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The Oceans of Planet Earth: Truly the Last Frontier

The oceans have long been an important domain for exploration, resource extraction, shipping, national security, understanding of weather and climate, and more recently the emerging Blue Economy. The opening of Arctic sea lanes against the backdrop of climate change is a matter of national security. Sea level rise has severe ramifications for coastal infrastructure and populations. Moreover, the overall health of the oceans and integrity of the coasts are critical to the millions who live near and depend on them in this country alone. But when compared with the rapid expansion of knowledge of the universe, oceans are a woefully underexplored frontier—certainly if the utter disappearance of aircraft is any indication, there is much to be learned about Earth’s watery depths.

This issue is dedicated to the engineering methods used to enhance understanding of the world’s oceans. Maps no longer proclaim “Here be dragons,” but how much is known even today about the deep blue sea? What are the major challenges to ocean observation and surveying? What is the status of ocean monitoring? What technologies are emerging to explore the oceans, to enhance understanding of this realm, and assess ocean interactions with the atmosphere above and laterally with coastal zones?

Approximately 70 percent of the Earth is covered by ocean, and this vast expanse, in both surface area and depth, presents myriad engineering challenges, such as a corrosive environment, vast distances, opaqueness to electromagnetic remote sensing (in contrast to the atmosphere), pressures of the deep ocean, vandalism at sea, and biofouling. These in turn create challenges for communications, power, durability, and coverage, among others. At the same time, autonomous and other emerging technologies for observing the ocean can accelerate exploration, enhance resource management, and improve understanding of the role of the oceans in the coupled climate system.

The articles in this issue describe the interdisciplinary field of ocean science and engineering from the past to the decades ahead. In the opening article, Don Walsh traces the history of ocean engineering from the perspective of the United States’ use of the oceans in four categories: ocean science, ocean engineering, economics and public policy, and manmade constraints. A coherent US national ocean policy is essential to coordinate these uses to ensure the country’s interests.

Vice Admiral Paul Gaffney then provides a historical perspective on US campaigns to explore, survey, and observe the oceans. He describes previous observational methods and calls for renewed collaborative efforts to make the most of disparate data sources, limited resources, and emerging technologies that can greatly expand reach, coverage, and knowledge without increasing costs.

Arthur Baggeroer and colleagues survey ocean observations and observatories. They describe a paradigm shift in oceanography in the early 2000s away from sparse (in both space and time) ship-deployed observations to real-time data relayed from sensors to shore via cables or satellite uplinks. The engineering challenges in maintaining these observatories in the harsh ocean environment are highlighted.

Larry Mayer describes challenges and advances in mapping the bathymetry of the world’s oceans, from the
lead line to today’s satellite altimetry and multibeam sonar. Notwithstanding the advances, he points out that 82 percent of the ocean floor has never had a direct measurement of depth at a 1 km × 1 km scale. More is known about the topography of the Moon and Mars than about large swaths of the Earth’s seafloor.

William Kuperman delves into the details of imaging the ocean through the use of noise. Acoustic arrays detect noise that can reveal information about ocean floor depth and topography, water temperature, and ships and other bodies in the water. Sound propagation in the ocean and signal processing techniques are used to monitor changes in the ocean environment that influence the ocean sound field.

In the last article, Lee-Lueng Fu and Dean Roemmich explain how global sea level rise is measured from spaceborne and in situ sensors. They trace the evolution of early methods that constructed global mean sea level from sparse tide gauges to present-day estimates of sea level rise—3 mm/year—derived from satellite altimeters, spaceborne gravity missions, and some 3,800 in situ profiling floats operated by a coalition of 27 countries. The resulting global data are able to reveal the relative contributions to sea level rise from the thermal expansion of seawater and glacial ice melt.

We thank the authors for their thoughtful and enthusiastic contributions to this issue. Collectively, the articles depict how, why, and where the oceans have been observed, and how new and emerging technologies are changing knowledge and understanding of the oceans going forward.

We are also indebted to the following experts for their assistance in improving this collection of papers by reading and offering thoughtful comments on them: Kenneth Brink, Deborah Glickson, Arnold Gordon, Mardi Hastings, James Miller, and Robert Weller.
A unified national ocean policy is needed to support effective US engagement and leadership in the World Ocean.

Ocean Engineering and National Uses of the Sea: The Long View

Don Walsh

Ocean engineering is an interdisciplinary field (like oceanography) that can be defined as the application of all engineering arts and sciences to ocean-related problems. Present use of the term “sea power” often implies only military uses. But in strategic maritime thought from the late 1800s on, the term was meant to describe all national uses of ocean space. In this paper sea power refers to how a country uses the World Ocean as an instrument of national policy. I explain that uses of the sea can be best understood as a system of synchronized, somewhat overlapping efforts governed by a singular ocean policy.

Ocean Engineering: An Old-New Interdisciplinary Field

Ocean-related engineering began with the first port and coastal engineering works in the 8th century BCE. Thereafter the extension of terrestrial engineering skills sufficed to meet requirements in the “wet space.”

Naval architecture was perhaps the earliest wholly ocean-related engineering discipline. Over hundreds of years, ship design and construction led to more efficient vessels for military and commercial uses. Some of that engineering was quite advanced. For example, Polynesian and Micronesian wayfinders (navigators) roamed the vast expanses of Oceania for thousands of years in voyaging canoes designed to take advantage of prevailing winds. And the global voyages of Admiral Zheng He (1371–1435) in the Ming
Dynasty employed a large fleet of sailing vessels with up to nine masts and a displacement of nearly 2,000 tons. During the 19th century steam-powered ships replaced sail-powered ones, and a new discipline, marine engineering, evolved to design and build the machinery and systems needed. By the early 1960s diverse ocean technologies were advancing more rapidly than the maximum effort during World War II. The field of ocean engineering emerged to incorporate these developments—and to support national uses of the sea.

**Ocean Engineering**

Ocean engineering involves the application of almost all the engineering disciplines to uses of the sea. Here the engineering arts and sciences develop the equipment and machines to do work in the sea, with a vital feedback link to oceanographic activities through the development of better equipment for doing marine science. Ocean engineering is the critical link between scientific knowledge and application of that knowledge to work in the sea.

**Economics and Public Policy**

Economics and public policy determine whether the work being done is useful. The economic test is simple: Can the work produce a profit? Can something be done in or on the sea to develop or support a successful commercial enterprise?

The public policy test is a bit imprecise. A navy is the best example: The government considers that operating a navy is useful and vital to maintain national security.

As another example, in some less developed countries the government may set up and support a national fishing industry because there is insufficient private capital to do this. Ultimately the government can sell the industry to the people operating it and, as it becomes self-sustaining, it may become a commercial business. The government's public policy first determined that the work at sea was useful.

**Manmade Constraints**

This category is different from the rather precise scientific, technological, and economic determinism of the others. Manmade constraints include the Law of the Sea (see below), domestic political processes, and traditions as well as cultural and ethnic factors. These may take priority over the other categories because they can be very difficult to resolve and require longer-term consideration.

Perhaps political processes are the greatest impediment. Lack of a governing public policy and chronic underfunding have negative consequences for the creation of a robust sea power. The capacity for science and technology activities in and on the sea is greater than the capability for governing and funding them. There is a gap of 10–15 years between a slow-moving government process and the ability of science and technology to study and exploit the marine environment.

For optimal ocean management, the critical path is in the political and policy areas as well as the allocation of sufficient funding.
**Ocean Policy: The Governing Factor**

Larger, and often more developed, countries have the scientific and technical means to exploit their uses of the sea, and a challenge for major maritime states (i.e., users of the sea) is how to coordinate their various elements of national sea power to avoid deficiencies and duplication. The larger the nation the more complex these problems.

**Role of a National Ocean Policy**

High-level coordination is essential to ensure that the best interests of the state are served rather than those of various government ministries and/or the private sector. Of equal importance is that governments provide sufficient funding to make sure that sea power activities can be realized. The central vehicle for national coordination is a national ocean policy.

Yet, while land issues tend to be considered in a comprehensive way within and among states, attention to ocean issues tends to remain ad hoc and dispersed. The oceans are a relatively homogeneous medium shared by all nations who wish to use them, and many uses conflict with others. For these reasons addressing ocean problems by reaction rather than by thoughtful planning is wasteful—in terms of resources, missed opportunities, and misunderstandings among states.

Almost all major national and international issues more often than not have some sea power aspects, most of which concern multiple uses of the sea (e.g., by the navy, merchant marine, fisheries). An effective national ocean policy would permit the thoughtful integration of ocean issues into the business of statesmanship. But this simple concept of relating ocean policy to foreign policy seems to have eluded the leadership and parliaments of most states.

About the only clear example of contemporary centralized planning and direction of national ocean interests is the People’s Republic of China, a phenomenon that is less than three decades old. China has not been a great sea power since the global voyages of Admiral He, but the country’s commitment will certainly lead to a more effective, competitive exercise of sea power in a world where such planning is the exception.

For an analogous understanding of the situation, consider what US relations with other nations might be like if they were conducted entirely by the Department of State without coordination with other departments, Congress, and private entities. The result would be a vastly deficient foreign policy. Yet this is the situation in uses of the sea today. It is a matter of some concern that the dozen or so major maritime powers fail to recognize the liabilities in not dealing with ocean issues in an organized way.

What’s needed are general principles to guide a coherent, practical national plan for the oceans. Table 1 presents the national values, related ocean interests, and issues that illustrate why an integrated national ocean plan is vital for maritime nations that wish to exercise their inherent sea power rights.

Almost all major maritime nations have established some form of ocean policy framework, though activity within those frameworks varies widely. Some plans are “paper-intense,” with “fair words but few deeds,” while others have resulted in institutional changes with clear outcomes.

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**Addressing ocean problems by reaction rather than by thoughtful planning is wasteful—in terms of resources, missed opportunities, and misunderstandings among states.**

One key to success is the government level of program oversight: The closer to the top, the better the chance of success. For example, in Korea and Canada the ocean agencies are headed by a minister of the government, so ocean issues “have a seat at the high table” in governance decisions. In contrast, US national ocean policy developments are a story of nearly a half-century of plans, policies, and ultimate failure to act.

**50-Year Survey of US Ocean Policy**

The first major US effort to improve the government’s coordination and development for the national ocean interest was a two-year study (1967–69) by the US Commission on Marine Science, Engineering, and Resources (the Stratton Commission). The study resulted in the
TABLE 1 US national values, interests, and issues in uses of the world ocean

<table>
<thead>
<tr>
<th>National values</th>
<th>Related ocean interests</th>
<th>Issues</th>
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| Well-being (security) | 1. National security  
2. Viable national ocean policy  
3. Global leadership | 1. Serious national commitment to the oceans  
2. Adequate funding  
3. Adequate naval forces |
| Influence (national presence) | 1. Naval forces  
2. Viable merchant marine  
3. Resource development and production of living and nonliving resources  
4. Ongoing UN Law of the Sea issues and revisions | 1. Rights of use for passage, exploration, and exploitation  
2. Trade and security agreements  
3. Enforcement of rights  
4. UN Law of the Sea treaty accession  
5. Ocean conservation leadership |
| Respect (nationalism) | 1. Operative national ocean policy  
2. Naval forces in both quality and quantity | 1. National organization for ocean activities  
2. Development of a viable national ocean policy |
| Wealth (power) | 1. Greater capital investments in ocean-related industries  
2. Resource exploitation  
3. Marine transportation | 1. Marine-related infrastructure rebuilding and upgrading  
2. Leadership in marine pollution mitigation  
3. UN Law of the Sea treaty accession  
4. Science and technology transfer |
| Knowledge (science) | 1. Significantly greater investments in ocean sciences  
2. Increased ocean engineering training at graduate and undergraduate levels | 1. Freedom of scientific research in World Ocean  
2. Serious national commitment to the oceans  
3. International scientific cooperation |
| Skill (technology) | 1. Ocean engineering  
2. Marine engineering  
3. Trained personnel | 1. Serious national commitment to the oceans  
2. Marine pollution  
3. Investments of private capital |
| Rectitude | 1. Enlightened self-interest in ocean activities  
2. Enlightened leadership in UN Law of the Sea activities | 1. Serious national commitment to the oceans  
2. UN Law of the Sea treaty accession  
3. Maintenance of preeminence as a sea power for world stability |
| Kinship (altruism) | Assistance programs for developing coastal states | 1. Science and technology transfer to developing coastal states  
2. Resource sharing |

10-volume *Our Nation and the Sea*, which still offers much guidance for the coordination and support of the nation’s ocean programs. One major recommendation was the creation of a National Oceanic and Atmospheric Agency [sic]; NOAA was established in 1970.

But very few of the commission’s many other recommendations were adopted, and some of those initially adopted were later cancelled. An example is the National Advisory Committee on Oceans and Atmosphere (NACOA), established in 1971 and made up of experts appointed by the president with the concurrence of Congress. Studies conducted by NACOA were provided directly to the president and Congress without the intervention of any other agency. The committee provided high-level and welcome advice to the leadership of the nation, but lack of interest and budget issues resulted in NACOA’s termination in 1986.

Some frustrated ocean policy experts today (humorously) suggest that most of the Stratton Report would be valid now by simply changing the dates on the original.

In 2000 the president created the US Commission on National Ocean Policy to conduct a wide-ranging study of ways the nation could better develop and govern its ocean interests. At the same time, the privately funded Pew Oceans Commission undertook a similar effort.

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Both studies used the Stratton Commission’s work as a reference. The two final reports in 2005 were the basis for the Joint Ocean Commission Initiative that continues to serve as an advisory group.

In 2010 the president created the first official US ocean policy. It was intended to deal with ocean matters in a holistic way, interactively involving state, regional, and local governments. In many ways it was a national consensus plan. But the Congress was of the opposite political party and there was little the president could get done other than by executive order.

This all changed again in 2018 when the next presidential administration revoked the existing national ocean policy plan and issued its own. The new plan favors the extractive industries, especially offshore oil and gas production. The former plan balanced ocean conservation with sustainable resource development; that balance is missing from the new ocean plan, which hardly mentions conservation—including major concerns such as plastics in the ocean, ocean acidification, and sea level rise.

Actually, it is not the contents of an ocean policy but rather the policymaking mechanism that determines success. In Congress, ocean affairs are scattered among several committees (more so in the House than the Senate). Given the current combination of an uninterested presidential administration, 12 federal departments with ocean-related responsibilities,2 and the lack of a legislative home in Congress, it is very unlikely that any acceptable ocean policy will be implemented and funded. In addition, for over two decades the Senate has not voted its “advice and consent” approval for the United States to sign the United Nations Convention on the Law of the Sea (box 1). This means the nation will continue to have greatly reduced influence in the global shaping of a broad spectrum of ocean activities.

Historically the United States has been a major sea power. With a unified ocean policy framework in place, there would be a more productive national effort in the World Ocean.

The Way Ahead

A major role of government is to invest in far horizon activities that are either necessary for national security or not feasible for private enterprise. Oceanography is big science and requires an extensive and expensive infrastructure. It requires a certain level of effort and cannot be done on the cheap.

Various experts have estimated that only 10–15 percent of the World Ocean has been fully explored, yet there is no sense of urgency to organize a massive international effort to explore the rest. Considering the enormous costs in time and treasure (billions of dollars) for this global exploration, no one nation can do it all. The United States should be a leader in the effort but it is excluded from many opportunities (e.g., by not being a signatory to the UN Law of the Sea treaty). And at a time when there are stated national plans to return to the Moon and land humans on Mars, one has to ask, Shouldn’t we be doing our own planet first?

A fully funded national ocean initiative that recognizes the magnitude of the task must remain a goal in the hope of a better situation in the future. Those of us in the ocean community must persevere, although the history of the past five decades suggests that this may remain a distant dream.

Acknowledgment

The author thanks Bridge Managing Editor Cameron Fletcher for a superb job of editing and helping to shape this contribution.

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2 For example, NASA is a major sponsor of ocean sciences as they relate to its space missions and in 1989 started a program called Mission to Planet Earth. While it has done excellent scientific work with Earth remote sensing, this should be just one element of a national ocean program.
The United States cannot afford to be surprised by the oceans that surround the country and make it a world maritime power.

America’s Ocean Observations: A Perspective

Paul G. Gaffney II

America is the greatest maritime nation, a nation whose place in the middle of the global ocean system has enabled prosperous trade and a unique security situation. Yet that ocean system is still largely unexplored, undersurveyed, and sparsely observed. A world power unavoidably dependent on the ocean still does not understand the oceans’ full range of opportunities and dangers.

This paper concerns exploration, surveys, and observations: collecting measurements (data) to equally advance commercial, security, conservation, and science decision making. Along the way, I offer points to consider for future endeavors.

Nearly Two Centuries Preparing

“The US Ex Ex,” a creation of Congress (PL 24-24), a voyage of ocean discovery 175 years ago, was a deliberate step by a tentative nation with an eye on becoming a world power. A six Navy ship flotilla, with 346 military and civilian scientists, was charged to explore the vast Pacific, north and south. Called “The US Exploring Expedition,” it sought to discover the natural characteristics of the Pacific, extend US presence by connecting to new peoples, and collect data useful to US seaborne commerce and naval operations.

The notion to explore, survey, and observe was the happy result of a decade-long bureaucratic campaign involving both ends of Pennsylvania Avenue.
Lobbying for the expedition started in Congress and was endorsed by President John Quincy Adams, but finally got under way in the presidencies of Andrew Jackson and Martin Van Buren (delays were not new then, nor are they now) (Philbrick 2004). This national expedition brought together scientists, the Navy, culturists, those interested in foreign affairs, and the interests of commerce.

In the early 20th century, thanks in part to the invention of the sonic depth finder—the first fathometer and precursor to sonar, developed by the Naval Research Laboratory’s Harvey C. Hayes—others saw the opportunity to explore, survey, and observe again, together. Two geology professors (William H. Hobbs, University of Michigan, and William M. Davis, emeritus at Harvard), Navy physicist Hayes, Yale professor Herbert E. Gregory, and others thought of other joint surveys enabled by Navy ships and instruments. An initial Pacific exploratory survey occurred, but all wanted a larger and more enduring expedition plan. The then assistant secretary of the Navy, Theodore Roosevelt Jr. (son of the president), gave enthusiastic support for such campaigns. The idea had life in the early to mid-1920s, only to fall victim to budget pressures (Weir 2001). Nevertheless, its planning was another example of leaders in physical oceanography, geology, biology, national security, and commerce coming together to form an ocean campaign in which all would contribute and all would benefit.

The Navy continued to explore, survey, and observe to support its own missions, especially to gain and retain undersea superiority during World War II and the Cold War. Its investments gave birth to several of the great US academic oceanographic centers. Its deep ocean, acoustic-focused oceanography data collection efforts shifted to more complex shallower water research as the Cold War subsided and issues like mine warfare and coastal special operations took on new priorities. Today, there is a new oceanography and acoustic urgency spurred by the Chief of Naval Operations himself (Nicholas 2017).

In addition to the Navy, a number of federal entities as well as independent groups and business leaders, philanthropists, and venture capitalists have led efforts to enhance knowledge of the ocean.

The National Aeronautical and Space Administration (NASA) has provided continuous, global coverage of the ocean surface at many wavelengths and inferred information about the shape of the ocean bottom.

In 1970 Robert M. White, the first National Oceanic and Atmospheric Administration (NOAA) administrator (and subsequent NAE president), brought together fisheries, weather, charting, oceanography, ocean management, and much more in America’s lead federal ocean agency.

The first national ocean expedition brought together scientists, the Navy, culturists, those interested in foreign affairs, and the interests of commerce.

The Department of Interior’s Bureau of Ocean Energy Management (BOEM) and the US Geological Survey (USGS) have been significant gatherers of new information about the ocean, with principal interest in US resources in/near our exclusive economic zone (EEZ) and Outer Continental Shelf.

The National Science Foundation today is the largest federal investor in ocean science.

There are still more agencies with interest: the Army Corps of Engineers, the departments of Energy, Homeland Security (with its US Coast Guard), Transportation, and State and the National Institute of Environmental Health Sciences.

Now business leaders/philanthropists are stepping in, running ships that explore, survey, and observe. Just review the at-sea science accomplishments of the Schmidt family and Messrs. Dalio, Allen, and Cameron. Venture capitalists too are wetting their toes in ocean technologies. What a grand new complement to a historic government sponsorship monopoly in ocean science.

The Oceans Act of 2000 enabled a federal study on national ocean matters, authorizing the bipartisan US Commission on Ocean Policy (USCOP). The Pew Charitable Trusts chartered a parallel, but wholly independent, Pew Oceans Commission to study the same ocean issues. Rigorous efforts were made to ensure the independence of the two commissions. In the end, they validated each other by essentially recommending the same actions, with 80 percent or more congruity between the two reports (Pew Oceans Commission 2003; USCOP 2004).
The USCOP started with a simple philosophy: credible ocean information should inform policy. It is logical that its most prominent theme was the value of ocean observations—getting the data needed to understand the ocean so that reasonable policies could be made. Perhaps because it was written in Washington, its opening section laid out recommendations for a structure to bring more of the agencies together to do important work in the ocean. The ocean campaigns in America’s first two centuries had relied more on dazzling leadership and persistence.

Explore, Survey, and Observe

Oceanographers at sea explore, survey, and observe. These words, used separately, are found in federal budget documents. It is critical to bow to the line item descriptor if funding is expected, but it can set up silos that may not be entirely helpful. Generally, the ocean community uses the same talent, instruments, and processes to explore, to survey, or to observe.

This point was reflected in the work of one of the founders of the national ocean program, Roger Revelle. His incredibly influential role in the Navy in World War II and in helping to establish the principles of the Office of Naval Research at the end of the war showed the value of military and civilian cooperation in oceanography (Hlebica 2003).

Dr. Revelle used information gathered for either military use or civilian discovery, and he saw the value of exchanging that information. He could put together operational readings from a comprehensive, systematic survey with data collected from an exploration expedition with regular, repeated observations. When I spoke about him in 2009 for the 100th anniversary of his birth, I noted that he set an important example of the great value in any information source (military or civilian) of any type, from one-time, one-spot exploration to geographically complete baseline surveys to long-timeseries observations of places or cubes in the ocean.1

More recently another astute, but rather new student of the ocean, Ambassador Cameron Hume (2016), wrote a piece for the National Ocean Exploration Forum (NOEF) that captured this same idea. He warned that the public does not understand or need to understand the difference between exploration and observation.

America has the second largest EEZ (after France): these submerged land holdings—roughly 3 billion acres—are equivalent in surface area to the country’s land holdings. Yet, pick your ocean champion or alarmist, each will tell you very little has been characterized and even less observed over long time frames—less than 10 percent. Moreover, scientists would like to understand the whole ocean, not just that which contains American-owned resources.

Yes, too, absolutely, a globally ranging US Navy must understand the physical, geophysical, chemical, biological, and acoustical variability of the ocean, everywhere, all the time, to retain its undersea superiority.

In an enlightened decision, in the mid- to late 1990s, the Navy decided to make much of its previously unreleased ocean data available to civil researchers. It was done carefully with rigorous review to ensure that security would not be compromised. At the time, there was a national program called MEDEA whose principal task was to determine whether data collected or held by the national security community could be helpful to civilian scientists wrestling with global-scale environmental challenges (e.g., forest fire detection, pollution, climate variability). The Navy played a big role in MEDEA and even led an effort for US (Navy and NOAA) and Russian (Navy) Arctic data to be safely shared and merged into an atlas.

Point 1: It is a big US ocean, it is a bigger global ocean. There is too little baseline or regularly collected information, information so necessary to create understanding and policy. Let’s get data from any source, of any type, regardless of budget line item descriptor, regardless of the explorer’s, surveyor’s, or observer’s organizational affiliation. We cannot afford to be picky.

1 The centennial symposium, held March 6, 2009, was organized by Scripps Institution of Oceanography. Video of my remarks is available at https://ucsd.tv/search-details.aspx?showID=16410.
The American Campaign: New Efforts

NOEF 2016 and similar events started just a few years ago thanks to congressional direction in PL 111-11, which called for ocean explorers to come together regularly to better coordinate national tasks. The 2016 forum had two themes: campaign planning and doing more without absolute reliance on the few dedicated exploration vessels (Ausubel and Gaffney 2017).

The “US Ex Ex” and later expeditions showed that oceanographic campaigns could be organized and gain support. They had many partners, the data to be collected were for several reasons, different types of observations would be made, and joint advocacy and planning were apparent.

