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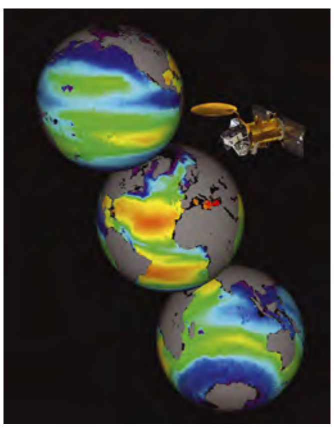
The State of Technology in 2013

Front Cover: A global perspective highlighting some of the key technology advances described in this issue (insets left-to-right): An artist's depiction of a fully automated seafloor analytical laboratory off the Pacific Northwest coast; Liquid Robotics Wave Glider® communicating in the Gulf of Mexico; USS *Makin Island*; Ekofisk complex on the Norwegian shelf (photo courtesy of Anne Karin Magnusson); Carnegie Wave Energy's© submerged buoy off western Australia; and (overhead) the Aquarius/SAC-D satellite. *Image courtesy of HARRIS Corporation*.
Back Cover: Three global perspectives of the yearly averaged surface salinity data measured by the Aquarius/SAC-D satellite in 2012. *Image courtesy of the NASA Goddard Space Flight Center, Aquarius Project Office*.



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The State of Technology in 2013
Guest Editor: Donna M. Kocak

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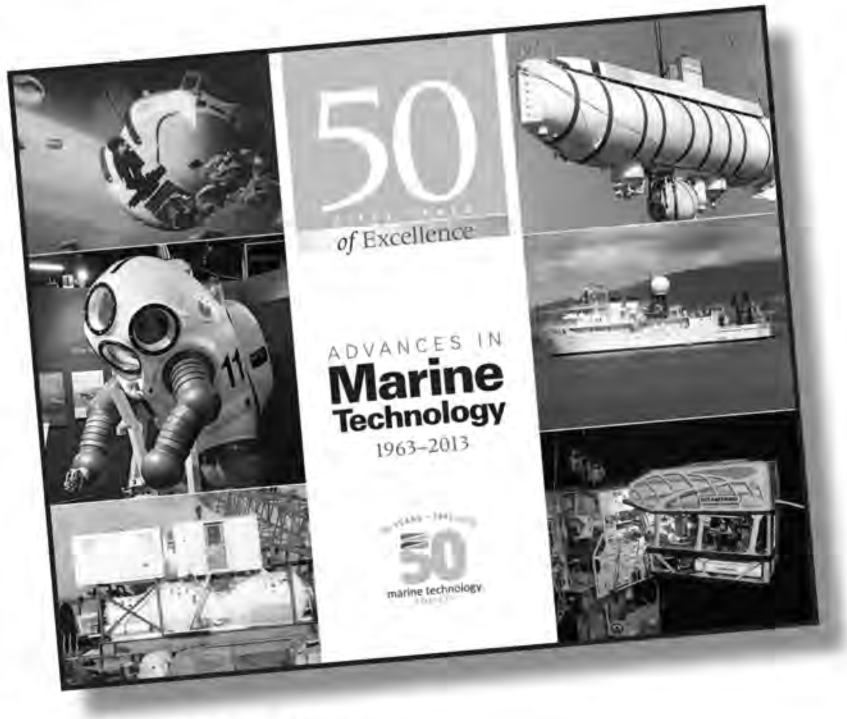
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FOREWORD

The State of Technology in 2013

Donna M. Kocak
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The last State of Technology special issue of this *Journal* was published in 2008. Since that time, a surprising number of truly transformative technologies have taken hold in the world, emerging more as incremental rather than disruptive innovations. Although it now seems an indispensible part of society's fabric, Apple's iPhone was only introduced in 2007. Since that time, "smartphones" have literally changed not only commerce but the actual everyday lives of most individuals living in the developed world. These devices and the attendant software applications ("apps") that have been spawned to support them are providing the "information at your fingertips" that has transformed the average person into a walking combination: encyclopedia, weather forecaster, news and photojournalist, navigator, and cartographer (among many other functions). By 2007, the ocean science community had already developed an appetite for receiving a continuous stream of as much information from as many locations as possible. "Citizen scientists" armed with smartphones and killer apps will likely become an increasingly larger contribution to this real-time information stream.

While the historical trend has been the maritime industry adapting technologies that were first developed for terrestrial applications, one example where these roles were reversed is driverless vehicles—long the domain of the subsea world. However, economies of scale will dictate that the heavy lifting (and heavy investment) for technology breakthroughs will most likely continue shore side, where the potential user market is measured in the tens and hundreds of millions. Earlier this year, Motor Trend Magazine's Car of the Year award went to the all-electric Tesla-S. This achievement would not have been possible without the sizable investment in making long-range, long-duration mobile batteries a reality. Still on the drawing board at Tesla (but almost ready for primetime) is an "electric-electric hybrid" system employing two different battery chemistries that portends to tremendously extend the range for electric vehicles even further. A primary lithium-ion battery for energy-intensive, "close-in" missions would be supplemented by a metal-air pack (with high energy density but low power density), well suited for longer hauls. Toyota and IBM are also investing heavily in next-generation solid-state batteries that could find their way into AUVs in the near future. Tesla has also tackled the issue of rapid refueling—in this case, by developing a system in which an expended battery pack can be swapped for a fresh one in less than 90 seconds. In the subsea arena, Schilling Robotics similarly recognized the importance of quick turnaround for maintaining

ROVs on the job. In his commentary, Tyler Schilling attributes the simplicity of replacing the toner cartridge of an HP printer as the inspiration for their design of a series of ROV subsystems where serviceable items have been moved to the outer layer, requiring only a few tools and minutes for service and repair.

According to the National Institute of Standards and Technology (NIST), cloud computing is "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." While the idea of cloud computing has been around by one name or another since the 1960s, it has really only been the past 5 years or so that has seen it begin to transform the IT world. Cyberinfrastructure is "the coordinated aggregate of software, hardware and other technologies, as well as human expertise, required to support current and future discoveries in science and engineering" (Berman, 2005). Fortunately for the ocean science and technology community, the formative phase of National Science Foundation's Ocean Observing Initiative's (OOI)-Cypberinfrastructure Initiative (CI)—one of the most ambitious efforts ever to be undertaken by this community in terms of data processing and management—coincided with the practical emergence of cloud computing. That fortunate coincidence enabled the architects of the OOI-CI to design the system to take full advantage of this powerful technological innovation from the onset.

The reader will no doubt think of other technologies that either already have or shortly will find their way into solving problems in the marine environment. We hope that you both learn from and enjoy this State of Technology special issue. At the current pace of evolving technology, it is likely that you will see yet another State of Technology issue by the end of this decade detailing the adaption of these transformative advances in the maritime domain.

Reference

Berman, F. 2005. SBE/CISE Workshop on Cyberinfrastructure for the Social Sciences, San Diego Supercomputer Center. Feb. 18, 2005. Accessed 18 Sept. 2013, http://web.archive.org/web/20060911191710/http:/vis.sdsc.edu/sbe/SBE-CISE_Workshop_Intro.pdf

COMMENTARY

Motivations and Methods for Modern Maritime Communications: A Survey of Recent and Emerging Trends

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Nearly 25 years ago, a similar article in this journal by Mel Briscoe (1987) brought readers up to date on that day's state of the art in ocean data telemetry. Since then there is much new technology to report in this rapidly evolving field. Rather than include a rehash of the previous article prior to covering what's new, a link[1] has been activated on the MTS Website where the interested reader can review that excellent piece and allow this survey to simply pick up where Mel left off. But first, as you read the other contributions in this year's State of Technology Report, note that a common thread links them together, whether explicitly stated or not. There remains a need for collecting timely and accurate data so well-informed decisions can be made. This is the "Why?" that Zdenka Willis and Laura Griesbauer discuss in their State of Technology commentary on the Integrated Ocean Observing System.

[1] Link for MTS members; nonmembers contact dkocak@harris.com https://www.mtsociety.org/MemberFileManager/streamfile.aspx?name=Motivations+and+Methods+for+Ocean+Data+Telemetry.pdf&path=journal%5c

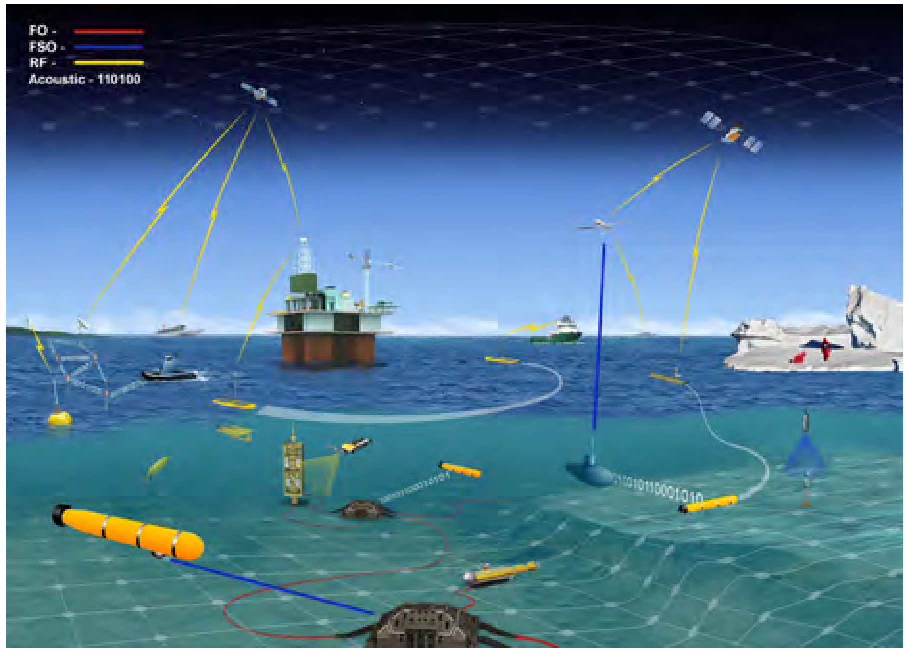
Recent Motivations

The cost of sending ships and personnel to sea is becoming increasingly prohibitive. There is a need to monitor larger volumes of the oceans at greater depths for longer periods of time and, in some cases, getting in harm's way to do so. These factors, along with technological advances and economics, have contributed to a proliferation of unmanned ocean-borne systems. In the coming years, unmanned systems will likely represent the largest users of maritime telemetry, relying on communication links to shore operations centers, ships, submarines, aircraft, and satellites in addition to other unmanned systems in close proximity. Among these unmanned systems will be autonomous underwater vehicles (AUVs), unmanned surface vehicles, subsea and surface gliders, remotely operated vehicles (ROVs), hybrid ROVs, and fixed platforms including buoys, seafloor nodes, motes, industrial infrastructure and machinery, cargo shipments, surveillance cameras, and environmental sensors that report their status, receive instructions, and even initiate tasks based on the information they receive. Unmanned aerial vehicles (UAVs) and high-altitude balloons can be considered in the discussion since they may also operate in the maritime domain as communications relay units. Two examples are Boeing's Insitu ScanEagle X200 and AeroVironment's Puma AE (All Environment) drones that were recently certified for civilian use by the Federal Aviation Administration. The ScanEagle will be deployed to survey ice floes and migrating whales for a major energy company, while the Puma will be used by emergency response crews to monitor oil spills and track wildlife over the Beaufort Sea (Lowy, 2013).

Unmanned systems impose a strict set of requirements. Their fundamental tenets for communications are persistence, endurance/reliability, survivability, and affordability. Unmanned vehicles typically undertake a preprogrammed mission, consuming only the limited power they can carry. Even if the vehicle is capable of generating power, as with a wave energy scavenger, the sensor payload is still energy constrained. Thus, low-power, low-energy solutions are a necessity for robust and reliable bidirection communications. That said, there are some situations where low-cost, short-life, one-way communication solutions are appropriate. Low-cost sensors may be deployed to operate and transmit for a limited period of time (days, weeks, or months), after which they are designed to sink to the bottom or float to the surface. Tracking sea life and ice floes or tracking an AUV are all candidates for such a "power stingy", one-way path. Vehicles must typically upload mission data and download new commands at sea and take periodic GPS fixes to update internal navigation equipment. Maximizing operational time is critical, as is having disparate and redundant methods for communications. This may include multiband line-of-sight (LOS) and beyond-line-of-sight (BLOS) solutions. Their communication systems must be able to survive the harsh ocean environment, submerged, and exposed to great hydrostatic pressure, biofouling, and corrosion. Finally, since unmanned vehicles run the risk of being lost, vandalized, or recovered by an unknown entity at sea, their communications system must be tamperproof and affordable. Using commercial-off-the-shelf (COTS) or government-off-the-shelf (GOTS) equipment, minimizing new (custom) designs, following standard formats and protocols, and utilizing robust, small, and low-power microelectronics components when possible can help to reduce costs. Small vehicles have a greater need for compact size (small), low weight and power (SWaP) communication systems, while military vehicles might also require communications security that denies unauthorized persons any telecommunications information.

FIGURE 1

Networking the global maritime domain using FO, FSO, RF, and acoustic technologies.



Recent Methods

Figure 1 depicts a variety of methods currently employed by manned and unmanned systems for networking in the modern global maritime domain. Common methods are radio frequency (RF), fiber optics (FO), free space optics (FSO), and acoustic technologies such as acoustic data modem (ADM).

Through the Ether

The electromagnetic radio spectrum has been utilized to communicate at sea for more than a century. The very high frequency and ultra high frequency bands are routinely employed for LOS (point-to-point or point-to-multipoint) communications over short distances. High frequency is still employed in tactical radios by the military and emergency managers for BLOS communications but has been substantially phased out for civilian use in the face of the increasing affordability of satellite communication (SATCOM) solutions. For 20 years, SATCOM service for the maritime community was almost exclusively the domain of the International Maritime Satellite Organization (Inmarsat), an international not-for-profit organization established in 1979 at the behest of the United Nation's International Maritime Organization. Prior to the massive data requirements of today's ocean going fleet, Inmarsat provided vessels at sea a sort of "payphone" service (for both voice and data) at appreciable cost per minute but sparing users the continuous cost of leasing a portion of satellite transponder. In 1999, Inmarsat became privatized, and since then a number of other SATCOM service providers have appeared on the scene to offer vessels and other offshore operators continuous broadband service at increasingly affordable rates.

SATCOM systems may be generally categorized by their satellite orbit, among the most common are geostationary Earth orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO), as illustrated in Figure 2 and summarized in Table 1. GEO satellites orbit about 36,000 km above the equator in the same direction and speed as the Earth rotates, making them appear fixed in space over a single point on the equator. They offer the highest throughputs and provide a "fixed" target at which to aim with an earthbound antenna as well as a large global coverage footprint, but they have the disadvantages of longer latencies due to the time-consuming round-trip for the data to travel and greater propagation losses from a ground-based emitter to the satellite. They are often spaced in positions that allow multiple satellites to be triggered if the ground-based antenna patterns are too broad.

FIGURE 2

Satellite orbits commonly utilized in maritime communications (Fitchard, 2013).

TABLE 1

Satellite orbit characteristics (Durofy, 2012).

Parameter	LEO	MEO	GEO
Orbital Altitude	≥ 160-1,500 km	5,000-12,000 km	35,800 km
Orbital Period	10-40 minutes	2-8 hours	24 hours
No. of Satellites	40-80	8-20	3
Satellite Life	< 15 years	< 15 years	~ 18-20 years
No. of Handoffs	High	Low	Least (none)
Gateway Cost	Very Expensive	Expensive	Cheap
Propagation Loss	Least	High	Highest

A minimum of only three GEO satellites properly positioned can provide global coverage. MEO satellites are located in orbits above LEO but below GEO satellites. GPS navigation relies on MEO satellites. MEO satellites require a larger constellation of "birds" to provide continuous global coverage in order to ensure a visible ground-based emitter as the satellites travel horizon-to-horizon. LEO satellites orbit closer to the Earth and, because of their proximity to Earth and subsequent quick orbit, require an even larger number of satellites than MEOs to provide global, continual coverage. LEO satellites offer the lowest throughputs but also suffer the least latencies and link losses. They make use of the smallest antennas and require less amplification for transmission due to their closer proximity to Earth. At any given frequency, LEOs experience ~22 dB less path loss than MEOs and ~33 dB less than GEOs. To put it simply, a GEO satellite requires 2,000 times more power to transmit the same amount of information as a LEO.

Highly elliptical orbit (HEO) satellites are a sort of hybrid class, with a low altitude perigee (~1,000 km approach) to Earth but a very high altitude (up to 36,000 km) apogee. This can result in a "hang time" that gives up to 12 h of coverage over a portion of Earth's surface. Satellites are commonly used to provide coverage of the Polar Regions, which are out beyond the range of satellites in equatorial orbit. HEOs are also used to study other satellites in GEO, MEO, and LEO orbits. NASA's Aquarius remote sensing satellite, the focus of Gary Lagerloef's commentary in this issue, is in a sun-synchronous (SS) orbit 657 km above the Earth. This is a special case LEO that sends the satellite on a path synchronized to pass over any specified Earth latitude at the same mean solar time at scheduled intervals.

Table 2 lists SATCOM bands and frequencies, coverage, and sample operators. L band is primarily used for lower bandwidth communications. C band is restricted in power and thus requires a larger antenna, usually more than 2 m in diameter. Due to its lower frequency range, C band performs better through atmospheric interference such as adverse weather conditions known as "rain fade." X band is primarily used for maritime radar and military communications and is ideal for Comms-on-the-Move (COTM) applications. The wide separation between adjacent X band satellites minimizes the danger of "lighting up" a neighboring bird with its high power beam while transmitting from an antenna bouncing around "on the move." Currently, the largest users of Ku band are consumer direct-to-home access providers, distance learning applications, retail and enterprise

TABLE 2

Satellite RF frequency bands (GHz) commonly utilized in maritime communications.

Band	Freq (Approx)	LEO	MEO	GEO	Global Access	Sample Operators
VHF	30-300 MHz	Y	N	N	Y	Orbcomm
UHF	0.3-3 GHz	-	-	Y	Y	Paradigm Argo
L	1-2 GHz	Y	N	Y	Y	Iridium, Globalstar, Thuraya, InmarSat
S	2-4 GHz	Y	N	Y	Y	Globalstar
C	4-8 GHz	N	N	Y	Y	Intelsat, SES, Telesat
X	8-12 GHz	N	N	Y	Y	Paradigm, XTAR
Ku	12-18 GHz	N	N	Y	Y	Intelsat, SES, Telesat, Eutelsat
K	18-27 GHz	N	N	Y	Y	Direct TV, Dish
Ka	27-40 GHz	N	Y	Y	Y	O3B (MEO), Inmarsat (GEO), Avanti
U	40-60 GHz	N	N	N	-	N/A
Q	33-50 GHz	N	N	Y	-	Alphasat
V	50-75 GHz	N	N	-	-	Telesat
W	75-100 GHz	N	N	N	-	N/A

applications. X band antennas are much smaller than C band and are more susceptible to rain fade. Ka band is primarily being used for two-way consumer broadband and military networks. Transmission power required for Ka band is significantly more than the other bands allowing for higher bandwidth, but due to its higher frequency, this band is also the most vulnerable to rain fade.

Every application represents a tradeoff among RF power (comprised of the power amplifier and its associated 20–60% efficiency), the antenna type (dish, planar patch, etc.), and gain. Other considerations are motion stabilization, modulation and coding waveforms, and of course cost. For almost every application, solutions may be found to achieve high data throughput, but sometimes at a prohibitive cost in terms of size, power, and/or money.

A new constellation of MEO satellites in the process of being launched this year by O3b Networks will orbit at an altitude of 8,062 km and provide satellite bandwidth approaching some fiber rates. O3b's goal is to deliver satellite Internet and mobile backhaul services to the "Other 3 billion" (O3b) of the world's population (emerging markets) who are currently without Internet access (Felix, 2013). This constellation will transmit over Ka band at up to 1.2 Gbps. Some large passenger cruise lines have already begun to presubscribe to this new service.

Alphasat I (Inmarsat-XL) is scheduled to be in operation by 2014, expanding Inmarsat's coverage for Europe, Asia, Africa, and the Middle East. This GEO satellite will be positioned over Africa as offshore energy exploration and production continues to grow in Western Africa. In addition to voice and data services, Alphasat will also carry technology demonstration payloads for the European Space Agency. Planned payloads include an advanced star tracker and an optical laser terminal for GEO-to-LEO communication at high data rates, something NASA is also planning in the near future. One payload will be dedicated to the characterization of transmission performance in the Q and V bands in preparation for possible commercial exploitation of these frequencies.

Iridium has announced the scheduled launch of their new NEXT (INX) LEO constellation for 2015. Based on the broad adoption by maritime unmanned systems of Iridium's existing constellation, this new constellation is also likely to be embraced since it is expected to offer higher data rates for both L band and Ka band services. Table 3 compares these and a few other recent SATCOM systems.

Another noteworthy communication satellite is CubeSat, a small (10 cm × 10 cm × 10 cm) cube-shaped satellite designed to piggy back within a standard launch payload bus to "share a ride" into space. Since 1999, CubeSats have been providing the National Reconnaissance Office, Department of Defense, and other users a platform for rapid technology maturation and rapid deployment at a relatively low cost. CubeSats are placed in a LEO designed to last an average of 18 months before the orbit decays.

Through the Water

FO submarine cables, acoustics, FSO, and RF all provide a means of communicating through the water. Each method has inherent advantages and disadvantages, but in combination their synergistic strengths can augment system performance under various operational environments. Figure 3 compares range versus data rate of these technologies. The red dashed line in Figure 3 indicates what many agree is the minimum acceptable data rate (10 Mbps) for compressed high-definition video.

Underwater FO Networks

Today, high bandwidth communication corresponding to terabits per second can be achieved over thousands of kilometers on field-installed, standard single-mode fiber as recently demonstrated by Huang et al. (2013). More

TABLE 3

Summary of some recent SATCOM systems.

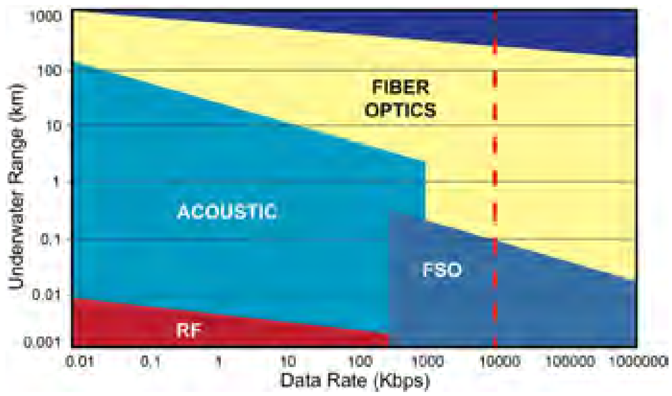
New SATCOM Systems	Frequency Band	Max Data Rate	Coverage	Aperture Size	Comments
Globalstar-2 (LEO)	L & S	9.6 kbps, 19.2 kbps available	Global	Mini-stick 7”x3/4” or 2.6” dia.	18 now in orbit; 24-48 planned
Iridium Next (LEO)	Ka & L	0.5 to 1.5 Mbps (L), 8 Mbps (Ka)	Global	9” x 22” (Pilot-Maritime Svc)	72 satellites at 780 km; deployment in 2015-2016
COMMStellation (LEO)	Ka	12 Gbps per satellite; Per-user rate TBD; intended for ISPs, cellular backhaul, etc.	Global	Data rate dependent	78 satellites, polar orbit, 20 ground stations; 2015 deployment
OG2 (Orbcomm Generation 2) (LEO)	VHF	4.8 kbps (msg-based, NRT)	Global	2 ft whip or smaller with reduced performance	18 satellites, 15 ground stations, 100-140 passes per day, 1 to 20 mins latency; 2012-2015 deployment; <1% duty cycle
O3b (Other 3 billion) (MEO)	Ka	256 kbps up, 1000 kbps down (50 cm antenna)	Global (±45° latitude)	50 cm or 100 cm, up to 3.5 m	8 then 16 satellites; 2013 deployment; very high throughput
Inmarsat 5 (GEO)	Ka & L	60 cm antenna; 10 Mbps up, 50 Mbps down	Global	60 cm and 100 cm	3 satellites; 2013-2014 deployment
Alphasat XL (GEO)	L	750 channels at 500 kbps	Centered at 25° E latitude	Data rate dependent	1 satellite; 2014 deployment; supplements Inmarsat 4 BGAN service

than a million kilometers of FO cables now span the oceans and well over 95% of the world’s international communications is routed through these cables (Carter et al., 2009). FO submarine cables are less costly to operate and provide faster service than SATCOM, the latter only beginning to achieve data rates above megabits per second. Initial construction and installation of submarine cables is costly, and they are not typically available in sparsely populated regions. Cables may also be somewhat susceptible to trawling and anchor damage near shore (Clark, 2006).

With the implementation of coherent transmission formats, FO data rates have increased rapidly over the past decade, from 10 Gbps, then 40 Gbps, and now to 100 Gbps. Perhaps even more important is the recent increase in bandwidth optical spectrum. Only a few years ago, an 18-nm optical bandwidth was typical. Today systems are being implemented that allow each fiber to carry 100 or more wavelengths. This provides potential opportunities for noncommercial users to team with telecommunications system owners on hybrid-use systems. It is now possible to dedicate a few wavelengths to ancillary uses without substantively reducing

FIGURE 3

Comparison of some common underwater communications methods.



the overall telecommunications-carrying capability of a commercial network.

In addition to more wavelengths, today's fibers can carry wavelengths of varying data rates. Seafloor instruments and environmental sensors with lower rate signals can now be multiplexed onto the same fiber as the 100 Gbps coherent telecommunications traffic. A new subsea Reconfigurable Optical Add/Drop Multiplexer under development will allow real-time wavelength allocation across the bandwidth (Enright and Manna, 2013), thereby providing the flexibility to accommodate additional traffic.

Offshore energy platforms being networked together with FO cables is also becoming commonplace (Clark & Kocak, 2011). BP's Gulf of Mexico network is one such example. With a goal to provide branching and subsequent backhaul for voice and data to the surrounding platforms of its competitors, the network stands as further testimony to the desirability of optical communications and the attractive business proposition of owning the network asset.

As for subsea hardware associated with submarine telecommunication cables, most related equipment is now qualified to carry 15 kV and can support even more Power Feed Branching Units in any given segment. Dual conductor cables are able to supply both high voltages for the backbone while also providing lower voltages for specialized submerged equipment. Powered FO cables are increasingly being employed by the growing number of ocean observatories being deployed for decadal monitoring of the oceans (Clark, 1999 and 2003, Kocak, 2013). A recent cruise led by John Delaney, whose Commentary appears in this issue, successfully installed the secondary infrastructure associated with the Regional Scale Node cabled observatory network.

Acoustic Communications

At this point, the most common method of wireless communications through water is via acoustic transmission. Acoustic waves have the advantage of being able to travel long distances (100s km) in seawater; however, there is a trade-off of data rate versus range. The speed of sound in seawater is highly dependent on environmental conditions including salinity, temperature, and pressure, though these effects are generally well known and modeled. A new commercial modem has successfully implemented Wi-Fi modulation techniques to achieve 3–10 times higher data rates (depending upon environmental conditions) than previous designs, providing robust communication links in the presence of echoes and reverberations (Li et al., 2008). These and other advances should result in more effective multiple node network configurations and allow multihop wireless communications for redundant communication paths. Other recent research has been focused on small, low-cost, disposable acoustic nodes that can be dropped from aircraft to gather intelligence or communicate and coordinate underwater assets in a region (Economist, 2013). More information on the latest acoustic technologies is presented in the State of Technology commentary by Milica Stojanovic and Lee Freitag in this issue.

Underwater FSO

FSO is an emerging technology for high-bandwidth communications, both above and below the ocean's surface (Scholz, 2011). Underwater FSO is achieved using lasers or light emitting diodes (LEDs), typically in the blue or green (or blue-green) wavelengths. Lasers provide a highly collimated beam, resulting in greater bandwidth and long range. Broad beam LEDs consume less power but suffer higher losses as their beam is dispersed over a greater angular field of view. One advantage of the LED's broad beam is that it can eliminate the strict pointing requirements needed to connect with the narrow beam laser. The implementation and geometric configuration of FSO optical systems depend upon the application, bandwidth, and range requirements. LEDs in clear water conditions are typically limited to 10 Mbps at distances of 100 m or less (to the left of Figure 3's red dashed line), while lasers significantly extend this range (the area to the right of Figure 3's red dashed line). Nonetheless, both lasers and LEDs suffer from losses due to scattering and absorption, as well as with structural and biological obstructions. Novel distributed laser techniques are now being investigated that employ multiple platforms to distribute laser transmitters and detectors in bistatic and multistatic geometries (Dalgleish, 2012). These techniques could both improve laser communications and facilitate imaging in highly turbid conditions and may even allow signals to be received "around corners." These and other novel methods are discussed in more detail by Dalgleish et al. in their State of Technology technical paper on laser imaging in this issue.

DeepStar®, a consortium comprising offshore energy operators (and the subject of a special focus in the May/June issue of this *Journal*), has identified a future need for high-bandwidth wireless communications. Some goals stated by DeepStar are rapid data harvesting from subsea equipment and command and control (C2) of AUVs when they are in close proximity of subsea equipment. One concept of operation (CONOP) would have a pilot on the surface take control of the AUV when the vehicle transits within a specified radius of the equipment. A high-bandwidth FSO communication link would transmit compressed high-definition video from the vehicle's cameras to a communication node fixed on the structure or seafloor that is hard-wired to the surface. From here, the pilot would transmit lower-bandwidth commands back through the node to the AUV. This CONOP would provide for inspection or light intervention operations. Once the man-in-the-loop operation is completed, control would be returned to the AUV.

Other recent research has been focused on developing and testing FSO laser communication methods to transmit secure information across the air/sea interface, between submarines at depths of up to 100 m and satellites or airborne platforms. *Naval-Technology.com* (2012) reported research using quantum key distribution protocol. Rather than traditional bits of 1s and 0s, this method utilizes "qubits", the quantum state of a photon. Research currently underway is exploring the feasibility of this as another method of undersea FSO.

Underwater RF Communications

Low RF frequencies transmitted from the surface using large, high-power antennas (kilowatts to Megawatts) can penetrate water (one way) at very low data rates (10s bps) to depths of up to 100s m over very long ranges (100s km). However, much lower power (16 W transmit/4 W receive) commercial underwater RF communications systems are available that operate completely underwater at data rates up to 156 kbps at closer range (up to 10 m). These systems can achieve greater range (over 30 m) at the expense of lower data rates (100 bps). Advantages of RF include its resistance to degradation by environmental conditions, its ability to transmit data across water-air and ground-air boundaries, its ability to penetrate the surf zone, ice, harbor walls or other solid materials, and a wide field of view that does not require strict pointing. RF is, however, susceptible to in-band electromagnetic interference (EMI).

Another option in the electromagnetic spectrum that can be used for very short range (<2 m) wireless communications is near-field magnetic induction (NFMI). Standard RF modulation schemes can be employed, but instead of using an antenna to generate and transmit a beam, the transmission energy is localized within the magnetic field between two devices. This method of communications is virtually immune to interference from other RF signals and reasonably secure due to its short operational range. Typical subsea applications are data and power transfer on AUV docking stations and vertical profile systems.

Emerging Motivations and Methods

Tomorrow's challenges might be predicted by looking at trends across all sectors of the maritime domain—academia and science, industry, government, and the modern battlefield. Several topics of interest are discussed in the following sections.

Increased Situational Awareness

One trend common to all maritime stakeholders is the need for increased situational awareness (SA). In the offshore oil and gas industry, operations are moving into more remote regions of the world where there is scant communications infrastructure in place, and energy exploration continues to push the envelope in terms of water depth. It has become essential to be able to reliably and continuously provide communications to personnel on rigs and FPSOs (floating production, storage, and offloading platforms) for business and entertainment (ArabianOilandGas.com, 2012), subsea equipment for real-time state of health (SOH), "barrier assurance" monitoring for alerts and notifications, and transportation services for carrying personnel safely between platforms. A longer-range goal of the oil and gas industry (and the military) is to minimize personnel at sea. Unmanned systems provide a means of achieving these goals both above and below the surface. "Resident" AUVs are envisioned that will "live" for months or years at a time on the seafloor near oil and gas infrastructure. These AUVs might rely on cabled docking stations for stationary power and communications and support a variety of inspection and maintenance tasks.

Government entities like the National Oceanic and Atmospheric Administration (NOAA) rely on real-time data from satellites in addition to coastal and offshore observatories in order to predict and track storms and monitor sea ice extent in the vicinity of shipping channels to provide vital and lifesaving alerts. The ability to collect more and better data in a timelier manner during extreme events will demand even more from communication systems. Perhaps surface gliders may need to be deployed to ride out hurricanes. In any event, multiple disparate and redundant methods will be required to assure communications in the event one fails due to poor environmental conditions.

In military applications, knowing the precise location of both friendly and hostile assets and personnel is vital to maintaining dominance. Assets that provide this advantage can include subsea, surface or aerial unmanned vehicles.

In the near future, SA will likely become a background task of the C2 communications structure, analogous to the role GPS now plays in consumer mobile communications. Today, whether or not you like it or are even aware of it, position information is routinely (if not securely) appended to your day-to-day voice and data traffic. In a military scenario, this information might be routed to a SA collection point or control center allowing decision makers to plan and execute missions with full advantage of seeing the "big picture."

More Bandwidth and More Speed

Having now entered what some have termed the "Big Data Revolution," regardless of the amount of bandwidth made available, the appetite for more is insatiable. As the number of platforms that carry sensors increases, the resultant resolution these sensors provide increases in kind. This is particularly evident with the high-resolution sonar and optical imaging systems that have been described elsewhere in this State of Technology Report. Another example of this demand that increased resolution puts on bandwidth is found in the burgeoning field of Full Motion Video (FMV), key to the success of UAVs. Similarly, mission durations are increasing—now *days* in the case of AUVs, *months* with regard to ocean gliders, and *decades* when considering offshore production facilities and ocean observing systems. A nearly unfathomable quantity of environmental data is already being collected in real time, much of which must be processed in near real time to be of optimal value. In an effort to minimize the volume of raw data that must be transmitted, specialized low-power, onboard processors such as graphics processing units, field programmable arrays, and microcontrollers are now essential to preprocess data. As a result, more onboard memory will be required to archive raw data for post mission downloading or to transmit when a high-bandwidth channel becomes available.

The increased need for real-time information is driving the need for not only higher speed data transmissions but also lower latencies. Advanced hardware and improvements in algorithms are facilitating enhancements in communication speed. Examples of this include O3b and INX satellite constellations, Wi-Fi protocol embedded in acoustic modems, and the recent FO technologies that have all been discussed here.

Improved Information Security and Secure Data Links

Secure data links are of course required for military applications but have also become essential in the transmission of financial, personal, and all manner of business transactions. Improved security will require stronger, embedded encryption/decryption for voice and data traffic. Military research continues to advance electronic counter-counter measures (ECCM) to sustain communications in the presence of intentional jamming, and the use of Low Probability of Intercept (LPI) and Low Probability of Detection (LPD) methods for the safety of forward-deployed troops operating in hostile areas.

A balance between data rate versus energy must be struck in considering both LPD and LPI. A fixed measure of energy is required to transmit each bit of data, regardless of transmission rate. Higher data rates consume more energy per unit time (instantaneous power) than lower data rate transmissions, but the total energy consumed remains approximately the same. The first rule of thumb to achieve good LPD/LPI is to minimize the transmit time. The second rule is to eliminate radiation in undesired directions. Finally, the third rule is to use spreading waveforms to reduce the spectral energy density. Another factor that comes into play is antenna design. High gain directional antennas need not consume more energy, but they can provide significantly reduced probability of detection and intercept. Due to their complexity, directional antennas are more expensive than simple omnidirectional antennas.

Spread-spectrum, which purposely spreads a signal (electrical, electromagnetic, or acoustic) to achieve a wider bandwidth, is commonly employed with secure communications. Frequency hopping is another basic modulation scheme used in this type of signal transmission, which can provide a defense against jamming (interference).

Tactical Networking

The "Holy Grail" of tactical networking is to establish robust, seamless, and secure networked communications between multiple manned and autonomous platforms for land, sea, and air missions. Communications must support a seamless IP networking interface to multiple systems and applications. This may involve such techniques as self-forming and self-healing networks, antijamming capabilities, and low-profile detection. Advanced channel access protocols are also under development intended to ensure the maximum effective use of the available frequency spectrum (HARRIS, 2000). Packet data transmissions enable multiple applications to be simultaneously supported on a priority-driven basis, allowing voice and data traffic to coexist on a single, narrowband radio channel. Packet data transmission, combined with high-speed receive-to-transmit switching techniques, allow a simplex channel (one that alternately transmits and receives on the same frequency) to emulate the performance of full-duplex channels (one that receives and transmits on different frequencies simultaneously). Heretofore, two radios were required for retransmission, one to receive and the other to transmit simultaneously on another frequency. A new breed of radios is emerging that can now accomplish this with a single device. The trend in this area is to build a seamless network supporting any combination of point-to-point and point-to-multipoint voice and/or data connections. Information would be encrypted and decrypted only at the origination and destination stations, thereby ensuring security from end-to-end. Tactical networking will become an enabler for many applications including: C2 systems; SA systems; automatic range extension; tactical messaging systems; fire-control systems; common database access; and combat net radio interface systems, which link tactical and land-based infrastructures.

The need for machine-to-machine communications and networking for groups of "swarming" underwater drones (Naval Drones, 2012; Manyika et al., 2013) is also on the horizon. Coordinating activities, sharing data, synchronizing positions, combining visual scenes, projecting light from multiple perspectives, and other features will be useful for inspecting ship hulls, performing mine countermeasures and anti-submarine warfare, visualizing and mapping an area, performing search and rescue operations, forming perimeter fences around an area, as well as numerous nonmilitary applications. Advances in behavior-based artificial intelligence, combined with improved sensors, data fusion algorithms, and computational power, are making increasingly autonomous decisions and behaviors possible. One or multiple through-the-water wireless methods will ultimately network these vehicles. The same fundamental tenets apply, but with more emphasis on low SWaP and redundancy.

Data sharing over a network by multiple vehicles may be performed on a cloud. Cloud networking provides high data storage capacity at high bandwidths. Cloud-based data storage capability may also evoke new business models for ocean data services and analytics that can be shared among a variety of stakeholders.

Robust Systems for Challenging Environments

As mentioned previously, the need to communicate in remote regions at greater ocean depths and in varying sea-states is introducing additional challenges that may require hybrid and multiband terminal solutions. Warming of the Polar Regions is already resulting in increased ship traffic and will likely result in increased fishing, mining, and oil and gas exploration, where there is presently sparse communication infrastructure, even when considering SATCOM. Figure 4 depicts

FIGURE 4

Different bands for different propagation media.

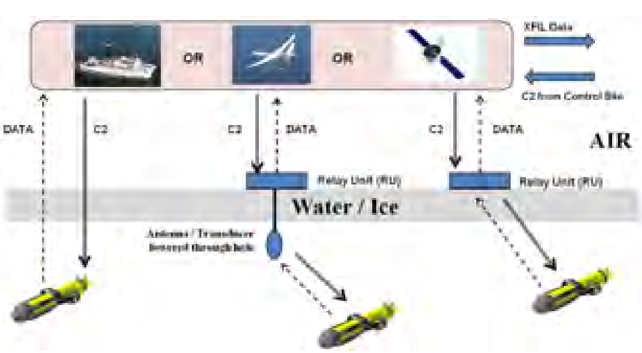


TABLE 4

Comparison of some wireless maritime communication methods through a medium.

Comms Source	Application / Frequency Bands	Pro (Inside medium)	Con (inside medium)
RF	ULF/ELF/VLF 100's of Hz – 10's of KHz	• Penetrate ground/earth/water around the globe regardless of conditions • Small Rx antennas (loops/wires) • Very reliable	• Very low data rates (<~10's of bps) • Very high Tx powers (KWatts – MWatts) • Very large Tx antennas (100's of meters)
	MF – HF 100's KHz – 30 MHz	• Moderate ability to penetrate ground, limited in seawater, good in sand • Small Rx antennas, low Tx power • Global INFIL/EXFIL reach possible with right conditions	• Low – medium data rates (~1000's of bps) over short distances inside a medium • Low Tx powers – few Watts to penetrate sand, lower for ice • Medium sized Tx antennas (10's of meters) • Throughputs subject to soil moisture conditions
	VHF – UHF 30 – 3000 MHz	• Limited ability to penetrate ground or seawater beyond ~10m – best ground penetration using Magnetic Induction (MI) inside the medium • Asymmetric link performance for above ground to underground units	• Low data rates (100's – 1000's of bps) over short distances (< 20 meters) • Moderate Tx powers (~several Watts) • Small – Medium sized Tx antennas • Throughput subject to soil moisture conditions
	>> UHF (L,S,C,K,Ka,Ku bands and higher)	• Large bandwidths available to support high data rates • UHF and L bands reasonably penetrate sandy soil < several meters deep	• S, C, K, Ka, Ku not usable for any transmissions inside of a medium (<<1m) – propagation losses are large (> 40's of dB/meter) • Throughputs subject to soil moisture conditions
Acoustic	Sound in media/water	• Excellent seawater penetration • Long distance in water 10's of km possible (e.g. whale calls, sonar, etc.) at kb/sec data rates (depending on channel characteristics, frequencies and power used)	• Audio frequencies not useful for long distances through air, inside dirt or solid mediums • Low – moderate data rates (100's bps – several kbps) • Not ideal for water-ice-air unless the transducer is below the ice
FSO	Optical (e.g. Blue-Green)	• Good – excellent sea water penetration • Extremely high bandwidths available • Short – moderate distances possible inside static mediums (100's m thru seawater, 100's km air+seawater)	• Limited/Noise penetration, no ground penetration • Very small beam widths – need to establish LOS link between Tx and Rx platform • Limited COTS available of high data rate lasers

scenarios for transmitting data through water or ice from a submerged vehicle to a platform at the surface, in the air, or in space. Typically, high-bandwidth data would be exfiltrated from the platform to a control site, while low-bandwidth C2 data are infiltrated from the control site to the AUV. Table 4 lists some communication options for transmitting through different media along with the attendant advantages and disadvantages of each method. Optimal bands can be selected based on the application; for example, sending video and images requires high bandwidth whereas command and control can utilize lower bandwidths. Multiple bands might be combined to provide robust "hybrid" solutions (e.g., optical for high bandwidth communications through clear water combined with RF for use at closer ranges when clarity is poor).

Communications for Stealth Deployments

This year the Defense Advanced Research Projects Agency (DARPA) launched two new programs, Upward Falling Payloads (UFP) and Hydra. These programs aim to develop novel methods for inserting unmanned air and underwater assets into operational environments ahead of the time so they are readily available in times of a need. The concept is to deploy these assets set to a "sleep mode" at designated locations in protective enclosures years in advance of their anticipated need. In the ocean, Hydra will address shallow water deployments, while UFP deployments may reach 6,000-m depths. Stealthy long-distance communications will be required both to monitor the systems' long-term SOH/SOM (State of Mission) and to "wake them up" when they are needed to spring into action. Programs like these will continue to engender new methods, technologies, and techniques that will further the state-of-the-art in maritime communications for civilian applications.

Summary—A Maritime Internet of Things

An "Internet of Things" (IoT) is a fairly recently minted expression that refers to uniquely identifiable objects and their virtual representations in an Internet-like structure. Essentially, it is the notion of connecting literally everything to the Internet—from the controls of a chemical plant to the toaster in your kitchen. In the maritime domain, it is not difficult to imagine an emerging category of sensors, actuators, and data communication technology embedded in physical objects enabling them to be tracked, coordinated, and controlled across a data network (Manyika et al., 2013). However, innovators of marine technology should take note of the serious concerns already facing terrestrial applications. While driverless cars are still a few years away, fully autonomous vehicles already represent our reality. DARPA recently funded researchers to explore how vulnerable today's cars are to hackers. By simply accessing the diagnostic ports of a Toyota Prius and a Ford Escape, they were able to disable the brakes and control the speed, steering, and instrument displays of these "manned vehicles" (Greenberg, 2013). Other published hacks have demonstrated the ease with which the smart phone of an unsuspecting user can be remotely converted into a device to surreptitiously video, record, and track one's own activities. Perhaps most disturbing, pacemakers and other implanted medical devices have not only been shown to be vulnerable to fatality-causing remote hacking, they can also be commandeered to "go viral," infecting nearby similar devices to spread this malware.

As discussed throughout this article, the physics of the maritime domain limits the available bandwidth for though the water communication links and therefore the encryption techniques that have been in play thus far. At a recent Def Con conference, a gathering of "friendly hackers" whose objective was to flush out such vulnerabilities in order that they may be corrected prior to being exploited for nefarious reasons, one exercise used to exemplify a potential real-world threat was to hack into and take over control of a wellhead and pipeline.

As technological advances and lowering costs of MEMS (Micro-Electro-Mechanical Systems), power management, miniaturization, and high-volume manufacturing pave the way for the world of unmanned undersea infrastructure to become more interconnected, with that must come an increased awareness and necessary attention to improved encryption, threat detection and security of these vital assets.

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COMMENTARY

U.S. IOOS: An Integrating Force for Good

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Whether you realize it or not, you rely on ocean and coastal observations everyday. With federal, regional, and private sector partnerships, the U.S. Integrated Ocean Observing System (IOOS®) is one of our nation's best kept secrets to achieving a 1 + 1 = 3 (or more) result. In these tough economic times, this commentary is about U.S. IOOS and believing that this concept is still worth pursuing.

In a talk on how great leaders inspire action, famed author and expert Simon Sinek (http://www.ted.com/playlists/60/work_smarter.html) states, "People don't buy what you do; they buy why you do it." Sinek states that most people think that money and talent are the keys to success but counters that success lies in communication. Figure 1 is Sinek's Golden Circle, which depicts how we communicate. He states that most people communicate their story from the outside circle to the inside circle, but truly successful ventures start with "Why" they are doing something. He defines "Why" as the cause we believe in, the reason we get out of bed in the morning.

Sinek's talk struck us because U.S. IOOS and, globally, the Global Ocean Observing System continue to advance in a fiscally constrained environment. So what is it about IOOS that is helping us gain momentum? Perhaps it is because we share a passion for what we do and that we have a deep understanding of the "Why." We made an attempt at applying Sinek's Golden Circle to IOOS in Figure 2.

FIGURE 1

Simon Sinek's Golden Circle.

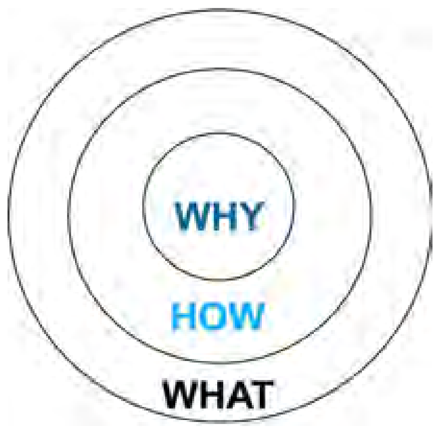
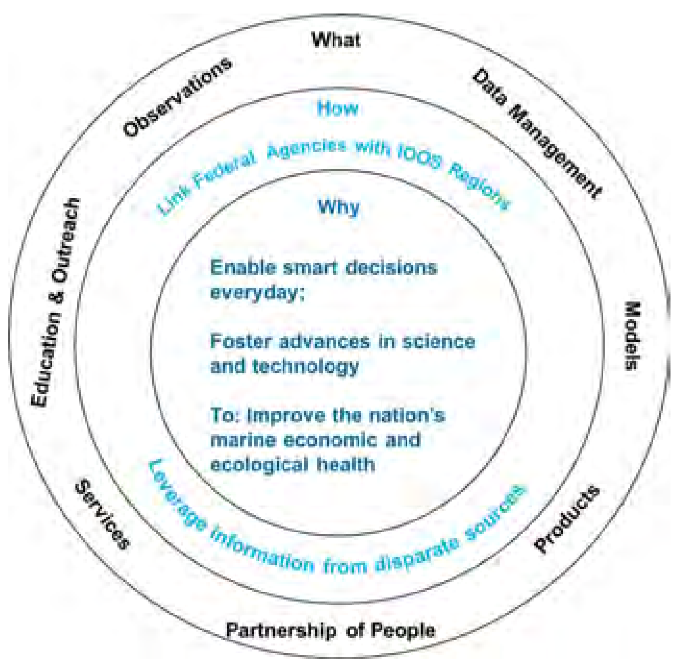


FIGURE 2

IOOS' Why, How and What.



We put forward the "Why" of IOOS because it enables decisions everyday, fosters advances in science and technology, and improves the marine economic and ecological health of our nation. To prove our hypothesis, we offer the following examples to demonstrate the Why, How, and What of IOOS.

