New Windows into the Ocean: Enabling Next-Generation Ocean Observing Systems

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The Challenge

Working in the ocean is difficult, and deceptively simple questions such as 'how will changing CO_2 levels effect the biota in the deep ocean?' require the best scientific and engineering talent to work cooperatively to obtain answers. However, in this period of rapid technological change, the threshold for participation is rising. Individual research groups must master increasingly complex technologies to successfully field powerful but costly instrumentation. Without a strong supporting infrastructure, new sensors and platforms are difficult to develop, and once created, remain relatively inaccessible to most of the oceanographic community. This leaves many creative minds in the oceanographic community unable to participate in the use of exciting new platforms and technologies. Oceanographic facilities have the potential to break this impasse, and provide the mechanism to couple new technological capabilities with the great science questions of the time.

These challenges are important because disparate engines of change are driving oceanography into a new phase of discovery of the world's oceans. New technologies are enabling the creation of more powerful sensors, robotic platforms for mapping and exploration, and observatories that distribute power and communications to the once inaccessible seafloor. The tools of genomics are opening our eyes to a world of microbial factories hiding in every drop of seawater. Our growing understanding of global climate is revealing the great extent to which the oceans hold the key to understanding our planet's future. It is critical that we find ways to efficiently provide the scientific community with the best tools available to address these and other important issues, and do so in a way that the data produced is of the highest quality and made rapidly accessible.

The broad range of science investigation of the ocean and the diverse suite of technologies being brought to bear will create great challenges for future ocean science facilities. Specifically, the challenges include:

1) We need to finds ways to provide access to the broad range of platforms entering use, including advanced Remotely Operated Vehicles, Autonomous Underwater Vehicles, and of course Ocean Observatories. In the same way that the Stratton Commission laid the groundwork for increasing the accessibility of ships, this commission could provide a foundation for greatly extending access to the ocean for the oceanographic science community by fostering the development of new platforms that can be made generally available.

2) There is a gradient of maturation amongst oceanographic sensors, and currently the most robust and generally available are physical sensors. Just on the horizon

however, are technologies that will illuminate the chemical and biological ocean. These sophisticated new in situ sensors provide us windows into aspects of the chemical and biological ocean previously hidden from view, and greatly amplify the impact of observational platforms such as AUVs and Ocean Observatories. Just as ocean sensors on spacecraft are developed and made available on a community basis, so too should new in situ sensors and tools for operating in the ocean be promoted.

3) Many scientifically important regions are logistically extremely difficult to access and maintain presence, one among many being the Arctic Ocean. The tools and methods developed by the oceanographic community for the open ocean often do not adapt to functioning off an icebreaker, especially during the harsh Arctic winter. Tools need to be developed and made available to provide accessibility to the Arctic basin.
4) Time-series measurements of oceanographic parameters provide a fundamental touchstone by which we can understand the temporal variability of the ocean and detect and trace processes such as climate change and anthropogenic effects on the marine environment. Given the broad significance of time series measurement, these might be better supported as facilities, rather than as individual investigator projects.
5) Oceanographic field programs attacking interdisciplinary problems often require large numbers of sensors and platforms operated in a coordinated manner. At present, the infrastructure of communications, platforms, and sensors has difficulty supporting such efforts.

These challenges need to be addressed in a manner that allows facilities to evolve to support new observational paradigms, bringing the best possible tools to bear efficiently and rapidly. In a time of great change and opportunity, we need an infrastructure that is an advocate of progress.

A Glimpse of the Future

In summer of 2000, the Monterey Upper-water column Experiment (MUSE) was carried out in Monterey Bay, California, employing a variety of platforms and advanced sensors. This experiment was designed to understand the bio-geo-chemical response of Monterey Bay to episodic iron fertilization driven by coastal upwelling. MUSE was characterized by a large number of autonomous platforms, ships, aircraft, and satellite systems, all linked by various communications systems (see figure). Coordinated operations with these platforms generated a highly interdisciplinary, multi-scale data set.

MUSE focused on the response of Monterey Bay to an impulsive injection of iron-bearing sediments. Wind events in late summer drive upwelling along the California coast to the north of Santa Cruz, bringing sediment-bearing water from the seafloor to the surface. This iron-rich water enables the growth of various phytoplankton species that in turn provide grazing for organisms higher in the food chain. The observational needs of MUSE were tremendous. Not only are nutrients introduced through the interaction of a

host of physical processes acting on different time and space scales, but the nutrients trigger a cascade of transformations throughout the ecosystem.

To answer the demands of the MUSE experiment, a large number of assets were employed, including:

- R/V New Horizon: continuous measurement of physical, chemical, and biological parameters.
- R/V Pt Sur: AUV operational platform.
- R/V Pt Lobos: ROV Ventana operational platform (MBARI).
- R/V Shana Rae, R/V John Martin, and R/V Ed Ricketts for mooring deployments, logistical support, and some near-shore sampling (UCSB).
- 2 Odyssey IIb AUVs: CTD, fluorescence, bioluminescence, oxygen, optical backscatter (MBARI/MIT).
- 4 gliders (‘Seaglider’)from University of Washington and 2 gliders (‘Spray’) from SIO/WHOI (2 UW vehicles deployed): CTD.