A slightly different kind of campaign, equally successful, was concocted in a little room at Woods Hole Oceanographic Institution (WHOI) in 1996. Fred Grassle, then of Rutgers University, and Jesse Ausubel, then of the Sloan Foundation and Rockefeller University, dreamed of a multiyear, multiparticipant, international and global census of life in the ocean, aptly called the Census of Marine Life (CoML; www.coml.org). Their dream came true during the decade 2000–10.

CoML was a coalition effort, a campaign. Many methods of discovering marine life were used, and ancillary oceanographic data from the waters surrounding the creatures were discovered. And, like Wilkes, Hayes, Hobbs, Revelle, and other predecessors, Ausubel and Grassle were indefatigable champions.

In 2017 NOAA (as principal funding sponsor and leader), the Ocean Exploration Trust (OET), the Navy, and the Schmidt Ocean Institute’s exploration vessel Falkor completed their first designed-from-scratch exploration campaign of parts of the central and eastern Pacific. The mission, which included deep sea mapping and close-up video inspection of specific deep ocean features (geological and living), gathered data for navigation safety, fisheries management, and archaeological priorities (Bell et al. 2017).

NOAA, with support for USGS and BOEM, has been planning and is currently executing an ocean exploration off the Southeast US coast. It will use various platforms including its own dedicated ocean exploration vessel, Okeanos Explorer. The campaign will map extensively and characterize ocean bottom geology and deep marine life habitats (USGS 2017).

The National Academies of Sciences, Engineering, and Medicine’s (NASEM) Gulf Research Program is making solicitations for a decadal campaign to better understand the physical processes of the Gulf Loop Current system to improve forecasting (NASEM 2018). Core funding will come from NASEM-held penalty monies from the Deepwater Horizon incident, not from federal agencies. But strong emphasis in the planning, and in successful proposals, will be on partnerships among principal investigators (when selected) and with federal agencies and international colleagues. The campaign will also feature spot exploration, systematic survey, and long-time-series observational components.

Point 2: It is a big ocean, insufficiently understood, expensively measured. Campaigns that bring together several funding or other types of sponsorship (ships, data centers, instruments, talent) and plan to gather many types of data during those expensive days at sea make sense. There are models for success. A charismatic leader helps.

The Future Is within Reach

Measurements are nonpartisan: they serve civil and military, research and operational needs. Observations are necessary in the 3 billion acres of US undersea “lands” and in the broad oceans that both connect and insulate America. Tools are at hand to do the work needed to advance knowledge of the oceans.

A recent Pacific mission gathers data for navigation safety, fisheries management, and archaeological priorities.

Measurements at Sea and Modeling

The observations collected must be analyzed, quality controlled, and archived. Their numerical values are then assimilated for insertion in models, which are continuously updated in their physics and their mathematical techniques.

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None of this is cheap, but most costly is going to sea or launching and operating an ocean instrument from space. Observing is so “not cheap” that the temptation exists to cut back on at-sea observing infrastructure, even autonomous observing. If the job is nearly done, then yes, cut back. But the job is not even 10 percent done.

If ocean science cheats on observations it becomes “cubicle science” carried out in 10' × 10' × 10' rooms on laptops where just a few bits of data can be inserted in a model and, voila, a new result. But is it a better result?

The ability to use sophisticated computation in the ocean sciences is as revolutionary in our lifetime as satellite observations, multibeam sonar, and autonomous vehicles. But the need to feed the beast has not diminished. The brilliant and exceptionally polite Walter Munk is quoted: “I’m a little worried about so many people doing computer experiments and losing their ability, the American leadership, in measurements at sea” (Galbraith 2015). The community and its sponsors must commit to a balanced measurement-model path.

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**Telepresence through digital communications yields more exposure to the sea, with only marginal new cost.**

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At the 2016 NOEF, it was noted that the distinction between exploration and observing is smudged. The forum championed campaigns and organized its working sessions around basin campaigns. As important was that ocean exploration and observing no longer had to be confined to dedicated single-purpose exploration vessels, of which there are very few (Ausubel and Gaffney 2017).

Fortunately, decades of federal investment in the great academic ocean centers spawned new autonomous devices, now commercialized.

- The Navy is purchasing over 100 gliders, from businesses, to deploy worldwide.
- Recently, WHOI discovered a deep wreck off Colombia with a completely autonomous bottom mapping/imaging vehicle (the Remus 6000).
- OET is complementing its exploration vessel Nautilus with a “flyaway” remotely operated vehicle (ROV) system that can be put on any moderately sized oceanographic vessel or offshore support ship, anywhere.

Such autonomy and agility increase the aperture to observe, without increasing the number of ships or people at sea.

Speaking of people at sea, OET and NOAA (through the Inner Space Center that it sponsors at University of Rhode Island) can connect the few oceanographers at sea in real time to the many scientists (and the public) ashore. This telepresence concept is well proven and will likely advance as commercial digital communications improve. It yields more exposure to the sea, with only marginal new cost.

**Point 3:** “Flyaway” ROV systems, gliders, autonomous undersea vehicles, and even autonomous surface vehicles enable more exploration, surveys, and observations with less reliance on classic, single-mission oceanographic ships. And the oceanographic ships that continue in service will have a much wider aperture.

**Passive Acoustics: An Oceanographic Tool, Again**

Navies always have focused on the relationship between the dynamic ocean and acoustic paths. Acoustic sensors are critical in undersea warfare. Navies have collected acoustic data in key parts of the world at many frequencies to understand the ambient soundscape. Some would argue that US Navy investment drooped at the end of the Cold War. This is a concern. Fortunately, several NAE acousticians are advising on the Navy’s acoustic future in the Navy’s Task Force Ocean study.

New acoustics challenges rose in the 1980s related to perceived impacts of manmade noise on marine life. Books and court transcripts chronicle the debate between those who worry about these perceived impacts and the scientists who use acoustic energy in geophysical investigations, industry that uses sound for initial prospecting or renewable energy site construction, and navies that emit sound to prevail in serious undersea “cat and mouse” games.

Passive acoustic sensing is not controversial. Some trade routes and enterprises have shifted since the Cold War. Should we not measure chronic sound changes associated with those shifts? Navies need to know if there are new ambient noise patterns. So too the diligent conservation community will be better off if armed
with facts about changing noise patterns: frequencies, source levels, and areas.

Long-time-series listening to a broad range of frequencies—near a reef system, for example—can help map baseline biodiversity and changes to that activity over time. This could be a complementary follow-on to the successful CoML.

Several experiments, like the current National Ocean Partnership Program–funded ADEON (Atlantic Deepwater Ecosystem Observatory Network) expedition, match up oceanographic conditions, passive acoustic recordings, and marine life observations (Miksis-Olds et al. 2018). Others use acoustics to gain rainfall-at-sea data. Wonderful.

Could oceanography sponsors devise similar experiments in key places over a very long time series? There are many moorings that could host passive sensors. The famous Navy underwater listening system, called SOSUS, at one time could have been part of such a plan. That opportunity has passed. Nevertheless, the Navy is using passive acoustics to create soundscapes in some training areas to make responsible decisions about sonar emissions when whales might be lurking. Biologists should soon find passive acoustics observation investments very useful as well.

**Point 4:** It is time to renew the nation’s commitment to passive acoustic sensing. It is a trusted tool, useful in new ways and in new places.

**Tracking Marine Life: eDNA**

Have whales returned to the “dirty” and “noisy” New York Harbor? That busy thoroughfare has oft been characterized as polluted and the New York–New Jersey maritime roads are bustling with ships putting noise in the water.

Yet progress has also been reported. Whales have been spotted under the George Washington Bridge. But what about other species interesting to recreational fishermen, commercial sea harvesters, and sentries who watch out for biodiversity or invasive species?

A new tool is available. From simple collections of water samples, observers can strain free-floating DNA, called environmental or extracellular DNA (eDNA). After it is analyzed and compared to an expanding DNA reference library one can say that X fish or Y marine mammal passed this way. This technique to spot a particularly delicious fish or a dreaded invasive species is useful to all kinds of decision makers as an alert. The work of Mark Stoeckle in and around New York City shows the possibilities in this new observation (Stoeckle et al. 2017). Perhaps whole volumes of water in interesting areas can be categorized, by season, poststorm, post–oil spill, post-anything.

Long-time-series listening to a broad range of frequencies can help map baseline biodiversity and changes over time.

Perhaps passive acoustic information and eDNA collections together can more assuredly determine how marine life and humanity can best live together . . . with fewer partisan or legal arguments. The Wildlife Conservation Society’s ocean biologists at the New York Aquarium, led by Howard Rosenbaum, are discussing such a campaign with regional colleagues.

**Point 5:** In laboratories from New York–New Jersey to Monterey Bay to Seattle to those abroad, marine eDNA is an emerging observation concept that can lead to a more complete understanding of the ocean.

**Conclusion**

America is unique in that she sits among the great oceans. Her prosperity and safety can be linked directly to the “greatest maritime nation” label. As populations migrate closer to the ocean edge and increasingly rely on the ocean, they will need to understand more than 10 percent of the surrounding wet space. Thus, the need to explore, survey, and observe grows. A day at sea is always expensive, but campaigning together is naturally synergistic. Opening the observing aperture to more offboard collection devices relieves the oceanographer of the burden of too few dedicated, special-purpose ships. Finally, new and renewed techniques are opportunities to understand that are not to be missed.

Measurements are nonpartisan: they serve civil and military, research and operational needs. The Trump Ocean Policy Executive Order (Trump 2018) has its advocates and critics, but its data-centric theme should
inspire explorers, surveyors, and observers to make their case to do more, now.

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References
Despite significant engineering challenges, technological advances are expanding the capabilities and coverage of ocean observatories around the world.

Ocean Observatories: An Engineering Challenge

Arthur B. Baggeroer, Bruce M. Howe, Peter N. Mikhalevsky, John Orcutt, and Henrik Schmidt

Observatories are important components for ocean research in most developed countries with a coastline. For many decades oceanographic institutions followed what one might term “expeditionary research”: ships went to places to investigate various ocean processes; observations were made and often sensors were deployed to record data for subsequent retrieval. But the observations were sparsely sampled temporally and spatially, leaving many...

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processes not well understood because of the transient and regional nature of the data. As Walter Munk put it, “The key change between the century of the Challenger and the last 50 years is adequate sampling. The key product of the Technology Revolution is sampling” and “the requirement of the sampling theorem” (NRC 2000, p. 49). Ocean observatories will continue to meet the ever increasing requirements for adequate sampling of the oceans.

**Introduction**

In the early 2000s oceanographers changed their paradigm to deploy what are collectively termed “observatories.” The resulting near-real-time series from ocean sensors coupled to shore with several methods of transmission enable monitoring of changes at all time scales, from daily to climatic and geodetic.

Ocean observatories enable monitoring of changes at all time scales, from daily to climatic and geodetic.

These observatories use sophisticated nodes with arrays attached for directional information for seismic, geodetic, and acoustic signals; current meters; sensors for conductivity (salinity), temperature, and depth (CTD), pH, oxygen, CO₂, and other chemicals; and biologic sensors such as fluorometers and bioacoustics. They also use autonomous underwater vehicles (AUVs) to sample the local water space. There are many opportunities for novel instrumentation.

Numerous questions remain about the role of the ocean in climate change; ways to quantify fluxes of heat, water, momentum, and gases at the air-sea interface; carbon cycling and the role of the ocean for CO₂ absorption; improved models of mixing and ocean circulation and for the crustal and deep Earth; transient biological activity such as algal blooms; ways to assess the health of the coastal ocean; monitoring of earthquakes and seismicity; and tracking of tsunami events, to name a few. Long-term time series from ocean observatories are providing answers to these questions.

**Challenges for Observatories**

The ocean environment presents many engineering challenges for deploying long-lasting, reliable observatories, compounded by high costs for equipment (Howe and McRae 2017). Sensors and cables must work in a corrosive environment often at the extreme pressures of the deep sea. Data transmission must choose between relatively low-bandwidth acoustic modems or higher-bandwidth cables. Currents can move or shake equipment. AUVs and their interfaces for energy and data exchange are complicated. Opportunities for repair once in place are limited. The data acquired from long-term and continuous monitoring are voluminous and require sophisticated software to disseminate to scientific, government, and industrial users. Following are major categories of challenges:

- **High pressures:** Hydrostatic pressure increases by 1 atmosphere for every 10 m of depth. The coastal ocean is nominally 100 m deep, implying nearly 150 lb/sq-ft of pressure, and the deep ocean is on average 4,000 m deep (6,000 lb/sq-ft of pressure). Housings for pressure vessels occasionally fail because of hydrostatic pressure. Penetrators into the interior of a vessel and O-rings for mating housing components are the bane of experimentalists because of failures. Their technology is expensive and requires skill to install.

- **Corrosion:** Seawater is very corrosive. Anything metal, especially stainless steel, corrodes over the long deployments expected of an observatory. Catalytic corrosion is accelerated between dissimilar metals, so identical materials must be used for metal structures, bolts, and screws. Some plastics do not fare well. Titanium, aluminum, and glass are most robust, but titanium is difficult to fabricate and expensive to acquire. Aluminum that is properly heat treated and anodized can last many years. Commercial glass balls are not reliable after several deployments and, for flotation, syntactic foam has become much more popular.

- **Fouling:** Any equipment in the upper water column can rapidly accumulate fouling as both animals and plants attach themselves. Antifouling paints have a finite lifetime, so eventually equipment accumulates large masses that interfere with moving parts and propulsion units.
• **Fishing, trawling, and vandalism:** The ocean is shared by many users. Fishing gear damages equipment and destroys moorings. Trawling rips cables off the seafloor even though seafloor packages are designed to be trawl-resistant. Vandalism is common in some areas because of the perception that equipment is valuable and can be sold.

• **Electronics:** Ground loops associated with AC power supplies are notorious because of the opportunities for seawater groundings. These shorts to ground are often very difficult to find and the chances increase with the number of subsystems connected. Ground loops can be very damaging to sensitive, high-impedance electronics such as sensor preamplifiers.

• **Calibrations:** Oceanographic research relies on the ability to compare amplitudes and phases from sensor outputs to (1) detect changes over space and time or (2) combine signals to create an array for gains against noise and determine directions by spatial processing, or beamforming. Calibration errors and/or sensor drift degrade these abilities, especially for long-term climate and geodetic measurements.

• **Opportunity costs:** Oceanographic equipment is typically deployed by ships at remote locations with per-day costs of $50,000 or more. These ships also are tightly scheduled, so there is often little funding or time for academic budgets to support costly deployment delays or to return to fix a faulty installation.

Notwithstanding the challenges, ocean observatories are largely effective in gathering myriad data through both cabled and moored systems, using autonomous equipment and new technologies for sensors and communications.

**Cabled Ocean Systems**

Cabled ocean systems have a long history and a future rich in possibilities. Because they can be quite expensive and maintenance of the myriad instruments is challenging, the number of future national systems is likely to be limited (a system under development in China is the only one we are aware of). Multinational systems are more likely. Capability ranges from broad trans-ocean coverage with simple sensors to systems that add multiple nodes along the route (as in the Arctic, where costs are justified by societal, military, and scientific needs to better understand this rapidly changing region of the world).

**History**

Early forays included sound surveillance array systems (SOSUS) and occasional single-node systems, the Acoustic Thermometry of Ocean Climate (ATOC) network, and the hydroacoustic stations of the Comprehensive Test Ban Treaty Organization (CTBTO). By the end of the 1990s the essential elements of what is considered a cabled observatory were proven: substantial power and bandwidth (optical fiber), plug-and-play capability for connecting instruments, and use of human-occupied vehicles (HOVs) or remotely operated vehicles (ROVs) for service. By 2010 regional-scale multinode, high-power, and high-bandwidth systems were in operation. Sensor network infrastructure has been developed, with secondary nodes, extension cables and laying capability, and cable-connected moorings with deep and shallow water column profilers.

Beginning in the 1950s

SOSUS was probably the first cabled ocean “observatory,” providing the United States with acoustic surveillance of Russian submarines beginning in the 1950s. Early sites were near shore with hydrophones individually wired back to shore in large-diameter armored cables with limited bandwidth.

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**Seawater is very corrosive. Anything metal corrodes over the long deployments expected of an observatory.**

The deployment and repair of these cables led to the creation of special cable-laying ships. Subsequent systems used thinner coaxial cables with multiplexed cable telemetry and were deployed at sites much farther offshore, usually taking advantage of opportunistic bathymetry to place the arrays at the desired depths. The end of the Cold War led to the abandonment of many SOSUS nodes, but a smaller SOSUS system using fiber-optic cables continued with data telemetry from the hydrophones. Bandwidths and channel counts are no longer issues.

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1 A notable development failure is for AUV docking stations to facilitate the spatial extension of fixed cabled systems; this is being rectified, as discussed below.
Important takeaways from SOSUS are that (1) cabled systems and their infrastructure are expensive and (2) it enabled much of the technology for cabled systems since the research community could not have afforded the technology development.

**Since the 1990s**

In 1993 the ATOC project cabled two acoustic sources to shore, one off Kauai (figure 1) and one off California (Pioneer Seamount). Navy SOSUS receivers and autonomous vertical line arrays were used as receivers. The intent was to determine large-scale ocean temperature changes by measuring changes in travel times (dividing known distances between sources and receivers by travel time gives sound speed, which is proportional to temperature changes) (ATOC Consortium 1998; Dushaw et al. 2009).

In 1996 the CTBTO began establishing an international monitoring system (IMS), with six cabled-to-shore hydroacoustic stations (Lawrence 1999). The installation of some of these was extremely challenging; the one at Crozet Island in the Antarctic Circumpolar Current was only finally (reliably) installed in 2017 (Haralabas et al. 2017). The IMS is the first truly international, global, real-time ocean (acoustic) observing network with (nominally) open data. As these systems near the end of their projected 25-year design life, the CTBTO is planning upgrades, with the expectation that attributes of scientific cabled systems (e.g., additional instrumentation with plug-and-play capability) will be incorporated (Zampolli et al. 2017), to better interpret local acoustic conditions and serve the ocean and Earth observing communities.

The first Scientific Uses of Submarine Cables (SSC) conference was held in 1990 in Honolulu; US-Japan collaboration in the use of out-of-service telecom cables was the focus for more than a decade.

In 1996 Fred Duennebier, a pioneer of cabled ocean observatories, installed the Hawaii Undersea Geo-physical Observatory on the active Lō‘ihi Seamount volcano just south of the Big Island. This was a key proof of concept for ocean observatories, with substantial power (5 kW), fiber-optic communications, and (homemade) electro-optical underwater mateable connectors; the multiport node was serviceable by HOV/ROV (Duennebier et al. 2002). The system worked for 6 months before the cable to shore failed from abrasion (this was not unexpected; an armored cable could not be afforded to run over the lava along the cable route).

In 1998 the US Hawaii-2 Observatory (H2O) was installed (Butler et al. 2000) and holds the record for the deepest observatory, at 5,000 m. The ALOHA Cabled Observatory project began in 2002, based on the work of Duennebier and colleagues (Howe et al. 2012). In 2007 a proof module was connected to a section of the optical fiber cable at Station ALOHA, 100 km north of Oahu (Duennebier et al. 2012), and in 2011 an 8-port node and instruments were attached, with several ROV service visits (Howe 2014; Howe et al. 2015). While the primary infrastructure and a core set of instruments have worked since installation, a number of other instruments have failed, likely because of cables
and connectors. Given limited ROV access and time, addressing the problems is challenging. To our knowledge, this is the last reuse of a retired cable; sponsoring agencies prefer to invest in local/regional purpose-built cable systems.

In 2009 Barbara Romanowicz installed the cabled Monterey [Bay] Ocean Bottom Broadband Observatory, with an attachment to the Monterey Bay Aquarium Research Institute’s Monterey Accelerated Research System (MARS) cable, funded by the National Science Foundation (NSF). The system continues to operate. Scripps installed a seafloor seismograph on the cable, as part of the Ocean Observatories Initiative (OOI), to test the new Advanced Message Queueing Protocol for transferring observatory data. The network functioned reliably (except briefly when a backhoe ashore severed the communications cable).

Seismic Studies

For some of these systems, the primary mission is seismic and tsunami early warning. A significant tsunami was recorded based on data from an open server operated by the Incorporated Research Institutions for Seismology (Thomson et al. 2011). The most comprehensive seafloor cabled observatory for early warning is the Dense Ocean Floor Network System for Earthquakes and Tsunamis (DONET) (Nakano et al. 2013), installed in 2010 offshore Japan. DONET2 was completed in 2016, and now 50 DONET stations are deployed in the Nankai trough west of Japan (Kaneda 2014; Kawaguchi et al. 2015).

DONET consists of two independent ring systems each about 400 km long with five 8-port nodes. Each node has four local observatories on 10 km extension cables with seismic and ocean sensors, can provide 500 W (using constant current power), and includes a triaxial broadband seismometer and triaxial strong-motion accelerometer. All signals are digitized at 200 Hz with 24-bit resolution. The lifetime is anticipated to be 20–30 years. Seismometers are typically buried in caissons. A special 10 km small diameter (6 mm) cable-laying capability was developed to connect local observatories to the primary nodes.

After the March 2011 Tohoku earthquake, the Japanese government commissioned the S-net system. An in-line system was designed in 6 months, with seismic sensors in an extended-length repeater housing laid in a continuous fashion. Six independent systems, with 200 sensor locations, have been laid off the east coast of Japan, completed in 2015 (Kanazawa et al. 2016).

In 1988 John Delaney began advocating a cable system on the Juan de Fuca Plate off the Washington coast to study life in the extreme environments of hot vents, volcanoes, and subduction zones (Delaney et al. 1988). The 1998 NEPTUNE project led to VENUS in the Salish Sea, MARS, NEPTUNE Canada offshore Vancouver, and the OOI Regional Cabled Array off Washington/Oregon.2 They represent a vision of what might be accomplished with large amounts of subsea power, high bandwidth, precise timing, and essential elements of the sensor network infrastructure (e.g., extension cables, moorings, profilers, AUVs) (figure 2).

Power Systems

It was quickly realized that starting small was prudent. The first low-voltage (400 V) VENUS nodes in shallow water were installed in 2000; MARS, funded in 2002, was finally installed and operational in late 2008. It was the first node with ~10 kW, 1 Gbps, and 1 μs timing accuracy, with 8 ports at 908 m water depth. It has been used as an instrument testbed and for local science.

Cabled in situ ocean infrastructure provides undersea power and communications for year-round, real-time monitoring and data collection.

A significant technical development that differentiated these systems from previous ones was the use of a constant voltage (CV) power system (commonly used on land) vs. a constant current (CC) system (used in all other submarine cable systems); both use direct current with one conductor and seawater return. The CV system provides up to twice the power of a CC system and

2 NEPTUNE = Northeast Pacific Time-Series Undersea Networked Experiments; VENUS = Victoria Experimental Network under the Sea.
enables a mesh structure that may improve resiliency in subsea networks (Harris and Duennebier 2002). However, it will collapse with any shunt (short to ground) fault in the system, whereas the CC system can continue operation; this may be useful or even essential if the primary purpose of the system is seismic and tsunami early warning (where the high power of a CV system is less important). A new high-voltage power supply was subsequently developed (Howe et al. 2002) and used in MARS (Howe et al. 2006) and NEPTUNE Canada.

As these systems evolved, the nodes shrank in mass and volume, simplifying deployment and service. The design and servicing of the sensor network infrastructure and instrument packages is highly dependent on the ROV used and the tooling associated with it (e.g., small cable laying, through-frame heavy lift capability).

**Future Cabled Systems**

The integration of geophysical sensors in future commercial submarine telecommunications cable systems may provide early warning of earthquake and tsunami events and expand understanding of the ocean’s role in Earth’s climate. Today’s cables include repeaters that amplify the signal every 50–100 km and could be a home for smart sensors for oceanographic measurements; these “smart cables” could eventually provide global coverage at a fraction of the cost of dedicated systems (Howe and Panayotou 2017; You 2010) (figure 3).

**Smart Cables Joint Task Force**

The Smart Cables Joint Task Force (JTF) is a partnership of three UN agencies3 and science, telecommunications, and government stakeholders worldwide. It is working with manufacturers to develop prototype sensor suites (for bottom pressure, acceleration, and temperature) that can be included in cable repeaters without affecting the telecommunications (Barnes et al. 2016; Butler 2012; Butler et al. 2014). South Pacific island nations are particularly suited to host initial systems: they have high tsunami and earthquake risk, access to development bank funding, and significant government involvement for connecting communities.

Submarine telecommunications systems are optimized for high-capacity data transmission over long distances.

