NATIONAL OCEAN EXPLORATION FORUM | 2017

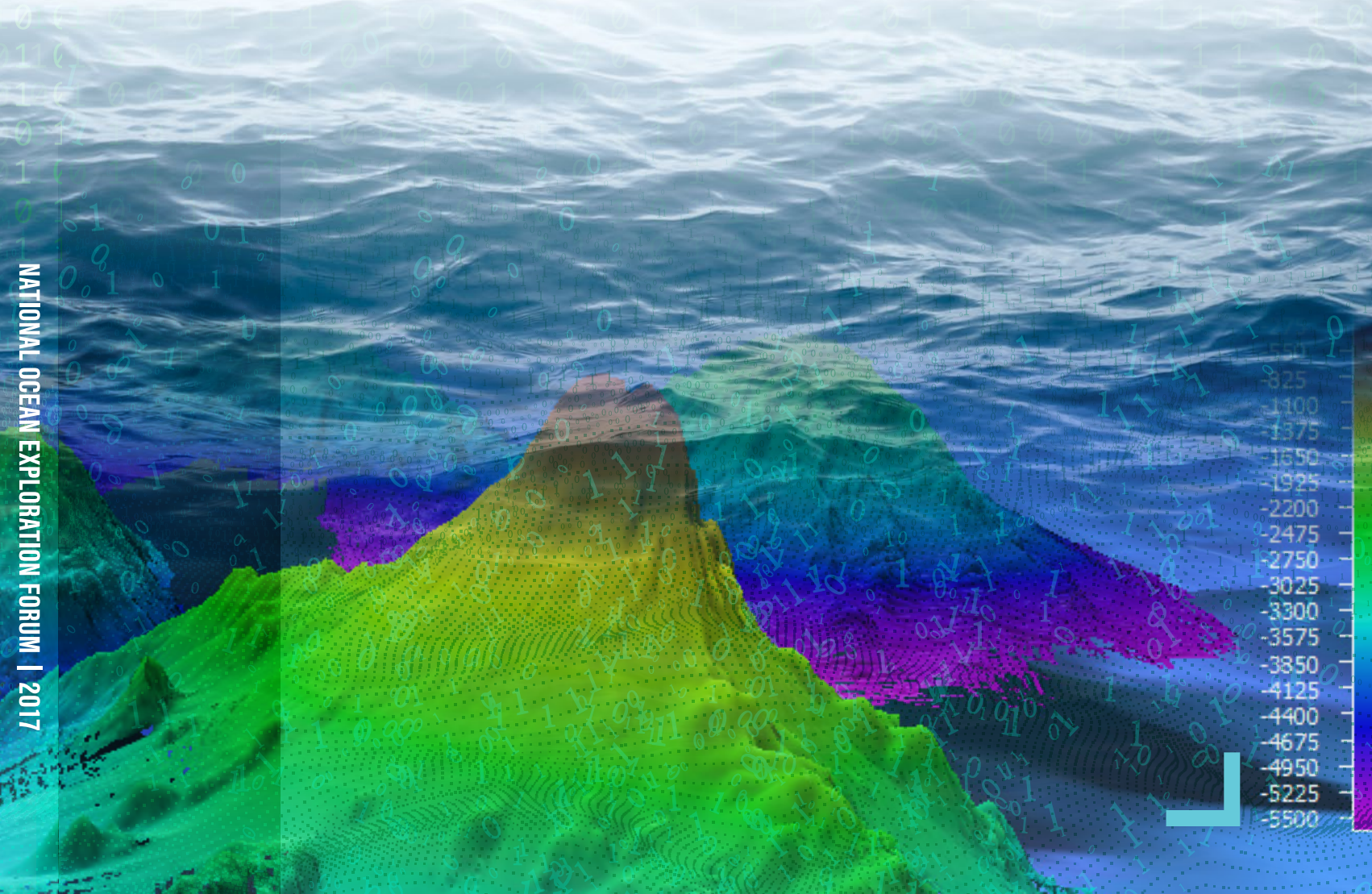
REPORT

OCEAN EXPLORATION IN A SEA OF DATA

REPORT

SATURDAY, OCTOBER 21 + SUNDAY, OCTOBER 22

QUALCOMM INSTITUTE | UNIVERSITY OF CALIFORNIA, SAN DIEGO



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National Ocean Exploration Forum 2017 participants in front of the sculpture titled 'Bear' at the Jacobs School Academic Courtyard at the University of California, San Diego.
Photo by Alex Matthews and Amiel Capinpin for Qualcomm Institute/UC San Diego

Executive Summary and Recommendations

On October 21-22, 2017, nearly 125 experts in fields including ocean exploration and data science convened for the fifth National Ocean Exploration Forum at the University of California (UC) San Diego's Qualcomm Institute (QI).

Partners from QI, the Lamont-Doherty Earth Observatory (LDEO) of Columbia University, the National Oceanic and Atmospheric Administration (NOAA), and others gave presentations, provided demonstrations on priority areas, and held discussion groups. Thinking of "ocean exploration" in broad terms, Forum participants considered how relevant data—whether from satellites, airborne and ocean sensors, hydrophones, or deep ocean cores—could be integrated, analyzed, and visualized to gain additional insight into the deep ocean.

Ocean exploration is multidisciplinary—oceanographers, marine geologists, marine biologists, marine archaeologists, and others—collaborate to plan and participate in expeditions and participate to ensure as much as possible is learned when exploring an unknown deep ocean environment. *Ocean Exploration in a Sea of Data* broadened the ocean exploration community's traditional notions of multidisciplinary collaboration to include data scientists, computer scientists, and visualization experts from QI—some of whom are also musicians, and artists. This synergistic blend

of expertise, discipline, perspective, and sensibility allowed participants to experience and understand ocean data in new—and sometimes unexpected—ways.

Forum participants were given a series of demonstrations that presented novel ways of experiencing data to enable new discoveries and consider opportunities for making data more accessible and understandable. New data science and visualization techniques challenge the ocean exploration community to think beyond the limitations of traditional approaches and can have real impact on current data acquisition, data analysis, and data management practices. These techniques also have the potential to bring new life to legacy data and present exciting opportunities for more effective communication of results.

Day One: The Future is on the Horizon

Ocean Exploration in a Sea of Data was designed to first introduce a common understanding of challenges and opportunities in ocean exploration data. After a review of the National Ocean Exploration Forum process provided by Jerry Schubel, host of the first forum, *Ocean Exploration 2020*, and a key architect of subsequent events, the Forum featured two distinguished keynote speakers to set the conceptual stage for the rest of the program:

- Margaret Leinen - The Director of the Scripps Institution of Oceanography discussed the challenges and opportunities of rich datasets, highlighting the differences between deduction and induction. The abundance of data, combined with growing trends in data science (e.g., data mining and machine learning), are moving us towards exploring ocean data in addition to exploring the oceans.
- Larry Smarr - The founding Director of the California Institute for Telecommunications and Information Technology (Calit2) focused on our increased ability to move very large volumes of data at high speeds among distributed processing clusters and the opportunities this creates for ocean and other science enterprises.

A special presentation followed from John Delaney, Professor of Oceanography at the University of Washington, on ocean exploration of data in the time domain, using the Ocean Observatories Initiative and cabled observatories in general, to illustrate how time-series observations can inform ocean exploration.

Demonstrations

Ocean Exploration in a Sea of Data Forum organizers solicited the development of five practical demonstrations that would allow participants to explore and experience data in new ways. The demonstrations at the 2017 Forum relied on technologies developed at QI, utilizing the unique capabilities of their visualization and audio laboratories, and their dynamic culture of experimentation and development driven by innovative students and professors—many without prior ocean exploration experience.

Forum participants were organized in small groups to rotate through the five demonstrations, plus a sixth facilitated discussion session that allowed for the sharing of impressions, ideas, and implications of the demonstrations.

Discussion

In the discussion session, participants agreed that the Forum demonstrations highlighted the rapid development of visualization technology, allowing researchers to transform their ability to explore, experiment with, and begin to more deeply understand the complex processes that take place throughout global ocean basins. Participants shared impressions of the demonstrations and discussed how these tools could impact their work, areas of interest, and the ocean exploration community. They noted that visualization and audio spatialization techniques like these:

- Could give instant access to data in real time and allow users to control the data.
- Would require new best practices, employing stewardship to provide context, and would be transparent, scalable, and developed for multiple interfaces.

- Could allow scientists to make sense of large quantities of data and lead to new understanding and insights.
- Could "get water out of the way" to reveal the deep ocean and make it accessible to most people.
- Would encourage participation in oceanographic research from people of all backgrounds, thus enhancing interdisciplinary and multidisciplinary collaboration.
- Would need to be standardized across platforms and to lay the groundwork for developing new interfaces and user experiences.

Engaging the Public: Space vs. Ocean

Reception and dinner speaker Bob Weiss, Vice Chairman of the XPRIZE Foundation, treated the group to his thoughts on making ocean exploration as exciting to the public as space exploration. As a veteran Hollywood producer, Mr. Weiss' observations about the challenges—and opportunities—of engaging the public in ocean exploration were particularly relevant for a national ocean exploration forum focused on visualization and anticipated the 2018 Forum on public engagement, titled *All Hands on Deck*.

Day Two: Navigating to the Future

The Forum's second day focused on technologies and opportunities close at hand that can help bridge the current state of ocean exploration and its diverse data sources and archives, and a future state where the techniques and technologies demonstrated on Day One might be used routinely. Two case studies using advanced visualization approaches were presented in order to demonstrate what is possible now.

Panel Discussion

A panel discussion comprised of the case study presenters and other experts in ocean data science examined the implications of the case studies and the previous day's demonstrations. Vicki Ferrini (LDEO), Forum co-organizer and expert in deep-sea mapping, moderated the panel of Dawn Wright (Esri), Jessica Block (QI), Alice Winter (NASA), Vid Petrovic (QI), and Stuart Sandin (SIO), which discussed data science solutions to integrating temporally and spatially sparse data. The key points and recommendations from that discussion included:

- When integrating data, maintain access and connections to source data, not just derived data products. Aspire to keep the source data in one place and move the algorithms in order to enable a whole range of products.
- Building community and enhancing communication is the key to integrating disciplinary scientists and data scientists.
- Adding new technology to a field means asking questions differently and changing the way science in that field is conducted. Data science provides opportunities for finding signals that traditional processes might not identify. The ocean exploration community is evolving and needs to make incremental steps in adopting new technologies.
- Culture change is ongoing with respect to data sharing and code-sharing. The community needs to incentivize data and code-sharing, but also needs to recognize that sharing code/data easily falls down the priority list when development and analysis are underway—there is only so much time.
- Open data is the first step, but public accessibility of curated content is critical for engaging people and encouraging them to know and care more about our oceans and planet.

Discussion Groups and Recommendations

The organizers structured the Forum to provide participants, regardless of discipline or experience, with common information and experiences to bring to breakout sessions. The keynotes, panel discussion, case studies, and especially the demonstrations were intended to share new information, provoke thought, spark creativity, and encourage dialogue across ocean exploration and data science and visualization disciplines. A snapshot of participants' conclusions include:

An important part of the Forum is the opportunity to converse with other experts in the field. This dialogue helps the community leverage investments, identify opportunities for collaboration, and lead toward increases in the scope, pace, and efficiency of ocean exploration in areas important to the national interest.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute / UC San Diego

- Visualization can help accelerate and advance new scientific discoveries.
- New technologies and data visualizations can enhance efforts to better engage the public about ocean science and exploration.
- Ocean exploration should be made more accessible and inclusive by developing new tools and technologies to lower the cost of ocean exploration, creating more opportunities for virtual exploration, and speeding up data availability.
- In addition to the data routinely collected during ocean exploration expeditions, acoustics, data from towed instruments, and environmental genomics should also be collected.
- The scope of data collection and sensor capabilities must be expanded—even if not all of the data collected is used—to increase the possibility of using these data in future studies.
- The community should take greater advantage of telepresence technology and increase the utilization of new technologies (e.g., autonomous underwater vehicles (AUVs)) with less elaborate ships.
- To fully engage the public effectively, it is important to also highlight the positive aspects of what is found while exploring the deep ocean to convey the excitement and wonder of the deep to the interested public.
- Legacy data are highly relevant. New techniques should be established for data analysis, using algorithms and standards, to facilitate the use of legacy data that may not otherwise be accessible.
- Each sector involved in ocean exploration has a role to play in increasing our understanding of the deep ocean:

> “More positive messages and public interaction with the data using these tools can help the public understand the importance of the deep ocean in new ways.”

  - Academia should encourage ocean scientists to connect with data scientists and should work to ensure that all existing data are made available. Academia also plays a critical role in developing future generations of ocean explorers and scientists.
  - The federal government should focus federal funding on national priorities and encourage agency or program communications and partnerships. Federal data management policies should encourage proper, and long term, data stewardship and open access.
  - Not-for-profits’ flexibility allows for higher risk or “off-the-wall” proposals to proceed–and potentially results in breakthroughs in discovery and innovation. But revenue streams need to be stabilized over the long term and new revenue streams should be investigated.
  - The private sector should be encouraged to maintain relationships with researchers after development and proof of concept. Open source, non-proprietary, and expandable standards should be adopted across sectors so everyone from researchers at sea, to students, to government analysts can visualize and share the same types of data.
- Data synthesis and visualization techniques can help engage the public.
- More positive messages and public interaction with the data using these tools can help the public understand the importance of the deep ocean in new ways.
- As the lead U.S. government agency for ocean exploration, NOAA should leverage the abilities of those who already work in ocean exploration and data science and invest more in the curation, production, and presentation of data. NOAA should continue to refine and clarify priorities, then communicate them to the community, in part through facilitating an active conversation between stakeholder groups.

Close of *Ocean Exploration in a Sea of Data*

A final panel discussion with Jerry Schubel, Margaret Leinen, and Larry Smarr reviewed what the community should do next. The Forum closed with remarks from Dominique Rissolo and a reminder that the 2018 National Ocean Exploration Forum, *All Hands on Deck*, will continue to build upon previous recommendations. This upcoming Forum will review ways to better explain ocean exploration to students and the public with the goal of developing recommendations for more effective messaging and engagement strategies.

A National Ocean Exploration Forum Community

This Forum would not have been possible without the active engagement of its participants. Thanks are due to all participants for making the time to join this National Ocean Exploration Forum and their willingness to work with their colleagues, and across disciplines, to investigate the exciting world of ocean exploration and data visualization.

Dominique Rissolo, assistant research scientist at UC San Diego's QI and member of the Ocean Exploration Advisory Board, served as Master of Ceremonies for the 2017 Forum. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

INTRODUCTION

Introduction

The 2017 National Ocean Exploration Forum: *Ocean Exploration in a Sea of Data* (NOEF 2017) was the fifth in a series of annual forums focused on establishing a national strategy and program of ocean exploration, as called for in the statute authorizing the National Oceanic and Atmospheric Administration (NOAA)'s ocean exploration program.

The first Forum, *Ocean Exploration 2020: A National Forum* (OE 2020), held at the Aquarium of the Pacific in Long Beach, California, in July 2013, asked participants to describe elements a successful national ocean exploration program should exhibit by the year 2020. *National Forum 2014* (NOEF 2014), held in September 2014 at the National Aquarium in Baltimore, Maryland, was much smaller and focused on how to comprehensively address national ocean exploration needs and connect ocean exploration results to NOAA mission priorities, assessing the community's progress toward the ambitious targets set in OE 2020. The 2015 National Ocean Exploration Forum: *Characterizing the Unknown* (NOEF 2015), also held at the National Aquarium in Baltimore, challenged participants to describe requirements for first-order exploration that satisfy multiple user requirements and could set a new standard for exploring unknown ocean areas and phenomena. The 2016 National Ocean Exploration Forum: *Beyond the Ships* (NOEF 2016), held at the Rockefeller University in New York City, highlighted the opportunities and challenges created by new technologies and promoted a shared vision of exploration across new exploration models.

NOEF 2017, hosted at the the University of California, San Diego's Qualcomm Institute (QI), took a new approach. Expanding the idea of ocean exploration into a truly broad and multidisciplinary concept, this Forum brought together ocean explorers with data scientists, computer scientists, and visualization experts from QI, including musicians and artists. This synergistic blend of expertise, discipline, perspective, and sensibility allowed participants to experience and understand ocean data in new—and sometimes unexpected—ways.

The Forum challenged participants to think beyond traditional ocean exploration and to also consider exploration of data. Forum participants considered how relevant data—whether from satellites, ocean sensors, hydrophones, or deep ocean cores—can be integrated, analyzed, and visualized to gain a novel understanding of the ocean. Taking advantage of QI's visualization and acoustics laboratories, this Forum demonstrated what can be done with rich data sets intended for these laboratories, what might be done with historical and contemporary ocean exploration data, and was meant to inspire participants to consider new opportunities for exploration and science enabled by these techniques. In collaboration with members of the ocean exploration community, graduate students, early career professionals, and professors at QI created demonstrations of how data might be visualized and understood differently both to advance science and to convey results to the public. These demonstrations included photogrammetric models of deep-ocean environments, point-cloud analysis of complex habitats, deep ocean soundscapes, three-dimensional under-ice exploration, and a synthesis of mulitbeam bathymetry and backscatter data in a data-sparse landscape. A key goal of this interdisciplinary Forum was to advance the data visualization and analysis practices of the ocean exploration community into the future and enable new discoveries through the exploration of data.

Forum Welcome

It is our pleasure to welcome you to the fifth annual National Ocean Exploration Forum, *Ocean Exploration in a Sea of Data*. Congress has charged the National Oceanic and Atmospheric Administration (NOAA) with coordinating these National Forums to help set national priorities, identify partnership opportunities, advance new concepts in ocean exploration, and to help strengthen and grow the community of ocean explorers. The first Forum, called *Ocean Exploration 2020*, gathered 150 members of the community of ocean explorers to discuss a framework for a national program of ocean exploration. Subsequent Forums have refined priorities, identified new technologies, and helped form new partnerships to advance our pressing need to understand the deep ocean.

One of the key recommendations from *Ocean Exploration 2020*, and reinforced in Forums since, was the need for better access to data, new techniques for data management, and new tools for visualizing data. Our event amplifies those themes by bringing together data scientists and visualization experts with ocean explorers to consider how current and emerging data science and visualization techniques can help us understand the deep ocean in new ways. *Ocean Exploration in a Sea of Data* will take full advantage of the Jacobs School of Engineering and Qualcomm Institute's visualization and acoustics laboratories to demonstrate what can be done with rich terrestrial data sets, what might be done with historical and contemporary data from the deep ocean and its limitations and challenges, and the potential for conducting science differently using these techniques to reach a new understanding of this critical domain.

Qualcomm Institute professors, students, and technical experts have collaborated with partners from Scripps Institution of Oceanography, Lamont-Doherty Earth Observatory, University of Washington, NOAA, and others to create what we believe are compelling demonstrations of the application of new and emerging techniques to ocean data that may have important implications for ocean exploration. Based on these demonstrations along with keynote talks, panel discussions, and case studies, we will ask you to contribute recommendations for how data science and visualization can be applied to pressing challenges in the use and collection of ocean exploration data and what changes are needed in ocean exploration modes of operation and data collection strategies so these new approaches can be applied to accelerate the rate at which we understand the deep ocean.

We're grateful to our many partners and contributors for their creativity and support. We want to express particular appreciation for the wise counsel of Jerry Schubel, President and CEO of the Aquarium of the Pacific—and the primary architect of the National Ocean Exploration Forum process; of Larry Smarr, Director of the California Institute for Telecommunications and Information Technology; and Margaret Leinen, Director of the Scripps Institution of Oceanography. And we would like to thank you for making time to join us for this National Ocean Exploration Forum and for your willingness to work with your colleagues and across disciplines to take up the exciting challenges before us.

Dominique Rissolo, *Qualcomm Institute, University of California, San Diego*

Vicki Ferrini, *Lamont-Doherty Earth Observatory, Columbia University*

David McKinnie, *NOAA's Office of Ocean Exploration and Research*

Adrienne Copeland, *NOAA's Office of Ocean Exploration and Research*

Opening Remarks

RAMESH RAO
Director, Qualcomm Institute

Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

Dr. Ramesh Rao, Director of the Qualcomm Institute (QI), welcomed *Ocean Exploration in a Sea of Data* participants with remarks that set the 2017 Forum in the context of the intersection of technology and the oceans. As technologists, he said, we stand back and observe what science is driving. The ocean is an indicator of climate change, ensures food supplies are adequate, and drives geopolitical discussions. The ocean is no longer just a space to explore. With more informed data, we should be better able to base policies on science.

He noted that San Diego has deep, historical roots and connections with oceanography. The city is undertaking a major redevelopment effort downtown; there will be a new aquarium and new opportunities for engagement with the public. San Diego continues to benefit from the educational institutions that have been here for a long time and its relationship with the ocean sciences—in fact, the University of California, San Diego (UC San Diego) was born from the Scripps Institution of Oceanography.

Dr. Rao described the QI as bringing together faculty members, technical and professional staff, student workers, undergraduate scholars, graduate fellows, postdoctoral researchers, project and research scientists, and industry partners. QI's strategic vision stresses collaborative, interdisciplinary research to benefit society in culture, energy, the environment, and health. QI also prototypes and builds enabling technologies and plays a leadership role in the development of new institutes and research centers for the UC San Diego campus, on topics ranging from robotics and the brain to design.

Finally, he described how the Forum demonstrations were designed to give a sense of how the investment in capabilities and interdisciplinary teams enables new research in archeology and ocean science and stated his hope that participants would mingle and learn from each other across disciplines, from music to engineering.

Opening Remarks

Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

ALAN LEONARDI

Director, NOAA's Office of Ocean Exploration and Research

Adding his own welcome to Dr. Rao's, Dr. Alan Leonardi, director of NOAA's Office of Ocean Exploration and Research, then reviewed the importance of the National Ocean Exploration Forum process, both to NOAA and to the ocean exploration community. Since the 2013 National Ocean Exploration Forum, *Ocean Exploration 2020,* when the Forum process began, he noted that the ocean exploration community and the national program for ocean exploration have continued to grow, evolve, and achieve results. He observed that while each Forum has had a different emphasis and approach, the recommendations from participants have been remarkably consistent. Participants have been clear about the geographic priorities, including the Arctic, trenches, and seamounts, the need to understand processes and phenomena, such as ocean chemistry and under-ice exploration, and to ask ocean explorers to investigate new areas, whether the water column or soundscapes.

A quick review of the Tables of Recommendations from past Forums clearly shows the consistency of the recommendations (see page 69). In 2016, Rockefeller and Monmouth Universities collaborated to host *Beyond the Ships*, which focused on new and emerging technologies for ocean exploration, independent of ships. *Beyond the Ships* zeroed in on a subset of recommendations related to ships, undersea vehicles, and technologies. Participants were asked to consider a world where ocean exploration was conducted largely without the ships we rely upon now. *Beyond the Ships* invited participants from the technology sector, new to the ocean exploration community, to develop effective and useful results.

Ocean Exploration in a Sea of Data focused on data science and visualization, and, like the 2016 Forum, brought together community experts with the ocean exploration community. Dr. Leonardi stressed that by continuing to push the boundaries of our knowledge, bringing in additional stakeholders to give us new perspectives, and finding opportunities to leverage the research of our colleagues with these Forums, we can drive the science of ocean exploration into the future. As a case in point, he noted that the preparations for the demonstrations had already sparked future collaborations that spanned academic, industry, and government sectors.

Dr. Leonardi concluded that *Ocean Exploration in a Sea of Data* was an opportunity to observe, to share, to think, to be creative, to be innovative, and above all, to form partnerships to explore in new and innovative ways. He extended his thanks to everyone for their participation in this Forum and expressed his view that the participants' expertise, vision, creativity, and passion help to set new standards for how to explore the deep ocean and to blaze a trail in the advancement of science and discovery.

Participants listen to the opening remarks during the 2017 National Ocean Exploration Forum.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

A Brief and Incomplete History of the Ocean Exploration Forum Process and Some Observations on Data, Big and Small

JERRY SCHUBEL
President and Chief Executive Officer of the Aquarium of the Pacific and director of the Aquarium's Marine Conservation Research Institute

Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

In the summer of 2013, Dr. Jerry Schubel, president and CEO of the Aquarium of the Pacific at Long Beach, co-hosted the first National Ocean Exploration Forum with the National Oceanic and Atmospheric Administration (NOAA). Called *Ocean Exploration 2020*, the event brought together a diverse group of ocean explorers—from veteran scientists to educators—to discuss what a national ocean exploration program for the U.S. should be in the year 2020. Dr. Schubel has since played a significant role in each of the subsequent Forums. In his remarks to *Ocean Exploration in a Sea of Data* participants, Dr. Schubel traced the development of ocean exploration policy in the U.S. and the influence the National Ocean Exploration Forum process has had on a national program.

Dr. Schubel began with a quote President Bill Clinton made during the White House Millennium Council on June 12, 2000: "We must continue as a nation to set out for new frontiers, whether under the sea or into the heavens. We must continue to try to conquer the seemingly impossible, to discover the unimaginable, to find out more about what's out there and in the process about ourselves and who's here."

