Prepared for the 2022 National Ocean Exploration Forum

Exploring the Dynamic Ocean: Technology for Exploration and Public Stewardship

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Vision Statement

By 2032, ocean exploration will leverage massively-scalable, low-cost sensing and communication technologies to provide the public with greater access to the ocean and useful data/information, increase engagement, and improve the public's ocean literacy.

Exploring the Dynamic Ocean

The history of exploration is fundamentally the story of filling in the empty spaces on our maps. Where are the lakes, where are the mountains, where are the valleys? The golden age of scientific ocean exploration, from the HMS *Challenger* to Seabed 2030, has similarly been rooted in geography: where are the ocean's valleys and mountains, and what's missing in maps of the ocean floor?

One of the great lessons of the last century of ocean exploration is that maps are not enough – the geography that often matters most lives in the dynamic three-dimensional structure of currents and eddies, the fluctuating distribution of nutrients and biota, and the landscape of light, which evolve from hour-to-hour, day-to-day, and season-to-season. If you want to find antelope, go to the valleys and follow the water; if you want to find oceanic biomass, go to the eddies and follow the light. The "maps" needed for science, for industry, but most importantly for public policy and stewardship, live in a huge liquid volume and can change dramatically from moment to moment.

The decade ahead will see a dramatic shift in the focus of ocean exploration, from fine-grained, one-time bathymetric mapping to persistent monitoring of the dynamic ocean volume across many orders of magnitude in length and time. Making this possible is the explosive evolution of key underlying technologies – the commoditization of sensors and instrumentation – coupled with new generations of scalable ocean platforms and open, collaborative data pipelines. This dense and detailed view will enable everyone – the public, industry, government – to understand with dramatically greater clarity the impacts of our activities on the ocean and will empower the public to steward oceanic resources more wisely and in ways that better align industrial economic incentives with ecological responsibility – the central mission of the blue economy.

The barriers to realizing this vision, and the challenges to our community of ocean exploration and stewardship, are superficially technological but fundamentally cultural. The traditionalist view of ocean exploration is that it happens on ocean-going ships, from the *Victoria* to the HMS *Challenger* to the NOAA Ship *Okeanos Explorer*. We need to reimagine exploration as something that happens not only with massive ships and exquisite scientific instrumentation but with massive fleets of disposable sensors, with commoditized floats, autonomous vehicles, CubeSats, and deployed networks of fixed instruments. We need to encourage, with carrots and sticks, the active participation of industry, from aquaculture to shipping to coastal development. We need to embrace the general public as partners – in policy, in regulation, and in exploration.

More is Different

The ability to measure environmental data densely in space and time qualitatively changes the ways we can intervene. Walk into any modern manufacturing facility and you are likely to find temperature sensors distributed like candy along and around the production line. These sensors are technological marvels – platinum circuits laser-trimmed onto tiny ceramic plates, coated with a microlayer of glass, and matched to precision low-power integrated circuits that can detect fluctuations of fractions of a degree. They are also completely commoditized – manufactured in the millions and costing a couple of dollars apiece, they represent a rounding error in the total cost of the factory. The result is production lines that can detect problems long before they arise, providing actionable, profitable, and risk-mitigating information with influence far down the supply chain, altering the economics of the entire operation.

We need the same level of insight in the ocean; we need radically more data, on a vastly wider array of length and time scales, so that we can make better, wiser, and actionable predictions. Consider a municipal waterfront dealing with intermittent harmful algal blooms; if the city could determine, in a cost-effective manner, that a local golf course is dumping nitrate-rich runoff at 2:00 AM on Thursday nights off the 14th tee, a host of actions could follow. Also consider the golf course itself, which may be unaware of the runoff. The wasted fertilizer, and a regulatory risk, are costs which they would be better off avoiding if the runoff could be monitored with inexpensive tools and methods. Consider an aquaculture farm monitoring temperature, water chemistry, and pathogens, or regulators monitoring the farm's ecological impact; knowing what's in the water, and more broadly, how these data change every few minutes for years on end, can have huge implications for where to farm, when to harvest, what to harvest, and how to anticipate logistical and supply chain challenges a day, a week, and/or a season in advance. Consider the management of open water fisheries; knowing where conditions (e.g., thermal, chemical, biological, optical) are likely to lead to dense biomass distributions of specific species that are of interest or concern could have actionable consequences with large-scale environmental implications on daily, seasonal, and decadal timescales.

Observing the ocean across this wide range of scales – from meters to miles, from seconds to seasons – will require deploying exponentially more sensors, on a wide array of distinct platforms, with much greater efficiency in dollars and in power than currently possible. Just as measuring temperature in a factory has become default thanks to commoditized sensors and economies of scale, measuring temperature – as well as chemistry and biology – in the ocean needs to become default, needs to become commoditized, and needs to exploit exogenous economies of scale. In the next few sections, we will list some key examples of dynamic ocean environments, identify some of the length and time scales that define them, describe strategies for exploring them, and propose a vision for the technology landscape that will help extract actionable information from the ocean.