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3 The International Telecommunication Union (ITU), Intergovernmental Oceanographic Commission of the UN Educational, Scientific and Cultural Organization (UNESCO/IIOC), and World Meteorological Organization (WMO).
and routinely achieve operating lives of 15–25 years without internal faults or failures. These systems comprise pressure housings (incorporated in the cable at intervals of 60–150 km), optical fiber amplifiers, simple power supply circuits, and little else. Modification—to incorporate temperature, pressure, and acceleration sensors and deliver communications and power to them with negligible impact on the repeaters’ primary telecommunications functions—presents certain engineering challenges.

To guarantee complete separation of telecom and science systems, a separate (less expensive) fiber pair with ethernet regenerators could be used for science communications, and power transferred to the (necessarily) external pressure and temperature sensors via a short optical fiber with laser and photocell at respective ends (with no galvanic electrical penetration of the pressure case), providing the necessary 15 kV isolation (Lentz and Howe 2018).

Arctic Cabled Observatory

The Arctic Ocean is both uniquely important and suited for in situ cabled ocean observing systems. Although the Arctic is rapidly progressing toward ice-free conditions in the summer, it will continue to be ice covered in the winter, making satellite coverage and surfacing for GPS and communications very difficult if not impossible. Cabled in situ ocean infrastructure provides undersea power and communications for year-round, real-time monitoring and data collection from instrumented moorings and underwater vehicles. It also supports the implementation of multipurpose acoustic networks for passive monitoring of ambient sound (ice, seismic, biologic, anthropogenic), active remote sensing (thermometry, tomography), underwater communications, and navigation for autonomous vehicles and floats (Mikhalevsky et al. 2015). This is in direct analogy with the use of the Global Navigation System of Systems for many similar purposes beyond navigation.

The reduction of ice cover makes the Arctic Ocean more accessible for shipping, tourism, oil and gas exploration, mineral extraction, fishing, and search and rescue, all of which raise complex geopolitical and economic issues and will affect the environment in ways that are impossible to predict. In situ ocean, terrestrial, and atmospheric observations will be needed to show these changes, identify impacts, and inform strategies among nations to protect and manage the uses and resources of this vulnerable environment.

Trans-Arctic acoustic thermometry was among the first measurements of the influx of warm salty Atlantic water (AW) in the Arctic Ocean in 1994 (Bold et al. 2001; Mikhalevsky et al. 1999). It showed an increase in the average AW maximum of ~0.4°C relative to Arctic Ocean climatology (EWG 1997), confirmed by submarine and icebreaker transects, demonstrating the feasibility and value of this method of active acoustic remote sensing. The experiment was repeated in 1998–99 (Mikhalevsky and Gavrilov 2001;
Mikhalevsky et al. 2001) and an additional ~0.5°C was measured as well as evidence of a warm pulse of AW entering the Arctic from Fram Strait (Gavrilov and Mikhalevsky 2002).

The Coordinated Arctic Acoustic Thermometry Experiment will be conducted with an acoustic source deployed on the ice as part of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC) cluster next to the research vessel (RV) Polarstern, which will be frozen in the ice and drift across the Nansen Basin in the Arctic Ocean to Fram Strait. A moored source will be deployed in the Canadian Basin along the acoustic section, where fixed receiver moorings will receive signals from both the fixed and drifting sources and provide year-long time series of a large swath of the Arctic Ocean and along the trans-Arctic section for 25 years after the first measurements (Sagen et al. 2018).

The Arctic Watch program envisions a trans-Arctic cable that will instrument a large portion of the Arctic Ocean and provide for continuous real-time in situ observations, including support for multipurpose acoustic networks. It will be useful to consider a system that combines telecommunications, distributed simple robust sensors, and a small number of science observatory nodes. Such a system spanning the Arctic from Norway to Japan is being proposed (figure 4). The science component is a significant cost (because of the nodes and the scale), but commensurate with the scientific need to observe the Arctic Ocean given its climatic importance (Moritz et al. 1990; Polyakov et al. 2017). (A significant portion of the system is in the North Pacific, with equally relevant climate and tsunami warning drivers.) Such a system can provide a fiber pair (15 Tb) dedicated to scientific research, “science telecom” both between land points and from the ocean floor, a handful of branch units supporting “science observatories/nodes” (to add/drop wavelengths), and simple sensors (pressure, temperature, and acceleration) deployed along the cable every 60–100 km on the 10,000 km route (a quarter of Earth’s circumference). Telecom branches to landing sites can also support science and may facilitate more nodes/power and spatial diversity off the trunk cable route.

To support the additional power requirements and ensure separation of telecom and science, a dual conductor cable will likely be required. The nodes will support vertical water column profilers, AUV docking stations, and long-range acoustic tomography/navigation/communications equipment; all of these will extend the sampling footprint of the entire network throughout the basin and under the ice. The incremental cost for the science portion of such a system will be on the order of a “small” OOI, but with several countries involved the cost can be bearable, especially in this region of extreme science interest and need.
Moored Observatories

For moored observatories, suspended above the seabed on cables and buoyed by floats, the design of the cable and buoys is an engineering challenge. A very taut, stiff cable requires a lot of flotation and can be prone to vibration/strumming; but a loose, compliant cable leads to a large “watch” circle as the surface module is pushed by tidal currents. The high-stress environment from high surface waves requires isolation systems that can withstand large forces (e.g., from “snap” loading, whereby a taut line is suddenly stressed). The continuous wave action causes fatigue. Finally, cathodic currents as the result of dissimilar metals and biofouling of equipment near the surface are often failure points.

TOGA

The decade-long Tropical Ocean Global Atmosphere (TOGA) construction program (1985–94) focused on El Niño/Southern Oscillation (ENSO) in the equatorial Pacific (McPhaden et al. 2010). El Niño and La Niña are major climate signals, and TOGA supported research for forecasting the ENSO warm water (El Niño) and cold water (La Niña) mass oscillations with nearly 70 autonomous temperature line system (ATLAS) moorings arranged on north/south lines crossing the equator from Indonesia to South America. The moorings have temperature and depth sensors down to 700 m and meteorological sensors mounted on a toroidal buoy. The data were transmitted to users by the Argos satellite system and supplemented with data from drifting buoys, near-shore tide gauges, and TOPEX/Poseidon, the European Space Agency Remote Sensing Satellite (ERS-1), and US Department of Defense satellites, plus ships of opportunity. TOGA (now known as the TAO array) demonstrated the value of long time-series data for oceanography and climate. Arrays in the Indian Ocean (RAMA) and the Atlantic (PIRATA) are also providing ongoing data for climate studies.

Ocean Observatory Initiative

The OOI was a major NSF effort supporting the concept of ocean observatories (Delaney and Kelley 2015; Smith et al. 2018). The regional cabled array components, NEPTUNE and VENUS, are described above. The moored components were systems of coastal and deepwater global arrays, with several moorings primarily to obtain directional information. OOI goals were sustained measurements over 25 years with (1) real-time (or near-real-time) availability; (2) two-way communication links for control; (3) ports, power, and bandwidth for expandable instrumentation; and (4) adaptive sampling for episodic events such as earthquakes, eruptions, and phytoplankton blooms.

Coastal Arrays: Endurance and Pioneer

The Endurance Array comprises two lines off the coasts of Washington and Oregon, deployed by the University of Oregon and moored inshore (~30 m), shelf (~100 m), and offshore (600 m) water. Each array has a surface buoy, one of several profiler moorings, and a “multifunction” mooring anchor. The surface buoys have a complete set of meteorological instruments for monitoring solar radiation, near-surface water temperature and salinity, surface wave directionality, near-surface currents, and momentum and buoyancy. They also have profilers that sample the water column by traveling up and down the mooring cable, with thermometers and chemical sensors for dissolved O2, pH, and optical properties. An acoustic Doppler current profiler (ADCP), which measures currents by backscattering from suspended particulates, is located above the maximum profiler excursion depth. These are supplemented by a fleet of buoyancy-driven gliders and on-station Wave Gliders (by Liquid Robotics/Boeing). Sampling rates cover the range appropriate for the processes studied, and the data are transmitted inductively on the mooring cable by satellite to shore or by a fiber link to the cabled array. Wind turbines and solar panels charge batteries to provide power.

The reduction of Arctic ice cover will affect the environment in ways that are impossible to predict. In situ observations will be needed to show these changes.

The Endurance Array works with the NEPTUNE/VENUS cabled observatory to measure coastal anomalies from ENSO, the Pacific Decadal Oscillation, the
wind-driven up-/downwelling caused by the Columbia River, hypoxic and anoxic events, algal blooms, and ocean acidification.

The Pioneer Array, on the shelf break off New England, has an instrumentation suite similar to the Endurance Array, with ten mooring locations over a 9 km × 47 km area from 95 to 450 m deep. These fixed moorings are supplemented by six coastal and two profiling gliders that run a preset track to interpolate the mooring observations and sample eddies of the Gulf Stream.

Global Arrays: Irminger Sea, Station Papa

Four deepwater global arrays were planned for OOI. The Irminger Sea Station is southeast of Greenland and Station Papa is west of Canada. Two others—in the Southern Ocean (planned west of southernmost Chile) and the Argentine Basin (southeast of Rio de Janeiro)—were deployed and recovered, but programatically terminated because of budgetary issues.

Global arrays need to be able to operate in very high winds and waves, so the engineering challenges for long-term survivability are great.

The global arrays need to be able to operate in very high winds and waves, so the engineering challenges for long-term survivability are great. Each array has a triangle of global/surface moorings separated by approximately 10 water depths (nominally 40 km). Each triangle has redundant meteorological systems, a covariance flux system, and sensors for wave spectra, irradiance, air-sea \( \text{pCO}_2 \), dissolved \( \text{O}_2 \), nitrate, fluorescence, salinity, and temperature. Each array has a CTD profiler that samples the water column. Additionally, CTDs and ADCPs are deployed in the upper water column down to 1,500 m. Inductive coupling on the mooring cable provides communications (by internet linked by Iridium) from the profilers and instruments. Energy is provided by wind turbines and solar panels charging lead acid batteries.

There are three goals for these arrays: (1) observations of the full water column and sea surface; (2) sampling of physical, biological, and biogeochemical variables; and (3) sampling of eddy scale variability. The triangular geometry enables directional analysis of mesoscale variability.

Ice-Tethered Profilers

While there is the hope for an Arctic Ocean cabled system, there is now no long-term observatory capability in this critical ocean. The semipermanent Ice-Tethered Profiler (ITP) from the Woods Hole Oceanographic Institution (WHOI) measures ice drift and samples the upper water column using profiler buoys installed by operations of opportunity (Toole et al. 2006). Nearly 100 ITPs have been deployed by drifting ice stations, icebreakers, aircraft, and other means such as submarines; locations vary since they are dependent on the field programs. Most ITPs start out drifting in the Beaufort Gyre of the western Arctic or in the Transpolar Drift of the eastern Arctic; almost all either exit the Arctic into the north Atlantic or are destroyed by ice activity.

Each ITP has a GPS and a profiler. Every 4 hours the profiler measures CTD and \( \text{O}_2 \) on the upward excursion from a depth of 750 m. The data are transmitted to WHOI through the Iridium satellite system and, after being edited for quality, posted on the internet. Recent measurements of the horizontal velocity of the profiler as it ascends the mooring line have provided the first synoptic data of Arctic Ocean processes such as ice rheology, currents, eddies, halocline formation, and water mass intrusions. Combined with satellite observations they have yielded new insights about Arctic oceanography.

Sensors

To make reliable measurements over long periods, ocean sensors must be free of drift over time and the clocks used to record data must be highly accurate. We illustrate selected sensor challenges and solutions.

The Wendy Schmidt Ocean Health XPRIZE competition offered $2 million in prizes to inspire accurate, durable, and affordable pH sensors for the study of ocean acidification. Two prizes were awarded, for accuracy and affordability.

Global ocean acidification is increasing, but spatial and temporal measurements are challenging given the relatively small yearly changes. The same problems arise
with other ocean observables such as temperature and salinity. The ARGO program deals with the stability problem over the >5-year deployment of each float by using sensors uniformly manufactured to detailed specifications, often from a single provider. (The use of sensors that differed from the specifications has led to anomalies in measurements.)

Timing is difficult in the deep ocean beyond the reach of GPS, especially the measurement of travel times between widely separated acoustic sources and ATOC receivers. If the time is known accurately, the travel time of signals over hundreds and thousands of kilometers can be determined over decades to provide an accurate measure of ocean warming. But over large distances, say 1,000 km, 1 m°C results in a 2 millisecond change in travel time. Temperature changes can be inferred by travel time changes only if clocks are stable and accurate.

Acoustic thermometry measurements require an error of less than 1 ms during a year, or $1.32 \times 10^{-10}$. A solution did seem to be in hand with new relatively low power Chip Scale Atomic Clock (CSAC) technology. The manufacturer had claimed an error of $3E-10$ s per month, but over longer periods of time the accuracy degenerated to unacceptable levels. While this is an improvement over previous clocks, it is still necessary to use a rubidium oscillator (using significant power) that checks the clock frequency at prescribed intervals (Worcester et al. 1985). This combination—the rubidium oscillator turned on and off with a very low duty cycle and the CSAC running continuously—can provide times accurate to a ms over the course of a year. As frequencies of interest decrease, the accuracy required also decreases; for example, the Global Seismic Network (GSN) requires an accuracy of 10 ms over a 2-year period (1.59E-10) using GPS. But seafloor GSN stations (or other instruments) do not have the advantage of connecting to GPS to determine time. Thus, the use of atomic clocks is critical in the oceans.

An ocean geodetic measurement that requires in situ correction involves seafloor pressure. The goal is to use accurate pressure measurements at the seafloor to measure ocean thickness that could be attributed to sea level rise due to melting land ice, or the depression of the seafloor due to plate tectonic movement.

Realizing that commercial quartz pressure gauges drift slowly over time with either sign, Sasagawa and colleagues (2016) designed an instrument that calibrates pressure gauges at the seafloor using deadweight testers, precision weights on a piston-cylinder assembly, to measure drift over time. Commercial quartz pressure gauges drift slowly over time with typical rates of 20–30 cm/yr. For more than a year, calibration sessions on the Juan de Fuca Ridge were repeated 22 times. Each session required approximately 20 min, with 12 repetitions to improve the statistics of the estimate. The pressure drift corrections provided a consistent record of uplift for both instruments. In another recent technical development, to measure the drift (offset vs. time) the pressure sensor is switched occasionally between the external water to internal air in the instrument case, with the latter pressure measured by a barometer. Initial results show drifts of ~1 mm/yr that can be compared with ~3.2 mm/year for globally averaged sea level rise (Wilcock et al. 2017).

If time is known accurately, the travel time of signals over thousands of kilometers can provide an accurate measure of ocean warming.

Seafloor geodetic measurements associated with plate tectonics can be measured without drift through GPS-A (A for “acoustic”; Chadwell and Spiess 2008). Accurate measurements of ship position can be transferred to a geodetic/acoustic monument on the seafloor. The initial result in measuring the velocity of the Juan de Fuca Plate with respect to North America is $63.6 \pm 3.6$ mm/a to the southeast ($67.2^\circ \pm 7.9^\circ$). Chadwell and Spiess (2008) substituted a Wave Glider autonomous surface vehicle (ASV) for the ship, launched from the shoreline to the monument to make the necessary measurements. The technique has been adopted in Japan to augment DONET’s seismic measurements.

Accurate seismic measurements on the seafloor can be made over a very broad spectral band. Triaxial broadband seismic measurement extends from $10^{-4}$ to 50 Hz with a 360 s natural period mass; 24-bit digitizers have been used to measure displacements as small as 1 nm, the size of the C60 Buckyball molecule. A new seismometer measures mass displacements in seismometers using laser interferometry with an accuracy of a femtometer ($10^{-15}$ m), the size of a proton (Zumberge et al. 2018).
There are no electronics involved in the measurement, unlike the very broadband systems discussed above. Nevertheless, considerable computing power is required to track the interferometric fringes as the masses move. The Laser Interferometer Gravitational-Wave Observatory (LIGO) similarly detects gravity waves in space-time; eventually it will be possible to make such high-bandwidth measurements on the seafloor. Pressure measurements using differential pressure gauges extend from the tides ($10^{-5}$ Hz) to at least 50 Hz.

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**Observatories at the seafloor need to communicate with “offboard” sensors and AUVs that are not connected by either electrical or fiber-optical cables.**

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**Communications**

Communications for observatories were a challenge until the availability of satellites such as the Argos and Iridium systems. Even now links to deep-sea observatories can be problematic. We divide systems into three categories: cabled, moored, and drifting.

- **Fixed systems connected to shore by cables:** The most notable of these systems are DONET, OOI, and Ocean Networks Canada, whose system design includes wide-bandwidth, multichannel communications.

- **Moored systems on an anchored tether:** These can have two forms: (1) a vertical line array of sensors sharing a cable to a central module that periodically surfaces for a data dump to a satellite system or (2) a module that has only a surface expression and is designed for wave stresses. In some installations, a surface extension (e.g., Wave Glider) may maintain station above a seafloor observatory, forming a “virtual” tethered system with satellite communications.

- **Drifting systems:** These are floats deployed either to set depths in the ocean (e.g., 2,000 m) or on the ocean or ice surface. They drift with the currents and periodically surface to report their data usually by a satellite link. They have been robust and provided sparse but widespread sampling of the CTD and dissolved oxygen levels of the ocean interior. They are expendable and originally lasted 4 years; plans exist to extend their lifetime to 6 years and their use to the deep ocean. By far the most successful and important are Argo floats (see Fu and Roemmich 2018 in this issue).

In the Arctic Ocean the ITP is a hybrid of all three categories (Toole et al. 2006).

Observatories at the seafloor need to communicate with “offboard” sensors and AUVs that are not connected by either electrical or fiber-optical cables. The two modalities are acoustics (“acomms”) or more recently optics. Acomms operate at 1–15 kHz depending on the range desired and power available; bit rates typically range from 100 bps (bits per second) for very long range links to 10 kbps for near-line-of-sight ones. Modern communication modulations and coding have led to low error probabilities, but there are often outages due to propagation variability. The WHOI Micromodem (Freitag et al. 2005) uses frequency-hopped (Hedy Lamarr, US Patent 2292387A, 1941), frequency shift keying modulation, but other methods (orthogonal frequency division modulation, turbo coded) are being tested. In most applications these systems have not been bidirectional. For the Scripps seafloor seismic system in deep water, the modem efficiency is highly reliable (Berger et al. 2016).

Optical links have been tested (Farr et al. 2016), and ranges up to 100 m and bit rates of 10–20 Mbps in clear dark water have been claimed. These systems use hemispherical LED sources, photomultiplier receivers, and time-division-multiplexed bidirectional links. Another approach involves a narrow beam laser and sensitive single photon detectors based on transmissions from the Moon. Rates close to 1 Gbps at 150 m have been tested (Hamilton et al. 2017). The technology challenge is to keep the laser pointed amid sensor platform motion and ocean turbulence.

Once data are at the surface there are several methods for transmission to users and for users to command observatory operations. We classify these as satellite or radio frequency systems. The former include Argos, Iridium, and FleetBroadband (Inmarsat). An Argos platform transmitter sends a message (up to 256 bits) to a satellite in near-polar, sun-synchronized orbit; the message is downlinked to a receiver site and sent to processing centers in either the United States or France, from which it is made available on the internet.
The Iridium low Earth orbit (LEO) constellation of about 66 satellites is a very popular means for transmitting data. The system operates in the L-band (1616–1626.5 MHz) and has 240 channels, each providing 2.4 kbps with a 5 W uplink power. The low power and approximately 10 cm form factor of the transmitter make these satellites very convenient for many oceanographic applications. Importantly, Iridium enables connectivity in polar latitudes.

FleetBroadband uses three geosynchronous satellites and can provide up to 432 kbps (depending on the size of the antenna). The fastest rates, using 50 W for uplink power, are appropriate for large buoys. The geostationary orbits limit their use in polar latitudes.

If an observatory is close to shore, several non-commercial technologies are available, including cell phones. These ad hoc systems use both the high-frequency spectrum, with ground-based propagation, and very high frequency, with sonobuoy technology developed by the US Navy. Scripps Institution of Oceanography pioneered the provision of internet to the Academic Research Fleet with support from ONR. Ships, which are often used to install, maintain, and retrieve observation systems, themselves now serve as mobile observatories, continuously returning data of interest to shore in near real time.

The HiSeasNet project, launched in 2002, provides internet access to ships at sea in the University-National Oceanographic Laboratory System (UNOLS) fleet over satellite, at 21.5 Mbps speeds from shore to ship and 1.5 Mbps ship to shore. With the growth and expansion of research and communications technologies it is mission critical that HiSeasNet provide uninterrupted internet access with sufficient bandwidth for scientific teams at sea to support research and communications with shore-based scientists and educators. Initially implemented on global C- and Ku-band channels, these systems use geosynchronous satellites such as the Intelsat network. After nearly 16 years of service, for the early adopter ships of HiSeasNet the lifecycle replacement of key systems has begun, with new equipment to promote effective system maintenance and management and simplify operations for both shipboard and shore-side technicians. Scientific parties will experience more uniform, higher-bandwidth network access across all UNOLS vessels.

The installation on NSF’s ice-strengthened RV Sikuliaq has maintained communications as far north as 75°N, where the geostationary satellite is very close to the horizon. The Sikuliaq must move around ice coverage to reach targets near the pole, and satellite imagery access is essential for daily cruise planning.

The bandwidths cited above are much smaller than normally available through university or home connections (e.g., >100 Mbps), making data rates painfully slow for shipboard users. Scripps is planning experiments with small satellites ("CubeSats") to significantly increase bandwidth and decrease costs. The shipboard antennas for LEO and MEO (medium Earth orbit) satellite systems are compact, flat synthetic aperture systems that do not require a large, expensive steerable antenna on board. Gbps bandwidths are already available and will continue to grow. In addition, the miniaturization of antennae will soon support communications with ASVs.

**Uninterrupted internet access with sufficient bandwidth is critical for scientific teams at sea to support research and communications with shore-based scientists and educators.**

**AUVs and ASVs**

Oceanographic research has traditionally relied on the use of ships at sea for sampling as well as instrument deployment and recovery. Many scientific problems will continue to require the use of ships, but to contain costs, continuing research will require the use of battery-dependent AUVs and ASVs that draw on wave or wind energy for propulsion and solar power for instrumentation. The costs for construction and operation of autonomous vehicles are substantially less than for surface ships or submarines.

Acoustic modems enable the transfer of data to and from deep seafloor sensor packages to an ASV (Berger et al. 2016), which connects to the Iridium satellite constellation for transmittal to laboratories ashore and thence to an open repository for scientific community access. Future systems may take advantage of small
satellites to enhance data rates and reduce costs. Blue-green light can be used for transferring data much more rapidly, but the range between such modems is very limited, necessitating additional vehicles for data transfer (Farr et al. 2016) (figure 5).

**Operational Paradigms**

Ocean monitoring and observation systems can be significantly enhanced by autonomous mobile platforms attached to the cabled observatory infrastructure. AUVs and ASVs can be launched by operators in response to episodic events detected by other sensing modalities. The persistence and sensing capabilities of such small platforms have improved dramatically, and AUVs and ASVs are now widely used in oceanographic research. Autonomous undersea sensing systems are also valuable for the detection and tracking of marine mammals and man-made sources of sound in the presence of ambient noise.

**Limitations of Human-Operated Platforms**

AUVs and, to a lesser extent, ASVs are almost entirely operated from staffed surface platforms, where operators program the vehicles for a specific sensing mission (e.g., measuring salinity, temperature, or bathymetry in a “lawnmower” survey pattern). This approach is of limited utility for AUVs responding to episodic events.

Because such events are often of limited extent in both time and space, traditional sampling strategies would spend most of their time in areas of quiescence with little useful information collected relative to events. This comes back to the fact that the ocean is undersampled both temporally and spatially.

Effective use of resources requires that platforms be redirected during a mission (e.g., to closely follow a plume or frontal boundary). But the ability of human operators to redirect autonomous assets in real time is severely constrained—even impossible—because of the bandwidth-limited and intermittent communications connectivity. Even with today’s advanced acoustic communications technology, the propagation physics of the ocean waveguide allows for the transmission of only a few hundred bytes per minute, with typical intermittency of tens of minutes over distances beyond a few kilometers, effectively prohibiting the human operator from redirecting an AUV mission in less than hours—the duration of a typical AUV mission anyway.