Dr. Schubel reminded participants that President Clinton put that statement into action by directing the Department of Commerce to convene a panel of experts to develop recommendations for a national ocean exploration strategy. The panel was chaired by Dr. Marcia McNutt, then President of the Monterey Bay Aquarium Research Institute (MBARI). Among the most important recommendations were that we should, as a nation, establish a NOAA-led national ocean exploration program. A comprehensive list of panel recommendations for the proposed ocean exploration program can be found in the report titled

[1]https://oceanexplorer.noaa.gov/about/what-we-do/program-review/presidents-panel-on-ocean-exploration-report.pdf

Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration[1]. Included in these recommendations was the first mention of an ocean exploration forum.

Continuing his summary of key studies and policy milestones, Dr. Schubel noted that in December 2000, Congress directed the National Academies to assess the feasibility and value of implementing a major coordinated international program of ocean exploration and discovery. In response, the Ocean Studies Board created the Committee on the Exploration of the Seas, which was chaired by John Orcutt, a professor of geophysics and Deputy Director of the Scripps Institution of Oceanography. Among their major recommendations, they reaffirmed that ocean exploration remains necessary.

In 2009, Public Law 111-11 (33 USC 3400 et seq.) mandated NOAA to create and coordinate a U.S. national ocean exploration program and host a national forum. Dr. Schubel noted that this was the second time the forum had been mentioned. While the law assigned the federal lead for ocean exploration to NOAA, it also urged the participation of other agencies with oceanographic capabilities and charged NOAA with facilitating regular national ocean exploration forums. Recognizing the value of the collective experience, wisdom, and capability of persons and organizations in and outside of government, the statute called for a national ocean exploration forum to gather ocean exploration experts together, encouraging communication and intending to foster collaboration and the sharing of knowledge to enhance the national program.

Dr. Schubel described the first independent review of the NOAA ocean exploration program, conducted under the auspices of NOAA's Science Advisory Board. The report, *NOAA Ocean Exploration Decadal Review: Ocean Exploration's Second Decade*[2], endorsed the importance of ocean exploration and the recommendations of the President's commission and urged NOAA to begin holding national ocean exploration forums.

He continued his summary with brief statements about the significance of each of the subsequent Forums. In July of 2013, the inaugural forum, *Ocean Exploration 2020 (*OE 2020*)*, brought together ocean exploration stakeholders from academia, foundations, government agencies, and

Jerry Schubel comments on the role of big data in ocean exploration. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

the private sector. The program asked participants to describe elements a successful national ocean exploration program should exhibit by the year 2020. National Forum 2014 was a mini-Forum that focused on comprehensively addressing national ocean exploration needs, connecting ocean exploration results to NOAA mission priorities, and assessing the community's progress toward the ambitious targets set in OE 2020. The 2015 National Ocean Exploration Forum: *Characterizing the Unknown* challenged participants to describe the requirements for a first-order baseline characterization that meets multiple requirements and could set a new standard for exploring unknown ocean areas and phenomena. The 2016 National Ocean Exploration Forum: *Beyond the Ships* highlighted the opportunities and challenges created by new technologies and looked to a future of expanded exploration activities with more platforms capable of measuring, sampling, or imaging yet-to-be explored areas.

A table of the recommendations from all of these Forums can be found in the appendix of this report.

In October 2017, Dr. Schubel said some of the leading minds in ocean exploration and data science and visualization gathered at the University of California, San Diego's Qualcomm Institute for the 2017 National Ocean Exploration Forum: *Ocean Exploration in a Sea of Data*. Anticipating the Forum results and highlighting his hopes for the following two days, Dr. Schubel said that *Ocean*

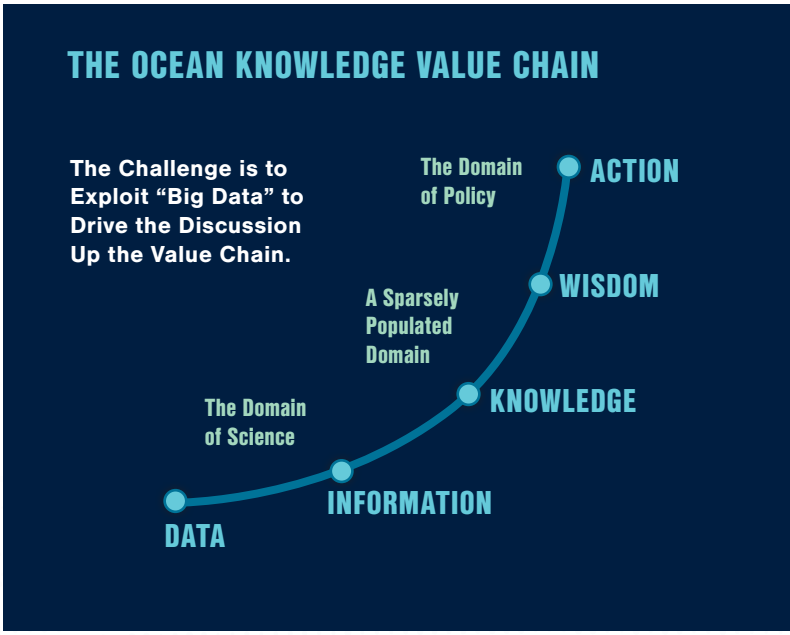
[2] https://oceanexplorer.noaa.gov/about/what-we-do/program-review/2012-oe-review-report.pdf

> "We must continue as a nation to set out for new frontiers, whether under the sea or into the heavens. We must continue to try to conquer the seemingly impossible, to discover the unimaginable, to find out more about what's out there and in the process about ourselves and who's here."
>
> *–Former President Bill Clinton*

Exploration in a Sea of Data would demonstrate some of the powerful visualization tools that will become increasingly necessary, both to make sense of these growing volumes of data and also to more effectively tell ocean exploration stories to decision makers and the public. He described ocean explorers as "storytellers", stating that all ocean explorers need to relay information effectively and to spur action.

Dr. Schubel closed his remarks with the statement that to make sense of big data and to create powerful stories, we need transdisciplinary teams that can communicate across boundaries. As Ptolemy said, "The role of the scientist is to tell the most plausible story that saves the facts." The challenge of big data is to drive the discussion up the Ocean Knowledge Value Chain. The domain of science resides at the base of that chain. We need to drive the discussion up from data, to information, to knowledge, wisdom, and to action. *Ocean Exploration in a Sea of Data* helped us to envision new ways of telling our stories.

To make sense of big data and to create powerful stories, we need transdisciplinary teams that can communicate across boundaries.



The challenge of big data is to drive the discussion from data up the Ocean Knowledge Value Chain until policy action is achieved.

SECTION 02

Description of Approach: National Ocean Exploration Forum 2017

Keynote Talks

Ocean Exploration in a Sea of Data was designed to first introduce a common understanding of challenges and opportunities in exploring ocean data. The Forum featured two distinguished keynote speakers. Margaret Leinen, Director of the Scripps Institution of Oceanography (SIO), University of California, San Diego (UC San Diego) Vice Chancellor for Marine Sciences, and Dean of the School of Marine Sciences, discussed the challenges and opportunities of rich datasets, highlighting the differences between deduction and induction. The abundance of data, combined with growing trends in data science (e.g., data mining and machine learning), are moving us towards "exploring" ocean data in addition to exploring the oceans. Larry Smarr, founding Director of the California Institute for Telecommunications and Information Technology (Calit2) who also holds the Harry E. Gruber professorship in Computer Science and Engineering at the Jacobs School of Engineering, focused on our increased ability to move very large volumes of data at high speeds among distributed processing clusters and the opportunities this creates for ocean and other science enterprises. These talks set the conceptual stage for the rest of the program.

Demonstrations

Ocean Exploration in a Sea of Data Forum organizers solicited the development of five practical demonstrations that would allow participants to explore and experience data in new ways. The demonstrations relied on technologies developed at the Qualcomm Institute (QI), the unique capabilities of the visualization and audio laboratories at QI, and the dynamic culture of experimentation and development driven by innovative students and professors—many without prior ocean exploration experience.

Forum participants were assigned small groups to rotate through the five demonstrations, plus a facilitated discussion session that allowed for the sharing of impressions, ideas, and implications of the demonstrations. The demonstrations included photogrammetric models of deep ocean environments, point-cloud analysis of complex habitats, deep ocean soundscapes, three-dimensional under-ice exploration, and a synthesis of multibeam and backscatter data in a data-sparse landscape.

Case Studies

Two case studies were presented at the Forum, the first from professors and students from SIO and QI, and the second from the National Aeronautics and Space Administration's Jet Propulsion Laboratory. Using advanced data visualization approaches, these case studies were presented in order to demonstrate what is possible now with real world applications.

Panels

Two panel discussions gave Forum participants an opportunity to learn from and ask questions of the experts. The first panel discussion comprised of the case study presenters and other experts in data science examined the

implications of the case studies and the previous day's demonstrations. Panelists discussed data science solutions to integrating temporally and spatially sparse data. The final panel discussion with Jerry Schubel, Margaret Leinen, and Larry Smarr summarized *Ocean Exploration in a Sea of Data* and reviewed what the community should do next.

Breakout Sessions

The organizers structured the Forum to provide participants, regardless of discipline or experience, with common information and experiences to stimulate breakout sessions. The keynotes, panel discussion, case studies, and especially the demonstrations were intended to share new information, provoke thought, spark creativity, and encourage dialogue across ocean exploration and data science and visualization disciplines.

Breakout session participants were asked to rely on this common information, as well as their own expertise and experience, to address several questions that the organizers intended to help spark discussion about how new techniques in data science and visualization can be applied to ocean exploration to understand the ocean in new ways and to develop recommendations for ocean exploration stakeholders and specific sectors involved in exploring the deep ocean. Each breakout group then presented the results of their discussions in plenary.

Participants

Nearly 125 experts in fields including ocean exploration and data science participated in this event. Ocean exploration is multidisciplinary—oceanographers, marine geologists, marine biologists, marine archaeologists, and others collaborate to plan expeditions and participate to ensure as much as possible is learned when exploring an unknown deep ocean environment. *Ocean Exploration in a Sea of Data* broadened the ocean exploration community's traditional notions of multidisciplinary collaboration to include data scientists, computer scientists, and visualization experts from QI—some of whom are also musicians and artists. This synergistic blend of expertise, discipline, perspective, and sensibility allowed participants to experience and understand ocean data in new—and sometimes unexpected–ways.

Results

Ocean Exploration in a Sea of Data resulted in recommendations for how data scientists and ocean explorers can collaborate to expand traditional concepts of ocean exploration and drive toward new discoveries, greater access to contemporary and historical data, and engaging the public. Concepts and approaches the participants described are revolutionizing the way we do and present science. Data analysis and synthesis tools allow for inductive lines inquiry.


NATIONAL OCEAN EXPLORATION FORUM | 2017
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Keynote Talks

Through the emerging national program for ocean exploration, scientists have demonstrated a certain facility for collecting data at sea. But how does the ocean exploration community meet the numerous challenges that these data present? And how does the community better explore ocean data?

> "*Ocean Exploration in a Sea of Data* was designed to first introduce a common understanding of challenges and opportunities in ocean exploration data."

Ocean Exploration in a Sea of Data was designed to first introduce a common understanding of challenges and opportunities in ocean exploration data. The Forum featured two distinguished keynote speakers to set the conceptual stage for the rest of the program. Margaret Leinen, Scripps Institution of Oceanography, discussed the challenges and opportunities of rich datasets, highlighting the differences between deduction and induction. Larry Smarr, California Institute for Telecommunications and Information Technology, focused on our increased ability to move very large volumes of data at high speeds among distributed processing clusters and the opportunities this creates for ocean and other science enterprises.

In addition, this Forum featured a special presentation on ocean exploration in the temporal domain by John Delaney, Professor of Oceanography and the Jerome M. Paros Endowed Chair in Sensor Networks at the University of Washington.

2017 National Ocean Exploration Forum keynote speakers Jerry Schubel, Margaret Leinen, and Larry Smarr. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

KEYNOTE TALKS

Approaching Ocean Exploration from a Different Angle

MARGARET LEINEN
Director of the Scripps Institution of Oceanography and University of California, San Diego
Vice Chancellor for marine sciences and Dean of the School of Marine Sciences

Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

Dr. Margaret Leinen, Vice Chancellor for Marine Sciences at the University of California, San Diego (UC San Diego), and Director of the Scripps Institution of Oceanography, gave the first keynote address from the perspective of ocean science and the challenges and opportunities dramatic increases in the volume of available data about the ocean present. She described the initial focus of ocean exploration was to explore parts of the ocean that had never been seen before. Things have changed and our sense of exploration has matured. Physical exploration—even with new instrumentation—is seldom enough to achieve the insight we seek. Dr. Leinen noted that we want to go beyond initial discovery to gain a deeper understanding about the ocean. There is a need to explore data, spatially and temporally, to understand processes and the evolution of those processes over time. We need multiple observations, which will result in far more data than we've ever gathered and managed before. We need new approaches to effectively use these data.

Throughout the history of modern-day science, Dr. Leinen observed, we have used deductive reasoning—following the scientific process that begins with questions and a hypothesis then draws conclusions from experimental results. But this approach may limit our ability to see what is actually happening, especially in complex systems like the ocean. An alternative method is inductive reasoning, exploring the data to allow patterns and insights to suggest conclusions and new hypotheses. This could be a better approach for extremely complex systems. Large datasets and data science techniques allow us to explore ocean science data using inductive reasoning have already seen some interesting examples of the benefits of this approach.

Dr. Leinen provided several examples of how inductive reasoning—using relatively new analytical tools to explore vast data sets—can result in new discoveries, which are reviewed below:

Argo Example

The Argo program has deployed nearly 4,000 autonomous floats in the global ocean to continuously measure the physical properties of the upper 2,000 meters of the water column; each sends back a rich data set (temperature, pressure, location, and conductivity) every five days. With these rich data, we can quantify ocean heat increases and decreases around the globe, radically changing physical oceanography. Additionally, we can now map the salinity change around Antarctica as a measure of the mass balance of melting of Antarctic ice.

Chlorophyll A Example

Scientists have been looking for explanations to predict harmful algal blooms (HABs) before they occur. Using an empirical, dynamical modeling approach, letting the data guide the question, scientists found that the ocean was setting up for a HAB weeks in advance of the actual event. They were able to predict all of the HABs in the 2011 to 2016 segment of the data with the predictive algorithm from the 1983 to 2010 data set, which had never been done before. This powerful predictive ability did not come from hypothesis-driven science, it came from the data.

3D Modeling Example

Scientists interested in detecting the impact of individual components of a multi-stressor (warming, acidification, physical disruption, pollution, deoxygenation) system on corals employ systematic diver photo surveys, taking the many thousands of resulting images and converting them into 3D mosaics. They use different colors for computer-generated identification of specific species and are then able to review these 3D models in time series approaches to see which species are being affected over time.

Dr. Leinen stressed the importance of legacy data, stating that it is time for us to recognize the value of legacy data. Many legacy data, while perhaps less constrained by modern data, represent a unique observation in time and space and can be critical to understand the ocean and how it is changing. If we are going to explore the modern and legacy data, she asked, what are the challenges and how can we overcome them?

She identified curating data—and making it available in a way that can be routinely accessed by people and software—as one of the biggest challenges we now face. With the explosion of different devices being used for sampling and increasing resolution, there is a need to be able to store, manage, and make sense of our data. Putting it all together, getting it into the same format, and doing quality assurance and quality control are increasingly important if we want the ability to integrate and analyze ocean data.

A second challenge, she said, is keeping observations going. While long-term monitoring programs are crucial for understanding change over time, they are continually at risk for funding. This is a critical issue. These data sets are not just legacies, they are enduring indicators of our changing world.

A third challenge Dr. Leinen identified is making data accessible—not just curated and existing—but also making it possible for people to find what they need in those data sets. Beyond the metadata, information is needed to give context. Even if large, well-curated datasets exist, they need to be accessible to those in other fields, people who may have ideas about how their variables may affect the ones ocean scientists typically are interested in.

We need to look at both the opportunities and challenges inherent to crowdsourcing. We need to think about what will happen with the data—who will take responsibility for it and ensure it becomes part of a quality controlled, verified, usable, accessible, and long-lasting database. We may be able to benefit from the power of the Internet to solve oceanography problems, as crowdsourcing gives us the ability to involve thousands of people with our work.

Dr. Leinen closed by observing that the importance and uniqueness of ocean data demand that we strive for open access and open source analysis tools. We need to assign DOIs to data sets, cite data sources, and give professional credit for data sharing. The politicization of science demands that we build in vigilance and stewardship of data. We should delight in our data, our ability to use the data, in the things we are able to share with each other, and how much excitement we have about the ocean.

The demonstrations from *Ocean Exploration in a Sea of Data*, she said, will allow us to think about existing data and information—and how we can use it. Beneath it is this legacy, this responsibility, this call for opportunity. The funding that has been devoted to exploration of the ocean, and especially the generation of these data, demands that we explore them, start bringing them into the light, and use them to try to address these problems.

KEYNOTE TALKS

Big Data Cyberinfrastructure and the Future of Ocean Exploration

LARRY SMARR
Founding Director of the California Institute for Telecommunications and Information Technology who holds the Harry E. Gruber professorship in Computer Science and Engineering at the Jacobs School of Engineering at UC San Diego

Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

As ocean instruments collect an increasing diversity of data and data volume grows exponentially, the challenges of moving data around and the infrastructure needed to analyze, model, and collaborate must keep pace. Dr. Larry Smarr, founding director of the California Institute for Telecommunications and Information Technology (Calit2), described cyberinfrastructure as essential to marine science and data generation. Science creates enormous amounts of data; sharing those data over the standard Internet can present major challenges. To accelerate the rate of scientific discovery, researchers must get the data they need, where they need it, and when they need it. This requires a high-performance data freeway system in which we use optical lightpaths to connect data generators and users of data. Our increased ability to move large volumes of data at high speeds among distributed processing clusters has created opportunities for ocean and other science enterprises.

Dr. Smarr said that some scientists doing ocean modeling runs have found that the highest speed research networks like the Pacific Research Platform (PRP) and the Corporation for Education Network Initiatives in California (CENIC) get almost an order of magnitude speed-up in modeling runs and large dataset transfers over conventional high speed networks. What were once individual research servers now are interconnected, increasing efficiency and speed. As costs come down over time, emerging technology allows conversion to higher capabilities and capacities. As the bandwidth increases, the workflow for data products changes.

In terms of the science, he said, this provides an increased ability to do science steps—meaning steps can be taken more frequently with faster data processing. This new cyberinfrastructure has the potential to be transformational as computational and transfer constraints are eliminated.

Further, Dr. Smarr explained, machine learning is becoming a key part of science and also increases the pace. For example, machine learning can perform incredibly well on image analysis and classification. The computer can look at each image to determine what's there. Scientists can then check to see if it is a known species or not, classify them, and do the statistics on the ecology distribution and changes over time.

Having big data in multiple fields will require machine learning. Now that there is enough data and the means to transfer large data sets quickly, computer scientists are needed to develop machine learning algorithms and for other developments that will allow scientists to take full advantage of advanced networks and machine learning technologies. Dr. Smarr described the UC San Diego response in creating a Master's Degree in Data Science and a new undergraduate degree in Data Science.

Focusing in on the *Ocean Exploration in a Sea of Data* themes, Dr. Smarr stressed that open access to big ocean data is critical. Scientists need to make data available, preferably in the cloud. People can then take the datasets and the hardware and link them together by simply clicking on a screen. UC San Diego is leading research and development into new ways to link data and hardware, but those in the marine sciences need to determine how best to take advantage of it and organize amongst themselves how best to proceed so that the ocean science community can benefit.

Dr. Smarr acknowledged that many of the concepts he presented were highly technical and that terminology he used might be new to ocean explorers and ocean scientists. But that it was nevertheless important that the community become familiar with these concepts and the vocabulary of high-speed networks. This is the new infrastructure on which the next age of ocean exploration will be run. He said that people in the data science world would love to see their counterparts in ocean sciences step forward and become early adopters of these techniques, perhaps inspired by what they would see at the Forum. Many of the demonstrations at this Forum did not exist a week prior to the Forum, he said, and came into being because of this Forum. It drove people to do something they hadn't been able to do before in order to share them with this community.

> "...people in the data science world would love to see their counterparts in ocean sciences step forward and become early adopters of these techniques, perhaps inspired by what they would see at the Forum."

Dr. Smarr's closing observation was that soon we will have hundreds or thousands of times more data coming in every second than we do now. The only way to manage these high volumes of data will be to visualize it and scale the visualization, storage, computing, and network coherently. The demonstrations prepared for *Ocean Exploration in a Sea of Data* will help to show what's possible, and where we need to go for the future.

Ocean Exploration and the Temporal Domain

JOHN DELANEY
Professor of Oceanography and the Jerome M. Paros Endowed Chair in Sensor Networks at the University of Washington

Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

Typically we think of ocean exploration as involving a ship setting sail for an area of interest. The ship serves as a platform for various sensors, such as multibeam sonars, and as a deployment platform for submersibles like remotely operated vehicles. But University of Washington oceanography professor, John Delaney, argues that we should think of exploration as including investigations in the time dimension. The ocean, he said, is the planet's essential life support system and its final frontier. Thus, we need to gain a better understanding of marine ecosystems. The ocean is an incredibly complex system in which thousands of physical, chemical, and biological processes continually interact and interoperate over many scales of time and space. Our goal needs to be sustainable ocean management. While this may be beyond our reach right now, it shouldn't be beyond our aspirations.

Dr. Delaney described our challenge as optimizing the benefits and mitigating the risks of living on a planet dominated by two major energy sources: sunlight driving the atmosphere and much of the upper ocean, and internal heat driving plate tectonics and portions of the lower ocean. The human element has begun to fundamentally modify the way the planet works. We need to know, he said, how dependable the ocean is as a source of resilience, what the limits to that resilience might be, and how best to assess the resilience. Dr. Delaney stated that the ocean has been under-sampled for as long as humans have been trying to characterize its complexity. In order to understand the ocean and marine ecosystems, we need to permanently and comprehensively enter the ocean to study it from within—every hour of every day for the rest of the lifespan of humanity. There are ways in which we can maintain a sustained presence, studying it in great detail and depth. The next generation of ocean exploration and education involves using a range of innovative technologies

to capture, image, document, and measure ocean phenomena. New research approaches should allow broad spectrum, interactive ocean processes to be studied simultaneously and interactively by multiple scientists in multiple disciplines.

As an example of this new approach, Dr. Delaney cited Axial Seamount, located on the spreading center between the Juan de Fuca and Pacific Plates. Researchers from the University of Washington and other institutions wired it with a fiber optic cable, connecting it to shore. A network of instruments deployed around the seamount relay data in a continuous flow back to shore. This sustained approach creates long-term human presence in the ocean using underwater volcanoes as the study target and looks at the linkages and interdependencies among the physical, chemical, and biological processes in Mid-ocean Ridge (MOR) systems. He described the monitoring infrastructure as adaptable and expandable, currently utilizing about 140 instruments. The data coming back to shore from all instruments are in real time and are available to anyone who accesses the system from the Internet.

Dr. Delaney described the benefits: scientists have had a limited understanding of the materials volcanoes put out when they erupt. Axial Seamount erupted while under surveillance; giving new insights into the MOR system. The middle of the caldera fell almost 2.5 meters and the water temperature went up almost 0.7 degrees Celsius. That should have caused the fluid to rise, but it didn't. Although we don't have direct measurements, he said, scientists' conclusion was that the caldera was full of salt; the hydrothermal systems at Axial are boiling and when they boil, the gas rises off and the salt settles. In addition, the team recorded the sound with a hydrophone. The signal did not come through the ground as an earthquake, it was generated through the water. Scientists think these are explosions that are associated with the lava coming out and releasing gas into the overlying ocean.

Dr. Delaney used the Axial Seamount example to illustrate the need to plan for the future, to think about where oceanography is going to be in 10 to 30 years. The rhythms of the ocean and the recovery of atmospheric and ocean systems are long-term issues that require long-term thinking. With technological progress expanding, we could make tools with thousands times more capability than we currently have.

If we want to understand how the ocean works, he said, we have to understand the different volumes of the ocean themselves and how they interact with one another. We need sensors that can map out these volumes, save the data, and communicate through mobile platforms back to the scientists, giving us real-time communication continuously throughout the entire volume of the ocean.

Dr. Delaney described a future of ocean exploration that includes myriad streams of real-time data flowing continuously, captured by people who accumulate these data and put them into an expanding reservoir of globally accessible historical data on the Internet. Scientists need to take advantage of the rapid convergence of communications, genomics, artificial intelligence, nanotechnology, and other technologies. Where all of these overlap, he said, is where we have the potential for unbelievable progress in the world of mobile platforms. We need to try new things out and have enough bandwidth to surveil the failures. We learn from our failures, just as we do from our successes.