The first example is a tale of two storms—Hurricanes Irene (August 2011) and Sandy (October 2012). This example covers a breadth of IOOS capabilities. U.S. IOOS observations and forecasts supported the National Oceanic and Atmospheric Administration's (NOAA) hurricane and storm surge forecasts. Technology used in new ways showed potential to improve hurricane intensity forecasting, and through the U.S. IOOS partnership of people, the new use of technology made a difference. Buoys, gauges, high-frequency (HF) radar, and high-resolution forecasts from NOAA's National Data Buoy Center (NDBC) and Center for Operational Oceanographic Products and Services (CO-OPS), U.S. Army Corps of Engineers, and the IOOS Regional Associations from the Caribbean to New England served crucial information to guide forecasts in both hurricanes. After Irene, John Cannon of the National Weather Service (NWS) Weather Forecast Office (WFO) in Gray, Maine said, "Buoy 'A' and 'B' [IOOS' Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS)] were our focus due to unique positioning along and just upstream of the seacoast of New Hampshire and Southwestern populated beaches in Maine to determine the extent for the potential of coastal flooding…the real-time information was crucial for our needs. Short Term Forecasts were lowered to account for the ongoing situation during Irene's approach. The observation of limited wave action was a critical benchmark which caused our office to (accurately) limit our forecast and warnings for coastal flooding to 'minor'." John's words underscore IOOS' capability to support decision makers.

Looking back at the data, track forecasts for Irene and Sandy were accurate days in advance. Intensity forecasts, however, were less accurate, with Irene's intensity overpredicted and the rapid acceleration and intensification of Sandy just before landfall underpredicted. As Irene approached the mid-Atlantic, the IOOS' Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) had a glider in the water supporting the Environmental Protection Agency's monitoring of a benign but large algal bloom. The glider collected the water column characteristics as Irene passed over. After the storm, scientist at Rutgers University examined the data from the glider and HF radar and found that the ocean's surface had cooled well before the eye of the hurricane passed. When they reran models using a cooler sea surface temperature, the resultant intensity was much closer than forecasted.[1] While this is only a single storm, the fact that the glider collected critical water column information without endangering lives showed that the use of this technology has the potential to help NOAA's hurricane forecasting.

So where does "buying why we do this, not what we do" come into play? The over-forecast of the intensity of Hurricane Irene caused skepticism with the dire forecasts of Hurricane Sandy. This time, IOOS' MARACOOS deployed gliders ahead of Sandy. Then, as they compared the data with the model runs, they were confident that this Hurricane would hit the mid-Atlantic with the forecasted intensity (Figure 3). A decision on whether to evacuate "ground floor" apartments faced the mayor of Hoboken, New Jersey. Fortunately, Dr. Michael Bruno, Dean, Schaefer School of Engineering and Science, and Professor, Stevens Institute of Technology, who is part of the IOOS partnership of people, was present at the briefing for the Mayor. The fact that he was known and highly regarded by the Mayor and her staff and his confidence in the forecast allowed the Mayor to overcome the skepticism created from the over-forecast for Irene of the year prior. The Mayor ordered an evacuation of "all ground floor apartments" by midnight Sunday night. This single decision saved lives, because there are thousands of street-level and basement-level apartments in the city.[2]

Another effort where decision-making and science shines through is rather unexpected—supporting the local sanitation district. The Southern California Orange County Sanitation District (OCSD) discharges treated water from an outfall that terminates roughly 4.5 miles offshore. The plume typically stays well below the surface and away from recreational areas. OCSD has a secondary outfall just 1 mile off the coast with a permit allowing outfall only in emergencies, as the discharge is expected to reach recreational areas. In 2007, the IOOS' Southern California Coastal Ocean Observing System (SCCOOS) and the Central and Northern California Ocean Observing System (CeNCOOS) provided modeled surf zone waves and currents, near real-time meteorological observations, and products during planned ocean outfall repairs as part of a monitoring contingency plan. In June 2012, a permit allowed OCSD to use the 1-mile-out discharge point for nonemergency operations. In September, OCSD diverted the flow from the farther outfall to the closer one as part of a project to inspect, assess, and rehabilitate the Outfall Land Section and Ocean Outfall Booster Pump Station Piping. The IOOS Regions tracked the plume, concentrations of bacteria, nutrient levels, and changes in phytoplankton speciation and density

[1] Glenn, Scott et al. Process-driven improvements to hurricane intensity and storm surge forecasts in the Mid-Atlantic bight: Lessons learned from Hurricanes Irene and Sandy, OCENAS'13 MTS/IEEE Bergen conference proceedings.

[2] The Marine Technology Society–Tech Surge: http://www.ioos.noaa.gov/communications/superstorm_sandy2013/mts_tech_surge_sandy.pdf.

FIGURE 3

Hurricane Irene (top) approaches the East Coast. Hurricane Sandy (bottom) approaches the mid-Atlantic, glider track and HF radar depicted.

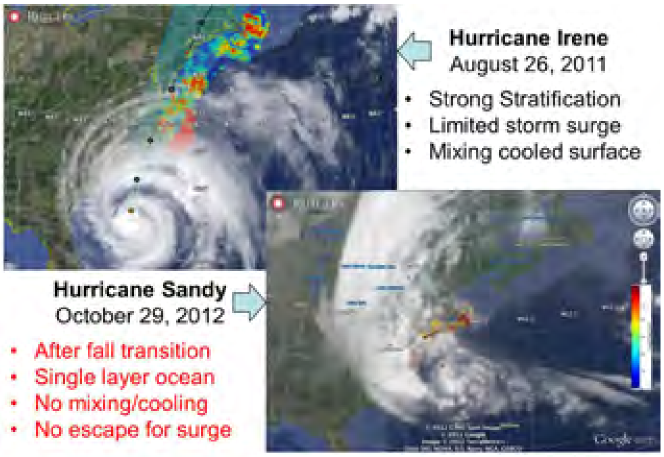


FIGURE 5

Penobscot pilots at work. Photo credit: Penobscot Bay and River Pilots Association.

by gliders, HF radar, pier stations, and model forecasts using the Regional Ocean Modeling System. This augmented OCSD water quality and discrete sampling. At the same time, through coordination with NOAA's National Centers for Coastal Ocean Science, additional glider and ship-based sampling was conducted to monitor harmful algal bloom development. Figure 4 shows the complete monitoring picture. SCCOOS and CeNCOOS will evaluate the data collected during the 2012 project in order to help OCSD find cost-effective solutions to mitigate water quality and public health impacts and determine best practices in ocean modeling and monitoring in support of future diversions to the closer outfall.

IOOS decisions translate to cost savings. The Penobscot Bay and River Pilots Association in Maine routinely access IOOS' NERACOOS buoys, wave, and wind forecasts to decide when to board ships (Figure 5). In February 2013, pilots encountered 4-foot seas at the boarding area when a ship left Boston, but the Northeast Atlantic IOOS Region predicted there would be 8- to 11-foot seas with a short period when the ship was scheduled to arrive at the boarding area. The pilot cancelled the job well ahead of the vessel's arrival and rescheduled boarding for the next day, when conditions were predicted to be better. The forecast was verified, and while the boarding was challenging, it was safe. Furthermore, the ability to accurately predict the seas provided the shipper with a firm idea of when his ship would dock. Captain

FIGURE 4

Monitoring water from above and below. Sources: OCSD; University of Southern California, Scripps institution of Oceanography, Teledyne Technologies. Photo credit: Molly Zisk at the Orange County Register.

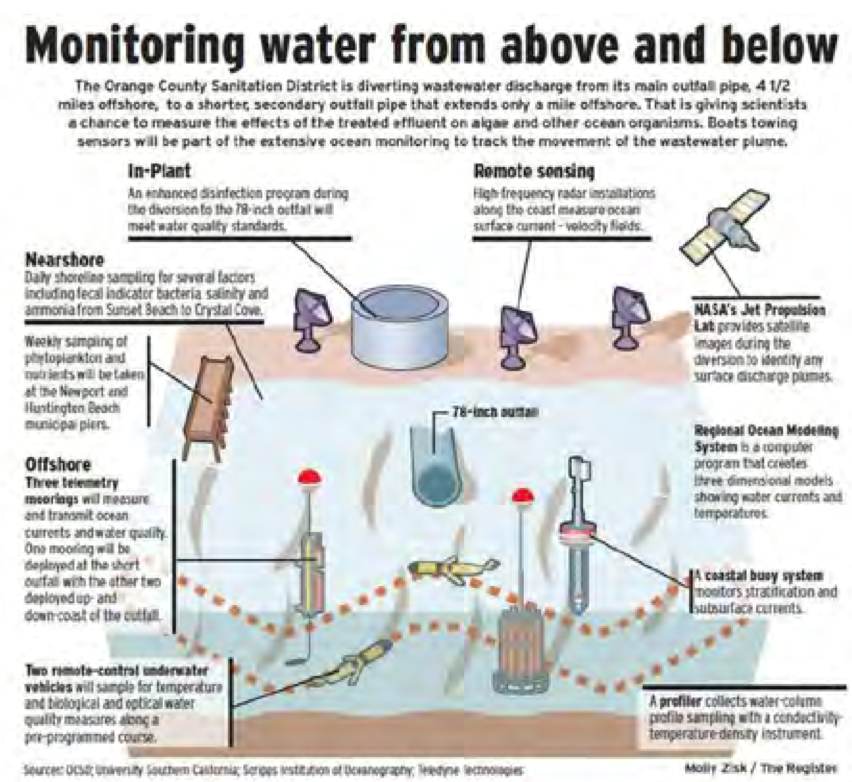
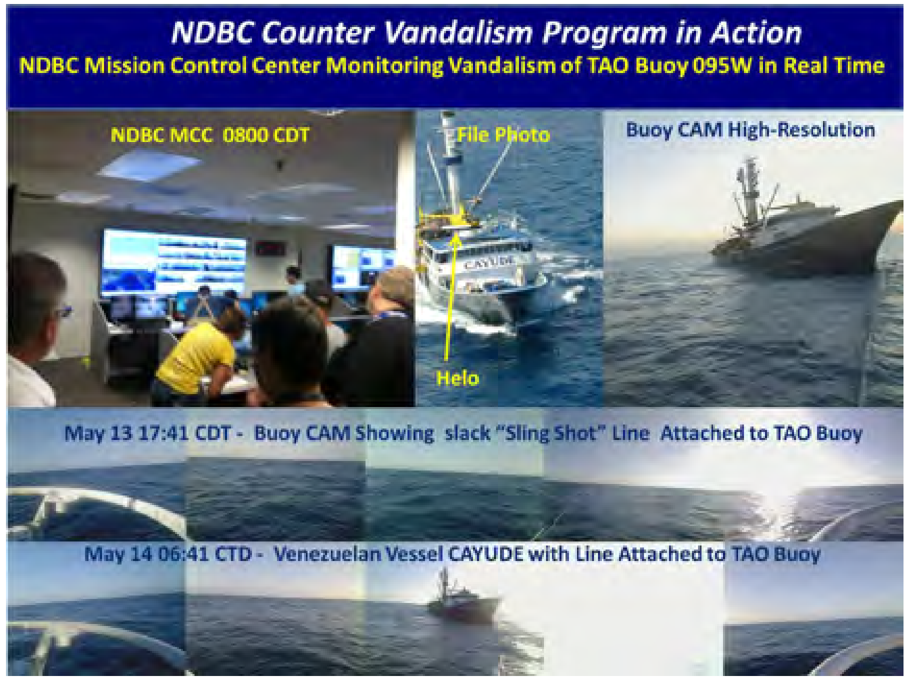


FIGURE 6

Camera on DART buoy.

FIGURE 7

Countering vandalism.



David Gelinas, Penobscot Bay and River Pilot, described the power of IOOS information, stating "the coast of Maine supports multi-million-dollar fishing and tourism industries, so when making decisions about bringing a 700-foot tanker full of fuel into port, we need the best ocean and weather information possible, which is why we depend on IOOS buoy observations and forecasts to ensure safety and efficiency of these critical operations."

U.S. IOOS contributors are tackling buoy vandalism, a worldwide problem vexing the ocean observing community. NDBC, which is a major IOOS partner globally and regionally, looked to technology to help solve this issue by developing and installing a camera system (Figure 6) on seven Tropical Atmospheric Ocean Array (TAO) buoys, a coastal buoy in the Gulf of Mexico, and a Deep-Ocean Assessment and Reporting of Tsunamis (DART) buoy in the Gulf of Alaska.

With the camera, they monitored in real time the Venezuelan fishing vessel *Cayude* as she attached a line to the TAO buoy and started to tug. Based on the images, enforcement bodies took action. The U.S. Coast Guard (USCG) warned the vessel, and NOAA enforcement engaged the international fisheries community. NWS International Affairs and the U.S. State Department engaged the Venezuelan government to prevent further episodes. This is generating high-level positive attention as a way to reduce vandalism. Figure 7 shows the sequence of events. Not only have the cameras on the TAOs and in the Gulf shown fishing vessels, but the cameras can also serve as eyes on the sea, giving NDBC personnel the ability to monitor the sea state and sky during passing tropical storms.

Data Management and Communications (DMAC) is the centerpiece of the U.S. IOOS. In essence, this translates to everyone using the same recipe to provide easy access and use of physical, chemical, and biological data from both legacy and new systems. In April, we finalized the recipe by publishing the IOOS Sensor Observation Service (SOS) template 1.0 and two implementation software packages (52North and ncSOS). We are testing these services now and will complete introduction of these packages into 5 of 11 IOOS Regions, CO-OPS, and NDBC by October 2013.

The IOOS SOS and data services are catching on. In June 2013, the first private company, Satlantic is offering data through the IOOS SOS website (http://gcoos.tamu.edu/?p=4369), which is open to the public. The Satlantic Land Ocean Biochemical Observatory system with SOS was deployed by the Sanibel Captiva Conservation Foundation's (SCCF) River, Estuary, and Coastal Observing Network in Southwest Florida as a means of providing automated access to SCCF data to one of their sponsors, IOOS' Gulf of Mexico Coastal Ocean Observing System Regional Association (GCOOS).

Google has come to IOOS. Through IOOS' Southeast Coastal Ocean Observing Regional Association (SECOORA), the Google crisis map automatically picks up and posts ocean information. In the "Ocean Observation" layers, high winds, waves, and water levels are plotted. Figure 8 shows NOAA's fire conditions overland and IOOS sourced ocean information along the Gulf and Southeast United States.

Quality data are critical to IOOS. We formally established the Quality Assurance of Real-Time Ocean Data (QARTOD) (www.ioos.noaa.gov/qartod/) 1 year ago as part of the DMAC services. Three quality control procedure manuals addressing oxygen, waves, and currents have been released. Developed with observing experts and sensor vendors, these quality control standards represent a major step forward for IOOS by providing best practices for quality control tests of measurements from commonly used sensors.

We are working on integrating biological data through two efforts: first by promoting the standards for biological data and second by organizing a data portal for a marine animal telemetry network.

The objective of the Biological Observations Data Project is to develop easy access to biological observations (i.e., fish species and abundance). The first phase reconciled community data/metadata content and access standards based on existing international standards for biodiversity data. IOOS' Pacific Islands Ocean Observing System (PacIOOS) implemented these standards, thereby improving access to reef fish data collected by NOAA, National Park Service. This information is now used to establish reef fish annual catch limits for the U.S. Pacific Islands as defined by the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act. The second phase showed that these standards were portable with IOOS' SECOORA and GCOOS having implemented them on key fisheries data sets in their areas. Now in the third phase, we are concentrating on a process where all partners at the federal and regional levels can register their biological data into DMAC.

Aquatic animal telemetry is an emerging technology that allows data measurements of animal movements and their environment to be made at a distance. Affixing tracking devices known as "tags" or "biosensors" to animals allows scientists to analyze their behavior. These data are critical for preventing extinctions, preserving biodiversity, and implementing ecosystem-based management of living resources. Animal

FIGURE 8

Google crisis map.

telemetry also delivers high-quality physical oceanographic data at a relatively low cost. Animals are particularly adept at finding areas of interest to oceanographers (e.g., fronts, upwelling areas). The community is also developing a strategic plan to establish a U.S. Animal Telemetry Network under U.S. IOOS. The U.S. IOOS Program Office collaborated with the Office of Naval Research, the Naval Oceanographic Office, the NWS National Centers for Environmental Prediction, and the Tagging of Pacific Predators (TOPP) Program at Stanford University's Hopkins Marine Station to provide access to 8,138 observations from TOPP. The data were used for model reanalysis and proved that animal-borne sensor data are sufficiently accurate and of high enough quality to be useful in filling existing observation gaps in undersampled ocean regions (i.e., boundary currents, ocean fronts) and to improve operational ocean models.

NOAA and a number of IOOS Regions are involved in animal telemetry. IOOS' Alaska Ocean Observing System (AOOS) is working with Canadian and Russian partners to develop an Arctic Animal Tagging Network to increase ocean and animal observations in remote Arctic waters. IOOS' PacIOOS supports animal tagging by University of Hawaii researchers as well as acoustic arrays throughout the Pacific. IOOS' Great Lakes Observing System (GLOS) and the Great Lakes Fishery Commission launched the Great Lakes Acoustic Telemetry Observing System (GLATOS) tool in May 2012 to answer fisheries management and ecology questions in the Great Lakes. The system tracks more than 1,700 fish of four species—lake trout, walleye, sea lamprey, and lake sturgeon—tagged between 2010 and 2013. Tracking information will influence a range of fish population restoration actions, including improved sea lamprey control, better data for fish stocking decisions, and enhanced understanding of fish spawning behavior.

U.S. IOOS also leads the way with other ocean observing technologies such as HF radar and profiling gliders, two efforts that are almost completely delivered by the IOOS Regions. Regionally and nationally, HF radar supports a range of applications, including reducing search and rescue time conducted by the U.S. Coast Guard. On the international level, U.S. IOOS set forth a bold task through the Group on Earth Observations to establish a global HF radar network (http://www.ioos.noaa.gov/globalhfr/welcome.html). There are 90 countries participating in GEO, 72 of which have a "salty" coast, a necessity for HF radar to work well. We believe there are more than 350 HF radars worldwide in 35 countries. U.S. IOOS is co-chairing this task with representatives from Australia and Spain. Collected success stories for HF radar show the range of applications that HF radar supports. These include circulation studies; oil spill/pollution tracking; search and rescue; beach closures; tsunami, typhoon, hurricane detection; maritime safety and operations; buoy tracking; fisheries; green energy; and water quality and recreation.

In recent years, the use of steerable gliders has added significant potential and adaptive sampling to the portfolio of platforms in the U.S. IOOS system. Over the past 5 years, U.S. glider operators have flown more than 25,722 glider-days funded by many sources. The resulting infrastructure provides a solid framework for a nationwide, operational, glider network. IOOS is working on a National Glider Plan and a Data Assembly Center and bridging this effort to the European Union's project Gliders for Research, Ocean Observations and Management, and Australia's Integrated Marine Observing System.

Missions conducted by gliders are as varied as the sensors they can carry. In addition to the previously highlighted efforts in hurricane forecasting and supporting the outflow diversion, examples include glider missions to gain a better understanding of the dominant Gulf of Mexico red tide organism *Karenia brevis*. Tandem gliders were used to catch a red tide bloom in progress to gain a better understanding of how to forecast and track harmful algal blooms. Yet another example that is pushing the boundaries of glider technology is using them to seek out endangered sturgeons. Through the generosity of a private donor, but leveraging the IOOS infrastructure, scientists developed an acoustic telemetry glider (OTIS) and flew a 3-month mission searching for endangered Atlantic sturgeon. During the mission, they detected dozens of sturgeon and some sand tiger sharks as well. For example, OTIS detected a large male sturgeon off the Delaware beaches that had been detected by researchers in the James River less than a week earlier, showing the animal made the 200+ mile trek in only a few days.

Educating the next generation of scientists is a strong tenet for the U.S. IOOS community. For example IOOS' Caribbean Coastal Ocean Observing System (CariCOOS) has teamed up with NOAA's Puerto Rico's Weather Camp to introduce coastal weather and ocean observing tools. The purpose of the camp is to broaden and increase exposure of high school students to academic programs, career opportunities, techniques, and research in atmospheric sciences, meteorology and oceanography. In 2012, the U.S. Virgin Islands Marine Action Group sponsored the first student from USVI. On average there are 15 students per class, and more than 45% of the previous attendees stayed in the meteorology or oceanography fields. Another example took place off the coast of Washington when, on Earth Day, IOOS' Northwest Association of Networked Ocean Observing Systems (NANOOS) redeployed a buoy containing ocean acidification sensors. Six Ph.D. students from the University of Washington Oceanography Department were on the cruise to assist in the internal wave studies and to gain valuable experience at sea. Joining the research scientists and graduate students aboard the R/V *Thompson* were six "guests" from the education community: two classroom teachers, three NOAA volunteers, and one Seattle Aquarium staff/preservice teacher. The teachers' goals included using actual cruise/mooring data on joint projects with their science and math students, learning about on-board scientists' research projects and priorities to share in the classroom, and communicating with their students throughout the cruise via email and Skype. The volunteers hoped to boost their knowledge of current ocean science research off the Washington coast to inform their many national and international visitors. The buoy deployment will help educate our nation's future scientists and leaders about the topics of ocean observing and ocean acidification, while simultaneously delivering data to aid decisions that improve our nation's safety, economy, and environment. In addition to the more formal classroom or field work described, IOOS is also providing informal education opportunities to stimulate the interest of youngsters (and their parents) in the marine environment, leading hopefully to the next generation of scientists. The award winning *Eco Hero* game of GCOOS is another example of how the community of IOOS educators came together with support from IOOS' GCOOS to provide informal marine ecosystem education to the general public. The game is an interactive, conservation game to understand the environmental value of the Gulf of Mexico and to "bridge the gap" between research conducted within the Gulf and the relevance of scientists' findings to the public's everyday lives.

We hope you agree with us that U.S. IOOS works. While U.S. IOOS is made up of many contributions from federal agencies and institutions along with state, local, and tribal governments, academia, industry, nongovernmental organizations, and the public, we believe that sharing the same passion and commitment to partnership is really the success of U.S. IOOS.

COMMENTARY

Ocean Salinity and the Aquarius/SAC-D Mission: A New Frontier in Ocean Remote Sensing

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The latest new technology for exploring the ocean from space is to measure sea surface salinity (Figure 1). Utilizing microwave measurements in the L-band (1–2 GHz), the salinity of the upper ~1 cm of the surface is derived with sufficient accuracy to map the global field, its seasonal to interannual variations, and smaller-scale features associated with major river outflows and ocean current meanders. The data provide many new opportunities for scientific studies of the coupling between changes in the global water cycle, ocean circulation, and climate. This note describes the Aquarius/SAC-D mission (Lagerloef et al., 2008; http://aquarius.nasa.gov), launched in June 2011, which is a partnership between the United States (NASA) and Argentina (CONAE; http://www.conae.gov.ar/). The satellite maps the globe every 7 days with a spatial resolution between 90 and 150 km. Salinity measurements from NASA's Aquarius instrument are complemented by data from the European Soil Moisture and Ocean Salinity mission, which has somewhat better spatial and temporal resolution and somewhat less accuracy. Both missions strive to map the global salinity field at a resolution of 100–200 km and monthly error of less than 0.2 on the practical salinity scale.[1]

How Aquarius/SAC-D Supports NASA's Science Objectives

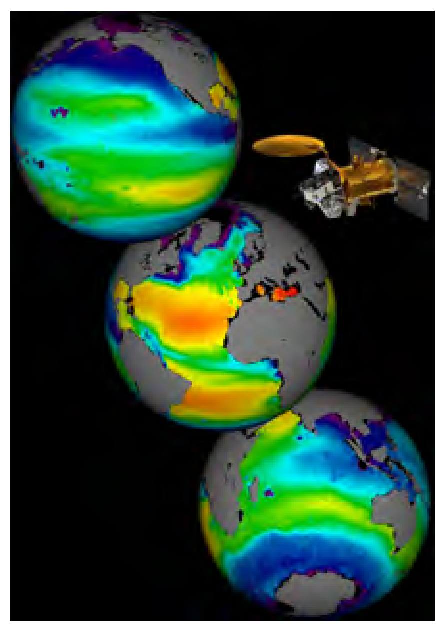
Measuring ocean salinity fills a key niche for studying the ocean's role in climate variability. Salinity is a parameter that links ocean circulation and climate variability to large-scale changes in the global water cycle. It is an indicator variable whose changes are a direct reflection of ocean currents and the freshwater fluxes between the ocean and the atmosphere, cryosphere, and land (rain, evaporation, ice freeze/melt, river runoff) that define our climate. We now observe salinity trends over recent decades from historical ship and buoy data around the global ocean, indicating an intensifying global water cycle, increasing salinity (from increasing evaporation) in the arid ocean regions and decreasing salinity (from increasing precipitation) in the maritime rainfall zones (Durack et al., 2012). This "spin-up" of the global water cycle is a predictable feature of Earth's warming climate.

NASA's strategic plan includes a focus to advance Earth System Science to meet the challenges of climate and environmental change. The program explores interactions among the major

[1] The practical salinity scale of 1978 (pss-78) is the oceanographic measurement standard based on electrical conductivity. Sometimes reported in practical salinity units (psu), the numerical value closely matches that of the mass ratio of dissolved salts in parts per thousand (g/kg). Thus, 0.2 represents a measurement uncertainty of 2 parts in 10,000, which is about the same change as mixing a pinch of salt in a gallon of water.

FIGURE 1

Three global perspectives of the yearly averaged global surface salinity data, shown in false color, measured by the Aquarius/SAC-D satellite (inset) in 2012. Note that the highest surface salinities are found in the subtropical regions of the North and South Atlantic (red color), and the lowest are in the North Pacific, surrounding Antarctica, the tropics, and other smaller regions (blue color). (Image NASA/GSFC). (Color versions of figures are available online at: http://www.ingentaconnect.com/content/mts/mtsj/2013/00000047/00000005.)



components of the Earth system—continents, oceans, atmosphere, ice, and life—to distinguish natural from human-induced causes of change and to understand and predict the consequences of change. The Aquarius/SAC-D mission was selected in 2002 by NASA's Earth System Science Pathfinder Program in order to address key science questions concerning how the water cycle, ocean circulation, and climate are related.

The Aquarius/SAC-D Mission and Salinity Remote Sensing

Aquarius/SAC-D (Figure 2) is an international collaboration between the United States and Argentina, including participation from Italy, France, Brazil, and Canada. It carries multiple science instruments with diverse objectives, with the primary being NASA's Aquarius microwave salinity sensor. The instrument consists of three microwave radiometers operating at 1.413 GHz (L-band) arranged with an offset 3 × 2.5 m antenna reflector to provide a three-beam "pushbroom" pattern on the surface (Figure 3). The footprint pattern has a ~390-km-wide measurement swath consisting of three elliptical beam footprints of sizes 76 × 94 km, 84 × 120 km, and 96 × 156 km. A radar transmitting at 1.2 GHz is integrated with the radiometers (so-called passive-active design) to provide a simultaneous radar backscatter measurement of the ocean's surface roughness to correct for the effect of winds, waves, and foam on the radiometer measurement. The satellite flies in a sun-synchronous orbit, crossing the equator at 6 pm (northward) and 6 am (southward) local time for each orbit. The orbit covers the globe and repeats the same ground track every 7 days. The antenna points away from the sun to minimize stray L-band microwave solar radiation that would affect the data.

Salinity remote sensing is possible because the microwave emission of the sea surface at L-band depends on the dielectric coefficient of seawater, which in turn is related to salinity and temperature (Klein & Swift, 1977; Meissner & Wentz, 2004). The total power of the emission is measured remotely with the Aquarius microwave radiometers. The output is given in terms of a parameter called brightness temperature (T_B), which is the product of the surface emissivity and the absolute temperature of the sea surface. For emissivity = 1, T_B is the absolute temperature in Kelvin. However, seawater emissivity is about 0.3. Figure 4 illustrates the physical model for a nadir view (Aquarius actually measures at three off-nadir incidence angles between 29° and 47°) in terms of how T_B varies with sea surface temperature for various salinity values. The open ocean salinity varies between 32 and 38 psu, and thus, T_B varies over a very small range of a few units Kelvin (K). To measure these small T_B variations, the Aquarius sensor was built with an unprecedented measurement T_B error of less than 0.1 K, which translates to salinity error of 0.2 psu on average.

The first global image of Aquarius data was publicized in September 2011 (http://www.nasa.gov/mission_pages/aquarius/news/aquarius20110922.html), within a few weeks after the sensors were turned on. What surprised us most was the spatial detail we found in this early data, especially

FIGURE 2

A conceptual illustration of Aquarius/SAC-D over Patagonia. The Aquarius microwave sensor is on the left side of the satellite. It shows the 3 × 2.5 m antenna reflector (gold-colored oval) and the three separate radiometer antenna feeds (circular openings under the reflector, each about 0.5 m in diameter). The solar panels are on the right side. Various other science instruments are on the bottom side of the satellite (not visible in this illustration). (Image NASA and CONAE).

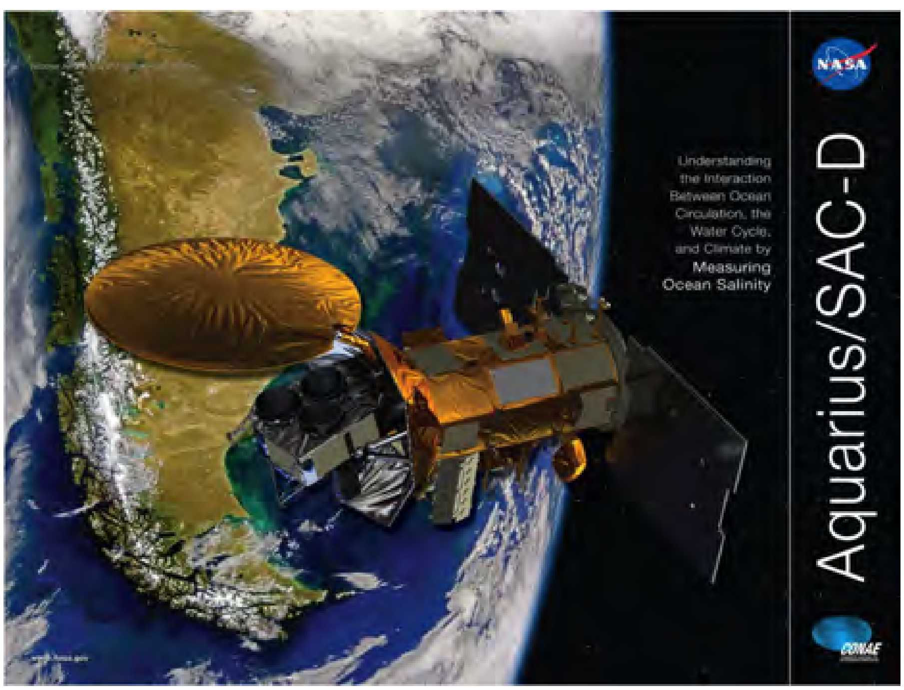
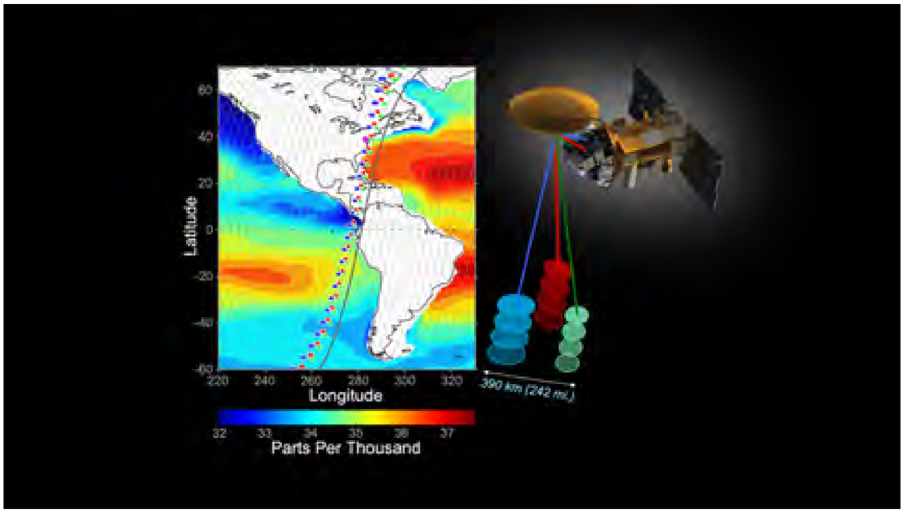


FIGURE 3

The Aquarius sampling pattern consists of three beams on the surface across a 390-km-wide swath. The orbit pattern repeats every week covering 100% of the globe, except at the poles. (Image NASA).



the low-salinity surface waters of the Amazon River outflow. The image quality has improved with time, and Figure 5 zooms in on this feature and superimposes the surface current pattern derived from other satellite data (Ocean Surface Current Analyses—Real time; Dohan & Maximenko, 2010). A study based on Aquarius data has been published on the interaction of Hurricane Katia (2011) and the offshore flow of the Amazon/Orinoco river plume (Grodsky et al., 2012). In the Pacific Ocean, Aquarius data revealed new aspects of near-equatorial tropical instability wave dynamics (Lee et al., 2012). Many more scientific and technical papers will be submitted to major journals during the remainder of this year.

Upper Ocean Salinity

The seawater optical depth for L-band microwaves is ~1 cm, and to properly interpret the satellite measurements of this thin surface zone requires that we understand its relationship to the upper ocean salinity mixing and stratification. To this end, the Salinity Processes in the Upper Ocean Regional Study (SPURS) experiment was organized (http://spurs.jpl.nasa.gov/SPURS/). This ambitious year-long field experiment is taking place in the subtropical North Atlantic, in the region where the highest surface salinity is found anywhere in the open ocean (excluding inland seas such as the Mediterranean or Red Sea). SPURS employs many state-of-the-art technologies to measure upper ocean salinity and temperature, stratification, turbulence, mixing, and advection in the heart of the "salinity maximum." The field experiment includes multiple research cruises and various autonomous *in situ* platforms such as gliders, surface drifters, vertical profiling floats, and moorings, some of which will remain in the study area for up to a year. Coupled with the larger-scale surface data from Aquarius, the goal is to understand the oceanic mechanisms that maintain such high surface salinity and the path of this salty water as it descends and merges with the interior subtropical circulation. This is a region where surface salinity has been documented to have increased in recent decades, presumably due to increased evaporation and/or decreased yearly average rainfall. How this is coupled to the regional circulation and climate variability will be a subject of ongoing study in years to come.

Public Outreach

Thanks to Aquarius/SAC-D, Soil Moisture and Ocean Salinity, and the SPURS expeditions, the scientific community is gaining unprecedented insight into salinity's role in science and society. In parallel, NASA's salinity-related "Communications and Public Engagement" activities have focused on the themes of the water cycle, ocean circulation, and climate. Leading up to the launch of Aquarius/SAC-D, the NASA and CONAE outreach team collaborated to develop key messages, create outreach products, coordinate media opportunities, and facilitate the broader impacts of the mission's scientific goals. Collectively, the Aquarius/SAC-D mission has been featured in more than 2,500 news stories, through wire services, radio stations, television news broadcasts, and Internet media.

An important mission objective is delivering authentic content to broad audiences in efficient ways. To this end, the Aquarius team conducts webinars featuring NASA scientists and engineers, which are targeted at participants with diverse backgrounds such as educators, faculty/researchers, undergraduates, graduate students, and the general public. Aquarius webinars have engaged 249 attendees from eight countries (United States, Argentina, Brazil, Canada, Colombia, Greece, Italy, and Peru). In postwebinar surveys, over 90% of participants stated that they plan to use the subject matter and resources in their own work, which

FIGURE 4

The variation of the 1.413-GHz radiometer brightness temperature (T_B) measured by the radiometer (ordinate) versus sea surface temperature (SST, abscissa) is shown for various salinities and nadir view from the satellite. Surface salinity in the open ocean is between 32 and 37 psu. Simultaneous measurements of T_B and SST yield a unique solution for salinity.

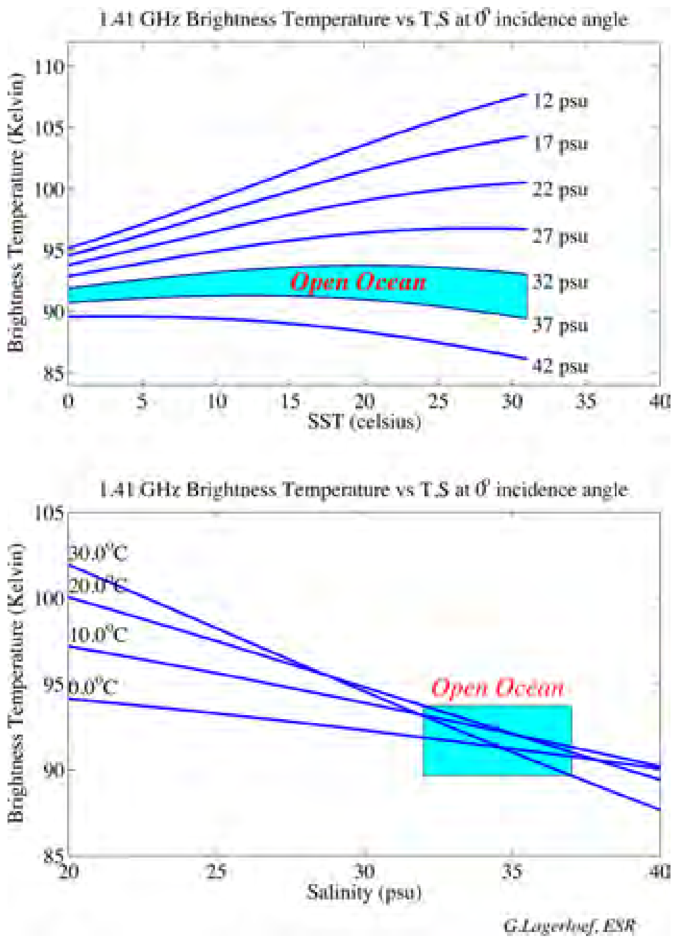
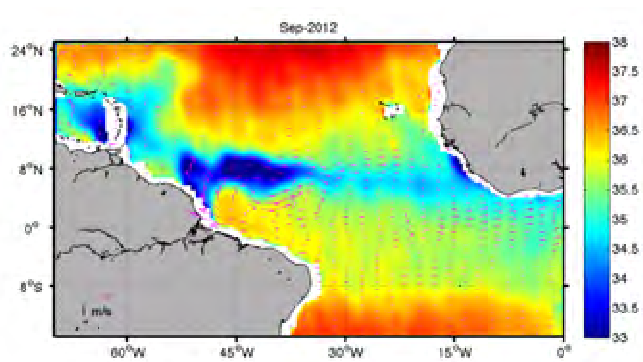


FIGURE 5

The surface salinity measured by Aquarius is shown in the tropical Atlantic highlighting the low salinity pattern from the Amazon and Orinoco river discharge in September 2012. Superimposed are satellite-derived surface currents from Ocean Surface Current Analyses—Real time (see text).



matches the evaluation feedback from Aquarius's in-person workshops (n = 93). These results demonstrate that Aquarius can continue to expand its geographical impact through webinars without sacrificing the quality or usefulness of the information. In addition, online archives of Aquarius webinars, which have been viewed over 8,400 times since early 2012, provide an efficient way to provide long-term access to scientist- and engineer-delivered NASA content.

Greater appreciation of the ocean's role in the global environment is more important than ever, given the increase in urgency to make decisions on complex environmental issues. Thus, the time is right for Aquarius to continue expanding public understanding of the crucial connections between salinity, water cycle, ocean circulation, and climate.

Mission Longevity

People often ask how long will the Aquarius/SAC-D mission continue to operate. Part of the answer is that the sensors and satellite subsystems have minimum design life requirements of 3–5 years. NASA's prime mission objectives will be met after 3 years of science operations. From that time onward, extended mission operations will be supported indefinitely as long as the scientific return is justified through a biennial review process. Typically, missions with similar 3- to 5-year design criteria tend to last a decade or more. Thus, we can anticipate measurements from Aquarius/SAC-D for years to come. A decade-long, high-resolution record of the ocean's surface salinity field will be an enormous benefit to ocean, water cycle, and climate research.

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COMMENTARY

Understanding the Planetary Life Support System: Next-Generation Science in the Ocean Basins

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Driven by solar and internal geothermal energy, the complex processes interacting within the global ocean basins constitute the "flywheel" of our planetary life support system; it is the massive volume of the ocean that drives long-term weather and short-term climatic variations across the seas and onto the continents. Entirely new approaches to understanding the complexity, power, and vagaries of this "oceanic modulator" are arising from the rapid implementation and use of submarine cable networks that will provide unprecedented electrical power and bandwidth to thousands of increasingly sophisticated robot sensor systems distributed throughout full-ocean environments. Partly triggered by the advent of a growing number of these cabled research systems, oceanographers are poised to benefit from a host of emergent technologies largely driven by investment from communities external to ocean sciences. Important developments include robotics, biotechnology, cloud computing, *in situ* chemical and genomic sensors, extraction of novel biochemical materials, digital imaging, nanotechnology, serious gaming, new visualization technologies, computational simulations and data assimilation, seismoacoustic tomography, and universal access to the Internet. Far more powerful than any one of these emerging technologies will be the convergence of the ensemble when applied to understanding the innate complexity of our planetary life support system—the global ocean. As these rapidly evolving capabilities are integrated into sophisticated, remote, interactive operations throughout the ocean basins for decades, a new era of a pervasive human telepresence throughout entire volumes of our once "inaccessible" global ocean will be realized. Such capabilities are required to meet the onset of immense environmental and societal challenges in the coming decades that can only be addressed through optimally informed international collaboration.

A Grand Challenge

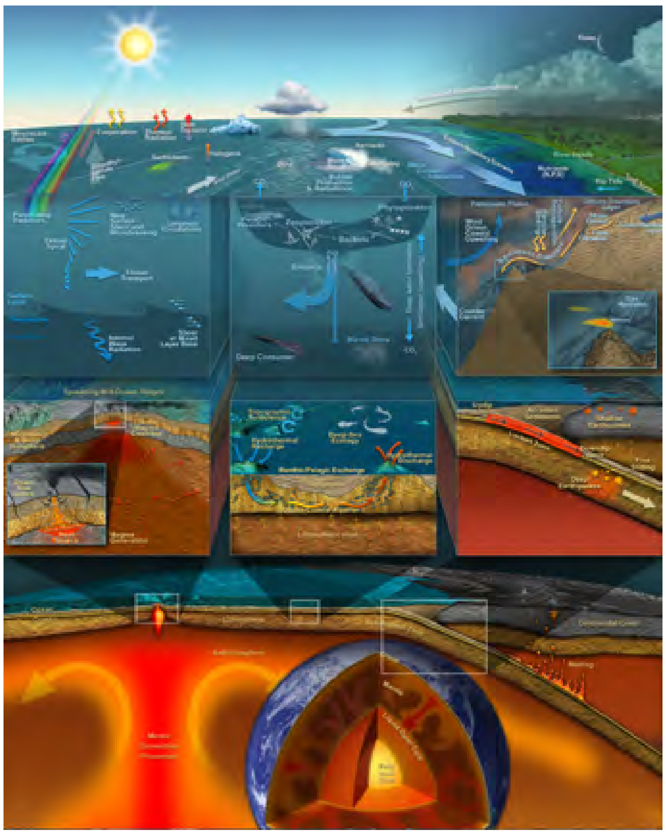
The concept of establishing long-term remotely operated ocean observatories has been in existence for several decades (Delaney et al., 1987). The advent of commercially available, high-bandwidth electro-optical cables spanning ocean basins harkens back to 1988 with the deployment of TAT-8 across the North Atlantic Ocean. Scientific use of these elegantly designed and constructed conduits has been sporadic, although the community dialogues in the past decade about the potential have been spirited and, in several cases, promising. Nonetheless, routine use of submarine fiber technology has lagged well behind its employment in the communications industry. This Commentary addresses the potential of a much more widespread use of extending the Internet to the seafloor and open ocean via fiber optic networks (Delaney et al., 2000; NRC, 2003).

Historically, oceanographers have gone to sea in ships to study limited portions of the ocean for short periods of time. We have utilized satellite systems for surficial imaging and for limited bandwidth communications (Iridium), extending the reach and duration of research in the oceans via Argo floats and glider technology. But the grand challenge in the ocean sciences for the coming decades will be the need to successfully design and aggressively implement novel strategies and innovative infrastructures to complement these capabilities and to dramatically increase our rate of discovery and understanding of the complex interactions operating throughout the volume of the ocean basins (Figure 1).

We must deliver these next-generation approaches fast enough and well enough to provide confident anticipation of short- and long-term ocean-generated threats to society as well as resource-based opportunities. These approaches must provide the basis for predicting, well in advance, positive and negative impacts of potentially nonlinear tipping points in our planetary ecosystem resulting from shifts in the dynamic behavior of this "oceanic engine." In a timely manner, we must also create opportunities to understand and assess all the living and nonliving resources

FIGURE 1

A major part of the challenge of studying the global ocean well enough to predict its long- and short-term behavior lies in the fact that the entire system of interacting physical, chemical, and biological processes have coevolved over the past 4 billion years. This complex system of many hundreds of interacting processes is the "flywheel" of our planetary life support system. Until the advent of humans as a major environmental agent, this system was dominated by two energy sources: solar energy from without and geothermal energy from within. Only by establishing a permanent and highly interactive, volumetric telepresence within this system will we come to understand it well enough to forecast its behavior with fidelity. (Illustration designed by John Delaney and Mark Stoermer; created by the Center for Environmental Visualization [CEV] for the NEPTUNE Program.)



distributed throughout the oceans and within the underlying seafloor.

Societal Pressure and Oceanic Impacts

By 2030 there will be a billion more people on the planet, with another billion arriving in the following two decades. These projections impart an urgency to understanding and harnessing the oceans. Arguably, humans will eventually have to learn to "manage" the entire planet, but we do not now have the insight, the knowledge, or the wisdom to do so. The next two to four generations must be spent preparing for the time when we will have no choice but to confront this awesome responsibility. Realistically, Earth is a "water-world," and we must learn its secrets; living on the continents, we are not well positioned to do so. Furthermore, because seawater is effectively opaque to electromagnetic radiation, the oceans are very difficult to explore. Some say it is easier to map the moon or Mars with satellite laser altimeters than it is to map the seafloor of our own ocean using acoustic techniques. Yet with comparable investments in "inner space," we could substantially enhance our capacity to design solutions to some of the key challenges facing the entire human society.

Indeed, it was whimsically asserted in the midst of the space program that we knew "more about the moon's behind than we knew about the ocean's bottom." In some ways this is still true, but the era of exploring the spatial distribution of major features in the ocean basins (and on the moon) is mostly past. Our focus now is shifting to exploration of the time domain, meaning that we must understand the complex behavior of the ocean to anticipate and guard against or to use the unexpected.

In this regard, the ocean basins are still the last physical frontier on Earth. Not only do they episodically deliver devastating impacts on human society, they harbor potentially vast mineral and geomicrobial wealth that is virtually unexplored in many respects. Furthermore, the patterns of ocean circulation and changing sea-surface temperature distributions correlate closely in time with ever-shifting patterns of drought and flooding on the continents. It is, therefore, not surprising that the dynamic behavior of the ocean is linked directly to patterns of food growth and famine on the adjacent continents; we must learn to understand and predict these and many other powerful, global process linkages that play out in both time and space.

Four-Dimensional Telepresence, Global Connectivity

Simple monitoring of the ocean using traditional technologies is no longer sufficient. Moving to the next level of understanding and predictive modeling requires interactive capabilities projecting four-dimensional human telepresence across entire volumes of the ocean from the atmosphere to well within the seafloor. We must be able to detect significant behavioral excursions, both expected and unexpected, within the volume of the ocean basins, and we must be able to reconfigure our sensing/measurement modalities to fully, quantitatively, and adaptively characterize all the processes unfolding within these energetic and linked phenomena.

Success in this endeavor will be a computationally intensive and communications-extensive challenge. As it succeeds, it will require massive storage/archiving activities, supplemented by facile global transport of vast, ever-growing amounts of data from the natural environment, and from increasingly sophisticated model simulations, to globally distributed users. Scientists, policy makers, and citizens linked by the Internet will become increasingly engaged in our ocean as it becomes more and more accessible to all. This next-generation connectivity offers myriad opportunities for engaging the public through ever-more-sophisticated social media. Even the exploration of life beyond Earth is likely to focus on extraterrestrial bodies with liquid water "on board," so ocean science in all its complexity can begin to merge with some of the more captivating forms of cultural fascination involving space odyssey-type public engagement. Oceans via the Internet may become our seagoing equivalent of the night sky for most of the human race.