Exploring Across Scales

It's useful to take a step back and think about the length and time scales that matter most for a handful of key oceanic environments the community would like to explore, understand, and protect.

For example, consider the following question: where is the bulk of the biomass in a given region of the open ocean? A reasonable guess might be that biomass should follow production; the bulk of the biomass should thus be roughly uniformly distributed within the first couple of hundred meters of the open ocean, where photosynthesis is possible.

This turns out to be dramatically wrong for a host of interesting reasons. For one thing, production is far from spatially uniform – eddies in the ocean can increase nutrient levels many-fold, enabling greater production within their cores than in nearby nutrient-poor waters, leading to large differences in phytoplankton density inside versus outside an eddy. Mesoscale eddies can range from tens to hundreds of kilometers in size and lead to large environmental variations on spatial scales of hundreds to hundreds of thousands of meters. Meanwhile, such eddies, and their less explored but also important smaller variants, can form, evolve, and decay on timescales of days to weeks and months to seasons. Like watering holes in the savannah, these eddies define a geography in the ocean that concentrates biomass, from primary producers to top predators. A similar story applies to storm systems and clouds as well as nutrient plumes that develop due to coastal injection or fish pen waste – many natural and anthropogenic processes can create or become distinct ecosystems by concentrating biomass. The geography that matters to biology in the ocean is not just the seafloor and often is largely independent of the ocean bottom.

Another complication is that much of the biomass in the open ocean does not, in fact, stay near the primary production, but rather migrates up and down the water column every day at dusk and dawn, hiding from predators in the deep during the day and rising to graze and predate in the relative safety of night. Heuristically, these migrators seem to seek out a "light comfort zone" to which they are peculiarly adapted, for example, by counterilluminating to cancel their own shadows in the middle of the "twilight zone," or by diving far deeper and far faster to avoid the light entirely. Light thus shapes the geography within which these grazers live and feed, forming the valleys and mountains that provide safety and protection for this migrating biomass. Exploring this geography means following the light.

Similar stories obtain for a host of other critical ocean environments and ecosystems. We summarize some of the key length and time scales in Table 1 below. The key lesson we draw from this table is that, for every environment listed, the scales of spatial and temporal variability that lead to actionable decisions are impractical to explore using conventional ship-based exploration paradigms, which generally lead to relatively small numbers of extremely precise and enormously data-rich point-samples in space and time. Exploring these variable realms, and understanding the dynamic geography that defines them, requires new sampling paradigms, new technologies, and a new vision for exploration.

Table 1:

ENVIRONMENT	TYPICAL TIME SCALES	TYPICAL LENGTH SCALES	TYPICAL DEPTHS
Municipal Waterfront	Minutes to Monthly	<50m over O(10km)	0-40 meters
Ocean Twilight Zone	Hours, Daily, Seasonal	<100m over O(1000km)	200-1000 meters
Open Ocean Aquaculture	Hours to Seasonal	<100m over O(10km)	0-300 meters
Fisheries	Weekly, Seasonal, Decadal	<1km over O(1000km)	0-O(1000 meters)
Aquifers/Watersheds	Hours, Daily, Seasonal	<100m over O(100km)	Variable

Exploring the Dynamic Geography: Sampling Strategies and Key Technologies

To understand this dynamic landscape, we need to explore with much greater density across a much wider range of scales than is currently possible. For example, consider the environments listed in Table 1. What would exploration strategies that resolve the scales of interest actually look like?

For coastal monitoring, where many important sources are point-like and impulsive, we need to measure a handful of key scalar parameters (e.g., temperature, salinity, nutrients, pH) with moderate (but not necessarily extreme) precision, and we need to make these measurements regularly (every few minutes or more frequently) and persistently with sample scale in the tens of meters across an overall sampling region that can extend for tens or even hundreds of kilometers along a waterfront. That means deploying thousands of individual sensors along that waterfront, and possibly, orders of magnitude more. This is economically impractical using current commercial off-the-shelf (COTS) instruments and deployment methodologies; the instruments alone might cost $50,000 each and the infrastructure required to deploy them is correspondingly expensive. Even neglecting these capital costs, the labor required to deploy, collect data from, and maintain the calibration of such instruments makes the idea completely impractical. What's needed is a new generation of inexpensive, ultra-low-power, and easy-to-deploy sensors that are sufficiently commoditized – and environmentally responsible – that can be lost at sea and simply replaced at a marginal cost and with negligible environmental impact. We need the analog of those platinum temperature sensors from the factory. We also need a low-overhead way to get these sparse data home – a low-bandwidth, low power communication channel, acoustic or otherwise. Again, the cost of such a network using COTS components is unrealistically large. What's needed is a ground-up redesign of both sensors and communication devices with deployment on these industrial scales in mind.