He further described a future with the right kinds of platforms and sensor packages moving through the ocean and sending data back, as well as the right kind of infrastructure that can manage information coming ashore. Dr. Delaney's challenge to *Ocean Exploration in a Sea of Data* participants was that they should look for multiple types of broad-spectrum, evolving capabilities and multiple types of sensors—sensors capable of repairing and replicating themselves.

In the years ahead, he said, we will begin to explore oceans on other planetary bodies in the solar system. We will fly through the plumes that penetrate the ice into the overlying space; eventually we will get below the ice. If there's tectonic-type activity there, there may indeed be something like life. Bringing together the idea of outer space, oceans, and life is incredibly powerful as a driver for discovery.

DEMONSTRATIONS

Introduction to the Demonstrations

Ocean Exploration in a Sea of Data Forum organizers solicited the development of five practical demonstrations that would allow participants to explore and experience data in new ways. The demonstrations at the 2017 Forum relied on technologies developed at the Qualcomm Institute (QI), the unique capabilities of the visualization and audio laboratories at QI, and the dynamic culture of experimentation and development driven by innovative students and professors—many without prior ocean exploration experience.

Forum participants were assigned small groups to rotate through the five demonstrations, plus a sixth facilitated discussion session that allowed for the sharing of impressions, ideas, and implications of the demonstrations.

Short summaries of the demonstrations follow.

Ocean Exploration in a Sea of Data participants observe a demonstration of a point cloud representation of a coral reef displayed in the WAVElab. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego.*

DEMONSTRATIONS

Exploring Ocean Data Through Audio Spatialization and Sonification

SHAHROKH YADEGARI
Qualcomm Institute

GRADY KESTLER
Qualcomm Institute

ADRIENNE COPELAND
NOAA's Office of Ocean Exploration and Research

Sound is ubiquitous in the deep ocean environment. Geological events, like earthquakes, can contribute significant levels of sound to the deep ocean. Many marine animals, from shrimp to whales, use sound to communicate and assess their environment. Humans generate a wide array of sounds as well. This combination of physical, biological, geological, and anthropogenic sounds make up the marine "soundscape". Exploring marine soundscapes can lead to a better understanding of the deep ocean; it is an important aspect of the characterization of these marine environments.

Rapid advancements in technology have allowed us to present acoustic data in a new way. The Audio Spatialization Lab (SpatLab) allows for a 3D exploration of sound, the acoustic dimension of ocean phenomena. Its audio systems are a critical tool for understanding complex scientific data.

Forum participants experienced the basic capabilities of the SpatLab, including the geolocation of sound sources. The lab has a focus on auditory realism; they attempt to simulate auditory signatures and spatially isolate or highlight some sounds while suppressing others. The large array of speakers around the room allowed participants to experience the sounds of a virtual rainstorm. In addition, the SpatLab has developed a system for delivering localized audio through compacted series of speakers. They can direct sounds to various angles so different sound fields can be generated for different listeners, based on their location. Using this technology, Forum participants experienced a lifelike "virtual haircut".

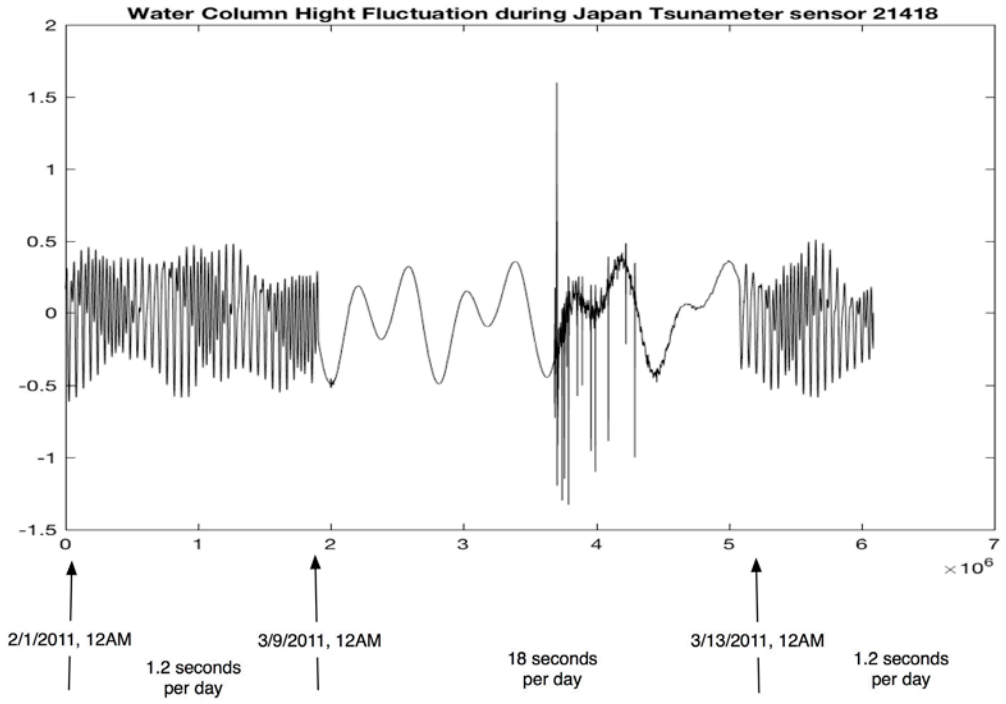
The demonstration explored different aspects of deep ocean soundscapes, from undersea volcanoes to ensonifying non-acoustic tsunameter data. Participants also observed how ocean phenomena could be modeled acoustically and how sound could be used to explore and understand aspects of the deep ocean in ways otherwise not possible. Using virtual reality goggles and a joystick, participants could locate themselves in relation to different sounds. Participants also watched a predator-prey interaction based on

Forum participants observed how sound could be used to explore and understand aspects of the deep ocean in new ways.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

sound data that demonstrated how whales move through the water while feeding, geolocating individual marine mammals through acoustic arrays.

These visualization techniques can help improve audio imaging for ocean exploration. They allowed participants to experience audio data in new ways and, perhaps, find ways to adapt these techniques to their own data.

The SpatLab is ground zero for the Qualcomm Institute's Sonic Arts Research and Development (R&D) group. The space is optimally designed for audio research and music composition. Researchers are able to simulate, emulate, reproduce, and even predict sounds as they might be experienced in different acoustic environments. SpatLab specializes in ambisonics, acoustic beam-forming, and sonification of data. The Sonic Arts R&D Group works hand-in-hand with leading university and industry partners in an interdisciplinary environment. These unique partnerships integrate and commercialize next-generation mobile, game, and cinema audio technologies.



A multi-rate graph of the fluctuation of the ocean water column height based on the water column pressure obtained by the closest Tsunameter sensor (21418) to the epicenter of the Japan 2011 earthquake. This graph was used for sonification of the data presented at the 2017 NOEF as an example of how audio could be used for ocean data analysis.

A Forum participant uses virtual reality to experience geolocation of ensonified data. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

Forum participants learn how new visualization techniques can reveal ice structure and under-ice bathymetry.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

DEMONSTRATIONS

WAVElab Underwater Photogrammetry: Point-Based Visual Analytics and Habitat Characterization

FALKO KUESTER
Qualcomm Institute

DOMINIQUE RISSOLO
Qualcomm Institute

Structure-from-Motion (SfM) photogrammetry has become an empowering and widely adopted technique for documenting underwater features or sites in 3D. The combination of relatively straightforward image acquisition protocols and the ability to render both geometrically accurate and photorealistic models (using readily available software) has made the technique popular, particularly for limited photo-mapping of shallow benthic environments. SfM photogrammetry presents numerous challenges, including the computational power required to process and postprocess massive image-sets; the ability to assess the integrity of the models produced; and the extent to which these 3D data can serve as the basis for new analytical approaches.

The Wide Area Virtual Environment lab (WAVElab) is a large-scale immersive visualization system. The large screen display gave Forum participants an opportunity to see these data in a vibrant 3D model. The models are crafted from thousands of images, shot by divers who swim over targets in a gridded pattern, taking a photo every second. Researchers then run the series of images through photogrammetry software to create the 3D model, stitching together thousands of photos into a single 3D image. The resolution shows detail to within a centimeter and allows them to visualize these data in a new way.

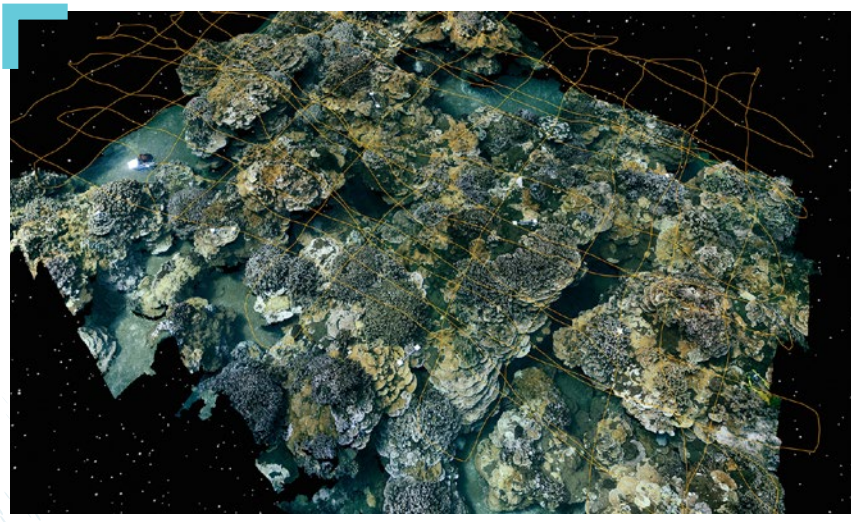
Through the high-resolution images and 3D models, participants were able to see these models, which are digital surrogates for real locations. They explored how the scientific potential of these data can be realized through the use of these new analytical tools. Researchers have photographed coral reefs, shipwrecks, and submerged Pleistocene megafauna around the world with this technology. This tool allows them to spend hours extracting data from a single dive with these models, transforming their ability to collect data and learn from them in an entirely new way.

These models can become a baseline for understanding a feature like a reef. Researchers can revisit a site at a later date and repeat the process. This can be incredibly valuable for understanding change over time.

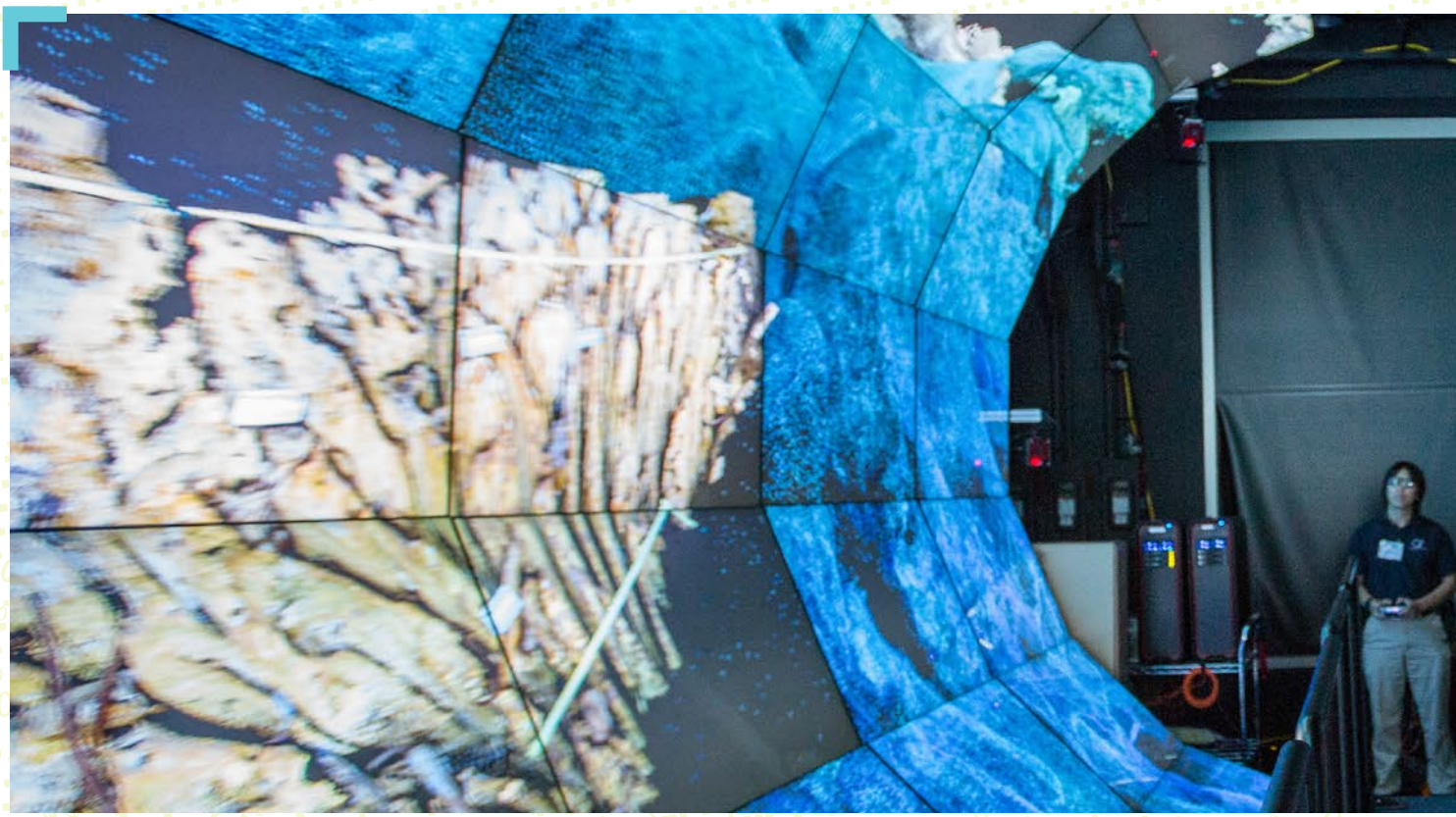
Forum participants observed how sound could be used to explore and understand aspects of the deep ocean in new ways. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

The same techniques can be used for maritime archaeology and other fields. Participants were encouraged to think about how they can bring this to their own areas of expertise.

The WAVE further pushes the envelope of 3D "big-virtual reality (VR)," exploring techniques that enable the creation of ultra-high-resolution, immersive, walk-in, virtual environments for collaborative research, development, data analytics, and scientific storytelling. The WAVE geometry approximates a half-cylinder lying on its side, allowing users to freely move along its center on a raised platform. It



A point-cloud of a section of coral reef off Kaho'olawe, Hawai'i. The 10m x 10m plot was documented using SfM photogrammetric techniques. A geometrically accurate model of the reef was derived from 1,969 images and is comprised of 316 million points. The yellow lines in the visualization represented the camera's path. *Image courtesy of 100 Island Challenge*



QI staff engineer, Eric Lo, flies Forum participants through a point cloud of a coral reef on the WAVE. *Photo by Alex Matthews and Amiel Capinpin for Qualcomm Institute/UC San Diego*

The WAVElab's large-scale immersive visualization system gave participants an opportunity to experience photogrammetry data in a vibrant 3D model. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

"The WAVE further pushes the envelope of 3D "big-virtual reality (VR)," exploring techniques that enable the creation of ultra-high-resolution, immersive, walk-in, virtual environments for collaborative research, development, data analytics, and scientific storytelling."

uses 35, ultra-narrow bezel, passive stereo, high-definition display tiles in a 5×7 layout to approximate the half-cylinder (cresting-wave) geometry, providing up to 160° horizontal and 180° vertical (toes-to-sky) field of view. Its offers a total resolution of 9,600 x 7,560 pixels (72,576,000 pixels), or approximately 36 megapixel per eye. The WAVE is powered by 18 display nodes with dual graphics cards and 40 gigabits per second (Gbps) network interconnected and controlled via an additional head node. A light-based tracking system is used for head, wand and gamepad tracking for intuitive interaction. WAVE uses the Qualcomm Institute's WAVEnet experimental network, providing over a terabit worth of network bandwidth within the WAVElab and connects to the campus research network and beyond at up to 80 Gbps. WAVE is the first operational big-VR system tapping the potential of the Pacific Research Platform (PRP)—a new National Science Foundation project that uses fiber-optic networks to connect researchers at universities throughout the West Coast, enabling them to share "big data" at an unprecedented speed. The WAVE hardware design as well as its open-source software stacks, called CGLX and CalVR, were entirely developed in-house.

DEMONSTRATIONS

SunCAVE: Seabed Mapping – New Perspectives from Immersive Visualization

VICKI FERRINI
Lamont-Doherty Earth Observatory

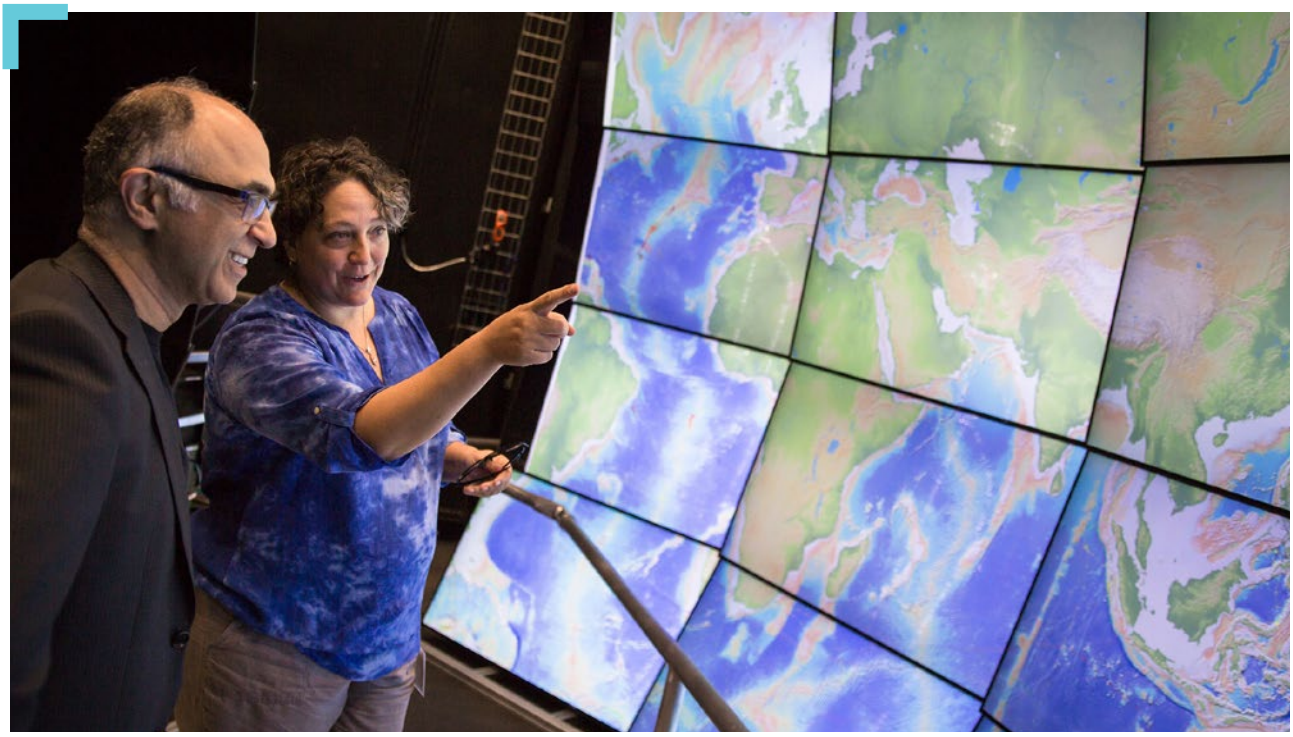
Seabed mapping provides critical baseline information for ocean exploration. Bathymetric data are typically presented in one of two formats: map contours with color schemes familiar to anyone who has examined a nautical chart, or as colored, shaded 3D renditions of gridded data. While these data representations can be easily manipulated for a variety of applications, neither allows us to intuitively understand and feel the scale of seafloor bathymetric features. A similar challenge of scale in ocean mapping is related to how few people outside the ocean exploration community truly understand the magnitude of how little of the ocean has been mapped.

The SunCAVE (Cave Automatic Virtual Environment) is an immersive 3D environment that allows for near-360° presentations of video and data. Projections of scientific models and animations literally surround the viewer, allowing researchers to simulate immersion into a variety of different environments. Forum participants were first immersed in a colored point cloud visualization of the archaeological world of Tikál, Guatemala, and were then immersed into 360° video from under Antarctic sea ice.

These presentations were followed by undersea mapping data visualizations that enabled participants to experience the deep-ocean landscape as though they were standing on the seafloor. This demonstration presented seafloor mapping data as an immersive visualization with the goal of improving our understanding of scale and enabling new perspectives and understandings of seafloor features.

This type of data visualization with seafloor bathymetry and other attributes of the deep ocean can inform science and strengthen public interest in ocean exploration, help educators explain the ocean, and engage more of the public in ocean exploration through new visualization techniques.

The virtual cave can enable scientists to take ocean data and view accurate 3D replicas of large-scale features such as underwater volcanoes, rift zones, and trenches as well as smaller-scale features



Vicki Ferrini discusses the capabilities of the SunCAVE with Shahrokh Yadegari, the demonstration lead for SpatLab.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

like hydrothermal vent structures and bedforms. The power of visual analytics can bring remote sites like these to the scientific community, allowing for greater understanding about undersea features.

The SunCAVE is the Qualcomm Institute's highest-resolution virtual reality (VR) system and, in terms of pixel count, is one of the largest systems in the world. The SunCAVE allows researchers to view detailed information in a contextually different way than ever before. The geometry of the SunCAVE is a full 360° field of view from left to right and is nearly a complete spherical structure surrounding the point of origin. The CAVE was designed to be a full 360° walk-in environment, which means that the CAVE requires two separate elements: a main CAVE environment and a second curved back wall structure, to allow for users to freely walk in and out of the space. The main CAVE structure consists of odd and even columns, each designed so the odd columns overlap the even ones. The overlap allowed the design engineers to create the curved structure. The rear structure is at a wider angle and open to allow users to walk in while maintaining consistency in QI's stereo parallax. The SunCAVE tiles together 70, 4k/3D displays giving a total of approximately 500 million pixels ([3840x2160] x 70) which brings us closer than ever before to the resolution of the human eye. The CAVE is driven by 35 computer nodes, each featuring 2 Nvidia 1080 graphics cards, and all with 40 Gbps connectivity. Considering that the CAVE has 70 high-end graphics cards, QI can use the graphics processing unit (GPU) power as a computing resource for running large data sets for various campus groups. The SunCAVE is also a test environment for containerizing QI visualization software. Like other QI visualization environments, the SunCAVE hardware design and software were developed in house.

SECTION 04

Participants explore the SunCAVE's near 360° 3D immersive environment. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

"The SunCAVE is the Qualcomm Institute's highest-resolution virtual reality (VR) system and, in terms of pixel count, one of the largest systems in the world."

DEMONSTRATIONS

Cultural Heritage Engineering Initiative Lab: Visualizing Antarctic Ice Shelf and Bathymetry with Airborne Radar Data

ROBIN BELL
Lamont-Doherty Earth Observatory

NICHOLAS FREARSON
Lamont-Doherty Earth Observatory

Ocean exploration in remote polar regions presents unique operational challenges. Acquiring good bathymetry in remote under-ice environments is critical to understanding these important deep ocean regions. Under-ice bathymetry is required to understand how ice sheets are changing. For example, the shape of the ocean floor controls how warming ocean water can reach the West Antarctic Ice Sheet. Good bathymetric data is fundamental to predicting how fast sea level will rise in the future. Future ocean exploration and research in the polar regions will become increasingly important for understanding how large ice sheets change over time.

The Cultural Heritage Engineering Initiative (CHEI) Lab allows for 3D displays of high-resolution images, video, and photogrammetric point clouds. The ROSETTA-Ice Project is mapping the least known ocean floor on our planet through the use of aerogeophysical techniques: the use of aircraft as platforms for radar, gravimeters, and other instrumentation. Gravimeters are used to approximate ocean depth from aircraft flying 2,500 feet above the ocean or ice surface and radar systems map the structure of the ice that floats on it; ice that can be up to one kilometer thick. Planes fly in a grid pattern over the survey area to compile the data, which is then brought to the lab for processing.

This demonstration integrated these aerogeophysical data and streamlined the data for analysis. Forum participants were shown images of a large rift in the Antarctic Larsen C Ice Shelf. The demonstration also included a fly-through of the ice penetrating radar data, displaying the data for the participants on a large screen. While "flying" over the ice in Antarctica, they could see the thickness of the ice and where there might be differences in the ice structure, helping them to visualize how the ice shelf changes.