- 2 instrumented drifters: temperature, salinity, pCO_2, optical backscatter, fluorescence, and irradiance (MBARI).
- 6 moorings: wide range of physical, optical, meteorological, and biological sensors, including the Environmental Sample Processor (ESP) configured for in situ genetic identification of micro-organisms (MBARI).
- Twin engine Navajo aircraft: sea-surface temperature and meteorological measurements (Naval Postgraduate School)
- C-130 aircraft: sea-surface salinity (NASA).
- HF Radar: surface winds and currents (Naval Postgraduate School).

The large number of platforms and complementary nature of their instrument suites provided opportunities for synergistic sampling programs. However, the evolving nature of the iron fertilization event and its aftermath imposed the requirement that survey plans be rapidly adapted to changing conditions. Each system was tuned to address a part of the observational problem, and coordination of these assets was central to extracting a more complete picture. A wide range of combined operations was carried out, including multiple ships, ships and AUVs, ship and AUVs and aircraft, and ships and AUVs and drifters. Many of these operations focused on frontal processes, which evolved significantly in the course of a single day. Planning for the coordinated operations therefore occurred on a short time-scale, and imposed heavy demands on rapid data processing, communication systems, and manpower.

The MUSE experiment provides a view of the opportunities next-generation ocean facilities might enable, and highlights some of the challenges as well. The observational assets in the experiment, with the exception of the ships, were operated by the organization that created them, and would have been inaccessible to the general oceanographic community. This issue of accessibility is a central problem that must be addressed by future oceanographic facilities.

Looking further to the future, the MUSE experiment demonstrates that for an ocean observation system to be more than the sum of its parts, the elements must function as integral parts of a larger system. For the full power of the multi-platform sampling system to be realized, the observational assets must function within a fast-turn around cycle of activities that carries observations through analysis to the planning of the subsequent survey again and again. Since these elements are complex devices in their own right, the infrastructure demands are daunting.

Exploring Solutions

Expanded UNOLS

The University National Oceanographic Laboratory System has provided access to ships for the oceanographic community for decades. Why not expand the UNOLS charter to satisfy the present and future demands of the oceanographic community? Part of the solution could indeed be to extend the existing UNOLS infrastructure, since it already provides access to the ocean through ships, human occupied submersibles, and remotely operated vehicles. Why not observatories and AUVs as well?

What UNOLS does not address is the increasing importance of advanced sensors and tools in achieving the full potential of a given platform. Even when access to a platform is obtained, the level of technical expertise required for an investigator to introduce a new instrument to an AUV, ROV, or observatory is significant. Thus for an observatory facility to be successful as a community asset, it must do more than provide 'plugs in the ocean.' It must also provide a level of technical support for individual PIs that assures they have access to the best possible instrumentation while simultaneously allowing them to focus on science rather than the supporting technology. Other communities have mastered these conflicting demands, and one of the challenges of the future ocean facilities will be to draw on these lessons for the benefit of the oceanographic community.

Future facilities must also take a much greater responsibility for data. Experience with the Hubble Space Telescope has shown that ensuring data quality and making data available over the internet multiplies the number of users of a given data set many times. The next-generation of large-scale ocean observatories will have thousands of instruments and sensors of many different types. The data flow will be continuous 24 hours a day, 365 days a year. The quantity of data transmitted to shore stations will be in the range of hundreds of terabytes (10^{12} bytes) per year. This data flow is an order of magnitude greater than that for the current generation of astronomical telescopes. The existence of archives of astronomical data with well-described metadata catalogues has led to the development of powerful tools for searching, visualizing, and accessing data sets. The differences with astronomy projects lie in the large heterogeneous instrument suite planned and foreseen for the ocean environment and in the need to support concurrent execution of many experiments.

Perhaps the clearest demonstration of the need for quality control, archiving, and management of data to be facility functions is provided by considering a possibility of a time series facility. Here the primary function of the facility would be to obtain the data, assure its quality, and make it available to the community. This is a very different mission than the one UNOLS is currently structured to support.

NSF Facilities

NSF successfully sponsors a large number of sophisticated scientific facilities. Why not simply adopt an NSF facility model?

A problem that would remain unresolved, if this were the only solution, is that the current NSF funding process is poorly geared to encourage technological innovation, primarily because it is not tuned to the time-scales required for creating successful oceanographic systems. Development for an innovative oceanographic system might be expected to last on the order of a decade. While the system likely produces scientific data much earlier, the process of creating a system that is used routinely at sea by people other than the inventors is a lengthy process.

The length of the development process greatly increases the risk of losing funding support before the development process is complete. Since typical funding cycles are three years, three or more rounds of funding must be obtained through processes that are highly competitive and have a significant element of chance. The consequences of a short-term problem at the wrong time in the process can be catastrophic. Subsequent cycles of the proposal process are relatively decoupled from earlier cycles, so ‘memory’ of guidance given in earlier proposal cycles may be lost. Furthermore, issues as keeping a highly trained team together are not visible in the proposal process. Finally, many projects are unable to navigate the fund raising chasm between proof-of-concept and functional sea-going system, as this typically requires substantial support for engineering tasks that do not appear innovative. Thus the complete development process undergoes ‘proposal jeopardy’ a number of times with catastrophic consequences for a mis-step or just bad luck.