**Behavior-Based Platform**

For a powered AUV to be an effective part of an ocean observatory, the operational paradigm must rely on artificial intelligence (AI), to allow the AUV to respond to its sensors, and have a high level of onboard situational awareness. Without the possibility of transmitting large amounts of data back to the operators, the onboard autonomous function must be capable of completing the mission objective (i.e., sampling and characterizing an event) and of adapting to the environment in a manner that is optimal for the tactical situation and mission stage, without any human intervention or assistance. To achieve this, the AUV must be controlled by
a behavior-based autonomy system that does not require reprogramming or reconfiguration between missions or even mission phases to ensure optimal data collection. Such a system can autonomously respond to both predictable and unpredictable sensor events, requiring operator intervention only via simple, high-level status messages and commands for switching between mission modes.

“Nested autonomy” is such an operational paradigm, centered around a multiobjective optimization helm that makes constant decisions on speed, heading, and depth based on onboard situational awareness, sensor processing, and modeling and forecasting (Schmidt et al. 2016). The AUV can thus adapt its navigation and sensor modalities for completely autonomous detection, classification, localization, and tracking of episodic—usually unpredictable—events.

In addition, individual nodes may actually collaborate with others without a human operator in the loop (Schneider and Schmidt 2010). Network nodes within (at least occasional) acoustic communication range of each other may fuse their data with those obtained and broadcast by others in the vicinity. For example, two AUVs with acoustic arrays may track a marine mammal and collaboratively create an accurate localization by triangulation.

A typical acoustic or optical sensing system generates data at a rate of megabytes per second, which the acoustic communication capacity of the undersea environment is totally inadequate to transmit to operators. Therefore, in contrast to air- and land-based equivalents, data processing cannot be performed centrally but must be largely distributed to individual nodes. Similarly, real-time “tethered” control of underwater assets is impossible because of the latencies imposed by the use of occasionally surfacing gateway nodes. Consequently, real-time command and control decisions must be made locally on the nodes, in turn requiring that not only the data processing but also the analysis and interpretation, traditionally performed by human operators, be done on the nodes. This requires fully integrated sensing, modeling, and control equivalent to what is available on crewed submersibles in terms of intelligence and resources. In effect, the autonomy system must have “cloned” versions of all the domain experts required for achieving the mission objectives—an onboard “oceanographer,” “acoustician,” “communications engineer,” and, most importantly, “captain” who makes the final decision for any action based on input from the domain experts weighed against the objective of maintaining operational safety. This AI-based design is at the core of the nested autonomy paradigm (Benjamin et al. 2010).

AI-based autonomy also enables adaptive control of mobile nodes to take optimal advantage of an environmental and tactical situation through modeling and forecasting. For example, a mission to map internal waves on the continental shelf requires the AUV to focus its sensors on the main thermocline (Petillo and Schmidt 2014), which is not optimal for communication with a gateway buoy because of the strong downward refraction of the shallow water waveguide. For the vehicle to communicate its status and event reports to the operator, the helm must change depth while communicating, with minimal time away from the thermocline. To do this, the helm asks the onboard “acoustician,” through a high-fidelity embedded acoustic model, to provide a robust estimate for the optimal acoustic communication depth.

An AUV’s onboard function must be able to adapt to the environment in a manner that is optimal for the tactical situation and mission, without any human intervention.

Docking Stations and AUVs
An AUV downloads data from an ocean bottom seismometer (OBS) and uploads them to a Wave Glider surface gateway via the Iridium satellites. This can work well if the system operates within the radius of the so-called reliable acoustic path (near-vertical ray paths).

A central node and possibly several AUVs would provide local reconnaissance of the seafloor, physical oceanography data (e.g., CTD), and chemical and biological samples. This has been called “bits for joules”: an AUV would gather data and return to the observatory node where the data “bits” would be transferred and the AUV batteries recharged with “joules” from the node. The technology is considered well within reach.
but, aside from some tests with the LEO-15 observatory, docking stations remain a future possibility, largely because of concerns about a very expensive AUV being at risk and the need for a costly recovery operation.

For the docking process the AUV is guided to a cone by high-frequency acoustics, typically around 20 kHz, and/or optics (if the water is clear). The final homing uses directionality similar to split beams whereby up/down and port/starboard steering corrections align the vehicle with the cone axis, which has been aligned “upwind” of the current to provide control. Then either a waterproof mechanical connection or an inductive coupling transfers energy to recharge the AUV batteries. Data are downloaded either by a waterproof electrical connection or by optics. Other modalities have been suggested such as linking with a cable that is either moored or deployed from a surface buoy. Development of practical docking stations is under way—a 2 m AUV repeatedly docked at 100 m water depth in the South China Sea (Y. Chen, personal communication; Lin et al. 2018). It is expected that in the near future docking stations will be connected to cabled observatories, enabling both routine surveys and event response. This will finally force the severing of the bond between AUVs and their direct human operator (i.e., on a nearby ship).

**Summary Comments**

We have reviewed the engineering challenges for staging observatories to sample the oceans and their depths (on average 4, but sometimes 12, km deep). The need for data from these observatories is critical. The oceans are the greatest driver of the Earth’s climate since they store nearly 95 percent of its heat content. Virtually all commerce rides on them and the world’s data networks run beneath them. US national defense depends on control of the seas.

The technologies of observatories must often work at extreme pressures in a very corrosive and challenging environment and they push the state of practice. Observatories are complicated systems that draw on many disciplines of engineering and science—from hydrodynamics to digital communications, from metallurgy and corrosion to biological processes, from acoustics to optics, and more. Interdisciplinary capabilities are imperative.

Observatories for long-term observations complement the traditional expeditionary approach of ocean science to enhance understanding of the dynamics of planet Earth.

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**References**


New technologies and approaches are emerging to significantly expand high-resolution mapping of the ocean.

Mapping the World’s Oceans

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Larry A. Mayer

Mapping is fundamental for exploring, navigating, engineering, exploiting, protecting, and understanding the world. Through the great advances of modern remote sensing technology, it is now relatively simple to image and map the one-quarter of the earth’s surface that is readily visible to optical sensors on aircraft or satellites. A 5-year-old using Google Earth can interactively visualize almost any place on the Earth’s surface at a meter-scale resolution with just a few mouse clicks. Detailed three-dimensional depictions (Digital Terrain Models) of the Earth’s surface are easily downloadable and offer critical information for a range of applications. With the addition of multispectral satellite imagery, information derived from remote sensing enables characterization of the nature of the surface (e.g., forests, deserts, crops, etc.).

Unfortunately, the electromagnetic waves used for Earth imaging cannot penetrate more than a few tens of meters through seawater (depending on water clarity). Thus for the three-quarters of the Earth’s surface that lies beneath the oceans other sensors are necessary to map the ocean depths and to image subsurface ocean processes.

A Brief History of Ocean Mapping

For thousands of years, a weight at the end of a rope (or wire), called a lead line (figure 1 inset), was the only means to determine ocean depth,
measuring only a tiny spot of the seafloor. In shallow water (tens of meters), a lead line measurement was reasonably accurate and could be completed in a few minutes, but with increasing depth, accuracy decreased and the collection of a single depth measurement could take hours. Each sounding was positioned by the best technology of the day, typically celestial navigation, which, in general, has an accuracy of ±2 nautical miles (Defence Council 2011). The resulting charts showed sparsely spaced soundings with contours or isobaths representing lines of constant depth interpolated between the few measured soundings (figure 1). At best they were broad approximations of what might lie below.

Remarkably, the lead line was the primary tool to measure depth until the early 20th century, when the sinking of the Titanic led to early experiments with acoustic sources to detect objects in the ocean and, eventually, to the development of echo sounders (D’Amico and Pittinger 2009). Echo sounders generate an acoustic pulse that propagates from a transducer (typically magnetostrictive or piezoelectric materials) that oscillates when a voltage is applied to it.

Unlike electromagnetic waves, acoustic waves propagate easily in ocean waters. At frequencies of approximately 15 kHz or less, they can propagate the full range of ocean depths (>11,000 m), reflecting off the seafloor (due to the contrast in acoustic impedance between seawater and the seabed) and back to the echo sounder. If the speed of sound in seawater is known (nominally 1,500 m/sec and easily measurable), the two-way travel time of the acoustic pulse can be converted to an accurate measurement of depth.

Single beam echo sounders form a single beam of sound from the source. Their typical beam width is 15–30 degrees, resulting in an area of ensonification on the seafloor (the beam footprint) with a diameter between one half and one times the water depth (figure 2). Thus in 4,000 m of water, a typical single beam echo sounder would ensonify an area on the seafloor with a diameter of 2,000–4,000 m. The echo from the seafloor represents the shallowest point in the beam footprint but, with no angular resolution in the beam, its position can only be assumed to come from directly below the ship (figure 2). The resulting bathymetric information is thus a spatially averaged (over the scale of the beam footprint) representation of the true depth of the seafloor.

By the end of World War II single beam echo sounders had been improved to provide rapid, but laterally averaged, measurements of seafloor depths. By the end of the 20th century, the National Geophysical Data Center (now the National Center for Environmental Information, NCEI), a repository for global bathymetric data, had approximately 70 million single beam depth soundings, allowing the production of generalized maps depicting interpolated contours between sparse ship tracks to indicate bathymetric trends. Today the
NCEI database has more than 96 million single beam soundings.¹

Current Technologies
Toward the end of the 20th century two great advances were made in seafloor mapping: the development of techniques to use satellite altimetry to predict seafloor bathymetry and the evolution of multibeam sonar technology from classified military applications to the academic and commercial communities.

Satellite Altimetry
Bathymetry can be derived from satellite altimetry through the fact that the ocean surface deviates from mean sea level in response to the excess (seamounts) or absence (trenches) of mass created by deep-sea topography. Satellite altimeters measure the topography of the ocean surface and, by relating the altimeter measurements to real bathymetric measurements, Smith and Sandwell (1997) demonstrated an approach to predict depth measurements for the global ocean. The bathymetric maps produced by satellite altimetry were revolutionary, providing an unprecedented view of seafloor topography and tremendous insight into tectonic-scale processes. However, such maps are limited in achievable resolution (altimetry resolution is in bands from 20 km to 200 km, whereas interpolated maps are produced with pixel resolution of 1–12 km; Smith and Sandwell 1994, 1997) and fall far short of the resolution achievable with modern multibeam sonars.

Multibeam Echo Sounders
Unlike single beam sonars, multibeam sonars use two arrays, a transmitting array oriented in the direction of vessel transit (along-track) and a receiving array orthogonal to the transmit array (a Mills Cross or Mills T). The transmit array produces a fan-shaped acoustic pulse that ensonifies a swath of seafloor that is wide (typically 150°) in the across-track direction and very narrow (typically 1°) in the along-track direction. The receive array forms a number (up to several hundred) of indi-

¹ Brian Meyer, associate scientist, Cooperative Institute for Research in Environmental Science (CIRES), NCEI affiliate, personal communication by email, July 16, 2018.
individual beams that are narrow in the across-track direction (typically on the order of 1°) and a bit wider in the along-track direction. The result is the simultaneous high-resolution mapping of hundreds of small patches of the seafloor based on the intersection of the transmit and the receive beams, across the entire swath (figure 3).

Like all acoustic systems, multibeam sonars must balance the tradeoffs between propagation range (which decreases with increasing frequency due to higher attenuation at higher frequencies) and resolution (which increases with higher frequency due to shorter pulse lengths and increased bandwidth). Small, high-frequency (>400 kHz) systems with arrays of a few 10s of cm in length are capable of centimetric resolution of seafloor features but with propagation ranges of a few hundred meters or less. Large (many meters long) arrays operating at lower frequencies (~12 kHz) are capable of propagating to full ocean depth, but with lateral resolution of 10s to 100s of meters depending on water depth and sonar beam width (e.g., a 1° × 1° multibeam sonar would ensonify a 70 m diameter patch of seafloor in 4,000 m of water).

Despite these tradeoffs, the resolution achievable by multibeam sonars is significantly higher than that achievable by satellite altimetry or single beam sonars and, when combined with modern satellite navigation, has revolutionized the ability to map and image the seafloor (figure 4). The resolution, density, and coverage of multibeam data have offered new perspectives of seafloor topography that have yielded many insights into seafloor and ocean processes (e.g., sediment dynamics and the origin and creation of oceanic crust), led to new engineering applications (e.g., cable and pipeline surveys, offshore platform installations), improved navigation safety, enhanced maritime heritage studies, and enabled numerous national security applications.

Most multibeam sonars also simultaneously record the amplitude of the seafloor return that, when appropriately processed and georeferenced, produces an image of seafloor backscatter that can be related to the roughness or composition of the seafloor (figure 5). More recently, multibeam sonars have begun to collect information on scattering targets in the water column, with applications in fisheries science, physical oceanography, and most importantly the location and quantification of natural and man-made gas seeps (figure 5; Stranne et al. 2017; Weber et al. 2014).

While most multibeam sonars are deployed on surface vessels (typically low-frequency, deepwater systems on large vessels and high-resolution shallow water systems on small, near-shore vessels), small, high-resolution multibeam sonars can also be deployed on remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs). When operated close to the seafloor they are capable of producing very high (centimetric) resolution maps in deep water, though only over small areas and at very slow speeds.

How Much of the Seafloor Is Mapped?

How much of the ocean has been mapped with modern sonar technology?

The international General Bathymetric Chart of the Oceans (GEBCO) has, for more than 100 years,
been collecting and distributing publicly available bathymetric data for the world’s oceans (Hall 2006). The most recent GEBCO compilation (GEBCO_2014) is a gridded (approx. 1 × 1 km) product that incorporates single and multibeam sonar data on a backdrop of satellite altimetry (figure 6).

An evaluation of the GEBCO database shows that only 18 percent of all grid cells in the compilation contain any bathymetric data and only 9 percent contain modern multibeam sonar data (Weatherall et al. 2015). Thus at a 1 × 1 km scale, approximately 82 percent of the seafloor has never had a direct measurement of depth. The sparsity of high-resolution seafloor mapping data became painfully obvious during the search for Malaysia Airlines flight MH370; the existing bathymetric dataset was so inadequate that the searchers had to conduct surface ship–deployed
The BRIDGE

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multibeam sonar surveys in order to know what depth ratings were needed for the AUVs that were necessary to resolve the wreckage.

The Quest to “Fill the Gaps”

Recognizing the poor state of knowledge of ocean depths and the critical role of such knowledge in understanding and maintaining the planet, the Nippon Foundation–GEBCO Seabed 2030 Project has been established to facilitate efforts to promote the mapping of the entire deep sea floor by 2030 at a resolution higher than that of GEBCO_2014. The project has established target resolutions ranging from 100 × 100 m grid cells in depths up to 1,500 m to 800 × 800 m resolution for water depths of 5,750–11,000 m (Mayer et al. 2018).

The Seabed 2030 effort has set up regional data assembly and coordination centers whose short-term goal is to locate regional data not yet made available to global compilations and whose long-term goal is to coordinate and facilitate regional mapping efforts that will “fill the gaps.” A global data center will handle central coordination and production, establish data standards, and distribute global gridded products.

Using the new variable resolution grids, only 6 percent of the seafloor has been mapped by multibeam sonar. What would it take to map the entire seafloor with multibeam sonar? Excluding depths of less than 200 m (which represent only 7 percent of the global seafloor, are typically within the territorial waters and exclusive economic zones of coastal states, and are inefficient to map because of the depth-dependent coverage of multibeam sonar), it would take approximately 350 ship-years to map the 93 percent of the world’s seafloor deeper than 200 m using current multibeam sonar and surface ship technology (Mayer et al. 2018), at an estimated cost of $3–6 billion.

For context, what is the likelihood of spending billions of dollars to produce high-resolution maps of a planet? This has actually been done. The Moon and Mars have been mapped to much higher resolution (on the order of meters, in many cases) than the Earth’s seafloor. While the cost of individual planetary mapping missions has varied, there is no question that many billions of dollars have been spent over the years. This has been well-spent money—the information returned from these missions has greatly increased knowledge and
understanding of these celestial bodies. Why, then, the unwillingness to devote a similar level of expenditure to understand this planet?

**New Technologies**

New approaches and technologies may reduce the estimated cost of high-resolution mapping of the seafloor. With the widespread use of echo sounders on commercial and recreational vessels, the concept of “crowd sourcing” of bathymetric data is gaining momentum. Echo sounders do not have the resolution of multibeam sonars, but the large number of soundings by “the crowd” can increase the percentage of the seafloor mapped. Quality control is always an issue with crowd-sourced data, but efforts are under way to explore the feasibility of low-cost, “authoritative” echo sounders that are self-calibrating and offer data of known uncertainty. The jury is still out concerning the value of crowd-sourced data for global bathymetry, but in the simplest terms, something is probably better than nothing.

Given the vast areas of unmapped seafloor and the tradeoffs among resolution, propagation, and coverage, the biggest constraint in collecting global multibeam sonar mapping data is the cost associated with the relatively slow-moving surface survey vessels. There are limits to the speed at which multibeam sonar data can be collected (without degrading quality and/or leaving mapping gaps), and a vessel’s fuel costs go up significantly as its transit speed increases.

One approach to reduce costs is to use autonomous vessels for survey operations (Manda et al. 2015). While early efforts have focused on small vessels with shallow water mapping systems, the growing use of autonomy for larger vessels offers the possibility of developing an “autonomous mapping barge” (figure 7, upper). Such a vessel is ideally suited for a large multibeam sonar array and can carry huge supplies of fuel, be piloted remotely, and transmit data to a base station in real time. Such “telepresence” technology is already well established (Marlow et al. 2017) and will advance rapidly.

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in the years ahead. The multibeam barge can also be a platform for many other autonomous measurements (oceanographic, atmospheric, etc.). The estimated cost of operating such a platform would be one-half to one-third that of a staffed research vessel, and with a significantly lower cost of construction.

In addition, efforts are under way to mount a multibeam sonar on an autonomous sailing vessel; the viability of this method for the collection of oceanographic data over long periods (e.g., 6 months) has been demonstrated (Voosen 2018). The developers of these small “Saildrones” are working with a sonar manufacturer to install a deepwater multibeam system on a large (22 m) Saildrone (figure 7, lower). Remotely piloted and with a satellite link to transmit data to a control center, fleets of these vessels may be able to collect high-resolution multibeam sonar data in remote areas of the ocean in a very cost-effective way.

**The Moon and Mars have been mapped to much higher resolution than the Earth’s seafloor. Why the unwillingness to devote resources to understand this planet?**

While the approaches described above focus on reducing platform costs, innovations in the distribution of acoustic sensors (e.g., sparse arrays) may also be important in future mapping efforts.

**Conclusions**

Only 6–9 percent of the seafloor has had a direct measurement of depth at a scale needed to understand ocean processes, protect or exploit seafloor resources, or support engineering operations. With growing awareness of the ocean’s fundamental role in sustaining life, mediating climate, and supporting commerce, there is increasing interest in seeing the entire seafloor mapped at the scales needed to appropriately understand and manage ocean resources. Efforts involve both the search for existing data that are not yet publicly available and, most importantly, the organization of global and regional efforts to collect new high-resolution mapping data.

The costs of ocean mapping can be reduced through the use of “crowd-sourced” data and autonomous surface vessels that can be deployed for long periods in remote areas at a fraction of the cost of staffed research vessels. The goal of completely mapping the ocean’s seafloor and providing the critical geospatial context needed to address a plethora of ocean-related issues is achievable, but will require international collaboration, a long-term commitment, and the recognition that understanding Earth is worth the effort.

**References**


Sophisticated technological methods for acoustic imaging are enhancing knowledge and understanding of the world’s oceans.

Using Noise to Image the Ocean

William A. Kuperman

This article is about opportunities for using noise to image the ocean, its bottom, and objects in the water. I review aspects of ocean sound propagation, sources of ocean ambient noise, and some relevant signal processing to deal with the fluctuating, incoherent nature of noise. Then, the processing methods are applied to noise. Finally, potential opportunities and applications are discussed in the context of developing technology.

Background

In the atmosphere there are electromagnetic (EM) and sound waves for sensing, whereas the physics of seawater more or less limits the ocean environment to sound propagation. In the atmosphere, imaging in the optical regime is typically based on incoherent processing that takes advantage of refraction using lens-like devices. At lower frequencies used in communications, radar, TV, and the like, antennae take advantage of the coherence of the signals, providing both gain and directivity. In the ocean, the highest acoustic frequencies are attenuated and randomized by the irregular medium such that propagation is limited to very short ranges, whereas frequencies

1 The noise methods discussed have also been applied to a range of mechanical wave propagation, from earth (Sabra et al. 2005; Shapiro et al. 2005) and helioseismology (Duvall et al. 1993) to structural health monitoring (Tippmann et al. 2015) and even some medical imaging (Gallot et al. 2011; Sabra et al. 2007).
below, say, a few kilohertz can propagate to respectable distances. Even for signals not extinguished by attenuation, medium complexity diminishes their coherence.

At the lower frequencies, antennae, typically referred to as acoustic arrays, can coherently process signals at a level analogous to that of EM signals. For example, at the height of the Cold War, acoustic arrays (the sound surveillance system, known as SOSUS) were detecting very low frequency sounds (say, less than 100 Hz) emitted from submarines at distances of thousands of kilometers. The detections were possible because the signals after array processing exceeded the ocean noise background.

Because the extraction of signals of interest is limited by competing ambient noise, noise has, until recently, exclusively played the role of spoiler. An alternative to this nuisance role is to make noise the signal of interest.

**Ocean Acoustics**

**Propagation**

The ocean is an acoustic waveguide bounded above by air and below by the ocean bottom (figure 1a) (Jensen et al. 2011). The acoustic index of refraction, typically represented by the ocean sound speed, is mostly dependent on temperature and then depth and salinity. Aside from geometric loss (spherical spreading for short- and cylindrical spreading for long-range propagation), seawater attenuation is roughly proportional to frequency squared, thereby restricting long-range propagation to lower frequencies.

Acoustic propagation paths obey Snell’s law, which can be thought of as bending sound paths toward low-speed or away from high-speed regions. There are many types of paths, some interacting with the ocean boundaries and others totally contained in the ocean water column.

In the deep ocean, the upper water column is warmest at the surface and then cools with depth, producing a sound speed that decreases with depth; then, with increasing depth, pressure takes over and increases the sound speed. The result is a sound speed minimum at some intermediate depth referred to as the deep sound channel axis (figure 1b). This axis identifies the sound fixing and ranging (SOFAR) channel, which is near the surface in polar regions but gradually goes down to ~1,000 m at midlatitudes.

For example, the SOSUS arrays were placed at midlatitudes on the bottom topography intersecting the

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2 Unless otherwise indicated, figures are the result of federally funded research and hence not bound by private, assignable copyright.
The SOFAR channel. Since Snell's law dictates that sound emitted near the minimum sound speed axis will oscillate about that axis without undergoing any boundary scattering loss as it propagates, submarines hiding under the ice could be detected thousands of kilometers away. The effectiveness of these arrays decreased as submarines became quieter relative to ocean noise. In this case, the dominant source of low-frequency noise was shipping.

**Noise**

Just as incoherent optical “noise”—light—is used for seeing, the analogy in the ocean is referred to as acoustic daylight (Buckingham et al. 1992), and the acoustical analogue of a lens is used for short-range imaging.

Noise in the ocean is either man-made (e.g., from ships or other activities) or natural (e.g., from the ocean surface, seismicity, or biologics).

- Ship noise is dominant in regions where most long-range passive sonars operate (below 1,000 Hz). Not surprisingly, it is loudest in the frequency regimes where detections are mostly sought.

- Surface-generated noise, dependent on wind speed, occupies the higher frequency region. Noise from ocean surface activity, for example, emulates a diffuse sky.

- Seismic noise, extending considerably below 1 Hz, originates in the earth except for the microseismic region (≈0.1–0.3 Hz), whose source is nonlinear, coupling ocean wave activity with the ocean bottom.

- Ice noise originates from cracking, analogous to the acoustic emissions studied in structural health acoustics and the collision of ice floes. It is of particular interest in the context of global change.

All of these types of noise cover large frequency bands so that the relative absence of shipping (at one frequency) might be filled in by ice or surface noise. Figure 2 illustrates the distribution of shipping noise and of ocean surface wind speed that can be translated into noise levels using Wenz (1962) curves (Porter and Henderson 2013).
**Signal Processing Using Acoustic Arrays**

Common to all noise types is that their aggregate, either in total or by category, creates a mostly nonstationary, temporally incoherent input to an acoustic array. There are therefore various measures of noise complexity.

A Fourier decomposition of broadband noise would reveal that each frequency component has a random phase relation with respect to the other frequencies, resulting in a rather short temporal coherence. Further, the analogous spatial decomposition would reveal limited spatial coherence. These properties enable the extraction of coherent signal from noise fields by using a correlation time dictated by the space-time coherence.