These data may contribute to a better understanding of phenomena such as mass calving events, like the Antarctic Larsen C Ice Shelf's Delaware-sized calving event in 2017, or the Antarctic Larsen B Ice Shelf collapse that occurred in 2002. This knowledge will help give scientists insights into the potential future impacts of climate-

Nicholas Frearson discusses the use of aerogeophysical techniques for data collection to Forum participants.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

related warming on polar ice. The CHEI Lab at the Qualcomm Institute (QI) brings the power of advanced data processing and visualization to world heritage documentation, analysis, and preservation. At the core of the CHEI Lab's visualization capabilities are two WAVElets and four OptiPortables. The WAVElet is a miniaturized, mobile relative of the Wide Area Virtual Environment (WAVE) and successor to the OptiPortable. The WAVElet packs a fully integrated, high-resolution, passive stereo virtual reality (VR) system into a shipping container, creating a modular and scalable building block for the development of multi-user VR environments. Its 2×2 display layout creates a 110″diagonal, 3D 4K (quad-high-definition (HD)) resolution display canvas. The left and right 1×2 tile assemblies are hinged at the center, allowing them to be folded back-to-back and lowered into a shipping-hardened box via a motorized lift mechanism. The WAVElet allows the CHEI Lab to take their research to conferences, workshops, trades shows, museums, into classrooms, and most of all, "into the wild" for applied research. The WAVElet hardware design as well as its open-source software stacks, Cross Platform Cluster Graphics Library (CGLX), MediaCommens and CalVR, were entirely developed in-house at QI. The OptiPortable creates a "display-in-a-box" or "science-in-a-box" capability. It integrates four narrow-bezel display tiles in a 2×2 layout, delivering 2D 4K (quad-HD) resolution, across a combined 110 diagonal. Its butterfly frame configuration, allows the left and right 1×2 tile configuration to be folded back- to-back, and retracted into a shipping container for rapid field deployment. The OptiPortable integrates all vital components, from the display, network, render and control nodes to sound system, in one easily to manage, modular building block.

DEMONSTRATIONS

Being There Without Being There: Using the QI Vroom (Virtual Room) Display Wall

JOHN DELANEY
University of Washington

TIMOTHY CRONE
Lamont-Doherty Earth Observatory

FRIEDRICH KNUTH
Rutgers University

AARON MARBURG
University of Washington

The recent completion of the Cabled Array of sensor networks is a major component of the National Science Foundation's (NSF's) Ocean Observatory Initiative (OOI). The observatory offers unique opportunities to explore the scientific and educational benefits of real-time access to a highly active portion of the Global Mid-Ocean Ridge (MOR) System—a 70,000 kilometer-long volcanic feature that extends around the world like strings on a baseball.

This Forum demonstration focused on the linkages and interdependencies among the physical, chemical, and biological processes in the MOR system, highlighting the evolution of the vigorously venting heavily colonized hydrothermal structure, recently dubbed "Mushroom".

This fiber-optic system is about 900 kilometers of electro-optical cable, 10 gigabit per second (Gbps) bandwidth, eight kilowatts of power, and 140 instruments. Researchers put over 20 instruments inside the caldera at the summit of Axial Seamount atop the Juan de Fuca Ridge, including seismometers and a high-definition (HD) video camera. Presenters could control an HD video camera which is located 400 kilometers due west of Astoria, Oregon—1,400 meters below the sea surface.

The data coming back to shore from all instruments is in real time and is available to anyone who accesses the system from the Internet. The demonstration highlighted the importance of continuous real-time monitoring to understand change in the deep ocean and the significance of ocean exploration in the temporal domain.

Ultimately, participants were given the opportunity to imagine having myriad streams of real-time data flowing continuously from all over the world's ocean, captured by people who accumulate these data and put them into an expanding reservoir of globally accessible historical data on the Internet. This would allow for new types of visualization that would give researchers incredible insight into real-time ocean conditions.

The Big Wall in the Vroom is a tiled display environment, using an 8×2 tile layout, for a total of 32 narrow-bezel displays. Each of the 55 tiles has full HD resolution (1,920×1,080

Forum participants experience a demonstration focused on the linkages and interdependencies among the physical, chemical, and biological processes in the Mid-Ocean Ridge system with the Vroom hyperwall. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

Experts discuss the Vroom hyperwall. *Photo by Shanni Jin for The Qualcomm Institute/UC San Diego*

pixels), adding up to 66 million pixels on the entire wall (15,360 x 4,320 pixels). Vroom is equipped with multi-channel audio with beamforming capability, and large-area optical tracking. The wall realizes a modular design approach, combining eight OptiPortables in a 4×2 configuration, each contributing a 2×2 panel segment to the larger system. The bottom row of OptiPortables is deployed directly from their integrated shipping containers, while the upper row is suspended from the ceiling above. The displays are driven by 16 display nodes with dual graphics cards and 10 Gbps network interconnects, running Linux. In addition, three separate control (head) nodes are used to provide direct access to its three different software stacks, including Cross Platform Cluster Graphics Library (CGLX)/MediaCommons, System for Automated Graphics and Explanation (SAGE), and CalVR.

DEMONSTRATIONS

Participant Input from the Demonstrations

TIFFANY FOX
Qualcomm Institute

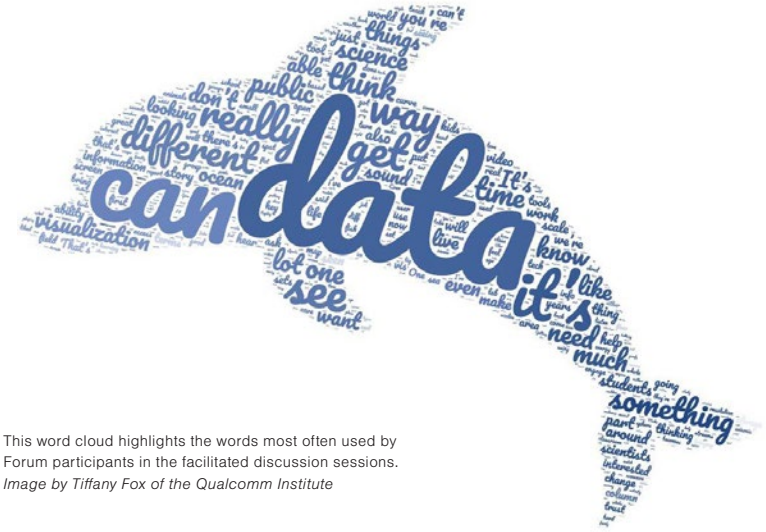
DAVID MCKINNIE
NOAA's Office of Ocean Exploration and Research

The facilitated discussion sessions, part of the demonstration series, was an opportunity for participants to share their impressions of what they had observed in the visualization and acoustic demonstrations. The discussions were also intended to help identify areas of potential collaboration between the data science and visualization experts and the ocean exploration community.

During the discussion sessions, participants agreed that the Forum demonstrations highlighted the rapid development of visualization technology, allowing researchers to transform their ability to explore, experiment with, and begin to more deeply understand the complex processes that take place throughout global ocean basins. When participants shared their impressions of the demonstrations,

Tiffany Fox facilitated a discussion session about the demonstrations, giving participants an opportunity to share their impressions.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

> **"Many participants expressed an interest in data synthesis so that different types of data could be organized and queried with questions over time."**



This word cloud highlights the words most often used by Forum participants in the facilitated discussion sessions. *Image by Tiffany Fox of the Qualcomm Institute*

they discussed how these tools could impact their work, areas of interest, and the ocean exploration community.

Two main themes emerged from the discussions; participants agreed that visualization is important both for engagement and for science.

Participants were interested in new ways to engage the public—getting their attention with these techniques and holding their attention with the story. They felt that science is a continuum, from domain experts to school children, and everyone can be a scientist. They thought these tools could help with education, engagement, crowdsourcing, citizen science, winning political support, and affecting policy change. For public engagement, they noted that—at their best— visualization and audio spatialization techniques:

- Could "get water out of the way" and help reveal, through multiple senses, a glimpse of the deep ocean world in terms relevant to most people.
- Convey fundamental aspects of the deep, from size and scale to topology and animal populations.
- Could give instant access to data in real time and allow users to control the data.
- Would require new best practices, employing stewardship to provide context, and would be transparent, scalable, and developed for multiple interfaces.

Many participants expressed an interest in data synthesis so that different types of data could be organized and queried with questions over time. They felt trust and data stewardship would be important. They expressed a need for open data, data access, data indexing, and data quality assurance to have trust in the data and to feel the data are reliable. For science use, they noted that—at their best—visualization and audio spatialization techniques:

- Could allow scientists to make sense of large quantities of data and lead to new understanding and insights.
- Would encourage participation in oceanographic research from people of all backgrounds, thus enhancing interdisciplinary and multidisciplinary collaboration.
- Would reveal new understanding and insights (sometimes immediately) not available through other means.
- Would need to be standardized across platforms and would lay the groundwork for developing new interfaces and user experiences.

“The idea that ‘we are looking for life on another planet’ is inherently more interesting to the public than ‘we are killing the ocean.’”

RECEPTION HIGHLIGHTS

Engaging the Public: Space vs. Ocean

Reception and dinner speaker Bob Weiss, Vice Chairman of the XPRIZE Foundation, treated the group to his thoughts on making ocean exploration as exciting to the public as space exploration. As a veteran Hollywood producer, Mr. Weiss's observations about the challenges—and opportunities—of engaging the public in ocean exploration were particularly relevant for a national ocean exploration forum focused on visualization and anticipated the 2018 National Ocean Exploration Forum, *All Hands on Deck*, which will focus on public engagement.

Using his vast knowledge of Hollywood films and applying a keen wit, Mr. Weiss led participants on a review of famous (and less famous) science fiction and ocean-themed movies to make a series of observations about the the public's perception of space and the ocean and suggestions for how those who want to communicate information about the deep ocean might frame that information. Among his key points, based on works also published by XPRIZE:

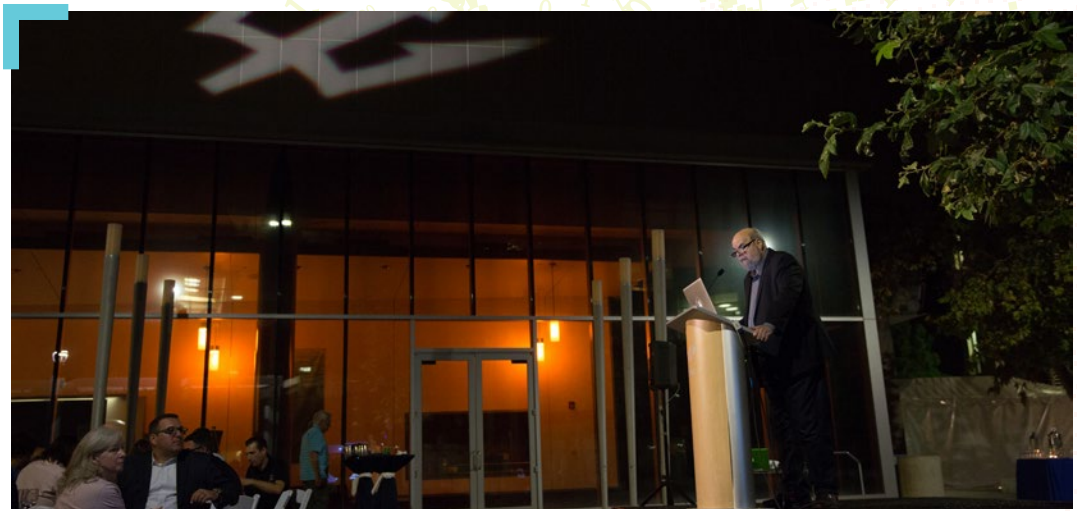
- Space stories generally are positive and have positive outcomes, while ocean stories often are negative. The idea that "we are looking for life on another planet" is inherently more interesting to the public than "we are killing the ocean." A positive message is more compelling and more likely to spark action than a negative one.
- Space stories trigger the imagination; ocean stories are more mundane. Space is vast, open, and panoramic. The ocean is cold, dark, and confining—at least in terms of human perception. Combined with messages stating the wonder of space (e.g., "the possibility of extraterrestrial life is exciting") the "openness" of space invites the imagination to roam. The cold, dark ocean is often combined with messages of overfishing or ocean acidification with the result the people react negatively.
- Space stories communicate real risk and danger to a mission while ocean stories often minimize risk to mission but covey generalized risk that is hard to grasp. For example, a rocket may blow up on the launch pad or otherwise fail. Everyone can understand this. While the ocean is an unforgiving environment and ocean technology has its own risks, these are minimized and a generalized risk of environmental harm presented instead.
- Space stories are forward looking and about an exciting and compelling future. Ocean stories are often the reverse, conveying a depressing, deprived future—or stories about the past.
- Space stories often involve exciting new technology and concepts that bring out the best in humans and human achievement. Ocean movies very often involve the past (e.g., sailing ships, submarines) and there are fewer examples of universal human achievement.

Mr. Weiss suggested that more creative and positive approaches to ocean stories could help change public perceptions and make the public more open to information about the ocean. The ocean community should look to Hollywood—but also to new ways of presenting and visualizing information to inspire the public.

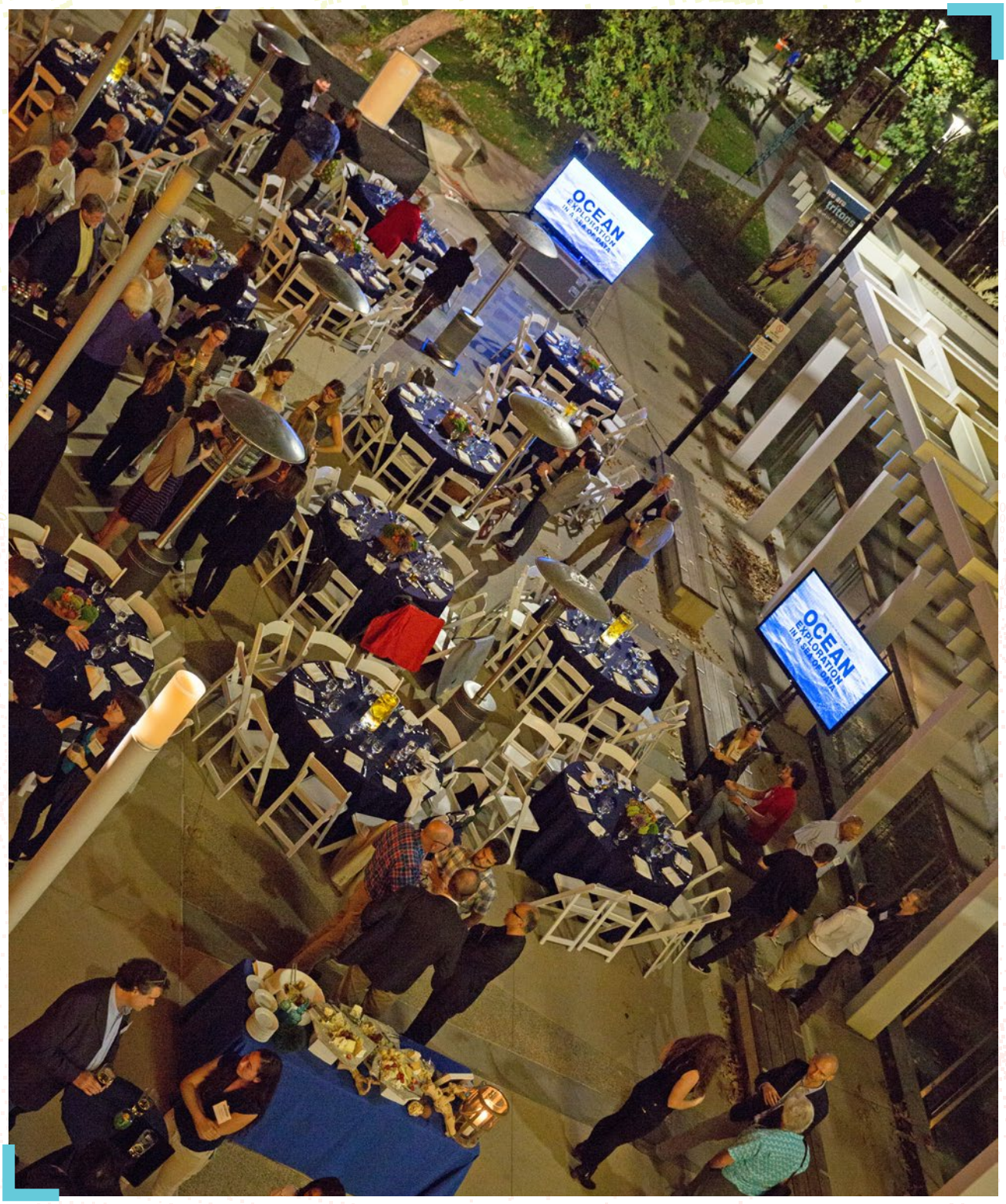
Participants gathered at the reception and dinner, which was an ideal time to mingle and share ideas about how to apply ideas from the Forum to their own work. During the reception, participants enjoyed a presentation by XPRIZE Foundation Vice Chairman, Bob Weiss.
Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego

NOAA's Office of Ocean Exploration and Research Engagement Lead and Forum co-organizer David McKinnie introduces the guest speaker, Bob Weiss at the Reception. *Photo by Alex Matthews and Amiel Capinpin for The Qualcomm Institute/UC San Diego*

"Coral reef" table centerpieces made from terrestrial plants and flowers designed by Qualcomm staff. *Photo by Alex Matthews and Amiel Capinpin for Qualcomm Institute/UC San Diego*



XPRIZE Foundation Vice Chairman Bob Weiss gives remarks during the reception. *Photo by Alex Matthews and Amiel Capinpin for Qualcomm Institute/UC San Diego*


OCEAN
EXPLORATION
OCEAN
EXPLORATION

This visualization technique has helped in terms of data acquisition, data archiving, and allowing scientists to have immersive experiences in environments like coral reef habitats.

Coral Reef Point Clouds and Classification

STUART SANDIN
Scripps Institution of Oceanography

FALKO KUESTER
Qualcomm Institute

VID PETROVIC
Qualcomm Institute

NICOLE PEDERSON
Scripps Institution of Oceanography

In the first case study presented at the Forum, professors and students from the Scripps Institution of Oceanography and the Qualcomm Institute demonstrated and explained their coral reef point cloud and automated classification scheme. High-resolution photogrammetric images are converted to point clouds. Algorithms automate the classification process so that each point contains location and type information as metadata; detailed analysis is possible.

The team described how this visualization technique has helped improve data acquisition, data archiving while allowing scientists to have immersive experiences in environments like coral reef habitats. These technologies and visualizations help to address some of the issues with data consistency and inter-comparability. They also increase the reach of these data; the visualizations give a broader audience exposure to ocean exploration.

To acquire raw imagery, divers capture large area imagery from coral reefs using a platform that houses three cameras, two for still images and one video camera. Using standard practices for photogrammetry, the divers imagine a particular target site, move the camera slightly while ensuring 75% overlap, and take the next image along a transect. Having this much redundancy helps build trust in the data. In the post-processing step, analysts take all of the images and determine how they relate to each other. Once they have this information, the team knits together and geo-references the images into a photometric model, then converts it to a point cloud. Divers also get angles so that the sides of the corals can be included in the point cloud, which is a digital surrogate, or cyber twin, of the coral reef.

Each of the digitized large area images is composed of between 3,000 to 6,000 individual images. After the images have been stitched together into a point cloud using photogrammetry software, team members identify the different species—digitizing, annotating, and classifying the entire landscape. The software that constructs the models allows the user to pull the raw image that corresponds to a

Stuart Sandin and Nicole Pederson discuss how coral reef point clouds have been used in their research.
Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

Falko Kuester and Vid Petrovic discuss designing and engineering this photogrammetry tool for use with field research.
Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

> "The model is a virtual reef that scientists can take back to the lab and archive. The point cloud can help answer questions they have not even thought of yet."

specific location, or coral, directly on the model, so scientists can zoom in and see the texture and detail. They can then use this information to run in-depth analysis on the reef.

By repeating this process at the same location at a later date, scientists can then analyze change over time. This means that they are learning not only about the negative stories on the reef, the death and destruction, but are also learning about the positive stories like new colonization and growth—growth that counteracts some of the dramatic losses scientists have seen. This method can also be used to compare to historical data sets that were collected using methods like photo quadrats to determine percent coral cover. It is not entirely human-centric annotation, which is time consuming.

The presenters commented that these tools are available to people who are not engineers and don't know how to program; it is a matter of taking photos and extracting data. As with Photoshop, the corals are all assigned on different layers, allowing scientists to turn on and off layers to see specific species in isolation on the 3D model. This allows them to understand distribution, clustering patterns, random distributions, size variations, and more—allowing analysts to learn about biological self-organization on a reef. The model is a virtual reef that scientists can take back to the lab and archive. The point cloud can help answer questions not yet posed.

But the process is labor-intensive, because each of the annotations is done by students hand-tracing the colonies and identifying them. As some species look similar, classifiers often need to reference the raw imagery to ensure an accurate interpretation of the data.

The goal for the future application of this visualization technique will include machine learning, if machines are able to learn to annotate the different species. The team said that creating algorithms to automate the annotation would free up significant time for those wanting to analyze the data. The current prototype for this involves user-supervised annotation. Scientists can define an area of interest and tell the system to do the best possible job to identify its overall geometry. The user can then go back and fine tune as needed. The team reported that this preliminary step to full annotation is working well so far, and noted that deep learning remains the ultimate goal, as it would be a game changer for efficiency.

Visualization and New Understanding: JPL's OnSight Immersion Environment

ALICE WINTER
NASA's Jet Propulsion Laboratory

In the second case study, Alice Winter, a user experience researcher at the National Aeronautics and Space Administration's Jet Propulsion Laboratory, described how OnSight Immersion Environment and other programs are allowing scientists to explore and conduct science on Mars with avatars in a "mixed reality" environment based on live data feeds. OnSight, or similar technologies, could be the next generation of telepresence-enabled deep ocean exploration, as autonomous vehicles and sensor networks augment—and perhaps replace—ship-based exploration in the future.

Ms. Winter described how JPL researchers work in multidisciplinary teams to build software for mission exploration. Teams include developers, designers, psychologists, scientists, and more. JPL teams are inspired by the technology behind gaming software and its possibilities to revitalize and change the way they explore space. They wanted to be able to put their scientists virtually where they cannot yet be physically. Scientists are meant to explore in a 3D world, she said, but have often been limited to exploring in 2D on computer screens, requiring them to use a significant amount of mental effort to cognitively reconstruct an environment before they can even get to their scientific questions. JPL's OnSight team wanted to bring Mars to the scientists, allowing them to walk around and navigate it naturally like they do on Earth. Additionally, they wanted to let scientists meet with their colleagues in this virtual world as a notable improvement over conference calls, video conferencing, and emails.

When the Curiosity rover sends its data back from Mars, the team can downlink these data into an environmental build—the virtual environment—within two hours. Using HoloLenses to see the virtual Mars environment constructed from near-real time data, this working mission tool enables scientists to work together on Mars from their offices. The HoloLens display lets them see the peripheral environment, so they can walk around and navigate on their own. But they can still look at their computer screens and access other data and information they may need as they explore Mars "in person."

Alice Winter, NASA's JPL, discusses new understanding through data visualization with JPL's OnSight immersion environment. *Photo by Shanni Jin for The Qualcomm Institute/UC San Diego*

> "JPL's OnSight team wanted to bring Mars to the scientists, allowing them to walk around and navigate it naturally like they do on Earth."

Ms. Winters reported that these tools allow scientists to "look back" and "look forward" as part of the science mission. "Looking forward" is determining what the rover is going to do—what images to get, where to get geochemical data, and more. "Looking back" allows scientists to pour over the images, get the scale bars, reconstruct the data. OnSight is software that can be run on the web, in augmented reality (AR), and in virtual reality (VR). This tool lets scientists get directly to using their mental energy on the questions. Recently, it allowed one researcher to find the first mud cracks on Mars.

The Mars Science Laboratory team has been brought closer together with OnSight, she said. They have regular, biweekly, virtual field trips on Mars. This group of people get together with their avatars walking around on Mars, while they are actually in Arizona, France, Denmark, and other places. They can walk together to a specific data point and discuss it together. While nothing is ever as good as people actually being physically present together, this is pretty close. It has allowed Mars geologists to work like field geologists again.

Ms. Winters concluded by observing that the future of this technology may be full immersive, shared tele-exploration—where scientists could all explore together. Perhaps when the first astronauts go to Mars, everyone can be virtually present with them. Similarly, when people are exploring the depths of the ocean, it's not possible to bring everyone along physically, but they could join the adventure because they could see through this software and explore together.