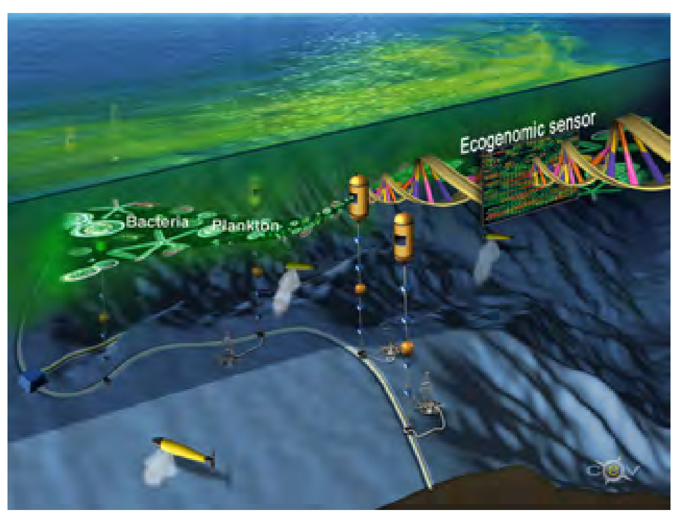
Amplifying Technology Spirals

Ocean science is rapidly becoming a beneficiary of the convergence of a host of powerful, exponentially evolving, emergent technologies driven by widely diverse engineering and economic forces essentially external to the world of ocean research. These cutting-edge capabilities include, but are not limited to, very-high-bandwidth communications, nanotechnology, biotechnology, information technology, *in situ* genomic analysis, remote mass spectrometry, extensive data archiving and search capabilities, computational modeling, imaging technologies, and robotics. More powerful than any single technology will be the progressive integration of all these enabling capabilities into highly sophisticated systems designed to conduct challenging remote operations in novel ways (Figure 2). The potential of these next-generation ocean science research and operational systems to function independently, or nearly so, under harsh and/or remote conditions will rapidly transform human capacity to conduct sustained, comprehensive studies of entire, rapidly evolving marine ecosystems using a volumetric, sensor-robotic telepresence that is not yet possible.

The term "eco-genomics" refers to the concept of scientists using advanced molecular techniques to assess the relationships between biodiversity and environmental health. It has been coined to anticipate the technologies that will continue to evolve at an exponential pace following the completion of the Human Genome Project. The amount of time for and the cost of sequencing a genome has dramatically decreased in the past 10 years, as has the size of the laboratory equipment necessary to complete the analysis. Pioneering efforts using derivative capabilities in the actual ocean have been tested by Chris Scholin of the Monterey Bay Aquarium Research Institute and are expected to be in routine use within 5 years.

FIGURE 2

A vision of the type of next-generation application that might flow from the incorporation into oceanographic research strategies of a rapidly evolving *in situ* genomic analysis capability within selected volumes of the ocean. This capability will launch a revolutionary shift in the manner in which we study ocean systems using on-demand genomic analyses of living communities that dominate the base of the oceanic food chain and that can vary widely depending on the environmental conditions. (Scientific concept by Ginger Armbrust; graphic design by Mark Stoermer for CEV.)



Half of the Nobel Prize in Physics in 2009 was awarded for work leading to digital imaging that is revolutionizing our capacity to capture both motion and still imagery with a fidelity and visual acuity that rivals or far exceeds human vision. Full application of these and other data-intensive sensing techniques within the global ocean would be impossible without the other transformational element recognized by the Nobel Committee for Physics, also in 2009: optical communication. Derivative research has opened the entire planet to high-bandwidth communications especially in the deep ocean where we humans generally do not spend much time collecting images. The incorporation of semiconductors into more conventional fiber transmission systems holds the potential to dramatically enhance the effectiveness and flexibility of utilizing fiber in the oceans to conduct science and to enhance education and public awareness. The initial vision embodied in articulation of Moore's law regarding the exponential doubling capacity of integrated circuits for computers can be seen as an analogue to these and other rapidly emergent technologies.

In the hands of innovative scientists working with inspired engineers, many of these emergent technologies will be used to leverage the effectiveness of the many other capabilities—as in the field of robotics. The concept that numerous technologies may be coevolving in an exponential manner may be the basis for suggesting that the technological innovations utilizing ensembles of these novel designs could evolve even more rapidly. The bottom line is that provision of very high bandwidth and abundant power via submarine cables may optimize the rate of innovation supporting next-generation technological and scientific developments in the ocean basins by aggressively capitalizing on a full suite of emergent technologies (Delaney et al., 2000; NRC, 2003; Delaney & Barga, 2009; Barletto et al., 2010). The recent use of cables for ocean science may be an early phase tending toward worldwide networks of submarine cabled sensor networks, both dedicated *and shared*, throughout the global ocean, to vastly enhance remote human telepresence in a fashion heretofore unimaginable (Delaney & Barga, 2009).

Ocean Complexity—Long-Term Natural Laboratories

Understanding the complexity, the dynamics, and the resilience of the ocean reservoir and the dynamic underlying crust is central to achieving the capacity to address increasingly urgent issues of population expansion, biotechnological innovation, and environmental devolution. Over the next several generations, researchers will not be able to encompass the entire global ocean with equal focus and coverage. Initially, we must carefully select key representative ocean volumes for intensive study of interlinked major and minor processes, at all relevant scales comprising the full scope of oceanic complexity and marine ecosystem dynamics.

Interactive, distributed sensor networks using novel technologies can create large-aperture "natural laboratories" employing real-time experimental control over the entire "laboratory" volume. Fixed and mobile assets distributed throughout a given volume, all communicating via the Internet at nearly the speed of light, can allow constant surveillance of, and response to, a wide spectrum of physical, chemical, and biological processes interacting within key portions of the ocean

FIGURE 3

An artist's depiction of a fully automated seafloor analytical laboratory within an active submarine hydrothermal system—operated serially or in parallel by different remote science groups on land using the power and bandwidth provided by industry standard electro-optical cables. Real-time analysis, *in situ* specimen dissection, and complex experiments can be conducted on any and all materials flowing through the environment of this volcanically driven ecosystem containing exotic microbial fauna. Full operation of such an environmental laboratory will require integration of many emergent technologies discussed in the text. A system of this type and a host of others will become commonplace as the emergent technologies are increasingly integrated into next-generation forms of human telepresence in the oceans. (Scientific concepts by John R. Delaney; graphic design by Mark Stoermer for CEV.)

system. Cabled laboratories will extend unprecedented power and bandwidth to a wide range of interactive real-time sensors, instruments, and robots that can carry out routine experiments, or be programmed to investigate emergent events like erupting volcanoes, major storms, fish stock migration patterns, or progressive environmental anomalies such as ocean acidification or low oxygen "dead zones." Over the coming decades, with progress in machine learning as a powerful adjunct activity, these new capabilities will empower many investigators to push the envelope on high-level creativity, rapid innovation, insightful adaptation, and bold exploration of the time-space domain within a number of natural systems (Figure 3). Selected volumes of the ocean will initially be captured within such natural laboratories, allowing many hundreds of experiments to be conducted simultaneously in a well-documented spatial framework (Barletto et al., 2010).

Initial approaches must simultaneously and comprehensively address all levels of ocean dynamics within selected volumes obtaining sufficient detail to allow comprehensive data assimilation and modeling that can lead to prediction of any and all transient, or steady state, outcomes. This approach requires that dozens of experiments be conducted for decades to document, model, and eventually predict essential interactions operating within these dynamic ecosystem volumes. Results of such experiments must then be progressively integrated into simulations of even more complex global ocean systems in anticipation of specifying the ocean's ultimate behavior well into the future.

Cables can uniquely support widely distributed or densely packed 3-D arrays of sensors distributed *in situ* so that the information available is transmitted from many locations simultaneously—a powerful check on the most sophisticated ocean simulation models. All data must be fully archived (with metadata) and indexed in time and space, for extensive analysis by scientists across the world, many of whom may never have been directly involved in the original collection (Delaney & Barga, 2009; Gray, 2009).

Broader Potential—Cabled Human Presence Within the Sea

Cabled submarine, sensor-robotic infrastructure is but one piece of a comprehensive marine research infrastructure needed in the coming decades. Vast undersea networks may be thought of as the first undersea "interstate" highway that fosters mobility, rapid growth, and enhanced discovery as it links and enables the full potential of existing and evolving tools such as University-National Oceanographic Laboratory System (UNOLS) research vessels, satellites, Argo Floats, autonomous underwater vehicles (AUVs), robotic swarms, fleets of gliders, and unmanned aerial vehicles (UAVs). For example, more demand may arise for UNOLS vessels as traditional research platforms and as service platforms for building and tending long-term, focused experimental sites within the volumetric footprint of more extensive suites of sensor arrays. Another example might include enhanced use of existing data platforms (ships, satellites, AUVs, gliders, UAVs) for identifying novel areas worthy of being configured for rapid response or sustained interactive observation.

Similarly, traditionally single-focus commercial cabled infrastructure may eventually become available to host globally distributed data ports that might function as a site for many mobile assets to plug in and transmit massive amounts of data from the deep open ocean to prearranged accumulation centers. These data might be quickly analyzed in the "cloud" computing environment, then returned to proximal ensembles of mobile assets and used for near-real-time mission validation, response, upgrades, or redefinition. Although the installation cost of cabled infrastructure is not cheap, when considered over a 25-year lifetime, maintenance costs are low, as are data transmission costs. When viewed as the number of observations amortized over the full life cycle cost of the installation and because of the bandwidth necessary to thoroughly interact with complex and dynamic ocean systems, cabled scientific-observational infrastructure may emerge as a surprising bargain (Delaney & Barga, 2009; Gray, 2009).

Global Problems Require International Solutions

Over the coming decades, many different nations, for many different reasons, will implement cabled sensing systems in offshore extensions of their territorial seas, continental shelf-slope environments, and exclusive economic zones. As these powerful new forms of integrated marine infrastructure become more sophisticated and as the data become more routinely accessible, the Internet may emerge as one of the most powerful oceanographic research tools on the planet (Delaney & Barga, 2009; Gray, 2009).

In response to unexpected, energetic transient events in ocean environments, the rapid reconfiguration of key sensor arrays linked via the Internet to submarine electro-optical cables could allow us to image, measure, and respond to unanticipated, previously inaccessible episodic phenomena. These events may include catastrophic natural events such as erupting volcanoes, large submarine mass wasting events, massive earthquakes, giant storms, and tsunamis, as well as progressively more devastating environmental anomalies that include ocean acidification, hypoxia events resulting in "dead zones," super-storm hurricanes, and harmful algal blooms.

Like the atmosphere and outer space, oceans in their entirety do not belong to any single nation, yet we are all dependent on the planetary scale "ecosystem services" they provide. To address and eventually learn to manage some of the potentially profound changes possible in the dynamic systems operating within the ocean basins will require high levels of international collaboration. Because submarine cabled communication systems now bind the international community together, it is fitting that these remarkable products of private industry emerge as an integral part of the solution to one of the major questions confronting our global society: How does our planetary life support system actually work?

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TECHNICAL NOTE

Advantages of Natural Propulsive Systems

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ABSTRACT

The screw propeller has been the mainstay of marine propulsion, but new developments in biomimetic propulsion can provide advantages in terms of speed, maneuverability, efficiency, and stealth. The diversity of aquatic animals provides designs for drag-based paddling and lift-based oscillatory hydrofoils that can be incorporated into engineered propulsive systems for enhanced performance. While the screw propeller will remain the prominent propulsive device, the choice of alternative biomimetic propulsive systems will be dependent on particular applications, where the specifications dictate improved performance criteria.
Keywords: biomimicry, speed, maneuverability, stealth, efficiency

In recent years, engineers have looked to biomimetic solutions for application to marine systems (Fish & Kocak, 2011). In particular, propulsive systems by animals hold the promise for improved performance by machines and vessels operating in the ocean environment (Bushnell, 1998; Fish & Rohr, 1999; Triantafyllou & Triantafyllou, 1995). Naval interests have been concerned with improvements to propulsive systems with regard to speed, maneuverability, efficiency/economy, and stealth, including silence and wakelessness (Bushnell, 1998; McKenna, 2011; Shaw, 1959). Although the screw propeller has been considered more effective compared to other forms of propulsion for over 160 years (Carlton, 2012; Larrabee, 1980), it has certain limitations with respect to the list of performance attributes, which are of interest for naval operations. Screw propellers have problems related to cavitation, a small operational range of maximum efficiency, reliance on control surfaces maneuvering, and a detectable and identifiable acoustic signature. The propulsive systems of animals may alleviate some of these limitations.

Motion through water requires the development of thrust from a propulsor by the acceleration of fluid into a wake to counter the resistive drag and added mass forces. To generate thrust and effectively move in water, aquatic animals have evolved a diversity of propulsive mechanisms correlated with their biological role, evolutionary history, and association with the aquatic environment. To locomote in water, these animals must produce hydrodynamic thrust by acceleration of the water from their body and appendages while simultaneously reducing the resistance to their motion. Because of their swimming capabilities, aquatic animals have recently gained wide attention as models for underwater vehicles (Anderson & Chhabra, 2002). The mechanism of propulsion used by animals is considered a viable alternative to traditional marine propulsors. Indeed, aquatic animals are considered to be superior in their propulsive abilities compared to technologies developed from marine engineering (Anderson & Chhabra, 2002; Fish et al., 2011; Triantafyllou & Triantafyllou, 1995).

The focus of this technical note is concerned with how thrust is generated by the various propulsive mechanisms exhibited by animals. A survey of the biomechanical and hydrodynamic mechanisms of biological propulsive systems will permit identification of innovative mechanisms that may be transitioned to manufactured designs. In this regard, the examination of animal propulsive systems will be confined to high Reynolds number, inertial-based swimming. This mitigates scaling problems inherent in application of small, viscous-dominated systems to large-scale systems associated with current technologies and tasks. With the exception of jet propulsion by cephalopods (e.g., squid, octopus), the majority of analysis on swimming and related hydrodynamics of undulatory bodies and oscillatory appendages has been performed on fish.

Propulsive Forces

The diversity of propulsive surfaces and structures can be classified with regard to the forces generated. For animals, the pertinent forces are pressure drag, acceleration reaction, and lift (Fish, 1996; Webb, 1988; Webb & Blake, 1985). These forces are generated actively by motion of the propulsive surfaces (e.g., fins, flippers, flukes, legs) or from flow ejected from volumetric contraction (i.e., jet propulsion).

Pressure drag is a resultant of the asymmetry of the fore and aft flow around an appendage. This asymmetry creates a pressure difference, which is the basis of the drag and can be used for propulsion. Drag-based propulsion is associated with paddling. The paddle is unstreamlined with a broad distal end, thereby increasing propulsive efficiency by affecting a large mass of water (Alexander, 1983). In animals, the stroke cycle is divided into power and recovery phases (Fish, 1996; Webb & Blake, 1985). During the power phase, the posterior sweep of the appendage generates drag, which provides an anterior thrust to the animal. The recovery phase repositions the appendage. To prevent an increased pressure drag on the appendage that will negate the thrust generated, the appendage is collapsed or feathered. Examples of drag-based swimmers include labriform fish, frogs, turtles, ducks, and semi-aquatic mammals. Paddling is typically associated with slow surface swimming and precise maneuverability.

Acceleration reaction results from changes in the kinetic energy of water accelerated by action of the propulsive body structure (Daniel, 1984; Webb, 1988). The acceleration reaction differs from drag in that (1) the acceleration reaction is directly proportional to the volume of an object, while drag is proportional to the surface or cross-sectional area, and (2) the acceleration reaction depends on changes in velocity of an object, resisting both acceleration and deceleration, while drag depends on the instantaneous velocity of the object, resisting acceleration but augmenting deceleration (Daniel, 1984). Animals use the acceleration reaction when swimming by undulation by passing waves down the body or through fins (Daniel & Webb, 1987; Webb, 1975, 1988). Flattening of the undulatory surface enhances the magnitude of inertial effects (Lighthill, 1969).

Acceleration reaction is used also for jet propulsion (Daniel, 1984), which is a means of propulsion used by cephalopods (squid, octopus), jellyfish, scallops, salps, and frogfish. Thrust by jetting results from the forceful expulsion of a mass of water from an internal cavity. As the fluid is not heated to rapidly expand its volume as it occurs in conventional jet engines, jetting animals are required to have a body that can retain a large quantity of water prior to expulsion. The water is expelled through a constricted aperture. This constriction permits a longer duration jet with a higher velocity relative to the velocity of the organism (O'Dor & Webber, 1986). In addition, some jetting animals (e.g., squid) can direct the aperture to vector the thrust of the jet for maneuvering control. Jetting over extended periods involves pulsatile flow, as the contraction of the cavity responsible for ejecting the fluid must be refilled.

Appendages, which are used to generate lift-based forces for propulsion, are relatively stiff hydrofoils. To maximize lift, the hydrofoil has a crescent, winglike design with high aspect ratio (Lighthill, 1969; Webb, 1984). This shape provides the hydrofoil with a high lift-to-drag ratio and high propulsive efficiency. As the hydrofoil is oscillated, the angle of attack is controlled (Fish & Lauder, 2006; Lighthill, 1969). The angle of attack is generally a small angle corresponding to the deflection of the hydrofoil from the flow. Lift arises from asymmetries in the flow. The asymmetry generates a pressure difference between the sides of the hydrofoil with a net force normal to the incident flow. Lift is generated continuously with a steady flow. Although the hydrofoil produces some resistive drag, it is small compared to the lift. Tuna, sharks, sea turtles, penguins, cetaceans, sea lions, and phocid seals use lift-based propulsion.

Screw Propeller Versus Natural Propulsion Systems

Within the immense diversity of aquatic animals is a variety of solutions to effect locomotion through water. The varied morphological features and their structural organization and kinematics present a rich resource of novel designs that may be incorporated into propulsive systems. Because both engineered propulsive systems and animals must contend with the same physical laws that regulate their design and performance, there are instances in which the propulsive systems of animals can be superior to the performance of machines. As stated above, there are four parameters (speed, maneuverability, efficiency/economy, stealth) that needed to be examined in animals for inspiration and the development of potential new designs that would be advantageous for marine propulsive systems.

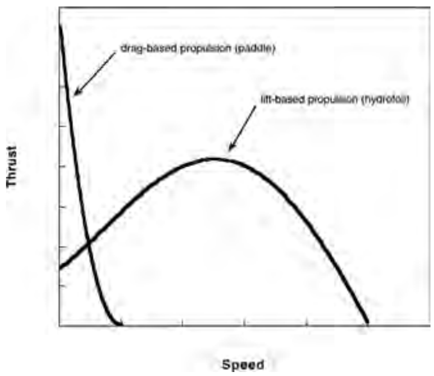
Speed

The most dominant attribute of performance is speed for both animals and engineered vehicles. Maximum speed and acceleration are often considered the most important factors of speed as they reduce the time to a target or destination and can quickly remove one from danger. For animals, these factors are subject to strong evolutionary selection pressures. However, lower routine speeds and long-term endurance can be equally important.

The performance of the drag-based and lift-based propulsive

FIGURE 1

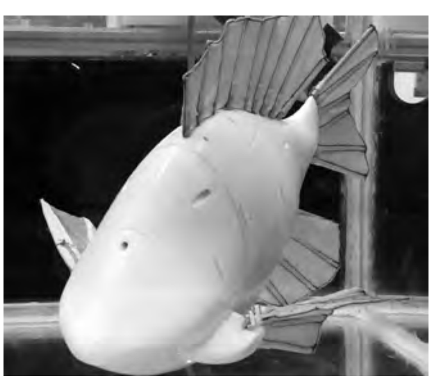
Comparison of lift-based and drag-based thrust production in relation to swimming speed. Drag-based paddling can result in substantially greater thrust production than lift-based swimming when a body is stationary. As speed increases, drag-based paddling becomes less effective compared to lift-based thrust production. Redrawn from Vogel (1994).



systems is limited by swimming speed (Figure 1). Drag-based paddling operates most effectively at low speeds, whereas lift-based hydrofoils perform best at higher speeds. As a flow field needs to be established for a lifting surface to work, hydrofoils are limited in use to conditions where the body of an animal is already in motion. Paddles can be used when the body is stationary. A paddle of large area can impart sufficient momentum to a mass of water to induce recoil in a stationary body. The reaction force can be used to accelerate the body and produce a maneuver. Because the thrust production by the paddle is dependent on its movement in the direction opposite the body movement, thrust decreases as the velocity of the body increases. At a speed where the body and paddle speeds are equivalent, thrust can no longer be produced (Vogel, 1994).

FIGURE 2

Biomimetic fish with fins controlled by mobile fin rays. Courtesy of J. Tangorra.



The highest swimming speeds in animal systems are found for the oscillatory lift-based propulsors. Swordfish (*Xiphias gladius*) and marlin (*Makaira indica*) have the highest maximum speeds of 70 kts (Aleyev, 1977), which may only be for brief periods of time. This speed is faster than for fully submerged vessels, except when supercavitation is employed. Whales and dolphins can travel at speeds up to 22–34 kts (Fish & Rohr, 1999). Routine speeds for cetaceans, which are used for sustained cruising and long migrations, are 2.5–7.0 kts (Fish & Rohr, 1999).

Maneuverability

Standard engineered propulsive systems work in concert with control surfaces (e.g., rudders, fins, dive planes) to maneuver. In addition, lateral thrusters and vectored thrust mechanisms (e.g., water jet, outboard motor) can produce turns. While various marine organisms use similar mechanisms through combinations of fins (e.g., boxfish, cetaceans) and vectored thrust (e.g., squid), there are animals in which the propulsor can provide maneuvering control and thrust simultaneously.

The bluegill sunfish (*Lepomis macrochirus*) uses its pectoral fins to hold station, maneuver, and provide thrust. The control of the fin occurs through complex manipulation of the individual fin rays. Robotic fins have been developed to mimic the motions, forces, and flow control of the natural fins (Figure 2; Tangorra et al., 2011).

The manta ray (*Manta birostris*) and other batoid fishes have enlarged pectoral fins that act as propulsors, stabilizers, and control surfaces (Moored et al., 2011). The action of the manta's fins provides efficient thrust production for migration in the open ocean and enhanced maneuvering control around environmentally complex coral reef communities. The development of a robotic ray, based on the manta (Mantabot), has shown promise in its ability to maneuver (Figure 3). The flexible fins are actuated by an internal tensegrity skeleton (Fish et al., 2011). The Mantabot can execute

FIGURE 3

Sequential images of a swimming robot based on the morphology and kinematics of the manta ray (Mantabot). The pectoral fin is oscillated in the vertical plane by actuation of an internal tensegrity skeleton. The pathway of the oscillating fin tip is indicated by the sinusoidal trace. Courtesy of H. Bart-Smith.

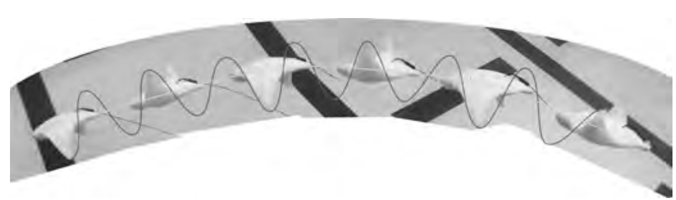


FIGURE 4

The Robojelly is an artificial jellyfish, which swims by pulsations of its bell-like body. Courtesy of S. Priya.

turns with a radius of 0.72 body lengths at over 59 deg/s; whereas, the AUV Remus turns with a radius of 2.9 body lengths at a rate of 9.9 deg/s (Stanway, 2008).

The ability to maneuver also involves swimming motion to maintain position and station hold, particularly when subjected to external perturbations. Animal propulsive systems can be used to generate thrust or increase drag to orient forces in opposition to currents, wave action, buoyancy changes, and collisions with other bodies. An artificial jellyfish (Figure 4) could hold position and operate in the open ocean over an extended deployment like the real jellyfish, whose swimming motions use minimal energy (Joshi et al., 2011).

Efficiency/Economy

Standard marine propellers are limited with regard to hydrodynamic efficiency. The efficiency of a typical marine propeller is less than 70% (Breslin & Andersen, 1994; Carlton, 2012; Larrabee, 1980). The efficiency of a propeller is dependent on the kinetic energy losses due to the rotation rate and swirl induced to the fluid. The energy losses of the propeller are largely due to friction drag on the blades, tip leakage, rotational flow, and propeller-induced axial/swirl flow (Larrabee, 1980; Olsen, 2004; von Backström et al., 1996). Axial losses account for the majority of kinetic energy losses under high thrust production (Breslin & Andersen, 1994). Many propellers have a fixed pitch of the blades, which limits the maximum efficiency to a narrow operational speed and load range (Fish & Lauder, 2006).

The thrust performance of animal propulsive systems has been considered superior to screw propellers (Peterson, 1925; Pettigrew, 1893; Triantafyllou & Triantafyllou, 1995). Although the efficiencies of paddle propulsion are less than 0.33 (Fish, 1996), body and caudal fin propulsion for fish and marine mammals efficiencies typically range from 0.7 to over 0.9 (Fish & Rohr, 1999; Webb, 1975). These high efficiencies are associated with lift-based thrust production from oscillation of a caudal hydrofoil. The oscillatory motions of flexible-bodied fish and dolphin tails were considered to be able to adjust to velocity changes and maintain effective thrust production over a large speed range (Fish et al., 2006; Peterson, 1925; Pettigrew, 1893; Saunders, 1951, 1957).

There are advantages to the application of the concept of an oscillating propulsor (Carlton, 2012; Vermeiden et al., 2012). There is the possibility of larger propulsive areas to accelerate a large mass of water and increase thrust production compared to the typical propeller. This action would reduce axial kinetic energy losses and would reduce the thrust loading of the blades to increase efficiency and reduce the likelihood of cavitation. When the area of the oscillating propulsor is distributed in a high aspect ratio configuration as displayed by a number of animals, there is reduced induced drag (Vermeiden et al., 2012). Furthermore, the flow regime over the blades would be almost two dimensional (chordwise). Such a flow enhances efficiency by reducing spanwise flow, which is associated with energy losses from the spin of a screw propeller.

The caudal fin of fish and flukes of cetaceans can be self-adjusting hydrofoils in which the highly flexible structure automatically alters its camber (Fish et al., 2006; McCutcheon, 1970). Thus, the caudal fin and flukes regulate the hydrodynamic load and distribute the load over the propulsor in the same way at all speeds. Vermeiden et al. (2012) found that the chord of a flexible oscillating fin had reverse camber at midstroke that produced a small gain in efficiency as the fin reversed direction at the end of the stroke. The flexibility of the fin associated with direction reversal suggested energy storage and recovery at the start of each stroke. This effect would be particularly prevalent with a highly flexible trailing edge as found in fish and marine mammals (Fish & Rohr, 1999).

Flexibility across the chord can increase propulsive efficiency (Bose, 1995; Katz & Weihs, 1978; Prempraneerach et al., 2003; Vermeiden et al., 2012). The efficiency of an oscillating, flexible hydrofoil is increased by 20–36% with a small decrease in thrust, compared to a rigid propulsor executing similar movements (Katz & Weihs, 1978; Prempraneerach et al., 2003). Cambering would change the flow over the propulsive surface to increase the lift generated. Cambering would be beneficial to maintain lift production at the end of each oscillatory stroke as the propulsor changes direction, when there is a period of feathering (i.e., parallel to the incident flow, producing no thrust and reducing efficiency).

Camber is provided in fish by the bony fin rays, which act like flexible girders when subjected to hydrodynamic forces (Flammang et al., 2013; McCutcheon, 1970). Movement of the half rays by muscle activation can also produce bending. The flukes of cetaceans can be bent along the axes of chord and span. Structurally, the flukes are lateral extensions from the tail, and there are no bony supports in the fluke blades. A model two-blade propeller with electroactive polymeric artificial muscles to induce cambering produced a 15% enhancement of thrust (Bandyopadhyay, 2002).

The efficiency of jet propulsion is lower than for swimming by undulation. Squids have a propulsive efficiency that is only one third of a similarly sized fish (O'Dor & Webber, 1986). The squid loses substantial kinetic energy as it must accelerate a smaller mass of water to a higher speed than a fish to obtain the same thrust. Although squid can accelerate as rapidly as fish (39 m/s^2), the squid uses more than twice the energy to travel half the speed of a fish.

FIGURE 5

Biomimetic glider that has a mobile caudal fin for low energy movement. Courtesy of X. Tan.

A substantial increase in efficiency in animals can be realized by using passive gliding. Negatively buoyant fish conserve energy by gliding downward with no propulsive motions and then regaining altitude by actively swimming. This strategy is used by AUV gliders (Figure 5; Tan, 2011).

Stealth

Submarines are almost, by definition, a form of stealth technology. The first submarine design to incorporate biomimetic propulsion was proposed by Borelli (1680). Propulsion would be accomplished by oars projecting through the hull and fitted with watertight seals. The oars would paddle like the feet of frogs or geese. During the power stroke, a flexible paddle at the end of the oar would expand to push on the water, whereas during the recovery stroke, the paddle would fold passively to reduce the drag on the oar. Borelli considered, however, that propulsion of the boat would be easier if a flexible oar were positioned at the stern emulating the motion of a fish tail. The development of such stealth technology would take centuries before becoming fully operational and then without biomimetic propulsion.

Propulsive systems move objects so that compression waves are propagated through the water to create hydrodynamic sounds. Much of the anthropogenic noise in the marine environment is the result of ship traffic. Propeller noise is the dominant factor with respect to the radiated noise signature of marine vessels (Carlton, 2012). Propeller noise is generated by displacement of the water, pressure differences between blade surfaces, flow over the blades, periodic fluctuations, and cavitation. Cavitation is due to the production of shock waves as bubbles formed from rapid pressure changes around the propeller blades collapse. Fully developed cavitation can emit a noise between 170 and 185 dB over a frequency range of 32 Hz–18 kHz (Carlton, 2012).

Large swimmers, such as dolphins and tunas, could experience cavitation at shallow depth at speeds of 5.1–7.7 kts, but this performance may be rare as cavitation would limit swimming speed (Iosilevskii & Weihs, 2008). The hydrodynamic sounds of swimming fish are generally low in frequency, which ranges down to subsonic (Tavolga, 1964a). The hydrodynamic sounds are nonharmonic with frequencies ranging from 100 Hz to below 10 Hz (Kasumyan, 2008; Moulton, 1960). These sounds are characterized as primarily near-field displacements and can only be detected over a short range when produced at a high intensity (Tavolga, 1964b). Body shape, speed, and trajectory of a swimming fish, and schooling affect the amplitude and frequency of the hydrodynamic sound produced (Kasumyan, 2008; Moulton, 1960).

Emulation is also a form of stealth. Biorobots that look identical with respect to the body form and swimming actions of an organism will blend into the natural environment. The problem with such mimicry is that other biological organisms may prey or parasitize the biorobot and thus degrade its performance or immobilize it. Sharks are known to bite oceanographic equipment, submarine cables, surfboards, and even submarines (Lowry et al., 2009; Papastamatiou et al., 2010). Sea turtles ingest plastic bags that have been misidentified as jellyfish, which are their natural prey (Carr, 1987). Future developments in aquatic biomimetic propulsion and biorobots will therefore have to consider rapid acceleration for escape or antibiofouling mechanisms for long deployments at sea.

Mission

The use of bioinspired propulsive system will probably never replace the general use of the screw propeller. The ubiquity of the screw propeller for marine applications is well established. It has only been in more specialized applications that novel modifications have been made to propeller designs. For example, water jet propulsion can be used in conditions requiring high efficiency, cavitation reduction, and low draught (Carlton, 2012); a pumpjet is quieter and more efficient than an open propeller (Zimmerman, 2000); and a ring thruster produces more thrust for a given power input than conventional thrusters (Holt & White, 1994). Cycloidal, vertical shaft propellers, such as the Kirsten-Boeing propeller and the Voith-Schneider propeller, are capable of high-efficiency propulsion or enhanced maneuverability and station-holding, respectively (Breslin & Andersen, 1994; Carlton, 2012; Jürgens & Fork, 2002). Contra-rotating propellers balance torques and provide directional stability in torpedoes.

Compared to an engineered propeller system, including the standard marine propeller, biomimetic propulsion can have enhanced performance with respect to speed, maneuverability, efficiency, and stealth. However, the use of biomimetic propulsive systems will be dependent on the specifications of a defined application or mission. Defining the mission requirements and matching them to the performance envelope of a biomimetic propulsor becomes crucial. Although biomimetic propulsion may have some utility or serve for inspiration to modify existing propulsion systems for large marine vessels, the benefits and applications in the near term will be confined to small robotic systems. Autonomous underwater vehicles can serve as test beds for developing biomimetic propulsion and find utility in performing missions that are outside the scope or performance levels of existing propeller technologies.

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COMMENTARY

Recent Trends in Underwater Acoustic Communications

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ABSTRACT

Advances in underwater acoustic communications technology are being enabled by more access to in-water data and an infusion of new techniques, researchers, and students. In-water data collection is being made possible by robust funding in the United States, the European Union, and other countries, typically to multiorganization consortia working on both physical and network layer research. At the physical layer, single and multicarrier modulation methods continue to be refined, with a focus on both low signal-to-noise ratio, low-rate and high signal-to-noise ratio, high-rate data links. Establishment of performance metrics for adaptive equalizers and other parts of the physical layer continue, and recent work on high-fidelity channel models that mimic the effects of small-scale ocean processes indicates that progress is being made.

Research in undersea acoustic networks continues to gain momentum as well, with multiple options available for integrating acoustic propagation models with network simulation, providing common frameworks for basing network design. The combination of these recent advances, plus continued interest by maritime science and industry in wireless communications, means that the field is poised to make new commercial breakthroughs in the next several years.

Introduction

In recent years, there has been a significant amount of activity in the area of underwater acoustic communications, primarily in research but also in development. As the field has matured, several survey articles have been published, addressing the link-level signal processing as well as networking challenges. In December 2008, the IEEE Journal on Selected Areas in Communications published an issue on underwater wireless communications and networks—the first of this kind. Following that, the IEEE Communications Magazine devoted its 2009 January feature topic to acoustic communications, and most recently, in January 2013, the Philosophical Transactions of the Royal Society published a survey article on recent advances in underwater sensor networks (Heideman et al., 2012). These volumes contain detailed accounts of technical aspects that captured the interest of the research community over the past few years. They also demonstrate that a wider, mainstream communications research community is developing an interest in acoustic communications. Meanwhile, the IEEE Journal of Oceanic Engineering and the Journal of the Acoustical Society of America continue to be the major sources of relevant information and new results in this area.

Beyond journal publications, topics related to acoustic communications continue to expand at regular venues such as the MTS/IEEE OCEANS Conferences. These topics are also addressed at regular meetings of the Acoustical Society of America, and specialized workshops are emerging as well. An example is the series of workshops on underwater wireless networks, which is being organized annually under the auspices of the Association for Computing Machinery and is currently in its eighth year. In addition, flagship conferences of the IEEE Communications Society and Signal Processing Society, such as Globecom and ICASSP, are starting to organize special sessions and workshops on underwater signal processing and networks. The long-standing Asilomar Conference on Signals, Systems, and Computers has had a special session on underwater communications for 5 years in a row. In other words, the field is flourishing.

Research activities in the United States are supported by funding from federal agencies, including the Office of Naval Research and National Science Foundation, and in Europe, similar organizations are supporting research there. Over the past several years, this funding has made it possible to conduct a number of large experiments, involving multiple research institutions such as the Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography as well as academia (participants included Arizona State University, University of California at

San Diego, University of Connecticut, University of Illinois at Urbana Champaign, Massachusetts Institute of Technology, Northeastern University, and several others). The experiments included the Surface Processes Acoustic Communications Experiment (2008), the Mobile Acoustic Communications Experiment (MACE 2010) (Figure 1), and the Kauaii Acoustic Communications Experiments (2008 and 2011), which took place in the United States. In Europe, major experiments took place in Norway, Italy, and several other countries. Researchers in Singapore, Norway, Germany, Italy, Spain, The Netherlands, and Portugal have also actively contributed to the increasingly international acoustic communications scene.

The availability of large experimental data sets is important for advancement because of their realism compared to models. However, the importance of models is growing as their fidelity improves and they become more realistic. A special workshop, organized by the NATO CMRE in Italy in September 2012, drew participants from all over the world to discuss the topic of acoustic communication and channel modeling, which is critical to standardizing performance evaluation and reducing the need for costly field experiments. Selected papers from that meeting will soon be published in a special issue of the IEEE Journal of Oceanic Engineering.

FIGURE 1

A tow fish with a four-element vertical source array is deployed on the *R/V Oceanus* during the MACE 2010 cruise south of Cape Cod, MA.

The growth that the field of underwater communications is experiencing has also led the community to realize that this topic cannot and should not be considered as a stand-alone one, separate from a much larger body of research that is evolving in parallel in the fields of navigation, localization, vehicular robotics, and system integration in general. The push has thus been for an interdisciplinary approach to research that will tackle complex problems of autonomous underwater systems. Such cross-cutting research is increasingly being promoted by the funding agencies (Edwards, 2013), and researchers are responding. Examples are evident in recent publications that address complex system optimization involving multiple vehicles that have to operate in a collaborative manner while sharing the limited acoustic bandwidth (Hollinger et al., 2012) or network relay systems dedicated to efficient image transmission (Murphy et al., 2013).

In what follows, we will focus our attention on summarizing the key components of acoustic signal processing that have emerged in the past few years and that define current research trends in this area.

Signal Processing for Communications

The past several years have seen a number of interesting developments in signal processing for communications, whose common goal is to increase the data rate and improve the performance of communication over band-limited acoustic channels. While the question of acoustic channel capacity remains open, these practical techniques have been steadily pushing the limits of traditional system design to adapt it to frequency-selective and highly Doppler-distorted acoustic channels. Specifically, work has been active on single-carrier as well as multicarrier modulation/detection techniques and on the attendant issues of adaptive channel estimation/equalization, multiple-input multiple-output (MIMO) signal processing, and adaptive modulation methods.

Single-Carrier Modulation and Detection

In the realm of single-carrier modulation/detection, significant advances have been made by using adaptive turbo equalization techniques (see Choi et al., 2011, and references therein). These techniques capitalize on combining channel coding and equalization to improve the system performance. Unlike the conventional equalization techniques, which form the backbone of existing acoustic modems and in which channel coding is treated separately from equalization, turbo equalization techniques are based on the idea of concatenated coding, where the outer code is applied at the transmitter, while the channel plays the role of the inner code. The receiver design is based on iterative decoding, which must also incorporate adaptive channel estimation. The underlying signal processing is quite complex, and the major research thrust has been on developing manageable-complexity receiver algorithms and improved channel estimation techniques. Cast in a MIMO framework, these techniques have shown substantial performance improvement over the existing systems (an order of magnitude or more reduction in the bit error rate at 15 kbps in 9 kHz of bandwidth is reported in Choi et al., 2011).

Another technique that has shown promise for equalization of single-carrier broadband systems on channel with extended multipath is that of partial response equalization (Roy et al., 2009). In this technique, the channel is first partially equalized to a shorter, *a priori* set response and then subject to further decoding.

Crucial to successful equalization is adaptive channel estimation, and recent work has recognized that, although the acoustic multipath is long, it is often sparse (Figure 2), and this can be exploited to improve channel estimation. Sparse channel estimation disposes of the traditional minimum mean square error (or norm-2) optimization and focuses instead on constrained norm-1 or mixed-norm minimization as a computationally feasible approximation to the (norm-0) problem of sparse channel estimation. While the literature offers a wealth of sparse estimation algorithms, in single-carrier equalization, sparse channel estimation has recently been addressed in Pelekanakis and Chitre (2013).

A special method that has long been used in conjunction with single-carrier equalization is time reversal (or phase conjugation in the frequency domain). Applied either actively (at the transmitter) or passively (at the receiver), a time-reversed replica of a received signal waveform is used to implement a filter matched to that waveform, thus aiming to optimize the input to the equalizer. Recent results in this area include Cho et al. (2011), which extends previous work to a multiuser framework, applying time reversal not only for equalization but also for interference cancellation as well.

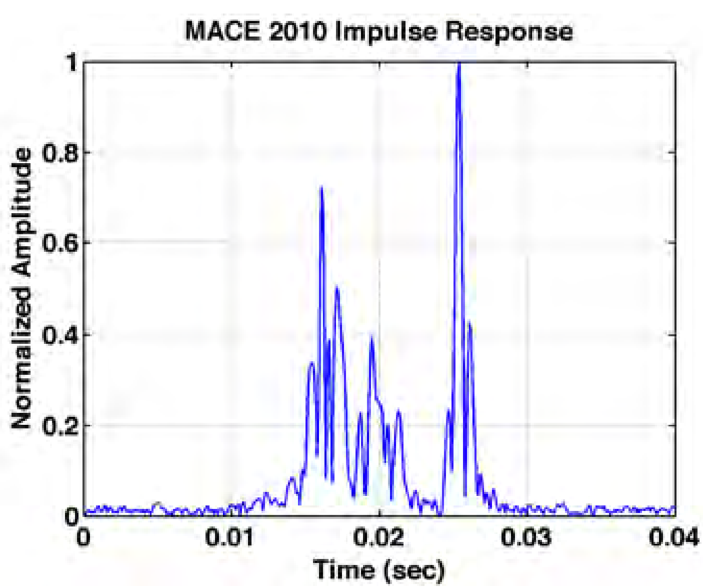
Multicarrier Modulation and Detection

An alternative to single-carrier modulation/detection techniques are multicarrier techniques, typically implemented in the form of orthogonal frequency division multiplexing (OFDM). While routinely used in many terrestrial systems (DSL, WLAN, Digital Audio/Video Broadcast, LTE, and standardized for the 4G cellular systems), OFDM has only recently begun to emerge in the acoustic world (Li et al., 2008). Recent years have seen a plethora of results, which attest to the fact that OFDM is a viable low-complexity alternative for combating the frequency selectivity of the acoustic channel. By virtue of dividing the frequency band into many narrow sub-bands, each of which can be treated as frequency-flat (nonselective), OFDM allows for simple FFT-based equalization; it is conducive to MIMO implementation for spatial multiplexing or transmit diversity gain, supports differentially coherent detection, and easily lends itself to adaptive modulation. Its major drawback, however, is the sensitivity to the time variation of the channel, which causes intercarrier interference (ICI). This problem has been the focus of recent research, and several techniques have been developed to address it. They include ICI equalization via augmented sparse channel estimation (Berger et al., 2010), recursive ICI equalization (Tu et al., 2011), and prefiltering methods based on multiple-FFT demodulation (Aval & Stojanovic, 2012). All of these methods have been demonstrated using in-water data, showing good performance in varying channel conditions (e.g., Aval and Stojanovic, 2012, reports on transmitting at 9 kbps over a 5-kHz mobile acoustic channel with a multihour average mean-squared detection error below −9 dB).

The quest for high-rate transmission over acoustic channels is tightly coupled not only with the receiver's ability to adapt to the changing channel but also to the ability to feed the channel state information back to the transmitter, so that it can adapt to the environment as well. While conceptually simple, the

FIGURE 2

Multipath measured during the MACE 2010 experiment during one of the source tows.



ideas of adaptive modulation are not nearly as easy to demonstrate in practice, as they require online experimentation. In reference, Radosevic et al. (submitted) reports on one of the first attempt to do so. Specifically, it focuses on multicarrier modulation, where both the modulation level and the signal power can easily be adjusted for each of the carriers. Two types of feedback-based power control are used, one that adjusts the total power level and another one that distributes it across the signal spectrum (carriers).

Future work on signal processing for acoustic communications will likely focus on improving our understanding of the channel distortions, so that they can be targeted in an efficient manner. Research trends will focus not only on conventional point-to-point links but also on multipoint-to-point links (in multiuser or cooperative communications frameworks), interference-limited regimes (links with unintentional or intentional interference), low probability of intercept/detection systems for secure communications, and others. Feedback-based methods, by which the receiver can inform the transmitter of its current state, are likely to draw attention, as they offer large potential gains through adaptive power and rate control. Understanding of channel distortions and classification of channel parameters into those that can be predicted, those that can only be estimated, and those that are intractable remain important research tasks.

Channel and Network Modeling

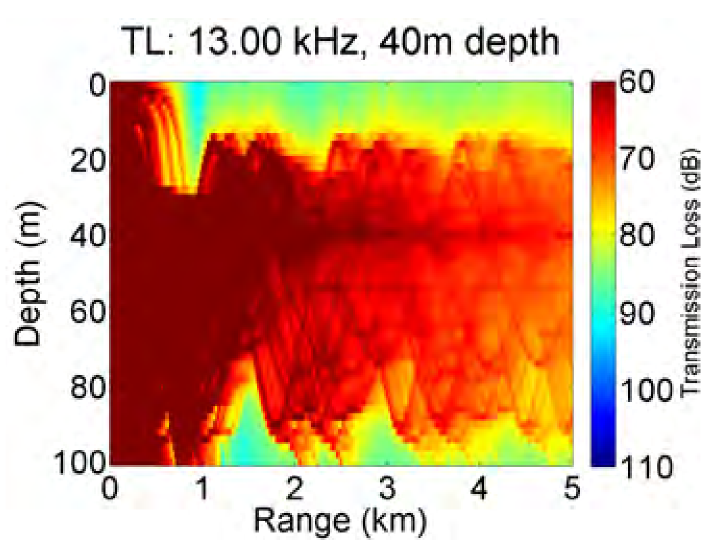
The need to investigate adaptive modulation methods as well as network protocols, which cannot be analyzed using off-line experimental data but require *in situ* experimentation, has sparked a renewed interest in channel modeling. Channel modeling—in particular, statistical channel modeling—is necessary for the development of channel simulators, which will aid in such analyses. While these simulators cannot replace experimental trials, they are expected to help in preparation for the (costly) deployments.

Ray tracing codes such as the Bellhop model (see reference list) are now in regular use for estimating the nominal channel characteristics (Figure 3), but they were not designed to simulate the random channel effects caused by small disturbances. Such disturbances result from the displacements of transmitter/receiver and the channel boundaries and other environmental changes including those caused by tides, currents, and wind-driven surface waves. The motion-induced Doppler effects have been addressed in a computationally more efficient manner by the VirTEX simulation algorithm (Peterson & Porter, 2012). The effects of the surface waves curvature and the amplitude and arrival time fluctuations that they introduce have been modeled in Deane et al. (2012). A statistical approach to channel modeling is taken in Qarabaqi and Stojanovic (in press), where micro-multipath caused by surface scattering is modeled as a complex Gaussian multiplicative distortion imposed on each surface-reflected path, with path-specific, frequency-dependent correlation. While much remains to be done on the subject of acoustic channel modeling for communications, the topic has clearly captured the attention of the research community, and we are likely to hear more about it in the future.

In parallel with the work on physical channel modeling, several efforts have been underway to develop network-level simulators (see Heideman et al., 2012, for an overview of recent activities in acoustic networking). In addition to implementing a suite of communication network protocols, these simulators typically employ a ray trace algorithm, coupled with digital ocean maps so that a user can specify the desired location and system geometry. Basic effects

FIGURE 3

Transmission loss computed using the Bellhop model for the sound-speed profile observed during the MACE 2010 experiment.



of acoustic signal delay, frequency-dependent attenuation, and noise are thus included in a network simulator. Inclusion of time-varying channel effects remains to be addressed as relevant physical link models emerge. Two frameworks that stand out are SUNSET from Sapienza University and DESERT Underwater from the University of Padova (see links in the reference list). Both projects include multiple investigators and collaborators and build upon the ns2 or ns2 MIRACLE network simulators.

Conclusions

The continued appearance of acoustic communications research in mainstream signal processing and communications publications (in addition to ocean- and acoustics-related journals) supports the contention that the area is rich enough technically to attract talented investigators from diverse academic backgrounds. The growth of student participation, manifested by completed Masters and PhDs plus a strong showing in posters at major conferences, also heralds the continuation of work by a new generation of researchers.

The recent advances, described so briefly here, are likely to be significant because of the rigor in the approach and the use of both in-water data for field trials and the inclusion of simple propagation models that at least include shadow zones and demonstrate that range is not the only important parameter. As higher-fidelity models (combining measured statistics and propagation) are made available to the community, standardization of methods for benchmarking algorithms will become more prevalent, allowing easier identification of significant advances. Reporting of both field results and computer simulations in terms of parameters such as the signal-to-noise ratio at the input to the receiver will make comparison and extrapolation much easier.

Ultimately, the undersea technology market will drive the investment in specific new physical layer and network techniques. While the first-generation "killer application" for underwater telemetry—communicating with and controlling an autonomous underwater vehicle—is reasonably well satisfied by existing technology, many improvements could be made. However, demand for hardware remains modest compared to consumer electronics, and the level of investment necessary to move from a laboratory prototype to real-time and ready-for-sale is high. Furthermore, the more sophisticated the solution, the more expensive the implementation.

