth (depths in meters) [top] and by backscatter intensity [bottom] with white indicating high intensity returns and black indicating low intensity returns.

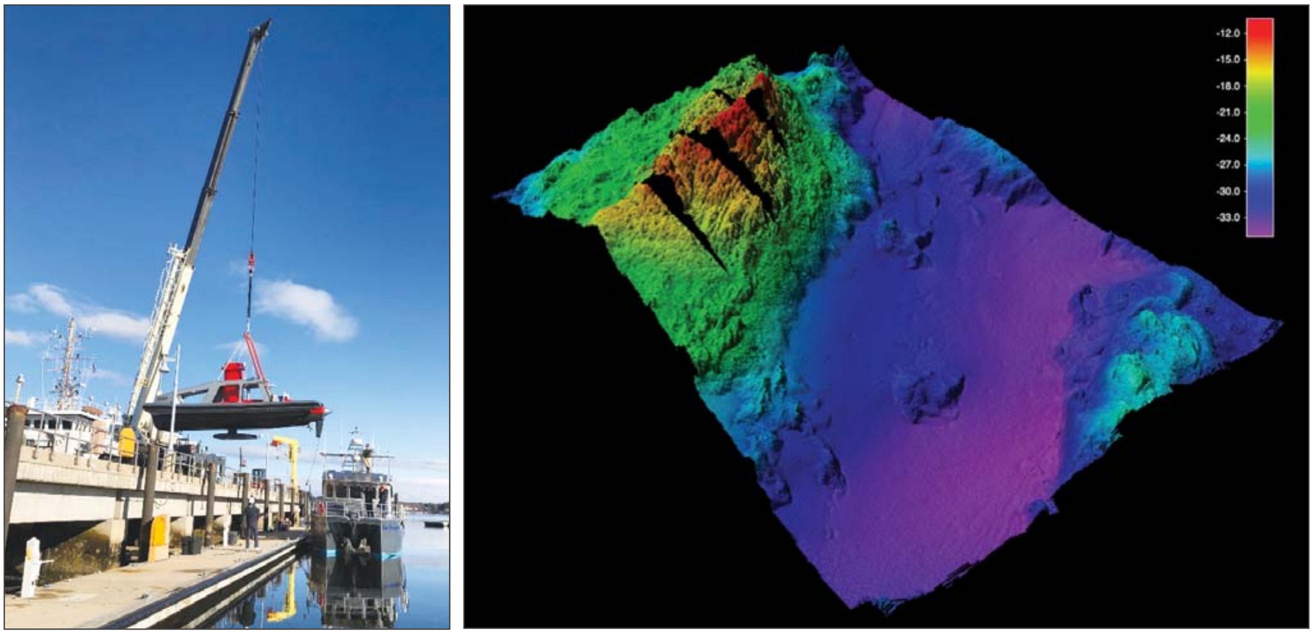


Figure ES-19. Left: Craning the DriX into the water at the UNH Pier. Right: DriX test survey area measuring 450 m x 600 m with water depths from 14 m to 35 m.

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 we 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.

Sector Boundary Offset Wobbles

A subtle but significant source of periodic bathymetric artifacts in multi-sector sonars is that offsets between the sector boundaries can appear and disappear with the transmit steering associated with yaw stabilization.

There are major benefits that come from the adoption of multi-sector yaw stabilization (most significantly more even sounding density and thus better target detection). However, the use of heavy transmit steering by yaw-stabilized systems significantly increases the requirement for precise array alignment and offset surveys (Figure ES-20).

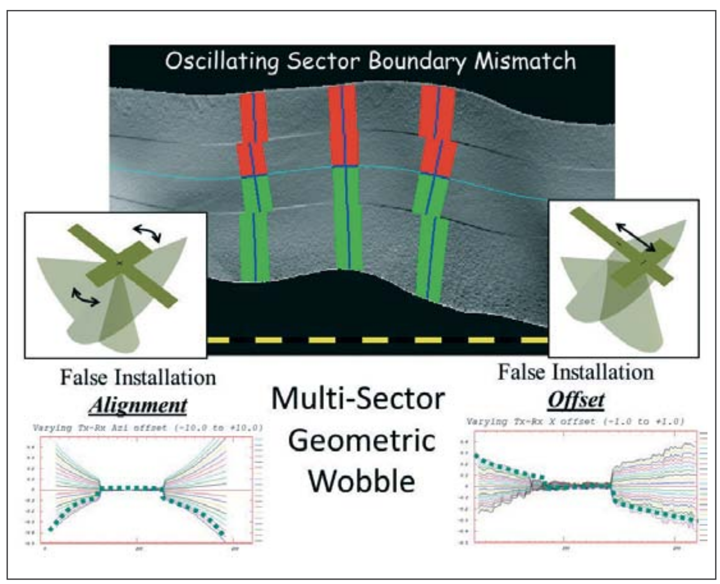


Figure ES-20. The appearance of periodic sector boundary offset due to incorrect transmit-receive alignment or offsets. With NOAA's recent conversion to multi-sector yaw-stabilized systems, these are a new potential source of error.

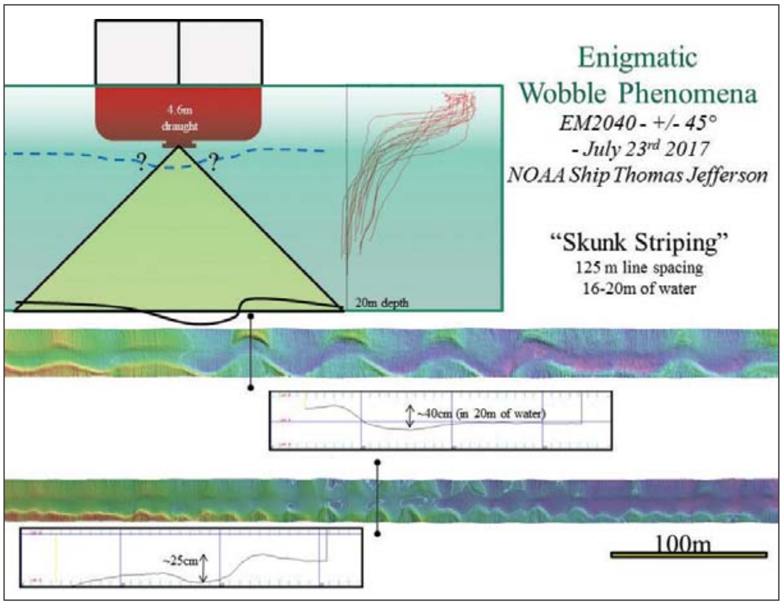


Figure ES-21. The appearance of the periodic artifact generated when the EM2040 on the *Thomas Jefferson* was operated very close to a strong summertime thermocline. Notably, while the anomaly is clearly motion correlated, the correlation is not consistently associated with a single motion (e.g., roll or heave). Thus it cannot be backed out in post-processing.

Thermocline-Associated Wobble

In July of the 2017 field season, a particularly disturbing motion-correlated bathymetric artifact was noted when the NOAA Ship *Thomas Jefferson* was operating off the coast of Virginia Beach in the presence of a strong thermocline that was particularly close to the depth of the EM2040 on the gondola (Figure ES-21). The anomaly is believed to be due to a dynamic distortion of the thermocline that results from the bow wave of the hull pushing the thermocline down just under the gondola. As such, it is very sensitive to the depth of the main thermocline relative to the depth of the keel.

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 data set. The new approach being developed by Maingot uses the individual beam depth errors as an input to a least squares minimization approach that can simultaneously solve for multiple sources of integration error which may be present at the same time. A sounding location equation is developed in which the impact of various integration errors is geometrically calculated. To test the efficacy of this approach, Maingot has developed a simulator which can generate depth anomalies through deliberate integration errors (Figure ES-22).

Through simulating the driving signatures of the sonar system (vessel orientation and motion, and resulting stabilization), as it passes over a model of a curved seafloor, an ideal synthetic data set may be generated containing various systematic errors.

Multiple regressions computed over contiguous domains provide statistical estimates of the integration errors and, thus, provide approaches for resolving the problem (Figure ES-23).

Sound Speed Manager (HydrOffice)

We also continue to focus on the development of 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 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 Survey 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

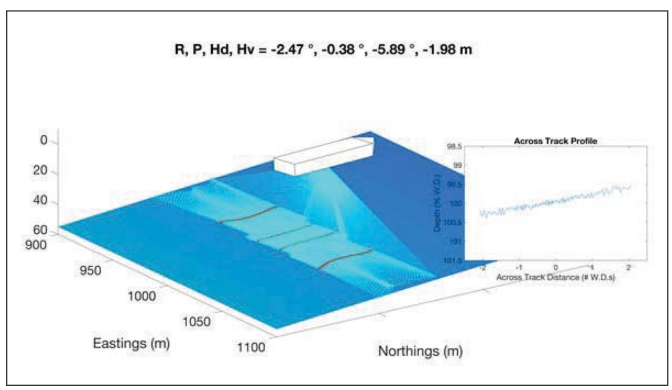


Figure ES-22. Snapshot of swath simulator modeling the sounding pattern of a multi-sector system irregularly sampling a seafloor with curvature. A synthetic seafloor is defined as a sinusoid with 100-meter amplitude and 4 km wavelength. A mathematical intersection with the surface is calculated and integration error of 20 ms motion latency is applied to the sounding position, producing true and erroneous dataset for analysis and comparison. Gaussian noise is applied to soundings resulting in the noisy across track profile, inset, while the tilt, or wobble, is entirely a result of integration error. (M.S. thesis of Brandon Maingot).

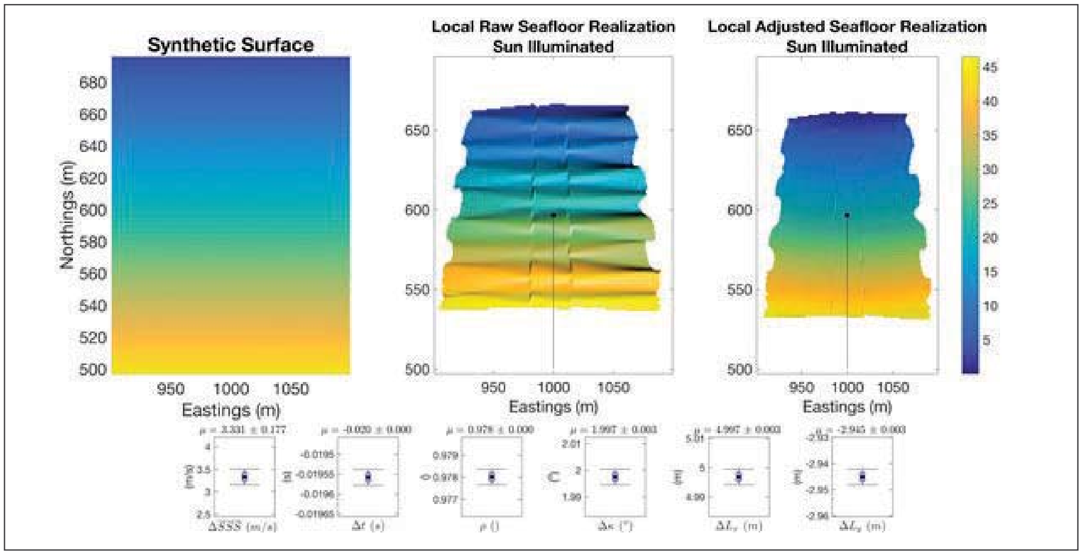


Figure ES-23. Plan view of surfaces gridded to 1-meter resolution: (left) synthetic surface (truth, A=100 m, L = 1,000 m); (center) data set simulated by system with multiple sources of error/two-degree heading mis-alignment; (right) same dataset calibrated by least squares regression (Least Squares Geometric Calibrator,

storage. (This tool 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)). The Sound Speed Manager is now in wide use across the NOAA, UNOLS, and other fleets. This past year has seen numerous improvements to the user interface, systems supported, database capabilities, and other functionalities (Figure ES-24).

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 areas where they are or will be working, Center researchers have been developing SmartMap (Sea Mapper's Acoustic Ray Tracing Monitor and

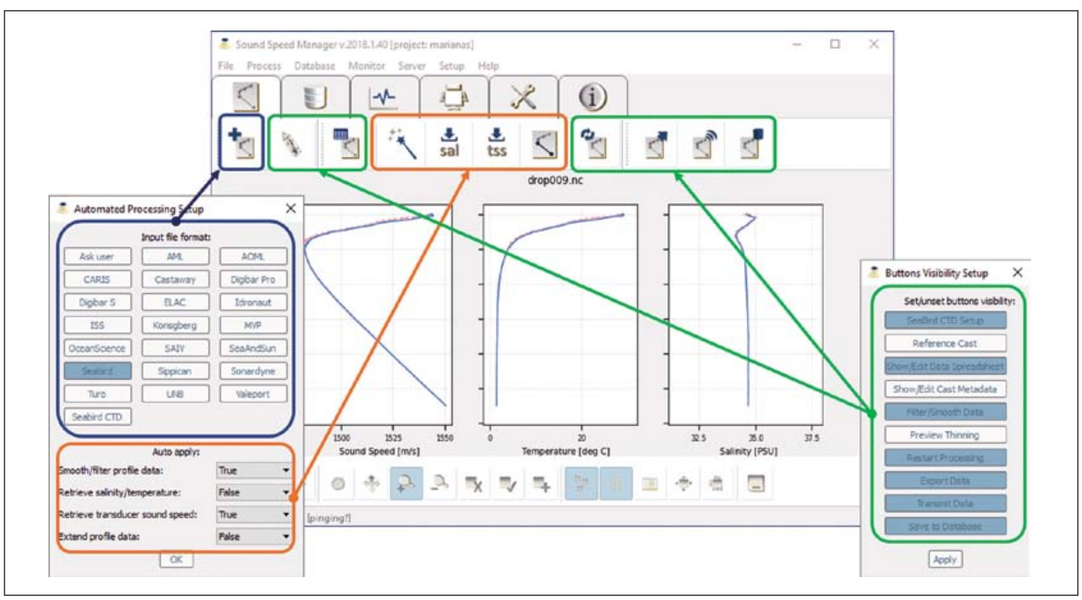


Figure ES-24. The Automated Processing Setup tool was introduced in SSM to reduce the number of clicks in processing. The user can now pre-select the file format (so that it does not need to be selected each time that a new profile is imported) and ask SSM to automatically apply several processing steps. The Buttons Visibility setup can be used to reduce unrequired clutter in the toolbars.