For aquaculture and coastal water quality measurements, we would want to add imaging, microscopy, and genetic measurements to the mix – what is the distribution of species present at any given moment, and how is that diversity varying with time? The length scales of interest are now longer, since sources are typically not point-like, but the complexity of the measurement is significantly higher, both in terms of the processing required (i.e., computation, sequencing) and in terms of the number of samples required to secure a characteristic measurement; filtering one liter of water to detect eDNA is only meaningful if you believe that specific liter to be characteristic of the entire volume of interest. The scale of required instrumentation is correspondingly larger and will require a more substantive platform (e.g., existing infrastructure, autonomous vehicles) to deploy. Importantly, the bandwidth requirements for images/video can be traded off for edge computing, which turns the images into spreadsheets. We don't, after all, need a thousand images of copepods, we just need to know that there were a thousand copepods. The availability of absurdly capable low-power processing at rapidly shrinking cost thus allows us to use low-bandwidth channels to send these data to a distant high-bandwidth backhaul.

In the open ocean, the story is more heterogeneous. The length scales of interest include everything from tens of meters in depth to thousands of kilometers across the surface. Tackling this challenge will require a host of diverse platforms – floats dangling sensor cables into the deep ocean, profiling floats, autonomous surface vehicles (ASVs) and autonomous underwater vehicles (AUVs) (e.g., *Argo*[1], *Saildrone*[2], *Sofar Ocean*[3], *Slocum Glider*[4]) – as well as more conventional maritime assets like ocean-going vessels, open ocean farming infrastructure, wind farms, etc. The bandwidth options are correspondingly limited, which again favors edge computation, though the introduction of new CubeSat-based communication channels (e.g., *Swarm Technologies*[5]) may change that calculus in the decade ahead.

Finally, for community watershed monitoring and citizen science, sampling will, by its nature, be sporadic and sparse, but may achieve volumes and reach locations that would otherwise be impossible using conventional approaches. In thinking of the technical requirements here, it's helpful to take a lesson from astronomy and ornithology, two fields where citizen-scientists have made (and continue to make) essential contributions. Citizen science has been influential in these fields not because they are peculiarly easy but because powerful, inexpensive, easy, and fun tools are available, at scale, thanks to exogenous economies of scale. (Thanks to David Lang for making this point more beautifully than we can reproduce it.) For ornithology, the appearance of detailed, beautiful, and easy to use field guides helped turn birdwatching into a more accessible, pleasurable pastime, releasing generations of independent naturalists into the woods armed with the tools they needed to discover the unexpected. For astronomy, the appearance of commodity charge-coupled device (CCD) imagers, motorized mounts, and computer tracking programs, all developed and commoditized for completely different

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1 *www.aoml.noaa.gov/phod/argo/*
2 *www.saildrone.com/*
3 *www.sofarocean.com/*
4 *www.teledynemarine.com/slocum-glider/*
5 *swarm.space/*

reasons, made it possible to peer deep into the night sky and notice things that might never have been seen otherwise. For watershed monitoring and the exploration of the water around us, the essential step will be creating tools that are similarly powerful, inexpensive, and, most importantly, easy and pleasurable to use. Data should be collected automatically, geo-tagged, and forwarded wirelessly to a central server automatically, with no intervention required by the user. The devices should be small, rugged, and easy to maintain, with data and power transported wirelessly and transparently. The results of the users' exploration – their discoveries and contributions to the field – should be made visible, compelling, and ideally in a way that is easily shared with their communities.

All these technologies will be coming online in the decade ahead. Low-cost, low-power, high-quality platforms for instrumentation and exploration are pouring onto the market (e.g., Saildrone, Sofar Ocean, and a raft of other AUV, ASV, and smart-float efforts). Intelligent data pipelines that take in heterogeneous data streams and return actionable information are being developed for weather, coastal monitoring, aquaculture, and beyond (e.g., Google, Sofar Ocean, *Conservify*[6], *Hohonu*[7], and many others). An explosion of commercial work, from startups to industry heavyweights, is focused on developing commoditized low-power sensors, interfaces, communications channels, and instruments to parallel in the ocean the temperature networks in industrial factories (e.g. Raytheon, Sofar Ocean, *Oceanic Labs*[8]). Precisely what is needed, how these efforts should grow and evolve, where we should push them, and how the ocean exploration community should engage them, are important questions that we will explore during the National Ocean Exploration Forum.

Community Questions and Recommendations

In our minds, the technological roadmap, in broad strokes, is relatively clear. The biggest challenges facing the ocean exploration community are cultural.

