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Scaling the Connected Ocean

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Vision Statement

By 2032, technology development and associated operational models for ocean exploration will be primarily driven by data required to address important societal issues. A broad portfolio of capabilities, operating across sectors and disciplines, will be utilized and scaled globally, including vessels, other crewed and uncrewed (i.e., autonomous) surface and subsurface platforms, robotics, automation, artificial intelligence, and more.

Introduction

The second half of the 20th century saw an exponential increase in our understanding of the universe through systematic exploration of space. International networks and national programs involving Earth- and space-based observation and exploration activities unlocked mysteries, from revealing the *black hole centers*[1] of many galaxies to the *large-scale structure of the universe*[2] itself. Over the last two decades, rapid acceleration of Earth remote sensing from space using large networks of small satellites (i.e., distributed sensing) was made possible by miniaturization of electronics, CubeSat standardization, and successful *public-private partnerships*[3]. The progress has been remarkable, and *continues today*[4].

In contrast, over 80% of our Earth's ocean remains unexplored. The ocean is essential to adapting to and mitigating changes to the Earth's climate, which are inevitable and accelerating. Changes in our climate have profound impacts on economies, security, and human health. Worldwide, there is a growing understanding that the marine environment is critical for our existence, and it is under threat from human activities. High-value fisheries are *moving north*[5], tropical storms are *intensifying*[6], and *harmful algal blooms*[7] are becoming more frequent.[8] As a result, funding for marine conservation across the globe has doubled over the last decade, to nearly *$2 billion*[9], and governments, philanthropies, industries, and citizens are increasingly supporting ocean causes, ranging from basic research, coral reef conservation, and data acquisition and modeling to marine plastic removal, endangered species protection, and habitat restoration.

We are currently at a pivot point. Over the next 10 years, advances in technology and increased societal pressure will drive the creation of "Ocean Big Data," which will accelerate ocean discovery and understanding similar to what we have seen in space exploration and remote sensing. The global ocean system is the next big data frontier. A successful strategy for accelerated scaling of ocean data acquisition and dissemination will drive opportunities to improve Earth system management, facilitate prediction and mitigation for a changing environment, and develop a thriving blue economy that benefits from effective collaboration among industry, academia, philanthropy, government, and citizens. The opportunity is clear.

Ocean industries capture an estimated 3-5% of world gross domestic product (GDP), which represents trillions of dollars annually. However, the effective economical footprint of ocean industries is much bigger than that. For example, global maritime shipping transports 90% of everything we touch and is critical to the *world's*

1 *www.nasa.gov/image-feature/almost-every-galaxy-has-one-a-black-hole-that-is/*
2 *press.princeton.edu/books/ebook/9780691206714/the-large-scale-structure-of-the-universe/*
3 *www.bloomberg.com/news/articles/2021-12-08/planet-labs-has-roller-coaster-debut-after-blank-check-deal/*
4 *www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework-_-December-1-2021.pdf*
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6 *www.c2es.org/content/hurricanes-and-climate-change/*
7 *www.sciencedaily.com/releases/2021/10/211028143654.htm*
8 *www.washingtonpost.com/weather/2021/07/09/extreme-weather-government-commercial-partnership/*
9 *oursharedseas.com/funding/funding-exec-summary/*

supply chain[10], aquaculture already exceeds wild catch in volume[11], and marine renewable energy will be an increasingly important part of a successful green energy future[12,13]. Security and coastal domain awareness institutions are also rapidly exploring the deployment of autonomous technology[14]. Together, these represent a "New Blue Economy[15]" where data, insights, and conservation replace prior emphases on extraction and exploitation. The National Oceanic and Atmospheric Administration (NOAA) has recognized this[16], with public-private partnerships and emerging science and technology groups[17] playing leading roles. Other encouraging developments include a renewed focus on oceans[18] at the 2021 United Nations Climate Change Conference (COP26), and increased venture capital investments in the ocean enterprise (e.g., Ocean Aero[19], Saildrone[20], Bedrock Ocean Exploration[21], Sofar Ocean[22]).