The random nature of noise and scattered fields tends to suggest their limited utility. Nevertheless, it is possible to coherently extract information from noise. First a review of the simplest array processing is in order.

**Array Processing for Signal Gain over Noise**

Localizing a source or scatterer is the most basic form of imaging. An acoustic array (for simplicity, discussion is restricted to line arrays but the physics easily generalizes to three-dimensional arrays) of \( N \) elements sums the data from each element. The idea is that the signal is coherent and the noise is less coherent, so the signal adds up linearly whereas noise ideally adds up as a random walk. In terms of intensity, which is proportional to amplitude squared, the signal adds up as \( N^2 \) and the noise as \( N \), with the signal-to-noise ratio (SNR) then being \( N \), which in decibels is an array gain of \( 10 \log N \).

The fast Fourier transform (FFT) has made frequency domain processing extremely advantageous, so received data are segmented into time snapshots and transformed with the associated time-frequency resolution: longer snapshots have narrower frequency bins. In the frequency domain, arrays actually sum the received fields with an additional element-to-element phase factor that is equivalent to a delay in the time domain, both phase and delay corresponding to an arrival angle. For future reference, time delay beamforming can be accomplished by correlating signals between elements. The strongest coherent fields will show peaks at the angles of arrival on the array (with some sidelobe ambiguity associated with the array aperture and ocean physics).

The size of the array aperture determines its angular resolution, which is related to the aperture size measured in wavelengths. Further, the beamwidth is narrowest broadside to the array and widest at “endfire,” which is along the array axis or in the direction between the two receiver elements being cross-correlated (e.g., top of figure 3a). For a narrowband source that remains in a resolution cell (i.e., a single beam), long-time FFT processing results in a very narrow frequency bin, reducing noise while retaining the signal. The signal received from a moving source will appear to come from the same angle if it stays within the beam and otherwise will “spill” out to other beams. Hence, a long integration time for a source crossing beams lowers the SNR in a particular beam since the signal leaves while the noise remains. For studies of background noise, this long-time integration presents opportunities of building up noise and averaging down signal.

**Despite the random nature of noise and scattered fields, it is possible to coherently extract information from noise.**

Coherence is another processing limitation. The frequency components of broadband radiation that originate from a random process have a correlation time related to inverse bandwidth. Therefore, while a narrowband signal can be integrated over long times, a 1,000 Hz bandwidth random radiator has only a millisecond coherence time, thereby limiting the accumulation of coherent gain. This also impacts methods to use noise.

**Simple Examples**

A very simple example of array processing involves using one’s own ship noise reflected off the ocean bottom and received on the ship’s acoustic array to determine properties of the ocean bottom (Battle et al. 2004). Another is using information from the Automatic Identification System (AIS) that provides the location of all ships greater than 300 tons to 10-meter or better accuracy (Verlinden et al. 2018).

Localizing ships in complex coastal environments is often difficult because their acoustic signature is distorted through sound propagation. The combination of noise from ships and AIS information provides the learning data to track ships not included in the pre-
collected data. Ships have different source signatures, and correlation processing produces data that are independent of individual ship radiation characteristics. Further, with continuous shipping, the learning data can be updated to include space-time changes in the ocean environment that affect the received noise fields.

**Tomography**

Inversion for medium properties is the most general form of imaging in the sense that a radiating object or scatterer can also be considered part of the medium. In ocean acoustic tomography, active controlled sources ensonify the medium for inversion (Munk et al. 1995; Sabra et al. 2016; Sagen et al. 2016; Worcester 2001; Worcester et al. 2013). The process is analogous to, say, a medical CAT scan in which a multiple source-receiver configuration provides information over different paths undergoing different attenuation representative of the medium along the paths. Inversion then provides an attenuation map that can be related to specific medium properties.

In the ocean, though, time delays instead of attenuation associated with the different paths are used and the inversion yields a sound speed map that can be converted into ocean medium properties (figure 1). The ocean method requires precisely known signals emitted by accurately synchronized (~0.001 s) and accurately positioned (<1 m) sources relative to the receivers. The total processing stream for this type of imaging involves fusing acoustic data with ocean models, referred to as data assimilation, to obtain an image of the ocean. Though using noise to accomplish the latter processing sequence with precision is problematic, this is precisely the new frontier that is being crossed.

**Noise Processing: Correlation and Deconvolution**

Because of the random nature of the sources of noise, processing must rely on either correlation or deconvolution. The correlation of data from two receivers in which the same signal (random or not) passes through...
both (endfire) yields a peak at the delay time of the propagation between the two receivers. Otherwise the time delay is associated with direction and sound speed, which are ambiguous. The endfire time delay peaks are related to the transfer function between the two receivers and hence invertible for the sound speed.

In the deconvolution process, the signal is a convolution of source and transfer function. If the source function can be eliminated, the transfer function remains (Anderson et al. 2015). A method used in communications does the opposite, eliminating the transfer function to obtain the source function that is the message.

Examples of correlation and deconvolution methods applied to the noise problem are presented below.

**Correlation Processing**

Correlation processing between two receivers yields peaks at the time delays of components of the traveling noise, whose path traverses both receivers in either direction and is independent of the specific spectral structure of the emitter. Noise can arrive from all directions but the endfire beam is the broadest and long-term correlation processing results in peaks only for the endfire direction.

Peaks rigorously derived from the endfire beam (Lobkis and Weaver 2001; Snieder 2007) represent the two-way transfer function (also referred to as the time-domain Green’s function, TDGF), in which one receiver acts as a source and the other a receiver and vice versa. Peaks associated with the time delays emerge at a rate proportional to the square root of the time-bandwidth product. That is, both receivers gather in all the noise but the correlation that builds up of the coherent part is only from the paths that travel through both receivers; so the noise on the individual receivers can be thought of as the self-noise while the noise passing through both receivers is the “signal.” The broader the bandwidth and the longer the time the better the result. However, if the ocean medium changes over the time scale of the correlation, the time delays will vary and not build up. Thus there is a limitation of the signal processing time versus the ocean time scale. Methods are emerging for circumventing this limitation with array processing (Fried et al. 2008) and optimization that reduces the required correlation time (Woolfe et al. 2015b).

Results of ocean noise correlation processing applied to ocean acoustic data are illustrated in figure 3 (Roux et al. 2004). Random ship noise was cross-correlated between acoustic arrays converting, for example, a receiver on one of the arrays to a virtual source to produce a coherent traveling wavefront that passes through all the elements of the other array.

In another example, collective noise from croaking fish (Sciaenidae), which emit signals very much analogous to those of fireflies, was received and cross-correlated between elements of an array to determine some bottom layer properties (Fried et al. 2008). There were many subsequent experimental validations of this type of processing but the most practical was with the passive fathometer (Siderius et al. 2010; figure 4). Rather than receive a well-timed bottom echo from an active source,
surface-generated noise was decomposed by a vertical acoustic array into up-and-down-going beams, which were cross-correlated to yield time delays equivalent to those from an echo produced by an active source.

Another application of noise correlation processing took advantage of the fact that an asymmetric two-way TDGF senses flow to detect and measure currents (Godin et al. 2014).

Correlation-based thermometry (figure 5) with polar ice noise uses only the last arrival (Woolfe et al. 2015a), so only the temperature in the region of the sound channel axis is obtained rather than throughout the whole water column. Results compared favorably with the oceanographic point measurements obtained from Argo (Roemmich et al. 2015; also see Fu and Roemmich 2018 in this issue), indicating a temperature trend.
Deconvolution Processing

As mentioned above, the efficacy of noise correlation processing is dependent on the time interval of the processing relative to the ocean time scale of the medium fluctuations that affect propagation. Hence, at first glance, it is difficult to precisely determine peak arrival times necessary for multipath tomography. But as shown in figure 1c,d, the final arrival in the SOFAR channel is quite robust.

The next step would be to obtain multiple peaks corresponding to a more complete representation of the TDGF with multiple arrival times (figure 1c,d). The goal is to convert the noise from random sources such as moving ships to tomographically useful, synchronized, precisely located individual sources (as opposed to the results shown in figures 3–5, in which noise is collectively processed).

Because it is not likely that individual absolute position or time measurements will reach the required accuracy of active tomography, the deconvolution processing involves differences in space/time corresponding to the order of centimeter/microsecond required precision. AIS provides the location of ships to an accuracy of order meters. Though not enough for the near surgical requirements of tomography, AIS can be extremely valuable by limiting the search space when combined with differencing and deconvolution to precisely determine the transfer functions from source to receiver. The deconvolution requires the simultaneous multiple-path receptions that an acoustic array can provide and then takes advantage of the fact that the source function for that instant has to be the same for all received paths, thereby providing enough information to eliminate the instantaneous source function (Gemba et al. 2018).

Figure 6 shows the processing sequence of deconvolution noise tomography. Not only do ships have different spectra (example shown in figure 6a) at different speeds but these received spectra differ with range. The deconvolution process must produce TDGFs from different ships, ranges, and speeds that can be assimilated into a single dynamic ocean model. The input for the deconvolution is shown in figure 6b. Each array (orange dot) receives the noise field from a moving ship and after beamforming the acoustic paths are identified using basic AIS information. For a given “snapshot,” the beam output corresponding to the identified paths has to have the same random source
function. That information is enough to deconvolve the source function from the TDGF.

An example of TDGFs is shown in figure 6c, indicating four ray paths from the source to the array. The wavefronts are analogous to those in figure 3d, but the deconvolution here yields the one-way TDGF as opposed to the two-way TDGF that emerges from correlations. A sequence of snapshots together with a model (in the sense of the lower plot of figure 1d) would correspond to the paths illustrated in figure 6d. At this point, the noise data have been converted to tomographic source receiver data and the subsequent tomographic inversion would follow the already developed methodology of tomography.

The use for tomographic deconvolutions is in its infancy, but already there is experimental evidence of localizing acoustic elements of arrays to order centimeters using noise from passing ships, an important step in the required position accuracy for tomography. An experiment for actually doing the tomography from ships of opportunity has been recently completed and the data are under analysis in an Office of Naval Research—directed Defense Department Multiple University Research Initiative program entitled the Information Content of Ocean Noise.

The Future

Both natural and man-made sources of noise will remain or increase in abundance. As an important example, with changing climate, ice noise is expected to increase because of more cracking and collisions among ice floes—and will make it easier to monitor global change.

The physics of the imaging processes, including tomography and ocean model data assimilation, is quite advanced. Probably the greatest technology enablers (still to be developed) will enhance the distribution of acoustic sensors, fixed and/or mobile, that have available energy sources and communication capability to deliver the data. Opportunities for using global noise as illustrated in figure 2 will increase with the growing sophistication of computers, data analytics, and acoustic, oceanographic, and satellite sensing technology.

In a future inversion scenario, ship location from AIS and noise would be the input data together with acoustic data and other information. The final step of global internal ocean imaging would be based on rapidly developing methods of artificial intelligence and machine learning pioneered with intelligent imaging as the main goal.

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Sea level rise is an indicator of the extent of the warming of the Earth’s climate as well as a major threat to the world’s coastal zones. The rate of the rise of the global mean sea level has been accelerating since the Industrial Revolution, reaching over 3 mm/yr at present. New technologies developed over the past 25 years have enabled great strides in monitoring global sea level with both spaceborne and in situ sensors, revealing information that is useful for understanding the phenomenon and predicting its evolution.

Introduction

Over the geological history of Earth, sea level has varied by hundreds of meters as a result of tectonic and climatic processes. The current ice age cycle started about 3 million years ago, with a 100,000-year cycle in the past 1 million years primarily caused by fluctuation in the Earth’s orbit around the Sun. During the most recent glacial maximum 25,000 years ago, sea level was about 130 meters below the present level. During the deglaciation that began 20,000 years ago, sea level began rising rapidly at 1 cm/year until 7,000 years ago, when the rate stabilized to 0.2 mm/yr (Carlson and Clark

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In the 20th century, however, the rate rose tenfold to 2 mm/yr and in the past 20 years it accelerated to 3 mm/yr, a third of the rate during the maximum deglaciation (Church and White 2011).

**Causes and Impacts**

The recent rise of the global sea level is caused by thermal expansion from the warming of the ocean and the melting of ice on land. During the past 20 years the former has accounted for about one third of the rise and the latter about two thirds according to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; Church et al. 2013). Based on the high end of the projected warming of the planet in the coming decades (compared with the period of 1986–2005), the IPCC estimated the rise of the global mean sea level (GMSL) at 52–98 cm by 2100, with a rate of 8–16 mm/year during 2081–2100.

The rising GMSL has already significantly affected the 10 percent of the world’s population living at elevations lower than 10 m near the ocean. The threats to low-lying islands of the Maldives and the coastal zones of Bangladesh are well known. In New York City the last 7 percent of the storm surge from Hurricane Sandy affected 11.4 percent more people and 11.6 percent more housing units, and caused 24 percent more total property damage, than it would have without the sea level rise of the past 100 years (Leifert 2015). The higher sea level makes many coastal cities prone to flooding during high tides and increases the frequency of so-called nuisance floods (e.g., Kruel 2016).

**Evolution of Efforts to Measure Sea Level Rise**

Before the advent of satellite remote sensing and its global coverage, it was not straightforward to measure the GMSL using only tide gauges, whose sparse and uneven coverage resulted in unknown sampling errors in efforts to determine the GMSL. In the late 1960s the concept of using a radar altimeter on an Earth-orbiting satellite to measure sea surface height was developed, and the first such altimeter, launched in the 1970s, demonstrated space observations of sea level. Within two decades the accuracy and precision of satellite altimetry were sufficient to determine the GMSL and small changes in it.

Two other advances important to understanding changes in the GMSL emerged in the 1990s. One was the deployment of autonomous profiling floats in the ocean to measure the temperature and salinity of the water column globally through an international program called Argo. The technique enables determination of water density as a function of depth and its effects on changes in sea level. For example, rising temperature would raise sea level via thermal expansion.

The other development was the launch of satellites to measure Earth’s changing field of gravity resulting from the changing distribution of mass near the planet’s surface. This satellite mission, called GRACE (Gravity Recovery and Climate Experiment), has determined the contribution of changes in the mass of the water column to sea level change.

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**Hurricane Sandy caused 24 percent more total property damage than it would have without the sea level rise of the past 100 years.**

Together, satellite altimetry, Argo, and GRACE provide an observing system for determining changes in the global sea level and their causes: changes in water density and mass. The resulting information has revolutionized both the capability to monitor small signs of global sea level rise and understanding of the physical processes needed to project future changes.

**Satellite Altimetric Measurement of Sea Level Change**

The measurement configuration of satellite altimetry is illustrated in figure 1. A radar altimeter on an orbiting satellite, operating at microwave frequencies of 10–35 GHz, sends short pulses to the sea surface and receives the return signals, and the round-trip travel time is used to determine the distance between the satellite and sea surface. With the height of the satellite relative to Earth’s center of mass (~1,000 km) determined by the technology of precision orbit determination, it is possible to calculate the geocentric sea level (the height of sea surface relative to Earth’s center of mass).
The shape of the sea surface is dictated to a large extent by the variation of Earth’s gravity field at its surface, caused by the uneven structure and density of the lithosphere, the upper layer of solid earth. The relief of the sea surface is within a couple of meters of a surface of constant gravity, called the geoid, whose relief relative to the reference ellipsoid has a range of about 200 m. The deviation of the sea surface from the geoid is called the ocean dynamic topography.3

Early Efforts

The first spaceborne radar altimeter was aboard the Skylab missions in the early 1970s (Krishen 1975), followed by the series of the Geodetic Earth Orbiting Satellite (GEOS) missions (Stanley 1979) in the mid-1970s to refine the measurement to an accuracy necessary to determine the shape of the geoid to a few meters. Not until the launch of Seasat in 1978 (Born et al. 1979) was the accuracy of satellite altimetry sufficient—within a few centimeters—for measuring the variability of ocean surface topography; the uncertainty of the satellite’s radial height was about 1 m over scales of 10,000 km.

Motivated by the desire to determine the ocean general circulation at the scales of the ocean basin, a satellite mission called TOPEX/Poseidon (T/P) was developed jointly by NASA and the French space agency, CNES (Fu et al. 1994). Launched in 1992, T/P was able to measure the ocean dynamic topography and geocentric sea level to centimeter accuracy, representing a remarkable achievement in improving the capability of satellite altimetry by a factor of 100 in 25 years.4

Increased Accuracy

A series of satellite missions carrying radar altimeters has been on orbit since the 1990s, yielding a continuous record of global sea level and ocean dynamic topography. Although the early mission development was not focused on the GMSL, whose required accuracy was too daunting a task in the 1980s, the breakthrough enabled by T/P has made the GMSL a key objective of current altimetry missions.

A time series shows the change of the GMSL from 1993 to 2018 (figure 2; Nerem et al. 2018). The record is the result of extensive calibration and validation on four missions (T/P and its follow-on Jason series). The GMSL during this period is estimated at 3.1 ± 0.4 mm/yr (the uncertainty is largely from calibration against the global tide gauge network). Other studies have placed the uncertainty at 0.3–0.5 mm/yr (Ablain et al. 2017). Before satellite measurement, it was not possible to rigorously estimate the GMSL and its uncertainty.

How good is the current capability of determining the rate of GMSL rise? The rate of acceleration to reach 70 cm rise above today’s GMSL by 2100 (roughly the middle of the IPCC’s high-end projection) is ~0.1 mm/yr². The recent study by Nerem and colleagues (2018) concluded, with high statistical confidence, that acceleration of this magnitude—0.08 mm/yr²—is already observed in the present 25-year record of altimetric GMSL. This finding suggests that the current capability of monitoring the GMSL meets society’s needs for rigorous assessment of future threats of global sea level rise.

Argo Float Measurement of Heat-Induced Sea Level Change

The profiling float (figure 3) is a free-drifting and wholly autonomous ocean instrument developed by Davis

5 The horizontal gradient of the dynamic topography is proportional to the part of ocean surface circulation that is balanced by the Earth’s rotation (the Coriolis force). This flow component, the geostrophic circulation, is responsible for the large-scale transport of ocean mass and heat, providing a fundamental motivation for the development of satellite altimetry in addition to the determination of sea level.

4 The tremendous progress of satellite altimetry is described in Fu and Cazenave (2001) and Stammer and Cazenave (2018).
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and colleagues (2001) for research use during the 1990s World Ocean Circulation Experiment. The instruments adjust their buoyancy and hence their depth by pumping mineral oil between a reservoir in the float’s pressure case and an external bladder. Changes in the volume of a float by a few percent cause buoyancy variation sufficient to keep the float on the sea surface, make it neutrally buoyant at intermediate depths, or send it to the ocean bottom. A sensor package mounted on top of the float collects profile measurements of temperature, salinity, and pressure. The float cycles between the sea surface and a depth of 2,000 m every 10 days, transmitting its GPS position and profile data via Iridium satellites when it surfaces.

Before the development of profiling floats, subsurface ocean temperature data could be collected only when a ship was present or from fixed-point moorings. Resulting datasets were very sparse and irregular in space and time, with most data obtained in the Northern Hemisphere, near continents, and in summer. The profiling float was a revolutionary instrument for oceanography because it provides high-quality data anywhere, any time.

In 1997 an international group of scientists proposed the installation of a global array, named Argo, consisting of 3,300 profiling floats (Argo Science Team 1998). A primary motivation was to assess climate variability and change, including GMSL rise due to ocean warming. The first Argo floats were deployed in 1999; by 2007 there were over 3,000 distributed globally, and about

FIGURE 2 Time series of the (global) mean sea level (MSL) in mm from the TOPEX/Poseidon mission and its follow-ons: Jason-1, Jason-2, and Jason-3, 1993–2018. From University of Colorado (http://sealevel.colorado.edu).

FIGURE 3 A profiling float is deployed by RV Southern Surveyor. Photo by Alicia Navidad, CSIRO. Credit: Argo Program.
3,800 have been maintained for the past decade. Begun in 2006 as a multinational effort, Argo is sustained by national programs in more than 25 countries (figure 4). Recent advances in profiling float and sensor technologies now make it possible to sample to the ocean bottom at depths of up to 6,000 m (Deep Argo; Zilberman 2017) and to sample additional parameters such as dissolved oxygen, nitrate, pH, and biooptical properties (Biogeochemical Argo; Johnson et al. 2009). The global Argo array greatly increases the accuracy of the earlier estimates of thermosteric GMSL rise based on the sparse pre-Argo datasets.

The thermal expansion coefficient for seawater varies with temperature and pressure. The top 1,000 m of seawater at the equator, if warmed uniformly by 0.1°C, would expand in height by 1.8 cm, while at 60°S the expansion would be 0.8 cm. Sea-Bird electronic sensors on Argo floats measure temperature, salinity, and pressure with high accuracy (.002°C, .01 psu, and 0.1 percent respectively). Given the sensor accuracy and the fact that float-to-float differences are mostly random, errors in large-scale temperature variability are mainly due to the array’s spatial coverage (figure 4). That is, limited data coverage in the deep ocean and spatial inhomogeneity are the main source of error in thermosteric GMSL estimates. Deep ocean warming below Argo’s present depth limit of 2,000 m is estimated to account for 0.1 mm/yr to GMSL rise in 1993–2010 (Purkey and Johnson 2010), or about 10 percent of the 0–2,000 m GMSL thermosteric contribution, which was 1.0 ± 0.2 mm/yr in 2004–16 (Thompson et al. 2017).

The Argo program has produced over 12 years of global data, which are freely available via the internet (www.argo.net) in near real time and as research quality after 1 year. A monthly interpolated version (Roemmich and Gilson 2009) is used to estimate the trend in steric height of the sea surface relative to 2,000 decibars as a function of location (figure 5). The same calculation is made over the same time interval with satellite altimetric sea level data.
Global patterns of the trend in altimetric sea surface height and steric height are compared in figure 5. Two aspects of this comparison are evident. First, the global mean of the altimetric height trend (upper panel, 3.3 mm/yr) is greater than that of steric height (lower panel, 1.3 mm/yr), and this 2 mm/yr difference is attributable to mass (discussed below). Second, discounting the difference in global means, the pattern of regional variability in the altimetric and steric height trends is similar, indicating that the mass trend, while large, is more spatially uniform than the steric height trend.

Regional trends in steric height (figure 5) can be much larger than the global mean. These massive redistributions of warm ocean water are largely wind driven and can increase the rate of sea level rise regionally for years or longer; some regions of large steric sea level rise, such as along 40°S, are known to have multidecadal timescales (Roemmich et al. 2016). In other cases the warm anomalies represent interannual changes that appear trend-like in the 12-year time series; for exam-

5 Changes in global mean steric height due to salinity are too small to detect in the 12-year time series, but there are regional examples, particularly at high latitude where the impact of salinity on steric height is significant.
The large maximum in the eastern equatorial Pacific is attributable to a major El Niño episode in 2015–16. A longer Argo time series is needed for effective separation of interannual and decadal variability.

**GRACE Measurement of Mass-Induced Sea Level Change**

The original concept of determining the ocean circulation from space required not only satellite altimetry but also the measurement of the geoid for computing the ocean dynamic topography. After many variations of the design of a spaceborne gravity mission, the concept of GRACE emerged to measure the minute change of gravity experienced by two spacecraft on orbit tracking each other using a microwave link (NRC 1997). GRACE can determine not only the near surface gravity field of Earth but also its change with time.

**How GRACE Works**

To be sensitive to the spatial variability of Earth’s gravity associated with the structure and density of the upper layers of the solid earth, the two GRACE spacecraft, launched in 2002, were placed in a near-Earth orbit of ~500 km, 220 km apart (figure 6). GRACE measures a “biased range” between the two spacecraft by tracking the carrier phase of a K and Ka band microwave signal (Tapley et al. 2004). The bias is constant over long periods so that the range change is very accurately measured. The wavelength of the K/Ka signals is about 1 cm. Careful design and averaging over several seconds yield accuracy between 1 part per thousand and 1 per ten thousand of the wavelength, corresponding to a few microns in range every 5 seconds. The data are often processed as range rate, which is good to about 0.1 μm/sec for 5-second averages. Since the measurements are one way from each spacecraft, it is important to know the time of transmission and reception on each spacecraft and to be able to synchronize those to about 100 picoseconds. The accuracy of GRACE in measuring the change of gravity can be expressed as that associated with the mass of water of 1–2 cm thickness over a circle with a radius of 300 km (Landerer and Swenson 2012).