Planning) to provide tools to evaluate the impact of oceanographic temporal and spatial variability on hydrographic surveys. The tool (Figure ES-25) highlights areas where particularly high or low variability in the sound speed are 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). Currently, the predictions can be made based on the Global Real-time Operational Forecast System (RTOFS), and the World Ocean Atlas 2013 for climatology.

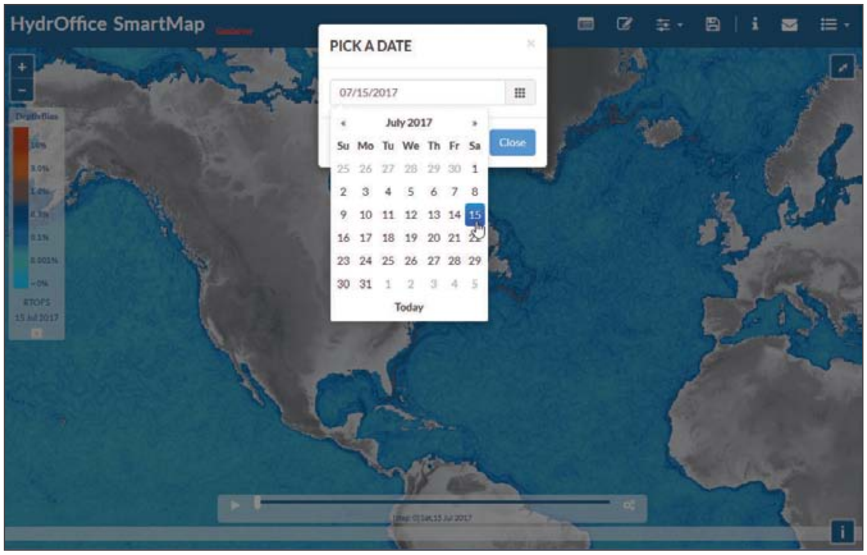


Figure ES-25. The SmartMap Web GIS provides access to past analyses that have been generated since July 2017.

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 a 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 the "wisdom of the crowd" for data quality, attempting to wring out valid data from uncontrolled observations, or trying to establish a trusted observer qualification, we consider 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. The originally proposed plan for this task was to develop such a system independently, but collaborating with SeaID, who already produces data loggers of this type and strongly interacts 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%), Figure ES-26, 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 antenna made by Harxon Corporation, which is the intended "production" antenna for the system (being significantly cheaper).

A key issue with any sort of community-based data collection is to establish the community. After discussions with cruise ship captains (Allen Marine Tours, Alaska) and Seabed 2030 (Dr. Martin Jakobsson, Stockholm University) on the potential for TCB systems to augment their respective efforts, Calder and his collaborators have drafted an "expectations" document that is intended to explain the goals of the project, the technology, and what would be required to integrate the system with a user's ship. The document is available from the Center's website publications list; the discussion with the interested parties is ongoing.

Data Processing

Next Generation Automated Processing Approaches – CHRT

In concert with our efforts focused on understanding the behavior and limitations of the sensors we use to collect hydrographic data, we are developing a suite of processing tools that aim to improve the efficiency of producing the end-products we desire and, just as importantly, to quantify 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 available data density. 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.

In principle, the core CHRT algorithm is complete and has been licensed to the Center's Industrial Partners for implementation, but modifications—some significant—continue to be made as the research progresses. Thus, in the current reporting period, the algorithm's dependence on OpenGL, which proved to be difficult to standardize across platforms and graphic card hardware implementations, was removed and a version of the level of aggregation (LoA) resolution determination—first developed for lidar data—was adapted for acoustic data. In addition, efforts continue to increase the speed and efficiency of CHRT through adaptation for distributed, embedded, and cloud-based processing.

Streamlining the NOAA Hydrographic Processing Workflow – HydrOffice

We continue to work closely with NOAA Office of Coast Survey (OCS) to identify challenges and needs facing those doing hydrographic processing using current NOAA tools, both in the field and in the office. Since 2015, Giuseppe Masetti and Brian Calder have collaborated with Matthew Wilson (formerly NOAA Atlantic Hydrographic Branch, now QPS b.v.) and NOAA HSTB personnel to develop a suite of analysis tools designed specifically to address quality control problems discovered in the NOAA hydrographic workflow (QC Tools). Like Sound Speed Manager and SmartMap, these processing tools were built within the HydrOffice tool-support framework (https://www.hydroffice.org), and have seen enthusiastic adoption 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.

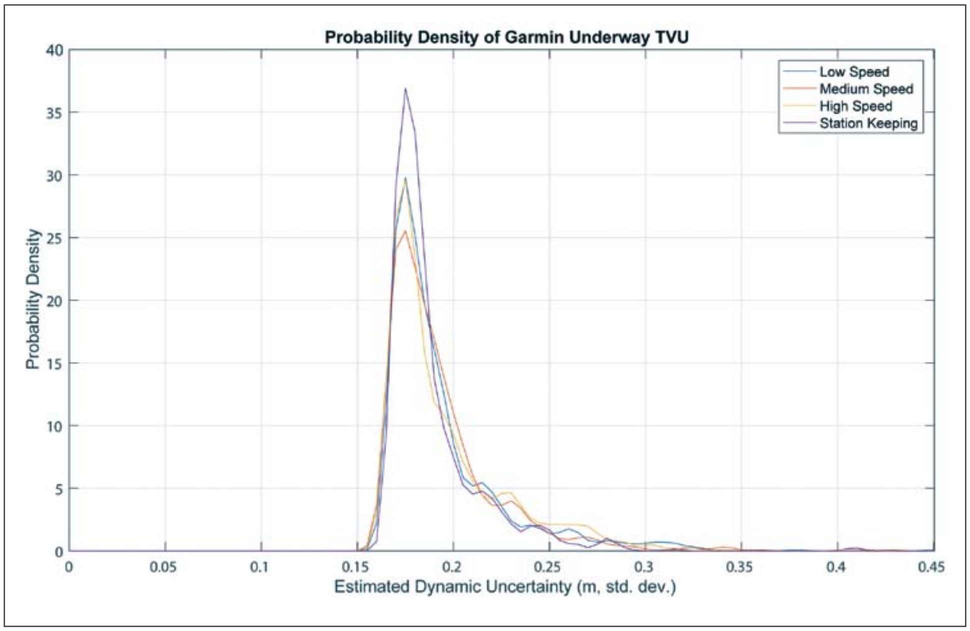


Figure ES-26. Estimated underway total vertical uncertainty (TVU) for all ellipsoid-referenced soundings in water of approximately 15m depth (to chart datum). Note the minimal variability in uncertainty associated with speed. The IHO S.44 Order 1B survey requirement for TVU in this depth is 0.274m on the same scale, which almost all of the observations meet.

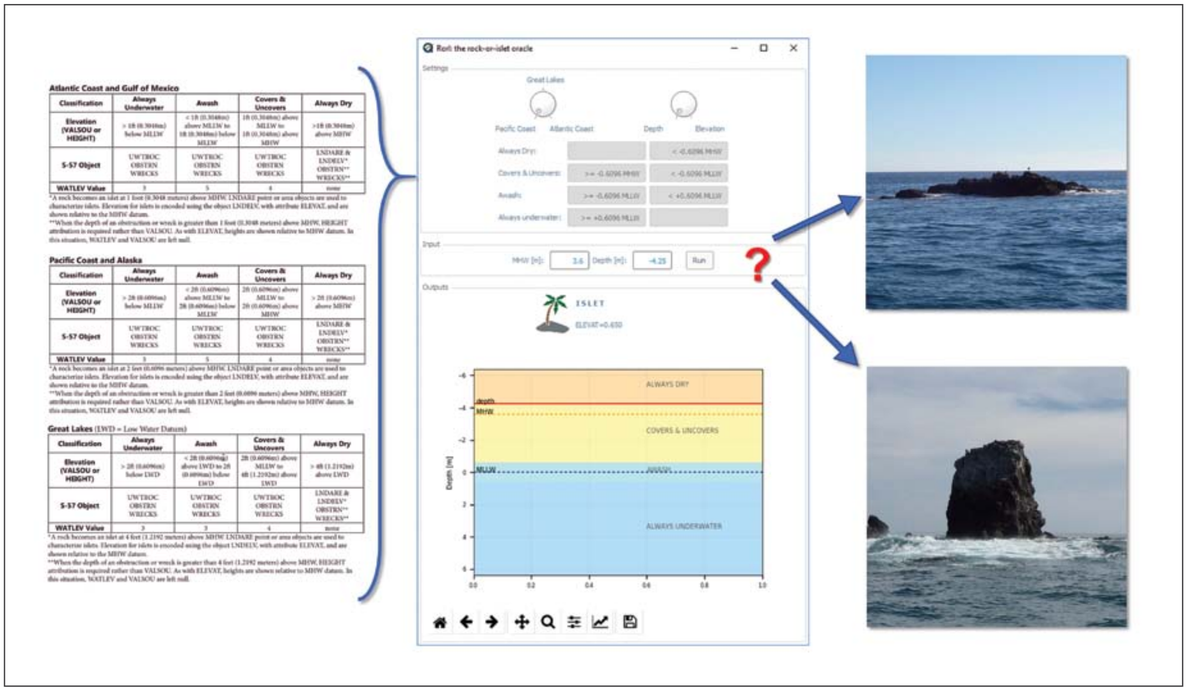


Figure ES-27. The Rock-or-Islet (Rori) tool supports the hydrographer in determining if a given feature is a rock or an islet. Rori also helps the hydrographer to visualize the difference between a rock and an islet for their survey using a graphic.

QC Tools, 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.

In this reporting period, QC Tools improved existing sub-tools to enhance the detection of anomalous data (the "Find Fliers" algorithm), to add the validation of elevation-related feature attributes in the Feature Scan algorithm and to support the creation of geo-tagged images and shapefiles from the bottom sampling information stored in the (Seabed Area) SBDARE features. In addition, two complementary tools have been introduced to aid the analyst during data processing: a tool to assist the hydrographer in defining a feature as a rock or an islet (Figure ES-27), and a tool to help the hydrographer examine and experiment with models of the total vertical uncertainty and total horizontal uncertainty of hydrographic data.

The QC Tools application is supported by publicly available documentation, as well as NOAA-generated instructional videos, available through the HydrOffice website or directly via YouTube. The QC Tools development team was invited by the Naval Oceanographic Office Fleet Survey Team to provide training on the application during the week-long FST/OCS/JHC Technical Exchange at Stennis Space Center (Stennis, MS) in November 2018.

Processing Backscatter Data

Seafloor Backscatter

Along with bathymetry data, our sonar systems also collect backscatter (amplitude) data. Previous progress reports 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 approaches to correct for sector beam pattern artifacts and to correct backscatter mosaics from drop-outs 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 have been developed that allow the user to extract the angular response for site-specific areas at all the available frequencies (between two and eight, depending on the sonar configuration and how many passes are acquired). As shown in Figure ES-28, different sediment types show significantly different angular response curves at different frequencies.

Water Column Backscatter

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 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.

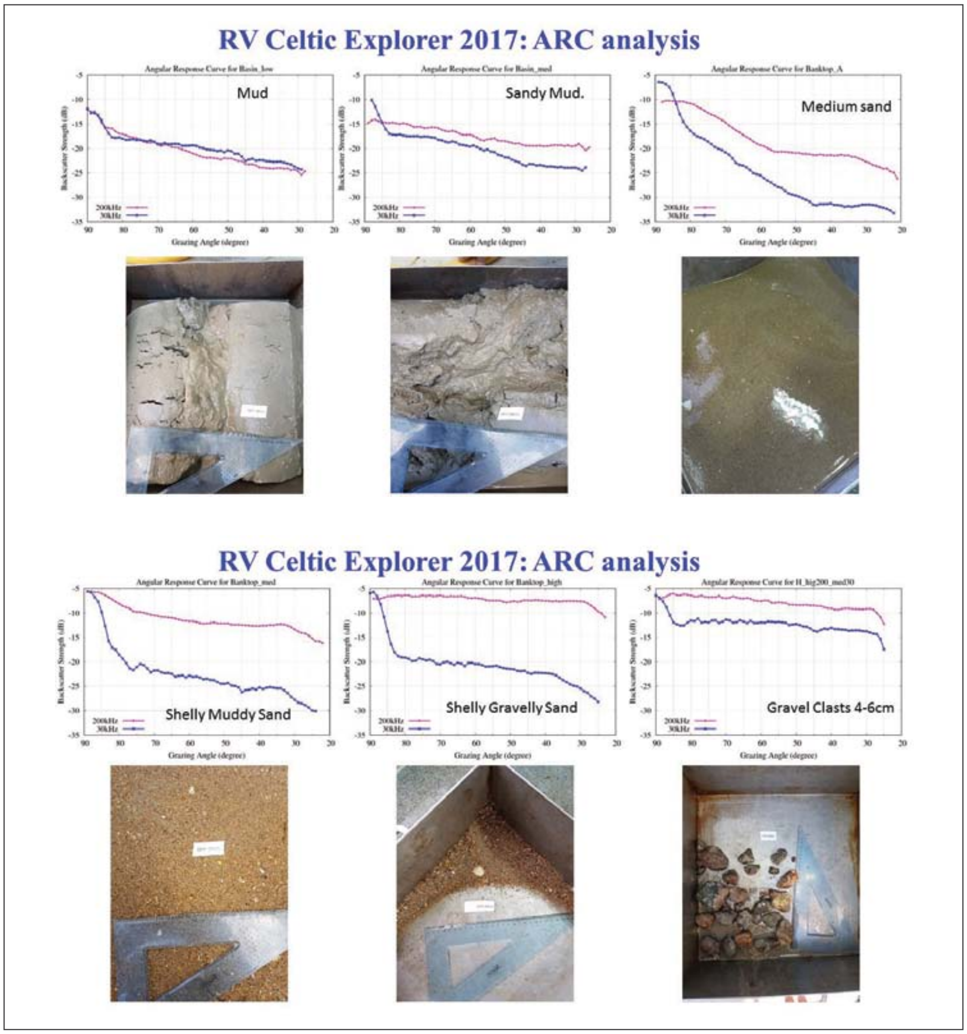


Figure ES-28. Six examples of paired 30 and 200 kHz angular response curves and the corresponding grab recovered from the Celtic Sea continental shelf (R/V *Celtic Explorer*, 2017).