First, we need to expand our default picture of ocean exploration to include not just ships and submersibles mapping the sea floor, but also fleets of thousands of commoditized AxVs, or millions of extremely simple floats, exploring the bulk of the ocean as well. Massively dense sensing allows us to explore the dynamical geography that grounds life in the ocean – eddies as lakes, light gradients as valleys, and microbiomes as seasons. Ships and bathymetry are certainly important, but even if we had centimeter-resolution maps of the entire seafloor today, most of the ocean would remain unexplored.

Second, we need to embrace industrial partnerships and industrial-scale activity to advance our exploration and stewardship goals. Creating floats or sensors at scale – tens of thousands at a time, or more – requires working with an array of industrial actors, and it means funding massively deployed projects at a scale that makes commoditization possible; scales similar to what is currently spent on individual ocean-going ships. It is not possible to build just ten one-thousand-dollar smartphones – but build one million and the economics start making sense. We need to expand our funding models – governmental, philanthropic, venture, and beyond – to invest at scale and make possible these exploration- and stewardship-directed technological innovations, and apply them for the public good.

Third, we need to work together as a community to develop, and actually use, standardized interfaces and standardized components. There is a good reason the computer industry uses USB, and it's not because USB is perfect – picking standards that are good enough and sticking to them is an essential step in commoditizing tools and going to scale. Crucially, this is not just about electronics – it's true of data pipelines and data formats, acoustic communications and interoperability, connectors and penetrators, logging and sensor interfaces; providing open standards is important (e.g., software, electronic, mechanical) so that swapping out one component does not require an entirely new system design. This is second nature in the software and electronics industries and is getting there in mechanical engineering – those of us who want to create the ocean technology of the future would benefit from learning from these examples.

6 *conservify.org/*
7 *www.hohonu.io/*
8 *oceanic-labs.org/*

Engaging the Public

Finally, we need to include in this robotic and big-data-centric model of ocean exploration, the communication and inspirational roles that big ships and cool submersibles have played. Inspiring the voting public to support wise policies, revealing to our fellow citizens their connections to the ocean (and dependence on its health), giving them the tools and the data to hold themselves, their governments, and the companies with which they deal accountable for their impact on the ocean, is an essential mission of ocean exploration. The grandeur and visual spectacle of ship-based ocean exploration has long played a central role in this story – and indeed a core reason to support the NOAA Ship *Okeanos Explorer* or the E/V *Nautilus* is to create powerful stories that engage the public in conversations about the ocean. However, kids don't start off caring about the bottom of the ocean, or its middle for that matter – they care about people, they resonate with the stories of the explorers who study the bottom of the ocean and discover the unknown, and they fall in love with the seafloor as a result. The lift here is to use a new set of tools – dense data, rich time series, computer modeling, and the power of data visualization in all its variety – to tell new adventure stories, too.

Milestones

Traditionally, milestones for ocean exploration have been about filling in the maps, from the voyage of the HMS *Challenger* to Seabed 2030. With an eye towards the larger vision of ocean exploration discussed above, it is useful to imagine some milestones for which we might aim in the years to come.

Concretely, by 2027 (five years from this writing), the authors would like to see:

- A collapse in the cost of ocean monitoring data, with commoditized instruments decreasing the cost per conductivity, temperature, and depth (CTD)-datapoint in $-Joules by two orders of magnitude compared to current COTS instruments and deployment methods.
- Investments (e.g., by NOAA, other public sources, national oceanographic organizations) in radically scalable monitoring that represents an O(1) fraction of conventional ship-based monolithic measurement approaches.
- The development and collaborative promulgation of open standards for specified interfaces (e.g., mechanical, electrical, computational) for ocean instruments, sensors, and components. Closed, proprietary, and monolithic engineering approaches represent some of the biggest, and most unnecessary, barriers to technological progress in this space.
- The establishment of partnerships between industry, academia, NGOs, and regulatory agencies to work towards the establishment of enforceable regulatory frameworks that depend on, and are enabled by, mass-deployed commoditized sensors and the infrastructure required to collect the resulting data and process those data into actionable insights.

By 2032 (10 years from this writing), the authors would like to see:

- Dense monitoring of at least 10% of municipal waterfronts, from the Atlantic seaboard to the Great Lakes, and the start of rapid growth into global ecosystems.
- Legally enshrined regulatory frameworks that depend on, and are enabled by, mass deployment of commoditized sensors.
- The vast majority of ocean instrumentation adopting a set of standardized interfaces (e.g., mechanical, electrical, software), accelerating development and dramatically simplifying deployment and maintenance of massively scaled monitoring networks.
- The NOAA Ship *Okeanos Explorer*, having reached end-of-life, replaced not by a newer ship but by a massive fleet of floats, AxVs, and other assets which allow us to explore the bulk of the ocean on length- and timescales which are currently inaccessible.