Discussion

The opportunities are clear, and the need is urgent. To accelerate ocean and climate understanding, we must scale sensing capabilities, develop dissemination pathways to overcome barriers to access (e.g., technological, economical), leverage advances in data-driven analysis to accelerate insight creation, and apply all for public benefit.

Collection Platform Collaboration

The National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone ("NOMEC[23]") underscores an increased emphasis on collaboration among industry, government, philanthropy, and academia; rapid advances in Ocean "Internet of Things" (IoT) enable new autonomous and scalable technologies to be deployed in our oceans; modern data hubs and application programming interface (API) technology create platforms to deliver ocean information to increasingly wide segments of society.

The opportunities for Ocean Big Data are clear and limitless. Powered by new and emerging sensor technologies, satellite communication networks, photovoltaic technologies, and cloud-based data storage and delivery systems, unprecedented data densities will become available. In parallel, advances in data-driven modeling (e.g., machine learning) will make data more valuable and accelerate ocean understanding and predictive capabilities beyond anything seen to date. Yet, there are significant and non-trivial challenges in transitioning from a data-deprived state to a state where data are abundant. Effective ocean exploration and sensing at scale will involve planetary-scale, distributed networks with advanced, heterogeneous nodes. In this vision, rapid success requires a fundamental shift towards collaborative models to open up data pathways across government, academia, philanthropy, and industry. Over the next few years, technological advances will enable execution of this vision, but to deliver meaningful societal impact immediately, we should focus on several key areas.

Standardization for Network Scalability

Given the scale and remoteness of the ocean environment and the data density and coverage required for meaningful impacts, successful ocean exploration and sensing infrastructure must take the form of distributed multi-platform networks consisting of advanced, autonomous sensing nodes that carry heterogeneous payloads,

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10 *www.washingtonpost.com/business/interactive/2021/supply-chain-issues/*
11 *agfundernews.com/the-ocean-is-a-100tln-market-opportunity.html*
12 *www.wired.com/story/offshore-wind-farms-are-spinning-up-in-the-us-at-last/*
13 *www.nytimes.com/2021/10/13/climate/biden-offshore-wind-farms.html*
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23 *www.noaa.gov/sites/default/files/2021-08/NOMEC%20Strategy.pdf*

capture (or bring) energy, and communicate via satellite (or other networks). Ocean autonomous platforms are leveraging advances in IoT and (land/space-based) autonomous vehicles, photovoltaic and other energy-capture technologies, and new communication options. Disruptive satellite communication networks (e.g., *Starlink*[24], *Swarm*[25]) will remove communication bottlenecks for remote systems and massively decrease cost.

A key remaining obstacle to scalability and innovation in the ocean space is the lack of standardization. A distributed multi-platform and multi-modal ocean network will be characterized by varied and challenging environments and requirements, diverse stakeholders and use cases, subsystems with distinct and separable roles, and factors that introduce extreme sensitivity to hardware margin costs. In other fields, connectivity standards have been in use for decades to enable modular systems, and they are profoundly impactful (e.g., Modbus in industrial applications in the 1970s, USB for desktop computing systems, *CAN bus*[26] in automotive industries, Bluetooth in mobile, CubeSat in space). However, no broadly adopted standard has emerged for ocean connectivity. Instead, there are a wide range of connectors, protocols, and electrical specifications for bespoke projects and platforms. As a result, a large part of available funding for fundamental ocean research and technology is spent on repeatedly overcoming unnecessary engineering integration challenges; innovation in marine sensing is slow, scalable growth of networks is difficult, and investments remain limited.

Advances in standardization are at an early stage, but if successful, they will be disruptive. An example is the *Bristlemouth project*[27], which aims to provide an open access, full-stack connectivity standard to support high-level plug-and-play modularity for marine applications. Powered by a public-private partnership between the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research (ONR), *OceanKind*[28], and Sofar Ocean, Bristlemouth illustrates the power of such partnerships in executing on a joint vision and removing barriers to scale.