**Uses of GRACE Data**

The gravity measurement of GRACE enables determination of the change of mass over large ocean areas and, when integrated globally, GRACE data reveal the contributions of ice melt in the change of the GMSL.
shown in figure 7, the combination of the steric sea level change (caused by the change of ocean density), estimated from the Argo data, with the barystatic sea level change (caused by the change of ocean mass) matches the altimetry measurement of total sea level change fairly well. The synergy of the three measurement systems creates an opportunity for cross-validation of the difficult and important measurement of the GMSL, which is an indicator of both the extent of climate change and impacts on humans.

GRACE data have revealed the rate of the melting of ice sheets on Greenland and Antarctica (Velicogna 2009), whose potential massive breakup and melting are the primary sources of the looming threat of sea level rise. The fragile West Antarctic Ice Sheet holds enough water to raise the GMSL by 5 m, in contrast to the 0.5 m capacity of the warming of the ocean. Distribution of the melt water will be uneven geographically, because of changes both in Earth’s gravity due to the massive ice loss in the polar regions and in the ocean’s density and circulation due to climate change. The greatest magnitude is projected to account for 20 percent of the change of the GMSL (Slangen et al. 2012). Such variability in regional sea level change is of great concern in efforts to plan for coastal adaptation. Figure 8 displays the 2005–14 pattern of sea level change due to the melting of polar ice sheets estimated from the GRACE data (Adhikari and Ivins 2016), qualitatively similar to the projection of Slangen and colleagues, given the relatively short data record.

An interesting feature is that the reduced gravity caused by the mass loss of the polar ice sheets has caused sea level to fall in regions close to the source of the melting in Greenland and Antarctica and rise elsewhere. As opposed to the interannual pattern of sea level change shown in figure 5, the pattern of change from ice melting has a much longer time scale, which is most relevant to coastal planning and decision making.

**Concluding Remarks**

Advances in technology for observing the ocean from spaceborne and in situ sensors make it possible to monitor the rise of the global sea level with unprecedented accuracy.

Signs of accelerating GMSL rise over the past two decades have been detected by the satellite radar altimetry system with high statistical confidence. The priority of the international space community is to maintain the present capability to monitor current and future changes. Spaceborne gravity measurement allows detection of changes in GMSL from water mass exchange between the ocean and the rest of Earth, primarily from ice melting. The in situ float system detects changes in water temperature and salinity, and hence density, with
the long-term trend primarily due to the warming of the climate.

The various systems together not only provide information to understand the causes of sea level rise but also enable cross-checking for consistency to ensure the accuracy of the observations, which are critical for dealing with climate change.

References


An Interview with . . .

Ira Flatow of Science Friday

RON LATANISION (RML): We are delighted to have you with us today, Ira. I understand you have a bachelor's degree in industrial engineering from SUNY Buffalo. Is that correct?

IRA FLATOW: Yes, class of 1971. I was an engineering student and I really wasn’t enjoying it. Engineering was not what I thought it would be and I was looking for other things to do.

I had been in a TV studio in high school, doing the technical side. I was working a camera, learning how to operate the board. We had a federal pilot program to broadcast educational television back in the mid-1960s—we broadcast news and Spanish classes and typing to six schools in the district. I got $1.00 an hour salary.

CAMERON FLETCHER (CHF): Ira, you said engineering was not what you thought it would be. What did you think it would be?

MR. FLATOW: I was one of these kids in high school and junior high who used to make all these science fair projects. When I was 14 I did a project that would read punch cards. I also created health kits, and I built an oscilloscope and a vacuum tube voltmeter. I loved tinkering.

But when I went to college and studied engineering, there was no tinkering. There was mechanical drawing, with orthogonal projections on a sheet of paper, which I couldn’t figure out. It was so bad that they discontinued the course the next year. In fact a lot of the courses I took were discontinued the semester after I took them.

So I gravitated to the radio station. They were looking for volunteers to learn to be reporters because the antiwar movement was heating up and there were also demonstrations on campus about racial issues and things like that. I was at a meeting and they said, “Anybody want to learn how to be a reporter?” I raised my hand and they said, “Here’s a tape recorder. Learn how to do this on the job.” I spent 2½, 3 years doing that and became head of the news department.

RML: Was your reporting mainly on issues relating to science and technology?

MR. FLATOW: No. The only time I did science and technology was the first Earth Day in 1970. I did an environmental story. I also sold a bit of the sound I got to ABC Radio for $25.00. That was my first professional network experience.

I was in the right place at the right time because the head of the radio station, Bill Siemering, was tapped to start NPR. He wrote the mission statement and went to Washington in 1970, and I begged him when I graduated to take me down to Washington. That’s how I got to NPR the first year they were there.

NPR was very welcoming to science stories. We did a lot of science coverage in those early days, and I helped create the science unit.

CHF: What was your role in the creation of Science Friday?

MR. FLATOW: I owe it all to Saddam Hussein, actually.

RML: That is not an origin I would have expected.
MR. FLATOW: Me neither. After years of radio work I got an offer in 1982 to do a television show called Newton’s Apple on PBS. I went back and forth to Minnesota doing the show for 6–7 years. It was a grueling way of living and I wanted to get back into radio. That’s when I saw that there were these new talk shows coming out.

So I went to NPR and a good friend, Bill Buzenberg, vice president of the News. I said, “I have this idea for a weekly science talk show.” He said, “That’s great, except for two reasons. One, it’s only 1 day a week. What do we do for the other 4 days? Second, we don’t have a talk show. How do we get the stations interested in a talk show?” I said, “You’ve got to do this because there’s a guy named Limbaugh and some other guy who are clogging the airways with [their talk shows].” So he said, “All right, come back to me with an idea.”

I went around asking people if they would host the other 4 days. Susan Stamberg said maybe. Diane Rehm said she’d think about it. Then in 1990 the Gulf War broke out and NPR started a daily talk show covering it. That war lasted only a few weeks but the stations now had their appetite whetted for a daily talk show. I said, “Remember my idea?” and Bill said okay. We started in 1991 and now we’re in our 27th year.

RML: I haven’t seen Newton’s Apple, but I’ve heard Science Friday many times. Was Newton’s Apple a precursor or was it entirely different?

MR. FLATOW: It was a totally different show. If you took MythBusters and combined it with Bill Nye the Science Guy, that’s sort of like Newton’s Apple. It was a family-friendly science demonstration show, pre-recorded with a student audience. We would answer questions from listeners or viewers. “How does the ear work?” “How do airplanes fly”—I’m still debunking the mythology of Bernoulli’s principle.

It was grueling because it was trying to get scientists and engineers to talk in plain English about what they do in concise sentences.

It became theater after a while. For example, how does your ear hear? We had a big model of an ear and we’d show all the parts of it and then an otologist would come on and explain it in 10 minutes. Well, we needed it in 7 minutes. So we’d do another run-through and cut out a few seconds. We’d huddle again. By the 15th time I knew what he was going to say and he knew what I was going to ask—it was like theater without the script. That’s why it took so long and was hard to do.

Ira holding a tape recorder microphone at an antiwar rally in Buffalo, NY. The speaker (with raised fist) is activist Bruce Beyer. Photo source and date unknown; ca. 1970.

RML: You mentioned Bernoulli’s principle. What is it you’re interested in debunking related to flight?

MR. FLATOW: Why airplanes fly. It is not [explained by] Bernoulli’s principle. In one of my first books, Rainbows, Curve Balls, and Other Wonders of the Natural World Explained (1988), I explained flight the classical way we all learned in school, with Bernoulli’s principle—basically, due to the flow of the air over the wing lower air pressure on top of the wing “sucks up” the airplane like you suck on a straw and the liquid rises. Lower pressure on top because the air molecules travel faster over the top of the wing than under the wing, . . . But all that’s never been shown, never proven, never tested.

When I was on a book tour—I think it was in Vermont—a professor in the audience came up to me with a sheaf of papers and said, “I want you to read this and see if you agree.” I took it home and read it and said, “This absolutely makes sense.” He had debunked Bernoulli’s principle. The most scientifically sound reason is that it doesn’t explain why airplanes fly from first principles, from Newton’s law. Bernoulli says the wings get sucked up. But for a wing to go up, Newton’s third law of motion says you have to have air going down—you need an action and a reaction. Where is the air
going down? Bernoulli doesn’t say anything about that. He just says there’s less pressure on top.

When you fly a helicopter, you know where the air is going. We’ve all seen that. Air goes down, plane goes up. A helicopter is a plane with a rotating wing.

RML: I’m interested in things associated with lift, and I think Bernoulli’s principle has been part of that, and I always associated it with flight, the thrust provided by the engines and the lift providing the air dynamics.

MR. FLATOW: But how do you get the lift? Two flight scientists/engineers—David Anderson and Scott Eberhardt—wrote a book, *Understanding Flight*, that really convinced me. It is a beautifully illustrated book, showing all the forces and the mythology and everything.

We had a brain teaser on *Newton’s Apple*: If you have a bunch of chickens in a truck and they’re sitting on perches as the truck drives and the truck hits a bump and the chickens all fly up in the air, what happens to the weight of the truck? Does it decrease, increase, or stay the same?

CHF: It decreases.

RML: I would imagine it decreases.

It would have to, right?

CHF: Yes. That’s very cool.

MR. FLATOW: Isn’t that cool? I have a video of that.

RML: I can see where your passion in your Science Friday shows comes from. You may not have practiced as an engineer but you certainly have a lot of the inclination in terms of your curiosity.

MR. FLATOW: I’ve always been a very curious person. That’s why I used to do blow-up things in my basement. I almost burned down my mother’s bathroom once with a science experiment in 8th grade.

I also have this show biz—storytelling side of me, which started in high school. I was a very quiet kid in the back of the room until we were in 11th grade reading *Death of a Salesman* in English class and the teacher yelled at me, “I want to see you at the end of class.” I thought, ‘What did I do? I’m the nerdy kid in the back of the classroom.’

I said, “Yes, Mrs. Kestenbaum, what did I do wrong?” She said, “You read Willy Loman’s part so well I want you to try out for the senior class play next semester.” So I tried out for the play, which was *Rally ’Round the*
Flag, Boys, and got the part played by Paul Newman in
the movie. I got the lead, and my theater career was
launched—except the theater I was using was the radio.

RML: When I listen to your broadcast on the radio it’s
clear that you have a theatric mindset, but with a deep
understanding of science and technology. That’s quite
a combination.

MR. FLATOW: That’s what we call STEAM\(^1\) today,
right?

RML: Yes, and there aren’t very many folks who I
think understand and appreciate it. There’s a lot of talk
about STEM, but STEAM doesn’t enter into very many
conversations.

MR. FLATOW: You know who understands this? The
entertainment and advertising industry understands
that people love science. It’s a myth that people hate
science. People love science. We are in a golden era
where people love and want to know more about sci-
ence. Where’s the evidence? The Big Bang Theory is the
number one show on television. It’s all about scientists,
right? Look at film. In 2014 what two films were vying
for best picture? The Theory of Everything, about Stephen
Hawking, and The Imitation Game, about Alan Turing.

CHF: And in 2016 we had the NASA mathematicians
in Hidden Figures.

MR. FLATOW: Right. The entertainment industry
knows how much the public loves science and they’re
capitalizing on it. Not only that, I watch a lot of media for
stuff like this, and a tire commercial came on and I almost
fell out of my chair. The commercial starts like this: It’s
a woman driving a car on a dark street. It’s very dark in
the car, it’s made to look like a dangerous situation, and
the announcer comes on and says, “This woman isn’t
thinking about her tires. She’s having deep thoughts.”
There’s a little simulated blackboard where you see dif-
erential equations popping up on the screen—these are
her thoughts. She’s not thinking about the safety of her
tires: she’s thinking big thoughts because she knows Tire

\(^1\) STEAM = science, technology, engineering, the arts, and math
The BRIDGE 68

Rack will take care of her tires, giving her a chance to think the big thoughts she needs to think.

Think of the Mad Men pitch meeting where it's the advertisers who sell Tire Rack sitting around: What kind of commercial are we going to write? Who's going to be attracted to Tire Rack? What kind of role model can we use to attract people to Tire Rack? And they decide, We need a female scientist.

Then a week later, I see a commercial with Stephen Hawking selling cars! Either Land Rovers or Jaguars. The advertising industry knows that people love science, and this is how they're going to sell their products.

RML: Ira, I appreciate your hope that the public is hungry for science, but I'm a little doubtful about it. I have some grandchildren who I would say are not so much passionate about science as they are addicted to technology. These kids are always on their iPads or iPhones, playing games, and that worries me.

I see a kind of addiction in the public—people walking down the street looking at their iPhone, not looking where they're walking. But I don't know that that's so much an admiration on the part of the public for science as a distraction, even an addiction.

MR. FLATOW: I would be very happy to have 27 million people looking at science. That means maybe 1 in 10, maybe 1 in 12 all looking at science. To me that's a pretty good number, 8 percent.

My point about where the people are is that it's not what I think or what you're telling me; it's where the money is talking. I'm very much into 'follow the money.' The big money, which doesn't like to be wasted, is invested in science products, science-related things. That's what I was explaining with the commercials, the movies, the ads, the TV shows.

CHF: Where are you following the money now?

MR. FLATOW: Teenagers. We get teenagers that come on Science Friday and we hear how motivated they are, how interested they are. Back in the day, 25 years ago, they were calling while they listened to Science Friday in their class. Now Science Friday has a huge educational component where we're very involved with 100,000 teachers—100kin10.org helps train and educate teachers. We create science experiments specifically for classrooms and teachers. We do Facebook live stuff helping teachers do science. We create easy-to-do experiments that anybody can do.

If you go to our website and click on “Educate,” we not only have the experiments but we make hundreds of videos about science, beautifully done videos like no one else does them.

CHF: I did look at the site, and you have at least 13 categories, each of which is very broad, and then you have a myriad of presentations in each category. How do you come up with the items and topics that you're going to explore and present?

MR. FLATOW: I guess it takes a village. We have different divisions. I'm most involved in the radio side because I started the radio program. We also have a social media side, people who follow Facebook and Twitter and others and create content specialized for that audience. We have a graphics side that creates the special graphics you see on that page.

And we do social events. For example, next week in New York City, where we're a new partner with WNYC studios, we're doing an orchid program. My favorite hobby is orchids; I have dozens of them. We're inviting people to come and talk orchids.

We used to go on the road for just 2 hours of Science Friday. We would do the show live from an auditorium, with 300–400 people. We don't do that any more. Now
we create an interactive audience event all around the country. It could be in a dozen cities. We have scientists come and they show stuff—like what we did with Newton’s Apple—and the audience asks questions. We have quizzes and trivia contests. We get 2,000 people and are sold out.

RML: Tell me about the Science Friday Initiative. It’s a nonprofit.

MR. FLATOW: It’s a fundraising side. When I started Science Friday, NPR would help us go out and raise money. NPR loved us. Then NPR went through eight presidents in 10 years, and one of the presidents decided they didn’t like Science Friday anymore and said, “This is your last year,” so we had to become independent.

We were always our own bosses because we were always a purchased program for NPR, not in-house. So when NPR killed the show Talk of the Nation, which was the other 4 days of the week, we were able to survive on our own. It just meant we had to go out and raise money and we had to become a nonprofit.

We had a nonprofit educational arm called Talking Science. Originally, we did small educational outreach, but when we left NPR we had to expand and change our business model and become totally nonprofit and bring the radio together with the educational side. We actually got a bigger audience once we left NPR and became more widely known for educational stuff and expanded our video content.

We did the first podcasts ever. We did the first one on NPR. In 1993 we did the first show that was broadcast on the internet, called “What’s This Thing Called the Internet?” We sent it out to Xerox PARC to be digitized and put it on the internet.

RML: That raises an interesting question, at least from my perspective, and I would like to hear your thoughts. The internet has evolved in ways that I don’t think the folks who developed it would have expected. It was intended to be a platform that provided information, and today it’s a platform that provides—as one of our interviewees suggested—more antisocial than social media. When you look at all the things that the internet has become, what’s your take on the pluses and minuses?

MR. FLATOW: The first commercial web browser was back in the mid-1990s, I think, and I was shocked to see the commercials on it. Once it became commercialized and there was money to be made, it went the way of all commercial products: The lowest common denominator is what sells most people.

So it lost the direction of its founders, who didn’t know they could lose control of it—like Facebook is realizing now—and it turned into something else. Once it left the realm of the university the commercial people did what they do, which is advertise.

People are discovering that they are content, they are the product. People are the product sold to advertisers on television: “We’re going to make a show that attracts 18- to 34-year-olds.” I think that’s really when things changed, when the internet became so overwhelmingly commercial.

RML: Do you think the internet, as it has morphed, is valuable to young people, or is it—?

MR. FLATOW: It’s terribly valuable, to everybody. In the early days, when we used to talk about what good is the internet, psychologists would explain that people with social ills who are afraid to talk to people in public or meet them face to face can now practice anonymously speaking with other people.

And I love the internet for finding quick bits. You can find information fast. Make reservations. It’s great.

RML: That’s what it was intended to provide. I’m thinking again of young people, and I really think addiction is—

The internet is terribly valuable to everybody. You can find information fast. And young people are using it to organize.

MR. FLATOW: Young people are using the internet to organize. Think of all the teenagers who marched on Washington. That’s why I think the future is for these teenagers. They’re motivated, and they use the internet to organize immediately. You couldn’t do that in years past.

2 The student-led March for Our Lives on March 24 was organized in the weeks after the February 14 shooting at Marjory Stoneman Douglas High School in Parkland, Florida.
**RML:** I quite agree. I think that’s an absolute demonstration of the power of the internet for constructive purposes. My point is that the internet is relatively unregulated, and some of the things it offers to people who want to create mischief are very tractable and you can create great mischief. Some of that mischief affects young people and that concerns me.

**MR. FLATOW:** Right, you should be concerned. And I think that sooner or later it will be regulated. Don’t forget, the United States isn’t the only country that uses the internet. Want to talk about regulation? China knows how to regulate the internet, so it can be done. We just lost net neutrality; there’s a little regulation of the internet. You may not like the direction it’s going, but it is possible to regulate the internet. There are tipping points and maybe we’ve reached one.

But back to my original point. I am most interested these days in teenagers. They are very enthusiastic, they’re a powerful group of people. They’re passionate and strong, and these are the people who are going to take over now. By 2020 there will be more millennials than there are baby boomers.

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**RML:** I agree entirely. The recent activities evolving from the Parkland School in Florida and the young people who are leading that give me a lot more comfort in the future. This is a demonstration of the capacity of a bunch of eloquent young people who are very committed to make things happen, and that is very encouraging.

**MR. FLATOW:** The early signs of this were in the Maker Faire. On *Science Friday* we had a booth at the first Maker Faire in New York, I think it was about 2008, at the old World’s Fair grounds. The first ones were in California. To see all these teenagers—which a lot of them were—building 3-D printers and all kinds of stuff—I got the first inkling about how powerful a force these young people are.

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**RML:** I agree that that’s an optimistic sign, yet the US high school graduation rate is deplorable. And it’s not just a matter of science and technology, it’s literacy, period.

**MR. FLATOW:** That is a funding priorities issue, not whether people are interested innately in science or not. They are. Our problem is with paying teachers enough to stay in schools, valuing them as much as we do soldiers, for example, paying them the same way. We don’t do that.

When I was a teenager the space race was on everybody’s lips. I think that’s why, when Elon Musk and other people talk about going to the moon or to Mars, or building a hyperloop, they capture people’s imaginations. They’re creating interest in big technology again.

A friend of mine travels to China and the Southeast Asian countries. She just came back from Thailand, Cambodia, and Vietnam and she was in shock. I said, “What’s the matter?” She said, “We don’t matter anymore. No one talks about the United States as being relevant because you’re almost a third world country the way you think.”

I asked her for an example. She said, “When you go around China or any of these countries you don’t have to get on an airplane.” She showed me a map of the high-speed rail systems through China and these countries and you’re there in an hour. We don’t have that.

**RML:** Yes, when you travel you begin to realize just how much this country has neglected its infrastructure and evolution.

**MR. FLATOW:** Yes, and it’s a leadership gap. In China they just need somebody to say, “We’re going to build a railroad now,” and they take federal money and build it.

**RML:** I’m mindful of the time, Ira, and want to ask you another question. You have a very large listener base and a platform for reaching people. How do you see your long-term goal in terms of *Science Friday*, or any other vehicle that you might be imagining?

**MR. FLATOW:** We look at *Science Friday* as a platform for critical thinking, and we look at the moving parts as helping each other. In other words, the radio program can leverage our educational division because we have 2 million radio broadcast and podcast listeners and we can say through the radio, “Hey, we have a new educational project. You might want to take a look at this and bring in the teachers to talk about what’s going to be this month’s experiment.”

**RML:** I am most interested these days in teenagers. They are very enthusiastic and passionate and strong.
We have book clubs. Every week we invite the audience to read a science-related book—could be historical science, could be *Hidden Figures*. They can read it in classrooms. We talk about it and create a trusted source where people can hear new ideas and socially relevant science.

We try to do as much science policy as possible. I spent 10 years in Washington and I understand about science policy. I get pushback from listeners who say, “I don’t want to hear about science policy. I don’t want to hear about politics. I want to hear about science.” I tell them, “The money for science comes from politics, and we can’t talk about science without talking about it getting funded.”

So we view ourselves, especially now when science is under attack, as a way to say, “We’re going to continue to create a platform where people can speak respectfully and critically and thoughtfully about science issues, and we will give opposing viewpoints respect to listen to them.”

We also realize that we have under-covered certain issues that need to be looked at. For example, we have a concerted effort to bring new voices to science—minorities and women. We’re probably the only science organization in the media that has 50/50 coverage of male and female spokespeople, expert scientists, on the show. Even though science is mostly still done by men, we seek out women to talk about it. And we seek out young voices, graduate students, postdocs, new voices. The only way you create the atmosphere for people to accept diversity of people and of ideas is to put them on the radio, give them voices, give them video.

RML: How do you identify young people and women for the show?

MR. FLATOW: There are resources, like a website called 500womenscientists.org. We look there. The entire staff of *Science Friday* is 21 or 22 people I think, and 16 of them are women.

RML: That’s impressive. And at many of the major research universities today there are now as many women as men in the undergraduate population. When I joined the MIT faculty in 1975 probably less than 5 percent of the undergraduates were women. I’m delighted with the new numbers, since the women are certainly as able and willing and interested as any of the young men I’ve met.

MR. FLATOW: I had one woman in my whole engineering school, but I’m sure that’s changed now.

There’s also the diversity of where these people come from, where their parents came from, whether it’s India or Pakistan or South America. My staff come up with really great people, a lot of them postdocs who basically do most of the research, so giving voice to these people is very important.

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**The money for science comes from politics, and we can’t talk about science without talking about it getting funded.**

My main point, though, is the importance of STEAM. We use the arts as much as we can and in different ways—not only the films and videos but the way we present stuff, having fun or talking to scientists.

Part of the way radio communicates is by emotion. You can’t see the person, so emotion is important. We ask scientists, “How do you feel about making this discovery?” and they just open up like no one has ever asked them that question before. You hear their excitement.

In 2013 there was a new Barbie doll that was a nerd. The company had asked girls, What do you want to have as a doll? And they voted for a nerdy Barbie doll. She had a laptop, she was dressed conservatively, and she wore flats instead of high heels.

In contrast, there was an advertisement in the European Union to try to attract women to science, and it had women “scientists” dressed up like they were models, and a guy scientist at a microscope who looked like a model himself and was looking at them.

They put the ad on the internet and it lasted about as long as cold fusion did, they pulled it so fast. But you can still see it. It’s called “Science, It’s a Girl Thing,” Not a woman’s thing, but “a girl thing.” There was such backlash that real scientists came out with their own videos about what real science is like, what really goes on in the lab, set to music and stuff.

I talk to a lot of people about communicating science. Next week I’ll be at the NIH talking to postdocs. I did this in 2010 and they asked me to come back. I’ll also be at the National Press Club to talk about how to communicate, about using the entertainment industry, and
Ira giving a public talk in Pittsburgh about communicating science, June 2014. © WESA.

what not to do, like that EU ad I just described. There are some very simple things to do, some very simple mistakes people make, assumptions they make about how we learn or know things.

CHF: I heard the enthusiasm in your voice when you were talking about teenagers. Do you go out and talk with them?

MR. FLATOW: When we take our show on the road we get an audience of about 2,000, and when people come to the mic and ask questions most of them are teenagers. It’s unbelievable. They’re coming to see a show about science and asking the best questions.

We had a teenager on last week who asked a terrific question. We were doing a piece about biology and genetics, and this teenager said, “When you were sampling stuff, how do you know you didn’t contaminate your sample with the cotton swab you used on the other person?” Whoa! It was quiet for a moment, and the researcher said, “That’s a great question.”