Commerical

Why not allow the commercial world to provide solutions to oceanographic facilities? After all, market pressures drive the nations industrial development powerhouse, creating a wide range of technologically sophisticated products. Indeed most advances in oceanographic sensors and platforms are driven by technology created outside the oceanographic community. Why not rely on the commercial sector to create the technology for and run the oceanographic facilities of the future?

When the oceanographic market is large enough, or when there is sufficient parallel between an oceanographic need and the need of another large market, the commercial sector does provide a strong partner. ROVs provide an example of a technology now being heavily driven by investments to satisfy deep-water oil and gas needs. Shallow-water AUV development is heavily driven by Navy investment to address mine-countermeasure and other military concerns. Telecommunications technology is being adapted to enable the next-generation of cabled seafloor observatories. However, many critical needs of the oceanographic community have no strong external economic driver, nor do they comprise a large enough market for significant commercial investment. Consequently while the commercial sector provides a strong partner for many critical activities, it will not provide the entire solution.

Center of Excellence

Could laboratories dedicated to the development of advanced oceanographic systems play a role? Possibly the greatest advantage of such environments might be to provide an environment in which the career choices necessary to foster instrument and platform development would be rewarded. Long term funding could provide project support over time-scales better suited to the development of innovative oceanographic instrumentation. Finally, such centers could serve as focal points for developing platforms and instruments on a community basis rather than as individual investigator projects.

The need to align career rewards with the realities of instrument development is illustrated in part by considering the pressures on investigators in academic environments. Careers of young investigators are highly driven by the need to produce important results in time to influence tenure decisions – usually six to seven years. For the technologist, the extended development time required by seagoing systems is unattractive. For oceanographic scientists, the potential for a technical failure caused by events beyond their control, and the unlikely nature of a ‘second chance’ to acquire tenure data, make technology development programs risky. Consequently, technologically innovative sea-going programs represent a significant career gamble for young investigators in typical academic environments.

Even for a more senior investigator, technology development requires making decisions not always aligned with career goals. Most oceanographic systems are developed in individual investigator laboratories. While highly innovative, such entities have great difficulty adapting to the demands of large development projects. This is a concern since many of the more exciting ocean technologies, such as AUVs and advanced biological sensors, require funding levels on the order of many millions of dollars, and the extended involvement of experienced engineers. Sustaining such efforts over many years requires a constant level of fund raising from the lead investigator. In a typical academic laboratory, this person will also lead the project, and thus the scale of the effort will lead to increased management responsibility as well. Finally, to maintain credentials, the lead investigator must continue to be scientifically productive. The pressures are severe, and it is likely that the lead investigator will spend most of their time on activities such as management that weigh little with regards to career advancement.

An important role for a center of excellence would be to cultivate a critical mass of engineering talent capable of efficiently executing significant development efforts. When a project requires a number of engineers work together for the development of a complex system, engineering process, project management, and system engineering become important. While highly prized in industry and very large projects, these skills are typically not as important for research-oriented, individual-investigator activities. Consequently, most oceanographic institutions do not cultivate or reward such individuals.

The center of excellence could also structure the reward system to encourage scientists to embrace and support technology development as well. Community instrument programs require the scientist’s involvement change in important ways compared to individual investigator instrument development. Scientific guidance via formal identification of functional requirements and assisting with cost-benefit trades becomes a central activity. The project scientist must represent community needs rather than pursuing personal research objectives. While this might be career suicide in a traditional academic institution, the project scientist role is key to the success of community instrumentation projects, and needs to be recognized and rewarded.

The Monterey Bay Aquarium Research Institute (MBARI) offers an example of an institution that in many respects is a center of excellence. Scientists are rewarded for embracing technology, even at times when academic success might have been achieved more rapidly with off-the-shelf systems. Project management skills are rewarded, as is attention to engineering process. Since MBARI is funded privately and can set internal priorities, it has been able to follow through on long-term projects. The development of the highly successful ROV Tiburon would not have been completed even under an S&T center time scales (5 years). Organizations that cultivate the talent and provide the continuity of effort to deliver complex systems will be central to the creation of first-class next-generation oceanographic facilities.

Parameters for Success

From the preceding review of opportunities and possibilities, a few ingredients can be identified that would provide the oceanographic community with flexible and powerful facility capabilities for the future:

1) Facilities with technical expertise and charter to support complex sensors, robotic platforms, and the data needs of the scientific community.
2) Centers of excellence to develop first-rate sensors, platforms, and observation techniques on a community basis.
3) Competitive processes that encourage periodic upgrades of facility capabilities.
4) Mechanisms to support adoption of new paradigms of ocean observation.

Great benefit can be realized by making the new generation of sensors and platforms broadly available to the oceanographic community. However, the greatest challenge is to provide a framework that will accommodate the tremendous new capabilities yet to come.