Engagement of Students in the Ocean Exploration Data Capstone Challenge

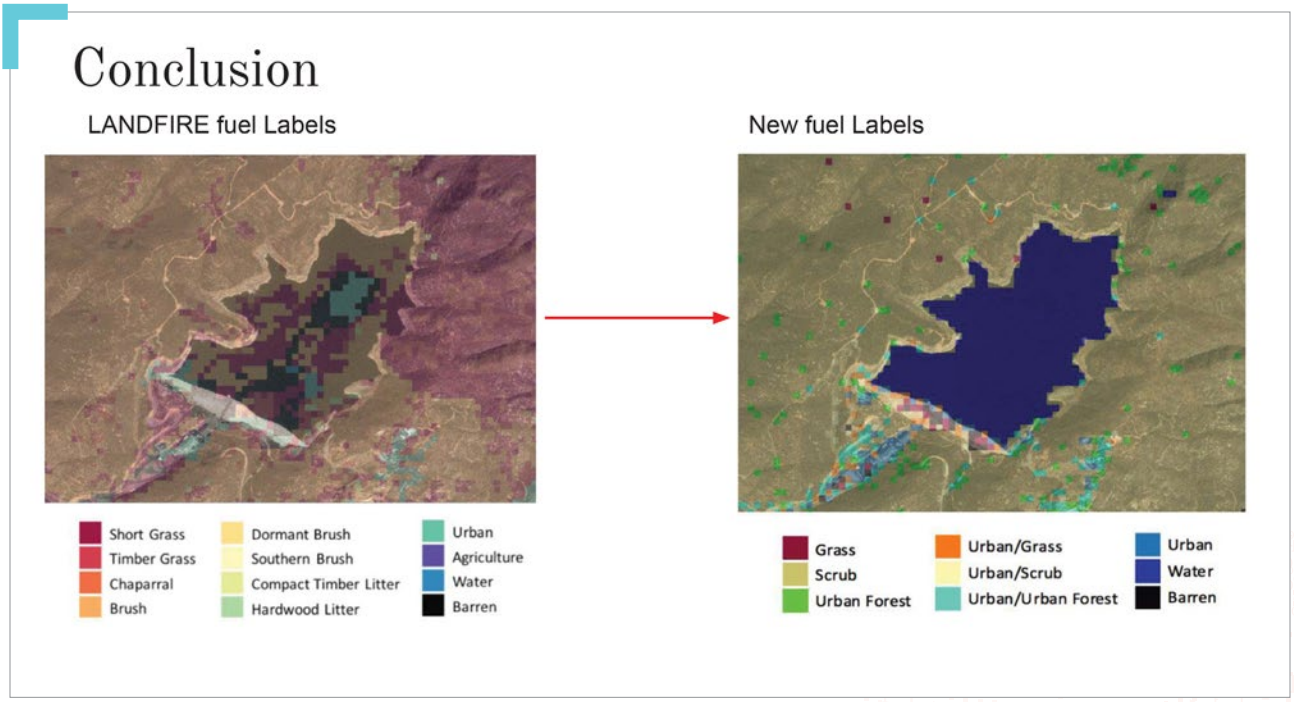
JESSICA BLOCK
Qualcomm Institute

Jessica Block, who studies the use of sensor networks, remote sensing, and geospatial visualization tools, gave an overview of new initiatives in "data exploration" intended to draw students into interdisciplinary research questions with important real-world application. Ms. Block highlighted the need to mobilize new skills, talents, energies, resources, and perspectives. There is a real and important interface, she said, between the scientist with domain experts, engineers, and computer scientists. That interface is a very human one and requires interpreters and translators.

We need to be good listeners and try to understand different perspectives. We need to be better about exposing data scientists and engineers to work in the field, where they experience the challenges of field work first-hand. They will gain a different appreciation for the context, which enriches the process by which we approach the data.

Ms. Block explained how the University of California, San Diego is working to get some of those future data explorers mobilized through interdisciplinary research questions, figuring out how data science can apply. Four years ago, the Data Science and Engineering Master's program was developed at UC San Diego. At the end of the program is a two-quarter capstone project. Students, working in small groups, tackle a topical area and address an issue with data science techniques. She gave an example of such a capstone project: a wildfire research project called WiFire, whose goal is to build a cyberinfrastructure for data related to wildfire research and response. WiFire participants are trying to create fire prediction tools that can be generated as data becomes available; typically that data is not real time.

Ms. Block explained that as a standard practice nationwide, fire agencies—local, state, and federal—don't hire anyone to use fire prediction software tools until a fire has burned uncontrollably for over 24 hours. The WiFire project built a tool that can can be implemented on a 30-second basis and the model can be rerun



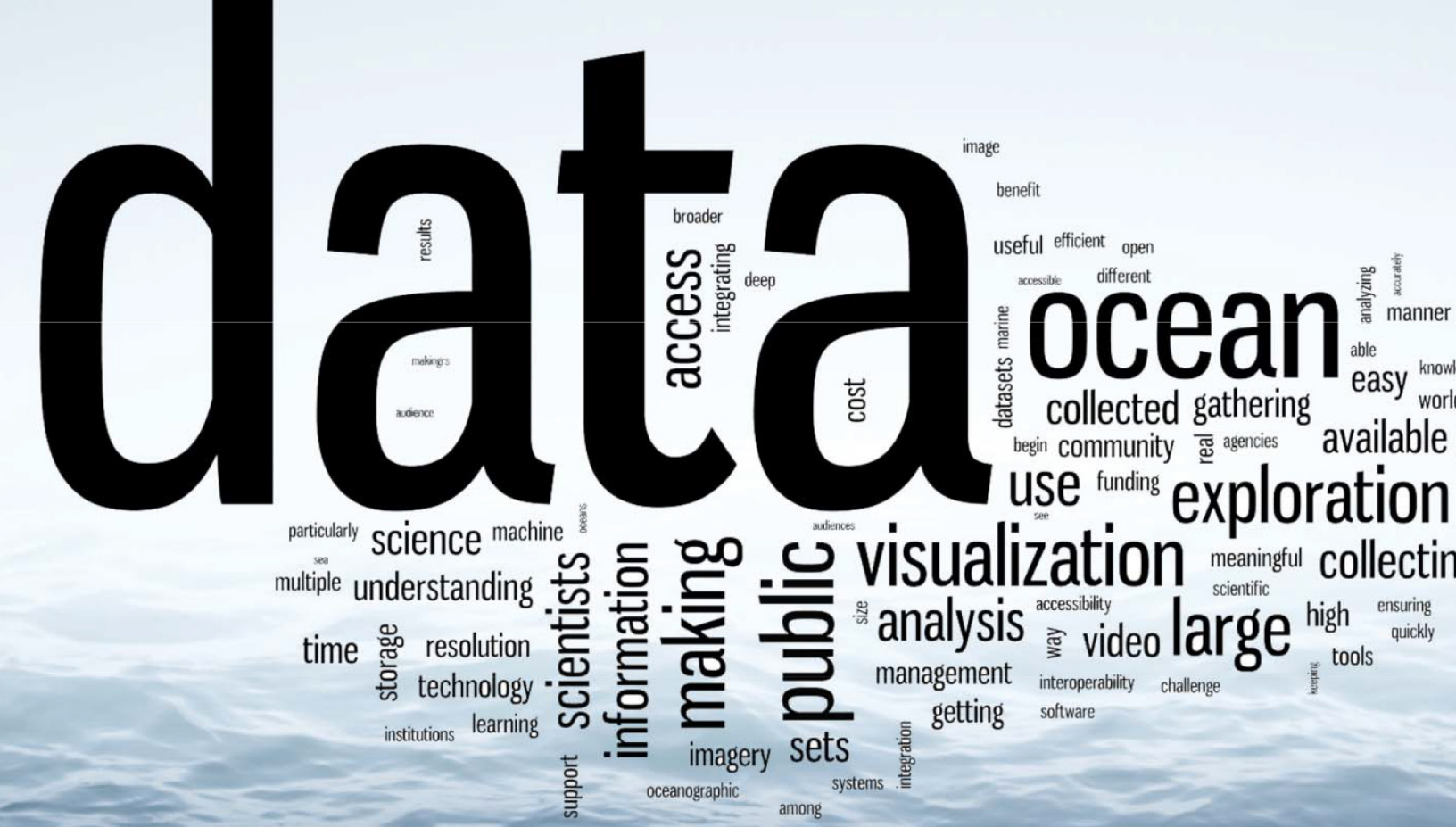
This presentation introduced a capstone project by students with the Qualcomm Institute who used tools outside of their discipline to find solutions. Another group of students will be working with oceanographic data on an upcoming capstone. *Image by Jessica Block of Qualcomm Institute*

the moment new data become available, whether from a satellite or via ground communications. A fuel map is generated. The properties of vegetation, known as fuel, are computed and a fuel burn ability is assigned, which goes into the prediction model. The fuel data come from the federal government's LandFire.gov data. That data set is old, as it takes two years to produce. It's a 30-meter-per-pixel dataset; higher resolution would be better to protect people's homes. The WiFire project ingested DigitalGlobe data, ran it through a machine learning workflow, and produced a higher-resolution fuel map to see if the accuracy and models improved.

In January, she said, four or five students will begin work on an oceanographic data capstone. The advisers will include Dominique Rissolo, Vicki Ferrini, Ilkay Altintas (the Chief Data Science Officer for the San Diego Supercomputer Center), and herself. "The data science and engineering capstone is an amazing opportunity to get five smart brains to think about a scientific problem differently. Our experience working with these students in the wildfire space has pushed us all in the research group to change the way we approach the data issues. With the massive oceanographic data collected, these students are sure to discover a lot," she said.

The advisors will encourage the students to collaborate as an interdisciplinary team, using data science to tackle interesting questions relevant to the ocean exploration community. The hope is that the results will be useful in the same way the WiFire project results are useful to the fire managers. Ms. Block said that the hope is the students will report back to the community on their progress at the next National Ocean Exploration Forum.

“The data science and engineering capstone is an amazing opportunity to get five smart brains to think about a scientific problem differently. Our experience working with these students in the wildfire space has pushed us all in the research group to change the way we approach the data issues. With the massive oceanographic data collected, these students are sure to discover a lot.”



“In an increasingly data-rich world, sharing knowledge and techniques across disciplines helps us overcome challenges and gain new perspectives.”

PANEL

Data Science Solutions to Integrating Temporally and Spatially Sparse Data

VICKI FERRINI
Lamont-Doherty Earth Observatory

DAWN WRIGHT
Esri

JESSICA BLOCK
Qualcomm Institute

ALICE WINTER
NASA's Jet Propulsion Laboratory

VID PETROVIC
Qualcomm Institute

STUART SANDIN
Scripps Institution of Oceanography

A panel discussion comprised of the case study presenters and other experts in ocean data science examined the implications of the case studies and the previous day's demonstrations. Vicki Ferrini, Forum co-organizer and expert in deep-sea mapping, moderated the panel of Dawn Wright, Jessica Block, Alice Winter, Vid Petrovic, and Stuart Sandin, which discussed data science solutions to integrating temporally and spatially sparse data.

The discussion aimed to prepare Forum participants for the breakout discussions on how ocean exploration can use techniques in data science and visualization to understand the ocean in new ways. The discussion began with some of the goals and challenges inherent to oceanographic data, including:

- The deep ocean is remote and hard to reach.
- Ocean water complicates things by limiting the ability to see over large distances and which tools can be used.
- The data are acquired over very different temporal and spatial scales, making them difficult to integrate.
- The ocean exploration community does not have information from every location at every point in time.
- The data are messy, they are acquired with many sensors using different techniques and workflows.

Word cloud created from the input that participants gave when they registered for the Forum about their thoughts regarding the biggest challenges to data in ocean exploration. *Image by Vicki Ferrini of the Lamont-Doherty Earth Observatory*

Panelists Stuart Sandin (SOI), Vid Petrovic (QI), Alice Winter (NASA), Dawn Wright (Esri), Jessica Block (QI), and moderator Vicki Ferrini (LDEO) involved with the lively panel discussion.
Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

- The data archives are growing and more effort needs to be put into managing, storing, and making accessible the data.
- There are opportunities for integration and exploration of data using new technical approaches and strategies.

Three questions were posed to the panelists to facilitate the discussion:

- Could they share examples of working with temporally and spatially sparse data and how they have tried to overcome it?
- What are the best strategies for getting more people involved, fostering relationships, and sharing techniques and technologies across disciplines?
- How would they advise federal agencies, nonprofits, and academic groups to foster these relationships and collaborations to move science forward to take advantage of these new techniques?

The key points and recommendations from that discussion included:

- When integrating data, maintain access and connections to source data, not just derived data products. Aspire to keep the source data in one place and move the algorithms in order to enable a whole range of products.
- Building community and enhancing communication is the key to integrating disciplinary scientists and data scientists.
- When new technology is added to a field, the questions are asked differently and the way science is done in that field changes. Data science provides an opportunity for finding signals that traditional processes might not identify. The ocean exploration community is evolving and needs to make incremental steps in adopting new technologies.
- Culture change is ongoing with respect to data sharing and code sharing. The community needs to incentivize sharing, but also needs to recognize that sharing code and data easily falls down the priority list when development and analysis are underway—there is only so much time.
- Public accessibility of curated content is critical—humanity needs to know and care more about our planet.

The panel accepted questions and comments from the audience. The topics ranged from open source software solutions, the path toward scaling out visualization techniques into the community, how to incentivize platform maintenance, data accessibility, and the sparseness of ocean data. It was acknowledged that while data and software sharing is very important to the community, the effort to manage and share data and software is non-trivial.

“Visualization can help accelerate and advance new scientific discoveries by encouraging work across disciplines, challenging the traditional hypothesis-driven workflow of science, allowing extraction of relevant data in more intuitive ways, and promoting onshore research of offshore data.””

Discussion Group Recommendations

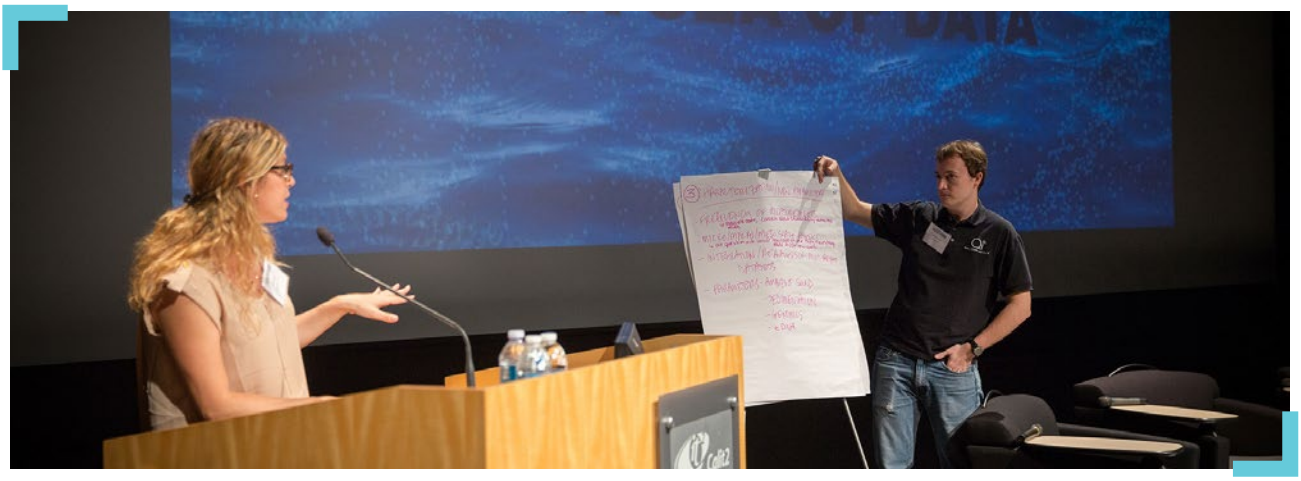
The breakout discussions allowed participants an opportunity to make recommendations for the ocean exploration community.
Photo by Shanni Jin for Qualcomm Institute/ UC San Diego

The organizers structured the Forum to provide participants, regardless of discipline or experience, with common information and experiences to bring to the breakout sessions. The keynotes, panel discussion, case studies, and especially the demonstrations were intended to share new information, provoke thought, spark creativity, and encourage dialogue across ocean exploration and data science and visualization disciplines.

Breakout session participants were asked to rely on this common information, as well as their own expertise and experience, to address several questions that the organizers intended to help spark discussion about how new techniques in data science and visualization can be applied to ocean exploration to understand the ocean in new ways and to develop recommendations for ocean exploration stakeholders and specific sectors involved in exploring the deep ocean. Each breakout group then presented the results of their discussions in plenary. Their conclusions are summarized below, organized by question.

What do you see as the major opportunities data science and new techniques for visualization offer?

Participants identified two major opportunities during discussions. First, visualization can help accelerate and advance new scientific discoveries by encouraging work across disciplines, challenging the traditional hypothesis-driven



Moderators and rapporteurs presented their groups' recommendations to the Forum. *Photo by Shanni Jin for Qualcomm Institute/UC San Diego*

workflow of science, allowing extraction of relevant data in more intuitive ways, and promoting onshore research of offshore data. Second, through thoughtful and targeted messaging, new technologies and data visualizations can enhance efforts to better engage the public about ocean science and exploration by capturing people's attention and immersing them in the data; helping people visualize and thus better understand the complexity, importance, and depth of ocean exploration; and reaching wider, more diverse audiences.

How should we change our concepts of ocean exploration? What are the implications for instrumentation and data collection?

One common theme among the breakout groups was the need to make ocean exploration more accessible and inclusive by developing new tools and technologies to lower the cost of ocean exploration; creating more and better opportunities for virtual exploration opportunities; and making data available to the public sooner, to spur innovation and take advantage of open source and citizen science opportunities. Participants also noted the need to rethink how collected data are managed, both during acquisition and for long-term archiving.

What are the implications for "characterization" of the ocean? What new parameters should we be thinking of?

Baseline characterizations allow scientists to define what is "normal" for areas of the seafloor, allowing people to better understand environmental impacts. Participants agreed that to create useful baselines, data collection and curation need to be standardized and easily accessible. In addition to the data routinely collected during ocean exploration expeditions, acoustic data, data from towed instruments, and environmental genomics should also be collected. They suggested optimizing operating costs through closer collaboration between projects; sharing resources; and prioritizing how the ocean exploration community characterizes, mines existing data, and plans for the costs of data storage.

The groups suggested that the scope of data collection and sensor capabilities be expanded—even if not all of the data collected is used—to increase the possibility of using these data in future studies. They thought the community should determine what data are lacking, turn around raw data interpretation more quickly, and curate data properly—including metadata and a reference library. As getting people to sea will remain a challenge, the community should take greater advantage of telepresence technology and increase the utilization of new technologies (e.g., autonomous underwater vehicles) with less elaborate ships. Tools under development should also be usable with the data that has been collected thus far.

Stuart Sandin discusses recommendations to NOAA during the breakout discussions.
Photo by Shanni Jin for Qualcomm Institute/UC San Diego

Student rapporteurs tracked breakout group discussions.
Photo by Shanni Jin for Qualcomm Institute/UC San Diego

> "Participants agreed that legacy data are highly relevant. It needs to be accessible, standardized (metadata and archiving), and preserved in a usable format."

In addition, participants felt that much of the communication about this work focuses on the deterioration of the ocean environment exclusively. To fully engage the public effectively, it is important to also highlight the positive aspects of what is found while exploring the deep ocean to convey the excitement and wonder of the deep to the interested public.

Are legacy data relevant? What should we do about it?

Participants agreed that legacy data are highly relevant. It needs to be accessible, standardized (metadata and archiving), and preserved in a usable format. New techniques should be established for data analysis, using automated and standardized methods to facilitate the use of legacy data that may not otherwise be accessible. The community should encourage people to digitize and share legacy data. It may be worthwhile to pursue crowdsourcing to help perform this function, as the community might find people who can successfully mine the data and leverage new infrastructures. The community should encourage new ways to store and access legacy data, including visualization techniques.

What should the following sectors do to encourage closer ties with the data science and visualization community and to promote adoption of new approaches that could yield new understanding?

Academia — The academic community should encourage ocean scientists to connect with data scientists. Participants agreed on the importance of making inaccessible or offline data public and felt the benefits of sharing data (advancing science, professional attribution, recognition) should be promoted. The community should embrace alternative approaches to funding and consider partnering with the private sector for research that may have commercial value. Universities should not lose sight of their role in producing future generations of ocean explorers and scientists.

Federal government — Federal funding should focus on national priorities and encourage agency or program communications and partnerships. Federal data management policies should encourage proper—and long term—data stewardship and open access.

Not-for-profits — Philanthropy plays a critical role in funding projects that federal grants can't or won't fund. The flexibility of not-for-profit organizations allows for higher risk or "off-the-wall" proposals to proceed—and potentially for breakthroughs in discovery and innovation. Revenue streams need to be stabilized over the long term and new revenue streams should be investigated.

Private sector — The community should create financial incentives for private sector companies to maintain relationships with researchers after development and proof of concept. Open source, non-proprietary, and expandable standards should be adopted across sectors so everyone from researchers at sea, to students, to government analysts can visualize and share the same types of data. Participants felt industry should steer away from a proprietary model to allow more people access to data. There was broad agreement that optimizing long-term preservation of and maintaining ready access to data is important.

> **"With more people involved, the work will have a larger global impact, a higher-level message, and is likely to yield the productive merging of data generation, curation, and dissemination."**

The groups concluded that the ocean exploration community needs to be proactive in bringing these sectors together and find mutually beneficial opportunities. Cross-sector, interdisciplinary collaboration should be encouraged. With more people involved, the work will have a larger global impact, a higher-level message, and is likely to yield the productive merging of data generation, curation, and dissemination.

Can we leverage new visualization approaches and products for public engagement? How?

There was strong agreement that these approaches and products can be leveraged for public engagement. Participants agreed that the community should look for opportunities to bring data and visualization experts, scientists, and storytellers together and merge their expertise with emerging engagement modalities like open source apps and virtual reality (VR), thinking ahead about future types of immersive experiences.

Participants suggested keeping a positive message and encouraging public interaction with the data through these modalities. The use of data visualization and VR in the classroom and beyond (museums, aquaria, etc.) should be supported. Field researchers and scientists should help identify ways to create better instrumentation, using human psychology to tailor these instruments and how data is presented. The community should:

On Sunday afternoon, each breakout group was given an opportunity to presented the results of their discussions to the full Forum group. Here Antonella Wilby, rapporteur, and Drew Stephens, moderator, presented their group's results. *Photo by Shanni Jin for The Qualcomm Institute/UC San Diego*

Alison Fundis, moderator, and Dominique Meyer, rapporteur, present their group's results.
Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

- look for engagement opportunities with crowdfunding, crowdsourcing, and citizen science.
- look for ways to coordinate science with private industry and allow for commercial development, including gaming.
- encourage follow-through with university projects by having subsequent students continue work when others graduate.

What is your best advice to the National Oceanic and Atmospheric Administration (NOAA), as the coordinator of a national program of ocean exploration?

Participants agreed that NOAA should encourage ways to immerse others into ocean exploration, using multiple senses, and invest in immersive experiences. The agency should invest, and encourage others to invest, in technology that maximizes autonomy, automated data capture, and rapid data processing—and should leverage the funding of high-risk innovation. NOAA should encourage standardization. It should encourage review and investigation of legacy data—exploring the ocean of the past through the archives.

NOAA should leverage the abilities of those who already work in ocean exploration and data science. The agency needs to invest more in the curation, production, and presentation of data. NOAA should continue to refine and clarify priorities, then communicate them to the community, in part through facilitating an active conversation between stakeholder groups. Finally, participants agreed that the agency should implement better NOAA branding and increase public engagement, as this will benefit all ocean exploration stakeholders.

“Participants agreed that NOAA should encourage ways to immerse others into ocean exploration, using multiple senses, and invest in immersive experiences.”

"The panel observed that scientists need to become better communicators and storytellers, portraying the ocean as the planet's life support system."

What Should We Do Next?

JERRY SCHUBEL
Aquarium of the Pacific

MARGARET LEINEN
Scripps Institution of Oceanography

LARRY SMARR
California Institute for Telecommunications and Information Technology

Jerry Schubel, Margaret Leinen, and Larry Smarr discussed what the ocean exploration community should do next in the concluding panel. *Photo by Shanni Jin for The Qualcomm Institute/UC San Diego*

A final panel discussion with Jerry Schubel, Margaret Leinen, and Larry Smarr discussed what the community should do next. The ocean is an important part of the international agenda, they said. However, it needs to be a bigger priority in the United States, with advocates both in the public and in government. There are many opportunities to do this, as fishing, maritime transport, national security, and conservation are all topics of interest to every administration.

The panel observed that scientists need to become better communicators and storytellers, portraying the ocean as the planet's life support system. The ocean exploration community should use these visualization techniques to help tell our stories, but ensure the technology does not compete with the stories. The community also needs to invest in science literacy.