Better modeling, new development tools, increased access to the sea for realistic data, and the emergence of new demand could change the situation quickly. The research field has reached a transition point, and the question really is, how long before development and application catch up?

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PAPER

The Future of Marine Propulsion: "Reading the Propulsion Crystal Ball"

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ABSTRACT

The marine industry is headed into a period of uncertainty as both environmental restrictions and rising fuel prices simultaneously converge unlike any time in its past. Yet at the same time, innovations in propulsion solutions have allowed the industry to keep pace with demands thus far, as the demand signal continues for both efficient propulsion designs as well as lower overall emissions. The growing calls for environmental compliance, and its origins will be examined, as well as solutions that will reduce propulsion emissions. New regulations and fuels with lower sulfur content will require reconfiguration of the propulsion plants. This paper primarily discusses both the background of the challenges that the industry will be facing as well as available solutions. Both the marine industry as well as the military will be reviewed.
Keywords: proplusion, environmental compliance, emmisions reduction

Introduction

A perfect storm in the form of propulsion requirements is beginning to take shape in the marine industry. The near-simultaneous implementation of two major new emissions regulations for the marine industry is unprecedented and will forever change the way ships are designed and operated. At the same time, the industry must contend with the ever-increasing demand for different types of fuel, the rising costs of those fuels, and the locations where they can be economically delivered. This all adds up to present serious economic and technological challenges for propulsion developments for the military and international shipping industries.

World Scene Setting

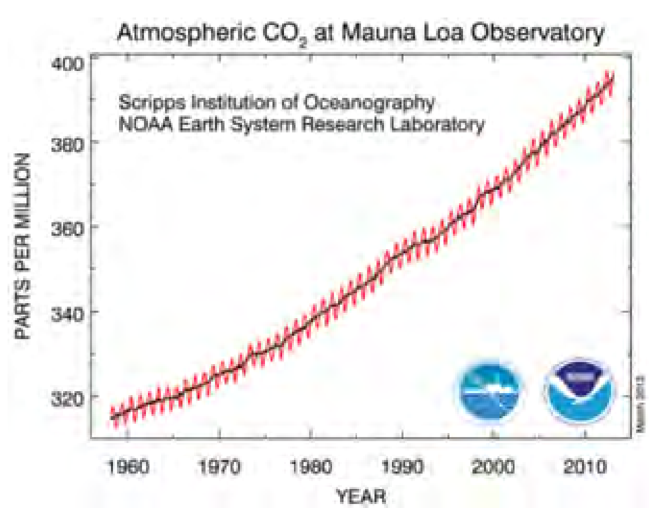
Climate change and its causes can be debated, but data show CO_2 levels have been steadily rising from 310 parts per million (PPM) in 1958 to 400 PPM this year (Figure 1).

Rising an average of 2 PPM per year, CO_2 needs to stabilize between 450 and 550 PPM in order to limit the impact of global warming to no more than 2° Celsius; otherwise, the effect on global weather and the general population's health could become catastrophic. This is why the world's governing bodies have pushed to limit the production of NOx (nitrogen oxides) and SOx (sulfur oxides) emissions worldwide.

The global marine industry is thought to be producing approximately 870 tons of CO_2 annually, which is about 3% of the world's total output. The concentration of truck/rail traffic in our ports makes these areas some of the worst pollution-generating regions in the United States. With the continuing expansion of global trade and the clear economic benefit of using shipping for transportation, it is predicted that harmful NOx and SOx emissions would more than double over the next two decades without intervention. The U.S. Environmental Protection Agency predicts that,

FIGURE 1

Atmospheric CO_2 at Mauna Loa Observatory.



without regulation, these emissions will result in 14,000 premature deaths, more than $110 billion in annual healthcare costs, and approximately 5 million respiratory symptoms in the U.S. alone.

The International Maritime Organization (IMO) took action on March 26, 2010, amending the International Convention for Prevention of Pollution from Ships (MARPOL) with two important SOx and NOx compliance regulations. The SOx regulation takes effect on January 1, 2015, and will impact existing ships and new builds. The NOx regulation takes effect the following year, severely reducing the emissions of NOx on new builds only. These emission control areas (ECA) are being established in North America and Northern Europe, and they could be adopted more broadly worldwide as technologies are developed to support compliance. The ECAs essentially extend out 200 miles off the coast of the effected countries (Figure 2).

The SOx Solution

Three methods are available to reduce SOx emissions for large ships with slow-speed diesel propulsion systems. These methods include the following:

- using low sulfur content fuels,
- cleaning the exhaust gas via scrubbers, and
- reburning or converting the ship to natural gas.

The sulfur content of fuel used in ECAs currently is 1% and will fall to 0.1% in 2015, and conversely the global cap on sulfur content in marine distillates worldwide will fall from the current 3.5% to 0.5% in 2020. With such significant changes, there is a provision to reevaluate these figures in 2018 to determine whether worldwide refineries can produce the fuel in quantities needed to meet global demand.

For ECA operations, the only fuel solution that will drive industry to 0.1% sulfur content is the operation of a dual fuel solution, in which existing ships will operate on heavy fuel oil (HFO) outside of the ECA and marine gas oil (MGO) inside the ECA. But this option is complicated by the fact that the world demand is increasing for MGO, and the 0.1% sulfur content limit will increase demand from today's 30 million tons to 45 million tons. It is questionable whether the refinery industry will have the capacity to support such a large increase.

Demand outside of the marine industry will dictate whether the refineries can keep pace. The price of low-sulfur diesel fuel will almost certainly continue to rise as demand increases. With the proposed global cap of 0.5% sulfur content distillate, MGO demand could drastically rise from the current production of 30 million tons to approach 250 million tons annually.

Additional options include installing scrubbers on existing ships using HFO or powering new builds with natural gas.

The NOx Solution

The major NOx restrictions take effect on January 1, 2016, for new ship builds and will also have three potential solutions.

The first option is to use a selective catalytic reduction (SCR) device, a proven engineering solution that is gaining success on road diesel trucks and high-speed marine diesel engines. SCRs reduce the NOx emission by 90% by letting the hot gases flow through catalyst elements. Urea is injected into the exhaust gas to enable the catalytic reaction. Additional options include using exhaust gas recirculation, which recirculates unburned exhaust gas into the intake air flow and natural gas-powered engines.

Cost as the Independent Variable

Achieving compliance for these new regulations is going to come as an economic shock to the international marine shipping industry, which is currently experiencing low trade volume and over capacity. Many ships

FIGURE 2

Emission control areas.

are operating on very low margins. These new regulations will put even greater pressure on the bottom line.

For example, MGO is 50% more expensive than HFO and will only become more expensive as demand increases. Investments in new scrubbers, dual fuel engines, and LNG conversion are all very expensive. Picking the right solution that balances cost with environmental compliance is proving difficult. For example, LNG is now plentiful in the United States, but the storage and delivery methods are not yet available. The infrastructure costs are going to be extensive if this solution is employed. Additionally, it is predicted that scrubbers will solve 25% of the world fleet in 2020 at an investment of approximately $15 billion.

With fuel being the largest life cycle cost of operating a commercial ship, and because ships take years to develop and build, the stakes are exceptionally high when settling on the new solution. For military operators, the new restrictions will have an influence on ship design, but the cost of MGO will increase pressure on the cost of operations. As a result, solutions for efficiency will be a motivating factor to examine different propulsion solutions.

Propulsion Answers

For the international shipping industry, the ECA location where ships operate in will drive the engine solution for the emerging regulations. Older ships that cannot be economically upgraded could be exclusively used outside of the worldwide ECAs until their end of service life. Existing ships built prior to January 1, 2016, that are transiting into and out of ECAs will require either a backfit on the engines to enable dual fuel use or the installation of scrubbers (Figure 3).

FIGURE 3

MAN dual fuel engine.

Today's large slow-speed diesel engines were produced for all sizes of tankers, bulk carriers, car carriers, and RoRo ships and have essentially been operating on HFO since the early 1980s. They are extremely forgiving designs and largely economical to operate. In the 1990s, with the increasing demand for LNG and the corresponding demand for LNG ships, these slow-speed engine designs were converted to operate with natural gas because of the readily available supply in their cargo tanks. The safety record has been outstanding, and the design evolution of LNG-powered engines has continued for the past 20 years, overcoming many challenges in utilizing this fuel. These hard-learned lessons comprise the basis of today's dual fuel engine technology utilizing separate injection systems that allow seamless operation with one or both fuel types. These two-stroke engines will increasingly be used in new builds, providing a complete solution to both the environmental restrictions as well as global fuel price fluctuations (Figure 4).

With lower natural gas prices in the United States, ship owners and builders are increasingly looking at LNG as the primary fuel. The abundance of LNG in the United States is clearly going to have an impact on the future of propulsion system selection. A recently announced LNG-powered cargo ship being built in the United States is just the beginning of exploiting LNG. Figure 5 below is the cut away of the NASSCO design for the LNG-powered propulsion plant, the first to be built in the United States of this size.

All Electric or Hybrid Trends

With the advent of better control systems and the associated variable frequency drives, choosing an all-electric solution is occurring at an accelerated pace. The three primary modes include the following:

- the all-electric solution, in which the generators function as the sole source of prime movers;
- the line-up depicted in Figure 6, where a mechanical gear box is supplemented in low-speed operations by an electric motor; and
- a power take-off (PTO)/power take-in (PTI) option with a two-shaft operation, in which a main diesel engine drives a single shaft and operates the electric motor in a generating capacity to either power the ship's load or a motor on the alternative propulsion shaft.

Long used in the cruise industry as a low-voltage solution, the all-electric platform offers increased flexibility as well as propulsion efficiencies. With more advanced control systems and integrated drive electronics, Offshore Support Vessels (OSV) are now employing an electric-hybrid solution as well. The key to a well-designed electric-hybrid propulsion system is to thoroughly understand the operating requirements. Even excellent

FIGURE 4

LNG fuel prices.

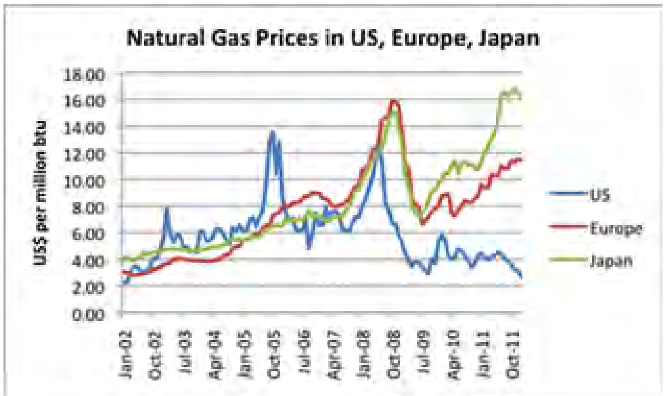


FIGURE 5

NASSCO design for LNG-powered propulsion plant.

equipment, when configured improperly, can result in a completely suboptimal design.

In general, a vessel that operates for much of its time in a loitering mode will make an excellent electric

FIGURE 6

Mechanical gear box supplemented by an electric motor.

propulsion choice. An electric solution is not necessarily a good solution for a vessel that operates most of its time at full load, such as a car ferry. Essentially, a vessel operated at full load tends to be a mechanical system, and one operated in loiter mode tends to be all electric. But for many ships, their operating mode is a mixture of full load and idle or low-speed operations. In this case, the hybrid option is being widely accepted as a very efficient and, in the end, money-saving configuration.

Once the decision has been made to pursue electric propulsion, the selection of the electric generators, low-voltage or medium-voltage drives, motors, and propeller types must be done in a single integrator method whereby the components are all selected to operate in a manner that produces the greatest efficiency for the lowest acquisition and installation costs. Once the generators and motors are sized, the designer must make the decision to use either low or medium voltage drives. This selection can be critical as both drives have different power range applications. Medium-voltage drives are an excellent choice in the 2–4 MW range because they use lower current flow for given output and do not require a heavy transformer. The lower size of the cables eliminates substantial installation costs and makes it a good choice for that power range. For power ranges above 4 and below 2 MW, a low-voltage solution is considered an industry standard.

Trends in Military Propulsion

Worldwide and in the U.S. Navy and Coast Guard, the military market is responding to commercial industry developments and is adopting many of the advances discussed above. However, the military has unique requirements of reliability and survivability that are supreme to propulsion efficiencies. The U.S. Navy, however, has embraced electric propulsion in a very unique way with its selection of the DC-powered DD 1000 program, which will use electric propulsion (Figure 7).

This revolutionary ship's use of electric propulsion has been tested extensively in land-based test facilities in a developmental risk reduction effort. The now operational, amphibious landing ship USS *Makin Island* is the first large-scale use of electric

FIGURE 7

DD1000 electric propulsion.

propulsion in a U.S. Navy combatant and the first amphibious combatant to go all electric (Figure 8).

Utilized in low-speed operations up to 8 knots, the electric drive aboard the ship is powered by the ship's electrical system and is operated above those speeds by gas turbines. Utilizing a low-voltage solution allowed for a low-risk auxiliary propulsion system.

The rest of the U.S. Navy and the U.S. Coast Guard are entering into IMO TIER III environmental restrictions for their high-speed diesel propulsion and medium-speed diesel-powered generation. These constraints will lead to wide adoption of SCR devices. Similar to catalytic converters in cars and now being widely applied to trucks, this technology is well suited for application to marine high-/medium-speed diesels due to its power and speed range.

A Crucial Decision

Not since sails gave way to steam in the late 19th century has the maritime industry faced such technological advances in propulsion. Both rising costs of fuel and the new environmental restrictions are now forcing ship owners, ship builders, navies, and propulsion integrators to innovate faster than they have done in the last 60 years. The choices are varied, and the stakes on the selection of propulsion solutions are extraordinarily high. Pushing for innovation is industry's best bet to realize highly efficient propulsion solutions that provide more compact power.

FIGURE 8

USS *Makin Island.*

PAPER

Review of Deep Ocean Manned Submersible Activity in 2013

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ABSTRACT

The world of manned underwater vehicles (MUV) in 2013 counts a total of 95 active submersibles used for ocean research, tourism, and commercial, leisure, and security applications. The MUV industry safety record remains pristine, with not a single incident involving loss of life in over 40 years. The paper reviews the state and future directions for the world's deepest ocean research submersibles. In 2012 and 2013, the world of deep research submersibles saw dramatic advances, reaching full ocean depth for the first time in more than 50 years. The record of the world's deepest submersible held by Japan's *Shinkai 6500*, rated to 6,500 m depth, for almost 25 years was surpassed by China's 10-year development project of the *Jiaolong* submersible, rated to 7,000 m. The *Jiaolong* successfully completed its multiyear testing program, achieving full design depth in June 2012. This record feat was eclipsed, however, by the surprise disclosure and full ocean depth dive by James Cameron's *Deepsea Challenger*, diving to a depth of 10,908 m in the Mariana Trench just months earlier. This depth had not been reached since the historic dive of the bathyscaphe *Trieste* in 1960, and brings new energy for several national organizations to develop full ocean depth submersibles. There are today a total of 14 national and commercial submersibles capable of diving 1,000 m or deeper, offering a wide range of services. This also provides a global network of rescue capability with locations in the United States, China, Japan, Russia, France, Spain, Canada, and Portugal.

Keywords: deep ocean research, manned submersibles, class societies, Mariana Trench, deep diving

Introduction

The year 2012 was eventful in the submersible industry, witnessing several great achievements in manned deep sea exploration by multiple organizations around the world. In the last year, explorer and filmmaker James Cameron dove his *Deepsea Challenger* to the bottom of the Mariana Trench 52 years after the historic dive of the bathyscaphe *Trieste*. China completed the full design depth sea trials of *Jiaolong* to a depth of 7,000 m, concluding a bold 10-year development project and surpassing the 6,500 m mark for research submersibles (i.e., a submersible with a pilot and passengers) held for 25 years by Japan. Woods Hole Oceanographic Institution (WHOI) completed the *Alvin* upgrade, and sea trials are planned for late summer 2013. The deep ocean realm remains an active theater of new design and developments driven by many nations' interest in exploring more of the deep ocean's resources of energy and minerals. India, with its primary access to the Indian Ocean, steadily progresses its procurement efforts for a 6,000-m-rated deep ocean research submersible. France (*Nautile*), Japan (*Shinkai 6500*), and Russia (*Mir 1* and *Mir 2*) are all maintaining their submersibles operational, all four dating to the late 1980s, almost 25 years of operation.

These activities are juxtaposed against a backdrop of reduced scientific research funding from traditional venues. The National Oceanic and Atmospheric Administration (NOAA) Ocean Exploration program's priorities for manned underwater vehicle (MUV) exploration have been impacted, and Europe and Japan also faced budget cuts. Innovative creativity has emerged from private organizations, large and small, the most visible being wealthy patrons excited by the potential of ocean exploration and new deep sea research. Alongside James Cameron's expeditions are projects from Richard Branson with the Virgin Oceanic flagship; Eric Schmidt, Google's executive chairman, and his wife, Wendy, with the research ship *Falkor*; billionaire hedge fund founder Ray Dalio's ocean exploration missions with M/V *Alucia* and its contingent of submersibles; and Paul Allen with M/Y *Octopus* and his *Pagoo* submersible. These efforts will expand and mature in 2013 as various private/government partnership formulas are being considered (Kohnen, 2013).

On the commercial scale, submersible manufacturers support a worldwide demand for small and large private endeavors. Manufacturers in the United States, Canada, and Europe continue to produce small two-person submersibles, increasing the maximum depth range to 1,000 m, and expanding cabin space to three, six, and more passengers. While there are still a number of private construction projects, most (not all) commercially sold submersibles are classed by one of several international class agencies, which assure prospect clients that the technology is not only functional but has been reviewed and certified by a third-party engineering team. The MTS MUV Committee database counts a total of 96 active submersibles today. These include all submersibles involved in tourism, research, commercial work, security, and leisure. From a regulatory standpoint, the main classification agencies in the industry remain: American Bureau of Shipping (United States), Germanischer Lloyd (Germany), and Lloyds Registry (United Kingdom).

Over the past 45 years, the American Bureau of Shipping has classed a total of 64 submersibles. Of these, the MTS MUV database shows that 41 are in active class status, and of those, 30 are operational and 9 are in layup/overhaul. The manufacturing date of the 30 ABS operational submersibles varies greatly (1972–2012), but 9 are new constructions built since 2003 (Thomas, 2013). Germanischer Lloyds, in Germany, has classed to date a total of 24 manned submersibles in Russia, Europe, North America, Asia, and Africa (Pauli, 2013). Of these, 16 vehicles are currently in class, and 6 new submersibles are under contract for class. New business development at GL in the past year included technology certification for a new process to produce acrylic windows and certification for individual Li-ion batteries for use on manned submersibles. Lloyds Registry shows a total of 19 submersibles currently operating in class status. A brief overview of the industry by classing agency is shown in Table 1. Another significant development in the United States has been the decision to certify the *Alvin* submersible to ABS and U.S. Navy regulations. The dual class program was eventually converted to U.S. Navy certification only, a special project for the Naval Sea Systems Command (NAVSEA) since it had been more than 25 years since the U.S. Navy certified a manned deep submersible.

Manned vs. Unmanned Debate

The old argument over manned vs. unmanned exploration took on a higher public profile this year. In light of the considerable economic pressures experienced by all governments, ocean science and research is an easy target for budgets cuts. It also fans the rhetoric of manned vs. unmanned vehicles. It has certainly been disquieting to see institutions exercise fiscal convenience by closing down submersible research centers around the United States. Stewardship of the oceans will always hinge on national political will exercised amidst ever constraining budgets as economic pressures continue to change around the world. What will not change, however, is the growing need for every nation to manage and sustain its national infrastructures into the future. These present untold challenges for engineers of the future, a task that is 10 times harder when working underwater. This will require concerted orchestration of all available manned and unmanned underwater technologies. The argument of whether this can best be done from the comfort of the living room and computer monitors only minimizes the absolute immensity of the challenge.

While it is hard to look over the horizon to exercise vision for long-term planning, its fundamental importance is shared by many professionals in the MUV industry. At the Underwater Intervention 2013 Conference, the MTS MUV committee celebrated its 10th annual MUV program. Over 150 of the world's leading experts in the manned submersible industry attended, representing 16 countries. The MTS MUV technical program is a tradition

TABLE 1

2013 active MTS MUV submersibles database by class agency.

ABS	American Bureau Shipping	USA	30
BV	Bureau Veritas	France	4
CCS	China Classification Society	China	1
DNV	Det Norske Veritas	Norway	4
GL	Germanischer Lloyd	Germany	18
IRS	Indian Register of Shipping	India	2
KR	Korean Register of Shipping	Korea	0
LR	Lloyd's Register	UK	19
NAVSEA	US Navy	USA	2
NK	Nippon Kaiji Kyokai	Japan	1
RINA	Registro Italiano Navale	Italy	2
RS	Russian Maritime Register of Shipping	Russia	0
None	Un-classed		9
?	Unknown Status		3
		TOTAL No. ACTIVE SUBMERSIBLES	95

that gathers the international community together and offer conduits of communication and creativity for all organizations to exchange progress from all corners of the world, whether working in tourism, commercial work, science and research, or for leisure. If the call to the conference was an indication of the prominence MUV technology holds into the future, it is clear that there is abundant room for creativity and imagination at all levels.

Deep Ocean Research Submersibles

Deepsea Challenger

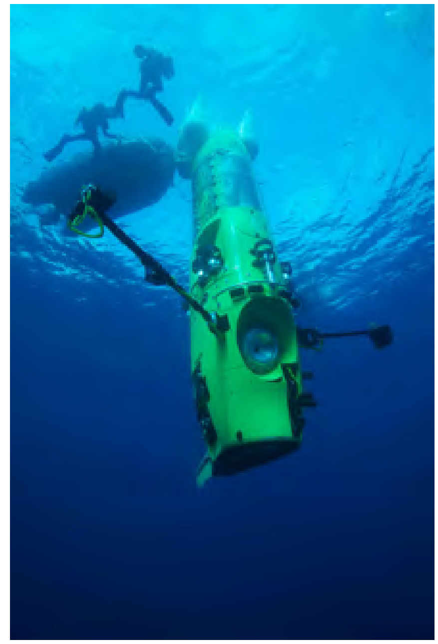
The long, narrow, 24-foot-tall (7.3-m), 11.8-ton green submersible is already immediately recognized; James Cameron's *Deepsea Challenger* made history for its record-breaking solo dive to the bottom of the Mariana Trench on March 26, 2012, to a depth of 35,787 feet (10,908 m). The *Deepsea Challenger* encompassed 10 years of planning and innovations at all levels to shorten the duration of travel and to gather more images, videos, and evidence than from the first dive to the bottom of the Mariana Trench with the bathyscaphe *Trieste* in 1960. At the core of the concept was the design of the smallest possible personnel sphere in order to maximize strength and reduce weight. With an external diameter of 48 inches, the steel sphere accommodates a single pilot. The steel solution is simple, robust, and reliable. The tradeoffs are comfort and limited vision through the acrylic viewing window. The second pillar of the design was the new high-performance syntactic foam, which represented 70% of the volume of the vehicle.

The third design pillar was the concept of traveling vertically through the water column, thereby reducing the vehicle drag during its long vertical voyage and getting a better ratio of travel time to bottom time. The submersible is launched in horizontal position, and once in water is deployed into its vertical position with the personnel sphere at the bottom. This configuration enables the submersible to travel vertically at a rate of 500 feet/min (150 m/min), compared to today's deep research submersibles, which typically travel at vertical speeds of 60–100 feet/min (18–30 m/min). The impact of decreasing the time to descend to depth is the potential increase in bottom time of up 20–30%. Like the traditional research subs, the *Deepsea Challenger* also used steel ballast weights, up to 1,100 lb to control buoyancy at depth and to resurface. The submersible was equipped with a full arsenal of propulsion, navigation, and communication systems powered by a lithium battery system. On the outside, the submersible was equipped with a dazzling array of underwater LED lights, HD cameras, and miniature 3D video systems. During the UI 2013 conference, Bruce Sutphen presented some early video footage of the deep dive in a closed door session and answered a long series of questions from the audience. The level of detail and attention exercised over a very short time schedule by a large engineering team, across oceans, was very exciting to hear (Figure 1).

The fourth pillar in the expedition concept was the idea that the dives were executed hand-in-hand with a set of unmanned landers that were equally equipped with sensors and video equipment and allowed the submersible to be filmed at depth. These landers were developed in parallel at Scripps Institute of Oceanography in San Diego, while the submersible was being constructed in Australia. During the UI 2013 video presentation, it was amazing to see the footage of Jim Cameron from inside the sub exploring the sea floor and then finding the landers. The effect was powerful, seeing the vast deep, dark expanse, visible only to the range of the lights, and then seeing a human structure appear out of nowhere. This produced powerful images and video from both points of view.

FIGURE 1

Deepsea Challenger, USA, 11,000 m.



In March 2013, James Cameron gifted the *Deepsea Challenger* to WHOI. The vehicle began its cross country journey on June 1st from the California Science Center in Los Angeles. During its journey across the United States, the submersible is scheduled to stop at several cities including Dallas, New Orleans, and Washington, DC, and is scheduled to arrive at Woods Hole in Cape Cod in late June 2013. WHOI will be harvesting the technology that led to the historic dives and applying their findings to benefit the science and technical community at large.

Jiaolong

Dr. Weicheng Cui, deputy chief designer of the *Jiaolong* submersible for the China Ship Scientific Research Center, presented the full history of the *Jiaolong* deep research submersible during the MTS MUV program at UI2013. The *Jiaolong* successfully completed its deep dive to the full 7,000-m depth rating in June of 2012. This marked the first deep ocean submersible construction project in China, a project that stretched over 20 years (Cui, 2013). The first proposal for a 6,000-m deep submersible was submitted by the China Ship Scientific Research Center (CSSRC) to the Ministry of Science and Technology in 1992 but was rejected as too risky. In 1999, the China Ocean Mineral Resources R&D Association (COMRA) submitted a new proposal for a deep manned submersible, expressing a national need for such technology for deep sea resources. This proposal was approved, and CSSRC started the *Jiaolong* project in June 2002.

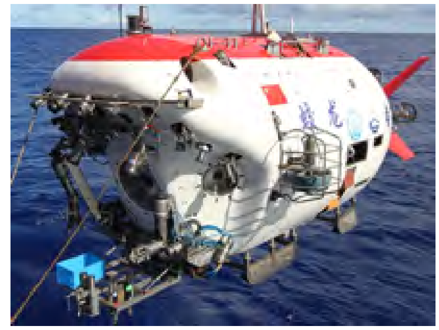
The *Jiaolong*, named after a mythical sea dragon, is China's deep ocean exploration submersible, a project undertaken through the State Oceanic Administration. After 3 years of effort by Chinese scientists, the design of the submersible was complete and ready for production in 2005. Ye Cong, chief pilot recalls, "It was like we had designed a car and were ready to build one, but none of us knew how to drive it." Fortunately, in August 2005, China and the United States held a cooperative deep-sea diving program, which allowed Chinese scientists to get aboard the U.S. submersible *Alvin*. The Chinese pilots became familiar with the operation of a submersible after 22 days of training with *Alvin*, including joining on two deep dives to more than 2,000 m deep. In 2007, *Jiaolong* started its first test dives and in 2010 completed 17 dives in the South China Sea with the deepest dive to 3,759 m. In July 2011, the *Jiaolong* reached 5,057 m diving in international waters in the Pacific. In June 2012, the *Jiaolong* made its full depth test dive to 7,000 m, just in time to head off the worse of the hurricane season.

In the design and development phase, one of the first tasks undertaken by the engineering team was to develop a new design standard for the pressure hull. CSSRC developed a new formulation to determine the required thickness of the pressure hull, a formulation that was then integrated in the Chinese Classification Society (CCS) rules. The *Jiaolong* submersible conforms to most traditional deep ocean research submersible designs, including a welded, "orange peel" type, titanium pressure hull from Russia, syntactic foam from the United States, and silver zinc batteries for power source. The personnel sphere accommodates three persons and is equipped with three acrylic viewports. The submersible integrated redundant underwater communication transponders, Ultra Short Baseline (USBL) acoustic positioning, a high-resolution side-scan sonar, an acoustic Doppler speedometer, an obstacle avoidance sonar and an imaging sonar. The vehicle also incorporated LED lights with HD camera and video as well as a hydraulic powered seven-function manipulator. *Jiaolong* was built with components from many countries, with 60% of the parts and equipment made in China. The main areas of challenge during testing were the communication system and the silver zinc batteries (Figure 2).

For 2013, CSSRC is preparing for *Jiaolong's* maiden cruise after her 4 years of sea trials. *Jiaolong* now enters its new "test application" phase, which is scheduled to last for several years until its new mothership and the China National Deep Sea Center construction are completed. *Jiaolong*'s maiden Cruise for 2013 will start from June 10 and will last till end of September. The cruise consists of three legs in South China Sea, Northeastern and Northwestern Pacific Ocean in COMRA's "Contract Area," respectively. Dr. Liu Feng will be the cruise leader for the 4-month expedition.

FIGURE 2

Jiaolong Submersible, China, 7,000 m.



Future development includes CSSRC's construction of a new generation deep submersible rated to a shallower depth of 4,500 m. The goal is to produce a smaller, lighter submersible, which is easier to deploy, and to develop more of its equipment in China. Concurrently, Dr. Weicheng Cui will lead a separate project through the newly formed Hadal Science and Technology Research Center at the Shanghai Ocean University for the development of a full ocean depth submersible, rated to 11,000 m.

Shinkai

Shinkai 6500 is the flagship deep ocean submersible for the Marine Technology and Engineering Center of JAMSTEC (Japan Agency for Marine-Earth Science and Technology). *Shinkai 6500* was built in Kobe, Japan, in 1989, a three-person deep ocean research submersible rated to a maximum depth of 6,500 m. Until 2012, it held the title of the deepest research submersible in the world. In 2011, the *Shinkai* was overhauled as part of its routine, 5-year inspection, which allowed for NDT inspection of the welds on the sphere. The inspection was almost complete when the JAMSTEC headquarters was affected by the Tohoku earthquake in Northeastern Japan. After the disaster, the JAMSTEC fleet was deployed on urgent environmental monitoring missions at Fukushima. Although the *Shinkai* was on stand-by for a while, demand for urgent diving research from many scientists increased. In response to this demand, a high priority survey cruise at the epicenter area was conducted in August and was a great success. Some of the new technology integration of the *Shinkai* included upgrade of its two HDTV cameras to smaller models (Niikura, 2013). The fixed camera was refitted with a wide-angle lens. All video data use "iVDR" as the recording media, a system that has worked well in the field. The next upgrade will be the image transmission system from *Shinkai* to the support ship using fiber optic cable. The project to replace the *Shinkai* thrusters began in 2008 and was completed in 2012. The original thrusters were replaced by new DC motor thrusters with a new addition of an aft horizontal thruster. Two new motors for a hydraulic pump and a seawater pump were also replaced because these motors were outdated. In order to accommodate the weight impact of these modifications, the battery pod was replaced with a new one made in fiber reinforced plastic (FRP) (Figure 3).

FIGURE 3

Shinkai 6500, JAMSTEC Japan, 6,500 m.

Since the enormous earthquake that shook the Northeast of Japan in 2011, a clear national interest is behind the study of the deep fault ridge along Japan's coast. Japan is the only country that is facing that situation and considers the development of a next generation manned submersible capable of going to full ocean depth a necessity and a national priority. Itaru Kawama from JAMSTEC attended the UI2013 MTS MUV conference and presented about the need for new technologies in the development of next generation deep manned submersibles. It is clear that traditional technologies have achieved a plateau in conventional concepts. JAMSTEC is looking ahead to a new age of deep sea research and development. JAMSTEC plans to upgrade *Shinkai 6500* for its continued deep sea research, until the next generation manned submersible is created and available (Kawama, 2013) (Figure 4).

FIGURE 4

Shinkai 6500, side view with new thrusters.

Nautile

IFREMER built *Nautile* in 1984, and it was the first of a new generation of deep research submersibles rated to 6,000 m. *Nautile* counts among its achievements 116 dives on the RMS Titanic between 1987 and 1998, early thermal vent exploration, even meeting up with Alvin at the bottom of the Atlantic in 1987. *Nautile* has logged more than 1,800 dives to date and spent a lifetime aboard its mothership. During UI 2013, IFREMER presented its comprehensive review of 25 years of maintenance data and presented numerous structural and maintenance issues associated with long life planning of deep submersibles (Drogou, 2013). Some of the findings support the conservative nature of design estimates and the life extension of the hull components. While budgets are strained worldwide affecting all manned operations, IFREMER has no plans to replace *Nautile* and projects an extended life program for the pressure hull and periodic technology improvements. The biggest improvement in productivity and improved cost amortization of research missions is the ability to run their 3,000 m AsterX AUV at night performing acoustic multibeam mapping and investigating points of interest with *Nautile* operating during day time. This type of mission planning has proven extremely effective and given the submersible a new positive profile in the research arsenal (Figure 5).

Mir

During the UI2013 conference, Dr. Anatoly M. Sagalevich, head of the Deep Manned Submersibles Laboratory at the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences in Moscow, presented the 25-year review of the *Mir 1* and *Mir 2*

FIGURE 5

Nautile, IFREMER France, 6,000 m.

FIGURE 6

Mir 1 and *Mir 2*, PPSIO, Russia, 6,000 m.

submersibles. The *Mir* subs were designed and built from 1985 to 1987 with Dr. Igor Mikhaltsev and engineers in Finland at Rauma Repola, headed by Sauli Ruohonen. The hulls were made of a unique maraging steel (superior strength and toughness) perfected in Finland. The two submersibles still have the same hulls that participated in 39 missions around the world (Sagalevich, 2013). These included 16 science, 7 film, 7 state, 5 underwater tourism, and 4 wreck/search missions. Among the highlights were numerous missions to the hydrothermal fields, missions on the nuclear submarine *Komsomolets* in the Norwegian sea, the *Kursk* submarine accident in 2000, eight expeditions to film the *Titanic* from 1991 to 2005, four expeditions to the *Bismarck* wreck, two expeditions to the Japanese I-52 submarine wreck, the North Pole expedition in 2007 and Lake Baikal from 2009–2011. The *Mirs* also participated in a number of deep sea films and documentaries that include *Titanica* (1992), *Treasure of the Deep* (1992), *Titanic* (1997), *Japanese Sub I-52* (1999), *Blue Planet* (2002–2003), *Bismarck* (2002), *Ghost of the Abyss* (2003), and *Aliens of the Deep* (2005) (Figure 6).

The *Mirs* performed upwards of 1,095 dives thru 2012, with roughly 50% for science, 25% for filming, and the remaining 25% for various work and tourism applications. These expeditions also generated 19 books on oceanography, exploration, and MIR submersibles. The operation of the MIR submersibles has always benefitted from and relied heavily on the contracting to outside organizations. The year 2012 proved to be difficult, navigating through a shifting political landscape that focused on more national utilization of assets. The rules for contracting the *Mir* submersibles to international entities was changed, requiring extensive waiting periods to ensure no national organizations needed the assets before they could be released abroad. This unfortunately coincided with the 100th anniversary of the *Titanic*, a staple expedition in which the *Mir* subs were used exclusively. A large contingent of patrons was already booked for July and August 2012. The necessary new waiting periods for the release of the *Mirs* interfered with these dates, and the submersibles could not be made available for these long anticipated dives. The P.P. Shirshov Institute continues to operate the submersibles, which remain in service and under full classification survey by Germanischer Lloyd.

Alvin

The WHOI's Deep Submergence Operations Group has completed a major upgrade to the manned deep submergence vehicle *Alvin*. The final assembly stage ended in the month of April and systems integration and major system verification and validation testing concluded in May (Uetz & Tarantino, 2013). The upgrade was funded through the National Science Foundation, and the vehicle will be owned by the Office of Naval Research. The submersible was originally to be classed by the American Bureau of Shipping, but with transfer to Office of Naval Research would need to be dual certified. For time and resource efficiencies, the ABS classification was eventually dropped for NAVSEA certification only (Figures 7 and 8).

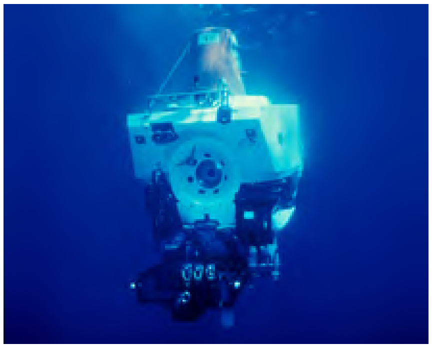
The vehicle was mobilized onto the R/V *Atlantis* on May 13th and departed for the Pacific Ocean on May 25th. Manned sea trials are scheduled for September pending NAVSEA approval and certification. The *Alvin* upgrade will see the submersible return to action with a brand new personnel sphere that features the latest in scientific instrumentation, a more comfortable cabin for scientists, the largest viewports of any of the deep subs, and a long list of new imaging systems (Figure 8). The submersible will be U.S.

FIGURE 7

Upgraded *Alvin*, WHOI, USA, 4,500 m.

FIGURE 8

Alvin submersible with original viewing.



Navy-certified and rated to a maximum depth of 4,500 m, while the cabin has already been tested and approved for operation to 6,500 m. The *Alvin* will require a separate upgrade program in the future to bring the rest of the vehicle to that maximum depth capability.

While WHOI was gifted the *Deepsea Challenger* submersible, the WHOI Marine Department is also managing operations of the M/V *Alucia*. Among other things, the vessel is tender to the *Deep Rover 2* and the first of class *Triton 3300/3*, hull 1.

India

The National Institute of Ocean Technology (NIOT) in India is interested in ocean mining activities of mineral resources such as polymetallic nodules, cobalt-rich manganese crust, and hydrothermal deposits in the future. The polymetallic nodules containing copper, cobalt, nickel, and manganese are considered potential resources to meet the increasing demand for these metals worldwide. India has a status of Pioneer Investor and has been allotted a site in the Central Indian Ocean Basin by the International Sea Bed Authority for exploration and technology development for polymetallic nodule mining. The Deep Sea Technologies and Ocean Mining Group of NIOT has been actively involved in the development of technology for polymetallic nodule mining from 6,000 m water depth. NIOT has issued a series of RFPs (Request for Proposals) for the procurement of a first 4,000-m-deep ocean submersible in 2007, followed by a superseding RFP for a 6,000-m-deep ocean submersible issued in 2011 (Kohnen, 2012). NIOT is serving as a technical arm of the Indian government's Ministry of Earth Sciences (MoES) and works in developing major underwater systems. Some of the technologies developed and commissioned by NIOT during the past 18 years include the following:

a) underwater crawler system for 500-m depth application,
b) low-temperature thermal desalination plant for islands,
c) *in situ* soil tester rated for 6,000-m depth application,
d) work class remotely operated vehicle (ROSUB 6000)—rated for 6,000 m,
e) development of acoustic tide gauges,
f) deployment of ocean data buoys and tsunameters for ocean data collection, and
g) deep water vessels ORV *Sagar Kanya* and ORV *Sagar Nidhi*.

The new 6,000-m manned submersible is planned to be used for (1) carrying out exploration for deep ocean mineral and energy resources, (2) support scientific investigation and sampling from deep ocean basins, and (3) provide engineering support for developmental projects in deep waters. The final contenders for the development award include James Fisher Defence in the United Kingdom and DCNS ship yards in France. There are no known commercial or private submersibles operating in India today for tourism, shallower research, or commercial diving.

Commercial Deep Submersibles

Beyond the first seven state-operated deep ocean research submersibles, there are today an additional six operational submersibles that dive to a maximum depth of 1,000 m with another half dozen under construction and in development.

Pisces IV and *Pisces V* (Hawaii, USA, 2,000 m)

The Hawai'i Undersea Research Laboratory (HURL) has accrued over 30 years of submersible operations and logged nearly 1,900 dives representing 9,300 h underwater. This has produced a benthic ecology database derived from in-house video record logging of over 125,000 entries based on 1,100 unique deep-sea animal identifications in the Hawaiian Archipelago. Until this year, HURL was the only U.S. deep submergence facility in the Pacific Rim supporting undersea research for the National Oceanic and Atmospheric Administration (NOAA). HURL was established by Cooperative Agreement in 1980 between NOAA and the University of Hawai'i, at which point it became a Regional Center in NOAA's Undersea Research Program (NURP). In 2009, President Obama signed Public Law 111-11 authorizing both NURP and Ocean Exploration and their administration under a merged program called the Office of Ocean Exploration and Research. This 33-year support ended in 2013 when NOAA cut out the HURL program from its budget, along with major funding to support shipboard submersible operations. The Center continues to support funded requests from private, state, or federal agencies (Figures 9 and 10).

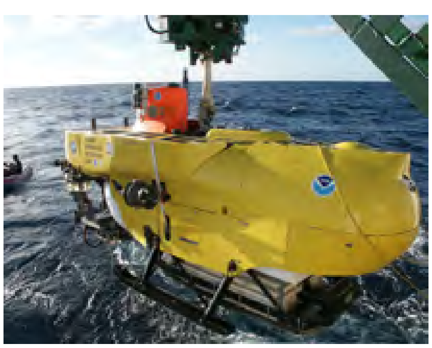
In an effort to provide a full range of competitive cost alternatives over the full shipboard capability provided by the KOK, HURL is reactivating a less expensive option for conducting submersible dive operations. The engineering team has reactivated the LRT-30a (Launch, Recovery, Transport). The LRT-30a is an ABS classed submersible launch and recovery platform. This method of launching and recovering a submersible was used from 1976 until 1996, before migrating to full ship operations with KOK. The LRT was used by the Deepwater Exploration company when diving with the STAR II as well as by HURL when diving with Makalii' (reconfigured STAR II) and *Pisces V*. The launch and recovery system has a long heritage of successful and safe operation through a wide range of ocean conditions (Figure 11).

FIGURE 9

Pisces IV, HURL USA, 2,000 m.

FIGURE 10

Pisces V, HURL USA, 2,000 m.



The Hawaii Undersea Research Lab began the ABS reactivation of the LRT-30a in 2008 and will be conducting science dives with the *Pisces V* and LRT-30a around the Hawaiian Islands during July and August 2013. According to Terry Kerby, Director of Facilities and Submersible Operations at HURL, it was clear that without the LRT option to continue deep submersible science diving operations, the program would have been closed down and the experienced crew with decades of submersible support experience would have been let go. The advantages of the LRT are that it can be supported with a much less costly support vessel and has the ability to dive in a much rougher sea state than conventional support vessels operating submersibles with a deck handling system. The heritage of the LRT has demonstrated that it is rare to lose dives due to weather conditions since launch and recovery operations are done subsurface at a depth of 20 m (60 feet). A further advantage for complex and advanced missions is that the submersible can dive with bulky science packages attached to the sub. Such a science package with a significant dry weight can quickly become hazardous to attach to the front of a submersible if deployed off the back of a ship. When launching with the LRT, the package can be secured on the deck of the LRT until released by the divers and taken down with the submersible for deployment at the bottom study site. The normal method for this type of operation with a shipboard handling system is to drop the instrument over the side and then go find it with the submersible and deliver it to the study site.

FIGURE 11

Pisces V launched from LRT launch platform in Hawaii.

This flexibility of operation does, however, come with some disadvantages. The biggest disadvantage of the LRT is its limitation on the operating area and the limitation that dives can only be made every other day. The deployment logistics requires access near protected waters to get the LRT alongside a support vessel to service the submersible and LRT for the next dive. HURL, however, estimates that it is not entirely limited to the Hawaiian Islands for LRT operations. During past expeditions, HURL did conduct 3 months of LRT-Makalii operations at Enewetak Atoll, Johnston Atoll, and a month of dives in the Northwestern Hawaiian Islands. The other disadvantage for HURL is the loss of being able to conduct two-sub operations. The two-sub dive capability provided HURL with a ready backup emergency capability but also offered significant research advantages in conducting two-sub multi-science capabilities.

HURL has conducted uninterrupted science dives for the last 32 years and continues to serve the ocean science and exploration community even in these lean budget times. The LRT-30a provides the efficiency and capability to deliver cost-effective undersea research. Until the budget climate improves, HURL will continue dive operations with the LRT-30a and a support vessel of opportunity. The KOK is still operating with the

University of Hawaii and remains available for *Pisces* sub and ROV operations, a proven and powerful combination for private, commercial, or scientific exploration.

ICTINEU-3 **(Barcelona, Spain, 1,200 m)**

The *ICTINEU-3* is a new three-person deep research submersible under development by Ictineu Submarins SA, based in Barcelona, Spain (Parareda & Fores, 2013). The submersible will be rated to 1,200 m and classed by Germanischer Lloyd. The design features a large acrylic bow dome window for an unobstructed view, a hull design that balances buoyancy without the need of syntactic foam and a power system based on a new pressure tolerant Li-ion polymer battery solution. The company invested more than 2 years in subsystem testing for certification, a large part dedicated to the certification of the lithium batteries (Fores & Parareda, 2013). The submersible is scheduled to complete its sea trials in mid-2013 and be available for research late in 2013 (Figure 12).

Deep Rover 1002 **(Woods Hole, USA, 1,000 m)**

The *Deep Rover DR2* is a well-known two-person research submersible built in 1994, which has been operated from aboard the M/V *Alucia* for many years. The submersible is fully ABS classed and operational along with several other submersibles on the research ship. The *Deep Rover 1001* (*DR1*) is the twin brother of *DR2*, and while it is not in class, it is an asset readily overhauled to bring into service along with *DR2* (Figure 13).

Deep Rover **(Vancouver, Canada, 1,000 m)**

Deep Rover is the original acrylic submersible built in 1984. The *Deep Rover* is operated by CanDive at Nuytco Research, in Vancouver, Canada. The submersible is a single occupant 1,000 m

FIGURE 12

ICTINEU-3, Spain, 1,200 m.

FIGURE 13

Deep Rover DR2, USA, 1,000 m.

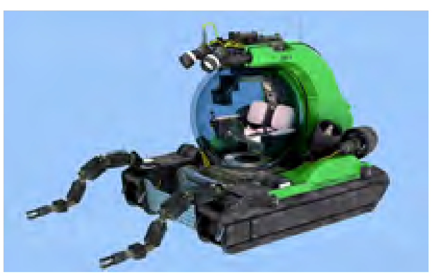


FIGURE 14

Deep Rover, Canada, 1,000 m.

FIGURE 15

Triton 1000/2 and *PC1201*.

FIGURE 16

Triton 3300/3, USA, 1,000 m.

FIGURE 17

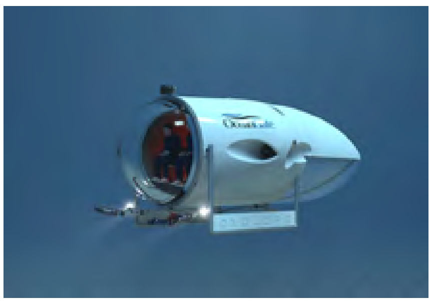
Lula 1000, Portugal (Azores), 1,000 m.

FIGURE 18

Deepflight Challenger, USA, 11,000 m.

FIGURE 19

Project Cyclops, USA, 3,000 m.



rated submersible with a long history of deep dives. The submersible is equipped with two large robotic manipulators in clear view of the operator. The submersible is classed under Lloyds Registry (Figure 14).

Triton 3300/3 (Florida, USA, 1,000 m)

The *Triton 3300/3* is a new three-person submersible, rated to 1,000-m depth from Triton Submarines in Florida. The company has delivered the first of these 1,000-m submersibles, which operates from the M/V *Alucia* mothership. The design offers a full acrylic hull holding one pilot and two passengers, a full complement of acoustic navigation equipment and software and high-definition video recording. The submersible is classed with the American Bureau of Shipping and three more of the same vehicles are under construction (Figure 16).

In January 2013, the company accomplished a milestone making the first dives in a manned submersible in Antarctica. The expedition was chartered with Henry Cookson Adventures aboard the *Suri* expedition ship. The dives were performed using both a *Triton 1000/2* and the *PC1201* submersible (Figure 15). Earlier, in summer 2012, the expedition ship M/V *Alucia* used the *Triton 3300/3* and the *Deep Rover DR1* to successfully film the first encounter of a giant squid at depths of 600–900 m off the coast of Japan. The ship also carries the *Deep Rover DR2* and a *DualDeepworker*. In 2013 the M/V *Alucia* and its submersibles were contracted to be managed by WHOI's Marine Department.

Triton Submarines is working on two deeper submersible concepts, which include the *5500/2*, a 5,500-feet rated

TABLE 2

Deep diving submersibles > 1,000 m.