Data Access and Self-learning Analysis

With our ocean environment transitioning from a data-sparse into a data-abundant state, new opportunities for dissemination and analysis immediately present themselves. Modern *APIs*[29] and geospatial dashboards allow for rapid integration of information flows into applications and data systems, and on-the-fly visualization of geospatial data is made possible for anyone (e.g., *Allen Coral Atlas*[30], *Aqualink*[31], *nowCOAST*[32]). Environmental data from high-density, heterogenous networks will drive improvements in our understanding of ocean physics, biology, chemistry, and geology, and the accessibility of real-time data will power new data-driven assimilation strategies to mitigate extreme weather and climate events. The rapid growth of autonomous data collection will fuel ocean geographic information systems (GIS) to new levels, similar to terrestrial geospatial practices which have become well developed over the last 50 years.

However, rich new data applications will rely on seamless access across public and private data sources and require business models focused on the sustained growth and scaling of data accessibility. Such Data-as-a-Service (DaaS) models have been successfully pioneered in spaceborne and terrestrial applications and can be used as a building block for successful data partnerships between industry and government organizations in ocean exploration.

If the community succeeds, the result will be unprecedented data density across every region of our ocean environment, powering combinations of traditional physics-based methods with machine learning algorithms to progress ocean understanding and predictability at rates we have never experienced before. The potential is enormous.

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27 *www.bristlemouth.org/*
28 *oceankind.org/*
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30 *allencoralatlas.org/*
31 *aqualink.org/*
32 *nowcoast.noaa.gov/*

Conclusion

The stakes are higher than ever, and time is of the essence. Over the next decade, we will witness a rapid transition toward a data-abundant ocean fueled by the increasing awareness of the societal economic importance of our ocean environment and powered by advances in core enabling technologies. The biggest challenges for the ocean exploration community are to drive standardization (to scale) and create pathways for data sharing and accessibility. The following strategies can help us move faster toward the shared goal of a more sustainable future:

- **Public-private partnerships.** Remove barriers of proprietary technology to advance community-wide technologies and standardization and enable industry to work with government agencies to allow access to larger data pools faster and at lower costs.
- **Policy changes.** Ensure that government agencies are incentivized and funded to work with industry. Low-friction contract vehicles are needed to support this and to develop a joint vision around a connected ocean and advance the blue economy.
- **Public relations.** Educate the public on the economic and climate importance of our marine environments and the critical value of ocean data, especially in the youth who will drive the next generation of technology evolution and breakthroughs.

To realize the opportunities of Ocean Big Data over the next decade, the challenge is not solely, or even primarily, technological. The technology is mostly available or already developing. Instead, success critically depends on how the global ocean community works together across organizations to remove friction to innovation, open up data pathways, leverage strengths and capabilities, and unite to scale. A successful path to scalable ocean exploration is not a zero-sum game and the resources needed far exceed current funding levels by several orders of magnitude. It is therefore clear that the funding to succeed cannot and should not come from government sources primarily. Instead, successful scaling must leverage large commercial opportunities and investments. In areas where commercial opportunities are available (e.g., weather, aquaculture, data acquisition) government agencies can become key customers or partners to enable commercial companies to drive efficiency and scale by creating demand and multi-customer business models. This also ensures that more focus and funding is available from government and philanthropic sources for societally-relevant research that cannot (and should not) create direct commercial value (e.g., deep-ocean circulation, climate research).

Key Factors for a "Blueprint" for the Ocean Exploration Community:

There is increasing awareness of the societal importance of our ocean environment. Accelerated scaling of ocean data acquisition, adoption of modern data storage and distribution technologies, and development of data-driven analysis methods is critical to deliver new insights. Enabling technologies will support rapid and sustainable growth of data acquisition systems over the next five years. The future of large-scale geophysical data acquisition is inherently multi-platform, multi-modal, and multi-organizational. As a result, the primary challenges to create a connected ocean are in ensuring free-flowing pathways for data and effective public-private partnerships to support that. The community has the opportunity to shape the future of ocean exploration by developing strategies that consider the following:

- Access to data from multi-platform networks with distributed ownership. The building of data pathways across private and public sources is critical.
- Standardized connectivity of components and systems to drive scalable growth and innovation in the marine space.
- Effective public-private partnerships to drive scale, remove barriers to growth, and create access.
- Robust commercial data service models to create seamless access to private data sources and drive new investments into the space.