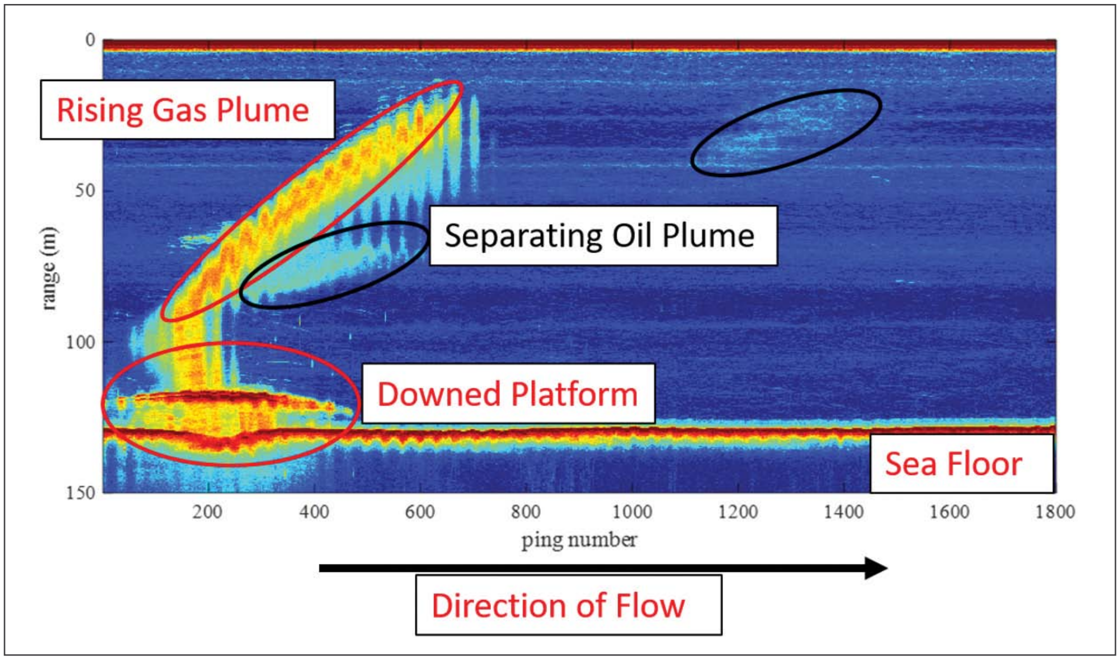


Figure ES-29. Acoustic results for Gulf of Mexico anthropogenic seep survey. The bottom left of the image shows the downed platform resting on the seafloor. The vessel was traveling in the direction of the dominant flow in the area. Higher ping numbers are associated with greater distance downstream. The oil can be seen below the gas plume and farther downstream due to its lower rise rate. The vessel temporarily traveled outside of the plume area before return to the plume at the second black circled area of rising oil. Many passes were performed to get a clear view of the entire plume.

This year, we had the opportunity to participate in a cruise dedicated to addressing these questions on the New Zealand-based 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 split-beam echo sounders operating at frequencies ranging from 15-25 kHz, a 30 kHz EM302, and a 200 kHz EM2040. Ground truth data was collected using a camera tow-sled and water sampling. The Center contributed a synthetic gas-bubble generator, developed by former student Kevin Rychert with funding from NSF, which was used to test detec-

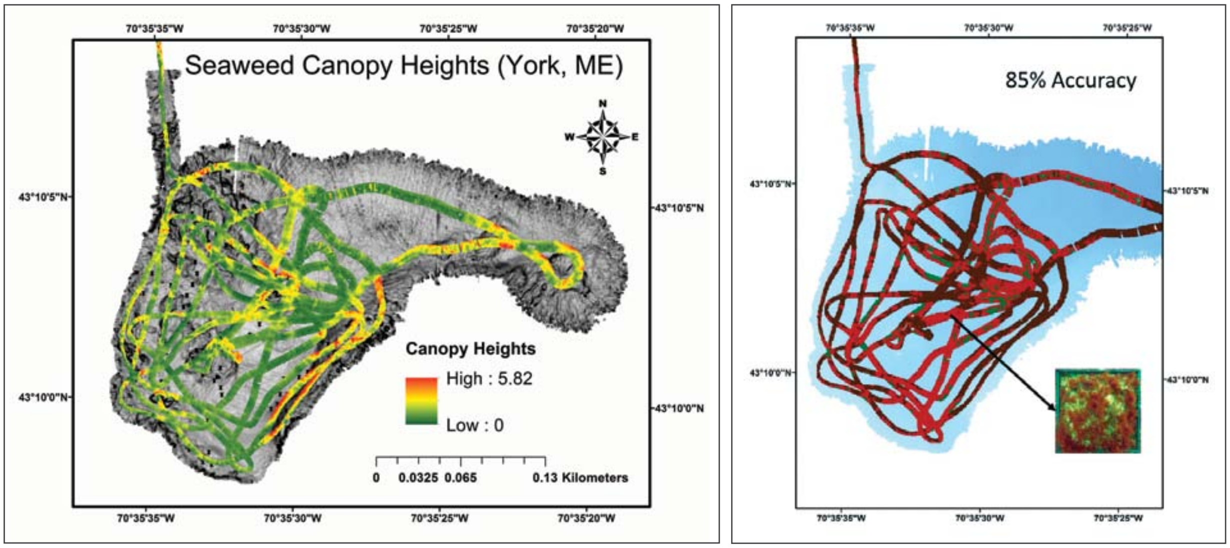


Figure ES-30. Left: Acoustically mapped macroalgae canopy heights and bathymetry of the cove at Nubble Light House, York, ME. Right: Interpretation of three habitat types [kelp (red), short macroalgae (brown) and bare space (green)]. Habitat patchiness is observed within the swath. The accuracy of the classification (kelp and short macroalgae habitat) was 85%.

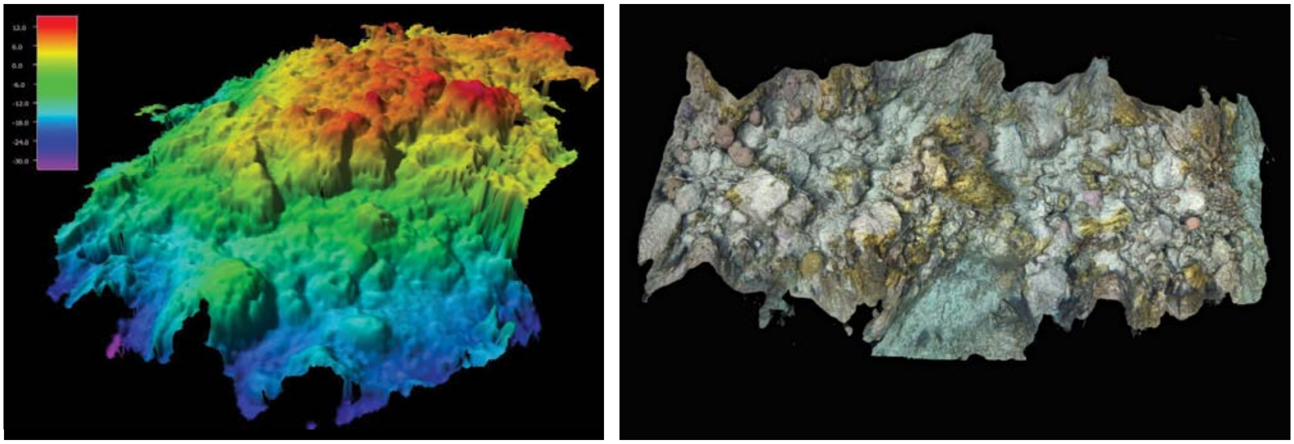


Figure ES-31. Left: Bathymetry created from underwater video footage of coral habitats. By creating these images of each coral site, we can calculate roughness, rugosity and slope. Right: Top-down view of 3D reconstruction of the seafloor from ~900 frames of video.

tion limits and perform cross-calibrations between different systems. Overall, the cruise represented many opportunities to collaborate with researchers interested in this topic from around the globe, and these collaborations seem likely to persist well into the future.

Our water column efforts also focus on oil and the ability to separate the acoustic imaging of oil and gas. Scott Loranger, under the supervision of Tom Weber and while working on his doctoral thesis—which he successfully defended in November—undertook both tank experiments where empirical observations of single oil droplets were made, as well as laboratory measurements of crude oil density and sound speed. The results of these efforts were applied to data collected at an anthropogenic seep site in the Gulf of Mexico (Taylor Energy site, MC20) where a broadband echo sounder has been used to characterize the leaking oil (Figure ES-29).

Mapping Eelgrass and Coral Reef Habitats

We are combining our efforts to quantitatively extract information about seafloor character from acoustic data with field studies aimed at the direct mapping of critical habitats. These studies include our efforts to better understand the acoustic character of eel grass under varying current conditions (Figure ES-30) as well as our work using structure from motion from video imagery to generate 3-D visualizations of coral habitats (Figure ES-31).

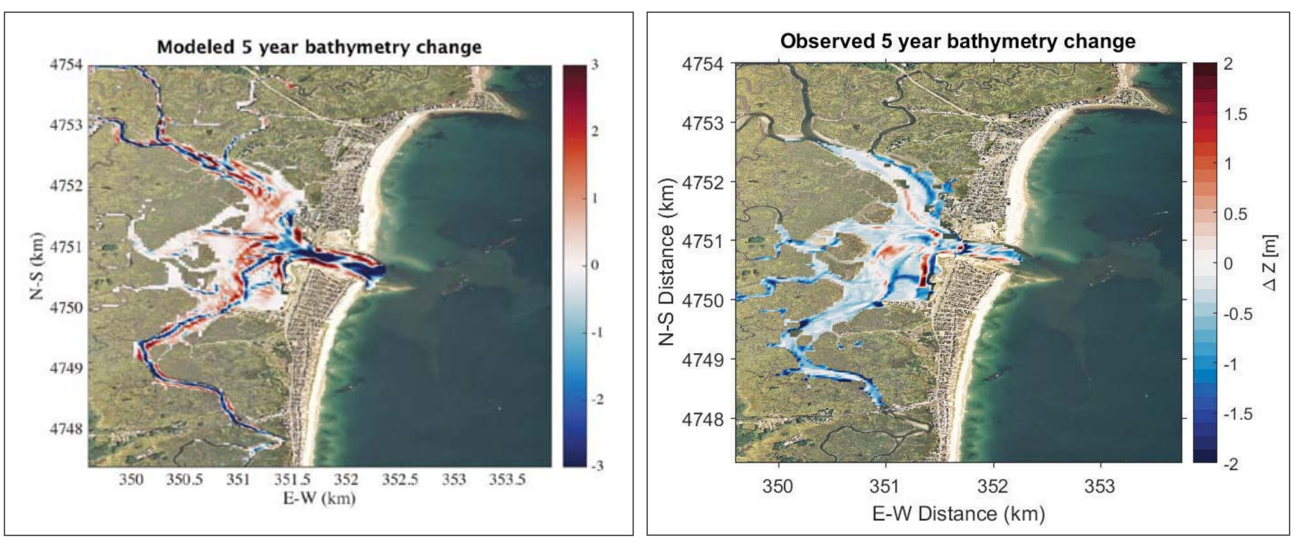


Figure ES-32. Left: Modeled bathymetric changes for five year period. Right: Observed bathymetric changes over five-year period.

Modeling Temporal Changes in the Seafloor

In the context of hydrographic surveying in there is an often ignored question of the temporal stability of the seafloor and how this impacts the need for repeat surveys to keep the charts at the needed level of accuracy. To explore this issue, Tom Lippmann and graduate students Kate von Krusenstiern and Cassie Bongiovanni are assessing the quality of bathymetric data in shallow navigable waterways, aiming to determine the "likelihood" that a nautical chart depth in an energetic shallow water region with unconsolidated sediment is valid a certain length of time after the data was collected. This will allow us to determine re-survey timescales in shallow water sedimentary environments with commercial and recreational navigational needs.

Von Krusenstiern's efforts have focused on the creation of a composite topographic-bathymetric model of the Hampton/Seabrook, NH region. A hydrodynamic model is used to initiate a sediment transport model within COAWST (the Community Sediment Transport Model, or CSTM) and five-year simulations were made, predicting the bathymetric evolution (Figure ES-32 left). This is compared to measured differences in bathymetry between 2016 and 2011 (Figure ES-32 right). The simulated changes to the bathymetric evolution occur within the inlet and back-bay areas and are consistent with the observations of the bathymetric evolution over the five-year period. In particular, changes to the tidal channels across the middle ground (flood tidal delta) are correctly simulated, and the infilling of the navigational channel passing by the Yankee Fisherman's Coop is predicted.