No	Submersible Name	Operator	Depth feet	Depth meter	Year Mfg	Capacity	CLASS	COUNTRY
1	DEEPSEA CHALLENGER	Woodshole Oceanographic Institute	36080 ft	11000 m	2011	1	None	USA
2*	DEEPFLIGHT Challenger	Virgin Oceanics	36000 ft	11000 m	2008	1	None	USA
3	JIAOLONG	CSSRC / COMRA	22960 ft	7000 m	2009	3	CCS	China
4	SHINKAI 6500	JAMSTEC	21320 ft	6500 m	1989	3	NK	Japan
5	MIR 1	PP Shirshov Institute of Oceanology, RAS	19680 ft	6000 m	1987	3	GL	Russia
6	MIR 2	PP Shirshov Institute of Oceanology, RAS	19680 ft	6000 m	1987	3	GL	Russia
7	NAUTILE	IFREMER	19680 ft	6000 m	1985	3	BV	France
8	ALVIN	Woodshole Oceanographic Institute	14596 ft	4450 m	1964	3	NavSea	USA
9	PISCES IV	HURL, Hawaii Undersea Research Lab	6500 ft	2000 m	1971	3	ABS	USA
10	PISCES V	HURL, Hawaii Undersea Research Lab	6500 ft	2000 m	1973	3	ABS	USA
11*	ICTINEU 3	Ictineu Submarins SA	3936	1200 m	2013	3	GL	Spain
12	TRITON 3000/3-1	MV ALUCIA	3300 ft	1000 m	2011	3	ABS	USA
13	Deep Rover	CANDIVE Ltd.	3280 ft	1000 m	1984	1	LR	Canada
14*	Deep Rover DR1	MV ALUCIA	3280 ft	1000 m	1994	2	n/a	USA
15	Deep Rover DR2	MV ALUCIA	3280 ft	1000 m	1994	2	ABS	USA
16	LULA 1000	Foundation Rebikoff-Niggeler	3280 ft	1000 m	2011	3	GL	Portugal

Note. *Submersibles in construction/overhaul.

TABLE 3

MTS MUV database list of active submersibles by country.

REGION	No Subs	Submersible Name	Type	Depth		Cap.	Operator	Year	CLASS	Manufacturer
Australia	2	DEEP-C	P	1100 ft	330 m	2	SUB-AQUA Enterprises Pty Ltd	2010	ABS	SEAmagine
		ODYSSEA	C	300 ft	150 m	2	ARIEL'S FLAME PTY LTD	2007	ABS	SEAmagine
Bulgaria	1	PC-8B	R	820 ft	250 m	3	Institute Of Oceanology, B.A.S.	1971	?	Perry Submersibles
Canada	5	Deep Rover	C	3280 ft	1000 m	1	CANDIVE Ltd.	1984	LR	Deep Ocean Engr
		Deep Worker #6	C	2000 ft	610 m	1	Nuytco Research Ltd.	1996	LR	Nuytco Research
		Deep Worker #7	C	2000 ft	610 m	1	Nuytco Research Ltd.	1997	LR	Nuytco Research
		Dual Deep Worker 1	C	2000 ft	610 m	2	Nuytco Research Ltd.	2000	LR	Nuytco Research
		Aquarius	C	1000 ft	300 m	3	CANDIVE Ltd.	1973	LR	HYCO
CARIBBEAN	Curacao	CuraSub	T	1000 ft	328 m	5	Curacao Sea Aquarium	2009	GL	Nuytco Research
	Aruba	ATLANTIS VI	T	150 ft	46 m	46	Atlantis Adventures, Aruba	1989	ABS	Atlantis Submarines
	Barbados	ATLANTIS III	T	150 ft	46 m	46	Atlantis Adventures, Barbados	1987	ABS	Atlantis Submarines
	Cayman	ATLANTIS XI	T	150 ft	46 m	46	Atlantis Adventures, Grand Cayman	1992	ABS	Atlantis Submarines
	St-Thomas	ATLANTIS XV	T	150 ft	46 m	46	Atlantis Adventures, St-Thomas	1995	ABS	Atlantis Submarines
China	2	Jiaolong	R	22960 ft	7000 m	3	China Ship Scientific Research Ctr	2009	CCS	CSSRC
		Meireniyu	T	246 ft	75 m	48	Aiske Submarine (Hainan)	1992	?	Mobinar
Costa Rica	1	DeepSee TRIUMPH	T	1500 ft	457 m	3	DeepSee Expeditions	2005	ABS	SEAmagine
Egypt	2	Sindbad 1	T	246 ft	75 m	48	Sinbad Submarines	1990	ABS	Mobinar
		Sindbad B	T	246 ft	75 m	48	Sinbad Submarines	1988	ABS	Mobinar
France	2	NAUTILE	R	19680 ft	6000 m	3	IFREMER	1985	BV	IFREMER
		REMORA 2000	C	2000 ft	610 m	2	COMEX SA	1995	BV	COMEX
Germany	1	JAGO	R	1312 ft	400 m	2	Leibniz Institute Marine Sciences IFM-(	1989	GL	Max Planck Inst.
Greece	1	THETIS	R	2000 ft	610 m	2	Hellenic Center for Marine Research	1997	BV	COMEX
Honduras	1	Idabel	T	2660 ft	810 m	3	Stanley Submarines	2002	None	Stanley Sub.
Indonesia	1	Odyssey II	T	150 ft	46 m	36	Submarine Safaris Asia Ltd.	1991	?	Intl Submarine Engr
Italy	2	VAS 525 I	C	525 ft	160 m	3	GSE Trieste	2003	RINA	GSE Trieste
		VAS 525 II	C	525 ft	160 m	5	GSE Trieste	2010	RINA	GSE Trieste
Japan	3	SHINKAI 6500	R	21320 ft	6500 m	3	JAMSTEC	1989	NK	JAMSTEC
		HardSuit 1000 A	C	1000 ft	300 m	1	Toyoma Diving, Japan	1990	LR	Oceanworks Intl
		HardSuit 1000 B	C	1000 ft	300 m	1	Kyokutou Kensetsu	1990	LR	Oceanworks Intl
Korea, South	3	Deep Worker #12	C	2000 ft	610 m	1	Commercial Diving	2001	LR	Nuytco Research
		Tritone	T	246 ft	75 m	48	Tritone Submarine Inc	1992	?	Mobinar
		Jiah	T	187 ft	57 m	48	Daeguk Submarine Tour	2003	?	Mobinar
Mexico	1	ATLANTIS XII	T	150 ft	46 m	46	Atlantis Adventures, Cozumel	1993	ABS	Atlantis Submarines
MONACO	1	RANGIROA	P	1250 ft	380 m	2	YCO Yacht Mgmt	2010	ABS	SEAmagine
Netherlands	8	EuroSub	C	820 ft	250 m	3	Eurosub	2009	?	AIResearch
		C-EXPLORER 2	P	328 ft	100 m	2	U-Boat Worx BV	2010	GL	Uboat Worx
		C-EXPLORER 5.8	P	984 ft	300 m	5	U-Boat Worx BV	2012	GL	Uboat Worx
		C-Questor 2A	C	328 ft	100 m	2	U-Boat Worx BV	2007	none	Uboat Worx
		C-Questor 3.1	C	328 ft	100 m	3	U-Boat Worx BV	2009	GL	Uboat Worx
		C-Questor 3.2	P	328 ft	100 m	3	Private MY	2010	GL	Uboat Worx
		C-Questor 3.4	T	328 ft	100 m	3	MED Explorer	2011	GL	Uboat Worx
		C-Questor 3.5	T	328 ft	100 m	3	NGO/NPO	2012	GL	Uboat Worx
PACIFIC	Bikini - M.I	T/T SOFIA	P	328 ft	100 m	3	Ferrum Inv. Ltd	2012	GL	Uboat Worx
	Mauritius	BS1000	T	328 ft	100 m	11	Blue Safari	1990	IRS	Malmari & Winberg
	Saipan	DEEPSTAR- SIRENA	T	245 ft	75 m	50	Pacific Subsea	1999	ABS	DEEPSEA Subs
	Bora Bora	Spirit of Pacific	T	164 ft	50 m	7	Spirit of the Pacific	2000	BV	PSI France
	Mauritius	BS600	T	164 ft	50 m	6	Blue Safari	1998	IRS	PSI France
	Guam	ATLANTIS V	T	150 ft	46 m	46	Atlantis Adventures, Guam	1988	ABS	Atlantis Submarines
Phillipines	1	PIROM	T	330 ft	100 m	48	Cebu Yellow Submarine Undersea	1990	GL	NV Boelwerf SA
Portugal	1	LULA 1000	R	3280 ft	1000 m	3	Foundation Rebikoff-Niggeler	2011	GL	Rebikoff-Niggeler F.
Russia	2	MIR 1	R	19680 ft	6000 m	3	PP Shirshov Institute of Oceanology, R	1987	GL	Rauma-Repola Oy
		MIR 2	R	19680 ft	6000 m	3	PP Shirshov Institute of Oceanology, R	1987	GL	Rauma-Repola Oy

REGION	No Subs	Submersible Name	Type	Depth		Cap.	Operator	Year	CLASS	Manufacturer
Spain	5	ICTINEU 3	R	3936 ft	1200 m	3	Ictineu Submarins SA	2013	GL*	Ictineu Submarins
		Golden Shark	T	246 ft	75 m	48	Atlantida Submarine	1991	GL	Mobinar
		Sub Fun 5 (L14)	T	246 ft	75 m	48	Submarine Safaris S.L.	1991	DNV	Mobinar
		Sub Fun TRES	T	246 ft	75 m	48	Submarine Safaris S.L.	1990	GL	Mobinar
		Balea Subcat	T	100 ft	30 m	31	SUBIBOR S.A., Marin, Spain	1999	ABS	Subobor SA
Turkey	1	CAROLYN	R	164 ft	50 m	2	Institute Nautical Archaeology	2000	ABS	SEAmagine
UK	2	HardSuit 1000 C	C	1000 ft	300 m	1	Acergy – Aberdeen	1992	LR	Oceanworks Intl
		HardSuit 1000 D	C	1000 ft	300 m	1	Acergy – Aberdeen	1993	LR	Oceanworks Intl
USA	35	DEEPSEA Challenger	R	36000 ft	11000 m	1	Woodshole Oceanographic Institute	2011	None	Deepsea Challenge
		ALVIN	R	14596 ft	4450 m	3	Woodshole Oceanographic Institute	1964	US Navy	Woods Hole Oceangr.
		PISCES IV	R	6500 ft	2000 m	3	HURL, Hawaii Undersea Research Lab	1971	ABS	HYCO
		PISCES V	R	6500 ft	2000 m	3	HURL, Hawaii Undersea Research Lab	1973	ABS	HYCO
		Deep Rover 1001 Jules	C	3280 ft	1000 m	2	WHOI - M/V ALUCIA	1994	ABS	Deep Ocean Engr
		Deep Rover 1002 Jim	C	3280 ft	1000 m	2	WHOI - M/V ALUCIA	1994	ABS	Deep Ocean Engr
		DeepFlight Challenger	R	3000 ft	1000 m	1	Virgin Oceanics	2008	None	Hawkes Ocean Tech.
		TRITON 3300/3-1	R	3300 ft	1000 m	3	WHOI - M/V ALUCIA	2011	ABS	Triton Submarines
		Oceaneering WASP2A	C	2300 ft	700 m	1	Oceaneering International	1982	LR	Oceaneering Intl
		Oceaneering WASP3	C	2300 ft	700 m	1	Oceaneering International	2005	LR	Oceaneering Intl
		DDW2000-2	R	2000 ft	610 m	2	WHOI - MV ALUCIA	2002	LR	Nuytco Research
		DDW2000-3	R	2000 ft	610 m	2	Harbor Branch Oceanographic	2006	LR	Nuytco Research
		Oceaneering WASP2	C	2000 ft	610 m	1	Oceaneering International	1979	LR	Oceaneering Intl
		PRM 1 Falcon	M	2000 ft	600 m	16	Phoenix International	2009	US Navy	Oceanworks Intl
		LULA 500	C	1640 ft	500 m	3	OceanGate LLC	2000	ABS	Marlin Submarines
		Deep Flight Aviator	C	1500 ft	457 m	2	Sub Aviators	2003	None	Hawkes Ocean Tech.
		ADS1200 - 01	C	1200 ft	365 m	1	Phoenix International	2004	LR	Oceanworks Intl
		ADS1200 - 02	C	1200 ft	365 m	1	Phoenix International	2004	LR	Oceanworks Intl
		ADS1200 - 03	C	1200 ft	365 m	1	Phoenix International	2004	LR	Oceanworks Intl
		ADS1200 - 04	C	1200 ft	365 m	1	Phoenix International	2004	LR	Oceanworks Intl
		Pagoo	P	1200 ft	365 m	8	Private Yacht	2007	ABS	Intl Submarine Engr
		NEMO	P	1000 ft	306 m	2	MY Mine Games	2007	ABS	Triton Submarines
		NOMAD	P	1000 ft	305 m	2	US Submarines	2009	ABS	Triton Submarines
		S201	C	1000 ft	305 m	2	Submergence Group	2006	None	Marlin Submarines
		Super Falcon	C	1000 ft	300 m	2	Hawkes Technology	2008	None	Hawkes Ocean Tech.
		Antipodes	R	900 ft	275 m	5	OceanGate LLC	1973	ABS	Perry Submersibles
		SNOOPER 2	C	500 ft	152 m	1	Undersea Graphics	2010	None	Undersea Graphics
		S351	C	300 ft	100 m	na	Submergence Group	2012	GL*	Msubs
		S301	C	200 ft	60 m	8	Submergence Group	2009	GL*	Msubs
		ATLANTIS IV	T	150 ft	46 m	46	Atlantis Adventures, Maui	1988	ABS	Atlantis Submarines
		ATLANTIS IX	T	150 ft	46 m	46	Atlantis Adventures, Kona	1991	ABS	Atlantis Submarines
		ATLANTIS VII	T	150 ft	46 m	46	Atlantis Adventures, Oahu	1990	ABS	Atlantis Submarines
		ATLANTIS X	T	150 ft	46 m	46	Atlantis Adventures, Oahu	1991	ABS	Atlantis Submarines
		ATLANTIS XIV	T	150 ft	46 m	66	Atlantis Adventures, Oahu	1994	ABS	Atlantis Submarines
		SEAmobile I	C	150 ft	46 m	2	SEAmagine Hydrospace Corp	1997	None	SEAmagine

Note. * Submersible in class review.

two-person submersible, and the the *36000/3*, a three-person, full ocean depth concept, featuring a clear glass pressure hull.

Lula 1000 (Azores, Portugal, 1,000 m)

Lula 1000 is a three-person research submersible designed, built, and operated by the Rebikoff-Niggeler Foundation (RNF), a nonprofit institution based in the Azores, Portugal. The submersible is rated to 1,000 m maximum depth. All factory and harbor acceptance tests have been completed. Sea trials started in September 2012 under surveillance of the classification bureau Germanischer Lloyd and are planned to complete in 2013 (Jakobsen & Jakobsen, 2013). The *Lula 1000* system is unique regarding its operational format. With its subcarrier, a 17-m catamaran (crew of two), the submersible can be towed and operated offshore at remote dive sites. The *Lula 1000*, as its predecessor, is specialized in quality video documentation and sampling of deep water species. RNF has operated the *Lula 500* in the Azores since 2000 and was able to incorporate 12 years of diving experience in its new design and operations logistics with the support vessel (Figure 17).

Deepflight Challenger (California, USA, 11,000 m)

Over the course of 2012 and beyond, Virgin Oceanic's *Deepflight Challenger* submersible plans to journey to the deepest part of all five oceans. The submersible initially designed for Steve Fossett was purchased by Chris Welsh and Richard Branson. The submersible uses a composite pressure hull and a unique sapphire glass dome. The dome continues to be ground from a single block, a process that has taken more than a year. Sea trials are planned for 2013/2014 (Welsh, 2013) (Figure 18).

OceanGate (Washington, USA, 3,000 m)

Under the recently announced *Project Cyclops*, *OceanGate* has commenced development of a five-person submersible capable of diving to 3,000 m to expand *OceanGate*'s subsea commercial, research, and exploration operations. *OceanGate* has partnered with a major defense contractor for the carbon fiber hull design and expects construction of that major component to commence in late 2013. In April 2013, *OceanGate* issued a $5 million engineering support contract with the Applied Physics Laboratory at the University of Washington for overall vehicle and subsystem engineering services.

The vehicle features a large 180-degree viewing dome for collective observation, a carbon fiber and glass hull, lightweight design, and advanced control systems. The *Cyclops* vehicle is to be operational in 2015 (Figure 19).

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COMMENTARY

2013 State of ROV Technologies

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Repurposing Items for Subsea Use

The product development technique of "Paint it, bottle it, and box it" is getting a bit long in the tooth. In the mid-1980s, the nascent ROV industry, like many industries before it, typically created equipment by repurposing items designed for other industries. This technique reduced the cost of developing equipment, which was desirable because the quantities to be built were uncertain or very low. Developers could conclude, for example, that the cost to develop a hydraulic filter that was optimized for deep-ocean use might not be justified if they planned to build only tens of systems, and if a filter designed for the factory floor did a reasonably good job.

"Paint it, bottle it, and box it" describes the ROV industry's repurposing techniques. You can put some marine paint on a device to almost protect it from salt water, or put the device inside a one-atmosphere pressure container (or bottle) to protect it from pressure and salt water, or put it in an oil-filled box to protect it from salt water. These methods save engineers countless hours when designing ROV components. Unfortunately, they also cost users countless hours during field repair and maintenance activities. Even worse, these repair and maintenance activities often occur on the critical path of the project being performed by the ROV. This can be a very costly trade-off for equipment users.

Designing for Subsea Use

In equipment design, another term for repurposing is using off-the-shelf components. Using components from the shelf of some other industry can be a great choice if the requirements of the two industries are closely aligned. But if the alignment is weak, the ROV developer must create his own "shelf."

Now that the ROV industry is maturing, it is time to switch the focus from making the developer's life easy to making users' lives (and their customers' lives) easier and more efficient. Developers should clearly focus on machine productivity by minimizing nonproductive time (the time that equipment is unavailable for work). In the offshore environment, having equipment that cannot be used when it is needed is incredibly expensive.

FMC Schilling Robotics recently adopted a design goal of creating systems that reduce service and repair times to less than 60 minutes. Our previous design goal of creating systems that were "easy to service and repair" produced designs with only marginally improved service and repair techniques and times. Once we had a quantifiable goal (the 60-minute metric), we quickly realized that you cannot successfully open and close a subsea bottle or a box (two of the go-to repurposing tricks) in 60 minutes, much less find and replace the component to be serviced.

This helped us understand the need to support offshore productivity by developing new, ROV-specific packaging techniques that move serviceable items to the outer layer of a machine's architecture rather than burying them deep inside. We further learned that ease of use was not enough, and that we also needed to "mistake-proof" the service and repair process.

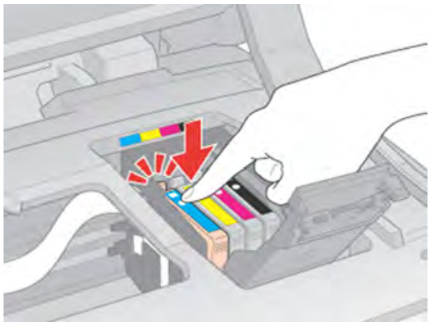
Making Service Easy, Quick, and Mistake-Proof

Luckily, the ideals that we were trying to embody in our new designs were demonstrated in a familiar product—the ink cartridge from the ink-jet printer. When Hewlett-Packard invented the ink-jet printer, the designers clearly understood that the product would be viable only if customers had a simple and mistake-proof way to replenish the ink. Ink cartridges provided an amazing solution, allowing customers to reliably make multiple electrical connections, make leak-proof fluid connections, and achieve precise mechanical alignment. Ink cartridge replacement could be accomplished without tools or training, and with a procedure so simple that instructions could consist of a sequence of pictograms on the printer cover (Figure 1).

Guided by the ink cartridge example, we designed a series of ROV subsystems with serviceable items that have been moved to the outer layer and that require few tools for service and repair. Further, through the use of kinematic interfaces, item removal and replacement have been made mistake-proof. Such interfaces precisely guide and sequence the connections, eliminating

FIGURE 1

Ink-jet cartridge replacement serves as an example of easy, mistake-proof serviceability.



or reducing rules that the user must follow to successfully complete the service task.

Figure 2 shows how a variety of connections between a hydraulic pump and its drive motor are accomplished in a fashion similar to the installation of an ink cartridge. This approach reduced the pump swap time by more than 80%.

Figure 3 shows a contrasting solution from the "paint it, bottle it, and box it" era. The tangle of hydraulic hoses connected to the pump clearly shows the variety of connections that the service technician must manage.

Similarly, we have developed an instrument power supply (Figure 4) that can be replaced by removing only three fasteners. This compares to a conventional design where the

FIGURE 3

Complex connections for a hydraulic pump.

power supply is housed inside a large, one-atmosphere pressure bottle. Again, the service time is reduced by more than 80%.

Reducing the time to perform critical-path repair operations by 6 to 10 hours can provide an enormous productivity boost during complicated offshore operations. In addition to reducing nonproductive time, the mistake-proof design philosophy also reduces the training burden on companies that need competent offshore personnel.

It's All About Ease of Use

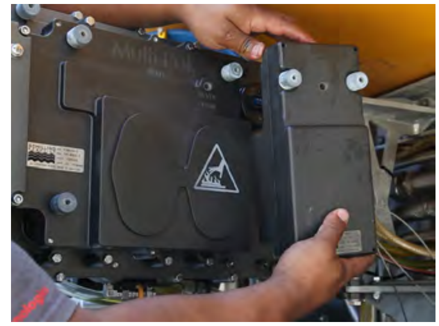
We have now entered the second era of work-class ROV design. While the first era was concerned with ease of design, this new era is about ease of use. Focusing on ease of use brings

FIGURE 2

Easy and mistake-proof connection for a hydraulic pump and its drive motor.

FIGURE 4

Instrument power supply designed for quick and easy replacement.



a host of critical benefits to the offshore environment. First, when a machine is easier to use, less training is required for operators to become proficient, saving ROV owners and their customers money as technicians and pilots "come up to speed" more swiftly. Second, when a machine or tool is easier to use, operators can focus on what they are doing with the tool rather than how to operate or service the tool. Remember, the objective is not to own ROVs, but to get things done with them.

Lessons from the Auto Industry

Every mature industry on the planet has been through an identical evolution of focus from ease of design to ease of use. The automotive industry provides a great example for our industry to learn from.

When automobiles were first available, drivers needed substantial training and practice to operate them properly. Spark advance adjustment and fuel mixture adjustment were manual functions (Figure 5), so drivers needed to know how to perform these functions for the auto's various operating conditions. Later in the history of the industry, engineers began to focus on making automobiles easy to operate,

FIGURE 5

Early automobiles required users to be knowledgeable and skilled.

and they invented systems that automatically made required adjustments for the user.

Thankfully, the modern car has been automated to the extent that drivers can perform most skill-based functions with little or no training. This feat is even more amazing because a modern automobile has so many more capabilities than the original, difficult-to-use predecessors. Most cars now have a button on the dash or console labeled "start" (Figure 6), and this, of course, is a very accurate description of the user's intent.

The ROV industry can learn a great deal from the automotive industry about ease of use, and we have been studying those lessons with keen interest. Imagine if drivers needed months or years to become proficient in the basic use of a car (that is, in safely getting from one place to another). The automobile industry would clearly be much smaller, and many more professional drivers would exist because the machines required special skills. In fact, this described the state of the automobile industry in its very early days.

FIGURE 6

Automated mechanism for starting an automobile.

Harder than It Looks

Unfortunately, ease of use is much simpler to imagine than it is to provide. All engineers start with the goal of designing easy-to-use systems, but along the way, they discover that such design is difficult and expensive. Putting several rows of terminal blocks (from some other industry) inside a big, oil-filled junction box is much easier than designing, developing, and testing a pluggable solution like the ink-jet cartridge.

Automating Operations

The benefits of ease of use are also valuable in a system's operation, and the same design difficulties apply. Consider, for example, the common task of using a manipulator to grasp a tool equipped with a T-handle. This seemingly simple task typically takes an operator 10 minutes or more to perform properly.

This amount of time may seem ridiculously long, but the task is fundamentally complex. A typical robot arm has six degrees of freedom (joints), the minimum number required to reach an arbitrary position and orientation in the workspace. To grasp a T-handle, the user must simultaneously and uniquely position all six degrees of freedom to align the gripper with the handle. This is very difficult to do, and takes substantial training and practice.

To dramatically increase manipulator usability, we have developed a vision-based technique that performs the tricky T-handle task for the user. To use this technique, the user positions the arm in any position and orientation from which the wrist-mounted video camera can see the T-handle. (Because the number of allowable positions is almost infinite, this is much easier for the user than putting the arm in the single position that allows the manipulator to grasp the T-handle.) The system's software then determines the position and orientation of the handle and moves the arm automatically to grasp it.

This technology dramatically reduces the training and practice required to grasp a T-handle and shortens the time to perform the task by a factor of ten. This is similar to the many ease-of-use breakthroughs that all of us unknowingly enjoy every time we get in our cars.

We are very excited about helping to usher in the second era of the work-class ROV. The challenges of designing for ease of use are difficult and many but the benefits will be very clear to equipment users in the subsea industry.

PAPER

Unmanned Maritime Vehicles: Technology Evolution and Implications

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ABSTRACT

This paper reviews the technological advances of autonomous underwater vehicles (AUVs) since 2008, evolution of gliders and remotely operated vehicles (ROVs), and the roles, designs, and capabilities of unmanned surface vehicles (USVs). It describes the uses for those vehicles, how they have evolved and gained trusting users, and how they converge in complementary roles. Predictions for the evolution of unmanned maritime vehicles' (UMVs) roles and operations are made. The paper is broad in scope and looks beyond the technology in an attempt to explain the relationship between technology evolution and user adoption. The research and findings stem from years of technical and business analysis, reports, interviews, and assistance to stakeholders of the unmanned maritime systems (UMS) industry by the author.
Keywords: unmanned, autonomous, remote, glider, vehicle

Introduction

The technology of unmanned maritime vehicles (UMVs) has evolved a lot since the last MTS State of Technology Autonomous Underwater Vehicle (AUV) review in 2008. Software and electronics have improved, and reliability has increased. More importantly, the user base has expanded, especially in commercial sectors and among governments not having a national development program, slowly embracing an unmanned maritime "solution." AUVs, unmanned surface vehicles (USVs), remotely operated vehicles (ROVs), gliders, buoys, vessels, and fixed subsea or surface equipment are increasingly working together. This paper examines the technical evolution and future implications of UMVs.

Technology Evolution of UMV

AUV

A number of new AUVs came to light since 2008, and perhaps more importantly AUV developers upgraded their models. There are two main reasons for this significant evolution: constant improvement of electronics and software and the attraction of more users as AUVs prove their unique abilities.

New AUVs

Very few entities are offering a new torpedo-type AUV, since existing systems are reliable and capable. Current AUV manufacturers have established a reputation and name. The market offers little room for another AUV with more or less similar characteristics. An inventory of AUVs in 2011 counted more than 100 models, yet new commercial vehicles are mostly updates to a product line. Half a dozen companies dominate the market, with roughly 15 vehicles. This nonfragmented market is unusual for a technology that continues to grow and gain new user types, evidence that developing an AUV geared for sale on the open market is complex, long, and expensive (Martin, 2011).

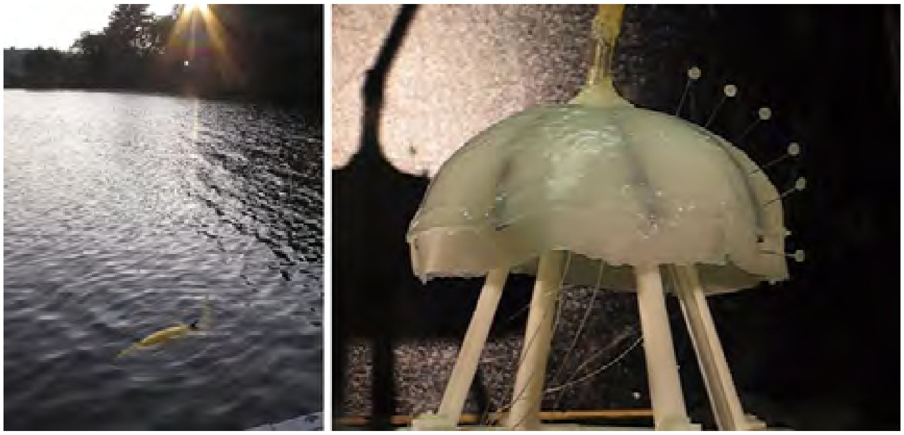
The new AUVs are instead exhibiting new designs, which enable new capabilities that are nonexistent or barely present in the traditional monopropeller, torpedo-shaped AUV.

Designs: A number of nontraditional AUV designs remind us of the link between design and propulsion. While the advancement of materials enable fish-like AUVs to move with a flexible body (Rufo, 2011), the jellyfish AUV uses a material that not only enables the AUV to mimic the appearance of the creature, but it uses its very material to propel the AUV (Yonas et al., 2009). Most biomimetic AUVs stay at a research phase for a very long time, and few, if any, are productized (Figure 1).

New designs are also originating from dual-use AUVs. For example, a large underwater vehicle can operate with humans as a swimmer delivery vehicle (SDV) or autonomously without anyone on board as an AUV (*Proteus* in Figure 2a). The resulting AUV design resembles a large SDV. Another example of dual-use AUVs are hybrid ROVs (HROVs): ROVs that can become tetherless and operate autonomously as AUVs do.

FIGURE 1

Biomimetic unmanned underwater vehicle (UUV). Left: GhostSwimmer artificial fish (photo courtesy of Boston Engineering). Right: Jellyfish (photo courtesy of University of Texas at Dallas).



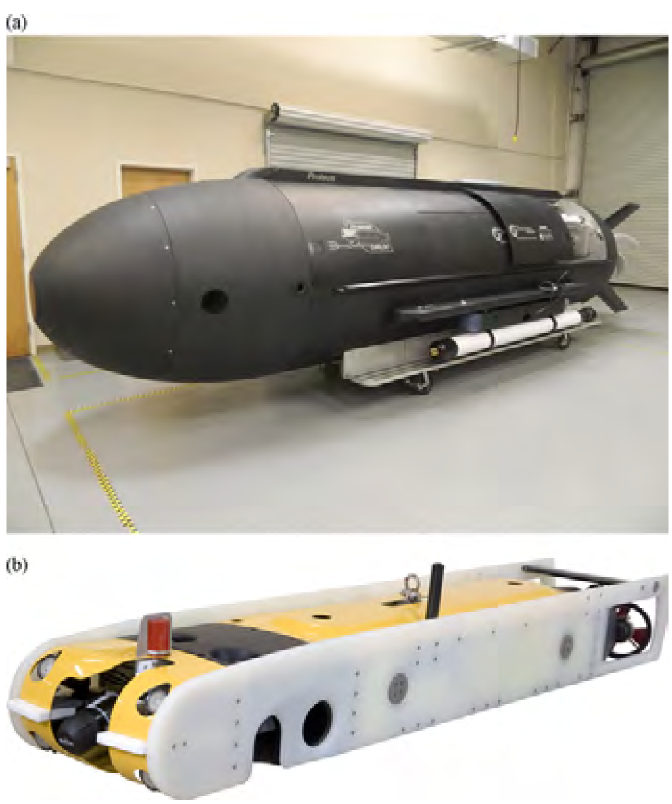
Variant and dual-use AUVs are motivated by a market need, where AUV developers blend in autonomy with an existing nonautonomous product. The evolutionary approach to meet a defined user need is a compelling reason for variant AUVs to quickly be adopted by a new type of user.

Propulsion: Adding horizontal or pitched propellers and motors enable an AUV to keep on station, thereby allowing a reef or a hull to be inspected without circling around and in a way replacing the basic functions of an inspection ROV. While those features have been employed on ROVs since nearly their conception, some AUVs now enjoy more degrees of freedom through multipropellers that are precisely controlled and thus offer an automated hover feature (*Sabertooth* in Figure 2b and *Marlin* in Figure 3).

New AUVs developed over the last 5 years have mostly included innovative designs and propulsion in order to address dynamic functions not present in torpedo-designed AUVs.

FIGURE 2

Unconventional AUV designs. (a) *Proteus* (photo courtesy of Battelle Memorial Institute). (b) *Sabertooth* (photo courtesy of Saab Seaeye).



Upgraded AUVs

Advances in electronics have improved how data are collected, processed, and stored and resulted in smaller electronic boards, while at the same time increasing reliability since components are, today, more tolerant to varying environmental conditions. Improvements in electronics have also greatly improved sensors, which are now more capable, often smaller, and consume less power.

Communications: As a function of the AUV's location, a number of communication methods are employed to have the highest bandwidth for data transmission, although high bandwidth is not necessary to change mission parameters.

FIGURE 3

AUV with Hovering Propulsion. *Marlin* (photo courtesy of Lockheed Martin Corporation).

Ethernet is used on the supporting vessel's deck, using an Ethernet cable as a secure and fast connection.

Wi-Fi is now common and practical as it enables data transfer without physically connecting the AUV to a computer. It is logistically advantageous since data transfer can happen before the AUV is on deck, secured, and wired. This saves precious time and reduces recovery and relaunch. Wi-Fi has a limited range and does not work when the vehicle is submerged. However, it is easier to use than a radio frequency (RF) modem especially since most users are familiar with using Wi-Fi communication at home and at work.

RF, usually 2.4 GHz or 900 MHz, performs best when the vehicle is at the surface, further away from the ship and out of Wi-Fi range. However, a high swell and a low angle from the top of the AUV antenna to the boat means line of sight (LOS) is not always achievable.

Satellite (via Iridium) is often an option for data transmission and is available once the vehicle surfaces, wherever it may be on the planet. However, due to the higher cost of satellite communications, AUVs mostly used this link for command and control (C2) data exchange.

Acoustic modems have improved, due in large part to the increasing amount of signal processing the modem can accomplish in real time, and are sometimes used to communicate to the vehicle while it is below the surface.

Laser and optical communication devices are most commonly found as research institutions' prototypes, and they are not yet offered on an AUV. However, based on an increasing interest for rapid data harvesting and data transfer, this is expected to change soon (Jacobson et al., 2013). The first applications will likely be over short ranges, such as when in close proximity to a docking or a communication relay point.

Batteries: Most AUVs use pressure-tolerant rechargeable lithium ion batteries. Significant built-in safety systems are implemented to avoid any hazards related to overcharging, discharging, and general use. Large AUVs with lots of volume to carry the batteries can provide approximately 30 h of endurance, although mission length is highly dependent on the AUV's speed and payload power requirements. Risk of explosion is an important issue with many energy sources; this can render air transport or ship certification an issue. Thus, having the best energy source for an AUV but not being able to conform to risk compliance for logistics displaces the problem from technology to operation. Hence, the energy issue is not one of only powering an AUV.

There is much debate on the type of fuel cell to adopt and implement in AUVs. A number of studies have been conducted by the US Navy (Deitz, 2011) and the European Defence Agency (ESUUV Consortium, 2012) and views differ. However, due to the need to have longer endurance, almost all AUV manufacturers are still aiming to have fuel cells as a power source option. Meanwhile increasing energy density of Li-ion batteries and accepted certifications for their transport and safety by international organizations means Li-ion remains the energy source of choice.

Navigation: A number of disparate sensors, each capable of adding information, are commonly employed together to continuously compute more accurate and reliable position and displacement data. Those sensors are as follows:

- pressure sensor
- altimeter
- compass
- gyroscopes
- inertial measurement unit (IMU)
- Doppler velocity (increasing the number of beams improves navigation)
- ultra short base line (USBL) and long baseline (LBL)
- terrain-referenced navigation (compares bathymetric measurements with a preloaded and known map in order to augment position information)
- acoustic transponders (for bearing and range)
- GPS receiver for surface "fixes"

Note that some of those sensors are *in lieu* of an IMU, while others complement the IMU. An IMU is sometimes integrated in 9-inch diameter AUVs, although the cost remains high. GPS fixes are not always possible for under-ice or in GPS-denied areas or not logistically practical for deep water operations. Note that IMU technology is improving. For example, fiber-optic IMUs are available that have no moving parts and low power consumption. Therefore, IMU presence onboard AUVs is increasing. Microelectromechanical systems (MEMS) also offer a low-cost alternative to IMUs for navigation systems.

USBL has improved, which in turn has slightly improved positioning accuracy. It is possible to reduce the position errors with postprocessing of sonar data. While not useful for navigation, this enhances the quality of the end-product such as bathymetric maps.

The bottom line is that while navigation accuracy has slightly improved, it remains a complex, expensive, and cumbersome ordeal for the integrator. The end-user need for accurate data is being satisfied by the fusion of disparate navigation sensors and the rapid processing that is now available.

In situ Sensors: *In situ* sensors are often referred to as probes. They sense and record the environmental data that are measured by the probe. Some of those sensors are necessary equipment for AUV operation. Communication and positioning sensors are not included here and are discussed in other sections.

The following *in situ* sensors are sometimes found on AUVs, depending on the mission and AUV model:

- sound velocity
- dissolved oxygen
- hydrogen potential
- conductivity temperature density (CTD)
- turbidity
- dissolved carbon dioxide
- chlorophyll fluorescence

Events such as the Macondo oil spill and Fukushima nuclear explosion have prompted the utilization of AUVs and gliders for accessing environmentally dangerous locations, monitoring large expanses and changes over time, and accommodating the integration of new sensors (Yahnker et al., 2012; Leroy, 2013).

Many other sensors exist beyond the traditional ones listed above, from radiation detectors to hydrocarbon sensors. The number of available sensors has increased because sensor manufacturers have recognized the large market potential for AUVs and are thus willing to start adapting their sensors to fit into them.

Remote Sensors: Sonars have evolved a lot in 5 years, having better resolution, more range, lower power consumption, smaller size, and more embedded real-time data processing.

Importantly, sonar data processing is completed much faster than before, allowing the sonar to reconfigure itself based on what it perceives. This configurability means a greater mission fit.

Synthetic aperture sonars (SAS) are now routinely integrated and used on AUVs and give a nonshadow image with constant resolution. While still expensive, their cost is starting to go down. In addition, more is accomplished in real time on the electronic boards of the sonar payload with an increase in resolution and decrease in power consumption. Commercial users are now starting to use SAS.

Multibeam sonars have improved a lot too, hence becoming more prevalent and much less expensive than SAS. While both multibeam and SAS have improved, SAS remains a high-price sonar needing specific electronics for real-time processing. However, as end-users get used to high resolution data, one can predict that SAS will be more commonly found in large AUVs.

Interferometric sidescan sonars have been increasingly used on small AUVs since about 2008 (Marani et al., 2009) and have augmented their bathymetric mapping capabilities that were previously only possible on larger AUVs.

A number of acoustic sensors are now commonly found on AUVs: echo sounders, acoustic Doppler current profilers, single beam, multiple beam, and dual-band side-scan sonars.

We are more commonly seeing video cameras and still cameras located in the nose of AUVs or downward-looking with a LED strobe in order to conduct inspection tasks that were seldom undertaken on an AUV 5 years ago. As noted in the propulsion section, AUV functions now encompass what was previously uniquely within the realm of ROVs.

Other remote sensors and sonars are as follows:

- magnetometers
- sub-bottom profilers
- dynamic aperture sonars
- laser optical plankton counters
- fisheries echo sounders

Some sensors often need to be towed by the AUV (e.g., ultrasensitive sensitive magnetometers).

Propulsion: No substantial improvement has occurred in propulsion systems. Propellers, gear boxes, and actuators are fairly reliable and require little maintenance. However, the Center for Maritime Research and Experimentation has shown that tail redesign can yield significant drag reduction (Maguer, 2013) and hence larger endurance (Figure 4).

Other changes in propulsion have included adding hovering capabilities, which in turn enables new roles in inspection and the ability to operate in tight maneuvering spaces, often found in subsea infrastructure and fisheries applications.

Safety: Although reliable, AUVs sometimes get caught in nets or reefs or are simply lost. Net cutters, obstacle avoidance forward-looking sonars, drop weights, pingers, and even airbag-like

FIGURE 4

Improvement in propulsion through AUV tail redesign. Ocean Explorer-C original (top) and new propeller design (bottom). Power consumption was reduced by up to a factor of 3 with the new design as well as a significant increase in the maximum achievable speed (from 1.4 to 2.1 m/s). Photo from Center for Maritime Research and Experimentation.

floats are available options. Strobe lights for surface localization and communications are ubiquitous. Virtually all AUVs have leak detection sensors that turn on an emergency mode should water get into spaces that it should not.

Commercially available AUVs are reliable: some have been used frequently for over 8 years (Griffiths et al., 2009) and some large AUVs used for oil and gas have been surveying more than 50,000 km—per vehicle. The AUVs that have most often been lost at sea are those under experimentation, where the end-customer has modified the software to develop the AUV for specific missions (in June 2010, four AUVs were lost and three never recovered in bottom mine detection exercises) or where the application environment was at high risk with sparse data available for premission planning. Most importantly, commercial end-users are gaining trust in AUV operations as a cost-saving tool. Oil and gas customers initially buy a unit or two but consistently increase their fleet of AUVs once they develop trust in the technology—although autonomous operations in close proximity to subsea equipment is not allowed today. Some oil and gas operators now say they could not do without AUVs. This is the most significant development in AUVs and correlates with repeat users and a growing user base.

Autonomy: The request by end-users for more autonomy has pushed the capabilities; for instance, to reduce the number of false-positive identification of mines, track pipelines, and "on-the-fly" piloting of an AUV in a port. Autonomy has improved not because of highly elaborate algorithms in vehicle intelligent behavior but mostly because of the real-time processing of sensor data that can in turn be directly used by the AUV without the need to recover, analyze the data, and relaunch. The military has been the driving force behind autonomy principally to reduce the time it takes to reconnoiter and possibly clear a mine field. Automatic target recognition (ATR) and data processing from mine warfare are beginning to transfer the technology to the offshore oil and gas industry. In short, sensors and computation improvements are instrumental in the autonomy improvements we have seen over the last few years.

More crucially important, users' trust of AUVs and their autonomous functions have been a critical stepping stone in terms of autonomy adoption. After months of mission planning and millions of dollars or euros spent, not seeing an AUV for hours while it is out of direct control by operators understandably creates fear. But AUVs continue to win users over, one by one. Late-coming AUV adopters such as offshore operators are now using them for subsea inspection and survey and building trust in their autonomy. In the future, as trust is fully established, AUVs will begin to be used for light intervention operations.

Deeper and longer uses of AUVs through autonomy are expected, as well as a plurality of interaction between AUVs and other equipment. Signs indicate that improvement in autonomy will be incremental as research conducted by academic institutions is vetted by real-world operations and then later integrated into commercial products.

Standards: The end-user requirements for standards have resulted in a few organizations taking on AUV, USV, and ROV development of standards, where progress has been made. The American Society of Testing and Materials (ASTM) committee F41 has been developing guides for AUV communications, physical payload interfaces, sensor data formats, and autonomy and control. The Society of Automotive Engineers (SAE) under the Aerospace Standards Unmanned Systems Steering Committee (AS-4) has been developing UUV and payload interface service sets to provide interoperability by defining message formats. The North Atlantic Treaty Association (NATO) has several Industry Advisory Groups (each known as a NIAG) working on Standardization Agreements or STANAGs. It is important to note that STANAG developments often apply to USVs as well. Standards organizations are nonprofits, and their contributing members are volunteers with already demanding day jobs, so strides in standards developments has been nonlinear and dependent on large development programs (Jacobson et al., 2013).

Modularity: The AUV user base is diverse and has very specific needs. AUV manufacturers often do not have the "spec" AUV that meets the end-user's needs. Manufacturers realize the users want a unique configuration or the ability to have a full sensor suite from the onset or to integrate them eventually. Hence virtually all AUV developers claim to offer modularity. Modularity is hard to quantify; it does not mean the user will be able to plug-in their own sensors. Generally today, the battery modules are modular and the AUV can also be fitted with module sections that elongate the AUV. A high modularity directly translates into lower logistical time (e.g., swapping the battery), faster integration time (e.g., ability to have a SAS chosen by the user), and lower costs (e.g., shorter software integration time).

Overall, AUV developers respond to the end-customers' requirements for modularity and are designing new AUVs as modular from the ground-up.

Note that modularity comes at a great burden of money and time to the manufacturers: hardware modularity has stringent mechanical and electrical requirements, and software modularity requires complex software development processes and tools.

Open Architecture and Open-Source Software: End-users in the defense industry often push for open architecture. Since AUV software has often been "closed," these users must go back to the original equipment manufacturer to do modifications. Application programming interfaces (APIs) often do not suffice for the end-users trying to use the AUV as a development platform rather than an operational platform.

For example, the U.S. Navy is striving for a level 6 of open architecture for its Large Displacement Unmanned Undersea Vehicle program (Ashton, 2011). With naval surface ships and submarines relying on open architecture, the U.S. Navy will want the same openness both in an attempt to reduce life program costs and in anticipation of AUV integration with other systems. Promoting openness from software architecture to actual lines of code, the U.S. Navy initiated the Maritime Open Architecture Autonomy as a government-owned, open-source software as a means to support further AUV autonomy development.

The Mission-Oriented Operating Suite Interval Programming, a set of open-source C++ modules, provides a degree of autonomy on autonomous marine vehicles (Benjamin et al., 2013), and has been ported to a number of AUVs and USVs.

USVs

The first USV came to light before an AUV. This was mostly because RF communications enable a remote operator to control USVs, something impossible underwater. Today, there are over 100 models of USVs developed by a more geographically diverse base than AUVs. New models of various shapes and sizes are announced every year.

Roles

The roles taken by USVs are very diverse. They are increasingly used by scientists to gather data in both underwater and above-water environments. USVs are used in inhospitable areas or where data collection occurs over weeks or even months. The military has long worked on USVs. Minesweeping vessels themselves are slated for decommission in many countries to be replaced with USVs. The second emerging use of USVs for defense is surveillance and protection. Among commercial end-users, USVs are used for bathymetric mapping and civil engineering. Scientists use USVs for remote sensing and climate change data collection. The oil and gas sector uses USVs as data relay "bridges" from subsea operations to the support vessel, although this role is still in a very early stage and about to expand. USVs provide a relatively inexpensive and flexible platform, and the technology is fairly mature as it leverages existing electronics and sensors from a number of industries.

User needs and acceptance of USVs have not yet matured. This explains why such a large number of USV models have been developed, yet a weak customer market exists. However, adoption of USVs is advancing, mostly to alleviate the constraints from decreased governmental budgets as well as the challenges of exploration and remote sensing in distant and/or dangerous places. These changes will force end-users to consider alternatives such as USVs, since, for example, they can be more effective than the currently employed large vessels. Such change takes time especially in large and conservative communities such as the oil and gas sector and government. In short, the late arrival of USVs as a viable working solution is not a sign of technology immaturity but a result of political and budgetary constraints, a fear of change and propensity towards risk mitigation where USVs clearly offer a solution.

Designs

Most USVs are not designed to fulfill a single role but are multidisciplinary. The reason is twofold: first, the USV application market is not well defined, causing manufacturers to appeal to various needs in order to stay in business, and second, USVs use of commercial-off-the-shelf equipment and system integration is not drastically constrained in volume and power, which renders USVs versatile by design.

Various designs exists, with the single hull design predominating, mostly because integrators often take a previously manufactured vessel and change what is necessary to remove the pilot. Catamarans, which already provide a high-level of stability, are sought after in scientific roles and remote-sensing projects such as bathymetric mapping. Sizes range from very small for furtive surveillance to a 17-m hull (*Sterenn Du* in Figure 5). However, many are in the 9- to 11-m range, providing adequate open-sea worthiness, range, and launch and recovery from large ships.

Besides variation in size, USVs have the advantage of being able to reuse existing vessels as a base

FIGURE 5

USV size examples. Left: *Sterenn Du* USV (photo by Mer et Marine, Gregoire Daviron). Right: *TSS* USV (photo by A. Martin).

for floatation and propulsion. For instance, pilotless jet skis or conventional boats with "sail by wires" have been used to develop navigation software. This drastically cuts down developmental costs.

Operational Capabilities

Most USVs relay information to a control station using RF communications. Range usually tops out at 10–12 nautical miles for midsize and open-sea USVs (typically based on the antenna height). USVs rely on GPS and have a preset route or are remotely controlled. Truly autonomous systems need to have obstacle avoidance, which rely on light detection and ranging or laser imaging detection and ranging (LiDAR), short-range radio detection and ranging (RADAR), and video image processing. Waves, foam, sea weeds, and water color variations make avoidance equipment complex, expensive, and rare on USVs. Open-sea conditions also blur the sensors' receptors, which degrades the sensors' quality. Long-distance USVs rely on the automatic identification system (AIS) to both signal their presence and detect the presence of other vessels in the vicinity so the route can be altered on a more automatic basis. Persistent USV utilize beyond line-of-sight via aerial relay or satellite communication to follow and reconfigure their mission and path.