Scientists need to collaborate across disciplines, not only with other scientists, but also with the Navy, engineers, data scientists, artists, humanists, and social and behavioral scientists. We need to continue to meet, expand the community, and forge new partnerships. The National Oceanic and Atmospheric Administration (NOAA) should facilitate this by

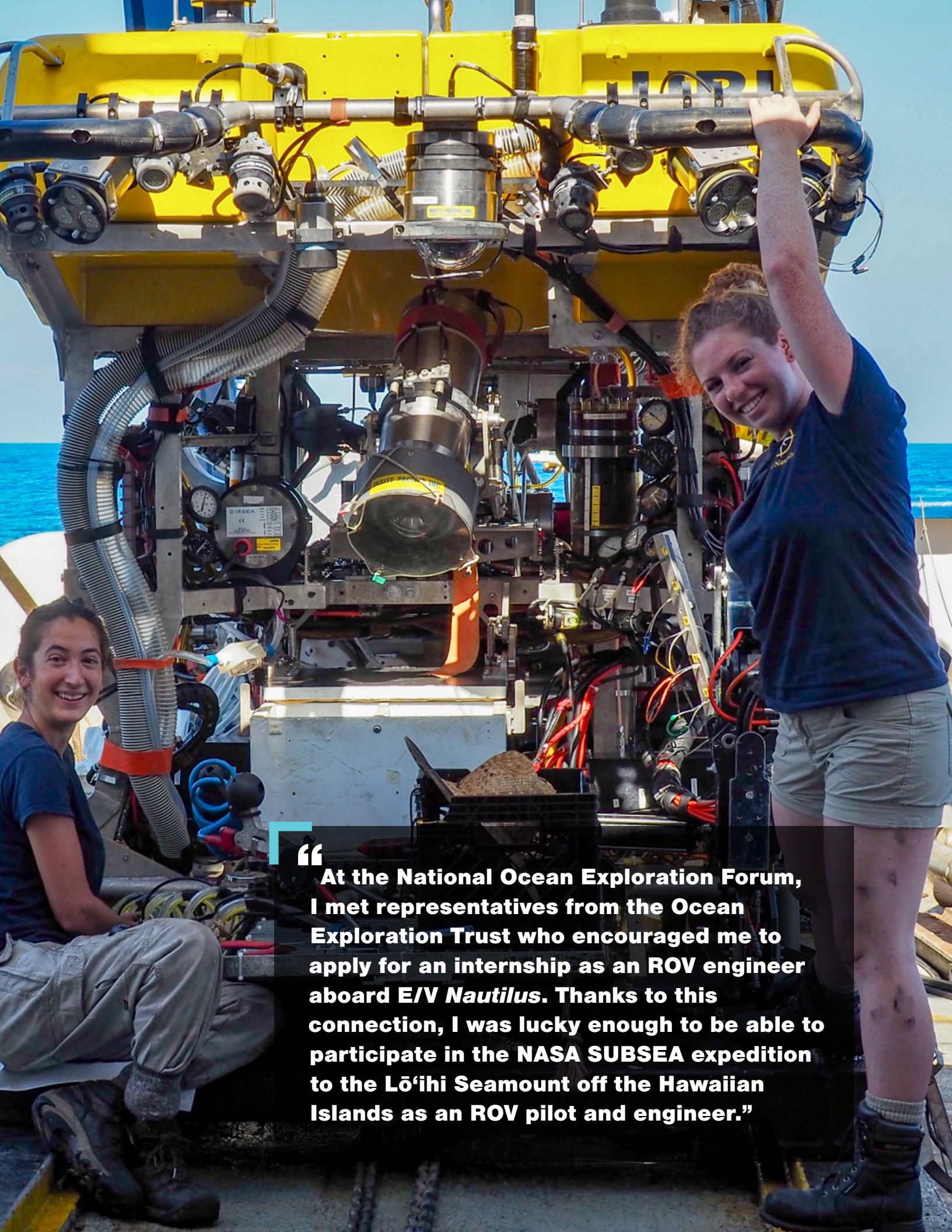
Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

providing postdocs, internships, connections, and sponsoring small grants—helping to leverage what has been done so far and allow for additional meetings. We need to look to industry and philanthropic groups for additional sources of revenue. They are looking for investment opportunities and there may be ways to organize matching funds.

The panel said that the community needs to prepare for the coming surge of data—it has many challenges and opportunities. Big data and visualization allow us to do science in different ways. We need to establish protocols for data to make it accessible and interoperable. We need to explore the data. Using algorithms and technology like artificial intelligence will allow us to do this more efficiently. We should find ways to continue

Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

using our existing platforms while adding new instrumentation. The panel closed with the the hope that collaborators who prepared demonstrations and otherwise began to work across data science, visualization, and ocean exploration disciplines would continue that collaboration between now and the next National Ocean Exploration Forum. They called on the community to monitor and support their progress and asked them report back to the group at the 2018 National Ocean Exploration Forum, *All Hands on Deck.*



“At the National Ocean Exploration Forum, I met representatives from the Ocean Exploration Trust who encouraged me to apply for an internship as an ROV engineer aboard E/V *Nautilus*. Thanks to this connection, I was lucky enough to be able to participate in the NASA SUBSEA expedition to the Lōʻihi Seamount off the Hawaiian Islands as an ROV pilot and engineer.”

Catalyzing New Research and Opportunity

Ocean Exploration in a Sea of Data catalyzed new collaborations and created unique opportunities for Forum participants to work together in ways that might not otherwise been possible. Of particular importance was this Forum's emphasis on including students and early career experts from data science and visualization disciplines, exposing them to ocean exploration challenges, and creating an opportunity for them to engage with ocean explorers and engineers. The ocean exploration community is expanding into new territory as young computer and data scientists are connecting with domain experts to take on a number of research challenges. This section highlights a few results of the dynamic environment at the Forum.

Immediately following the Forum, the Schmidt Ocean Institute invited Stuart Sandin to participate in the Coral Reef Survey Initiative Planning Workshop. There, the Scripps Institution of Oceanography/ Qualcomm Institute collaboration, featured at the Forum, reached an audience focused on transforming the way in which we document and study coral reef ecosystems.

Stuart's team went on to present at the 2017 Ocean Sciences Meeting in Portland, Oregon, in February. They were joined by Forum organizers Dominique Rissolo, Vicki Ferrini, Adrienne Copeland, and David McKinnie. In all, seven NOEF-related papers and posters were presented, including the SpatLab collaboration with Shahrokh Yadegari and Grady Kestler. Their experimental sonification of tsunameter data from the 9.0 magnitude Tōhoku earthquake in 2011 was a collaboration with Bob Dziak (Pacific Marine Environmental Laboratory) that has opened new research pathways.

During the Forum, the rapporteurs and demonstration guides interacted with participants outside the students' traditional academic communities. For Computer Science and Engineering graduate student Antonella Wilby and Mechanical and Aerospace Engineering graduate student Shreyas Kamat, these conversations led to time at sea.

← Forum rapporteurs Jessica Sandoval and Antonella Wilby, aboard Ocean Exploration Trust E/V *Nautilus* with the remotely operated vehicle remotely operated vehicle *Hercules* after the Forum. *Photo by Jenny Woodman*

"At the National Ocean Exploration Forum, I met representatives from the Ocean Exploration Trust who encouraged me to apply for an internship as a remotely operated vehicle engineer aboard E/V *Nautilus*. Thanks to this connection, I was lucky enough to be able to participate in the NOAA-NASA-Ocean Exploration Trust SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) expedition to the Lō'ihi Seamount off the Hawaiian Islands as an ROV pilot and engineer." –Antonella Wilby

"My first exposure to the oceanographic community was as a rapporteur for *Ocean Exploration in a Sea of Data.* Prior to the conference, I worked for the Qualcomm Institute with an emphasis on autonomous transportation, robotics and control systems design. My experiences at the Forum opened my eyes to one of the most intriguing and challenging environments to apply my skills as an aerospace engineer. The thing that immediately stood out at the conference was the importance given to interdisciplinary collaboration. Even though my oceanographic knowledge was limited, the community was approachable, respected my input and was excited to find new ways to use unmanned research platforms to gather and aggregate data.

As a result of the discussions I had at the conference, I went on to conduct research aboard *R/V Thomas G. Thompson* on a project to create improved prediction for the monsoon in the Bay of Bengal. As a drone operator aboard the vessel, I gathered temperature data by conducting flights off the deck of the *Thompson* using Infrared (IR) and Visual Spectrum cameras to collect data about the coupling between atmospheric and oceanic boundary layers.

Currently our project continues to progress as a collaboration between Qualcomm Institute and Scripps Institution of Oceanography. By pairing conventional data acquisition techniques (floats, wire walkers, seafloor cabling) with new techniques (unmanned aerial systems, autonomous surface vehicles, IR Camera), we continue to work towards the goal of resilient, autonomous and high-resolution ocean data acquisition systems." –Shreyas Kamat

Integral to *Ocean Exploration in a Sea of Data* was, as part of the event, the creation of research opportunities for graduate students enrolled in the new Data Science Program at University of California, San Diego Jacobs School of Engineering. The Ocean Exploration Data Capstone Challenge, involving graduate student teams, was announced by Jessica Block at the Forum and is ongoing. Working with domain expert and Forum co-organizer Vicki Ferrini, Columbia University's Lamont-Doherty Earth Observatory, and methods expert Ilkay Altintas from the San Diego Supercomputer Center, Jessica created data science research opportunities for data science graduate students. The project, entitled "Discovering the Ocean Floor Using Data Science," aspires to extend ocean exploration into the data dimension by using modern and historic open-access benthic image data that are available from distributed data systems to build new analytical tools to allow for ocean exploration in an otherwise chaotic sea of disparate historical and contemporary data. Initial results will be reported at *All Hands On Deck*, the 2018 National Ocean Exploration Forum.

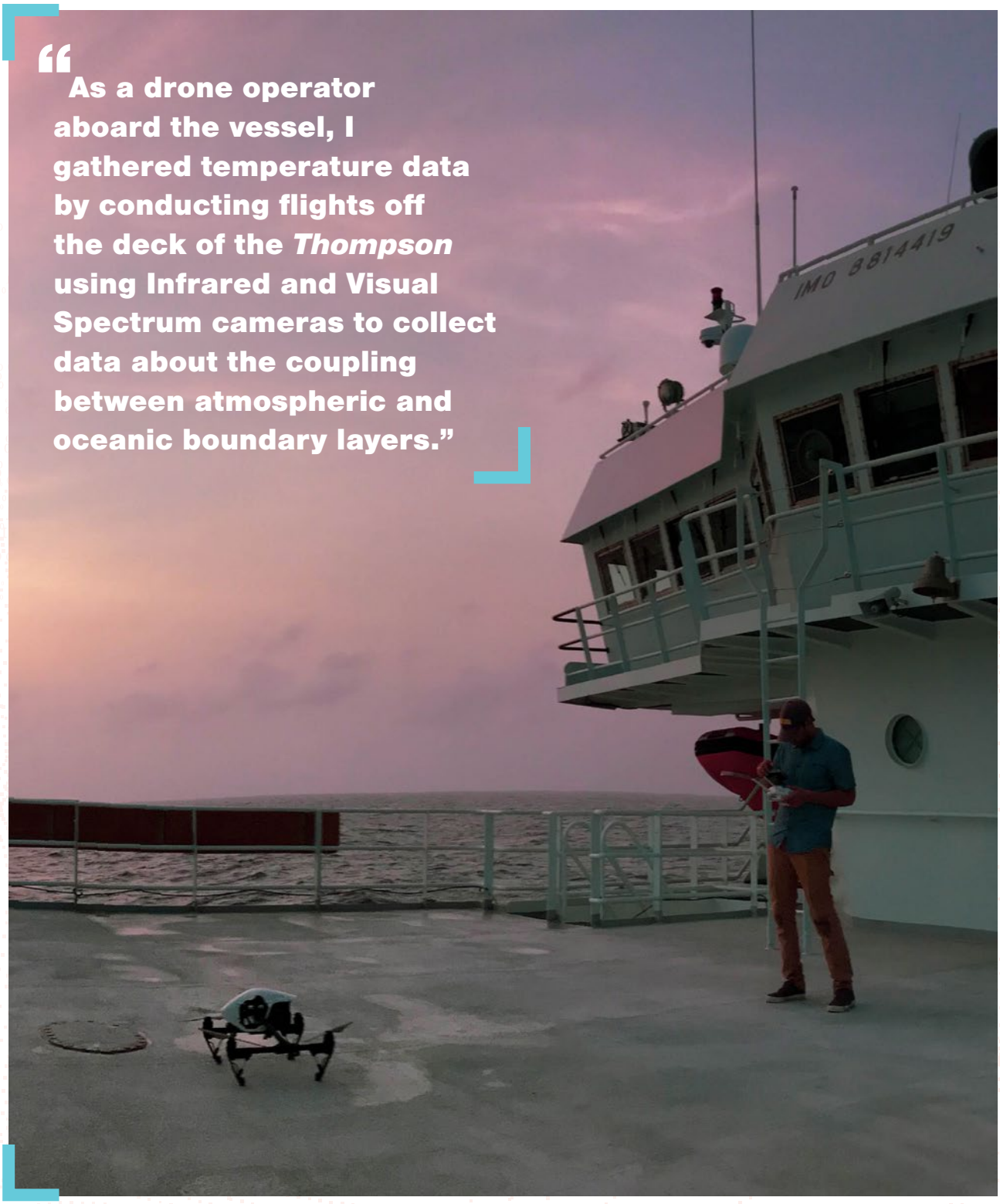
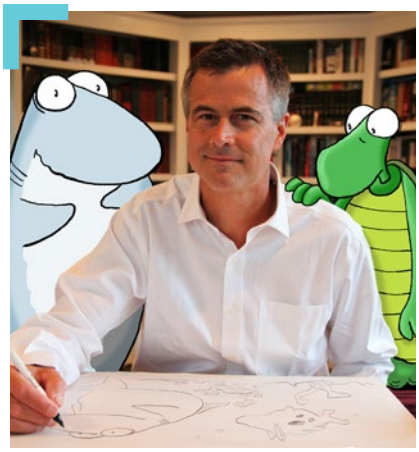


Photo: Shreyas Kamat, UC San Diego

Looking Ahead to the 2018 Forum

The organizers asked Jim Toomey, creator of the popular comic strip *Sherman's Lagoon* and creator and producer of award-winning short videos on ocean issues for the United Nations, Pew Charitable Trust, and the World Resources Institute, to share his thoughts about public engagement on ocean issues in advance of the next National Ocean Exploration Forum. *All Hands on Deck* (https://www.allhandsondeck.community/), hosted by NOAA's Office of Ocean Exploration and Research and the Massachusetts Institute of Technology Media Lab, will use themes of Imagine, Immerse, Play, Create, Explore, Connect and a series of workshops to explore new and creative ways to share the wonder, excitement, and joy of the deep ocean with people everywhere.

Ocean Exploration in a Sea of Data helped set the stage for *All Hands on Deck* with visualization techniques that display information about the ocean in terms anyone could understand. The 2018 Forum will add to these important concepts by bringing together representatives from an array of disciplines to create additional ways to engage the public by connecting them in powerful ways to the deep ocean.



Jim Toomey is an American cartoonist famous for his comic *Sherman's Lagoon*. He shared his thoughts on ocean exploration to help set the stage for the 2018 National Ocean Exploration Forum, *All Hands on Deck*.

> "*Ocean Exploration in a Sea of Data* helped set the stage for *All Hands on Deck* with visualization techniques that display information about the ocean in terms anyone could understand."

Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

SECTION 12

Thoughts on Ocean Communication By Jim Toomey

JIM TOOMEY
Cartoonist

> **"While space exploration seems to capture the public imagination with ease, ocean exploration still remains to most of us an intimidating prospect."**

Why is it important to communicate ocean issues to the public?

The ocean is still widely misunderstood. The popular image that the ocean is inexhaustible, or so vast that human activity has a negligible impact, still largely persists in the public mind. Ocean communication is necessary not only to better educate the public about the environmental issues facing the ocean, but to foster a better understanding of the environmental issues facing the planet, where land, ocean and atmosphere interact and are codependent. Most environmental outreach is focused on the terrestrial 30%, which produces only partial awareness of problems that will ultimately require a holistic approach. Beyond environmental issues, the ocean remains a largely unexplored and unstudied frontier that holds enormous potential to improve our lives, lift our spirits, and help us better understand ourselves and the planet we live on.

What's challenging about ocean communication in particular?

Historically, the ocean has represented danger, both real and imaginary, and we've filled a lot of the unknowns with superstition and fear. While space exploration seems to capture the public imagination with ease, ocean exploration still remains to most of us an intimidating prospect. Furthermore, while the ocean would appear to be readymade for storytelling and communication– with its myriad forms of life, large and small, alien and ordinary – because the ocean is devoid of human life, or even life forms that can be easily anthropomorphized, it remains a challenging platform for educating, entertaining or engaging people. On the other hand, the ocean offers countless opportunities for communicating science and technology. However, without a human element, it is difficult to make this kind of content appealing to a broad audience. Jacques Cousteau's unique success in this genre is due largely to the fact that he didn't lecture us about science - he took us on an adventure.

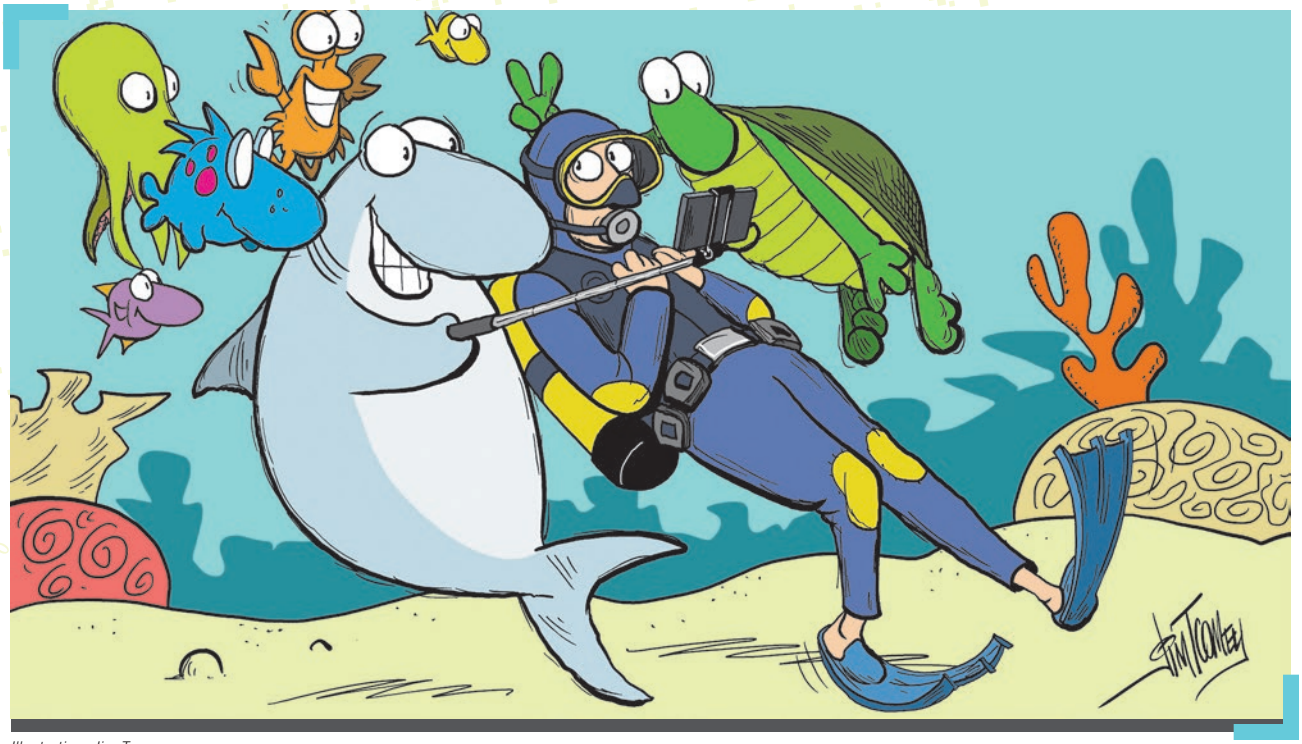


Illustration: Jim Toomey

What do we hope to accomplish by making the public more "ocean literate"?

History judges a society is on how it approaches the unknown. Some societies strive to know the unknown through exploration. Others leave exploration to prospectors with commercial interests. Unfortunately, throughout history, most societies have taken the latter approach, resulting in an enormous and permanent loss of culture and biodiversity. At this moment in time, we have a unique opportunity to explore the ocean differently. As we become more ocean literate as a society, we will create more political will to take this different approach.

Given limited resources, what's the best approach to ocean communication?

Short, online videos optimized for social media. Video production and editing has become inexpensive, and video content is more engaging than text or imagery. Elements of success include:

- short run time (2-4 minutes),
- new installments regularly (daily, weekly),
- a creative approach that takes advantage of the medium (animation, data visualization, fast paced),
- a human-centric story (it's about the scientist, not the science), and
- common branding elements that make the video unique (hosted by personality, graphic design elements, musical theme).

Ocean communication done within these constraints can potentially yield enormous returns on a very limited budget.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Acknowledgements

> "We'd like to extend our deep appreciation and gratitude to everyone who played a role in *Ocean Exploration in a Sea of Data*, from conference organizers and staff, to presenters and participants."

Throughout the years, the National Ocean Exploration Forums have helped to expand and reinforce the ocean exploration community. The priorities and recommendations that Forum participants identify are important to the National Oceanic and Atmospheric Administration (NOAA) and other organizations, including government, academia, not-for-profit, and industry. These Forums are intended to be beneficial to the community and provide opportunities to explore collaborative ideas. Without the community's contributions, these Forums would be impossible to organize. We'd like to extend our deep appreciation and gratitude to everyone who played a role in *Ocean Exploration in a Sea of Data*, from conference organizers and staff, to presenters and participants. Special thanks are due to Jerry Schubel, the principal architect of the National Ocean Exploration Forum process, who has played a vital role in each of the Forums to date. We also want to thank Ramesh Rao for his leadership. Additionally, we want to thank the events team at University of California, San Diego's Qualcomm Institute for their support. We would like to express our deep gratitude to our sponsors, the Schmidt Ocean Institute, Alucia Science, Jamie Austin, and NOAA's Office of Ocean Exploration and Research.

Similarly, we are grateful to all of those who prepared demonstrations that allowed us to expand our horizons in thinking about new ways to conduct ocean exploration. Additionally, we would like to thank the keynote speakers, the discussion group moderators, those who presented case studies, and the panelists for their many contributions to the 2017 Forum.