CHF: Do you have occasion to get together with or compare notes or interview other notable science communicators these days like Neil deGrasse Tyson or a popular inventor like Dean Kamen? Is there sort of a community of science communicators and innovators that ever get together?

MR. FLATOW: No. I’ve known Neil deGrasse Tyson for decades, since before he became famous. And Bill Nye I know pretty well; we still chat every now and then. Dean Kamen I know very well; I knew him before he was famous, too. But no, we don’t get together and talk about these things.

Over the years I’ve gotten calls from the National Academies about coming to a conference to talk about how to be a good communicator, and I’ll share with you one experience I had many years ago. The Academies convened a conference in California, with all these big producers, to talk about “How would you communicate? We want to recommend the best communication vehicle.”

We spent 2 days at the Beckman Center and we all talked and thought we had a great conversation. After 6 months I called the press office and said, “Remember that conference we had out there and we had all these great ideas—whatever happened? Was there a decision made about what you were going to do?” He said, “Yeah, we did make a decision.” I said, “What was that?” He said, “We’re going to make science placemats.”

[Laughter]

Here’s my last story. I know a famous physicist at MIT, Ken Brecher. We used to chat a lot about how to teach science. He tells a story, and I confirmed this with him to make sure I was telling it correctly.

Ken Brecher had an idea. He was reading the back of a cereal box at breakfast and he thought, ‘You know, everybody reads the cereal box at breakfast. Why don’t we put a little science on the back of the box? For example, as a freebie in the cereal box you have a toy—it’s a little plastic dome, you press it down and it pops up, you press it down and it pops up again in the air. Wouldn’t it be great to have an explanation for the kid who’s doing it for why that happens?’

So he called up Kellogg’s at Battle Creek and offered to come tell them his idea. He told me, “I had a meeting with the CEO of Kellogg’s in this big boardroom and I said, ‘Why can’t you do the pop-up?’ The CEO said, ‘That’s a terrific idea. I’m going to send in the head of marketing. I’ll see you later. Thanks for coming in.’

The panel doors close and another panel door opens and the head of marketing comes in and says, “What’s your idea? And before you tell me, if it doesn’t sell one more f***ing box of cereal I don’t want to hear it.” Ken just got up and left the room.

[Laughter]
RML: Just another day in the office! Ira, is there any message you would like to pass on to the members of the NAE or to engineering deans or members of Congress—the folks who receive *The Bridge*?

MR. FLATOW: Sure. I say, “Get out of your offices. If you want to know how things really work, get into the trenches with the people you want to reach. Learn how they listen and learn things and how they get interested in things.”

One thing we learned on *Science Friday* is that we can’t just be on the radio anymore: we have to go where people are. We have to find out where they are online now and where they’re interested, where they congregate. We go on the road.

There are science cafés now. We create more than a café experience. You have to be creative, get more creative. You’ve got to pay attention and try to stay ahead of the curve and not be afraid to be ahead of the curve instead of always following what’s been proven. Take a chance on something new.

CHF: It sounds like that comes pretty naturally for you.

MR. FLATOW: It comes from experience. Because I’ve always been my boss, more or less, I’ve been able to pioneer new things and take chances. I follow a lot of business stuff and you always hear the pioneers saying business is afraid to take a chance on anything new.

I used to talk to inventors all the time. I talked to a guy who had 400 patents but couldn’t get anything patented in the US—he had to go to Europe—because they weren’t interested in new things here. And they’re things that are standardly used now. You can’t be afraid of new stuff. You have to take a chance.

And listen to the young people. Invite them in to your meetings to show them that they have a stake. If they’re only being talked to instead of listened to—What kid wants to believe that you’re going to listen to anything they say unless you invite them in and listen to them? Invite them into the Academy when they’re marching on Washington. It’s a gorgeous building, got great stuff. It’s a great opportunity.

When the Clintons were in the White House they used to have a science lecture series. When the president does something it shows that there’s public interest. The Clintons brought in Stephen Hawking and other great scientists, and they talked about big things, big ideas. Science had a megaphone in Washington.

The Academies should take over that role publicly because you are so well respected. Take the megaphone to create buzz, create interest. You do all these studies and publish all these reports; get ahead of the reports, talk about the ideas you want to make a report about.

CHF: The NAE is doing a bit of spearheading in that direction with the Grand Challenges for Engineering, and there’s an international summit on the Grand Challenges. It had about 900 people in July 2017, about half of whom were students from around the world.

MR. FLATOW: That’s great. Do more of that. And get engineers on some of the talk shows to talk about the important issues. That’s a real challenge.

When I started out, my motto was to make science a topic of discussion around the dinner table, as much as sports or business. That’s still the challenge.

RML: You have a very effective megaphone in terms of your listeners and your broadcasts.

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**Get engineers on some of the talk shows to talk about the important issues.**

MR. FLATOW: Thank you. Another great challenge of communicating is changing people’s minds—you don’t change anybody’s mind.

CHF: What’s the rest of that thought? You don’t change anybody’s mind; what you do instead is—?

MR. FLATOW: Hopefully you can point out inconsistencies and some people with an open mind will think about the evidence you’ve presented. But some people don’t care.

We had an instance on *Science Friday* when we were talking about vaccination and autism, and we had Paul Offit, who is probably the vaccination guru of the country. A woman named Chantelle came on and started talking and went on for 8–10 minutes, the longest monologue we’ve ever had. She was well thought out and articulate about all the reasons she’s against vaccines, and she ended by saying, “I just don’t believe anything my government tells me.”
So I said, “Is there any kind of data in any form or amount that will change your mind?” She said, “No, I just don’t believe anything government tells me.” I then said, “Okay, tell me what kind of data you would like to see that would convince you.” And she said, “Well, I would like to see independent studies, a commission created.” I said, “Okay. And who’s going to put the commission together that would convince you?” There was a long pause and she said, “I think the government could do that.”

[Laughter]

This is what I call the right brain/left brain collision. A lot of stuff is emotional or political or religious, and you’re never going to get through that barrier.

CHF: But where do you go from there?

MR. FLATOW: You go for people who are still willing to be reasonable. There are going to be times when the data are so overwhelming— I think we’re seeing this with global warming now, where people cannot deny what their eyes are showing them. Even though they don’t believe it in their head, you can’t deny there’s no more ice in the summer in the North Pole, and the sea level is rising and you can see it swashing through the streets of Florida.

Then you start to see it in the language changing among the skeptics: “Yeah, there’s climate change, but it’s not doing this.” And then, “Well, it’s doing this but it’s not doing that.” What people acknowledge becomes a moving target.

I remember years ago my wife called me one day and said, “We were just watching Vice President Gore’s movie, An Inconvenient Truth”—she was in real estate and a bunch of them were watching this—“and I told the story about you being in Washington and watching Jimmy Carter put up solar panels on the White House roof, and then I told them what you told me—and I want to make sure this is true—that when Ronald Reagan came into office he took them off the roof.” I said, “Yeah, that happened.”

She said, “Well, I told that story and a woman said, ‘Your husband is a liar!’” I said, “Why did she call me a liar?” My wife said, “Because she was a big Ronald Reagan fan and she could not believe that anybody would be so stupid as to rip solar panels off anybody’s roof, especially Ronald Reagan’s.”

[Laughter]

MR. FLATOW: About a month later I asked my wife, “Whatever happened to that woman?” She said, “She called me back and said, ‘You know, I looked it up online and I apologize to your husband: he was right.’”

Once you get a paradigm shift—which is what I think we’re having on climate change—then people’s minds will change. But it does take, as Carl Sagan used to say, extraordinary evidence. He was talking about UFOs. And to some people this is like a UFO. You have to change their mind.

CHF: It also is a matter of coming at it from a different angle. People were really objecting to the idea that climate change was caused by humans, and once the focus was shifted to “regardless of the cause, here are the impacts that we have to deal with,” that changed the posture away from defensiveness about who was causing it.

MR. FLATOW: Yes. But now it’s going backward again, at least in this administration, which is reversing a lot of the climate rules and air pollution rules and going back to the 1960s.

But today’s teenagers didn’t grow up in the 1960s; they’re growing up in this environment and this is their real life experience. They’re very vocal and they are out there.

RML: Ira, I’ve really enjoyed this conversation and am very grateful that you had the time to talk with us today. Thanks.

CHF: Yes, thanks a bunch. It was a blast.

MR. FLATOW: You’re welcome.
Ray H. Baughman, Robert A. Welch Distinguished Chair in Chemistry, and director, Alan G. MacDiarmid NanoTech Institute, the University of Texas at Dallas, was recently elected to the European Academy of Sciences and Arts. He will be inaugurated with other members at a meeting of the academy in March 2019. The academy is a transnational and interdisciplinary network of experts in science and the arts, devoted to analyzing societal and ethical challenges in Europe and collaborating to solve complex issues.

C. Jeffrey Brinker, professor of chemical and nuclear engineering, Sandia Labs/UNM Advanced Materials Laboratory, University of New Mexico, has been elected a fellow of the American Academy of Arts and Sciences.

Simon R. Cherry, Distinguished Professor, Department of Biomedical Engineering, University of California, Davis, is the recipient of the 2018 Paul C. Aebersold Award. He received the award from the Society of Nuclear Medicine and Molecular Imaging (SNMMI) during its annual meeting in Philadelphia in June.

The Bay Area Lyme Foundation, a leading sponsor of Lyme disease research in the United States, announced the recipients of its 2018 Emerging Leader Awards, designed to encourage promising scientists who embody the future of leadership in Lyme disease research. George M. Church, professor of genetics, and Professor Ting Wu, Harvard Medical School, are among those honored. The two will each be awarded $250,000 to launch the Genomic Lyme Disease Research Initiative at Harvard Medical School. Lyme disease is a potentially devastating infection that affects more than 300,000 Americans each year.

Irvin Glassman, Robert H. Goddard Professor of Mechanical and Aerospace Engineering Emeritus, Princeton University, was awarded the 2018 Daniel Guggenheim Medal on August 18 for his education and inspiration of today's aerospace engineers and scientists and for his influential contributions to the fields of combustion and propulsion. The Guggenheim Medal is jointly sponsored by the American Institute of Aeronautics and Astronautics, American Society of Mechanical Engineers, SAE International, and Vertical Flight Society.

The 2019 IEEE Cledo Brunetti Award has been awarded to Alfred Grill, IBM fellow emeritus, and Daniel C. Edelstein, IBM fellow. They share the award with Chao-Kun Hu, IBM research staff member. All are at the IBM Thomas J. Watson Research Center. The Brunetti Award recognizes outstanding contributions to nanotechnology and technologies for microsystem miniaturization. The citation reads “For contributions to manufacturable, reliable, and scalable Cu interconnect and low-k dielectric technology for CMOS.”

Asad M. Madni, retired president, chief operating officer, and CTO, BEI Technologies Inc., has been chosen to receive the 2019 IEEE Frederik Philips Award for outstanding accomplishments in the management of research and development resulting in effective innovation in the electrical and electronics industry. He is cited for “leadership in and pioneering contributions to the development and commercialization of sensors and systems for aerospace and automotive safety.”

Ming Hsieh, trustee, University of Southern California, and CEO and chair, Fulgent Therapeutics, received a 2017 Ellis Island Medal of Honor on May 13, 2018.

During a plenary session of the 2018 BIO World Congress on Industrial Biotechnology, in Philadelphia on July 18, Sang Yup Lee, dean, KAIST Institutes, Korea Advanced Institute of Science and Technology, was awarded the 11th annual George Washington Carver Award for Innovation in Industrial Biotechnology. The award recognizes an individual who has made a significant contribution to building the bio-based economy by applying industrial biotechnology to create environmentally sustainable products. Dr. Lee is recognized for developing innovative products and processes that are sustainable and environmentally friendly and for being a leading advocate on the importance of industrial biotechnology through engagement with the public, policymakers, and decision makers around the world.
Eric S.G. Shaqfeh, Lester Levi Carter Professor, department chair, and professor of mechanical engineering, Stanford University, received the Alpha Chi Sigma Award for Chemical Engineering Research from the American Institute of Chemical Engineers. He was recognized for his work in suspension mechanics, non-Newtonian fluid mechanics, and nonequilibrium polymer statistical dynamics.

The IEEE Computer Society announced 2018 award recipients. Susan J. Eggers, professor of computer science and engineering emerita, University of Washington, received the Eckert-Mauchly Award in Los Angeles during the International Symposium on Computer Architecture (ISCA) 2018 in June. She was cited for “outstanding contributions to simultaneous multithreaded processor architectures and multiprocessor sharing and coherency.” She is the first woman to receive this award in its 39-year history. The following NAE members have been selected for 2018 Computer Pioneer Awards: Barbara Liskov, for “pioneering data abstraction, polymorphism, and support for fault tolerance and distributed computing in the programming languages CLU and Argus”; and Sergey Brin, cofounder and president, and Lawrence E. Page, cofounder and president, Products, Google Inc., for “the creation of the Google search engine and leadership in creating ambitious products and research initiatives.”

The IEEE has announced the following NAE members as recipients of its 2018 medals. Thomas F. Budinger, Professor of the Graduate School, University of California, Berkeley, E.O. Lawrence Berkeley National Laboratory, received the Medal for Innovations in Healthcare Technology for “pioneering contributions to tomographic radiotracer imaging.” The Jun-Ichi Nishizawa Medal was awarded to Joe C. Campbell, professor, Electrical/Computer Engineering Department, University of Virginia, for “contributions to the development of high-speed, low-noise, long-wavelength avalanche photodiodes.” Delores M. Etter, Caruth Professor in Engineering Education, Southern Methodist University, is the recipient of the James H. Mulligan, Jr. Education Medal for “contributions to engineering through innovative textbooks on problem solving with computing languages and software tools.” Bede Liu, professor, Department of Electrical Engineering, Princeton University, was awarded the Jack S. Kilby Signal Processing Medal, for “sustained contributions to the analysis and the development of low-complexity realizations of digital signal processing algorithms.” N.R. Narayana Murthy, founder, Infosys, and chair, Catamaran Management Services Pvt. Ltd., was honored with the Founders Medal for “visionary leadership at Infosys contributing to human progress through technology and for advancing corporate ethics and social responsibility.”

The 2018 Medal of Honor, given for an exceptional contribution or an extraordinary career in IEEE fields of interest, went to Bradford W. Parkinson, Edward C. Wells Professor of Aeronautics and Astronautics Emeritus, Stanford University, “for fundamental contributions to and leadership in developing the design and driving the early applications of the global positioning system.” Nambirajan Seshadri, professor of practice, electrical and computer engineering, University of California, San Diego, was awarded the Alexander Graham Bell Medal for “contributions to the theory and practice of wireless communications.” Eli Yablonovitch, professor of electrical engineering and computer sciences, University of California, Berkeley, received the Edison Medal for “leadership, innovations, and entrepreneurial achievements in photonics, semiconductor lasers, antennas, and solar cells.”

IEEE also announced winners of the 2018 Technical Field Awards. The Biomedical Engineering Award went to Mark S. Humayun, professor of ophthalmology and biomedical engineering and integrative anatomical sciences, University of Southern California, for “contributions to the bioelectronic retinal implant.” The Magnetics Award went to Tatsuo Itoh, Northrop Grumman Distinguished Professor of Electrical Engineering, University of California, Los Angeles, for “contributions to electromagnetic modeling, artificial materials, microwave electronics, and antennas.” Mark S. Lundstrom, the Don and Carol Sciﬀes Distinguished Professor of Electrical and Computer Engineering, Purdue University, received the Leon K. Kirchmayer Graduate Teaching Award, for “creating a global online community for graduate education in nanotechnology as well as teaching, inspiring, and mentoring graduate students.” The Eric E. Sumner Award went to Peter W. Shor, Morss Professor of Applied Mathematics, Massachusetts Institute of Technology, for “contributions to quantum communication and information theory.” Peter Stoica, professor emeritus, Information Technology Department, Uppsala University, Sweden, received the
Fourier Award for Signal Processing for “broad contributions to research and education in statistical signal processing and its applications.” “For fundamental contributions to the theory and design of nonlinear circuits and signal processing systems,” the Gustav Robert Kirchhoff Award went to Alan N. Willson Jr., Charles P. Reames Professor Emeritus, University of California, Los Angeles. John N. Tsitsiklis, Clarence J. Lebel Professor of Electrical Engineering, Massachusetts Institute of Technology, was honored with the Control Systems Award for “contributions to the theory and application of optimization in large dynamic and distributed systems.”

Bernard M. Gordon Prize for Innovation in Engineering and Technology Education

Paul G. Yock accepted the 2018 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education on May 22, in the Traitel Building, Hoover Institution, on the campus of Stanford University, in a ceremony with students, alumni, faculty, friends, and NAE members. The prize was awarded “for the development and global dissemination of Bodesign, a biomedical technology program creating leaders and innovations that benefit patients.” NAE president C. D. Mote, Jr., BMG Charitable Trust representative Daniel Gordon, and NAE Awards committee chair Asad M. Madni presented the award on behalf of the National Academy of Engineering, with Stanford University provost Persis Drell (NAS) facilitating the event. The public lecture will take place during the 2018 NAE annual meeting, on Sunday, September 30.

Dr. Yock’s Bodesign program is needs-driven and seeks to train the next generation of multidisciplinary leaders who will create innovations in health technology. It is a mentor-guided, entrepreneurial, and immersive experience that emphasizes and instills a comprehensive understanding of the innovation process for those in several fields.

Through his dedicated commitment to the Bodesign program, Dr. Yock has shown that innovation can be both organized and learned, allowing students to focus on and build sustainable careers as innovators and leaders. Since the development of Bodesign, a number of programs around the world have based their curriculum on it. Nearly 200 fellows have completed the Bodesign program at Stanford since its establishment in 2001.

Dr. Yock is the Martha Meier Weiland Professor of Medicine and cochair of Stanford University’s Department of Bioengineering. He began as an interventional cardiologist at the University of California, San Francisco, and then moved to Stanford in 1994. He founded the Stanford Center for Research in Cardiovascular Interventions, training dozens of fellows in intravascular ultrasound and interventional cardiology, and in 1997–98 was acting chief of the division of cardiovascular medicine. He received his MD from Harvard Medical School and was elected to the NAE in 2009.

Left to right: BMG Charitable Trust representative Daniel Gordon; NAE Awards committee chair Asad M. Madni; Paul G. Yock, Gordon Prize winner; and C. D. Mote, Jr., NAE president.
Acceptance Remarks by Paul G. Yock

Thank you, Dan, Asad, and Daniel. Needless to say, this is a wonderful honor—certainly the biggest honor in my career. I am deeply grateful to the members of the Academy and their colleagues for their work in researching and evaluating Biodesign. I’m particularly happy that our program is receiving an award in the name of Bernard Gordon, who is an extraordinary role model for all of us in the way he blended a career as a prominent inventor and a leading innovator in engineering education.

Every so often we get asked by a visitor what makes the Biodesign program effective. The answer is pretty straightforward, and I can illustrate it with a quick demonstration. I’d like to ask the staff and faculty of Biodesign, both past and present, to stand. Now I’d like to ask those of you in the audience who have at some point mentored Biodesign fellows, students, or faculty or taught in one of our classes to stand. If you are a department or division chair who hosted Biodesign over the years, please stand. And then I’d like to ask the Biodesign alums in the audience to stand—our powerful, secret teaching resource.

There you have it—the reason Biodesign has been effective. All of you have earned a share in this award. Thank you. Please take a seat again.

The bottom line is, we have an amazing community of experts in health technology innovation who have been exceedingly generous with their time and expertise in building a next generation of leaders.

The main impression I want to convey is how very proud we are of the alumni of Stanford Biodesign. In the early days we didn’t really appreciate how important a force this alumni community was going to become. It has turned into a very impressive network: 30 Biodesign alums are CEOs of the companies they founded. An additional set of alums from the earlier years of the program have risen to senior ranks—the equivalent of vice president and above—in established companies. Many of our engineers have assumed leadership positions in corporate and academic settings. Some of these folks lead innovation programs at their universities or companies. A number of our physician inventors, in academia and in practice, have cofounded companies, having seen a technical innovation from clinical need to implementation planning. And other leaders are in a fascinating range of positions in design, consulting, marketing, even patent law. This is an amazing group—I hope you get a feeling for why we are so proud of them.

A couple more thoughts to share. Although we are celebrating the success of the Biodesign program, I want to focus on two important challenges where we will be directing our strategic efforts and resources, including the Gordon Prize money.

The first is in the area of diversity. I am talking about diversity in the broadest sense of the term, including differences in educational backgrounds, intellectual talents, and values. In the 17 years that we have been working with interdisciplinary
groups we have learned how difficult it is to help shape a group of fellows with very different backgrounds into a functional team. Our fellowship directors and our team psychologist do a masterful job in guiding this process—and I am certain that from the fellows’ standpoint this is in fact the single most valuable part of the training experience that we offer. But, to be candid, our teams still struggle, and we struggle with leading them. We still have a lot to learn, and each new group of fellows provides a great opportunity for us to take another step forward.

In the past few years in particular it has become clear that we need to focus more energy on specific axes of diversity. We have a crisis in the health technology field with respect to gender balance. By some measures—senior leadership roles, for example—we are even less diverse than other tech sectors. On the plus side, this is a tremendous opportunity for us to move the needle, because Biodesign is attracting some of the most talented young women in the world. And this gives us the opportunity to provide a training environment where we focus on helping young men and women learn together to create a mutually supportive and productive intergender team experience. I’m happy to say that 7 of the 12 fellows joining us next year are women. We are also putting heavy emphasis on enhancing recruitment of underrepresented minorities to the program—this is a major thrust of our recruiting efforts for future fellowships.

Here’s the second major challenge. As many people in this audience are keenly aware, we are in the midst of a historic shift in the ecosystem of health technology innovation. Healthcare costs are out of control, and the payers—private insurers and the government—are aware that introduction of new technologies is one of the biggest drivers of cost escalation. These payers have reacted by placing major barriers in the way of paying for technology innovation. As a result, the entrepreneurial ecosystem in health technology innovation in this country has suffered a major disruption. The pipeline of innovations in health technology that are actually moving forward to patient care has become seriously clogged. More worrisome still, there is very little awareness of this fact and even less political will to do anything about it. In fact, I believe this is an issue where the National Academy might provide some very productive data and perspective on a policy level.

But for us in Biodesign, this challenge also presents a significant opportunity. The truth is that, in the 60 years of the modern medtech industry, inventors of new technologies have not paid primary attention to the cost of new technologies. With the innovation process we follow in Biodesign, where need drives invention, there is no reason we cannot make cost effectiveness a key component of the upfront clinical need. Over the past few years we have infused our training experience with a major dose of health economics—and we are beginning to see some real results in the area of value-focused, needs-based innovation.

This attention to cost effectiveness is important for another reason. In our strategy group we have been discussing the fact that the standard approach to health technology innovation—that is, inventing progressively more sophisticated technologies for increasingly more difficult diseases—inadvertently helps accentuate disparities in healthcare delivery. Inventions have disproportionate benefit for patients in the top economic levels who can afford them. A truly needs-based innovation process like that of Biodesign can, on the other hand, look at needs across the socioeconomic spectrum and provide new technologies that use the power of engineering to achieve less disparity in health care. This is a critically important and highly motivating challenge, and one that we are focusing on actively in Biodesign.

Let me add one final thing: a sincere thank you to all of you for being here this evening. Many of you are colleagues and friends who have worked shoulder to shoulder over the years as we built Biodesign. I feel enormously lucky to have had the privilege of partnering with you in this project. I can’t help but think we have been part of a special time and place here—our own little tipping point—and I will always be grateful for the opportunity to have gone through this wonderful experience together. Thank you all.
The Great Lakes Energy Institute of Case Western Reserve University (CWRU) hosted a National Academy of Engineering regional meeting on Perspectives on Global Climate Change on May 24 in Cleveland. Arthur Heuer and his colleagues organized the event, which drew a sizable audience from the CWRU and Greater Cleveland communities. (Preregistration, which totaled 789, was required to obtain free tickets for the event.)

CWRU president Barbara Snyder welcomed participants. She noted the activities of Case School of Engineering faculty Arthur Heuer, James Anderson, John Angus, and Hunter Peckham as well as Trevor Jones in organizing previous successful NAE regional and topical meetings.

She then introduced NAE executive officer Alton (Al) Romig Jr., who thanked CWRU and the NAE members for their organization of this public meeting on an important and timely topic. He further acknowledged their continuing and much appreciated efforts to support NAE’s public education mission.