Another aspect of this effort (the M.S. thesis of Cassie Bongiovanni; completed in the fall of 2018) was to develop a methodology for incorporating temporal change estimates of the seafloor into hydrographic health models (HHM). In this work modifications to the NOAA-derived HHM hydrographic gap are incorporated that provide quantitative estimates of bathymetric change from previous bathymetric surveys, historical sedimentation rates, or from numerical models for sediment transport. The proposed modification to the HHM hydrographic gap term is referred to as the Hydrographic Uncertainty Gap (HUG). HUG was implemented in ESRI ArcGIS version 10.4 along the central eastern coast of the United States between the New Jersey-Delaware and the Virginia-North Carolina borders. Figure ES-33 shows a comparison between HUG and HHM output. HUG survey priorities are more constrained than for the HHM and reflect the behavior of bathymetric temporal variability of the study area. By identifying the state of charted data in this area, it becomes possible for NOAA to limit their focus to specific problem areas within this region that exceed the defined maximum allowable uncertainty.

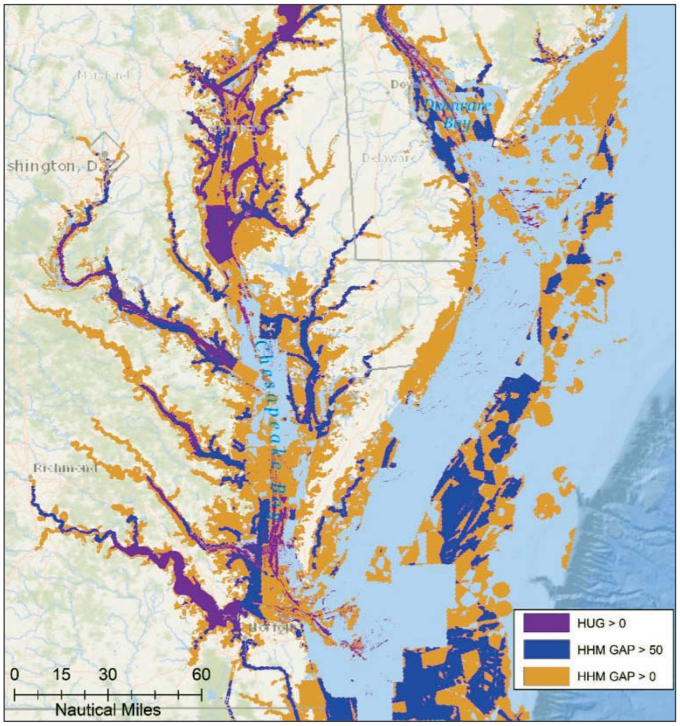


Figure ES-33. HUG and HHM output comparison. Purple areas are the HUG survey priorities (or areas that exceed the MAU). Blue indicate areas of the Hgap estimates that exceed the HHM DSS by more than 50. Tan areas are the Hgap survey needs, or all areas that exceed the HHM DSS (or values greater than 0). This figure shows both the overlapping priorities and the differences between the HHM and HUG model results which hint at the differences in the changeability calculations.

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 improve the ability to manipulate chart data much closer to the point of use. Our efforts under the second programmatic priority have focused on various aspects of meeting this goal, including the exploration of more robust approaches for sounding selection verification, the statistical characterization of contours, and the effort of the Integrated Coastal and Ocean Mapping group at the Center to work with NOAA's Hydrographic Services Division (HSD) to build and test a demonstration database that can be used to examine the issues involved in the creation of a single-source database (i.e., how to piece together different source data to form a consistent whole) for grid creation.

In the current reporting period, Christos Kastrisios, Brian Calder, and Giuseppe Masetti, in collaboration with Pete Holmberg (NOAA PHB) and Brian Martinez (NOAA MCD), continued to develop an algorithmic implementation of the triangle test with increased performance near and within depth curves and coastlines (Figure ES-34), an algorithmic implementation of the edge test for validation of selected soundings, as well as a method for the validation of soundings near the limits of the area of interest (Figure ES-35).

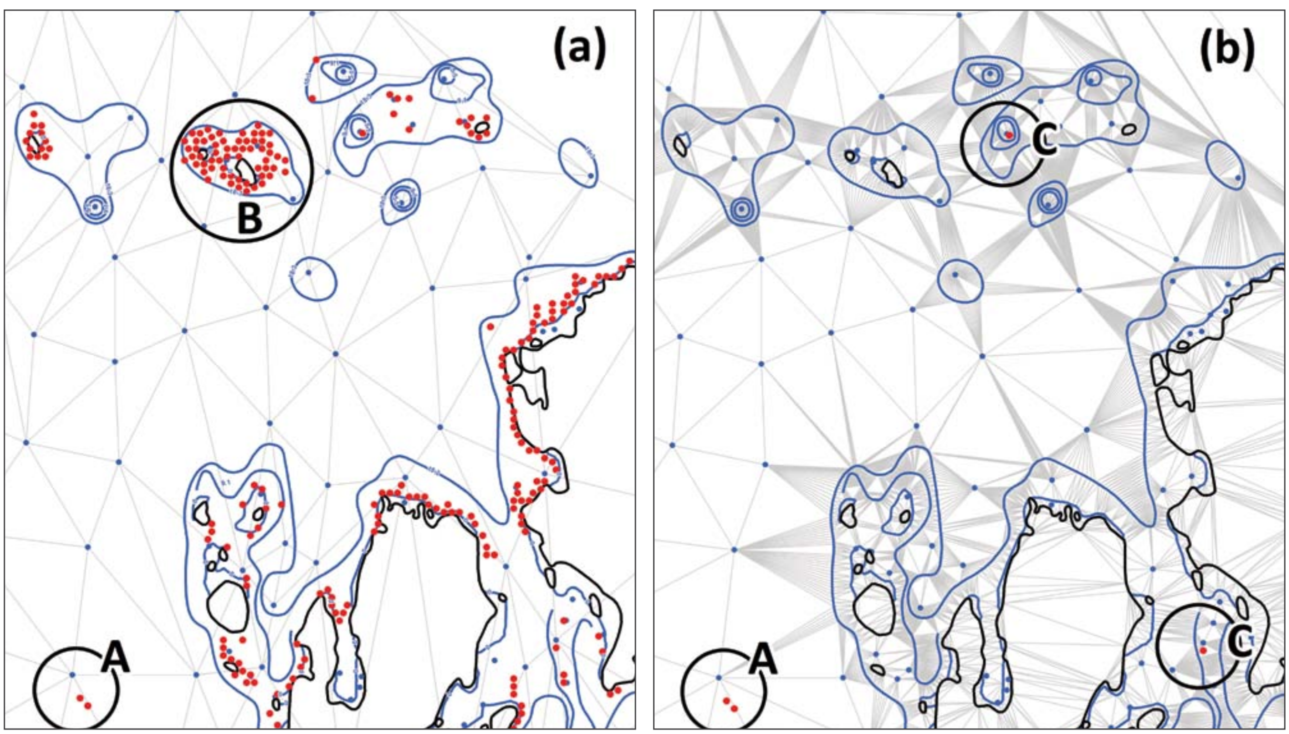


Figure ES-34. (a) The triangle test using only the selected soundings for the construction of the TIN, and (b) the proposed implementation which incorporates all the available bathymetric information from the selected soundings, depth curves, and coastlines.

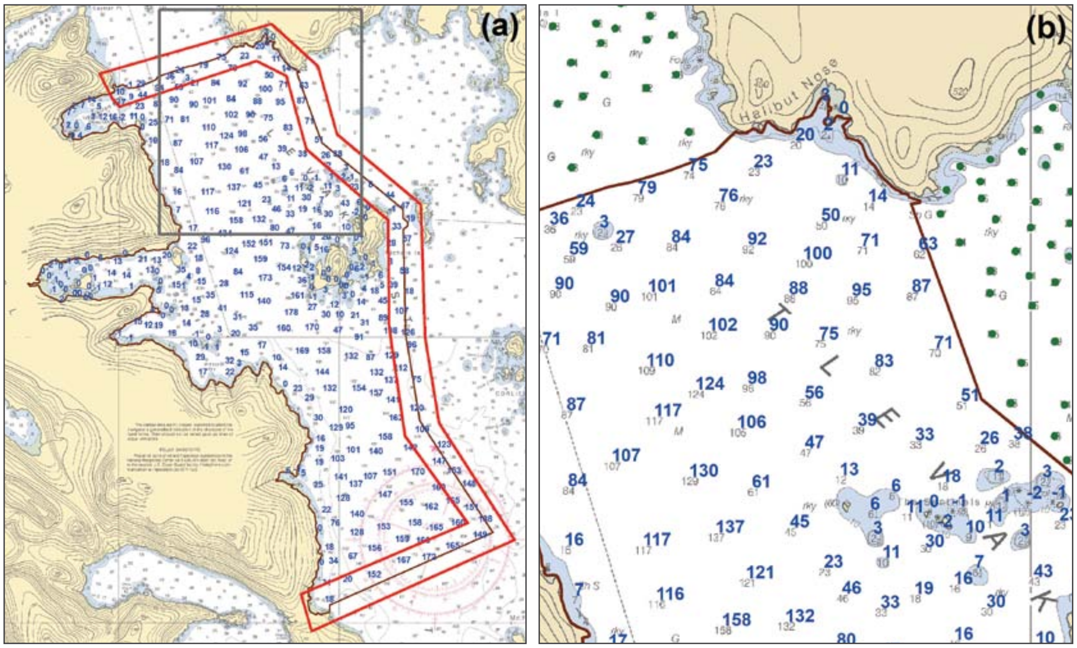


Figure ES-35. The validation of the selected soundings near the limits of the surveyed area (red polygon in Figure 37-2(a)) is improved by incorporating the charted bathymetric information from the adjoining ENC (see the charted soundings shown as green dots in Figure 37-2(b)).

Immersive 3D Data Cleaning

No matter how comprehensive and effective automated processing tools become, there is always likely to be some data that needs to be examined and manipulated by hand by a human operator. Therefore, as part of the ongoing effort to explore new interfaces for hydrographic data manipulation, Tom Butkiewicz and graduate student Andrew Stevens are creating an immersive 3-D, wide-area tracked, sonar data cleaning tool. The system they've developed relies on an HTC Vive virtual reality (VR) system, which consists of a head-mounted display (HMD), two hand-held, six-degrees-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 5×5 m tracked space (Figure ES-36).

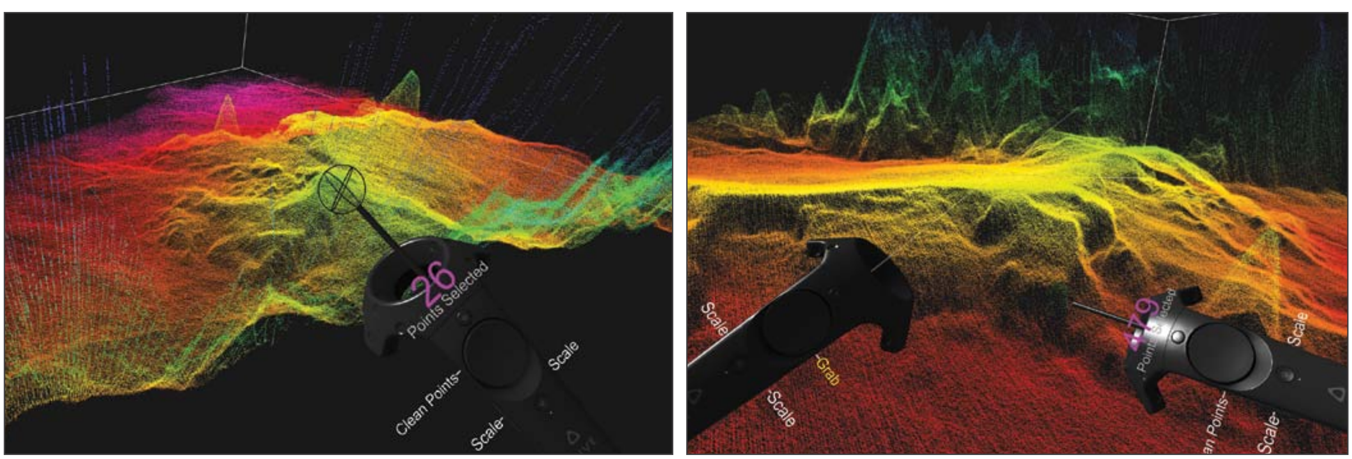


Figure ES-36. Screen shots of the VR Sonar Data Cleaning Tool, showing the new 3D point geometry with improved lighting/shading. The controllers can be used to grab, reposition, and scale the data, and have resizable spherical editing tools to select and flag points.

Comprehensive Charts and Decision Aids

Under-Keel Clearance, Real-time and Predictive Decision Aids

The ability of the hydrographer or cartographer to express to the end user the degree of uncertainty of the data being presented for navigational purposes has been extremely limited. Methods such as source or reliability diagrams on charts, or CATZOC objects in electronic navigational charts, have attempted to convey an aspect of uncertainty, but these methods mostly represent what was done during the survey effort rather than what the mariner may safely infer from the chart about the potential for difficulties in sailing through any given area. Our efforts to address this issue, led by Brian Calder, have focused on the risk engendered to surface traffic of transiting through a given area, taking into account such issues as ship parameters, environmental conditions (e.g., wind and wave effects), and especially the completeness and uncertainty of the bathymetric data available. Using a Monte Carlo simulation method to assess the risk associated with a trajectory through a particular environment, and taking into account environmental effects such as currents, wind, water level, estimated ship handling, etc., the model can be used to analyze resurvey priority and provide forward-prediction risk for particular ships by assessing the additional risk that would be engendered by changing the ship's heading over the achievable range of headings within a forecasting horizon on the order of a few minutes (Figure ES-37).