Finally, for their assistance with preparing this report, we would like to thank our writing, editing, and design team of Amy Bowman, *NOAA's Office of Ocean Exploration and Research on contract through CollabraLink Technologies,* Emily Crum, *NOAA's Office of Ocean Exploration and Research on contract through Cherokee Nation Strategic Programs*, Jennifer Ortiz and Tom Ho, *Albert Creative Services, LLC.*

Dominique Rissolo
Qualcomm Institute, UC San Diego

Vicki Ferrini
Lamont-Doherty Earth Observatory, Columbia University

David McKinnie
NOAA's Office of Ocean Exploration and Research

Adrienne Copeland
NOAA's Office of Ocean Exploration and Research

Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

APPENDIX

AGENDA

SATURDAY

OCTOBER 21, 2017 | **THE FUTURE IS ON THE HORIZON**

08:00–09:00	**CHECK IN AND BREAKFAST**
09:00–09:05	**Welcome to the Forum** Dominique Rissolo | Qualcomm Institute
09:05–09:15	**Welcome to Qualcomm Institute** Ramesh Rao | Director, Qualcomm Institute
09:15–09:30	**NOAA and Ocean Exploration** Alan Leonardi | Director, NOAA Office of Ocean Exploration and Research
09:30–10:00	**Ocean Exploration Forums and National Priorities** Jerry Schubel | President and CEO, Aquarium of the Pacific
10:00–10:20	**BREAK**
10:20–11:10	**Keynote Speaker** Margaret Leinen | Director, Scripps Institution of Oceanography
11:10–12:00	**Keynote Speake** Larry Smarr | Founding Director, California Institute for Telecommunications and Information Technology
12:00–13:00	**LUNCH**
13:00–13:40	**Ocean Exploration and the Temporal Domain** John Delaney | University of Washington
13:40–14:00	**Experiencing Ocean Data Demos, an Introduction** Dominique Rissolo | Qualcomm Institute
14:00–17:30	**Experiencing Ocean Data** Via a series of research driven demos, Forum participants will be physically immersed in ocean data from coral reefs, hydrothermal vents, below-ice environments, trenches and ridges, and deep-sea soundscapes.
14:00–14:25	**Demo 1**
14:30–14:55	**Demo 2**
15:00–15:25	**Demo 3**
15:30–15:55	**BREAK**
16:00–16:25	**Demo 4**
16:30–16:55	**Demo 5**
17:00–17:25	**Demo 6**
17:30–18:00	**Concluding Remarks** Dominique Rissolo | Qualcomm Institute
18:00–	**RECEPTION AND DINNER AT QUALCOMM INSTITUTE** DINNER SPEAKER: Bob Weiss | XPRIZE

APPENDIX

SUNDAY

OCTOBER 22, 2017 | **NAVIGATING TOWARDS THE FUTURE**

08:00–08:30 **BREAKFAST**

08:30–08:40 **Welcome and Recap**
Dominique Rissolo | Qualcomm Institute

08:40–09:00 **Report Out of Day One**
Tiffany Fox | Qualcomm Institute

09:00–10:00 **CASE: Coral Reef Point Clouds and Classification**
Stuart Sandin | Scripps Institution of Oceanography
Falko Kuester | Qualcomm Institute
Vid Petrovic | Qualcomm Institute
Nicole Pedersen | Scripps Institution of Oceanography

10:00–10:15 **BREAK**

10:15–11:00 **CASE: Visualization and New Understanding: JPL's OnSight Immersion Environment**
Alice Winter | NASA Jet Propulsion Laboratory / OpsLab

11:00–12:00 **Panel Discussion: Data Science Solutions to Integrating Temporally and Spatially Sparse Data**
Moderator: Vicki Ferrini | Lamont-Doherty Earth Observatory
Panelists:
Dawn Wright | Esri
Jessica Block | Qualcomm Institute
Alice Winter | NASA Jet Propulsion Laboratory / OpsLab
Vid Petrovic | Qualcomm Institute
Stuart Sandin | Scripps Institution of Oceanography

12:00–13:00 **LUNCH**

13:00–13:15 **How Do We Do This?**
Dominique Rissolo | Qualcomm Institute

13:15–13:30 **Engagement of Students and Announcement of the Ocean Exploration Data Capstone Challenge**
Jessica Block | Qualcomm Institute

13:30–15:00 **Breakout Discussions: How Can Ocean Exploration Use New Techniques in Data Science and Visualization to Understand the Ocean in New Ways?**
Moderators:
Amanda Demopoulos | USGS
Jacqueline Dixon | University of South Florida
Allison Fundis | Ocean Exploration Trust
Alan Leonardi | NOAA Office of Ocean Exploation and Research
Drew Stephens | Esri
Carlie Wiener | Schmidt Ocean Institute

15:00–15:30 **BREAK**

15:30–16:20 **Breakout Session Reports: Recommendations for the Future**

16:20–17:10 **Concluding Panel: What Should We Do Next?**
Jerry Schubel | President and CEO, Aquarium of the Pacific
Margaret Leinen | Director, Scripps Institution of Oceanography
Larry Smarr | Founding Director, California Institute for Telecommunications and Information Technology

17:10–17:15 **Closing Remarks**
Dominique Rissolo | Qualcomm Institute


Auditorium

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2013 Table of Recommendation

NOAA-Led National Ocean Exploration Program	Priorities Determined by Exploration Community	Platforms	Technology	Partnerships and Funding	Data and Information	Public Engagement
Create a clear national mission statement	**Geographic Areas:** Arctic, Antarctic, Indo-Pacific, Central Pacific, US EEZ and ECS **Ocean Processes & Phenomena:** Ocean acidification, under-ice communities Ocean Features: **Ocean Features:** Water column, trenches, coral ecosystems, methane seeps, marine life, seamounts	**Take advantage of data from:** Instrumented marine animals, stationary observing networks and sensors, seafloor observations Need for dedicated ships of exploration Utilize ships of opportunity Need for AUVs, ROVs, and HOVs with range of capabilities, including low-cost vehicles	Develop mechanisms to fund technologies to enhance and expand exploration capabilities Explore federal investment in technology	Look for public and private partnership opportunities Look for national and international partnership opportunities Think about crowdsourcing for funding Be more inclusive and nimble as a community	Encourage open data sharing with little to no cost Take advantage of all sources of available and relevant data Establish data repository	Promote the use of ocean exploration for STEM education Utilize a coordinated and positive approach to engaging the public Increase the use of telepresence Expand opportunities for Citizen Science

← *Photo by Shanni Jin for The Qualcomm Institute/UC San Diego*

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2014 Table of Recommendation

NOAA-Led National Ocean Exploration Program	Priorities Determined by Exploration Community	Platforms	Technology	Partnerships and Funding	Data and Information	Public Engagement
Increase OER visibility and make ocean exploration compelling to NOAA leadership	**A. Geographic Area** Arctic, Pacific – Territorial Trust Areas, US EEZ and ECS, newly protected areas	Need for more platforms suitable for under-ice exploration	New technology suitable for under-ice exploration	Create new partnerships across government, including U.S. Navy	Encourage open data sharing	Tailor expeditions to meet STEM education
Use NOPP working groups, IOOS, and IODP as models for promotion of program	**B. Ocean Processes and Phenomena** Ocean acidification, under-ice exploration, fisheries habitats, ocean resources			May need international partners with ice-capable ships	Transfer data management model both inside and outside of NOAA	Increase the visibility of ocean exploration
Provide recommendations to the OEAB	Set exploration targets in response to the drivers that are constant			Consider crowdsourcing for data and technological development	Collecting new data for baseline characteristics	Engage citizen explorers, indigenous peoples and the public
				Build new relationships with oil and gas	Prioritize the importance of data and data interoperability	
				Be more expansive in our definition of partners	Provide access to data quickly	
				Creative approaches to engage aquaria		

2015 Table of Recommendation

Priorities Determined by Exploration Community	Priorities Determined by Exploration Community	Platforms	Technology	Partnerships and Funding	Data and Information	Public Engagement
Build an inclusive community – not- for-profits, academia, private sector, government Advance the recommendations from previous Forums	**Ocean Features:** Arctic, Antarctic, Indo-Pacific, Central Pacific, US EEZ and ECS	Current exploration vessels need upgrades and eventual replacement	Utilize observation tools – including cable systems that host sensors and AUVs with multibeam, and sensors fitted to marine mammals	Partner with other Federal Agencies (USGS, BOEM, NASA, U.S. Navy, NSF)	Normalize data formats so that observation from different groups can be combined and analyzed together	Facilitate a coordinated approach to public engagement, communicate the importance of exploration
Create and reinforce stakeholder relationships	**Ocean Processes & Phenomena:** Ocean acidification, under-ice communities	Use and stimulate the development of new platforms	Need for innovation and sharing new developments with federal and non-federal partners	Increased partnership with NGOs (OET, SOI, Khaled bin Sultan Living Oceans Foundation, GFOE)	Decide best practices for how data & info are managed, archived, & disseminated	Heroes to convey the value of exploration in human terms
Build support for exploration among decision makers	Design ocean exploration expeditions using an “architecture of participation”	Use of UAS, AUVs, AUV swarms	Develop visualization techniques Create small, inexpensive sensors and platforms	Think creatively about funding models, more diversified sources of support	Share data quickly and widely, time limit of 2 years	Bring educators on board to add value
Create periodic syntheses to provide summary accomplishments	Hold workshops that bring experts together to identify priorities	Use of UNLOS vessels	Develop new instruments for passive acoustic monitoring Extend the range of AUVs and other sensors	Look for opportunities with the private sector (oil and gas, marine biotechnology)		Cultivation of young ocean explorers to excite the public
Need for vocal champions of exploration			Accelerate technology development	Identify opportunities for collaboration and participation		Engage with aquaria to use citizen science & telepresence
				Be rooted in a dynamic network of partnerships		Use social media to expand reach
						Expand the role of citizen science

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2016 Table of Recommendation

NOAA-Led National Ocean Exploration Program	Priorities Determined by Exploration Community	Platforms	Technology	Partnerships and Funding	Data and Information	Public Engagement
Create campaigns for exploration, have NOAA OER commitment	**A. Geographic areas** Arctic, Gulf of Mexico, Southeast Atlantic Bight, U.S. EEZ	Expand use of exploration vehicles as opposed to ships	R&D for broadband multibeam – cut costs	Benefit from different motivations for exploration with other Federal Agencies	Encourage open data/imagery sharing	Develop standardized telepresence package procurement plan
Develop measures and indicators to determine if an area is explored, and develop consistency	**B. Ocean Processes and Phenomena** Marine minerals, acoustics	Leverage ships of opportunity, outfit for exploration and modularize ROV systems for portability	Identify, adapt, and adopt new or yet-to-be-employed technologies, test emerging technologies	Use of prizes and other nontraditional competitive approaches	When campaigns are developed, assemble and synthesize all previous data from region	Design pre-campaign press coverage, solicit interest in campaigns
Gain multiyear commitments with lead sponsor and cosponsors – sponsor "owns" campaign	**C. Mapping** Goal to map the US EEZ and entire ocean, conduct Global Geological Survey of the Oceans	Long duration AUVs and AUV swarms	Robust AUVs capable of working in ice, smaller/cheaper AUVs, disposable AUVs, sensors, devices	Deepen and rank U.S. diplomatic opportunities associated with ocean exploration	Increase resources to carry data burden	Distinguish consistently between first time and one time
Facilitate processes for advice and participate in collaboration	Participate in processes that help prioritize candidate campaign areas	Think and plan beyond the ships	Include emerging technologies in campaign RFPS, require that tech developers join expeditions	Look at potential opportunities to partner with the private sector	Avoid stovepipes within disciplines	
Begin planning for 2020-2025	Facilitate processes for advice from science community and get further advice from workshops	Invest in support infrastructure to enable employment of new technology	Use campaigns as proving grounds for emerging ocean exploration technology	Leverage opportunities to partner in exploration of the high seas		
	Understand better the "demand" for exploration	Continue to use existing ships	Biological sampling – new, non-destructive means	Encourage cross-communication between partners		

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2017 Table of Recommendation

Priorities for NOAA	Priorities Determined by Exploration Community	Platforms	Technology	Partnerships and Funding	Data and Information	Public Engagement
Position funding pitches toward federal priorities and simplify funding requests	**A. Academia** Connect with university data scientists, promote shared data, look for alternative funding. Encourage follow-through with university projects by having subsequent students continue work when others graduate	Be less reliant on elaborate ships, look at other technologies – including AUVs	Expand the scope of data collection and capabilities of sensors	Encourage cross-sector, multidisciplinary collaboration	Use data visualization to advance scientific discovery & challenge traditional hypothesis-driven workflow	Use data visualization techniques to engage the public
Consider funding data management for projects in perpetuity	**B. Not-for-profits/ Foundations** Fund projects the government does not to drive innovation. Find new revenue streams	Enable scientists to bring their own instrumentation aboard vessels	Take advantage of telepresence technology and utilize new technology	Optimize operating costs: collaborate, share resources, prioritize characterization, mine data, and plan for data storage costs	Make data open source and available sooner, include metadata & reference library	Develop tools & technologies to lower the cost of ocean exploration – making it inclusive & accessible
Encourage agency and program communications & partnerships – multidisciplinary and more inclusive	**C. Private Sector** Maintain relationships w/ researchers, find industry philanthropists, democratize technology, & improve data preservation, video processing, & machine learning	Adapt to do more with less funding	Bring together data & visualization experts, scientists and storytellers to merge their expertise with expanding modalities (apps and VR)	Pursue crowdsourcing to digitize and update legacy data, may be able to leverage new infrastructures	Rethink how collected data are managed and curated – standardize and invest in the curation, production, and presentation of data	Advance citizen science opportunities to engage with data
Look for ways to leverage the abilities of those who already work in ocean exploration and data science			Be sure that tools under development are usable with the data collected thus far	Bring together sectors to find mutually beneficial opportunities and streamline communications	Promote onshore research of offshore data	Encourage the use of VR and data visualization in the classroom and beyond
Implement better NOAA branding and increase public engagement.			Field researchers and scientists should help identify ways to create better instrumentation	Coordinate science with private industry and allow for commercial development, including gaming	Include acoustics, data from towed instruments, and environmental genomics	Look for opportunities with crowdfunding, crowdsourcing, and citizen science
Keep refining and clarifying priorities, and then communicate them to the community			Use human psychology to tailor these instruments and how data is presented	Reinvest in technology that maximizes autonomy, automated data capture, and rapid data processing	Determine which data we lack	Increased focus on positive messaging
Facilitate the conversation between stakeholder groups and bring in new stakeholders				Leverage the funding of high-risk innovation	Find ways to use legacy data – make it accessible and standardized, include in visualizations	

References

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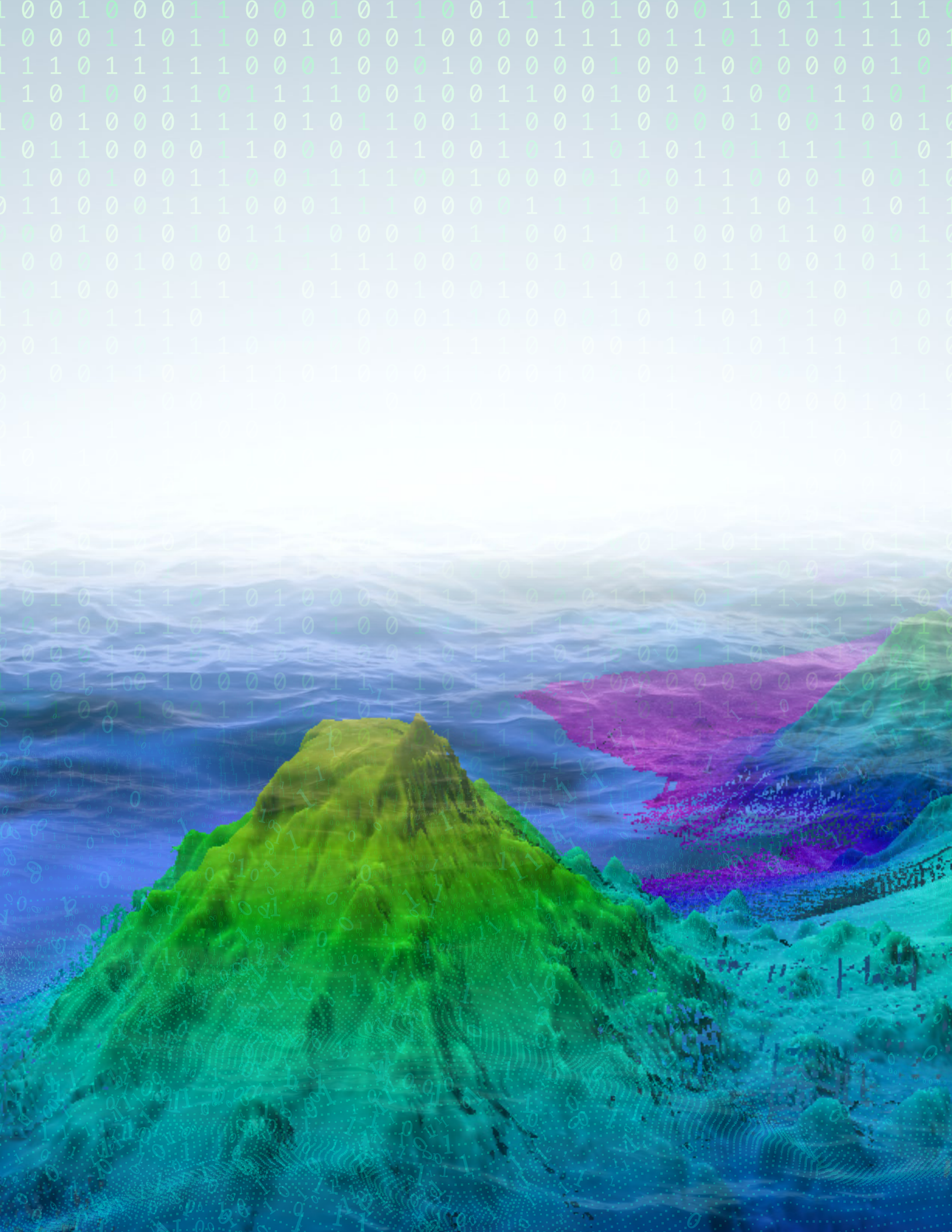

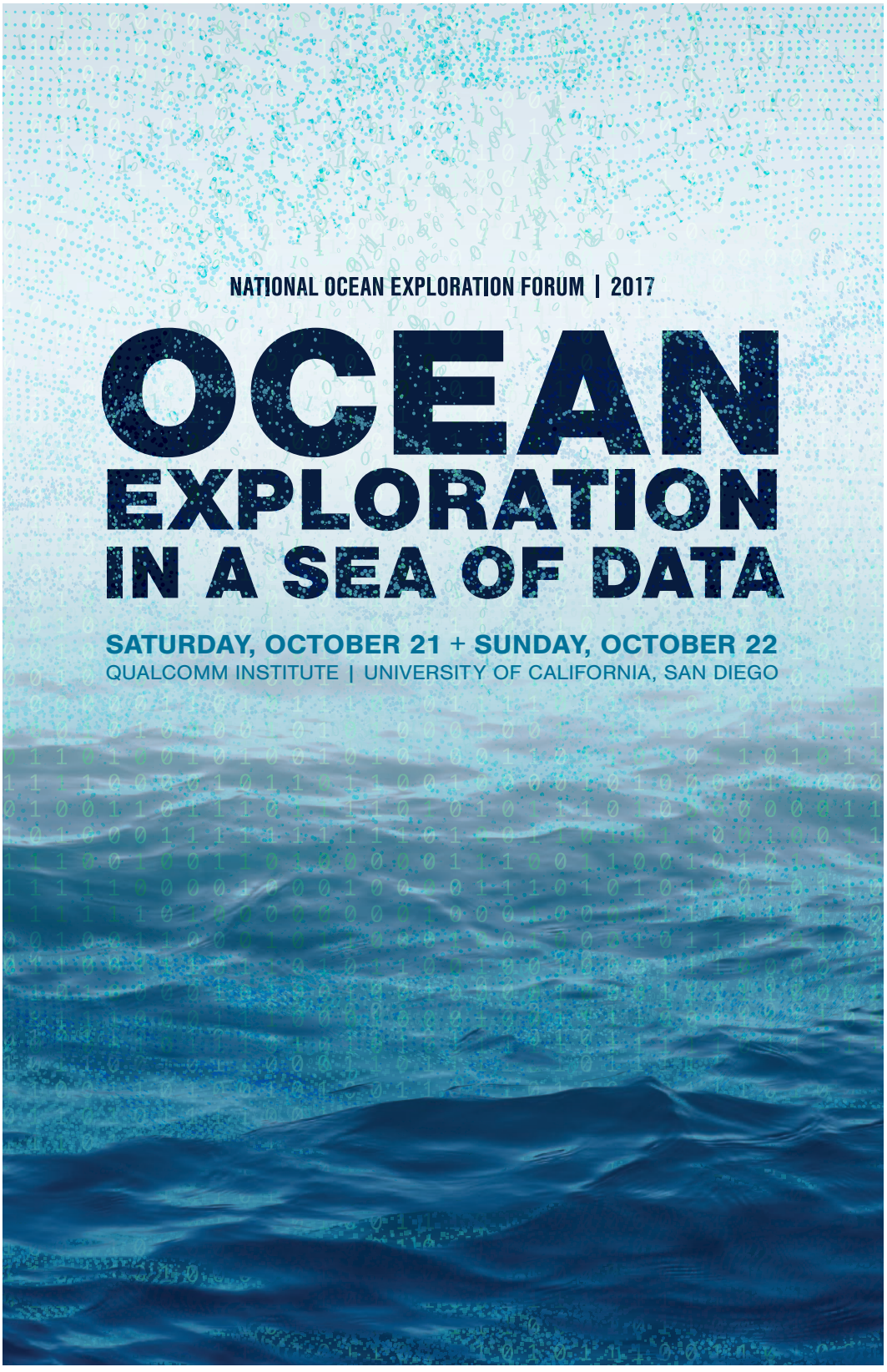
NATIONAL OCEAN EXPLORATION FORUM | 2017
OCEAN
EXPLORATION
IN A SEA OF DATA
SATURDAY, OCTOBER 21 + SUNDAY, OCTOBER 22
QUALCOMM INSTITUTE | UNIVERSITY OF CALIFORNIA, SAN DIEGO

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PROGRAM

THANK YOU TO OUR PARTNERS:

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WELCOME

It is our pleasure to welcome you to the fifth annual National Ocean Exploration Forum, *Ocean Exploration in a Sea of Data.* Congress has charged the National Oceanic and Atmospheric Administration (NOAA) with coordinating these National Forums to help set national priorities, identify partnership opportunities, advance new concepts in ocean exploration, and to help strengthen and grow the community of ocean explorers. The first Forum, called *Ocean Exploration 2020* gathered 150 members of the community of ocean explorers to discuss a framework for a national program of ocean exploration. Subsequent Forums have refined priorities, identified new technologies, and helped form new partnerships to advance our pressing need to understand the deep ocean.

One of the key recommendations from *Ocean Exploration 2020,* and reinforced in Forums since, was the need for better access to data, new techniques for data management, and new tools for visualizing data. Our event amplifies those themes by bringing together data scientists and visualization experts with the ocean explorers to consider how current and emerging data science and visualization techniques can help us understand the deep ocean in new ways. *Ocean Exploration in a Sea of Data* will take full advantage of the Jacobs School of Engineering and Qualcomm Institute's visualization and acoustics laboratories to demonstrate what can be done with rich terrestrial data sets, what might be done with historical and contemporary data from the deep ocean and its limitations and challenges, and the potential for conducting science differently using these techniques to reach a new understanding of this critical domain.

Qualcomm Institute professors, students, and technical experts have collaborated with partners from Scripps Institution of Oceanography, Lamont-Doherty Earth Observatory, University of Washington, NOAA, and others to create what we believe are compelling demonstrations of the application of new and emerging techniques to ocean data that may have important implications for ocean exploration. Based on these demonstrations along with keynote talks, panel discussions, and case studies, we will ask you to contribute recommendations for how data science and visualization can be applied to pressing challenges in the use and collection of ocean exploration data and what changes are needed in ocean exploration modes of operation and data collection strategies so these new approaches can be applied to accelerate the rate at which we understand the deep ocean.

We're grateful to our many partners and contributors for their creativity and support. We want to express particular appreciation for the wise counsel of Jerry Schubel, President and CEO of the Aquarium of the Pacific—and the primary architect of the National Ocean Exploration Forum process; of Larry Smarr, Director of the California Institute for Telecommunications and Information Technology; and Margaret Leinen, Director of Scripps Institution of Oceanography. And we would like to thank you for making time to join us for this National Ocean Exploration Forum and for your willingness to work with your colleagues and across disciplines to take up the exciting challenges before us.

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Qualcomm Institute, University of California, San Diego

VICKI FERRIN
Lamont-Doherty Earth Observatory, Columbia University

DAVID MCKINNIE
NOAA Office of Ocean Exploration and Research

ADRIENNE COPELAND
NOAA Office of Ocean Exploration and Research

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PROGRAM

SATURDAY

OCTOBER 21, 2017 | THE FUTURE IS ON THE HORIZON

08:00–09:00 CHECK IN AND BREAKFAST

09:00–09:05 **Welcome to the Forum**
Dominique Rissolo | Qualcomm Institute

09:05–09:15 **Welcome to Qualcomm Institute**
Ramesh Rao | Director, Qualcomm Institute

09:15–09:30 **NOAA and Ocean Exploration**
Alan Leonardi | Director, NOAA
Office of Ocean Exploration and Research

09:30–10:00 **Ocean Exploration Forums and National Priorities**
Jerry Schubel | President and CEO, Aquarium of the Pacific

10:00–10:20 BREAK

10:20–11:10 **Keynote Speaker**
Margaret Leinen | Director, Scripps Institution of Oceanography

11:10–12:00 **Keynote Speaker**
Larry Smarr | Founding Director, California Institute
for Telecommunications and Information Technology

12:00–13:00 LUNCH

13:00–13:40 **Ocean Exploration and the Temporal Domain**
John Delaney | University of Washington

13:40–14:00	**Experiencing Ocean Data Demos, an Introduction** Dominique Rissolo | Qualcomm Institute
14:00–17:30	**Experiencing Ocean Data** Via a series of research driven demos, Forum participants will be physically immersed in ocean data from coral reefs, hydrothermal vents, below-ice environments, trenches and ridges, and deep-sea soundscapes.
14:00–14:25	**Demo 1**
14:30–14:55	**Demo 2**
15:00–15:25	**Demo 3**
15:30–15:55	**BREAK**
16:00–16:25	**Demo 4**
16:30–16:55	**Demo 5**
17:00–17:25	**Demo 6**
17:30–18:00	**Concluding Remarks** Dominique Rissolo | Qualcomm Institute
18:00–	**RECEPTION AND DINNER AT QUALCOMM INSTITUTE** *DINNER SPEAKER:* Bob Weiss | XPRIZE

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SUNDAY

OCTOBER 22, 2017 | **NAVIGATING TOWARDS THE FUTURE**

08:00–08:30 BREAKFAST

08:30–08:40 **Welcome and Recap**
Dominique Rissolo | Qualcomm Institute

08:40–09:00 **Report Out of Day One**
Tiffany Fox | Qualcomm Institute

09:00–10:00 **CASE: Coral Reef Point Clouds and Classification**
Stuart Sandin | Scripps Institution of Oceanography
Falko Kuester | Qualcomm Institute
Vid Petrovic | Qualcomm Institute
Nicole Pedersen | Scripps Institution of Oceanography

10:00–10:15 BREAK

10:15–11:00 **CASE: Visualization and New Understanding: JPL's OnSight Immersion Environment**
Alice Winter | NASA Jet Propulsion Laboratory / OpsLab

11:00–12:00 **Panel Discussion: Data Science Solutions to Integrating Temporally and Spatially Sparse Data**
Moderator:
Vicki Ferrini | Lamont-Doherty Earth Observatory

Panelists:
Dawn Wright | Esri
Jessica Block | Qualcomm Institute
Alice Winter | NASA Jet Propulsion Laboratory / OpsLab
Vid Petrovic | Qualcomm Institute
Stuart Sandin | Scripps Institution of Oceanography

12:00–13:00 LUNCH

13:00–13:15 **How Do We Do This?**
Dominique Rissolo | Qualcomm Institute

13:15–13:30 **Engagement of Students and Announcement of the Ocean Exploration Data Capstone Challenge**
Jessica Block | Qualcomm Institute

13:30–15:00 **Breakout Discussions: How Can Ocean Exploration Use New Techniques in Data Science and Visualization to Understand the Ocean in New Ways?**
Moderators:
Amanda Demopoulos | USGS
Jacqueline Dixon | University of South Florida
Allison Fundis | Ocean Exploration Trust
Alan Leonardi | NOAA Office of Ocean Exploation and Research
Drew Stephens | Esri
Carlie Wiener | Schmidt Ocean Institute

15:00–15:30 **BREAK**

15:30–16:20 **Breakout Session Reports: Recommendations for the Future**

16:20–17:10 **Concluding Panel: What Should We Do Next?**
Jerry Schubel | President and CEO, Aquarium of the Pacific
Margaret Leinen | Director, Scripps Institution of Oceanography
Larry Smarr | Founding Director, California Institute for Telecommunications and Information Technology

17:10–17:15 **Closing Remarks**
Dominique Rissolo | Qualcomm Institute

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PROGRAM

DEMONSTRATION

DESCRIPTIONS

DEMONSTRATION 1:

Exploring Ocean Data Through Audio Spatialization and Sonification

Audio Spatialization Lab

Shahrokh Yadegari | Grady Kestler | Adrienne Copeland

Sound is ubiquitous in the deep ocean environment. Geological events, like earthquakes, can contribute significant levels of sound to the deep ocean. Many marine animals, from shrimp to marine mammals, use sound to communicate and assess their environment. And humans generate a wide array of sounds as well. This combination of physical, biological, geological, and anthropogenic sounds make up the marine "soundscape." The exploration of marine soundscapes can lead to a better understanding of the deep ocean and is an important aspect of characterization of these environments.