A high number of payloads are possible, from loudspeakers to hull-mounted sonars to missiles. The diversity of passive and active sensors shows the various roles of USVs. As with most unmanned vehicles, high-grade sensors usually drive up the price of vehicles, which can easily reach US$5 million for a military-grade USV.

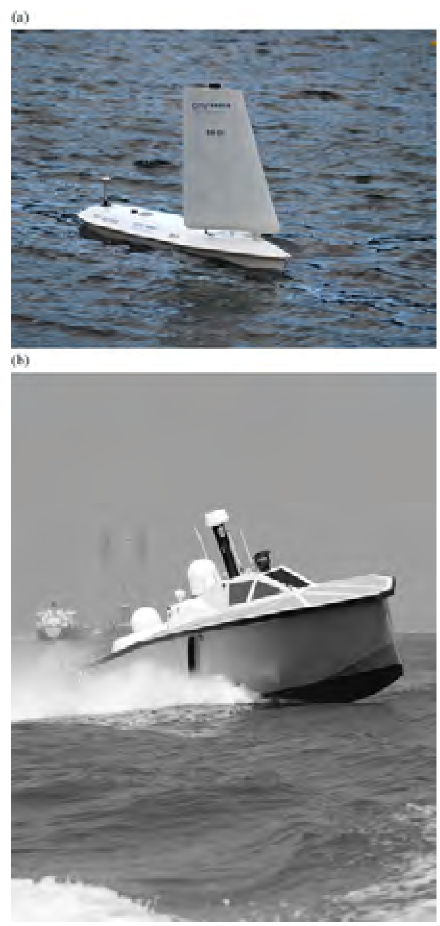
USVs often fall into two categories: shore-based or vessel-launched. Small USVs can usually be launched from anywhere, even dropped from the air. The launching of a USV presents compatibility issues with host vessels—except for small USVs launched from a crane. Sea states 4 and higher present a high risk of damage or simply the impossibility to recover the USV. Ramps and attachments need to be quick and secure. A large vessel recovering a USV needs to do so quickly so as not to alter its own operations. USVs offer the ability of being transferred from vessel to vessel, but this extends compatibility problems beyond the physical launch and recovery.

Persistent USV

Over the last 5 years, a few long-endurance USVs have emerged. They must either rely on a clever propulsion means by capturing energy in the open ocean (e.g., from wave displacements or wind as in Figure 6a) or use a traditional power source that requires that the USV be very large to hold a large amount of fuel yet be constructed of light material for low fuel consumption (Figure 6b). These long endurance USVs have opened an entirely new set of possibilities for this technology.

FIGURE 6

Long-endurance USV examples. (a) *SailBuoy* (courtesy of CMR Instrumentation and Sail-Buoy.no). SailBuoy relies on a hard sail and an internal battery to navigate for up to a year. (b) *Vigilant* Independent USV (IUSV) (courtesy of Zyvex Technologies).



Target USVs

Target USVs refer to the remotely controlled or preprogrammed unmanned vessels used in military exercises where the USV simulates an incoming "attack" boat. The military uses the target to practice shooting. Because a high number of target USVs are purchased, these disposable USVs far exceed the production of other nontarget USVs. Some target USV manufacturers have recently expanded to develop autonomous USVs.

Standards

The same standard organizations for AUVs have encompassed USVs over the last 5 years. The plurality of roles, models, user groups, and very low number of USVs in operation means there are few resources dedicated to standardize USVs. The main proponents for USV standards development are the various navies, either from North America or Western Europe. They want to standardize vehicles to increase the "life" of the USV design through various upgrades, get all contractors on the same page, and reduce integration costs resulting from proprietary and disparate systems. This would in turn also ease operations especially among joint forces. As an example, the Launch and Recovery System for Any small navy crafts (LAURA) joint project aims at standardizing the launching and recovering of USVs from host ships.

Progress has been made in creating regulations of USVs regarding navigation among general vessel traffic. Proposed regulations are going through the various chains of command for approval and comments, before the International Maritime Organization ultimately ratifies and changes the law of maritime navigation to accommodate USVs. There are still uncertainties and risk to the adoption and use of USV due to the rules of navigation.

ROVs

ROVs are a proven and mature technology with an experienced user base. The oil and gas industry helped drive the development of this technology, and now ROVs have become an indispensable tool, particularly in large subsea construction projects. The manufacturers' base has consolidated and many ROV "brands" from the same size class offer similar characteristics.

While ROVs have seen no drastic technical changes compared to other UMVs, the modular add-on tools now available for ROVs have provided a means to execute strenuous manipulations underwater.

What has been evolving significantly over the past 5 years is the quality of performance of small ROVs that have become more reliable and effective—although for a limited depth and with very limited intervention capabilities. Small ROVs now complement work-class ROVs during tasks, and it is now common for an operation to put various ROV classes to use. The small logistical footprint and rapid deployment are the main reasons small ROVs are used today in oil and gas development. In addition, small ROVs are becoming a common tool for industrial and inshore water activities, and their low price point has enabled a new set of users into the ROV realm. Moore's law will continue to empower small ROVs.

All-electric ROVs are now common and some work-class ROVs only have hydraulic manipulator arms. Strong "muscle" power is still hydraulic, although the tax in power and weight make a growing number of users prefer electrically actuated manipulators. Many analog components are being replaced with all-digital equipment. This marks a turning point in ROV evolution: software can now control most of the functions of an ROV and add intelligent functions. With deeper and more remote oil fields and a risk reduction due to the drastic environmental compliance constraints in energy extraction, ROVs will be employed more often and in more demanding work environments. Software for ROVs will improve the performance of repetitive tasks and its abilities in positioning and navigation so operators can focus on more critical maneuvers instead of the dull and repetitive ones. While the operator of an ROV will not go away, automation functions are introduced to ease the operator's job, decreasing the likelihood of errors during rote tasks and "elevating" the need for a human behind the control only when necessary. The increase of automation will defray the cost of scarce and expensive ROV operators, especially with the likely increase of operations in inhospitable places over the next 50 years.

Meanwhile the economics of energy exploitation have given birth to subsea exploitation with "resident" systems that do not get launched and recovered for every task. This will reduce risk and vessel support costs. The technological burden is being shifted to energy transmission, storage, utilization, and communication. "De-tetherable" ROVs will be needed to maneuver in large subsea factories, making them temporary AUVs through increasingly autonomous functions. Note that ROVs will more commonly carry their own power, where the tether only supports communications.

A growing breed of ROVs is attachable to ship hulls and can crawl on it or on the bottom of the ocean/harbor

Hull-scanning ROVs can perform a faster and more thorough inspection of a hull than divers. The goal of these ROVs is to scan a ship to detect cracks and abnormalities as well as explosives or other foreign objects. Two ROV models can clean hulls and decrease the resistance created by algae and deposits, which in turn decrease fuel costs. Other ROVs are designed specifically for hull inspection and explosive removal; those fall both under the crawler's category and the free floating category. Many ROVs now offer a module to make them stick to a hull, continuing the evolution of ROVs through add-on modules. Note that some models hull inspection tools are completely autonomous and only tethered to relay video.

Gliders

Underwater gliders have gained drastic user adoption beyond academics over the past 5 years. Their low cost and ability to conduct very long missions over large expanses are of interest to both scientists and governments. Their small logistical footprint is great for deployment and recovery alike. The order for up to potentially 150 gliders from the U.S. Navy in 2009 and 2011 for oceanographic purposes is a worthy note.

Gliders' designs from earlier generations have been improved, usually giving more volume for payloads and attempting to reduce the onboard battery consumption. As sensors shrink, the gliders can go beyond the initial water temperature and salinity data sensing. Beyond research, new uses established during the past 5 years include attempts to discover oil traces to locate oil sources and leaks, determining water movements from hurricanes, and missions performed by a fleet of gliders to rapidly cover a large area.

Biofouling remains an issue. The fear of losing the glider is real although actual loss is uncommon. New unconventional glider designs have emerged, although it is doubtful they will reach the low cost, long endurance capabilities of current gliders.

Hardware and Software Update Cycles

Constant evolution of semiconductors has given increasing computation availability to AUVs and gliders, while reducing the footprint and power consumption. At the same time, the availability and prevalence of software has been accelerating. There is therefore a *continuum* of improvement in software and electronics available to AUVs.

However, AUVs are vehicles developed at a specific point in time for a specific sensor suite. Upgrading AUVs is not easily accomplished due to mechanical design and volume constraints. For instance, integrating a smaller sensor means some redesign and volume/weight recalibration. Therefore, AUVs do not experience the technology improvement rate that electronics and software technology offer. For instance, whereas high-capacity graphic processor units (GPUs) have made their way in the computation of remote sensing data software at least 5 years ago, GPUs integrated into AUVs are a novelty (Maguer, 2013).

Because upgrades in electronics are not as constrained in USVs as they are in AUVs and gliders, the time to adoption of new electronics and software on USVs is shorter than with AUVs.

The update cycle rapidity is an indication of how reactive a technology can be to address a need and of its ability to proliferate.

Uses of UMV

Symbiotic Relationships of AUVs, ROVs, Gliders, and USVs

What has clearly emerged over the past 5 years is the use of UMVs in complementary roles during a single mission. The following examples illustrate this:

- A USV transitions from a large vessel to a mine field for survey. It is used as a transportation platform to deploy an AUV in the area. The AUV surveys the field and sends data acoustically back to the USV, which then relays the data over the air to the mother ship where experts review sonar data.
- An USV launches an ROV in order to perform a close-in visual inspection of potentially dangerous objects. The USV is teleoperated (remotely controlled through surface communications), and the ROV is teleoperated through the USV (remotely controlled through a tether), which provides power, maneuverability, communication, and monitors what happens on the surface.
- An AUV searches for a wreck. Once a few areas of interest are located, the host vessel moves to the area and launches an ROV to inspect and retrieve objects.
- A glider sails under the Arctic for months; scientists send in an AUV to measure ice thickness where the glider previously identified temperatures where ice thickness change is the most likely to occur.

Increasingly, too, static systems such as sonobuoys, surface buoys, or communication devices are interacting with UMVs. The examples above show how unmanned maritime systems (UMS) are used as a solution rather than a specific UMV as an independent tool. With the complementary operational uses, the "value add" of UMS is far greater than each vehicle taken independently.

Gaining Users

The existing user base is expanding its use of UMVs, in the following ways among many more:

- AUVs to map harbors
- AUVs in oil and gas to conduct surveys and pipeline inspections (Gilmour et al., 2012)
- Gliders operated in a fleet for rapid survey over a large area or for long-duration missions
- ROVs used by civil engineers, municipalities, or government for "first response" or security applications
- ROVs used in aqueduct and tunnel inspections

Emerging Uses

As early adopters continue to invest and utilize the technology in greater scopes, new users are taking interest and employing UMVs in their operations. There is often an economic incentive to do so, but economics alone usually do not push users enough to adopt the technology. There needs to be other elements valuable to the user and not attainable through the currently employed substitutes for new uses of UMVs to take place. Such elements can be to shorten operational time, decrease liability and prevent accidents, increase quality and compliance, preempt dangerous situations from developing, or obtain forensic evidence postincident. Emerging uses of UMVs include the following:

- USVs in the oil and gas sector, either as data relay stations, environmental monitoring stations, or to tow sonars
- ROVs in aquaculture for inspection of net anchors and cleaning
- AUVs to inspect aqueducts for cracks and tunnel mapping
- USVs for surveillance of gas refineries
- AUVs to map subsea infrastructure
- AUVs to perform conductivity tests of pipelines
- AUVs to follow a pipeline and record video for miles
- USVs for near-shore mapping or in-shore mapping before and after dredging
- Hybrid ROV-AUVs in tests for prolonged subsea operations
- AUVs used for environmental monitoring

Future

A number of reasonable implications can be made from having observed the technological and end-user bases change over the past few years:

- The UMV industry is in constant evolution and will continue to evolve as electronics and software become more accessible. More importantly, we will witness UMV growth for new uses and existing uses across various industries. The early adopters are creating the condition for a market pull instead of a technology push. Government customers will wither in favor of a true commercial industry.
- The complexity of AUVs remains high, and only a small number of private and public institutions will continue to develop them.
- Countries developing their endemic UMV technology will increase, especially in select countries in Asia and for USVs. The difficulty to develop a working AUV forces new countries eager to use the technology to buy it abroad and to keep their own AUVs in the phase of research and development in the near term.
- Military's push for long-endurance AUVs will bring radical innovation to AUV energy storage and consumption in the midterm and long term.
- Enhanced underwater communications will enable new roles and increased complementary roles between ROVs, AUVs, and USVs.
- USV adoption will remain slow in the near term, both by military for mine countermeasure and by scientists and engineers looking for innovative solutions to common industrial problems.
- In the midterm, the threat that an AUV might be lurking to collect strategic information or used by terrorist groups will be of concern.
- The oil and gas sector will continue to increase their use of all-electric ROVs, use more AUVs, and start using USVs.
- ROV enhancements will take place in automation and software.
- Improvement in autonomy will be linear in the short term.
- The sharing of data collected by UMVs for scientific purposes and exposed to the public will bring awareness of the "good" UMVs can offer; this data collection in the long-term will support an information economy relying on remote sensing data acquired by AUVs, gliders, and USVs.
- Research and development (R&D) nonprofit and public institutions will increasingly receive funding from private companies rather than governments.
- Biomimetic underwater robots will continue to surprise us, although very few will make it to commercialization.
- Sensor providers will inch toward "smart" and low-power adaptive sensing rather than purely outputting more data.
- The line between ROVs and AUVs will blur as ROVs take on intelligent

functions and will be untethered for short-range use and as AUVs will perform on-station and precise inspections. Yet the cultural "wall" between ROV and AUV manufacturers as well as the gap in complexity will remain a significant hurdle against collaboration and exploitation of those two technologies as a holistic solution.

- AUVs will take on new inspection and light intervention roles.
- Resident AUVs (hybrid AUV-ROV stationed on the seafloor for months at a time and able to regularly and quickly inspect and intervene) will complement AUVs and ROVs in the midterm, not replace them.
- A number of ship designs and manufacturing companies will be investing in USVs, sometimes investing in technology development for USVs in hope of transferring the technology to large ships and to reduce power consumption. Others will see USVs as a natural extension and evolution of ships and want to participate in USV development.
- Complex technology developed by the military, such as automated object recognition, fuel cell sources, and multivehicle operations, will transfer slowly to the commercial sector.

Conclusion

While the government will continue to play a critical role as a technology incubator for UMVs, companies will be increasingly drawn by necessity to a true commercial market; this is a sign of maturity and expansion for the still-small field of UMVs. The last 5 years have seen a significant change in technical evolution and user adoption of AUVs. Reliability has increased noticeably, and operational experience has given both technology development and users insight into how to move the technology and its usage forward.

The emergence of UMVs working together in complementary roles is starting to change the perspective from vehicles to solutions. The acronym UUV for "unmanned underwater vehicle" is being used more than before, enlarging the scope from AUVs to non-autonomous vehicles such as ROVs. Similarly, the word UMS shows that the discussion around what a USV or UUV can provide is seen as a one-system solution, including nonpropelled systems and ancillary technology.

Disclaimer

The status of technology and user maturity needs to be differentiated between what is being done in research and what is being employed in operation. For example, cooperative control of many UMVs has been researched and experimented for more than a decade, yet UMVs working autonomously together in an operational/commercial setting has not yet occurred. This paper takes the position of assessing the technology in an operational and commercial setting, where there is a true market for UMSs to fulfill a repeatable customer need.

It is hard to inform both connoisseurs and newly interested parties about such a diverse and emerging industry. This paper takes a broad approach on UMV technology and its applications in order to cover a wide-range of topics.

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PAPER

State of Technology in Autonomous Underwater Gliders

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ABSTRACT

Over the last few decades, a range of instruments and vehicles have been used to monitor the oceans. One example is the use of autonomous underwater vehicles to perform ocean surveys, and within this group, autonomous underwater gliders have made their mark. Gliders enable the scientist to make extended complex studies on topics such as the effect of metals, pesticides, and nutrients on fish abundance, reproductive success, and ability to feed or on contaminants such as chemicals or biological toxins that are transported in particulate form and may become incorporated into living organisms (plankton, bivalves, and fish) or become deposited in bottom sediments. With these vehicles, the scientist or environmentalist can detect hazardous substances in the ocean such as chemicals from an oil spill or toxic algae such as red tide.
Keywords: autonomous, AUV, gliders, Lagrangian, Slocum, underwater, vehicles

Introduction

Autonomous underwater gliders make up the newest field of underwater vehicles. These vehicles glide through the ocean at low speeds using changes in buoyancy to ascend and descend while their wings generate lift to propel them forward. These gliders conduct long-duration missions to acquire and communicate scientific data to researchers throughout the world without direct involvement of ships or personnel. With their slow glide speeds, they are deployed longer and for greater distances than standard powered autonomous underwater vehicles (AUVs). Consequently, gliders have become extremely valuable for long-term, large area, and deep-depth oceanographic sensing missions of the ocean.

Protecting the ocean is essential to future generations. Acquiring data directly at depth with high temporal and spatial resolution is necessary in order to continuously monitor and analyze ocean trends; learn about ocean processes; predict climate change; and acquire physical, biological, and oceanographic data (Davis et al., 2003). Currently, oceanographic data are gathered via different forms of remote sensing, deploying oceanographic instruments from ships and through the use of AUVs. Since remote sensing is limited to the ocean surface and deploying instruments aboard ships is very costly and time consuming, AUVs are widely used for data collection.

The more information scientists are able to accumulate, the better they will be able to determine the health of the ocean ecosystem and document the specific ecosystem parameters. Using an AUV glider, scientists can detect and quantify in an automated way various substances or phenomena; depending on the glider, water samples can be taken and analyzed to determine water quality as well as any contaminating chemicals. Thus, dangerous substances in the sea can be detected earlier, and their harmful effects can be dealt with quicker.

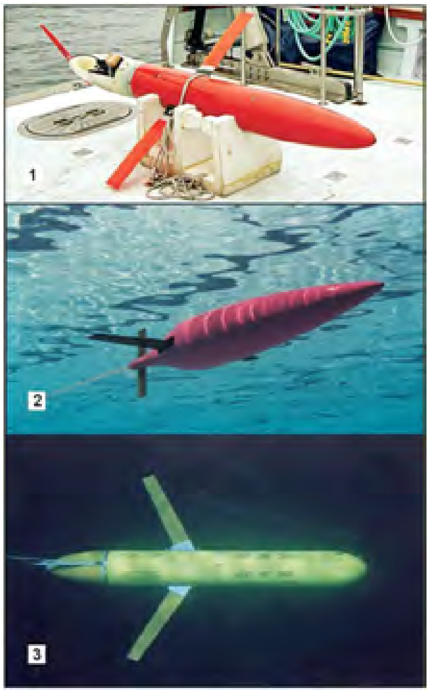
The AUV shown in Figure 1 is a propulsion-driven underwater vehicle that uses a propeller to move. Similarly, the autonomous underwater gliders in Figure 2 are low-power AUVs that use buoyancy changes for vertical movement and wings for horizontal movement to propel the glider forward. A glider is an easy and affordable way to acquire continuous data such as conductivity, temperature, depth, dissolved oxygen, and turbidity throughout the water column. Because gliders are small and low-power vehicles, they are able to log data up to months at a time and with minimal dependence on large ocean vessels.

FIGURE 1

Florida Tech's Bluefin battlespace preparation AUV.

FIGURE 2

(1) Spray, (2) Seaglider, and (3) Slocum glider.



During a mission, gliders can operate in harsh deep-ocean and coastal aquatic environments. They are able to circle an area of interest, wait at the bottom of a glide path for long periods of time, and quietly move undetected. Gliders have little impact to the environment and provide minimum threat to sea creatures because of their slender body and slow movement through the water. The characteristics and feasibility of gliders has led to a high interest in glider research at various institutions for oceanographic data collection, experience, and testing.

Gliders are primarily designed for deep water where the vehicle can traverse large areas with minimal use of energy and are specifically designed for the needs of the "Blue Water" scientist (Argo, 2013). Some of these glider AUVs have space for multiple scientific instruments and have the ability to obtain water or biological samples. Scientists who perform experiments in shallower water can also use the vehicle for short-duration gliding dives or under power if one of the hybrid gliders is used.

The general performance characteristics of standard underwater gliders are similar, but new hybrid systems and surface ocean wave-driven gliders are a new anomaly to the glider field. Gliders in general are excellent at the tasks they are designed to do (i.e., very long term, very little power, slow cruising of the ocean's water column), but they are limited as to the type of payloads they can carry, and they typically have no active propulsion for times that require more than buoyancy thrust (e.g., control of the vehicle at the surface). These autonomous underwater gliders each change their buoyancy to be able to travel horizontally in the ocean's water column using the lift on their wings, like a normal glider does to convert vertical velocity into forward motion. These vehicles are not capable of traveling in a horizontal path as would a typical propeller vehicle but follow a sawtooth path as the vehicle descends or ascends.

The original underwater gliders were designed specifically for long-term sampling and easy deployment and recovery by a minimal crew (i.e., one to three people) on any size boat or ship (vessel of opportunity). Consequently, this requires a design that has minimal space for instrumentation and is limited in its function/capabilities. These vehicles are relatively inexpensive, costing less than a week and a half of ship time for a research vessel.

As a group, most gliders can achieve four basic sampling modes: (1) vertical sampling where the forward motion of the vehicle counters any local currents to maintain position, (2) horizontal sawtooth sampling where the forward motion allows for the vehicle to obtain information both vertically and horizontally, (3) array sampling where multiple gliders form a distribution of sampling instruments covering an entire region, and (4) long life and repeated sampling over an extended duration.

History and Development of Underwater Gliders

The concept of underwater gliders was pictured first by Henry Stommel in 1989 when he envisioned a group of underwater floats called "Slocums" capable of moving vertically and horizontally in the water returning observations of the changing state of the ocean (Sherman et al., 2001). His vision led to the design of buoyancy-driven floats that turned into the development of underwater gliders.

Buoyancy-Driven Float

The Autonomous Lagrangian Circulation Explorer (ALACE) buoyancy-driven float shown in Figure 3 resulted from Stommel's idea. This float alternates between drifting and profile modes to acquire data directly at depth to gain an understanding of ocean dynamics (see Figure 4).

The ALACE float, along with the Profiling ALACE (PALACE) and Salinity Profiling ALACE (S-PALACE), is part of the Argo network, which is a global array of profiling floats that began deployments in 2000, totaling 3,633 floats as of October 1, 2013. These floats stay out for months capturing data with temperature, salinity, and current sensors and sending data back to shore through a satellite link to the Argo network (Argo, 2013).

Current glider buoyancy systems originated from a method similar to the buoyancy system on the ALACE

FIGURE 3

ALACE ocean float.

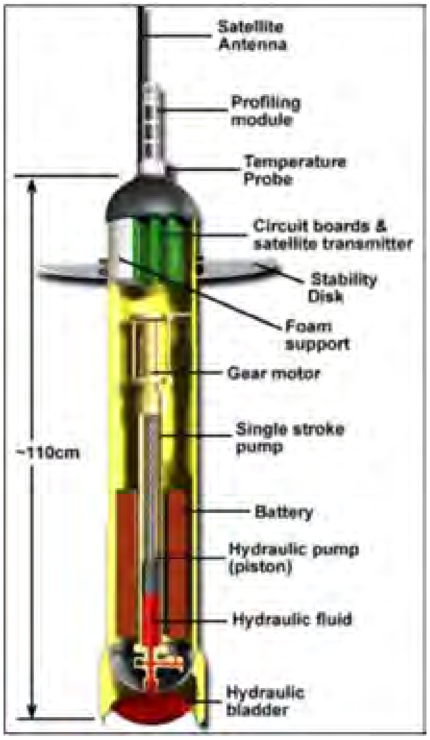
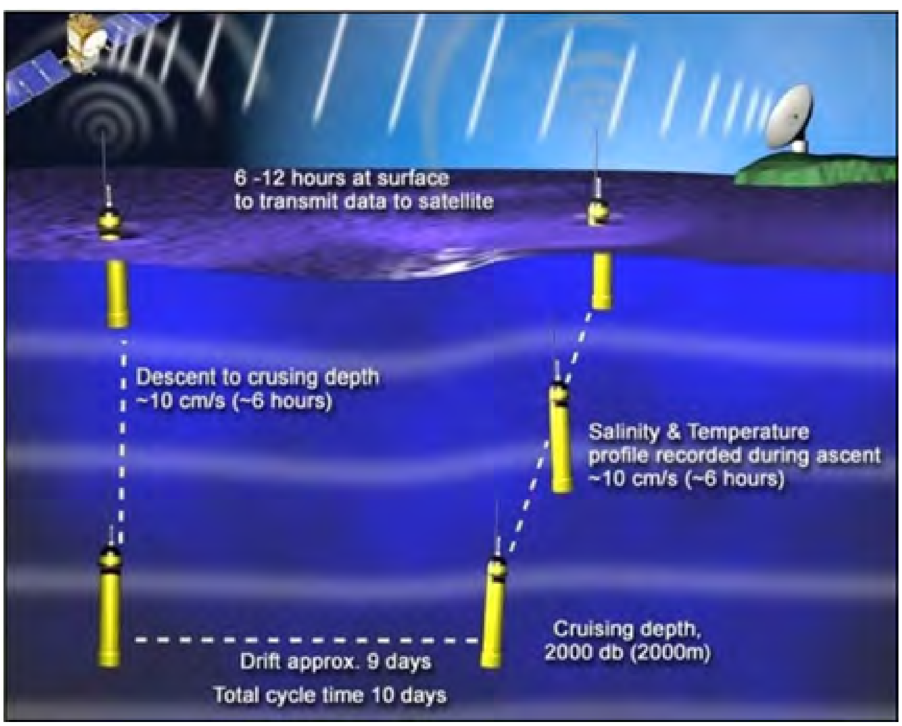


FIGURE 4

Ocean float dive path.



float known as the Leduc ballast system. This system contains an extruding piston that moves in and out of the bottom of the float by a motor-driven lead screw system. With a known volume change, the float can change from negatively to positively buoyant and move throughout the ocean. The float uses an ORBCOMM satellite uplink to transmit data, receive instructions, and allow scientists to obtain semi real-time observations to estimate the climate system and observe the physical state of the ocean (D'Asaro, 2003).

Buoyancy-driven floats have the advantage of mobility and low manufacturing costs. The disadvantage for floats is the lack of position control. Currents have a major influence on float location, and the float is unable to correct its position, speed, and direction. Due to the need for control, underwater gliders were designed to provide a control system, a navigation algorithm, and a low drag vehicle with appendages to observe all areas of the ocean (Skibski, 2011).

Current Underwater Glider Designs

There are currently four classes of underwater gliders: (1) those that use mechanical or electrical means of changing their buoyancy (i.e., drop weights or electrical power from batteries), (2) those that use the thermal gradient of the ocean to harness the energy to change the vehicle's buoyancy, (3) those that are able to use other means of power such as ocean wave energy, and (4) hybrid vehicles that use standard propulsion systems and glider systems.

The present-day commercial gliders include the University of Washington's Applied Research Laboratory and Kongsberg Maritime's Seaglider, Teledyne Webb Research's Slocum Electric and Thermal Glider, Scripps Oceanographic Institution, and Bluefin Robotics Corporation's (2013) Spray Glider. The design, development, and first sea trials of these gliders started in the early 1990s using the ALACE float technology.

- 1970: Sound fixing and ranging floats were developed to measure ocean currents (Richardson, 2006).
- 1990: Origins of the Argo network for buoyancy-driven floats began with the ALACE float (Argo, 2013).
- 1991: Spray Glider performed preliminary lake tests (Sherman et al., 2001). A prototype was designed and tested for the Slocum battery-powered glider in Wakulla Springs, FL, using an autopilot and flight recorder (Webb et al., 2001).
- 1995: Webb Research Corporation tested the hull of the Spray Glider

(Sherman et al., 2001). A vertical profiling vehicle powered by thermal propulsion was deployed in the Sargasso Sea (Webb et al., 2001).

- 1997: Design of the Spray Glider began (Sherman et al., 2001).
- 1998: A glider and thermal engine were deployed at Seneca Lake, NY, with a thermocline (Webb et al., 2001).
- 1999: First spray sea trail with the autonomous ocean sensing network experiment in the Monterey Underwater Canyon. Spray was recovered 11 days later with 182 logged temperature and conductivity profiles (Sherman et al., 2001). Seaglider Port Susan deployment to the Possession Sound with logged GPS fixes and dead reckoning displacements (Eriksen et al., 2001).
- 2004: Seaglider's launch in the North Pacific Ocean and recovery at the shore of Kauai, Hawaii (University of Washington, 2013).

Common Features of Current Designs

Features that are common to each of the three commercial underwater gliders include the following:

- Design for long-duration ocean sensing missions.
- Travel at a slow speed, which is crucial for oceanographic observations.
- Fairing shape that decreases vehicle drag, fixed wings, and a fixed tail.
- Relatively the same size, shape, and weight measuring about 2 m in length and 50 kg in weight.
- Antenna protruding from areas that does not increase vehicle drag.
- Internal mass movement to control pitch and roll.
- Ballast system that uses a hydraulic pump to move oil between the external bladder and internal reservoir similar to buoyancy-driven floats.
- Drop weight system in case of emergency.

The following discussions (Seaglider through Slocum Thermal Glider) compare the three commercial gliders in further detail.

Seaglider

The Seaglider was built, tested, and deployed by the University of Washington's Applied Physics Laboratory (Kongsberg Maritime recently obtained the rights to produce and further develop the Seaglider). The free-flooded hydrodynamic low drag fairing of the Seaglider is made out of fiberglass providing support for the wings, rudder, and the aluminum pressure housing (University of Washington, 2013). The airfoil section of the body and passive wings provide the highest overall lift-to-drag ratio for the low Reynolds number experienced with underwater gliders. The NACA 16-006 airfoil section of the wings provides laminar flow for up to 80% of the chord (Eriksen et al., 2001).

As seen in Table 1, the speed of the vehicle is greater than or equal to 0.25 m/s in order to overcome ocean currents and cover a large ocean range. The Seaglider can travel at glide slopes from 16° to 45°. Greater glide slopes result in a shorter range, and lower glide slopes result in the longer range ideal for oceanographic surveying (University of Washington, 2013).

TABLE 1

Seaglider Specifications (University of Washington, 2013).

Weight	52 kg
Hull diameter	30 cm
Vehicle length	1.8 m
Wing span	1 m
Maximum depth	1000 m
Speed	0.25 m/s
Range	4600 km
Glide angle	16°–45°

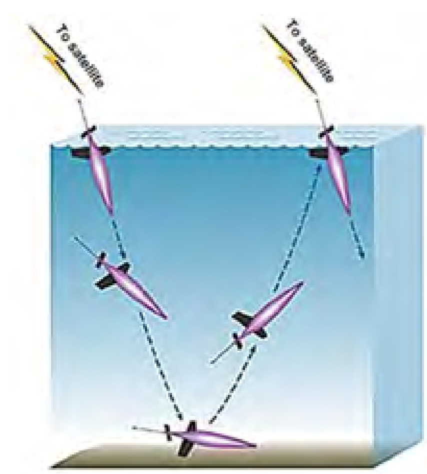
The Seaglider completes the sawtooth shown in Figure 5 where a computer decides on the bearing and glide slope to the target position. The vehicle's glide terminates at the surface with a vehicle pitch of 45° to expose the antenna located on the tail of the vehicle. The antenna contains a GPS and wireless modem to transmit and download information and new missions/directives (Eriksen et al., 2001).

The Seaglider has the ability to glide for months at a time by adjusting the volume in the buoyancy control system. Flight control is through the manipulation of the center of gravity relative to the center of buoyancy. The center of gravity and the center of buoyancy both change throughout a dive as a result of vehicle movement. The Seaglider moves the vehicle's battery pack fore and aft to provide pitch control and rolls the battery pack left and right for roll control instead of using external control surfaces (Eriksen et al., 2001).

The buoyancy system is similar to the design seen on the buoyancy-driven

FIGURE 5

Seaglider path.



ALACE floats. The buoyancy system includes a boost pump with a pump and motor manufactured by Hydro-Leduc (Eriksen et al., 2001). The internal reservoir made of a Bellowfram Diaphragm (Eriksen et al., 2001) contains a vacuum for oil to bleed from the external to internal reservoir. Moving the oil from the internal to external reservoir is done through an axial pump mechanism (Eriksen et al., 2001).

Sensors on the Seaglider include a conductivity cell, thermistor, dissolved oxygen sensor, pressure sensor, and acoustic transducer. Two battery packs of lithium thionyl chloride D-cell batteries provide high and low voltage to the vehicle. The navigation software provides a dead reckoning position during the dive cycles and corrected with actual surface positions by the use of a Kalman filter. An acoustic transducer located on the front of the vehicle is used for locating and tracking the vehicle (Eriksen et al., 2001).

Currently, the Seaglider is sold by Kongsberg Maritime and used by a number of companies and institutions to profile the ocean (e.g., one of the most famous missions was monitoring the after-effects of the Deepwater Horizon oil spill in May 2010). Seaglider milestones include the first glider to complete a mission greater than 3,800 km and the first to complete a multiglider mission. This glider completed a mission greater than 6 months in March 2005, which consisted of up to 191 days of runtime and up to 600 dives of 1,000-m depth (University of Washington, 2013). The limiting factor on duration of the Seaglider is the battery life and the longevity of the on-board components to the exposure of seawater.

Spray Glider

The Spray Glider was developed under the Office of Naval Research (ONR) with support from Scripps Institution of Oceanography and currently sold by the Bluefin Robotics Corporation. This AUV uses battery power to pump hydraulics through the buoyancy control system to change volume and power while gliding.

According to the vehicle specifications in Table 2, the Spray Glider is designed to dive up to 1,500 m at speed of up to 25 cm/s. It uses a see-saw path shown in Figure 6, controlling the dive angle during ascent and descent by moving battery packs of lithium DD-cell batteries forward and backward to change pitch and rotating battery packs to change roll. At the surface, the glider rotates 90° to utilize one of the GPS and Iridium antennas located on the wing transmit data to shore and allow operators to change the course of a mission to download new missions on the fly. The wings have a thicker airfoil shape to allow for better stiffness and protection for the enclosed antenna (Sherman et al., 2001).

Figure 7 shows the schematics aboard the Spray Glider. These include conductivity and temperature sensors located on the top of the flooded tail section, fluorometer, backscatter sensor, altimeter, and an acoustic pinger to allow for underwater tracking. The emergency system consists of a drop weight that allows the vehicle to surface in case of failure (Sherman et al., 2001).

TABLE 2

Spray Glider Specifications (Scripps Institution of Oceanography, 2013).

Weight	51.8 kg
Hull diameter	0.2 m
Vehicle length	2.0 m
Wing span	1.1 m
Maximum depth	1500 m
Speed	0.25–0.30 m/s
Range	4700–3500 km
Glide angle	19°–25°

Variables involved in the glide control algorithm include heading, roll, pitch, pressure, and altitude. Sensors measuring these variables include a compass, pressure gage, and acoustic altimeter. The control loop for pitch control is proportional with a low gain, and the heading control loop includes a proportional and integral term to account for errors. A simple navigation algorithm computes distance and heading from the GPS fix to the desired waypoint (Sherman et al., 2001).

Slocum Electric Glider

The Slocum Electric Glider was developed by Teledyne Webb Research and named after Joshua Slocum, the first person to circumnavigate the globe (Webb et al., 2001). Webb produces two types of glider, a 200 m and a 1,000 m.

The hull and fixed wings of the 1,000-m electric glider are made out of composites, whereas the 200-m hull is made out of 6061-T6 aluminum. In the 200-m version, pitch and roll are achieved by translating and rotating the main battery pack, whereas with the 1,000-m electric glider, pitch is achieved by shifting mass in/out of the nose reservoir. The battery pack is used as a vernier to trim the pitch but does not rotate to adjust the roll. The vehicle does not roll much, aside from its response to yaw adjustments. The yaw moment is achieved by using a rudder on the tail and mounting the wings aft of the center of buoyancy. The antenna is located on the tail of the vehicle for communication when surfaced (Webb et al., 2001).

FIGURE 6

Spray Glider path.

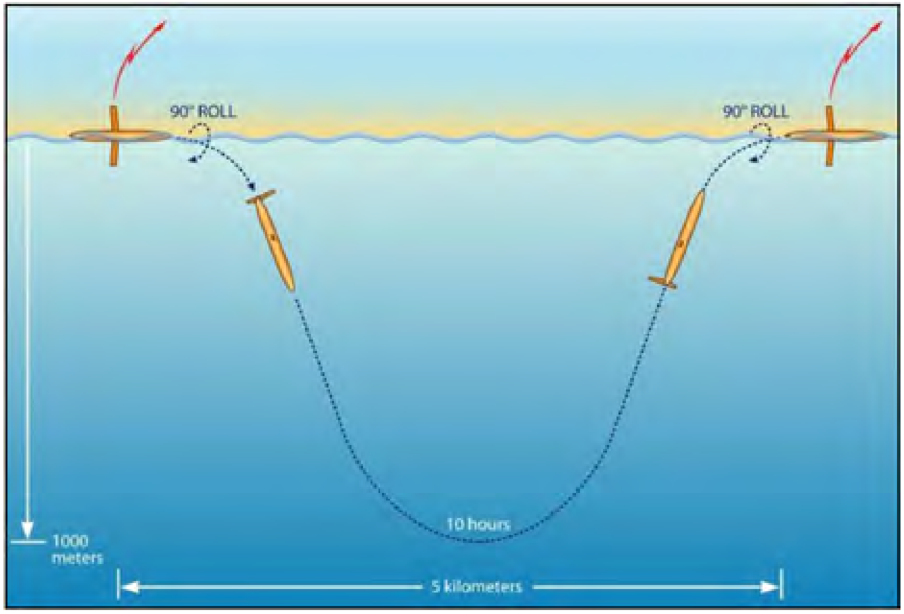
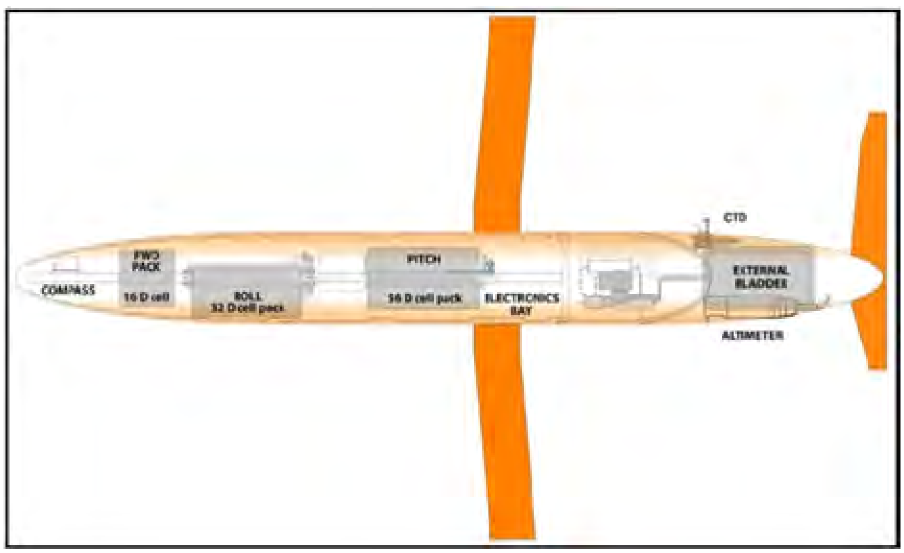


FIGURE 7

Spray Glider schematics.



The vehicle is powered by alkaline batteries, deploying from up to 30 days at a 600- to 1,500-km range as shown under the electric glider portion of Table 3. Sensors on board include GPS, compass, altimeter, RF modem, optical sensor, conductivity temperature depth (CTD) sensor, and an oxygen sensor (Webb Research Corporation, 2010). The Slocum electric glider has a buoyancy engine consisting of a single stroke pump that pushes water in and out of the nose of the vehicle. An air pump is used to inflate the air

TABLE 3

Slocum Glider Specifications (Webb Research Corporation, 2010).

Weight	51.8 kg
Hull diameter	0.2 m
Vehicle length	2.0 m
Wing span	1.1 m
Maximum depth	1500 m
Speed	0.25–0.30 m/s
Range	4700–3500 km
Glide angle	19°–25°

bladder using air that is in the interior of the hull. This provides additional needed buoyancy when the vehicle is on the surface of the water (Webb Research Corporation, 2010).

Slocum Thermal Glider

The Slocum thermal glider, similar to the electric glider as shown in Table 3, uses the environmental thermal energy to propel the vehicle vertically in the water. Also developed by Teledyne Webb Research, this glider's engine uses the melting and freezing of wax to harvest energy from the ocean and drive the buoyancy system. The thermal glider moves oil into a flexible bladder in the nose cone for pitch control. Figure 8 displays an image of the

FIGURE 8

Slocum thermal glider.

Slocum thermal glider that reveals features common to both electric and thermal gliders. The main difference is the thermal engine tubes located underneath the vehicle protruding past the antenna fin.

The feasibility of the thermal glider includes a long projected endurance of up to 5 years and the ability to operate in 65% of the world's oceans and dives down to a maximum depth of 1,200 m. The disadvantage of this thermal engine is that it can only be used when a thermal gradient is available (Webb et al., 2001).

ACSA SeaExplorer

The SeaExplorer is similar to the other electric gliders except that it does not have wings or external moving parts aiding launch and recovery operations while reducing the risk of entanglement. Its modular design includes an independent payload section located at the front of the vehicle that can be changed rapidly between missions. Sensors include a pumped CTD, oxygen optode, turbidity, chlorophyll, backscatter CDOM, hydrocarbon fluorescence, and an acoustic detector and recorder. (ACSA SeaExplorer, 2013).

Military Gliders

The military has also developed an advanced underwater winged glider based on the air force's Flying Wing design, the Liberdade XRay (Figure 9). This vehicle is "being developed as a part of the Navy's Persistent Littoral Undersea Surveillance Network system of semiautonomous controlled mobile assets. Persistent littoral undersea surveillance network uses unmanned underwater vehicles and AUVs to monitor shallow-water environments from fixed positions on the ocean floor or by moving through the water

FIGURE 9

XRay glider.

to scan large areas for extended periods of time (D'Spain et al., 2007).

The XRay was developed primarily with the aid of the Marine Physical Laboratory at Scripps Institution of Oceanography and the University of Washington's Applied Physics Laboratory, and also with the following institutes, universities, and corporations: University of Texas at Austin's Applied Research Laboratory; applied research laboratory at Penn State University; Massachusetts Institute of Technology; Woods Hole Oceanographic Institute; Harvard University; Scientific Applications International Corporation; Bluefin Robotics; Metron; Heat, Light, and Sound Research; and the Space and Naval Warfare Systems Center in San Diego.

The vehicle is the largest of all underwater gliders having a 6.1-m wing span, which is an advantage in terms of hydrodynamic efficiency and space for energy storage and payload. The glider's primary function is to track quiet diesel-electric and fuel cell submarines operating in shallow water. According to military doctrine, it can "be deployed quickly and covertly, and then stay in operation for a matter of months. It can be programmed to monitor large areas of the ocean (maximum ranges exceeding 1000 km with on-board energy supplies). The glider is very quiet, making it hard to detect using passive acoustic sensing" (D'Spain et al., 2007).

The vehicle was designed for easy and rapid deployment and retrieval as well as payload carrying capability, cross-country speed, and horizontal point-to-point transport efficiency. Liberdade XRay's first major ocean test was performed in August 2006 in Monterey Bay, California, where it reported real time via a 3.0- to 8.5-kHz underwater acoustic modem as well as with an Iridium satellite system while on the surface. The vehicle had an array of 10-kHz bandwidth hydrophones located in the SONAR dome and across the leading edge of the wing. The XRay exceeded a 10:1 glide slope ratio (ONR, 2008). Later deployments were in the Philippine Sea, near Hawaii, and in Monterey Bay using the hydrophone array "to detect low frequency source signals, marine mammals (blue and humpback whales), and ambient ocean noise" (Autonomous Undersea Vehicle Applications Center, 2013). The XRay glider is hoped to achieve 1- to 3-knot cruise speeds, have a 1,200- to 1,500-km range, and be able to remain on-station up to 6 months in partial buoyant glides.

Another glider developed for ONR is the Exocetus [x-o-seat-us] Coastal Glider. Eighteen gliders that were delivered to the U.S. Navy have a combined operating time of 4,500 h. These gliders were designed to operate in coastal waters where high currents and densities changes occur from fresh water entering coastal waters. The Slocum, Seaglider, and Spray Gliders are designed for open-ocean operations and do not have the capability of operating in coastal waters. The Exocetus Coastal Glider is designed to easily add more sensors without any or minimal changes to the glider housing (Exocetus, 2013).

Research Gliders

One of the first gliders is the ALBAC, which conducted sea trials at the Suruga Bay of Japan in 1992. The vehicle (Figures 10 and 11), developed at the University of Tokyo in the laboratory of Tamaki Ura, does not have an active buoyancy control system but has a simple drop weight system with only one glide cycle.

The ALBAC has fixed wings and a vertical and horizontal tail. It is 1.4-m long and 120-cm wide, weighs 45 kg, and can dive to depths of 300 m at speeds of 1–2 knots (0.5–1.0 m/s). It has horizontal tail fins that change angle at inflection from downwards to upwards gliding, a feature not present in other gliders. The wings and tail are larger in comparison to the body than on the Slocum, Spray, or Seaglider. ALBAC moves a battery pack internally to control pitch and yaw in the same manner as Seaglider. Because it has no ballast pump, ALBAC carries batteries to power only its instruments and actuators.

FIGURE 10

ALBAC glider schematics.

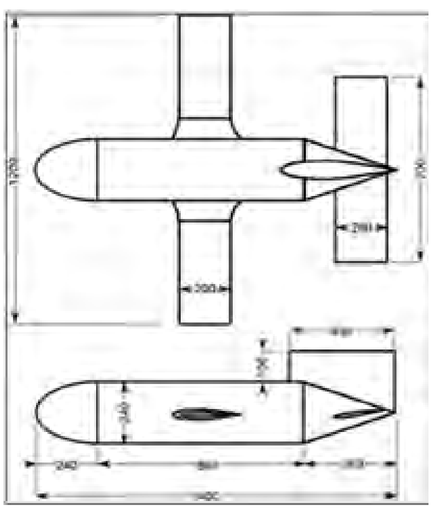


FIGURE 11

ALBAC glider.

ALBAC carries flight sensors including compass, depth, pitch, roll, and a propeller-type velocity meter. Note that Slocum, Spray, and Seaglider do not carry velocity meters in order to conserve power and because of the difficulty of accurately sensing velocity at glider operating speeds (Kawaguchi et al., 1993).

The ALBAC vehicle glides horizontally by up to 20° down from the horizontal plane and controls its trajectory by changing pitch angle and roll angle by displacing the center of gravity. To accomplish this, an internal actuator system changes the location of the center of gravity longitudinally and laterally by moving a weight. The vehicle has no external communication ability. It has a 3-L dry payload space for scientific measurement devices, which consists of a 0.5 ellipse-shaped front cap; a cylindrical pressure hull; a corn-shaped tail cap with a vertical stabilizing fin; a pair of wings; tail wings; and various electronic devices, that is, a depth sensor, a gravity sensor, a magnetic sensor, two CPUs, interface boards, and two actuators to trim and roll. A ranging sensor, a velocity sensor, a drop ballast system, a tail angle trigger, and a transponder are fitted in the front and tail caps (Alvarez et al., 2009).

A few research institutes have been experimenting with glider design. Florida Institute of Technology (Florida Tech) has been developing a research glider (Figure 12) that introduces a set of external control surfaces on the wings, also known as flaps. These external surfaces move up and down to aid in the pitch, roll, and horizontal movement control of the glider. The bendable live hinge on this glider is made out of a thin, flexible, low-modulus fiberglass. The glider has a system of external wing control surfaces for steering and a mechanical buoyancy engine. The vehicle is a fully functional underwater glider with a unique open interface buoyancy engine with the Raspberry Pi (http://www.raspberrypi.org/) as the controlling computer. The glider is designed for oceanographic education in shallow water and is a platform for artificial intelligence and navigation algorithm research. The vehicle is in very low cost (under $5,000) and small in size (i.e., deployable from a small boat). The current commercial gliders have an estimated construction cost ranging from $25,000 to $60,000 without instrumentation and a refueling cost ranging from $800 to over $10,000 depending on the battery type (Davis et al., 2003).

FIGURE 12

Florida Tech's glider.

Hybrid Vehicles

Hybrid designs are being developed by a couple of research institutions. For example, at the University of Pisa, Italy, the ISME laboratory has been involved in the development of the "Folaga" hybrid vehicle (Caffaz et al., 2010) (Figure 13). The Folaga buoyancy and pitch control is similar to that of the three commercial gliders but uses jet pumps and screw propellers for yaw and surge motion. The vehicle is targeted for shallow/coastal water applications and is very maneuverable. The vehicle can remain stationary in either a hover position, lie on the ocean floor, or dive vertically along the depth axis.