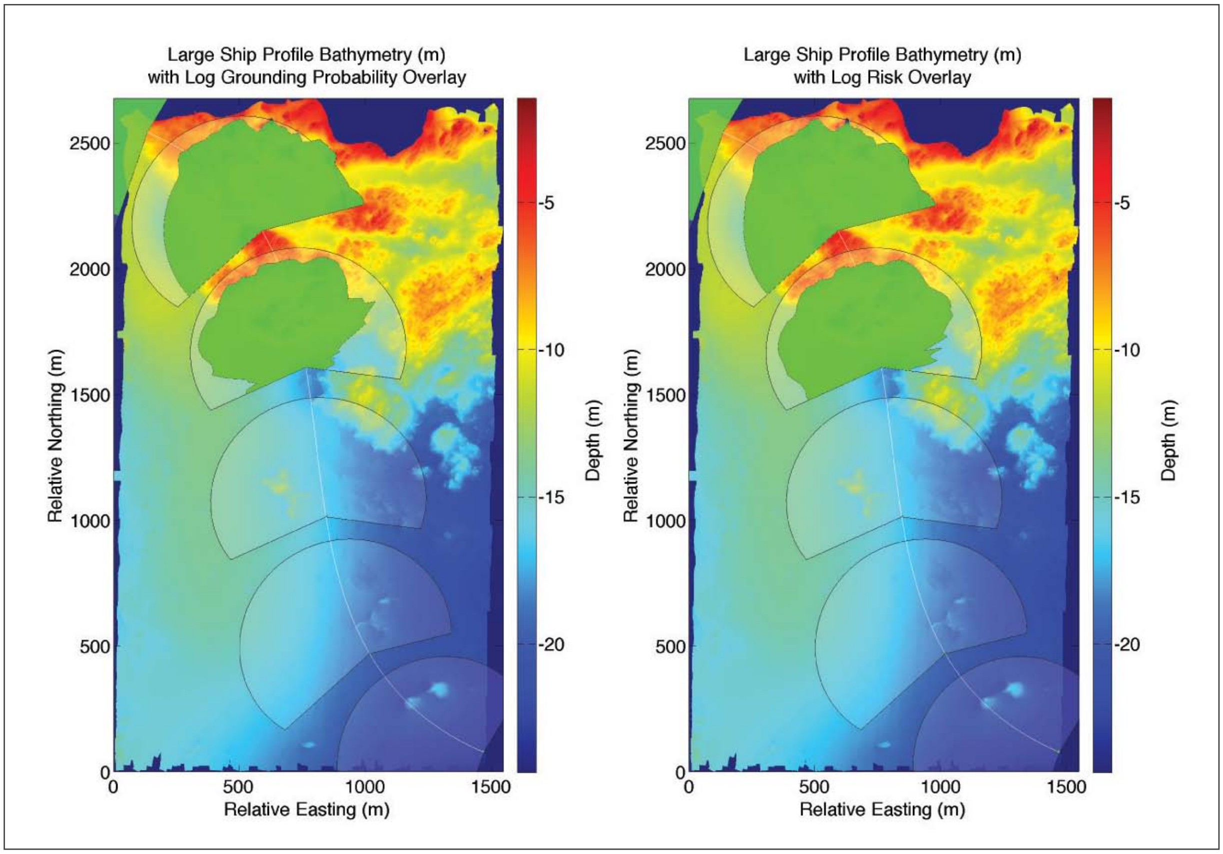


Figure ES-37. Example display of (simulated) real-time risk forecasts for a large ship in shallow water, following the white trajectory line from southeast to northwest, at intervals along the trajectory. The maneuvering area, forecast out several minutes, is shown as the transparent white overlay; grounding probability (left) and risk (right) corresponding to each potential heading is shown overlaid in green.

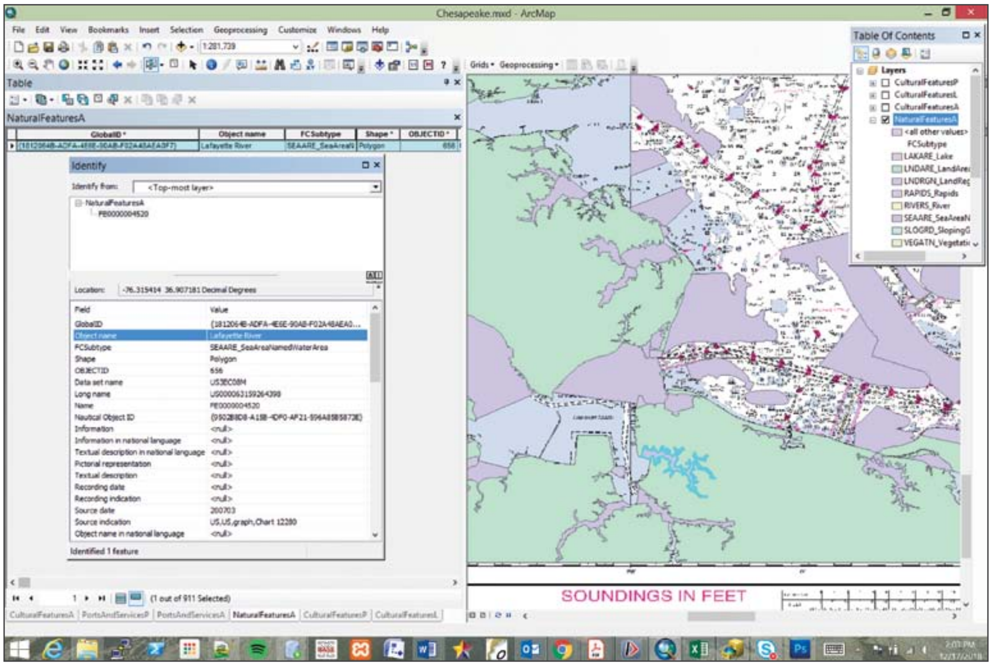


Figure ES-38. Using ArcMap to find features related to the Coast Pilot.

Digital Coast Pilot – Chart Update Mashup

The Coast Pilot, a traditional aid to navigators, has long been a static analogue product distributed in print or as PDFs. As such, it is unable to take full advantage of the richly georeferenced data sets it includes. Working in collaboration with NOAA's Office of Coast Survey, Briana Sullivan has been exploring approaches to the development of a proof-of-concept 3D digital version of the Coast Pilot driving by a digital database (iCPilot) converting the Coast Pilot from a publication based document to a web-based data-centric entity (Figure ES-38). The focus this year was on refining the separation of data so it can be in a formatted in a way that is useful for many things. Attention was turned from the interface for presenting the data to the actual data structure (using multiple iterations) and harmonizing it with the IHO S-100 data structures that already exist. The ultimate goal is to provide the mariner with exactly what they need when they need it and make sure they see only the information they need.

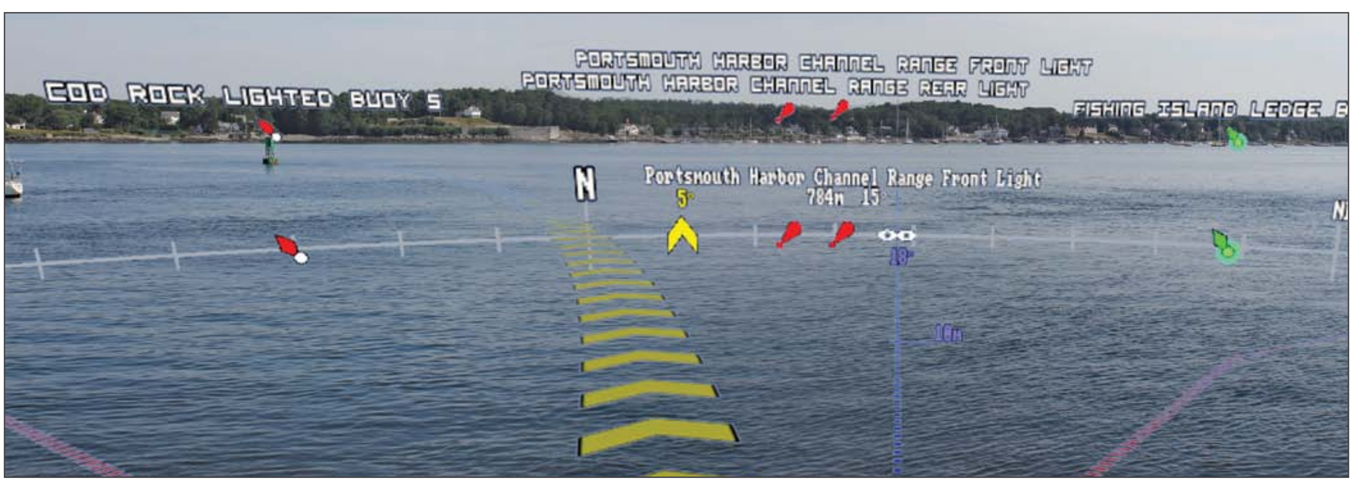


Figure ES-39. Simulated augmented reality overlay of nautical chart information.

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)—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 (Figure ES-39) for experimenting with a range of possible AR devices and information overlays, across different times-of-day, visibility, and sea-state/weather, allowing for safe evaluation in a more diverse set of conditions than available on our research vessel. The project's goals include identifying the technical specifications 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.

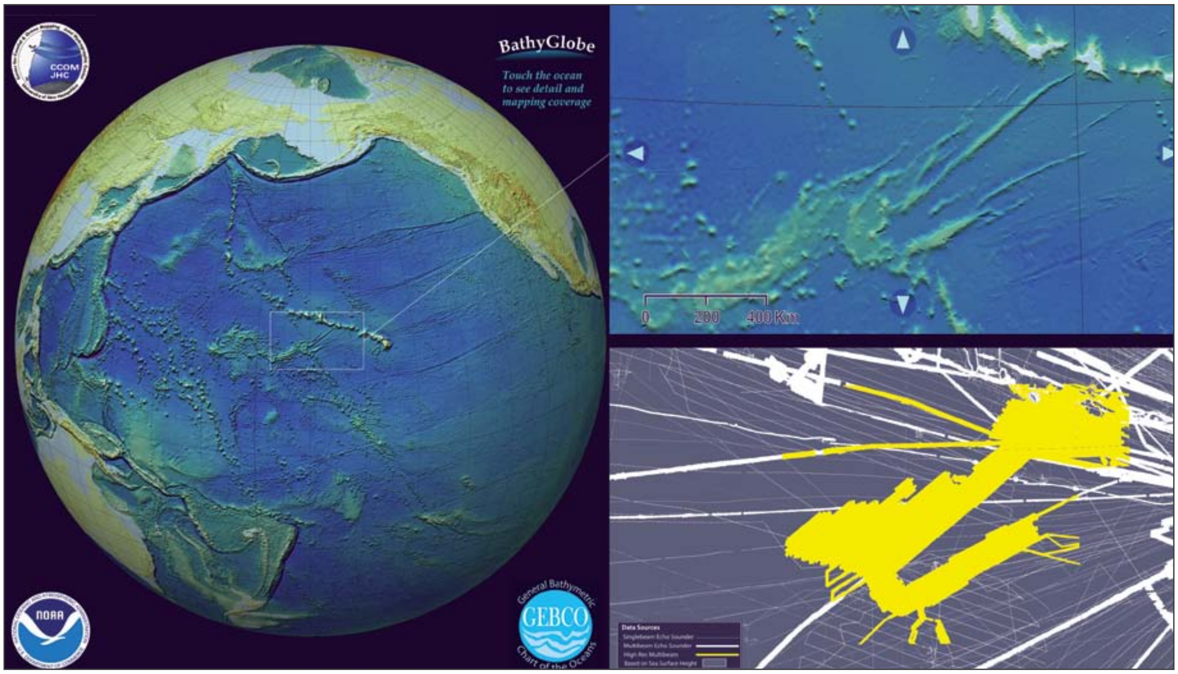


Figure ES-40. The Digital Bathymetric Globe. Left: A high resolution image of the globe with imagery based on GEBCO 2014 data. Right Top: The bathymetry of a section is magnified, showing the data at full GEBCO 2014 resolution. Right Bottom: Areas which have been mapped with either single or multibeam are shown in white, with high resolution multibeam shown in yellow.

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 (Figure ES-40). Along with these efforts, Ware is working to optimize gridding algorithms for multi-resolution global bathymetric data sets.

Programmatic Priority 3: Explore and Map the Continental Shelf

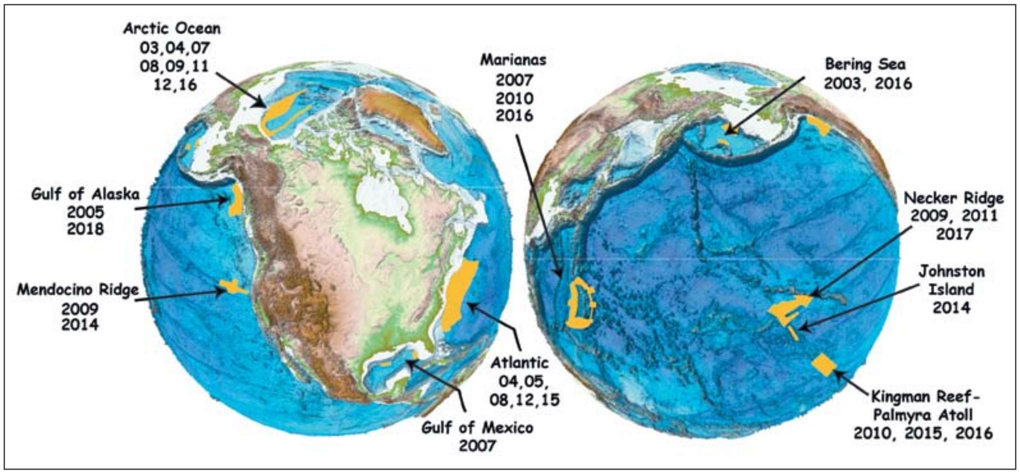


Figure ES-41. Summary of Law of the Sea multibeam sonar surveys mapped by the Center. Total areas mapped represents more than 3.1 million square kilometers since 2003.