The Audio Spatialization Lab (SpatLab) allows for a 3D exploration of sound, the acoustic dimensions of ocean phenomena. Participants will experience the basic capabilities of SpatLab, like the geolocation of sound sources, then observe demonstrations of how ocean phenomena can be modeled acoustically and how sound can be used to explore and understand aspects of the deep ocean in ways otherwise not possible. This demonstration will explore different aspects of deep ocean soundscapes, from undersea volcanoes, to ensonifying non-acoustic tsunameter data, to geolocating individual marine mammals through acoustic arrays.

DEMONSTRATION 2:

Seabed Mapping—New Perspectives from Immersive Visualization

SunCAVE

Vicki Ferrini

Seabed mapping provides critical baseline information for ocean exploration. Bathymetric data are typically presented in one of two formats: map contours with color schemes familiar to anyone who has examined a nautical chart, or as colored-shaded 3D renditions of gridded data. While these data representations can be easily manipulated for a variety of applications, neither allows us to intuitively understand and feel the scale of seafloor bathymetric features. A similar challenge of scale in ocean mapping is related to how few people outside the ocean exploration community truly understand the magnitude of how little of the ocean has been mapped.

The SunCAVE is an immersive environment that allows for near-360 degree presentations of video and data. SunCAVE technologies allow experiments with new ways to represent deep ocean bathymetry, seafloor features, and other attributes of the deep ocean. This type of data visualization can inform science and to strengthen public interest in ocean exploration, help educators explain the ocean, and engage more of the public in ocean exploration through new visualization techniques. This demonstration will present seafloor mapping data as an immersive visualization with the goal of improving our understanding of scale and enabling new perspectives and understandings of seafloor features.

DEMONSTRATION 3:

"Being There without Being There"—Interactive, Remote, Fiber-Optic Presence on a Major, Highly Active Mid-Ocean Ridge Volcano—Eruptions, Active Venting, and more...

Vroom

John Delaney | Timothy Crone | Friedrich Knuth | Aaron Marburg

The recent completion of the Cabled Array of sensor networks is a major component of NSF's Ocean Observatory Initiative (OOI). The observatory offers unique opportunities to explore the scientific and educational benefits of real-time access to a highly active portion of the Global Mid-Ocean Ridge System—a 70,000 km-long volcanic feature that extends around the world like the strings on a baseball.

The Vroom hyperwall and high definition projection systems allow for a demonstration of the OOI capabilities and benefits, focused on the evolution of the vigorously venting heavily colonized hydrothermal structure, recently dubbed "Mushroom." An additional element of this demonstration will involve controlling a HD video camera which is located 400 km due west of Astoria, Oregon, inside the Caldera at the summit of Axial Seamount, itself perched atop the Juan de Fuca Ridge. The demonstration will highlight the importance of continuous real-time monitoring to understand change in the deep ocean, and the significance of ocean exploration in the time domain.

DEMONSTRATION 4:

Visualizing Antarctic Ice Shelf Structure and Bathymetry from the Air

CHEI Lab

Robin Bell | Nicholas Frearson

Ocean exploration in remote polar regions presents unique operational challenges. Acquiring good bathymetry in remote under-ice environments is critical to understanding these important deep ocean regions. Under-ice bathymetry is required to understand how ice sheets are changing. For example, the shape of the ocean floor controls how warming ocean water can reach the West Antarctic Ice Sheet. Good bathymetric data is also fundamental to predicting how fast sea level will rise in the future. Future ocean exploration and research in the polar regions will become increasingly important for understanding how large ice sheets are changing.

The CHEI Lab allows for 3D displays of high resolution images, video, and photogrammetric point clouds. The ROSETTA project is mapping the least known ocean floor on our planet through the use of aerogeophysical techniques: the use of aircraft as platforms for radar, gravimeters, and other instrumentation. This demonstration will integrate aerogeophysical data and visualize the data to streamline analysis. Gravimeters measure the ocean depth from aircraft flying 2500 feet above the ocean surface and radar systems map the structure of the ice that floats on it; ice that can be up to one kilometer thick. The demonstration will also include a fly-through of the ice-penetrating radar data that illustrates how the ice shelf is changing.

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DEMONSTRATION 5:

Underwater Photogrammetry: Point-Based Visual Analytics and Habitat Characterization

WAVElab

Falko Kuester | Dominique Rissolo

Structure-from-Motion (SfM) photogrammetry has become an empowering and widely adopted technique for documenting underwater features or sites in 3D. The combination of relatively straightforward image acquisition protocols and the ability to render both geometrically accurate and photorealistic models (using readily available software) has made the technique popular, particularly for limited photo-mapping of shallow benthic environments. Photogrammetry presents numerous challenges, including the computational power required to process and postprocess massive image-sets; the ability to assess the integrity of the models produced; and the extent to which these 3D data can serve as the basis for new analytical approaches.

The WAVElab (Wide Area Virtual Environment) is a large-scale immersive visualization system. In this demonstration, we will visualize coral reefs, shipwrecks, and submerged Pleistocene megafauna, and explore how the scientific potential of these data can be realized through the use of these new analytical tools.

DEMONSTRATION 6:

Discussion and Debrief

The Design Lab

Tiffany Fox

This discussion session, part of the demonstration series, is an opportunity for participants to share impressions of what they observed in the visualization and acoustic demonstrations and what the implications could be for their work, area of interest, and the ocean exploration community. The discussions are also intended to help identify areas of potential collaboration between the data science and visualization experts and the ocean exploration community.

Key reflections and ideas will be captured and shared in plenary on the second day—and help start the process of developing recommendations that will be documented in the Forum report.

BREAKOUT

DISCUSSION OVERVIEW

Ocean Exploration in a Sea of Data is structured to provide participants—regardless of discipline or experience—with common information and experiences to bring to bear in the breakout sessions. The keynotes, panel discussion, case studies, and especially the demonstrations are intended to share new information, provoke thought, spark creativity, and encourage dialogue across ocean exploration and data science and visualization disciplines. Breakout session participants will rely on this common information as well as their own expertise and experience to develop recommendations for ocean exploration stakeholders and specific sectors.

Organizers have formed six groups that, to the extent possible, mirror the diversity of *Ocean Exploration in a Sea of Data* participants. These groups will stay together for the demonstrations (including the Discussion and Debrief that is part of the demonstration process) on the first day and remain together for the breakout sessions. Our hope is that by experiencing the demonstrations together and getting to know each other before the breakouts, the process of identifying and discussion recommendations will be accelerated.

SURVEY

We have asked all participants to complete a short survey about ocean exploration and data science and visualization before the Forum begins and again after the demonstrations, panel discussions, and case study presentations. Moderators will use survey results to help guide discussion; survey data will also be used in preparation of the Forum report.

PROCESS

Moderators will present the results from each breakout discussion group in plenary, to be followed by a final panel of Jerry Schubel, Larry Smarr, and Margaret Leinen, who will synthesize the entire event in their discussion. We will document breakout session reports and panel discussions for use in the Forum report.

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QUESTIONS

Moderators will ask each group to consider the following questions (among others) to help guide discussion in your session and to identify recommendations:

1. What major opportunities do data science and new techniques for visualization offer?
2. How should we change our concepts of ocean exploration? What are the implications for instrumentation and data collection?
3. What are the implications for "characterization" of the ocean? What new parameters should we be thinking of?
4. Is legacy data relevant? What should we do about it?
5. What should the following sectors do to encourage closer ties with the data science and visualization community and to promote adoption of new approaches that could yield new understanding?

   —academia

   —federal government

   —not-for-profits/foundations

   —private sector
6. Can we leverage new visualization approaches and products for public engagement? How?
7. What is your best advice to NOAA, as the coordinator of a national program of ocean exploration, in 15-20 words?

BIOS

DR. ROBIN BELL is the PGI Lamont Research Professor at Lamont-Doherty Earth Observatory, Columbia University, where she directs research programs in Antarctica and Greenland with a focus on developing technologies to monitor our changing planet. Robin has led a number of Antarctic expeditions, which have resulted in the discoveries of under-ice phenomena. Robin is president-elect of the American Geophysical Union.

JESSICA BLOCK is a research analyst with Qualcomm Institute at UC San Diego. She is an interdisciplinary geologist and urban ecologist specializing in the use of sensor networks, remote sensing, and geospatial visualization tools for disaster response, natural resource management, policy decision-making, and sustainability.

DR. ADRIENNE COPELAND is the 2017 Knauss Sea Grant Ocean Exploration Fellow for the NOAA Office of Ocean Exploration and Research. She specializes in the use of active and passive acoustic collection methods to understand open ocean predator-prey dynamics. Adrienne has designed and directed several at-sea research projects and has served as chief scientist on six expeditions.

DR. TIMOTHY CRONE is a Lamont Associate Research Professor at Lamont-Doherty Earth Observatory, Columbia University. As a marine geophysicist, he is interested in the interplay between relatively large-scale geophysical processes and the microbial biosphere. Tim is currently studying the tidal modulation of aqueous fluid flow within mid-ocean ridge hydrothermal systems.

DR. JOHN DELANEY is a Professor of Oceanography and the Jerome M. Paros Endowed Chair in Sensor Networks at the University of Washington. He directed the development of the regional cabled ocean observatory in the northeast Pacific Ocean as part of the NSF Ocean Observatories Initiative. John's research focuses on the deep-sea volcanic activity of the Juan de Fuca Ridge and the application of deep-sea research to off-earth scientific mission planning.

DR. AMANDA DEMOPOULOS is a research ecologist with the US Geological Survey. Her research focuses on coastal wetlands and deep-sea environments, where she studies benthic invertebrate community structure and function. Amanda is also a member of the Ocean Exploration Advisory Board.

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DR. JACQUELINE DIXON is the dean of the College of Marine Sciences at University of South Florida. Her research interests focus on the role of H_2O and CO^2 in the generation and evolution of basaltic magmas with an emphasis on submarine volcanoes. Jackie is also Chair of the Board for the Consortium for Ocean Leadership and a member of the Ocean Exploration Advisory Board.

DR. VICKI FERRINI is a research scientist at Lamont-Doherty Earth Observatory, Columbia University. She specializes in geoinformatics, high-resolution seafloor mapping in coastal waters and the deep sea, deep submergence vehicle data acquisition and integration, and management of marine geoscience data.

TIFFANY FOX is a public information representative for the Qualcomm Institute at UC San Diego and has spent the past decade helping researchers tell their research stories through articles, videos and public presentations. She also writes a weekly newsletter on research communications, Research Refined. Prior to coming to UC San Diego, Tiffany was a reporter and columnist for the San Diego Union-Tribune, and as a freelance journalist she covers a multitude of topics spanning science, engineering, technology and the arts.

NICHOLAS FREARSON is a researcher and lead engineer at Lamont-Doherty Earth Observatory, Columbia University. He has developed an airborne system for documenting and monitoring changing ice sheets in Antarctica and has produced new data on the ice shelf dynamics. Nick and his colleagues have explored sub-glacial mountains and other unseen frozen worlds from the North to the South Poles.

ALLISON FUNDIS is the vice president of education, outreach & communications for the Ocean Exploration Trust, where she brings a diverse background of education, science, and sea-going experience to engage students, educators, and the public in ocean exploration and research.

GRADY KESTLER received his BA in Music/Interdisciplinary Computing and the Arts and his MFA in Sound Design from UC San Diego. He is currently completing his M.S. at UC San Diego as a member of the SonicArts lab where he builds demos and develops software for audio spatialization. His research involves binaural HRTF interpolation and reconstruction from spatial and anthropometric data.

FRIEDRICH KNUTH is a data analyst with the Department of Marine and Coastal Sciences at Rutgers University. His background is in structural geology, acoustic seafloor mapping, spatial data visualization and marine environmental habitat modeling. Friedrich is the primary data evaluator for the Cabled Array section of the NSF Ocean Observatories Initiative.

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DR. FALKO KUESTER is the director of the Cultural Heritage Engineering Initiative at the Qualcomm Institute and the Calit2 Professor for Visualization and Virtual Reality. He is also an associate professor in the Department of Structural Engineering and the Department of Computer Science and Engineering at UC San Diego. Falko has led the development of digital workflows for the documentation and analysis of at-risk heritage sites around the world.

DR. MARGARET LEINEN is the director of Scripps Institution of Oceanography and the UC San Diego vice chancellor for marine sciences and dean of the School of Marine Sciences. An award-winning oceanographer and paleo-climatologist, her research focused on ocean sediments and their relationship to global biogeochemical cycles and the history of Earth's ocean and climate. Among her numerous leadership roles, Margaret serves on the board of the National Council for Science and the Environment and in 2016 was appointed as a science envoy by the U.S. Department of State focusing on ocean science in Latin America, East Asia, and the Pacific.

DR. ALAN LEONARDI is the director of the NOAA Office of Exploration and Research where he oversees NOAA's program of telepresence-enabled exploration via the ship Okeanos Explorer and with NOAA's partner organizations and agencies. A meteorologist and oceanographer, Alan has been with NOAA since 2003 and is the former Deputy Director of NOAA's Atlantic Oceanographic and Meteorological Laboratory.

DR. AARON MARBURG is a senior computer and electrical engineer with the Applied Physics Laboratory at the University of Washington. His research focuses on the development of robotic platforms for ocean exploration, with a focus on perception and situational awareness. Aaron has a background in remote sensing, photogrammetry, and precision navigation, and an interest in human-machine interfaces, and data and metadata management.

DAVID MCKINNIE is senior advisor and acting lead of the Engagement Division for the NOAA Office of Ocean Exploration and Research. His expertise includes development of domestic and international external partnerships, moving concepts to operations, and translating science for decision makers. David is the designated federal officer for the Ocean Exploration Advisory Board.

NICOLE PEDERSEN is the image digitization coordinator for the 100 Island Challenge project at Scripps Institution of Oceanography. Nicole uses large-scale images to assess spatial patterns of juvenile corals and works closely with research partners to build sophisticated models of reef environments.

VID PETROVIC is a Ph.D. candidate in the Department of Computer Science and Engineering at UC San Diego and has developed the visual analytics engine that powers projects at the Cultural Heritage Engineering Initiative and Scripps Institution of Oceanography. Vid has extensive experience capturing at-risk sites in the field and translating the data into detailed digital models.

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DR. RAMESH RAO is the director of the Qualcomm Institute and is a professor of Electrical and Computer Engineering at UC San Diego. As a researcher in the wireless field, his contributions include the development of energy-efficient communication techniques to support mobile multimedia users. Ramesh has led numerous projects and initiatives focused on disaster preparedness and response as well as health-related applications.

DR. DOMINIQUE RISSOLO is an assistant research scientist at the Qualcomm Institute, UC San Diego. He has coordinated several oceanographic and marine archaeological surveys and projects, and his current research focuses on paleocoastal human ecology and digital applications in underwater cultural heritage. Dominique is also a member of the Ocean Exploration Advisory Board.

DR. STUART SANDIN is a professor at Scripps Institution of Oceanography and is the director of the Center for Marine Biodiversity and Conservation. His research explores the dominant dynamics that structure marine communities, with a focus to date on coral reef communities. Stuart co-directs the 100 Island Challenge, which brings novel imaging and analytical tools to the study of threatened coral reefs over time.

DR. JERRY SCHUBEL is president and CEO of the Aquarium of the Pacific and director of the Aquarium's Marine Conservation Research Institute. He serves on the Board of Trustees of the California Ocean Science Trust and is a member of the Science Advisory Panel for California's Ocean Protection Council. Throughout his professional life, Jerry has explored the interface of ocean science, management, policy, and public engagement.

DR. LARRY SMARR is the founding Director of the California Institute for Telecommunications and Information Technology (Calit2), a UC San Diego/UC Irvine partnership, and holds the Harry E. Gruber professorship in Computer Science and Engineering at the Jacobs School of Engineering. He has spearheaded major developments in information infrastructure, including the Internet, scientific visualization, virtual reality, and global telepresence. Larry has served on numerous national councils and is currently leading the Pacific Research Platform.

DREW STEPHENS is the ocean industry manager at Esri, with experience in database design, training, and consulting. Drew explores GIS applications for marine ecosystems research, aquaculture and fisheries, coastal protection, and ocean-use planning.

ROBERT WEISS is Vice Chairman of the XPRIZE Foundation, which has active competitions in Lunar Exploration, Healthy Oceans, and Mobile Health Care, and is now developing XPRIZEs in Education, and Energy. Bob is a veteran television and film producer with passion for science communication.

DR. CARLIE WIENER is the communications manager for Schmidt Ocean Institute. She has extensive experience in marine science communications, involving research, outreach, evaluation, and professional leadership. Carlie also teaches courses on communicating ocean sciences and marine science for the public.

ALICE WINTER is a user experience researcher at NASA Jet Propulsion Laboratory. She works with the OnSight team, which develops and uses advanced visualization tools to virtually explore and study Mars in preparation for future human missions.

DR. DAWN WRIGHT is the chief scientist at Esri and is an oceanographer and GIS specialist. Dawn's research interests include geographic information science; ocean informatics and cyberinfrastructure; benthic terrain and habitat characterization; and the processing and interpretation of high-resolution bathymetry, video, and underwater photographic images.

DR. SHAHROKH YADEGARI is a professor in the Department of Music at UC San Diego and is the director of the Sonic Art R&D Group at Qualcomm Institute, where he is also director of the Initiative for Digital Exploration of Arts and Sciences. Shahrokh is a composer and sound designer who has worked on a broad range of creative and applied research projects.

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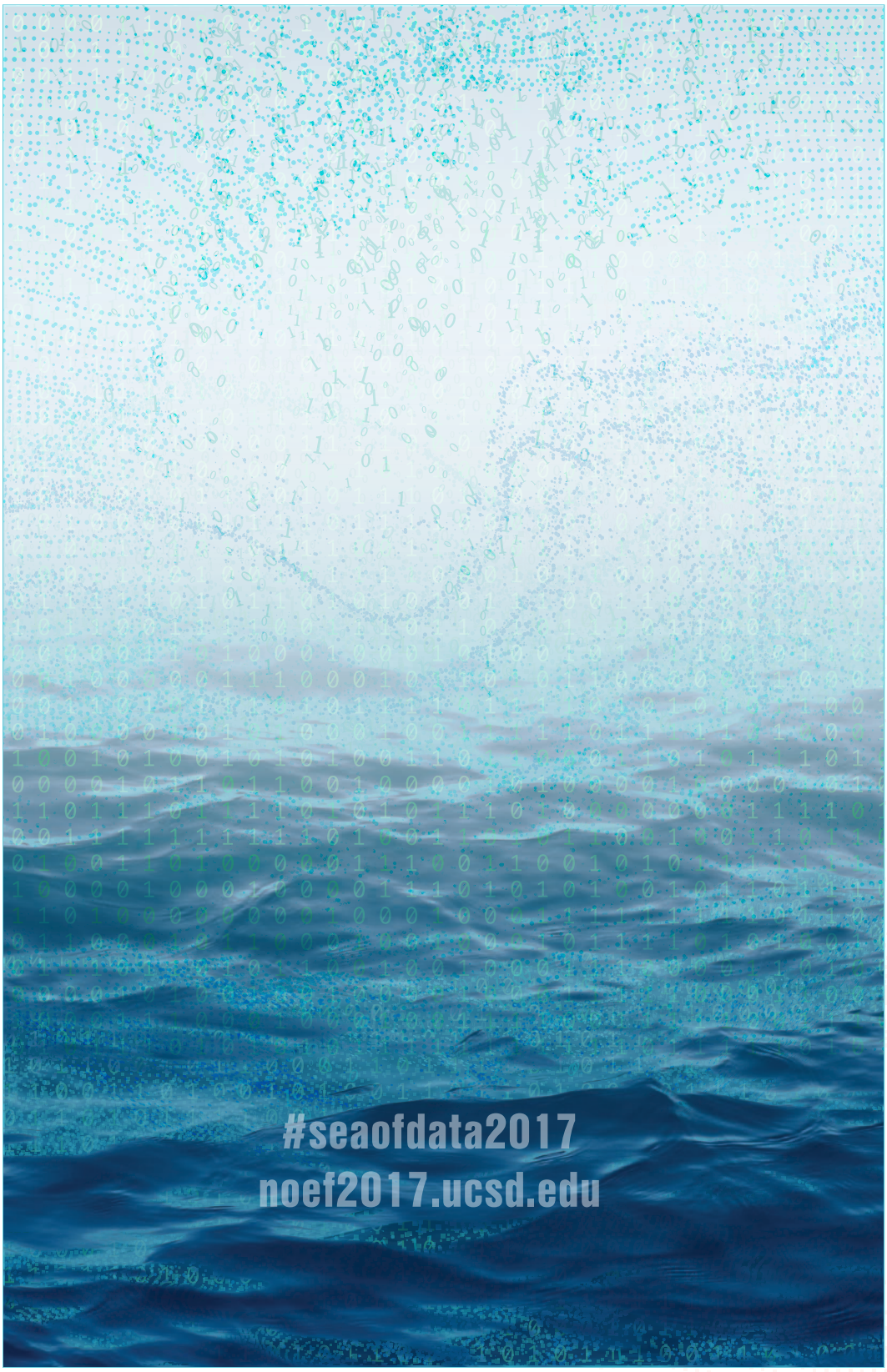

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Photo by Alex Matthews and Amiel Capinpin for Qualcomm Institute/UC San Diego

Acronyms

2D — two dimension

3D — three dimension

AI — artificial intelligence

AR — augmented reality

AUV — autonomous underwater vehicle

Calit2 — California Institute for Telecommunications and Information Technology

CENIC — Corporation for Education Network Initiatives in California

CGLX — Cross Platform Cluster Graphics Library

CHEI Lab — Cultural Heritage Engineering Initiative Lab

CPU — central processing unit

CTD — conductivity, temperature, depth

Esri — Environmental Systems Research Institute

Gbps — Gigabits per second

GIS — Geographic Information System

GPU — graphics processing unit

HAB — harmful algal bloom

HD — high-definition

JPL — Jet Propulsion Laboratory

LDEO — Lamont-Doherty Earth Observatory

MBARI — Monterey Bay Aquarium Research Institute

MOR — mid-ocean ridge

NASA — National Aeronautics and Space Administration

NCSA — National Center for Supercomputing Applications

NOAA — National Oceanic and Atmospheric Administration

NOEF — National Ocean Exploration Forum

NSF — National Science Foundation

OE 2020 — Ocean Exploration 2020, the first National Ocean Exploration Forum held in 2013

OER — Office of Ocean Exploration and Research

OOI — Ocean Observatory Initiative

PRP — Pacific Research Platform

QI — The Qualcomm Institute

R&D — research and development

ROV — remotely operated vehicle

SAGE — System for Automated Graphics and Explanation

SfM — Structure-from-Motion

SIO — Scripps Institution of Oceanography

SOI — Schmidt Ocean Institute

SpatLab — QI Audio Spatialization Lab

SunCAVE — Sun Cave Automated Virtual Environment

UC — University of California

VR — virtual reality

Vroom — Virtual Room

WAVE — Wide Area Virtual Environment

WAVElab — Wide Area Virtual Environment Lab

Photo by Shanni Jin for The Qualcomm Institute/UC San Diego

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REPORT

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