Another hybrid under development at Florida Tech will travel under power or in glide mode (Figure 14). This vehicle is being designed to obtain water samples, make photographic/video images of specimens in the water column, and specify the environmental characteristics of the data field. Furthermore, it is expected to possess a wide array of traditional oceanographic instruments that can be used by the vehicle's control system to make mission/navigational changes. The vehicle's ability to obtain specimen/water samples and photographs directly affects the design of the vehicle more than the addition of oceanographic instruments. Water samples are to be collected using a series of small automatically closing specimen bottles, and two digital cameras are used to document what is floating through the water column.

Florida Tech's powered glider design characteristics are mission applications to 6,000-m ocean depths, modular design with interchangeable scientific modules, quick assembly and disassembly of components, easy battery access for replacement and recharging during missions, greater scientific and instrument payload space, and ability to land. Unlike torpedo-shaped gliders, the structure of the Florida Tech's powered glider has a rectangular frame that is approximately 1.5×2 m^2. The vehicle is designed for easy assembly and disassembly with easy access to the two 17 inches in diameter and 3/8-inch-thick vehicle control system and scientific pressure housings.

A third hybrid glider is the Sterne Glider being developed at Ecole Nationale Superieure D'Ingenieurs in Brest, France. This hybrid glider has both a glide (buoyancy) and a thruster mode. The 4.5-m-long, 0.6 m in diameter, and 900 kg in mass vehicle has buoyancy control and a thruster for forward propulsion and is capable of gliding at 1.3 m/s.

The Sterne is designed to conduct surveys by gliding or by flying level using its thruster, which, when powered, has the range of an estimated 200 km with an estimated speed of 3.5 knots (1.8 m/s). The vehicle can go 2.5 knots (1.3 m/s) when gliding. It has two fixed wings, two actuated horizontal tail fins, and a vertical tail with rudder and moves a battery pack to control pitch (Graver, 2005).

The Wave Glider® (Figures 15 and 16) by Liquid Robotics is a surface vehicle that has a component that resides underwater; thus, it is included in this article for completeness. The concept uses ocean waves as its primary energy source for propulsion. During the spring and summer of 2008, the Wave Glider underwent extensive field testing in the Pacific Ocean and, since then, has performed superbly in numerous ocean surface studies throughout the world.

The vehicle consists of a surface float (similar to a surfboard) that is tethered to a subsurface glider about 6 m below the surface. This subsurface glider has six sets of wings (Figure 17) with a mechanism that "ratchets" in such a way that, when a wave at the surface lifts the float, the entire system (float and glider) rises and the wings propel the vehicle forward. As the wave passes by, the glider sinks and the wings pivot to create a downward pitch causing the glider to fly forward and slide downward at an angle. Because the float and glider are tethered together, the glider will stop at the end of the line's reach causing the surface float to move forward. Consequently, the whole subsurface system moves forward in a "sawtooth" pattern

FIGURE 13

Folaga hybrid vehicle.

FIGURE 14

Florida Tech's powered glider.

FIGURE 15

Liquid Robotics wave glider.

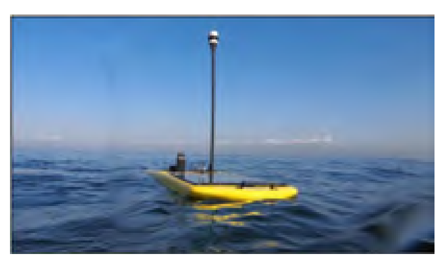


FIGURE 16

Liquid Robotics wave glider schematic.

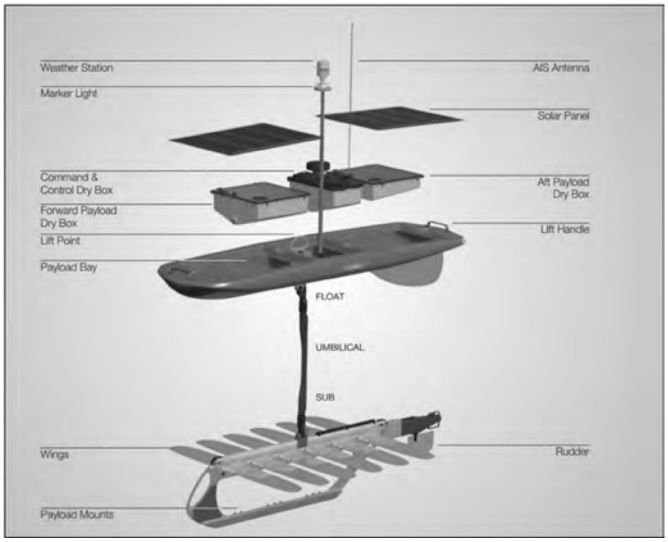
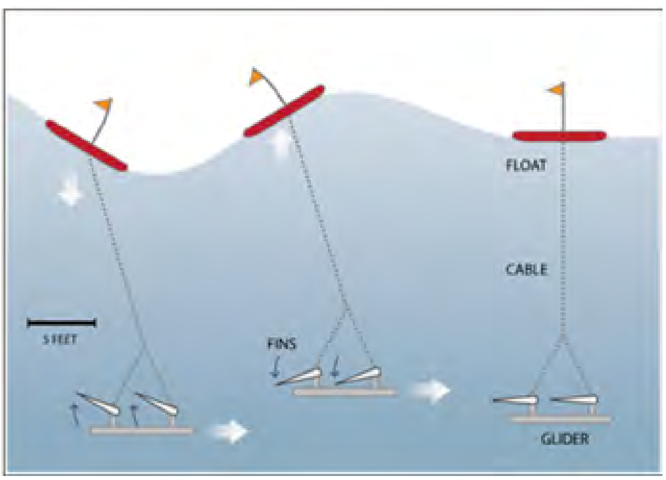


FIGURE 17

WaveRider wing action.



corresponding to the waves. The surface float shoots forward in small bursts across the water controlled by a rudder. The vehicle requires at least 7 m of water and a minimum wave height to operate. It has high endurance and is able to station-keep, and the method of movement allows it to move in any direction regardless of wave direction. The vehicle does not "surf" the wave but, rather, traverses up a wave. All it needs is the up-and-down motion that translates into forward motion of the vehicle. The vehicle moves quite slowly, and high currents are a problem.

The Wave Glider has a total mass of 90 kg. The underwater sub (40 × 191 cm) is attached to the surface float (208 × 60 cm) via a 6-m tether. Wave Gliders have survived hurricanes and extended periods at sea with waves over 6-m high and winds over 26 m/s. The vehicle can carry an array of sensors and on-board data collection tools, satellite telemetry, optical water quality sensors (e.g., to detect oil, chlorophyll, or CDOM), on-board weather station, solar charging panels with a 665 Wh rechargeable lithium-ion batteries. The data are streamed via the Iridium satellite network. The Wave Gliders can be programmed for autonomous operation or directly controlled by a remote pilot over the Internet. Continuous, nearly real-time (every 2 min) communication is provided either by the Iridium satellite network or by cellular phone or radio links, which can be used for piloting or data transmission (Coxworth, 2011).

The Wave Glider's surface float houses the electronics along with solar cells to recharge the electronic battery packs. The most significant problem with the vehicle is its recovery. To date, the designers have failed to implement a retractable system for the subsurface wings, making it difficult to retrieve. In 2012, Florida Tech students showed that a retractable system for the wings is feasible (Figure 18).

Sensors

Gliders are currently using a wide range of scientific instrumentation,

FIGURE 18

Florida Tech's retractable system.

but this instrumentation is limited due to vehicle size. As glider types increase in variation, size, and complexity, accommodations for collecting specimens and integration of large sensor packages will occur. The Slocum, Spray, and Seaglider are too small for specimen collecting or other larger instruments. Additionally, the sawtooth glide pattern is not optimal for certain types of data collection such as side-scan sonar. Only larger hybrid vehicles can make full use of all instrument types. Unfortunately, this forces the need of larger vessels and more manpower to deploy and recover these vehicles.

Some of the instruments used on AUVs that can/could be used on autonomous underwater gliders that are rated down to 6,000 m are Sidescan sonar, Falmouth Scientific NXIC CTD (a fully integrated instrument platform that is compact, robust, and equipped with fully integrated conductivity, temperature, and depth sensors) (http://www.falmouth.com/), Chelsea AQUAtracka III (a compact, lightweight, submersible fluorimeter for the detection of chlorophyll-a, dye tracing, or turbidity that, when connected to the CTD Sensor, provides measured values of chlorophyll, rhodamine, amido rhodamine, and fluorescein), UV-VIS Spectrometer, video cameras (provide high-resolution video or photo data that can be stored via a frame grabber to the integrated hard disk), and acoustic hydrophones.

Future

As autonomous vehicles are developed to take on more responsibilities, program algorithms will be developed to accommodate these tasks. Currently, new distributed on-board collaborative autonomous vehicle control programs are being developed that will enable an individual vehicle to coordinate and control multiple vehicles. This technique enables "collaborative" capabilities among multiple vehicles. With on-board collaborative control, the vehicles operate as a group, functioning together. The vehicles process and communicate relevant information allowing individual vehicles and the entire school of vehicles to change their mission, autonomously, in response to sensor inputs. The concept of working and acting collaboratively is very useful for science in sampling entire regions for a specific organism, substance, or phenomenon. The control of an AUV, whether powered or a glider, will also utilize some combination of traditional, artificial intelligence and neural network navigation that uses Kalman filters.

One of the requirements for a long-duration AUV, whether powered or a glider, is the need for a robust, fault tolerant navigation system. In addition to the robustness issue, there are core issues of nonlinear control as they pertain to maneuverability and sea keeping. In both issues, neural networks offer very promising solutions. For example, the calculation of the distances and the relative velocities will use positioning data as well as measuring inertial sensor data. In order to increase the reliability of the data, a reconciliation of both processes must be accomplished accurately and efficiently. The coordination of the target trajectories of AUVs can yield vital information for positioning prognosis.

Commercial powered AUV systems use a combination of internal inertial, compass, and accelerometer sensors, in conjunction with external active acoustic triangulation methods (long baseline, short baseline, ultra-short baseline). These have met with some success for applications of cable following, standard grid surveying, search and rescue, and signal following. But in each of these cases, the system is unable to respond to (a) abrupt changes in external environment, (b) system damage, and (c) uncertain or indeterminate data input. In these areas, some scattered research on the use of neural networks has been performed with success, addressing specifically the fault tolerance, docking, and ranging issues. For example, Wilson (Douglas, 2008) successfully evaluated the use of a neural network for a spaceship application providing robust navigation despite thruster failure. Most of the work in this area has been in spacecraft, but the work is directly applicable to underwater and surface vehicles. In most of the cases, a back-propagating network is applied using position, rotation, or acceleration error as the training tool. In each case, changes to the vessel control system itself or in the external environment (displacement forces) cause the system to update its training, which in turn prompts it to compensate for the change in forces. Ship navigation has been evaluated using neural network-based adaptive critic designs. For AUV control, a neural network has been modeled at the University of Hawaii for the problem of depth gradient descent only. In each case, the results were very positive, indicating that, if generalized, a full neural network system could provide robust navigation for an AUV.

In addition to the constituent issues above, powered and glider AUVs are beginning to address the search for environmental pollutants; identify and analyze biological systems; locate and identify artificial acoustic sources; scan long term for physical, biological, or chemical phenomena of interest; and further develop noninertial navigation.

These vehicles will also soon process multisensory data from the pattern recognition and data classification modules to provide control inputs for the navigation system. Thus, the system will be able to track and monitor multiple targets and integrate sensor inputs from a variety of sources into multisensory patterns, that is, acoustic with salinity, temperature and pressure, spectrographic with temperature, and so forth. Instead of traditional analytical methods where the individual data sets are correlated one by one, the system will be able to search for patterns in all sets together.

Conclusion

AUVs are robust commercial vehicles being used by industry, governments, military organizations, and communities throughout the world. The glider is the latest of these vehicles, which is becoming widespread for oceanographers and other personnel needing oceanographic data for their work. As stated by David Smeed of the National Oceanography Centre, Southampton, England, "gliders are one of the technological developments that are changing the way we observe the ocean, and it is very exciting for us to be at the forefront of their application in ocean and climate science" (Liquid Robotics, 2013).

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PAPER

Global Review of Recent Ocean Energy Activities

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ABSTRACT

Ocean energy is regarded as an important future source of energy generation in many countries for transition to a low-carbon future. While commercial interest in ocean energy is growing significantly at a global level, there are considerable investment costs and bottlenecks that will need to be overcome. Research and funds are spread over many different wave and marine current energy concepts under development, and there is still no technology convergence, in contrast to what happened in wind energy. Although an important marine energy resource, discussion of offshore wind energy is not included in this manuscript. This article focuses on the latest developments in ocean energy—in particular, open-sea testing facilities set up by several countries as a measure to encourage deployment and streamlining procedures—and gives an overview of projects going into the water this past year. In addition, the article highlights the importance of collaborative research and development on ocean energy projects and the unique role of the Ocean Energy Systems Implementing Agreement as an intergovernmental organization promoting the use of ocean energy (wave, marine currents, tidal, ocean thermal gradients and salinity gradients) for energy extraction.

Keywords: ocean energy, marine energy, Ocean Energy Systems, open-sea testing

Introduction

According to the Ocean Energy Systems (OES) Implementing Agreement, there is the potential worldwide to develop 337 GW of wave and tidal energy by 2050 and possibly as much again from Ocean Thermal Energy Conversion (OTEC) (Huckerby et al., 2012). As described in the OES "International Vision," deployment of ocean energy can provide significant benefits in terms of jobs and investments (nearly 1.2 million direct jobs by 2050). In a recent public consultation in Europe on ocean energy, there was a consensus that new technologies will require new skills and new specialized qualification programs, and therefore, ocean energy can contribute to the revitalization and diversification of marine economies (European Commission, 2012).

Marine energy technologies are in an early demonstration phase of single units; some of the deployments are short-duration testing programs, and a few prototypes are initiating the first steps towards the commercialization phase. Only tidal barrage systems are at a commercial scale and provide the principal contribution to the global ocean energy installed power. In Korea, the construction of the 254-MW Shiwa tidal barrage, inaugurated in July 2011, raised the worldwide ocean energy installed power to about 519 MW (France, Canada, Russia, China and Korea).

For wave and marine current technologies, the next key milestone for the industry will be to move from single prototypes to multiple machines deployed in arrays. This process will be the essential step to moving forward with economic and reliable solutions.

Open-Sea Testing Facilities Encouraging Ocean Energy Development

Some countries have in place policy measures to encourage research, development, and demonstration of marine energy technologies. In addition to direct support funding schemes, such as feed-in tariffs, the development of open-sea testing facilities is seen as a valuable policy measure. Providing such infrastructures encourages ocean energy development by enabling practical experience of installation, operation, maintenance, and decommissioning activities for full-scale prototypes and farms, as well as for developing services and streamlining procedures.

The United Kingdom was the first country to set up an open-sea testing facility, the European Marine Energy Centre (EMEC), for both wave and tidal prototypes. Located in the Orkney Islands (Scotland), this research grid-connected test center has, since 2004, seen a number of technologies deployed at its sites. Wave Hub, a grid-connected offshore facility, in South West England, was created in 2010, as the first infrastructure to be announced for precommercial array deployment (Figure 1). In 2012, Falmouth Bay Test site (FaBTest), a nursery facility, was created to enable wave energy device developers to test components, concepts, or full-scale devices in a moderate wave climate nearby a port infrastructure.

Other countries have now established recognized pilot plant test sites of different scales and services. Ireland has a 1/4 scale test wave energy site in Galway Bay and is developing the Atlantic Marine Energy Test Site, located offshore Belmullet, for full-scale, open-ocean testing. In Denmark, two full-scale testing facilities became operational in 2010, the Danish test site for Wave Energy Conversion (DanWEC) in Hanstholm and the Lindo Offshore Renewables Center, while the 1/4 scale Nissum Bredning wave energy test site

FIGURE 1

Wave Hub installation in South West England.

continues to be active. The Portuguese Pilot Zone (Oceanplug) formalized by the Government in 2008 is now closer to realization after the creation of the concession holder ENONDAS in October 2010. In Spain, the Biscay Marine Energy Platform (BIMEP), located on the Basque coast and promoted by Ente Vasco de la Energia (EVE) for full-scale prototype testing, is initiating the first works for the installation of the submarine power cables, after the administrative authorization in November 2012. Furthermore, the Spanish Government and the Regional Government of the Canary Islands are supporting an initiative called the Oceanic Platform of the Canary Islands (PLOCAN), which will, among other activities, build an offshore floating multiuse infrastructure for prototype testing. In the scope of the new institute, France Energies Marines, five test sites are being set up including a wave energy test site in Le Croisic (SEMREV), a tidal energy test site in Paimpol-Bréhat, an estuarine tidal test site in Bordeaux (SEENEOH), and two floating offshore wind test sites. Other research facilities for wave energy prototype testing have been created in the Scandinavian countries: the Islandsberg test site on the west coast of Sweden and the Runde Environmental Centre (REC) on the Norwegian west coast.

Outside Europe, a new in-stream tidal energy testing has been set-up in Canada, the Fundy Ocean Research Centre for Energy (FORCE), located in the Bay of Fundy, Nova Scotia. In the United States, the Northwest National Marine Renewable Energy Center (NNMREC) for wave and tidal energy has been developed through a partnership between Oregon State University and University of Washington. NNMREC is setting up the Pacific Marine Energy Center, a full-scale, grid-connected ocean energy test facility for commercial projects. Hawaii's National Marine Renewable Energy Center, established in 2008 to accommodate wave and OTEC testing, is collaborating with the U.S. Navy to expand existing facilities. Furthermore, the Southeast National Marine Renewable Energy Center (SNMREC) was established in 2010 at Florida Atlantic University as a testing platform for ocean current and marine renewable energy projects. SNMREC is a member of the Florida Energy Systems Consortium and works closely at the national level with the National Renewable Energy Laboratory and both NNMREC and HINMREC. In addition, the University of Massachusetts MREC has set up a tidal test site in Massachusetts waters and a wave test site in New Hampshire waters. These sites are being used in partnership with device developers and local towns with some funding provided by the Massachusetts Clean Energy Center. In China, plans have been initiated for creation of an open-sea testing facility for wave and tidal pilot projects.

Each of these test sites has a real advantage in that permits, licenses, and consents have been obtained, which eliminates one of the most demanding non-technical barriers for ocean energy technology developers, namely the administrative and regulatory requirements. Furthermore, they can make an important contribution towards the understanding of the interaction of the ocean energy technologies with marine life. Although the requirements for regulatory approval and environmental monitoring are different from country to country, early-stage collaboration between countries and stakeholders may significantly improve the understanding of the topic which, in turn, can be a cornerstone for accelerated future developments. In the related field of offshore wind energy, it is nowadays recognized that the comprehensive environmental monitoring initiative of the Horns Rev and Nysted wind offshore farms in Denmark contributed notably to the positive acceptance of offshore wind.

An international and concerted approach is the most efficient and credible way to tackle this issue. At the European level, the SOWFIA project is an example of such an initiative. It aims to facilitate the streamlining of licensing procedures for wave energy devices, focusing on the available information from test sites. This project, funded by the European Commission and led by Plymouth University in the United Kingdom, was running for 3 years until August 2013. Another relevant research initiative in this field is the Environmental Impacts Knowledge Management System (KMS) (dubbed "Tethys"), which was launched by the OES and led by U.S. Department of Energy (DOE). KMS is responding to the need for sharing the lessons on wave and marine current environmental research worldwide and was assisted by a consortium formed by the WavEC in Portugal and the Marine Institute of the University of Plymouth in United Kingdom. The main outcome of this research program is to gather, organize, and make available information on potential environmental effects of marine energy projects. Another project ("The Exchange and Assessment of Ocean Energy Device Project Information and Experience") running under the OES, also led by the DOE, was initiated in the second half of 2012 and aims to foster a better understanding and to accelerate the development of ocean energy technologies by sharing information about existing and planned tests sites.

Projects Going to the Water

In the last couple of years, several demonstration projects have been deployed worldwide with a focus in European countries, but with increasing activities in other countries such China, Korea, United States, Canada, and Australia.

As reported by the Crown Estate, as of January 2013, there are 41 wave and tidal projects under development or operation in U.K. waters, with a total potential installed capacity of over 2.0 GW (Callaghan, 2012). At EMEC several projects have been tested: two projects of 750 kW, utilizing the Pelamis device, commissioned by Eon and by Scottish Power Renewables, Oyster by Aquamarine Power (800 kW) and WelloOy Penguin (500 kW). Marine current prototypes, such as Atlantis Resources Corporation (1 MW), Open Hydro (250 kW), Tidal Generation Ltd. (500 kW), Scotrenewables (SR250 floating), and Andritz Hammerfest (1 MW), were also deployed at the tidal test site of EMEC. Further deployments occurred at other locations: Atlantis Resources Corporation (1 MW) at NaREC, the Fred Olsen Lifesaver deployed at FabTest since spring 2012, Neptune Porteus (500 kW) in the Humber Estuary since 2011, Siemens Marine Current Turbine's Seagen machine (1.2 MW) in Strangford Lough, Northern Ireland since 2008, and Pulse Tidal (100 kW) in the mouth of the River Humber in 2009 (Figures 2 and 3). Another 15 wave and tidal projects are in the pipeline for installation in U.K. waters during the next few years, and several other are awaiting consent decisions.

In Ireland, the 5 MW West Wave project led by ESB International in conjunction with a number of wave energy technology partners aims to develop the first operational wave energy project in Ireland by 2015 with support from the Sustainable Authority of Ireland.

In 2012, Tidal Ventures Limited (100 MW), a joint venture between Open Hydro Group and BordGáis Energy, awarded rights to develop the tidal renewable energy resource in Northern Ireland, as well as the consortium formed by Irish DP Marine Energy Limited with the Belgian

FIGURE 2

Fred Olsen Lifesaver deployed at Fab Test since spring 2012.

FIGURE 3

Seagen 1.2-MW device in Northern Ireland.

marine engineering company DEME Blue Energy (100 MW).

In summer 2012, WaveRoller installed a 300-kW prototype in Portugal, while the Pico Plant in the Azores has been operating intermittently for the last decade, connected to the grid (Figures 4 and 5).

In Spain, the Mutriku OWC breakwater promoted by EVE (the Basque Energy Agency) using Voith Hydro technology was commissioned in late 2011 (Figure 6).

Two prototypes are expected to be grid-connected by the end of 2013 using the Canarias PLOCAN infrastructure: INNPACTO Wave Energy and UNDIGEN. The Norwegian company Langlee has also established an office in Gran Canaria with a view to developing projects in the islands. Galicia Mar Renovables started the consenting process to install two wave energy farms in Ferrol and Gijón in Spain following testing in 2011.Ocean Power Technologies continues the development of a project on the Spanish coast under the WavePort European-funded project. OCEANTEC, a joint venture between TECNALIA and IBERDROLA, plans to test a prototype of a floating OWC device in bimep in 2014.

A group of Danish wave energy developers has been active in Denmark: Wavestar is installed at DanWEC, and Floating Power Plant is testing their combined wave and wind prototype at a benign site at the Vinde by wind park. Other planned tests in Denmark include Leancon Wave Energy, Resen Energy, Wave Dragon, Weptos, Wave Energy Fyn, and Wave Piston.

In Norway, the company Fred Olsen has continued to test their wave energy device "BOLT" in Norwegian waters and deployed last year a full-scale device "Lifesaver" (240 kW) at the FABTest test site in South West England. Andritz Hydro Hammerfest is moving into the commercial delivery of its marine current turbine (Figure 7). A few other Norwegian technology developers are active in Norway (STRAUM, Havkraft, Langlee Wave Power, Intentium, Flumill, Deep River, and Tidal Sails). Following the establishment of the world's first osmotic power plant in 2009 by Statkraft, an investment decision is to be taken by the company whether to build a 2-MW pilot plant.

In Sweden, the Sotenäs wave power demonstration project is being developed by the Swedish company Seabased in connection with Uppsala University where the research of the concept was initiated. The Sotenäs Project was initiated at the end of 2011, with 1 MW total installed power at a first stage aiming to expand to 10 MW.

A combined offshore wind (450 MW) and wave energy (20 MW) project is underway in Belgium led by the Mermaid partnership [OTARY RS and Electrabel (GDF SUEZ)].

In the Netherlands, Tocardo has been operating a 80-kW tidal stream turbine since 2008 and deployed in

FIGURE 4

Wave Roller during installation in Peniche, Portugal.

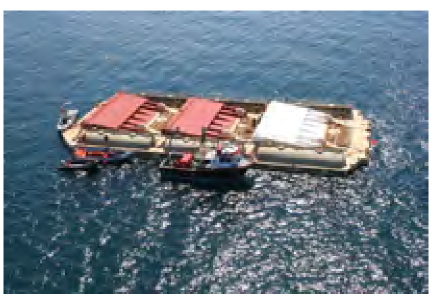

FIGURE 5

Pico Plant in the Azores in Portugal.

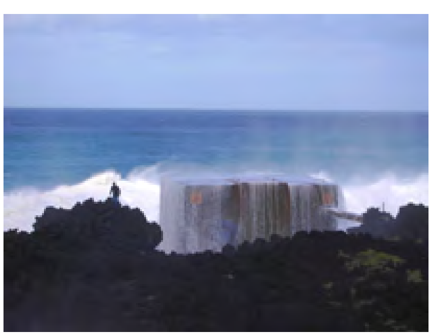

FIGURE 6

Mutriku OWC breakwater in the Basque Country in Spain and interior room with air turbines.

FIGURE 7

ANDRITZ HYDRO Hammerfest 300-kW prototype, the processor of the HS1000 tested at EMEC.

May 2013 its full-scale tidal turbine in the Dutch Wadden Sea (Figure 8).

In Germany a very strong marine energy supply chain is being developed with more than 20 component and system manufacturers and suppliers delivering components and parts for a number of ocean energy devices. Certification companies and consultants are contributing to technology and project development in the sector. Furthermore, major German utilities such as EON and RWE are active in the ocean energy sector with test installations and prototypes around Europe. Voith Hydro Ocean Current Technologies, a joint venture by Voith Hydro and Innogy Renewables Technology, deployed recently in EMEC the 1-MW horizontal axis turbine HyTide.

In FORCE, Canada's leading center for in-stream tidal technology research and development, several projects are being developed including Nova Scotia Power (with Open Hydro), ALSTOM (with Clean Current), and Minas Basin Pulp and Power (with Marine Current Turbines). Renewable Energy Research (RER) has been in operation with their 250-kW TREK turbine since 2010 in the Saint Lawrence River near Montreal, Quebec, and has plans to expand the project. Other technology players developing tidal current projects or seeking approval include New Energy EnCurrent, Fundy Tidal Inc., Clean Current, Idénergie, and Verdant Power (Figure 9).

Several projects were deployed and tested during 2012 in the United States with grant support from the U.S. Department of Energy. These include the Ocean Renewable Power Company's TidGen™ TGU device; the Wave Energy Technology–New Zealand (WET-NZ), which completed 6 weeks testing at the Northwest National Marine Renewable Energy Center off the coast of Oregon (Figure 10); Resolute Marine Energy, which tested a wave energy converter at Jennette's Pier in Nags Head, North Carolina, during 1 month in November; Vortex Hydro performed a 2-week test program in September in the St. Clair River in Port Huron, Michigan; FloDesign completed a short demonstration test of their device at the University of New Hampshire's Tidal Energy Site and in the Muskeget Channel in Massachusetts; and Dehlsen Associates demonstrated its Centipod wave energy converter off the coast of Santa Barbara, California, in late November.

Furthermore, three projects obtained FERC approval: Ocean Power Technologies wave farm (1.5 MW), Verdant Power (1.05 MW), and Ocean Renewable Power Company (300 kW); Public Utility District No.1 of Snohomish County (SnoPUD) is awaiting FERC approval for the Admiralty Inlet project (Everett, Washington), with the Open Hydro Group.

In New Zealand, Wave Energy Technology–New Zealand's ½-scale device (20 kW) was deployed at Moa Point in Wellington in May–June 2012 with Government funding support.

In Australia, Carnegie Corporation has recently received a federal government grant for the Perth Wave Energy Project (Western Australia) with a total project size of 2 MW. Other technologies expected to be deployed in Australia are Oceanlinx (1 MW), bioWAVE (250 kW), and Ocean Power Technologies Australia (initially 19 MW planned to be further expanded to 100 MW).

In Korea, the Sihwa tidal barrage power plant of 254 MW capacity has been reported to produce 396 MWh by the end of September 2012, since its operation in August 2011.The HyTide 110-5.3 horizontal axis tidal turbine, a product of Voith Hydro

FIGURE 8

Tocardo tidal stream turbine in the Dutch Wadden Sea, installed in May 2013.

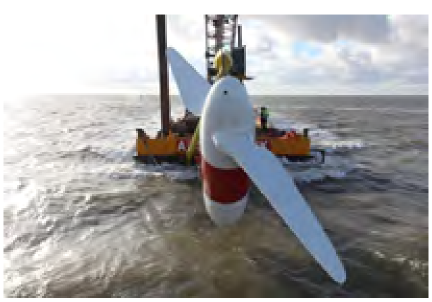

FIGURE 9

Free flow system turbines at RITE Project (September 2008). Photo by Christopher R. Gray/Verdant Power, Inc.

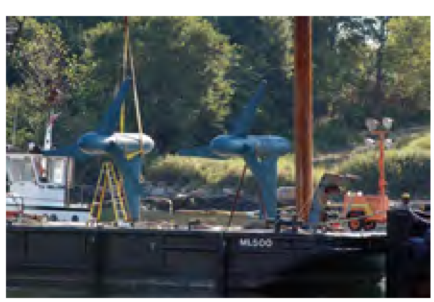

FIGURE 10

WET-NZ device at the Northwest National Marine Renewable Energy Center off the coast of Oregon.

with rated power of 110 kW and diameter of 5.3 m, was installed in Jindo in the Spring of 2011. The Yongsoo wave power plant, a pilot plant of 500 kW OWC wave energy converter developed by KIOST, being constructed at Yongsoo, Jeju, is expected to start test operation by the end of 2013 (Figure 11).

Several research projects conducted by Universities in China went in the water in 2012 with support from a national technology R&D program, with installed capacities ranging from 10 to 300 kW. The First Institute of Oceanography, under the State Oceanic Administration, constructed a 15-kW OTEC pilot plant near a coastal thermal power plant. The grid-connected hybrid power demonstration station (including a wave energy device) built in Daguan Island has been in operation for 18 months since June 2011. In Daishan, Zhejiang province, the 1-MW AR1000™ turbine is planned to be tested in the grid-connected tidal current demonstration site constructed by China Energy Conservation and Environmental Protection Group (CECEP).

In Japan, a 30-kW experimental OTEC plant at Saga University is operational, and many research projects with diversified ocean energy concepts have been recently tested on laboratory scale. Some of them are progressing to open-sea testing, with the involvement of major Japanese engineering companies, after an evaluation performed by the funding Japanese agency, NEDO (New Energy and Industrial Technology Development Organization).

FIGURE 11

500 kW OWC plant being constructed at Yongsoo, Jeju, Korea.

Final Remarks: Development of an Industry

The 2012 OES Annual Report offers a section dedicated to the Development of the International Ocean Energy Industry–Performance Improvements and Cost Reductions. ESB, Ireland's largest electricity utility, has been establishing readiness, cost, and performance criteria to guide suppliers of ocean energy technology towards viable early project investment propositions. In an article, "ESB Ocean Energy Projects—A Utility Perspective on Cost and Performance Requirements," the authors (Fitzgerald & Sharkey, 2012) comment that "while there are areas of significant cost and performance risk in the medium term, technical fundamentals indicate that ocean energy has the potential to meet the cost trajectory for all forms of renewable energy and contribute to meeting renewable energy targets." In a recent U.S.-published paper on Salinity Gradient Power, the author describes a developmental roadmap covering existing generation technologies and recent investigative research results into the feasibility of using alternative nipolar membranes (Merz et al., 2012). Another article, "Cost Reduction Pathways for Wave Energy" (Previsic, 2012), from a U.S. author, presents key areas in which cost reductions potentially can be attained within the near-term. In a further article, "From Turbine Prototype to Prototyping an Industry: A Critical Change in Perspective," the main focus of the Canadian authors (Campbell et. al., 2012) is on the challenges to finance and delivery of the first array projects and the emergence of a market pull. Critical issues associated with the scale change from device trials to prototype arrays are discussed, among which are new responses from regulators, supply chain, manufacturers, and financiers. The paper concludes that "demonstration of what this industry will look like and what it can offer" is essential for the necessary developments and support to make a transition from prototypes to arrays of devices to the development of an industry. And in April 2013, the U.S. Department of Energy announced up to $13 million in funding to develop and test advanced components and technologies to boost the performance of marine and hydrokinetic energy systems, which harness energy from waves, tides, or currents (U.S. DOE, April 2013).

There is a significant scope for collaborative working in research and development on ocean energy. In this context, the IEA OES, an intergovernmental collaboration between countries, has a unique position in connecting organizations and individuals working in the ocean energy sector; educating people globally on the nature of OES; inspiring governments, agencies, and individuals to become involved with the development and deployment of OES; and facilitating education, research, development, and deployment of OES in a manner that is beneficial for the environment and provides an economic return for those involved (Huckerby et al., 2012).

Acknowledgments

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PAPER

Verification of Wave Measurement Systems

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ABSTRACT

Given the societal importance of reliable and accurate ocean observations, the wave monitoring community (including academic researchers, agency scientists, resource managers, and representatives from wave instrument manufacturers) came together to develop a set of protocols for the test and evaluation of wave measurement systems in support of the 2009 National Operational Wave Observation Plan. These protocols are focused on a wide range of wave measurement instruments and their respective performance in successfully recovering the "First-5" Fourier components of the incident wave field. Performance is determined by comparing each system's output with a verifiable reference method over a predetermined range of wave frequencies. It is recommended that permanent wave test facilities are created on the West Coast (Monterey Bay, CA—deep water) and the East Coast (Duck, NC—shallow water) for continued evaluations of existing and new technologies. It was recognized that no absolute standard exists for the determination of the "First-5" across all spatial domains. Therefore, it was agreed that the Directional Waverider DWR-MkIII system was the best available reference/standard for the deep and intermediate water wave evaluations as verified by the laser array (LASAR) at the ConocoPhillips Ekofisk offshore platform complex in the North Sea. The long linear array at the U.S. Army Corps of Engineers' Field Research Facility could be used as the standard for shallow water wave evaluations. Finally, given the significance of wave measurements, an appropriate level of quality assurance and quality control procedures must be included as part of any test and evaluation effort. The details of the proposed protocols for the verification of wave measurement systems are described.

Keywords: waves, wave measurement, test and evaluation

Introduction

Surface gravity waves have a profound impact on modern society, from the deep sea to their dissipation on coastal beaches. The impacts of wind-generated waves affect commercial navigation, mineral extraction, recreation, and the economic vitality of coastal communities. These broad impacts drive a desire to both better understand wave generation, propagation, and dissipation as well as enhance measurement, reporting, and prediction capabilities. The need for accurate and precise measurement of surface gravity waves in oceans and inland seas from deep water to nearshore regions, under a wide variety of atmospheric forcing conditions, provides the impetus for the development of standardized test and evaluation protocols for the verification of wave measurement systems.

In 2009, the U.S. Integrated Ocean Observing System (IOOS), the National Oceanic and Atmospheric Administration (NOAA), the National Data Buoy Center (NDBC), the U.S. Army Corps of Engineers (USACE), and the Alliance for Coastal Technologies (ACT) developed community consensus on a plan for a comprehensive, high-quality surface-wave monitoring network for the United States, which is entitled "A National Operational Wave Observation Plan" (IOOS, 2009). The national system of surface wave observations proposed by this plan would increase the wave observation spatial coverage along and across the U.S. coasts and serve as a stimulus for wave modeling activities in verification/validation improvements, data fusion, and assimilation. This plan divides the U.S. coastline into seven primary geographic regions and four along-coast observational subnets (offshore, outer shelf, inner shelf, and coastal subnets). The plan focuses on real-time, *in situ*, directional wave sensors required to create a robust backbone across these four regions. It was further recognized by this plan that, as waves move from offshore to the beach, the observational technology changes, as does the accuracy requirements of the sensors employed and the range of user applications. The plan is being updated in 2013 (Birkemeier et al., 2012;

see also http://www.ioos.noaa.gov/waves/welcome.html).

This comprehensive plan recognized that, to serve the wide and ever-growing range of IOOS users, a national wave observation network should not only discern incident wave height and period but should also accurately resolve the directional spectra of the surface gravity wave field. To achieve this goal requires that the observations satisfy a "First-5" standard. The plan states, "Technically, First-5 refers to 5 defining variables at a particular wave frequency (or wave period). The first variable is the wave energy, which is related to the wave height, and the other four are the coefficients of the Fourier series that defines the directional distribution of that energy." Since both the incident wave characteristics change with water depth, as do the preferred methods of wave directional sensing, a clear test and evaluation protocol is required to ensure that operational wave sensing systems meet this stated goal. Such technology testing and evaluation is called for in the IOOS National Operational Wave Observation Plan in the protocols, facilities, and staffing section:

> The success of a directional (First-5) wave measurement network is dependent in large part on reliable and effective instrumentation (e.g., sensors and platforms).
>
> A thorough and comprehensive understanding of the performance of existing technologies under real-world conditions is currently lacking. An independent performance testing of wave instruments is required.

In 2010, ACT took an initial step in implementing the National Operational Wave Observation Plan by again developing broad consensus among the global wave measurement community in developing protocols for such a wave measurement system test and evaluation effort. This was undertaken in anticipation that a comprehensive testing of "state-of-the-art" wave sensors will be required in the near future. To achieve the goal of drafting and defining testing and evaluation protocols, ACT held a second focused workshop where consensus was built on test approaches and where protocols were refined. Participants of this workshop included academic institutions, members of the leading government agencies, USACE, NDBC, the NOAA National Weather Service (NWS), the Joint Commission for Oceanography and Marine Meteorology (JCOMM), researchers, scientists, and resource managers with expertise in wave measurements as well as representatives from wave sensor manufacturers. From this broad representation, a Wave Test and Evaluation Technical Advisory Committee was selected, which played a key role in organizing, drafting, and executing the final protocol document. The following protocols are based on community consensus, and this basic framework is intended to be of broad value to those interested in quantifying the performance of wave measurement systems over a wide range of incident wave conditions.

Wave Measurement Systems

To date, a variety of technologies exist to "measure waves," ranging from the relatively simple pressure sensors to the more complicated remote sensing technologies. The following provides a brief summary of the specific types of wave sensing technologies that are utilized in commercially available systems. In many cases, they rely on vastly different physics and range from surface to subsurface measurements, including remotely sensed technologies (ACT, 2007). The sensors are grouped according to their typical deployment location (i.e., seabed, surface mooring, remotely sensed, etc.) because this, in large part, establishes the types of constraints imposed on the varying technologies. The focus herein is on commercially available wave measurement systems or systems already in widespread use, such as the NDBC buoy network, that are appropriate for long-term continuous monitoring as part of IOOS. Although other technologies have been employed in customized applications or for limited duration studies, they are not addressed in this paper.

For a formal test and evaluation program, all instruments to be tested should be delivered by the manufacturer as a stand-alone package, regardless of technology, including data logging, data transformation/conversion equations, independent power, data transmission, and any other features (such as biofouling prevention) typically provided to the customer.

Seabed-Mounted Sensors

Most commercially available seabed-mounted directional wave sensors provide wave direction, wave height, and other wave statistics by combining a high-accuracy acoustic or electromagnetic current meter with a high-accuracy pressure sensor. This technology provides a direct measurement of two horizontal, orthogonal components of wave orbital velocity (U, V) and concurrent measurements of the fluctuating sea surface height as indicated by pressure (P). Hence, this method of directional wave sensing is commonly referred to as the

PUV method. Some systems also employ an independent, vertically oriented echo-sounder for acoustically tracking sea surface motion. Wave direction is determined by an electromagnetic (fluxgate) compass. Sensors can typically sample at rates of 1–5 Hz. Most sensors can be deployed in a multiple-mode format to allow periodic burst sampling of wave data as well as long-term averaging. Internal processing of spectral data allows simplified telemetry of wave data for near real-time wave reporting, including the First-5 Fourier coefficients.

Arrays of bottom-mounted pressure sensors can make directional wave measurements, such as the Long Linear Array, a 15-sensor pressure array located at the USACE Field Research Facility (FRF) in Duck, North Carolina (described below). At least three pressure gauges are required to form a "wave slope" array to sense the motion of the sea surface and derive the Fourier components for the directional wave spectra. The standard wave slope array utilized by the Scripps Institution of Oceanography Coastal Data Information Program (CDIP) consists of four high-resolution pressure sensors placed in a 6-by-6 m square frame. Pressure sensor arrays also have been mounted on fixed offshore platforms, as have other sea surface height sensors, such as acoustic, laser, microwave, or capacitance wire water level sensors, to provide directional wave measurements. As with other bottom-mounted wave systems, the pressure sensors are cabled to shore or an above-water platform for data telemetry. While the pressure sensors or other water level sensors themselves are commercially available, the wave slope arrays are custom-built for specific locations and purposes.

Surface Moorings

Surface moorings are typically associated with floating buoys. Hence, the motion of the platform becomes a critical component of the measurement system. Directional wave buoys are commercially available from a variety of manufacturers and are built by NDBC. Directional wave buoys measure and calculate waves based on inertial sensing of the buoy hull motions utilizing either 3-D accelerometers (vertical heave, pitch, and roll) or GPS to measure the x, y, and z positions of the buoy and presumably of the sea surface or three orthogonal angular rate sensors to measure hull pitch and roll, to measure the sea surface slope, with vertical heave acceleration measured by an accelerometer. In addition, a triaxial magnetometer or fluxgate compass is used to measure hull azimuth. Fourier analysis of the buoy motion yields nondirectional and directional wave spectra and provides the First-5 Fourier coefficients (Kuik et al., 1988). Buoy hull shape, met/ocean sensor payload, and mooring design are critical in determining the buoy's response to the wave orbital motion.

Remotely Sensed

Various remote sensing techniques exist for wave measurement (Grønlie, 2004; Tucker, 1991). Over the past few decades, the ability to sense detailed ocean surface wave parameters remotely using high-frequency (HF) radar current mapping systems has matured. This technology utilizes HF electromagnetic transmissions typically between 5 and 50 MHz to map ocean currents and monitors wave fields in real time. Currents are calculated from the first-order Bragg backscatter of the HF radar waves returned from ocean surface gravity waves. Wave information is obtained from second-order sea-echo Doppler spectra representing the interaction of long and short ocean waves. The antenna arrays are permanently mounted on shore, or an offshore structure and total on-site electronics require very low electrical power. HF radar systems use either a "direction-finding," two-antenna configuration or a "beam-forming" linear-phased array receiver with 12–16 elements. HF radar systems can observe wave directional spectra including the First-5 Fourier coefficients over a limited region, typically tens of kilometers, when there is appropriate overlap between two shore stations. This is typically done using an iterative method that inverts the observed Doppler sea echo. From a single station, only wave height and period can be directly observed.

Directional wave spectra can be derived from X-band marine navigation radar systems as well. Wave information from these systems is limited to a radius of a few kilometers from the radar antenna. Satellite measurements of waves can be made from synthetic aperture radar over large swaths of ocean surface or from aircraft-based LIDAR systems; however, these systems are outside the area of focus for this test and evaluation program for the reasons stated above.

Protocols, Facilities, and Staffing

It is stated in the IOOS National Wave Plan that "continuous testing and evaluation of operational and pre-operational measurement systems is an essential component of the National Operational Wave Observation Plan, equal in importance to the deployment of new assets." To have the ability to maintain a continuous testing and evaluation program, the protocols must be created as "living" documents, meaning they should be revisited at timely intervals and updated with lessons learned and new information. The results of continuous evaluations could not only be used to set accuracy requirements for new measurement devices and upgrades prior to implementation of the IOOS National Wave Plan but also allow users to determine the accuracy of historical data.

It is recommended that permanent facilities be created on the west coast (Monterey Bay, CA—deepwater) and the east coast (Duck, NC—shallow water) for continued testing as new technologies develop and current technologies are upgraded. These facilities also will provide unique guidance for defining operational requirements for servicing and replacement of sensitive components of the various platforms over time. This information will be critical for allocating appropriate resources within the national network.

The development of these permanent facilities would provide opportunities to evaluate sensor performance in extreme conditions in the future. These extremes may include extreme winds, wave heights, and/or currents, all of which may impact different aspects of sensors and associated mooring and communication systems. In these circumstances, it would be important to evaluate the full frequency-height response because there could be disparate effects on short and long waves. These "extreme tests" will inform Weather Forecasting Offices as to the validity of hindcast data used in understanding forecast model extreme events.

It is further recommended that all technology evaluations be conducted by a core staff of technicians well trained in the operation of wave sensor systems to be evaluated. The core staff should be responsible for all aspects of the evaluation from beginning to end to ensure consistency throughout. Evaluations should be overseen by a technical advisory committee consisting of experts in wave sensing technologies who have no conflicts of interest with the sensors being evaluated.

Verification Design

It was agreed that the protocols should follow a format that focuses on field tests to evaluate performance under a variety of environmental conditions (laboratory tests are currently not included). Due to the large scope of this evaluation approach, it has been broken down to five tasks and presented in order of feasibility and importance. Each of these components is described in detail in the sections that follow.

Test Verification Factors

Based on extensive discussions and deliberations, it was agreed that the test protocols should primarily be focused on the wave sensors' performance in successfully recovering the First-5 Fourier coefficients, henceforth, the "First-5" parameters. At a fixed frequency, f, the directional distribution of wave energy, $S(\theta)$, can be expressed as an infinite Fourier series,

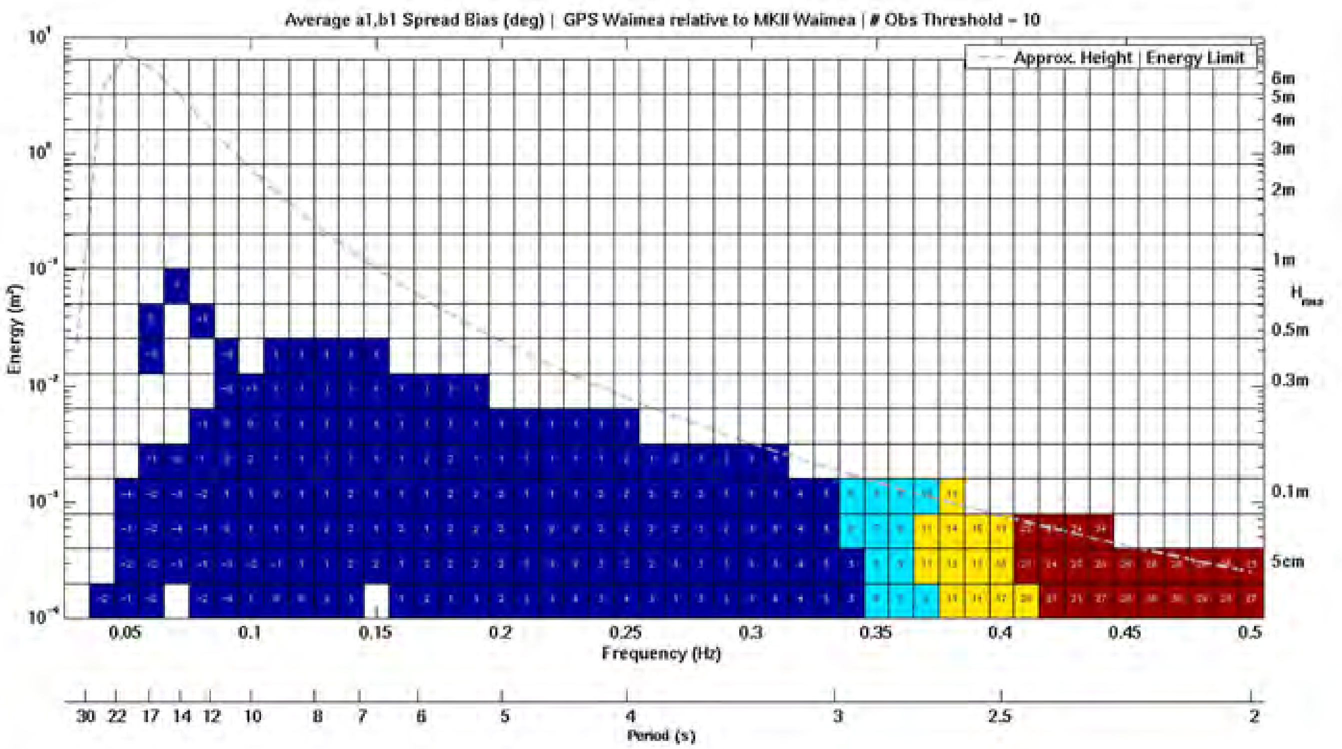
$$S(f,\theta) = S(f)[a1\cos(\theta) + b1\sin(\theta) + a2\cos(2\theta) + b2\sin(2\theta) + a3\cos(3\theta) + b3\sin(3\theta) + a4\cos(4\theta) + b4\sin(4\theta) + \ldots] \quad (1)$$

where $a1$, $b1$, $a2$, $b2$, $a3$, $b3$, … are "normalized directional Fourier coefficients" with values that range between −1 and 1 (Kahma et al., 2005). The term $[a1 \cdot \cos(\theta) + b1 \cdot \sin(\theta)]$ is referred to as the "first moment of the directional spectrum," the $a2$ and $b2$ terms are referred to as the "second moment," and so forth. The first and second moments are typically referred to as the "low-order moments" of the directional distribution of wave energy. The First-5 refers to the total wave energy (integrated over all frequencies) and the four directional parameters ($a1$, $b1$, $a2$, $b2$) that define the low-order directional moments of underlying directional distribution of wave energy.