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

Following up on the recommendations made in the study, the Center was funded (through NOAA) to collect new multibeam sonar (MBES) data in support of a potential ECS claim under UNCLOS Article 76. Mapping efforts began in 2003. Since then, the Center has collected more than 3.1 million square kilometers of new high-resolution multibeam sonar data on 35 cruises, including nine in the Arctic, five in the Atlantic, one in the Gulf of Mexico, one in the Bering Sea, three in the Gulf of Alaska, three in the Necker Ridge area off Hawaii, three off Kingman Reef and Palmyra Atoll in the central Pacific, five in the Marianas region of the western Pacific and two on Mendocino Fracture Zone in the eastern Pacific (Figure ES-41). 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.

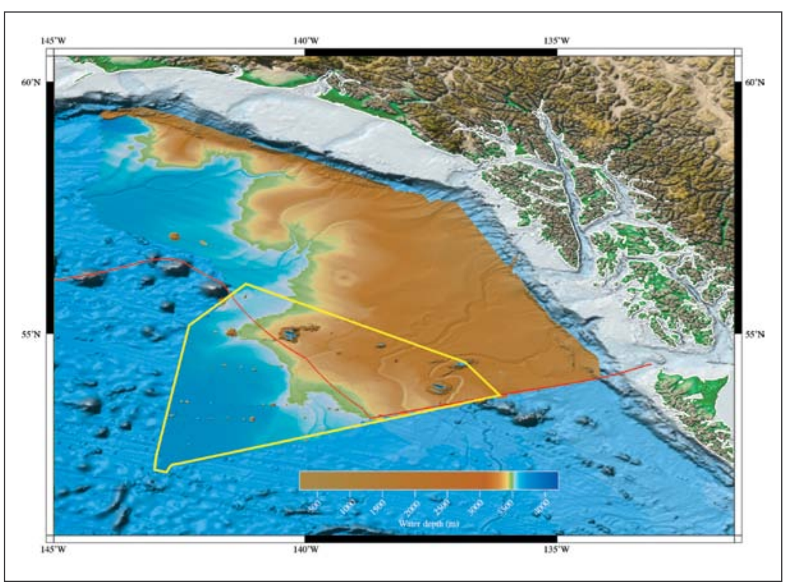


Figure ES-42. KM1811 bathymetry (yellow polygon) combined with KM0514 bathymetry. Red line is U.S. EEZ.

ECS Cruises

One ECS cruise was completed in 2018—a 34-day expedition aboard the University of Hawaii vessel *Kilo Moana* mapping key areas in the Gulf of Alaska. The cruise (KM1811) departed Honolulu, HI on 1 July 2018 and returned to Seattle, WA on 3 August 2018, having completed the mapping of 98,777 km^2 in the area of interest. The bathymetry, backscatter, and sub-bottom seismic data were processed and fused with bathymetry and backscatter from the Center's 2005 KM0514 cruise to provide a complete view of the data collected by the Center in the Gulf of Alaska (Figure ES-42).

ECS Data for Ecosystem Management

As discussed above, the Center has led in the acquisition of more than 3.1 million square kilometers of high-resolution multibeam bathymetry and backscatter data in areas of potential U.S. Extended Continental Shelf (ECS). There is strong interest in both OER and OCS in providing additional value-added utility to the ECS data sets by extracting further information from them that is useful to managers implementing ocean ecosystem-based management (EBM). The goal of this study is to interpret the acoustic survey data using novel classification approaches developed at the Center, in combination with existing ground truth data, to gain insights into predicted substrate types of the seafloor and to characterize the geomorphic features of the seafloor consistent with the Coastal and Marine Ecological Classification Standard (CMECS). Translating raw ocean mapping data sets from the Atlantic Margin collected by NOAA OER and the Center into CMECS compliant maps and databases is therefore a priority to ensure the full realization of the value of these data to NOAA and the nation.

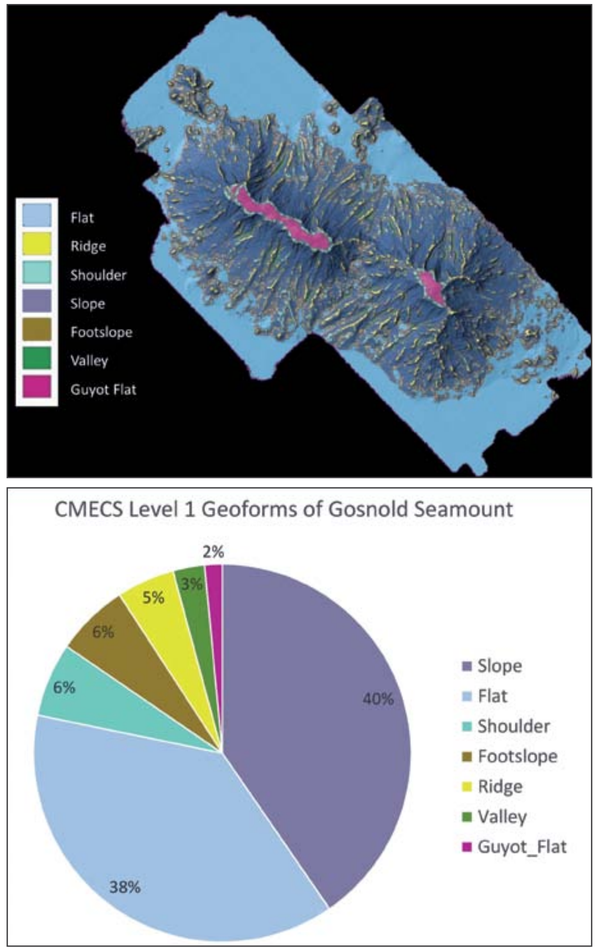


Figure ES-43. Map of landforms delineated for Gosnold Seamount. Note the accentuation of the distinct ridge features (yellow), the flat areas on the top of the guyot and abyssal plain (blue), and the shoulder features (turquoise) at the transition from the steep slopes to the guyot top.

As a first step towards this goal, the project team has tested and refined geomorphic classification methods on Gosnold Seamount within the U.S. Atlantic Continental Margin New England Seamount Chain (Figure ES-43). The geoform classifications are then compared to underwater video footage for this site that was collected by NOAA OER teams using the fully integrated, dual-body ROV system, the Deep Discoverer (D2) and Seirios. A customized ROV video analysis tool was used to facilitate playback and integrate CTD data files (salinity, temperature, depth, and dissolved oxygen), organism and sediment type were analyzed manually by a trained researcher and then integrated into a common annotation interface that used the shared time stamps associated with each data set that has navigation information (Figure ES-44).

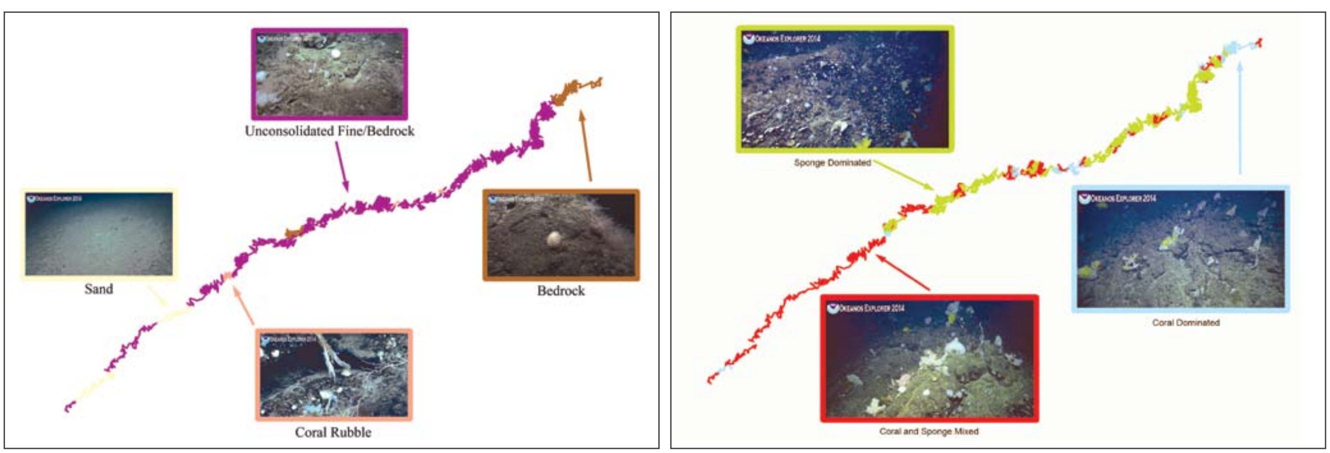


Figure ES-44. Left: Manually classified segments for dominant sediment types. Right: Biological communities classified in ROV track. Ten community types were found along the track.

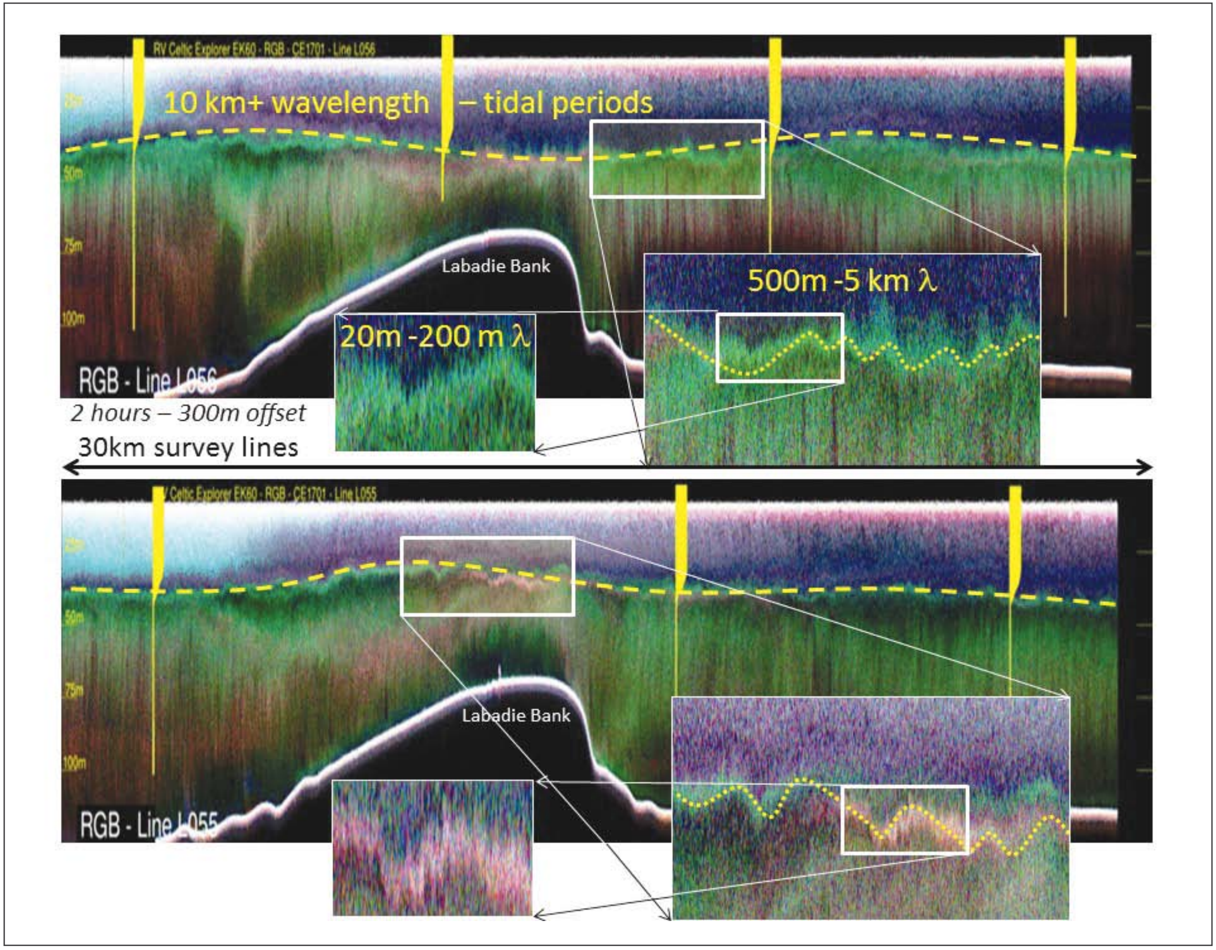


Figure ES-45. Two 30 km long sequential vertical sections of acoustic scattering with discrete MVP profiles superimposed (sound speed). Acoustic imagery data is an RGB composite of EK-60 volume scattering data (red: 18 kHz, green: 38 kHz, blue: 120 kHz). The base of the velocline/thermocline (as defined by the MVP) can be clearly seen to correspond to an abrupt shift in the volume scattering signature of the zooplankton. The imagery reveal a number of different horizontal length scales over which the thermocline is oscillating, ranging from 10,000 m to <100 m.

Potential of Multibeam Echosounder Data to Resolve Oceanographic Features

Much of the horizontal scale of active oceanographic structure is below the achievable lateral sampling capability of mechanical profiling (even underway-winched systems like an MVP). As a proxy to compensate for this, acoustic imaging has long been utilized. Such imaging, however, has, until recently, been restricted to single, broad-beam 2D profiles. Multibeam sonars, of course, can extend that imaging, providing both an across-track view and plan view (thereby getting the 3D structure), as well as utilizing narrower beams (thereby getting a higher resolution view).

Given that internal wave wavelengths are shorter than any mechanical sampling capability, it may be practical to use acoustic scattering profiles as a proxy for the instantaneous velocline depth (Figure ES-45). To this end, we are working with the Marine Institute in Ireland to compare MVP profiling (~2-5 km spacing) with MBES and EK scattering profiles to see if we can reasonably predict oscillations. This was the focus of the master's project of graduate student Jose Cordero Ros who successfully defended his thesis in July.