The program featured three noted climate scientists: Michael E. Mann, Distinguished Professor of Atmospheric Science and director of the Penn State Earth Systems Science Center; Stephen R. Palumbi, Jane and Marshall Steel Jr. Professor of Marine Science, Stanford University, and director of Stanford’s Hopkins Marine Station at Monterey, CA; and V. “Ram” Ramaswamy, director of the Geophysical Fluid Dynamics Laboratory, National Oceanic and Administrative Administration, at Princeton University.

Mann’s talk, “Understanding Global Warming,” began by reviewing the now solid evidence for a human influence on the climate of recent decades. Such evidence includes instrumental measurements available for the past two centuries, paleoclimate observations spanning more than a millennium, and comparisons of the predictions from computer models with observed patterns of climate change. He then addressed future likely impacts of human-induced climate change, including possible influences on sea level rise, severe weather, and water supply, and concluded with a discussion of possible solutions to climate change.

Palumbi’s talk, “The Effect of Climate Change on Ocean Life,” began by noting that the oceans absorb a large fraction of the heat and CO₂ that are causing climate change. As a result, they are responding in four ways that dramatically affect the capacity of oceans to support human well-being. First, the oceans are warming, and warm water events have caused widespread coral death—the biggest visible ecosystem effect of climate change in the world to date. Second, warm water expansion and glacial melting are causing sea level rise. There is high likelihood that 1–4 feet of sea level rise will occur by the end of this century. Even now, coastal cities are experiencing regular king tides that cause flooding. Third, high CO₂ levels cause acidity in the ocean to rise, damaging the way ocean animals
build their shells. Finally, increasing storms will rile the oceans as well as whip up the land: the combination of high storms and high tides will cause coastal infrastructure damage. Fortunately, marine species have several tools that may help them respond to these changes. Reef-building corals can acclimate and adapt to high temperatures. Coastal sea urchins have genes that can help them grow in acidified water. Fish populations have been moving north into cooler waters. These natural adaptations are not likely to protect ocean life for long, but they may afford a few decades to mitigate the climate crisis and help keep the oceans in a productive, healthy state.

The title of Ramaswamy’s talk was “The Climate Change–Atmospheric Processes Linkage: What Is the State of Our Understanding?” Climate changes involve interactions among the atmosphere, oceans, biosphere, and cryosphere on a variety of space and time scales. The composition of the atmosphere, the state of the Earth’s surface, and changes due to natural and human influences (“climate forcings”) perturb the heat balance and the hydrologic cycle of the planet. These perturbations in the climate system cause changes in the water vapor and cloud content of the atmosphere (“climate feedbacks”). The forcings and feedbacks together determine the sensitivity of the climate system. The resulting changes in global and regional temperatures, as well as changes in evaporation, precipitation, and atmospheric circulation, lead to extreme weather events such as hurricanes, winter storms, and heat waves. Knowledge of the links between atmospheric processes and climate change is needed to distinguish between trends and natural variations in climate. Robust understanding of the atmosphere and climate system is essential for informed estimates of their impacts on climate change, and for scientific inputs into societal decision making.

The meeting included ample opportunities for questions of the speakers.

2018 Japan-America Frontiers of Engineering Symposium Held in Tsukuba

The 2018 Japan-America Frontiers of Engineering Symposium (JAFOE) was held June 18–20 at the Tsukuba International Congress Center. It was cochaired by NAE member David Sedlak, Plato Malozemoff Professor in the Department of Civil and Environmental Engineering at the University of California, Berkeley, and Hidemitsu Furukawa, professor of mechanical systems engineering at Yamagata University. The NAE partners with the Engineering Academy of Japan to carry out this activity every two years.

The 2018 JAFOE symposium was attended by 60 early-career engineers from US and Japanese universities, companies, and government labs. They discussed leading-edge developments in four engineering fields: water treatment, bionics and prosthetics, smart structures and materials, and artificial intelligence. Rapid urbanization has put tremendous pressure on global water resources that are critical for human consumption, for agriculture to feed burgeoning populations, and other purposes. As a result, water-stressed areas are looking for new sources of water to support their populations. Talks in the session on the Water Treatment Revolution covered advanced technologies that facilitate drinking water production for more than 2.5 million residents in the water-constrained area of Orange County, California; research trends in the treatability of trace substances and evaluation of their behavior in the environment; water treatment technologies to treat increasingly complex wastewaters; and the use of membrane filtration and ultrafine bubbles to make high-quality drinking water. The speakers explored challenges and solutions to these issues in Japan and the United States.

The Bionics and Prosthetics session focused on research that uses brain signals to restore motor and sensory function to severely impaired individuals, thereby extending the brain’s capacity and, potentially, improving human performance. Moreover, combining bionics and neurotechnology with other fields such as cybernetics, robotics engineering, psychology, and sociology will result in additional transformative scientific and technological discoveries. The session began with a presentation on the science behind brain-machine interfaces. This was followed by talks on direct brain control of a remote prosthetic arm...
and a newly developed prosthesis that minimizes phantom limb pain. The session concluded with a presentation on direct brain interfaces for memory restoration.

“Smart” materials are those whose natural response to some stimulus can be exploited for an engineering application; examples include piezoelectrics, shape memory alloys, and electrochromic materials. The Smart Materials and Structures session highlighted the link between the fundamental understanding of materials chemistry, structure, and behavior and the engineering of smart structures that exploit a material’s response. The first speaker discussed the superplastic flow and microstructural development of the Earth’s mantle on global geologic processes. The next talk described how to use complex fluids that are responsive to thermal, electric, or magnetic stresses to tailor soft materials for robotic applications. This was followed by a presentation on a novel approach for autonomously directing material synthesis that integrates artificial intelligence in the additive manufacturing process. The last presentation covered advances in tools and techniques for making truly atomic-scale observations and analysis of structural and functional materials.

The symposium concluded with a session on how advances in artificial intelligence have impacted diverse and collaborative learning, which leverages the different roles played by machine programs, humans, and physical systems. These roles include processing data streams, mining for patterns, learning models, providing feedback on output, sensing the environment, and capturing contexts and situations as they change. Speakers covered anomaly detection techniques that enable collaborative learning by analyzing complex data streams incorporating human feedback, techniques to address challenges in learning for physical systems, reinforcement learning to enable robots to perform in physical environments, and advances in statistical learning approaches to discover knowledge from data.
In addition to the formal sessions, a poster session preceded by flash poster talks was held on the first afternoon. This served as both an icebreaker and an opportunity for all participants to share information about their research and technical work. On the second afternoon, attendees traveled to Mount Tsukuba, one of 100 famous mountains in Japan, where they could take a cable car to the top for scenic views, visit the Shinto shrine, or enjoy the hot springs. This was followed by dinner at the traditional Japanese inn Edoya and the comedic performance of a sales talk for a onetime medicinal ointment famous in the area.

It is an FOE tradition to have the dinner speech on the first evening of the meeting given by a senior-level individual from industry, government, or academia. Dr. Toyoko Imae, Honorary Chair Professor at the National Taiwan University of Science and Technology, described her professional career and areas of research. She commented on the impact of the Gender Equality Act on her career, the challenges of conducting research in a foreign country, and the importance of her relationships with her students.

Funding for this activity was provided by The Grainger Foundation, the National Science Foundation, and the Japan Science and Technology Agency. The next JAFOE symposium will be held in 2020 in the United States.

The NAE has been holding Frontiers of Engineering symposia since 1995. For more information about this meeting and the symposium series, visit www.naefrontiers.org. To nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at JHunziker@nae.edu.

Proctor P. Reid (1956–2018)

We are very sad to report the passing of Proctor P. Reid, director of the NAE Program Office, on June 28 at age 62. He had a heart attack.

Proctor oversaw the NAE’s program activities and staff and directed policy research programs on engineering, the economy, and society; engineering and health care; and engineering, energy, and the environment. He led NAE and collaborative committee studies, workshops, and symposia on the globalization of engineering; technological dimensions of US economic competitiveness; systems approaches to health and health care; the future of engineering education, research, and practice; and the vitality and diversity of the engineering workforce. He codirected a bilateral study of opportunities for US-Chinese cooperation in electricity generation from renewable resources and a consensus report on the role of noise control technology and policy in achieving a quieter environment, and he oversaw development of a joint National Academies–US Institute of Peace roundtable on technology, science, and peacebuilding.

Proctor began his tenure with the Program Office in 1988 as an NAE fellow and rose to become director in 2004. Before joining the NAE, he was an instructor in political economy at Oberlin College (1986–87) and a consultant to the National Research Council (1988) and the Organization for Economic Cooperation and Development (1984–85). He was elected a AAAS fellow in 2013, and was secretary to the AAAS Section on Industrial Science and Technology.

He received his MA (1983) and PhD (1989) in international relations from the Johns Hopkins University Paul Nitze School of Advanced International Studies, and his BA in German language and literature from Dartmouth College in 1979. Proctor was an avid and skilled skier, enjoyed fly fishing and the outdoors, and was a devoted husband and father. His generosity, kindness, and optimistic outlook were evident to all who knew him. The family has suggested that gifts in his memory be made to the Equal Justice Initiative (www.eji.org).
The BRIDGE

Rosalyn W. Berne, New Director of NAE Center for Engineering Ethics and Society

ROSALYN W. BERNE comes to the NAE from the School of Engineering and Applied Sciences at the University of Virginia, where she is an associate professor in the Science, Technology, and Society (STS) program. In addition to her academic position, her professional appointments have included director of admissions for the Darden Graduate School of Business, assistant vice president for administration at the University of Virginia, vice president for academic affairs for the Institute of Shipboard Education (Semester at Sea), and head of Tandem Friends School in Charlottesville.

In her research Dr. Berne interprets social-cultural phenomena in a technological context and explores the intersecting realms of emerging technologies, science, fiction, and myth, and the links between the human and nonhuman worlds, with an eye for areas of ethical concern. She has taught courses on ethics in nanotechnology development; the engineer, ethics, and professional responsibility; religion and technology; and STS and engineering practice. An NSF Career Award, “Ethics and Belief in the Development of Nanotechnology,” supported her research from 2002 to 2007.

Dr. Berne’s publications include two academic books, Nanotalk: Conversations with Scientists and Engineers on Ethics, Meaning, and Belief in Nanotechnology Development (Earlbaum Press, 2007) and Creating Life from Life: Biotechnology and Science Fiction (CRC Press, 2015), as well as numerous conference papers and journal articles. She has also authored a science fiction novel and two titles in the body/mind/spirit genre.

She earned her BA (1979) and MA (1982) in communication studies and PhD (1999) in bioethics, all from the University of Virginia.

Ros can be reached at RBerne@nae.edu.

NAE Program Office Summer Intern

YINHAO (TONY) GE joined the Program Office as a summer intern. A rising senior in chemical engineering at the University of Virginia, Tony is passionate about the food-energy-water nexus, renewable energy technologies, and strategic foresight. He was selected through the Policy Internship Program, a joint UVA-MIT initiative, to intern with the NAE’s Grand Challenges Scholars Program (GCSP) Network Office. The Policy Internship Program prepares a small number of UVA and MIT students each year for summer internships in Washington, DC, through coursework at their respective home institutions.

During his internship, Tony worked with GCSP Network staff Carl Anderson and Rama Ramakrishna, collecting information about current GCSP programs, activities, and alumni experiences; developing a white paper on a selected Grand Challenge to report technical progress, social impacts, ethical considerations, and future opportunities; and assisting with the planning and development of student engagement opportunities at upcoming GCSP workshops.

Tony attended high school in China, Germany, and the United States. His hobbies include chess, tennis, Chinese calligraphy, and classical music. Upon graduation, he would like to work with renewable energy and sustainability and explore how the industry is adapting to a more sustainable future.
Calendar of Meetings and Events

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<td>Seeking Solutions in Research Integrity: A View from All Perspectives</td>
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<td>September 28–29</td>
<td>NAE Council Meeting</td>
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<td>October 29–30</td>
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All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

JOSEPH A. AHEARN, 81, retired vice chair and senior vice president, CH2M Hill Ltd., and Major General, US Air Force Civil Engineer, died July 10, 2018. Dr. Ahearn was elected in 2010 for contributions to improving the environment and transportation infrastructure through engineering and construction projects.

THOMAS R. ANTHONY, 76, retired staff physicist, GE Corporate Research and Development, died December 12, 2017. Dr. Anthony was elected in 1990 for outstanding application of diffusion phenomenology to the development and fabrication of materials and devices.

GRIGORY I. BARENBLATT, 90, principal scientist, Institute of Oceanology, Russian Academy of Sciences, died June 21, 2018. Professor Barenblatt was elected a foreign member in 1992 for major contributions to understanding flow of fluids through fractured porous media that have aided production of gas and oil worldwide.

GRAEME A. BIRD, 88, professor emeritus, University of Sydney, died May 24, 2018. Dr. Bird was elected a foreign member in 1996 for the creation and development of the direct simulation Monte Carlo technique, including its application to chemically reacting, radiating flows.

GERRIT A. BLAAUW, 93, professor emeritus of digital technique, University of Twente, died March 21, 2018. Dr. Blaauw was elected a foreign member in 1998 for contributions to computer architecture.

ROBERT P. CLAGETT, 91, retired lecturer, Management Department, University of Rhode Island, died June 13, 2018. Mr. Clagett was elected in 1986 for key contributions to research in the advancement of manufacturing technologies.

JOHN E. DOLAN, 94, consultant and retired vice chair, Engineering and Construction, American Electric Power Service Corporation, died March 17, 2018. Mr. Dolan was elected in 1980 for engineering, innovating, and constructing technically advanced facilities in generation, transmission, and distribution for a major US privately owned electric system.

FRANCIS G. Dwyer, 86, independent consultant and retired senior scientist and manager, Mobil Research and Development Corporation, died December 24, 2017. Dr. Dwyer was elected in 1993 for his role in catalyst manufacturing and catalytic processing technology from laboratory to commercial scales.

JOHN C. FISHER, 98, retired consultant, GE Corporate Research and Development, died May 2, 2018. Dr. Fisher was elected in 1981 for conceptual leadership in solid-state rate theory, synthetic microstructure, technological forecasting, and inspired teaching ability.

HOWARD FRANK, 75, professor of management sciences, University of Maryland, died May 1, 2017. Dr. Frank was elected in 2002 for contributions to the design and analysis of computer communication networks.

PAUL E. GREEN JR., 94, retired director, Optical Networking Technology, Tellabs Inc., died March 22, 2018. Dr. Green was elected in 1981 for innovative applications of com-
munication theory and computer signal processing to spread spectrum and anti-multipath communications, radar astronomy, and seismology.

DEAN B. HARRINGTON, 94, retired manager, Generator Advance Engineering, General Electric Company, died September 13, 2017. Mr. Harrington was elected in 1981 for outstanding contributions to the design, development, performance analysis, and international standards of large steam turbine generators.

GEORGE A. HARter, 89, retired vice president and assistant general manager, TRW Electronics and Defense Sector, TRW Inc., died August 19, 2017. Mr. Harter was elected in 1981 for contributions to the engineering development of unmanned spacecraft and innovations in automated spacecraft testing and design verification.

ROGER LACROIX, 88, consulting engineer, died January 1, 2017. Mr. Lacroix was elected a foreign member in 1990 for pioneering leadership in conception, design, and construction of prestressed concrete nuclear pressure vessels, offshore structures, advanced buildings, and bridges.

ALAN M. LOVElace, 88, independent aerospace consultant and retired senior corporate vice president and chair, Commercial Launch Services, General Dynamics Corporation, died April 18, 2018. Dr. Lovelace was elected in 1974 for contributions to aerospace materials, particularly application of boron and graphite reinforced epoxies.

RICHARD H. MACNEAL, 94, consultant, MacNeal-Schwendler Corporation, died January 29, 2018. Dr. MacNeal was elected in 1996 for contributions to large-scale, general-purpose finite element analysis and for development of the NASTRAN program.

WILLIAM NEW JR., 75, chair, the Novent Group, died December 21, 2017. Dr. New was elected in 2010 for developing applications of pulse oximetry technology to clinical problems of blood oxygen monitoring, and for innovations in neonatal audiology.

ROBERT E. SCHAfRIK SR., 72, Presidential Distinguished Professor, industrial, manufacturing, and systems engineering, University of Texas, Arlington, died July 10, 2018. Dr. Schafrik was elected in 2013 for innovation in materials for gas turbine engines.

HAROLD N. SCHERER JR., 88, retired president, Commonwealth Electric Company, died October 10, 2017. Mr. Scherer was elected in 1989 for contributions to the development, design, and effective utilization of extra-high-voltage and ultra-high-voltage electric power transmission.

Publications of Interest

The following reports whose authoring committees included NAE members were recently published by the National Academy of Engineering or National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street NW–Keck 360, Washington, DC 20055. For more information or to place an order, contact NAP online at www.nap.edu or by phone at (888) 624-6242. (Note: Prices quoted are subject to change without notice. There is a 10 percent discount for online orders when you sign up for a MyNAP account. Add $6.50 for shipping and handling for the first book and $1.50 for each additional book. Add applicable sales tax or GST if you live in CA, CT, DC, FL, MD, NY, NC, VA, WI, or Canada.)

Autonomy on Land and Sea and in the Air and Space: Proceedings of a Forum. Autonomy is multidisciplinary, multicultural, and global in its development and applications. Autonomous vehicles rely on communications, artificial intelligence, sensors, virtual and enhanced reality, big data, security, and many other technologies. Each year the annual meeting of the National Academy of Engineering highlights an engineering theme that is quickly developing in the world. The theme of the 2017 meeting was autonomy on land and sea and in the air and space; this publication summarizes the presentations and discussions from the meeting. Free PDF.

Adaptability of the US Engineering and Technical Workforce: Proceedings of a Workshop. Technological developments, reengineered operations, and
economic forces are transforming the way products and services are conceived, designed, made, distributed, and supported, a transformation that is having profound effects on the world of work. Workers are being asked to upgrade their skills to become more productive and adaptable. To explore the effects of these changes on the workforce and on individual workers, the NAE held a workshop in November 2017, “Preparing the Engineering and Technical Workforce for Adaptability and Resilience to Change.” The first goal of the workshop was to increase stakeholders’ understanding of the importance, definition, and characteristics of workforce adaptability. The second goal was to provide an opportunity to share best practices for fostering adaptability and to identify needs for future study and development. This publication summarizes the presentations and discussions from the workshop.

Ewa A. Bardasz, president and managing officer, Zual Associates in Lubrication LLC, and the Lubrizol Corporation (retired); Nicholas M. Donofrio, NMD Consulting LLC, IBM fellow emeritus and retired executive vice president, Innovation and Technology, IBM Corporation; and Wanda K. Reder, president and chief executive officer, Grid-X Partners LLC, served on the workshop steering committee. Free PDF

Understanding Measures of Faculty Impact and the Role of Engineering Societies: Proceedings of a Workshop. In January 2017 the NAE, with support from the National Science Foundation (NSF), held a workshop on the engagement of engineering societies in undergraduate engineering education. Since then, the NAE has held a series of follow-up regional workshops to investigate specific issues identified in the January 2017 workshop as deserving of further discussion and evaluation. The second in this series of workshops, in February 2018, brought together about 45 representatives of professional societies, academic institutions, and businesses to explore the role of engineering societies in enhancing understanding of faculty impact on the engineering profession as part of the reappointment, promotion, and tenure process. This publication summarizes the workshop presentations and discussions.

Leah H. Jamieson (chair), Ransburg Distinguished Professor, Electrical and Computer Engineering, and John A. Edwardson Dean Emerita of Engineering, Purdue University; Don P. Giddens, professor and dean emeritus, Georgia Institute of Technology and Emory University; Asad M. Madni, independent consultant and former president, COO, and CTO, BEI Technologies Inc.; and John C. Wall, retired vice president and CTO, Cummins Inc., served on the workshop steering committee. Paper, $55.00.

Sexual Harassment of Women: Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine. Over the past few decades, research, activity, and funding have been devoted to improving the recruitment, retention, and advancement of women in science, engineering, and medicine. However, as women increasingly enter these fields they face biases and barriers, including sexual harassment. What are the impacts of this discriminatory behavior on women and their careers? This report explores the influence of sexual harassment in academia on the career advancement of women in the scientific, technical, and medical workforce. It reviews research on the extent to which women in these fields are subject to sexual harassment and examines its impacts on the recruitment, retention, and advancement of women pursuing scientific, engineering, technical, and medical careers. It also identifies and analyzes the policies, strategies and practices that have been most effective in preventing and addressing sexual harassment in these settings.

Sheila E. Widnall (cochair), Institute Professor, Massachusetts Institute of Technology; Alice M. Agogino, Roscoe and Elizabeth Hughes Professor of Mechanical Engineering, University of California, Berkeley; and Edward D. Lazowska, Bill & Melinda Gates Chair, Paul G. Allen School of Computer Science and Engineering, University of Washington, served on the study committee. Paper, $55.00.

Admissibility and Public Availability of Transit Safety Planning Records. In 2012 Congress gave the US Federal Transit Administration (FTA) the authority to establish a comprehensive framework to oversee the safety of the country’s public transit systems. In the 2015 Fixing America’s Surface Transportation Act, Congress asked the Academies to evaluate and provide recommendations on whether it is in the public interest for transit agencies to be allowed to withhold from civil litigation all records developed in compliance with the new federal safety planning requirement. This report considers the arguments favoring and opposing evidentiary protections for safety planning records and the
rationale for congressional decisions to grant such protections in other transportation modes. It examines factors that Congress must consider when deciding where the public interest balance lies. They include a desire for transit agencies to engage in high-quality safety planning without fear of the planning records being used against them in court and the preservation of a tort system that deters unsafe conditions and allows injured parties to be justly compensated. Recommendations to Congress and FTA are offered with these and other important factors in mind.

Thomas B. Deen, retired executive director, Transportation Research Board, National Research Council, served on the study committee. Paper, $46.00.

Improving Characterization of Anthropogenic Methane Emissions in the United States. It is essential to understand, quantify, and track atmospheric methane and emissions in order to address concerns and inform decisions that affect the climate, economy, and human health and safety. Atmospheric methane is a potent greenhouse gas that contributes to global warming. In addition, methane is a precursor to ozone pollution in the lower atmosphere and thus affects human health. This report summarizes current knowledge of methane emission sources and measurement approaches and evaluates opportunities for methodological and inventory development improvements. It will inform the research agendas of US agencies including NOAA, EPA, DOE, NASA, USDA, and NSF.

NAE member David T. Allen, Gertz Regents Chair in Chemical Engineering, University of Texas at Austin, was a member of the study committee. Paper, $90.00.

Onshore Unconventional Hydrocarbon Development: Legacy Issues and Innovations in Managing Risk—Day 1: Proceedings of a Workshop. Technologies to develop unconventional hydrocarbon resources in the United States have evolved in recent decades, and since about 2005 their application to US shale oil and shale gas fields has allowed the country to reduce its crude oil imports by more than 50% and to become a net natural gas exporter. But the economic and energy advances have been accompanied by both rapid expansion of the infrastructure associated with the development of these fields and public concern about impacts to surface- and groundwater, air, land, and nearby communities. This workshop looked at onshore unconventional hydrocarbon development in the context of potential environmental impacts and ways to manage the risks of these impacts. Participants examined the decommissioning and reclamation of wells and related surface and pipeline infrastructure, as well as industry practice, scientific research, and regulation to minimize environmental impacts throughout their active use and after operations have ceased. This publication summarizes the workshop presentations and discussions.

NAE member David A. Dzombak, Hamerschlag University Professor and department head, Department of Civil and Environmental Engineering, Carnegie Mellon University, chaired the oversight roundtable. Paper, $65.00.

2017–2018 Assessment of the Army Research Laboratory. The National Academies’ Army Research Laboratory Technical Assessment Board (ARLTAB) provides biennial assessments of the scientific and technical quality of ARL’s research, development, and analysis programs, focusing on ballistics sciences, human sciences, information sciences, materials sciences, and mechanical sciences. This interim report, summarizing the findings of the ARLTAB for the first year of this biennial assessment, addresses approximately half the portfolio for each campaign; the remainder will be assessed in 2018.

Jennie S. Hwang, CEO, H-Technologies Group, and board trustee and distinguished adjunct professor, Case Western Reserve University; George (Rusty) T. Gray III, fellow, Los Alamos National Laboratory; Wesley L. Harris, Charles Stark Draper Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology; William S. Marras, Honda Chair Professor and director, Integrated Systems Engineering Department, the Ohio State University; and Alan Needleman, University Distinguished Professor, Department of Materials Science and Engineering, Texas A&M University, served on the study. Paper, $50.00.