Over the past few years, we have demonstrated the ability of multibeam sonar and broadband echo sounders to image fine scale oceanography. This work, mostly funded through the U.S. National Science Foundation and Swedish grants, leverages

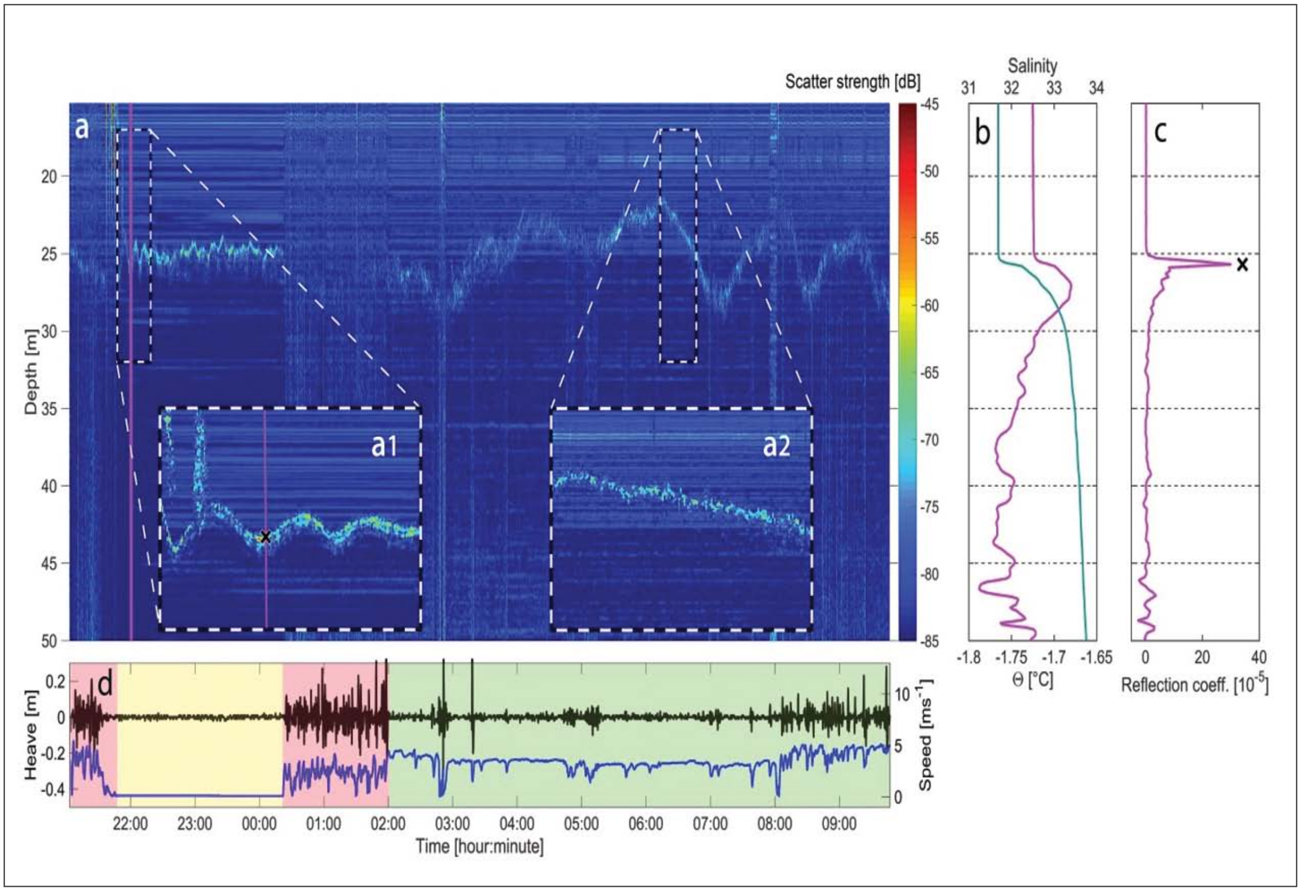


Figure ES-46. Continuous tracking of MLD in the central Arctic Ocean over a 117 km cruise track. (a) EK80 echogram (2 ms pulse length) with magnified insets (dashed boxes) showing data while drifting (left) and while steaming (right). (b) CTD profiles showing temperature (magenta) and salinity (cyan). (c) Reflection coefficients derived from CTD data (magenta) and from scatter strength (assuming -65 dB, black cross). (d) Heave (black), speed over ground (blue), and time periods corresponding to ice breaking (red), steaming (green) and drifting (yellow). Vertical magenta lines in (a) show the position of the CTD. The black cross in (a) (left inset) marks the depth of the reflection coefficient spike in (c). Note that the ability to detect MLD acoustically is severely reduced while breaking ice.

our efforts to explore the limits of imaging the water column using the sonars we traditionally use for seafloor or fisheries mapping. Last year we were able to demonstrate that we could acoustically image the fine-scale thermohaline structure of the water column in the Arctic. This not only has ramifications for our understanding of physical oceanography, but offers new approaches for us to understand the sound speed structure of the water column and how it impacts seafloor mapping. These results of the Arctic work have recently been published in *Nature Scientific Reports*.

This year, our work to map oceanographic structure has been extended to other regions of the Arctic where we have been able to acoustically map the depth of the mixed layer continuously over hundreds of kilometers (Figure ES-46). These results, published in 2018 in *Ocean Sciences*, offer the opportunity for vessels equipped with the appropriate echo-sounding equipment and processing tools to map the distribution of the mixed layer of the ocean (critical for global heat exchange and for modeling acoustic propagation) over large areas while underway.

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.

In early 2018, an experiment was conducted at the Southern California Offshore Range (SCORE), located in the San Nicholas Basin off of California's San Clemente Island using a 12 kHz EM122 on the R/V *Sally Ride* (Figure ES-47), followed by a second experiment at the AUTEC range in the Bahamas using a 30kHz, EM302 on the NOAA Ship *Okeanos Explorer*.

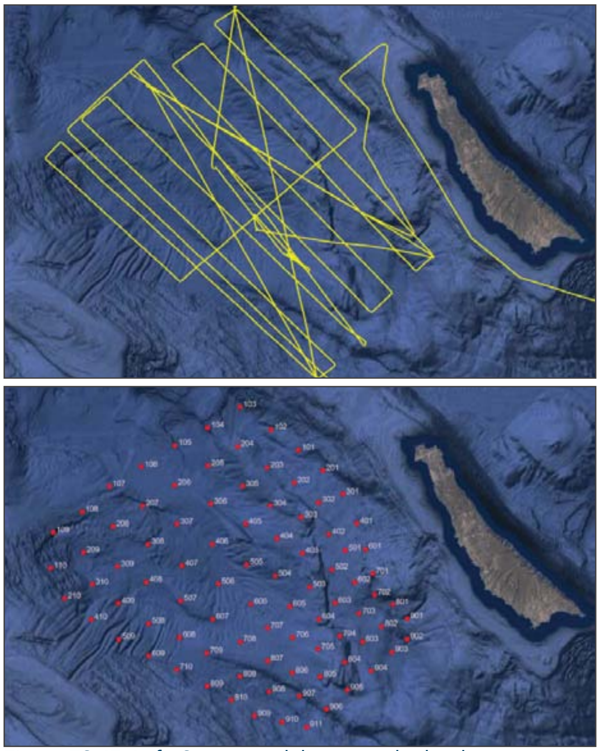


Figure ES-47. Left: Survey track lines over hydrophone range. Right: SCORE Hydrophone array with hydrophone placement and ID.

Analysis of the time series revealed regions of significant clipping, and subsequent discussions with the SCORE range operators revealed that the hydrophones had a limited dynamic range (a fact previously unknown to the Center (Figure ES-48)). A complete analysis of the data, including precisely geo-locating the ship for each sector transmission and using those positions along with a raytracing code in order to determine launch angles, resulted in the full (albeit clipped) radiation patterns.

In the second experiment, conducted in late December at AUTEC, lines were run over the AUTEC hydrophones (similar to the SCORE hydrophones). For this experiment, the Center also deployed a hydrophone mooring (Figure ES-49) which contained pairs of hydrophones known to have the necessary dynamic range at depths of 20 m and 500 m off the seafloor. These data are currently being analyzed.

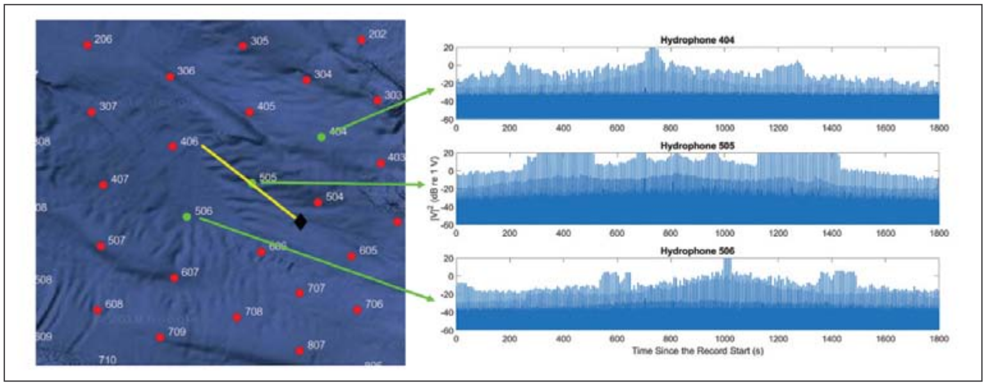


Figure ES-48. A half hour record of raw time series data from hydrophones 404, 505, and 506. Left: Geographic representation of the time series data. The ship track during the recording can be seen in as the yellow line with the ship indicated by the black diamond. The hydrophones from which the data was extracted are shown in green. Right: The corresponding time series data in seconds since the start of the record and dB re 1 Volt.

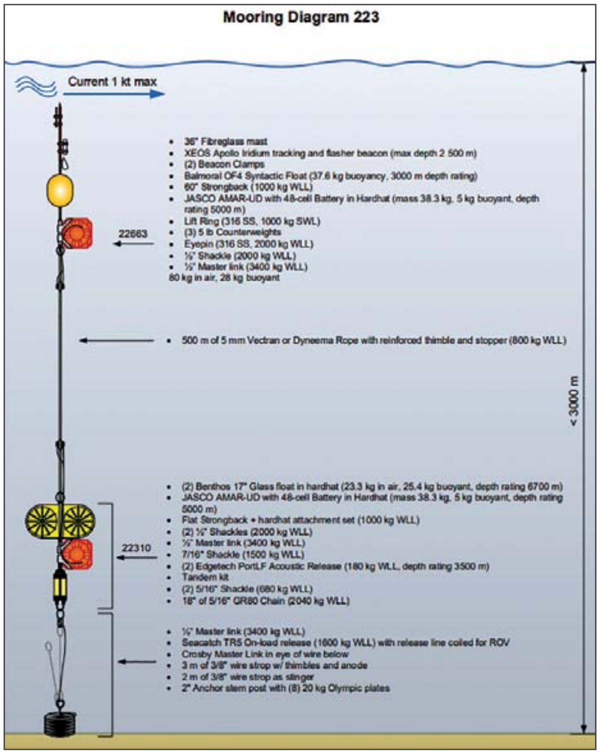


Figure ES-49. Notional mooring diagram provided by JASCO and deployed at AUTEC in December 2018.

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. To date only the data from the SCORE experiment have been analyzed, where the behavior of Cuvier's beaked whales have been investigated. 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.

There were no statistically significant differences between the six exposure periods with respect to the number of clicks per GVP or GVP duration (Figure ES-50). There were more GVPs **After** the EM 122 survey than there were **Before** or **Immediately After**, but no difference in the number of GVPs during the **EM 122 Survey** compared with any other exposure period. This result is in contrast to the findings from AUTEC where fewer GVP events were recorded when Blainville's beaked whales were exposed to mid-range navy sonars as compared to non-exposure periods.

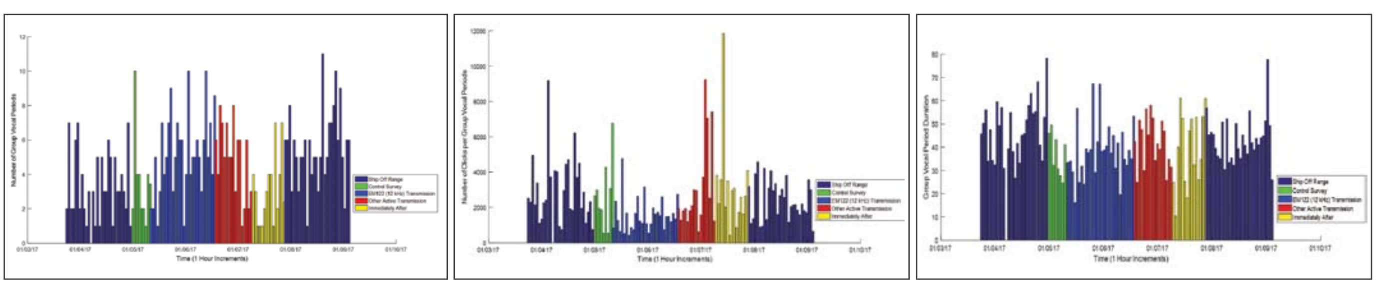


Figure ES-50. Plots of each GVP characteristic in 1 hour bins across the study time period. Purple indicates the time the ship was off the range Before and After the MBES survey. Green=Control Survey, blue=EM 122 (12 kHz) Transmission, red=Other Active Transmission, and yellow=Immediately After. Left: GVP per hour; Middle: Number of Clicks per GVP; Right: GVP Duration.

Education and Outreach

In addition to our research efforts, education and outreach are fundamental components of our program. Our educational objectives are to produce a highly trained cadre of students who are critical thinkers able to fill positions in government, industry, and academia, and become leaders in the development of new approaches to ocean mapping. Thirty-eight students were enrolled in the Ocean Mapping program in 2018, including six GEBCO students, one NOAA Corps officer and three NOAA physical scientists (as part-time Ph.D. students). This past year, we graduated three master's and one Ph.D. student, while six GEBCO students received Certificates in Ocean Mapping. Last year we implemented major changes on our Ocean Mapping curriculum, including the introduction of a new Integrated Seabed Mapping Systems course as well as a new Oceanography for Hydrographers course; this year we added a special Marine Geology and Geophysics course for Hydrographers. Our new curriculum was presented to the FIG/IHO/ICA 'International Board of Standards of Competence for Hydrographic Surveyors' (IBSC) and we are proud to say that the submission was accepted without modification and lauded as exemplary, extending our Category A Certification in Hydrography. The Center thus continues to be one of only two Category A programs available in North America.

In February, a GEBCO-NF Alumni Team was informed by XPRIZE that they had qualified to become a Finalist Team in the Shell Ocean Discovery XPRIZE challenge and would be eligible to participate in Round 2 of the Shell Ocean Discovery XPRIZE. This milestone award came with $111,111.11 prize money for the GEBCO-Nippon Foundation Alumni Team (Figure ES-51) along with only nine other teams. Three team members accepted the team award at the Milestone Award Ceremony held on 15 March 2018 at the "Catch the Next Wave" event in London, UK, alongside the Oceanology International 2018 Exhibition & Conference—the world's leading exhibition and conference for ocean technology and marine science. The GEBCO Team was one of only two teams to complete the final test assuring them either first or second place in the Challenge.

Figure ES-51. Yulia Zarayskaya, Ben Simpson, and Hadar Sade with Jyotika Virmani (XPRIZE) collecting the team award at the Milestone Award Ceremony.

We recognize the interest that the public takes in what we do, and our responsibility to explain the importance of our work to those who ultimately bear the cost. One of the primary methods of this communication is our website (Figure ES-52, http://ccom.unh.edu) which had 124,966 views from 31,794 unique visitors from 186 different countries in 2018. We also recognize the importance of engaging young people in our activities to ensure that we will have a steady stream of highly skilled workers in the field. To this end, we have also upgraded other aspects of our web presence including a Flickr photostream, Vimeo site, Twitter feed and a Facebook presence. Our Flickr stream currently has 2,486 photos and our 119 videos were viewed 4,132 times in 2018. Our seminar series (33 seminars featured in 2018) is widely advertised and webcast, allowing NOAA employees and our Industrial Partners around the world to listen and participate in the seminars. Our seminars are also recorded and uploaded to Vimeo.

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

Figure ES-52. The homepage of the Center's website.

In the SeaPerch ROV events, which are coordinated with the Portsmouth Naval Shipyard, students build ROVs, then bring them to the Center to test them in our deep tank and take a tour the Center and the UNH engineering facilities. 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-53). The 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 where students had to pick up hoops and cubes and strategically place them on another platform. Winning teams this year went on to represent the Seacoast in the Sea Perch Finals in Dartmouth, Massachusetts.

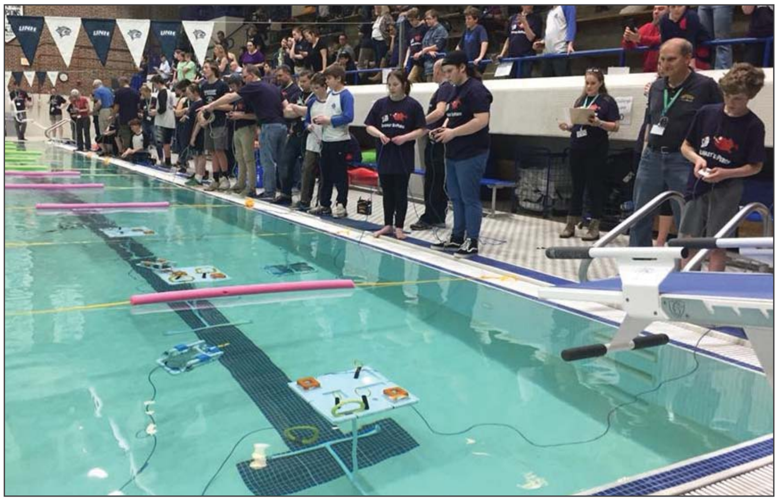


Figure ES-53. Student teams competing at the 2018 SeaPerch Competition in UNH's Swasey Pool.

The Seacoast SeaPerch program also participates in UNH Tech Camp. Tech Camp is a camp for boys and girls that offers two concurrent programs for campus entering grades 7 & 8 and 9 & 10, and one directed at females only called Engineeristas. This year, after the Engineeristas completed building their SeaPerch ROV they were able to speak through Telepresence

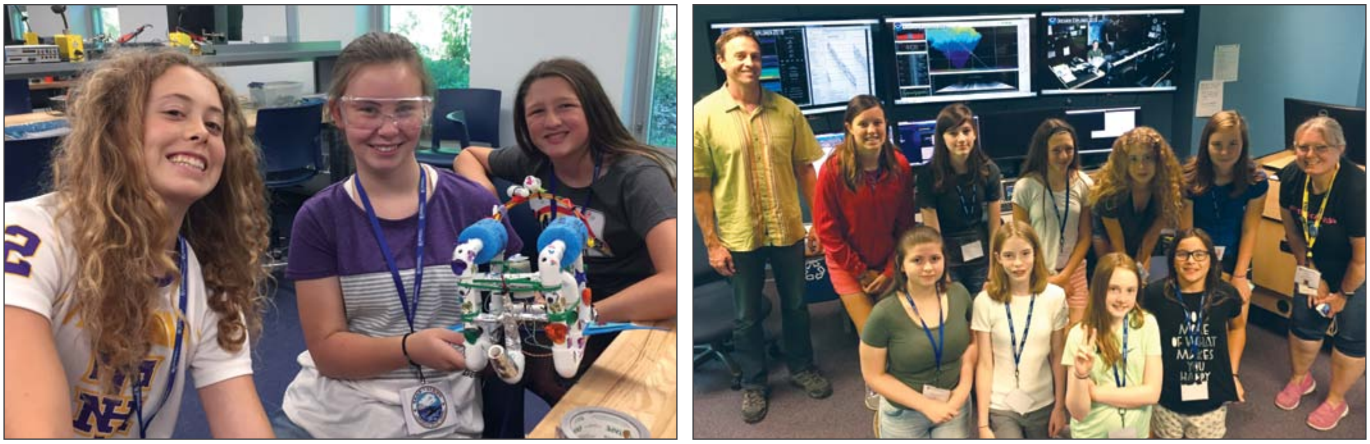


Figure ES-54. Engineeristas Tech Camp SeaPerch ROV build (left), and Telepresence with the NOAA Ship Okeanos Explorer (right).

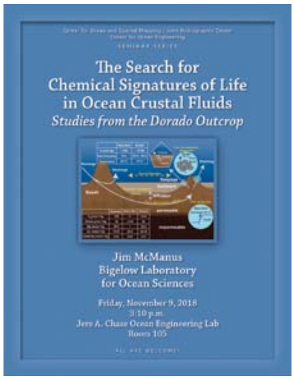
to Michael White aboard the NOAA Ship *Okeanos Explorer,* assisted on land by Derek Sowers. Mike is actually in the group picture (above right), but he is on the smaller top right hand monitor streaming from the ship, so he is hard to see (Figure ES-54).

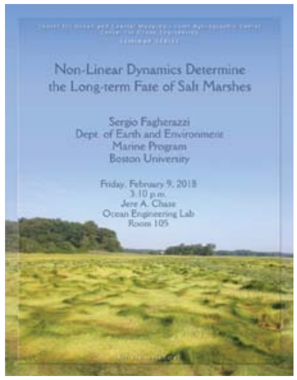
Ocean Discovery Days is an annual two-day event held at the Chase Ocean Engineering Lab. On Friday, 28 September, more than 1,500 students from school groups and home school associations from all over New Hampshire, Maine, and Massachusetts came to visit our facilities and learn about the exciting research happening here at the Center (Figure ES-55). Activities 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 also open to the public on Saturday, 29 September, when 800 more children and adults got to learn about the exciting research at the Center.

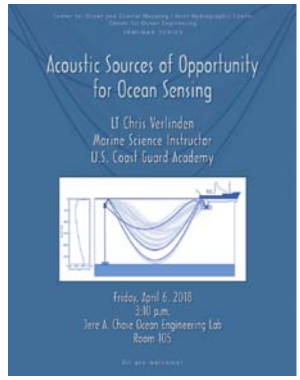
Figure ES-55. More than 1,500 students visited the Center during Ocean Discovery Day followed by another 800 visitors at the open house on the following day.

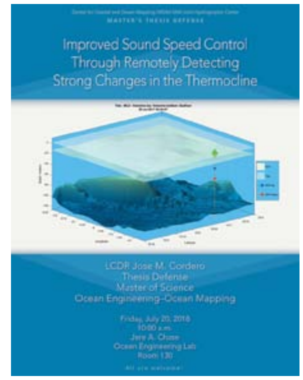
Center activities have also been featured in many international, national, and local media outlets this year, including *The BBC, Fox News, Smithsonian, Thomson Reuters, Strait Times, Marine Technology News, Voice of America, Union Leader, Foster's Daily Democrat, Concord City Press, Science Daily, Boston Globe, Afloat,* WMUR, WCVB, and WRAL.

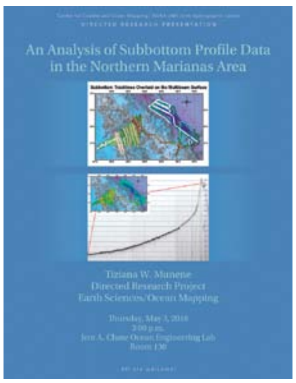
The highlights presented here represent only a fraction of the activities of the Joint Hydrographic Center in 2018. More detailed discussions of these and other activities, as well as a complete list of publications and presentations of the Center can found in the full progress report available at ccom.unh.edu/reports.

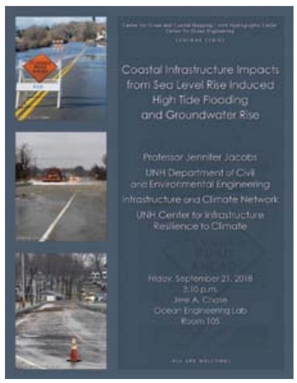


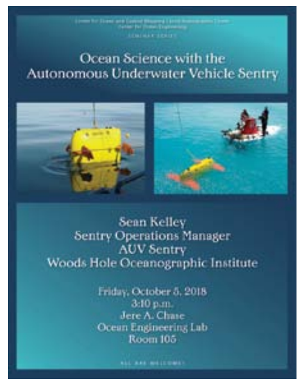


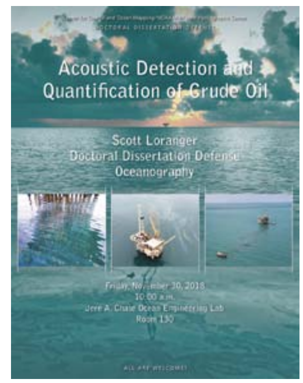


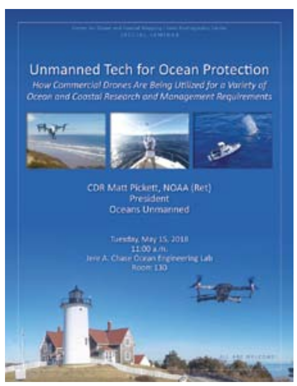


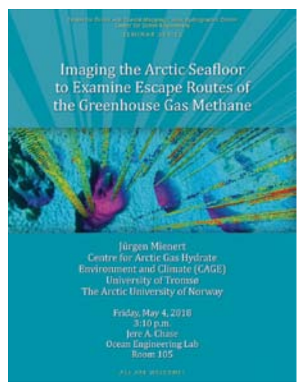


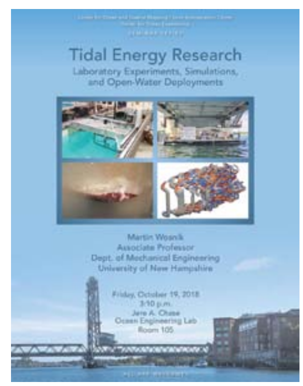


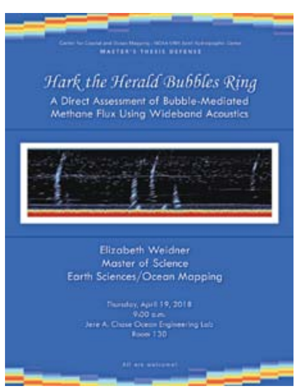


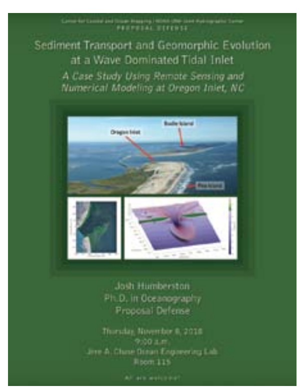


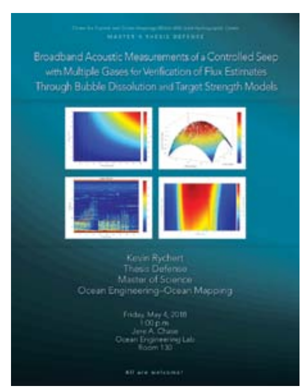












Flyers from the 2018 JHC/CCOM - UNH Dept. of Ocean Engineering Seminar Series.

NOAA-UNH Joint Hydrographic Center
Center for Coastal and Ocean Mapping
Jere A. Chase Ocean Engineering Lab
24 Colovos Road
Durham, NH 03824
603.862.1581 tel
603.862.0839 fax
www.ccom.unh.edu

Principal Investigators

Larry A. Mayer
Brian Calder
John Hughes Clarke
James Gardner
David Mosher
Colin Ware
Thomas Weber

Co-PIs

Thomas Butkiewicz
Jenn Dijkstra
Semme Dijkstra
Paul Johnson
Thomas Lippmann
Giuseppe Masetti
Yuri Rzhanov
Val Schmidt
Briana Sullivan
Larry Ward