Performance should be determined by comparing each instrument's output with the reference method over a predetermined range of wave frequencies. The test and evaluation should adopt an approach developed by CDIP that evaluates the differences between the first four directional parameters at specified frequency and energy bins (Figure 1). This practical approach to evaluating two sets of wave observations deviates from the traditional spectral representation of wave frequency-directional spectra as energy densities and instead interprets the spectrum as quasi-2D spectral wave components. It is motivated by the realization that directional wave instruments measure the frequency distribution of wave energy with greater resolution than the directional distribution. By defining the specific bins of frequency and energy

FIGURE 1

Sample frequency energy comparison plot of directional differences for GPS-based and MkII wave observations at Waimea, HI. Dashed line represents the extreme JONSWAP spectrum for a wave with a 20-m H_s (courtesy of Julie Thomas and Corey Olfe, CDIP/SIO).



to be compared, the ability of an instrument to measure the four directional parameters of each component relative to a second benchmark instrument can be directly evaluated.

The purpose for adopting this methodology is to provide comprehensive information on the sensors and their relative differences with the standard. Observed wave components are defined only by frequency and energy, and then the differences in the four directional distribution parameters are evaluated. The goal is to deploy sensors in appropriate locations and for sufficient duration to fill out the frequency-energy matrix. This will provide an understanding of how each sensor behaves for a variety of frequency-energy combinations.

When considering the First-5 and their accuracy, it must be kept in mind that there is a difference between the first coefficient (wave energy) and the other four (directional) coefficients. The wave energy spectrum is a clear concept, directly related to the variance of the sea surface fluctuations, easily translatable in terms of an effective wave height. The directional coefficients, however, are merely the first four of an infinite series of coefficients (all of which are inaccessible to single instruments), and their interpretation as direction and directional spread inevitably requires theoretical modeling (e.g., a $\cos^2$ s-model or an ME distribution). For example, when using a unimodal directional model for describing a multimodal wave system, directional estimators could be off the mark by as much as 90°, although the sensor accuracy in simulations or under laboratory conditions may be 0.01°. Hence, this ideal sensor accuracy in simulations or in the laboratory must be discerned from instrument accuracy at sea. In the latter case, the instrument response function, the statistical validity of the model, and the sampling variability are at least as important as the fundamental sensor accuracy.

The frequency dependence of the directional errors is particularly important because large differences in particular frequency ranges may be obscured by integrating over all frequencies. An example of this is shown in Figure 1, where differences between the Datawell GPS and MkII wave measurement systems become much larger as frequencies increase above 0.35 Hz. While this may not be important for an experiment in a swell-dominated regime, it will be significant in locations where the observed waves are fetch or duration limited. This methodology is consistent with other ongoing efforts (e.g., CDIP evaluation protocols) that will provide additional data for comparisons and will facilitate the involvement of databases obtained from other ongoing efforts.

The matrix (Figure 1) displays the range of conditions where it may be possible to evaluate instrument performance. The dashed line indicates the JONSWAP spectrum (Hasselmann et al., 1973) for an extreme wave with H_s of 20 m. The highest frequency included here (0.5 Hz) is the upper limit for the reference instrument (Datawell MkII) in typical deepwater conditions. While this includes most of the energy in the surface wave field, significant remote sensing applications focus on waves with frequencies higher than this cutoff. These waves will not be included herein. For a particular experiment to have achieved a robust comparison of sensors, there should be a sufficient number of samples at each frequency-energy bin to determine whether there is a significant difference between mean-derived parameters. This will require long-duration deployments to establish sufficient sampling over most of the intended range.

Unanimous agreement was obtained between both manufacturers and the user community that, to implement a practical, *in situ* test and evaluation, no absolute standard exists for the determination of the First-5 Fourier components of the incident wave field across all spatial domains. Hence, based on this recognized reality, the Directional Waverider DWR-MkIII manufactured by Datawell Oceanographic Instruments should be used as the reference/standard for the deep and intermediate water wave evaluations. For more details on this selection, see the Reference Methods section of this report.

Some manufacturers expressed concern about their technologies' ability to resolve the First-5. In some cases, this evaluation will serve as an exercise to determine whether, in fact, these instruments can resolve the desired parameters by establishing the following descriptors for comparisons with the reference instrument for each of the First-5 coefficients.

Wave measurement system evaluations should verify the following:

Accuracy: combination of bias and precision that reflects the closeness of the measured value to the true value. Accuracy should be determined in the field by a comparison of differences in the mean values reported by the test sensors versus values determined by the Datawell Waverider (see below) of the First-5.

Bias: consistent deviation of instrument measured values from the true values, here designated as the First-5 from the Datawell Waverider, caused by systematic errors in a procedure.

Precision: measure of the degree of agreement among replicate measurements of a sample, usually expressed as a standard deviation. Precision should be determined by a comparison of differences in standard deviation values produced by the test instrument versus values determined by the Datawell Waverider for a particular frequency/energy bin. The number of replications cannot be controlled because this is environment dependent; however, a minimum number of replicates are required to determine whether there is a statistically significant difference between observed values.

Drift: changes in the deviation of instrument measurements of the First-5 relative to the Datawell Waverider First-5 over the duration of the field test.

Reliability: measure of the ability to maintain integrity of the instrument and data collections over time while adhering to manufacturer recommendations. Reliability should be determined by comparing the amount of the data recovered versus the amount of the data expected.

Test Configuration

Wave sensor test and evaluation should involve a phased approach. This approach will allow the participants to focus on the evaluation for one environment while planning for testing in other environments, ultimately resulting in instrument testing in a matrix across a number of deployment environments. These prioritized environments, in order of action/importance, are as follows:

deep water on the West Coast of the United States,

shallow water on the East Coast of the United States,

enclosed large freshwater basin in the Great Lakes, and

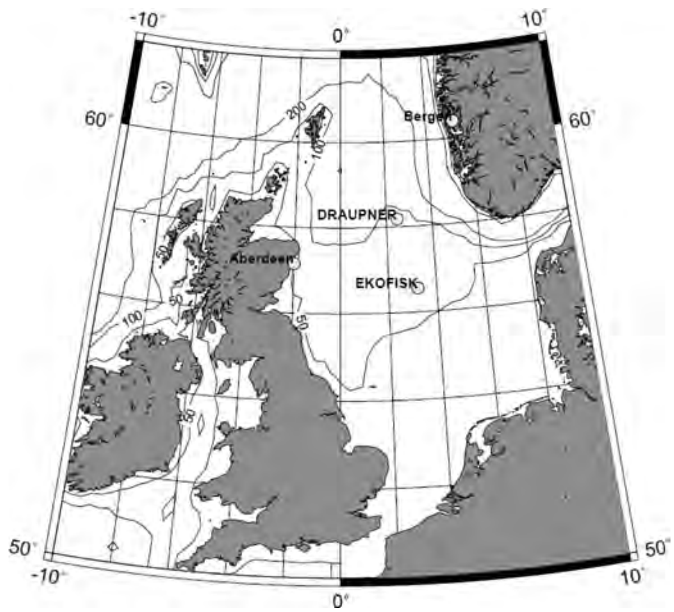
shallow water with potential episodic events in the Gulf of Mexico.

The deep water deployment in Monterey Bay should be the first test and evaluation task to be completed. It is suggested that the wave measurement test and evaluation build on existing infrastructure maintained by NDBC, CDIP, and Monterey Bay Aquarium Research Institute by creating a permanent buoy farm at this location for deep water wave sensor testing. The continued deployment of the sensors making up the buoy farm will require continued operation and maintenance funding to keep the buoys deployed in this location.

The shallow water deployment at the USACE FRF in Duck, NC, should serve as the permanent shallow water evaluation location. A Great Lakes Deployment and a Gulf of Mexico deployment should be the third and fourth priorities, respectively. Wave sensing instrumentation from participating manufacturers should be deployed for a full year at each test and evaluation location to ensure exposure to the full diversity of conditions for each environment.

FIGURE 2

Location of Ekofisk in the North Sea (Norwegian Meteorological Institute).



Reference Methods (Task 1)

There was complete consensus among subject experts, manufacturers, and users that, to implement a practical, *in situ* test and evaluation, no absolute reference standard exists for determination of the First-5 Fourier components of the incident wave field across all spatial domains. An exception to this observation may exist in one coastal (shallow water) and one intermediate/deepwater location. In the coastal region, the USACE FRF provides a unique measurement opportunity as well as long time series data of wind and waves. At the FRF, the long linear array exists in 8-m water depth, which provides excellent directional resolution of the incident wave directional spectra. Similarly, in deepwater, the ConocoPhillips Ekofisk offshore platform complex in the North Sea (Figure 2) provides a stable platform in a water depth of 70 m encompassing a laser array (LASAR) providing direct measures of wave height, period, and direction through a wide range of frequencies. These two unique facilities should be utilized in providing direct comparison for the proposed "reference standard" as described below.

Based on this reality, the Directional Waverider DWR-MkIII manufactured by Datawell Oceanographic Instruments should be used as the reference/standard for the deep and intermediate water wave evaluations, that is, in water deeper than approximately 20 m. The DWR-MkIII has established a long history of side-by-side comparisons with other wave measurement system and, in particular, with the long linear array at FRF. Based on this history of comparison, the DWR-MkIII was selected as the "reference standard" for the purposes of this technology test and evaluation protocol. The Waverider buoy uses Hippy heave-pitch-roll sensors to measure wave direction and energy. They also carry two horizontal accelerometers for measuring north-south and east-west displacements. This translational system uses pitch-roll to correct the buoy movement to a fixed *x-y-z* reference frame, giving it a better signal-to-noise ratio than buoys that use pitch-roll directly to estimate directional wave properties. The Waverider is the primary wave system operated by CDIP. The Waverider has been shown to effectively measure waves with periods from 7 to 17 s with an error of no more than 3% (O'Reilly et al., 1996).

As Task 1 of the Wave Test and Evaluation program, the Waverider will be verified for deepwater operations at the Ekofisk platform complex. The Ekofisk LASAR has been in operation since February of 2003 and carries four Optech laser altimeters for wave measurement in a square configuration (Magnusson, 2009; Magnusson et al., 2003). The laser altimeters determine the height of the sea surface at a fixed horizontal position by measuring the time from the emission of a light pulse to its detection after reflection at the air-water interface. The LASAR is mounted on a 100-m bridge between two platforms in the northern portion of the complex. The bridge is oriented east-west, with open sectors towards the north and south. Waves from the east and west may be subject to interference with the platforms. Sea spray from the platform legs in the vicinity of the sensors may interfere with measurements when waves are large, as during a storm. In addition to the LASAR, a WAMOS X-band wave radar is located on the eastern platform, and a MIROS radar altimeter, measuring nondirectional waves, is located on another nearby platform in the complex. A nondirectional Waverider is located to the west of the complex.

The scientific community is aware of some of the issues with LASAR at the Ekofisk platform. For example, at 70-m depth, the site is not truly deepwater as defined in linear wave theory for wavelengths longer than approximately 300 m or periods of longer than 14 s. However, there is strong consensus that a colocation exercise with a directional Waverider is necessary. At present, there is a nondirectional Waverider at LASAR. The Wave Test and Evaluation program should purchase the directional Waverider and be responsible for buoy deployment at the Ekofisk site with Ekofisk oversight. Predeployment calibration of the buoy should be performed by Datawell before deployment. This same directional Waverider should be used for all subsequent wave test and evaluation colocation exercises, thus providing a reference standard for all future testing and evaluation.

For data review and delivery during the reference standard evaluation, the buoy should be capable of both satellite and HF radio communication. Satellite and HF radio communication are considered necessary in case the buoy breaks loose from its mooring. Datawell produces a handheld GPS tracking unit, essential in recovery, which communicates via HF. Iridium satellite communication has proven to be very reliable offshore and in locations where HF is out of range.

For a similar comparison in shallow water, the long linear array located at USACE FRF in Duck, North Carolina, could serve as the verification standard. Wave frequency-direction spectra are obtained from a cross of pressure sensors with nine sensors located in a shore parallel line and six in a cross-shore line located on the 8-m contour about 900-m offshore. The long linear array hence is known also as the 8-m array and is described in the Reference Instrument Calibration and Deployment section below.

Field Locations and Deployments

West Coast, Deep Water Waves (Task 2)

In situ evaluations of wave measurement systems performance in a deep water, moored application should be conducted in Monterey Bay, CA. This location was chosen to capture the long period, energetic waves typical of the West Coast environment. It was noted that the complicated bathymetry of the Monterey Canyon causes large, along-shore, spatial variations in shallow water waves, making this a poor choice for a colocated shallow water wave test and evaluation. The depth at the proposed deepwater location (36.753°N, 122.423°W) in the Canyon is 2,115 m. Existing infrastructure at this location include NDBC 46042 (3-m discus buoy), MBM2 (NDBC 46092, a toroidial buoy), and a Scripps Datawell Waverider (NDBC 46236) as well as multiple HF radar installations.

The wave test and evaluation should take advantage of these existing operations by using the deployed Datawell Waverider for its standard and deploying the participating manufacturers' instrumentation near, on, or around the NDBC buoy 46042. The test instruments should be precalibrated by the methods designated by the manufacturer for operational deployment. Superstructure, bridle, and/or any other mounting hardware must be configured as it is to be deployed operationally. The mooring should follow manufacturer's recommendations for deepwater mooring.

Ancillary data can be provided by the NWS Weather Forecast Office (WFO) Monterey operationally running the SWAN wave model and by CDIP providing additional wave model output (see http://cdip.ucsd.edu/themes/user_groups/mariners). Wind speed, direction, atmospheric pressure, air temperature, relative humidity, and sea surface temperature are all available at this test site. Additionally, there are eight coastal HF radars (two long and six medium range) providing surrounding data. It was also noted that NOAA has stationed its LIDAR aircraft at Monterey and can also collaborate with satellite observations. This location was viewed as an ideal, multiparty collaboration.

East Coast, Shallow Water Waves (Task 3)

In situ evaluations of measurement systems performance in shallow water should be conducted at the FRF utilizing the long linear array. This high-resolution directional array produces estimates of incident directional wave spectra to approximately 2° under nominal East Coast wave conditions (Long & Oltman-Shay, 1991) and therefore represents an ideal shallow water test and evaluation location. Located on the Atlantic Ocean and Currituck Sound, the FRF supports coastal missions of the USACE and constitutes an IOOS Observatory. There is also a nearshore acoustic array in 3.5- to 11-m depth; two Directional Datawell Waveriders, one in 17.4-m depth and another in 26-m depth; and an NDBC Buoy (44014) in 48-m depth. NWS WFO Morehead City/Newport, NC, is running SWAN for this region and is also providing meteorological data. The Delft3D Model is also available for this location. Satellite observations can also be obtained.

This site could be used to evaluate PUV sensor measurement systems as well as buoys. Any acoustic Doppler-based PUV systems (such as RDI, Sontek, and Nortek) should be deployed a minimum of 30 m apart, to avoid cross talk, in 8-m depth. Electromagnetic current sensor-based PUV systems, such as FSI and Valeport, can be deployed directly within the pressure array with no concern of interference. If test buoys have an integrated meteorological package, they should be deployed further offshore and colocated with the 17.4-m-depth Waverider. All systems should be deployed along the same isobath in the alongshore direction. A Datawell may be deployed in 8-m array as well. Data from all instruments should be telemetered to shore in real time via cable, line of sight radio, or satellite to insure that systems are working for the entire deployment. Instrument maintenance should be per manufacturer recommendations. All raw data from instruments should be recorded and processed as in full operational deployment. Core staff should be on site to set up and deploy instrumentation with support from USACE.

The shallow water test at the FRF site would also heavily benefit the local NWS WFO and efforts to implement and improve their nearshore wave modeling efforts. Data from this colocation exercise should be made available to the WFO in near real time for this purpose.

Great Lakes, Deep Water and Shallow Water Waves (Task 4)

There are two potential sites for a colocated evaluation in the Great Lakes. The first is a deep water site (160 m) adjacent to NDBC 45007 in southern Lake Michigan. The deep water site is the top priority for the Great Lakes evaluation. A secondary, shallow water site was identified (20-m water depth) immediately offshore of the NOAA/Great Lakes Environmental Research Laboratory Field Station in Muskegon, MI. This region has cabled capability for instrument communication and data collection. Both sites would utilize the Datawell Waverider buoy as reference standard, as described above. Ideally, the evaluation should begin in March and end in November due to the constraint of winter weather (ice) conditions; however, nearshore wave measurements and wave instrument performance during the winter months are critical to the NWS WFO operations. One component of this test should be to keep bottom-mounted wave sensors in the water during the winter months to evaluate performance in this harsh environment.

Efforts should be made to determine the interest of the Canadian Government in investing their buoys for a Lake Superior deployment. If they have no interest in comparison, the wave test and evaluation should deploy the sensors in southern Lake Michigan. The Datawell Waverider should be colocated with NDBC Buoy 45007 and systems to be evaluated.

Gulf of Mexico, Episodic Events (Task 5)

The Gulf of Mexico site was chosen to provide an evaluation of instrument performance in shallow water, off Tampa Bay, during extreme events. The University of South Florida's Coastal Ocean Monitoring and Prediction System (USF/COMPS) operates and maintains a coastal and offshore monitoring network that measures currents, in-water parameters, and a full suite of meteorological variables. A colocation exercise off Tampa Bay would be ideal due to the amount of available ancillary data. Overall, meteorology is not significant for general wave climatology; however, tropical storm systems can spin up waves at least 6-m high. It would also be valuable to consider a deep water colocation evaluation using oil platforms as deployment sites. Most platforms are equipped with oceanographic sensors and capabilities for additional deployments. This would require collaboration and logistical support from platform operators. This was identified as a low priority. If the funding climate dictates, the East Coast deployment site is also capable of capturing episodic events in the form of tropical cyclones or severe winter storms.

An additional component of an Eastern Gulf of Mexico evaluation would include colocating wave sensing technologies within the existing USF/COMPS CODAR and WERA HF radar footprints. There is an operational two-site WERA system located on the West coast of Florida between Coquina Beach and Venice. There are also three CODAR sites in this region at Redington Shores, Venice, and Naples. The evaluation of the HF radar technology may include the First-5 in limited situations, and there is interest in comparing wave statistics from the Waverider to those generated by the radars, particularly for large amplitude, episodic events.

Test Instrument Deployment

At all test and evaluation deployment sites described above, both the reference and the test systems should be colocated to the extent feasible. It should be assured that there is substantial distance between the test site and hydrographic features that may cause spatial variation in the wave field. The system separation distances will be dictated by the water depth and mooring lengths. The instrumentation should be as close as possible without interference from one another, and each test system should be deployed in an equal distance from the reference buoy.

Ancillary Measurements

Measurements of local meteorological data as well as in-water ancillary data (water velocity and temperature) should be provided. Both recommended deep water and shallow water sites have existing infrastructure and monitoring for these variables. Availability of these data should be guaranteed to participating manufacturers and the local NWS WFO.

Reference Instrument Calibration and Deployment

Datawell Waverider

As described above, the chosen instrument standard is a Datawell Mark III Series Directional Waverider. The calibration of the Waverider consists primarily of the comparison of measurements performed in the so-called "ferris wheel" (henceforth "the rig") to the known dimensions and orientation of the rig, at three different frequencies (corresponding to 20, 12.5, and 6.25 s), as described in the Datawell DWR-MkIII manual (see http://datawell.nl). The predeployment buoy configuration and preparation should be verified according to the Datawell recommended procedures. Between each deployment, accelerometer and compass checks should be performed. Datawell suggests that, every 3–6 years, the buoy should be returned for calibration. Calibration rigs are presently located in the Netherlands at the Datawell facility or at CDIP in La Jolla, CA. Additional rigs could be manufactured as geographic coverage necessitates.

When deploying the Datawell, no additional superstructure or substructure mounts must be attached. The accuracy of the wave measurements is dependent on the frequency response of the buoy. The mooring system consists of a 30-m bungee and terminations supplied by Datawell, polypropylene line for the appropriate depth (2*depth or 1.5*depth in deepwater with little current) and large anchor chain links for the 1,200-lb anchor. Datawell approved deployment protocols must be used. The Mark III deployment is very straightforward and, depending on sea conditions and distance offshore, can be performed from small vessels. It is suggested that the buoy be capable of both Iridium satellite and HF radio data telemetry as stated above.

FRF Long Linear Pressure Array

The FRF long linear pressure array is perhaps the only location for which real and accepted "sea truth" exists for incident directional wave spectra. The fundamental work on this nearshore directional wave sensing system was performed by Long and Oltman-Shay (1991). The array consists of 15 bottom-mounted pressure sensors centered on the 8-m contour about 900-m offshore. Under most conditions, this location is beyond the active surf zone. The pressure array extends 250 m in the alongshore direction and 100 m in the cross-shore direction. Wave spectra are based on 8,192-s (2 h 16 min 32 s) time series of data collected at 2 or, rarely, 4 Hz. Time series are windowed and Fourier-transformed to compute cross-spectra between all unique pairs of gauges. Cross-spectra of pressure are surface-corrected to sea-surface displacement cross-spectra using linear wave theory and then ensemble and band-averaged for a final resolution bandwidth of 0.01 Hz (approximately 160 degrees of freedom). Directional spectral estimates are made using the iterative maximum likelihood estimator as described by Pawka (1983), using his recommended convergence parameters and a maximum of 30 iterations, on both the full 15-gage array (360° processing) and just the nine gages of the longshore linear array (180° processing). The latter calculation is necessary because refractive blurring occurs in the 360° analysis (Long, 1994). A description of the FRF linear array is given by Long and Oltman-Shay, and details of data analysis are given by Long and Atmadja (1994).

Data Management and Reporting

CDIP developed a wave instrument intercomparison tool that has been improved upon by the JCOMM

Expert Team on Wind Waves and Storm Surges, now known as the Wave Eval tool (Jensen et al., 2011). This tool should be utilized to allow wave data collectors and instrument developers to easily compare wave spectral data from different sources and to view the differences between spectral data sets in a standardized form. The tool compares wave spectra data sets that have been calculated by the user or by using the processing software provided by an instrument manufacturer. The sampling rates are sensor/manufacturer issues and not related to the Wave Eval tool.

The Wave Eval tool takes all spectra and redistributes them into equal-width 0.01-Hz bands. In addition, the tool is only useful when used with weeks- to months-long records of wave spectra from two different sources, not just a single record. The Wave Eval tool will be ideal to compare proposed longer-term colocation exercises. The intercomparison spectral data are permanently archived at the CDIP facility. All results are in the public domain.

Data should be uploaded from instruments as manufacturers' instructions indicate. Because of the long test duration, instruments may need to be serviced every 3–4 months to address biofouling issues or to retrieve data to avoid memory concerns leading to data loss. The surface buoy data from the Datawell Waverider and the NDBC buoys from the West Coast deployment should be transmitted via satellite in near real time and sent to CDIP. The data should then be disseminated to NDBC for distribution. CDIP currently has the ability to provide full spectral data for all of the NDBC wave data and should do so for all colocation exercises described here. Similar analyses should be performed on the data from the surface buoys for the East Coast deployment. Parameters from the accepted standard will be compared directly to the test instruments for the year-long deployment: amplitude, period, direction, and the First-5 Fourier coefficients.

Core staff and all others participating in the evaluation should work closely with the technical advisory committee and participating manufacturers to ensure consistency with comparisons to the Datawell Waverider. Test and evaluation reports for each instrument should be released within 3–4 months after the final instrument retrieval, although in this case, the data quantity will be an issue in determining timing because of the deployment length. The ability to retrieve and analyze the data in near real time and CDIP's contribution to analysis will alleviate some of the data management burden and will expedite the reporting process.

Quality System for the Testing and Evaluation of Wave Measurement Systems

Credible, high-quality performance information is one of the tenets of independent testing and verification of wave measurement systems. In order to provide verifiable and defensible data on the performance of wave instrumentation, the testing organization must control its technical and human factors that affect quality. Therefore, the highest appropriate level of quality assurance (QA) and quality control (QC) procedures should be applied throughout the test and evaluation process.

Only data collected under a well-defined, documented quality system should be considered for verification of wave instrumentation performance. The quality system provides the framework for planning, implementing, documenting, and assessing work performed by the organizations carrying out the testing and for carrying out QA/QC activities. The goal of the quality system is to ensure that decisions on technology performance are supported by data of the type needed and the accepted quality standards and practices.

There are several quality system standards and models that may be considered for wave test and evaluation, and there is considerable commonality among them, regardless of application. The quality systems for two technology verification organizations, the USEPA's Environmental Technology Verification Program and NOAA's ACT, are based on the national consensus standard ANSI/ASQ E4-1994. This standard (ANSI/ASQ, 1995) was developed to promote consistency among the many quality systems requirements for environmental programs throughout the federal government and the environmental industry. The standard provides a basis for planning, implementing, documenting, and assessing an effective quality system and describes the elements that, at minimum, should be in place to ensure that a functional quality system exists for organizations that perform environmental data operations and the design, construction, and operation of environmental technologies.

Third-party testing and verification systems for wave instrumentation should, to the extent possible, be based on internationally agreed quality standards and procedures. ISO/IEC 17025:2005, "General Requirements for the Competence of Calibration and Testing Laboratories," is the main international standard used by testing and calibration laboratories. This standard addresses issues such as the technical competence of personnel, use of well-defined test and calibration procedures, participation in proficiency testing (i.e., interlaboratory comparisons and/or reference materials), and providing of guidance on the contents of test reports. Another important reason why it was developed was to harmonize acceptance of test data throughout the world.

Successful implementation of a quality system for wave instrumentation test and evaluation based on the ANSI/ASQ E4-1994 and ISO 17025 standards will contribute to (1) increased data integrity and defensibility (i.e., technology performance data of known and documented quality based on sound scientific principles), (2) improved oversight for evaluation purposes, and (3) improved decisions on technology use.

Concluding Remarks

The Wave Test and Evaluation program described here is critical to ensure that observations from the National Operational Waves Plan accurately resolve the directional spectra of the surface gravity wave field as characterized by the First-5 Fourier coefficients. Implementation of the waves observing network must include resources to implement such a wave test and evaluation program. The Wave Test and Evaluation program must include both deep water and shallow water test facilities, as these environments present very different issues for accurate wave measurement.

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PAPER

Synthetic Aperture Sonar Technology Review

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ABSTRACT

Sonar imaging has numerous applications in the underwater domain. High-resolution sonar images are useful in marine research, underwater construction work, offshore oil and gas, search for objects, and in the military sector. Common in many applications is the desire for higher resolution, better image quality, longer range, and smaller hardware footprint. Synthetic aperture sonar (SAS) technology can improve resolution and/or range substantially compared to traditional technology. Recent developments in SAS make this technology more available now. This paper gives a review of SAS technology and shows example of SAS applications. The paper lists the current state-of-the-art and the future trends of SAS.

Keywords: synthetic aperture sonar, imaging, bathymetry

Introduction

The principle of synthetic aperture imaging is based on the coherent combination of data collected over multiple locations such that the along-track resolution is improved. This principle is well known in the radar community, and there are many examples of spaceborne and airborne synthetic aperture radar (SAR) systems (Franceschetti & Lanari, 1999; Massonnet & Souyris, 2008). Historically, synthetic aperture has also been known in the sonar community since the 1970s. In a detailed technical memorandum from 1971, Bucknam et al. (1971) clearly describe the synthetic aperture sonar (SAS) principle and the major challenges. Up to recently, SAS technology has been limited to a few groups in the world and is not readily available. The reason for this has been challenges especially in acquiring the required vehicle stability and navigation accuracy for successful SAS processing and SAS system cost. Although significant SAS work was accomplished by various defense contractors, a majority of the details were held as trade secrets or were classified. This work was started in the 1990s and continued through the early 2000s. High-resolution, long-range SAS were developed for the mine countermeasures community during that period, and great strides were made in SAS system development. Today, SAS technology is becoming more available for the nonexperts and is starting to be used in many applications. A comprehensive review of SAS research is given in Hayes and Gough (2004, 2009), and an introduction to SAS is given in Hansen (2011).

In this paper, we describe the principle of SAS and link SAS to other active imaging techniques. We list what the challenges are in SAS. We describe SAS interferometry and the possibilities with frequency variation or agility. We show numerous examples of images from data collected by HUGIN autonomous underwater vehicles (AUV) carrying the HISAS 1030 interferometric SAS (Hagen et al., 2008). Finally, we list current state-of-the-art systems and indicate trends in SAS.

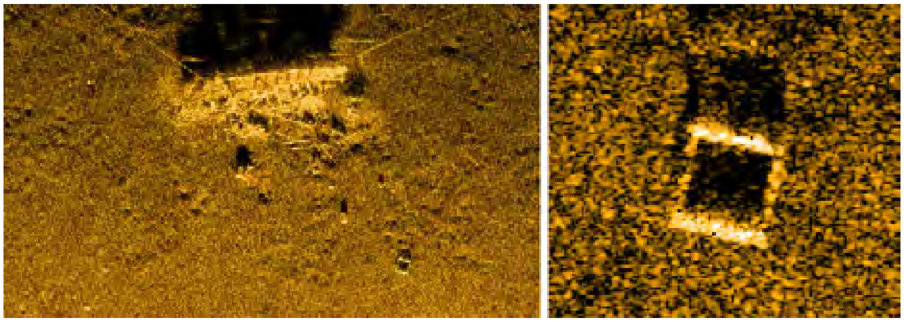
Figure 1 shows a SAS image of a shipwreck in poor condition. The image covers a seafloor footprint of 34 × 20 m size, and the range to the wreck is 50 m. The theoretical resolution in the image is 3.7 × 2.1 cm. The acoustic frequency of the system is 100 kHz for all the images in this paper unless otherwise stated. The scene contains debris and visible ropes. The right panel shows a 4 × 4 m zoom of the small 0.8 × 0.8 m box in the lower right corner. This demonstrates the image resolution achievable in SAS. The random variation in the SAS image (especially visible in the zoomed panel) is speckle or variability due to unresolved scatterers in the coherent imaging process (Oliver & Quegan, 1998). Speckle is present in all coherent active imaging systems.

Sonar Imaging

Active sonar imaging is the construction of images in range and direction from the backscattered echoes from transmitted pulses where the objective is to estimate the acoustic reflectivity of the scene to the highest possible geometrical resolution. The signal processing that focuses the signal from multiple receivers in a particular direction is known as beamforming (Burdic, 1984; Johnson & Dudgeon, 1993). Beamforming is implemented as digital delaying of the channels in the array so that the array look direction is steered to either side of boresight. The signal is then summed over the array for each range of interest (commonly known as delay-and-sum). This processing can be applied for all types of sonars: active,

FIGURE 1

Example of SAS image of a shipwreck at 50-m range.



passive, monostatic, bistatic, multistatic, real, and synthetic aperture. The principle of active sonar imaging is equivalent to ultrasound imaging (in medical applications), phased array imaging in radar, and seismic signal processing.

In classical beamforming, the limiting factor is low angular (azimuth) resolution. For an array of sensors, a rule of thumb states that the angular resolution is inversely proportional to the length of the array measured in acoustic wavelengths. There are two ways to improve the angular resolution: either increasing the array length or increasing the frequency (and thereby shortening the wavelength). Sonar systems with large fields of view and high angular resolution will have a large number of individual elements in the array. The range resolution is given by the signal bandwidth.

For sidelooking configurations on moving platforms, there are alternative techniques to collect and process the data to be used in a sonar image. Figure 2 shows three different approaches.

- A sectorscan sonar image (left) is a phased array image constructed for each ping. This is also known as a multibeam sonar image. Sectorscanning sonars can show one image per ping (typically on a real-time display) and work in forward-looking geometry as well as other geometries. High-end sectorscanning sonars have many array elements and require a large amount of computation.
- A sidescan sonar image (middle) is constructed by stacking one or more beams per ping during the flight in order to construct a two-dimensional image. By doing so, fewer beams (and thereby array elements) are required, and the systems may be more affordable. Typical sidescan sonars have only one beam and very simple hardware.
- A SAS (right) combines the data from multiple pings into each pixel such that an image over a large area can be constructed with high resolution. Practically, all existing SAS systems today are multielement receiver array systems. This means that a SAS system can also work as a sectorscanning sonar and a sidescan sonar. The difference is in the signal processing applied to the backscattered echoes as received by the sonar.

From a certain point of view, SAS is an evolution of sidescan sonar by employing sectorscan (or multibeam) processing of multielement data such that the resolution is improved. This is similar to the transition from side-looking aperture radar (SLAR) to SAR that was made in radar decades ago (Curlander & McDonough, 1991). An excellent overview of the different sonar technologies is given in Lurton (2010), and sidescan sonar is particularly covered in Blondel (2009).

SAS

The main purpose of SAS processing is to construct a synthetic array (or aperture) such that the along-track resolution is improved. This is done by coherent combination of multiple pings when moving along the synthetic aperture. Figure 3 shows the sonar image of a scene based on one ping (left), three pings (center left), seven pings (center right), and many pings (right). The left image is the sectorscan sonar image, and the right image is the full aperture SAS image. The image sequence clearly shows the resolution gain in SAS and thereby the image quality gain.

FIGURE 2

Sonar imaging techniques. Left: sectorscan sonar image. Center: sidescan sonar image. Right: synthetic aperture sonar image.

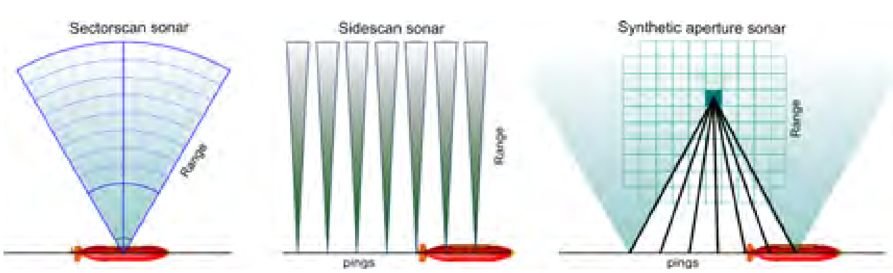
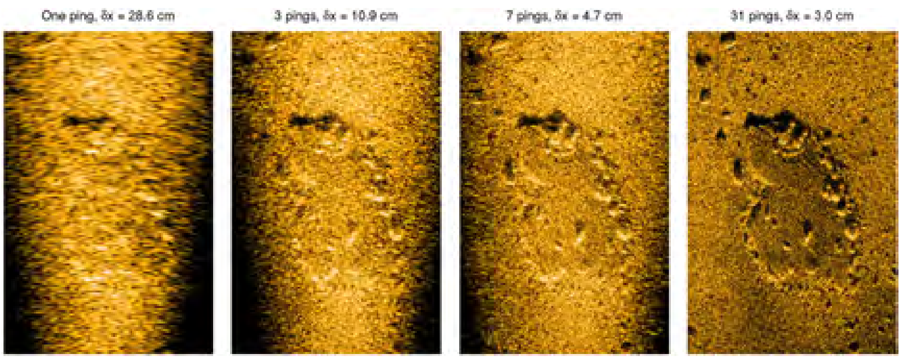


FIGURE 3

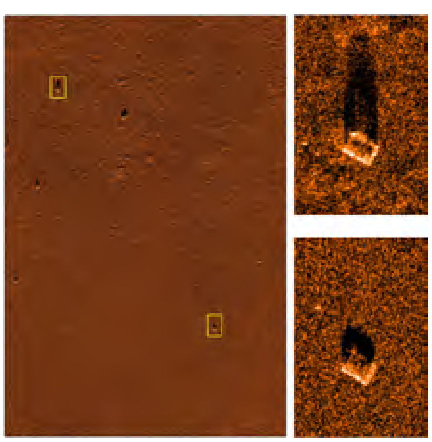
10 × 18 m image of the seabed with a large rock formation. The horizontal axis is along-track, and the vertical axis is range (cross-track). The range is 26 m. The displayed dynamic range is 40 dB in all images. The parameter δx in the text indicates the theoretical along-track resolution at the center of the image.



The maximum length of the synthetic aperture is given by the field of view of the receiver and transmitter elements. The theoretical resolution becomes range independent and only a function of the element size. This is realized by increasing the length of the synthetic aperture as a function of increasing range. This is a well-known result covered in multiple books (Curlander & McDonough, 1991; Franceschetti & Lanari, 1999). The image quality is still a function of range since the signal-to-noise ratio is range dependent. Figure 4 shows a SAS image of an 80 × 120 m scene with different objects. The range to the center of the scene is 90 m. The theoretical resolution is 3.7 × 3.2 cm. Two different sections of 4 × 6 m are shown in the right panels. These are from the 58- to 127-m range. Both sections show a drum of around 90 cm in length and 60 cm in diameter. The image indicates that the achievable geometric resolution is independent of range.

FIGURE 4

Example SAS image of a benign area with small objects. The image size is 80 × 120 m, and the range to the center of the image is 90 m. Two sections of 4 × 6 m are shown in the right panels. These are from 58 m and 127 m range. In both sections, a drum is present. The shadow behind the drum is longer at far range due to geometry. The theoretical resolution is 3.7 × 3.2 cm, and the displayed dynamic range is 40 dB.



Challenges

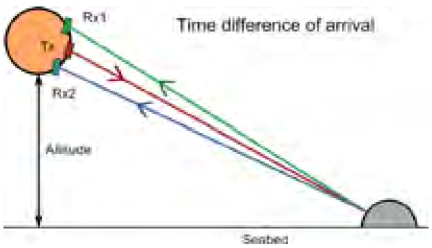
SAS is essentially space-time processing where the data are collected by a moving platform in time and thereafter processed to produce an earth-fixed spatial image. For successful SAS image processing, many challenges must be overcome. The first requirement is that the synthetic aperture (or array) must be well sampled, which dictates how the platform and sensor operate during the data collection. This leads to a requirement for the pulse (or ping) interval over the whole synthetic aperture, which again leads to a maximum range for a given speed (Cutrona, 1975). Constant area coverage rate is a feature of SAS processing, i.e., as the speed increases, the range decreases proportionally such that the product of speed and range is always constant for a given sonar system design. The next critical component is to estimate the position and orientation of the sensor at any position along the synthetic array (aperture). The accuracy required is a fraction of the acoustic wavelength for no loss of image quality. For a typical high-frequency (HF) SAS system, this leads to a relative position accuracy on the order of 1 mm, which is very difficult to obtain by traditional navigation (inertial navigation or other) on small platforms. Using the sonar data itself to improve the navigation accuracy (known as micronavigation) has been a critical step in improving the navigation precision for SAS (Bellettini & Pinto, 2002). Next, the ocean medium itself must be accurately described. A small error in the sound speed can lead to image quality degradation (defocus). In general, the seafloor topography must also be accurately described. This is particularly important when the platform carrying the sonar does not move on a straight line. In shallow waters, a particular challenge is unwanted acoustic echoes from the sea surface (known as multipath). All SAS images in this paper are from water depths where multipath has little effect. For a detailed description of the challenges in SAS, see Hansen et al. (2011).

SAS Interferometry

The principle of bathymetric mapping using interferometry is based on

FIGURE 5

Principle of interferometry in side-looking sonar imaging geometry.



estimating the time difference of arrival on two or more vertically spaced receivers as shown in Figure 5. The time difference is then turned into a direction of arrival and thereafter an estimate of the depth of the seabed. The major benefit of this technology is the potential for a large area coverage rate producing maps in the imaging sonar swath while maintaining high resolution. It requires, however, at least two vertically spaced receiver arrays. Interferometry also imposes strict requirements to the calibration and alignment of the hardware and high signal-to-noise ratio. The principle is based on estimating direction based on phase difference. A small error in the phase (not visible in the SAS intensity image) can lead to a large error in the estimated bathymetry.

Interferometry is used extensively in SAR with a level of sophistication and maturity that is impressive (Hanssen, 2001; Rosen et al., 2000). In SAR, there are typically two different ways to obtain the relevant data for interferometry: single pass with a system with two receivers or more and repeat pass where one radar antenna, typically on a satellite, revisits the same area repeatedly in order to collect data for the interferometric processing. Interferometry in SAS is similar to SAR, although there are some differences (Griffiths et al., 1997; Sæbø & Hansen, 2010).

Interferometry in synthetic aperture processing works by coregistering two (or more) images where the angle of incidence to the seabed is slightly different (as illustrated in Figure 5). Then, the phase difference is estimated in each pixel or in a group of pixels. The phase difference is then unwrapped to a time difference estimate and thereafter turned into a digital elevation map estimate. There are two major technological challenges in interferometry processing: the coregistration of images and the phase unwrapping (Ghiglia & Pritt, 1998). For wideband systems, there are alternatives to phase unwrapping in absolute phase estimation (Sæbø et al., 2013). All bathymetry results we present in this paper are processed using wideband techniques.

Figure 6 shows a fusion of a SAS image and the estimated SAS bathymetry where the depth estimate is color coded on top of the SAS image. The image shows a rock formation on a sandy seabed. The image size is 50 × 35 m, and the range to the center of the image is 50 m. The theoretical resolution in the image is 3.7 × 3.2 cm, and the geometric resolution in the interferometry is 18 × 18 cm.

Figure 7 shows a scene containing *Posidonia oceanica* seagrass on a sandy seabed. The image area is 24 × 28 m at 63-m range. The resolution is 18 × 18 cm. The seafloor depth is color coded where the depth difference between green and orange is 30 cm. This image illustrates the precision achievable both in the horizontal plane and in depth.

Figure 8 shows a fusion of a SAS image and SAS bathymetry of the Norwegian tanker Holmengraa that was sunk during World War II. The ship is 68-m long and 9-m wide. Depth is detrended and color coded where yellow equals 64-m depth and blue equals 81-m depth. The range to the center of the image is 95 m, and the image size is 50 × 80 m. The geometric resolution is the same as for

FIGURE 6

Fusion of SAS image and SAS bathymetry of a rock formation. Seafloor depth is color coded.

FIGURE 7

Fusion of SAS image and SAS bathymetry. The scene contains *Posidonia oceanica* seagrass on a sandy seabed. The depth difference between green and orange is 30 cm.

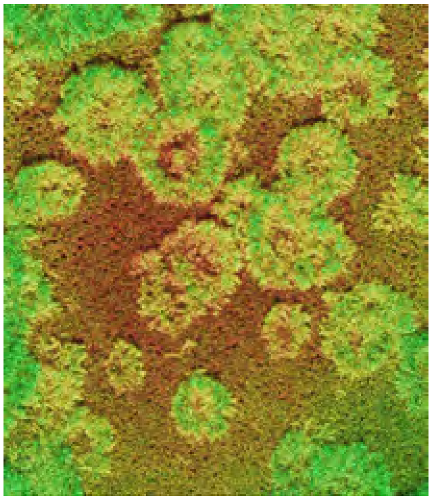
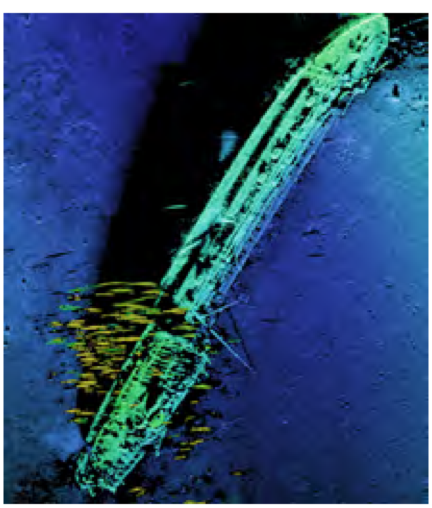


Figure 6. On top of the wheelhouse (lower left), there are some yellow streaks. These are caused by a school of fish that passed by during data collection. Each of the individual fish causes strong acoustic reflections, which makes them clearly visible. Since the fish move during data collection, they cause defocusing in the synthetic aperture processing, which typically leads to along-track smearing. This is very similar to the moving targets in SAR (Chen & Ling, 2002).

FIGURE 8

Fusion of SAS image and SAS bathymetry of the 68-m-long Norwegian tanker Holmengraa that was sunk during World War II. The yellow streaks in the image are due to fish. Data courtesy of Kongsberg Maritime, Norway.



Frequency Agility

The choice of acoustic frequency has always been a critical design parameter in sonar development. For traditional imaging sonar systems, the frequency is typically chosen as high as possible for the desired range. Since seawater is dissipative, there is an upper limit to the achievable range for a given frequency (Lurton, 2010). Then the physical array size is chosen as large as possible given limitations in cost, hardware, data processing, and space. This leads to an inevitable design dilemma: high resolution requires high frequency. Synthetic aperture technology offers an interesting possibility not available in any other type of sonar imaging. By changing the length of the array (the synthetic aperture) according to the field of view β, which equals the physical element d size measured in wavelengths λ, synthetic aperture processing can maintain frequency-independent along-track resolution. This allows for high resolution at low acoustic frequencies. In Figure 9, we illustrate this. To achieve the same along-track resolution, the lower frequency with longer wavelength λ_1 requires a longer synthetic aperture L_1 than the higher frequency with shorter wavelength λ_2.

Certain information about seabed properties and target properties are frequency dependent. The scattering from rough surfaces is also frequency dependent (see Jackson & Richardson, 2007, for a comprehensive review). Probing the seabed with several different frequency bands in SAS might therefore gain more information about the seabed and its features; however, this quickly increases the system cost. Low-frequency (LF) SAS techniques have been developed by several corporations in the defense industry to counter buried mines threats (Piper et al., 2002).

FIGURE 9

Frequency-independent along-track resolution can be obtained by choosing a synthetic aperture length as a function of frequency.

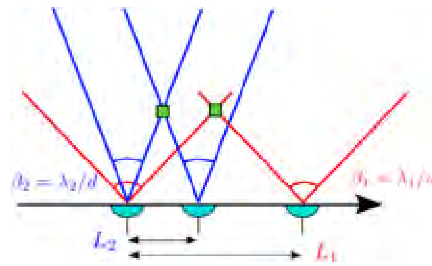
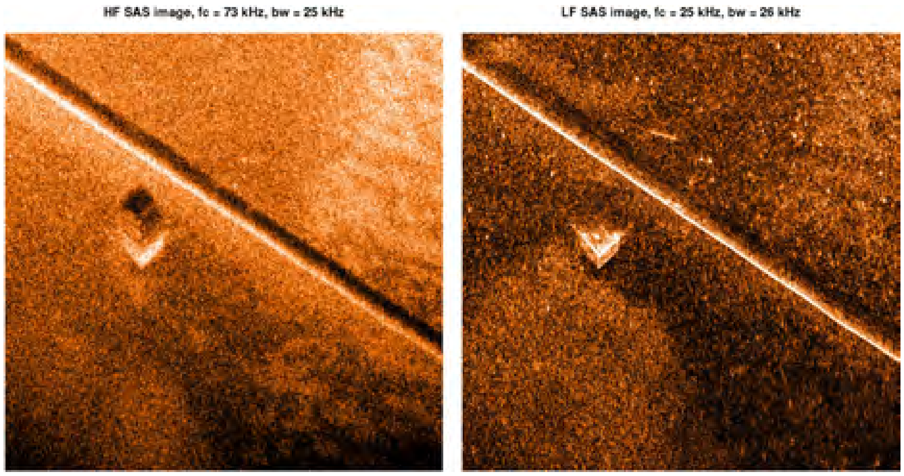


Figure 10 shows HF (left) and LF (right) SAS images taken of the same scene in the same pass. The theoretical resolution is approximately 3.8 × 3.8 cm in both images. The range to the center of the scene is 26 m, and the size of the image is 20 × 20 m. The displayed dynamic range is 40 dB in the HF image and 25 dB in the LF image. To obtain the same along-track resolution at low frequencies, the processed beamwidth is much larger at low frequencies (Synnes & Hansen, 2013). The scene contains a pipeline, a cube of size 1.5 × 1.5 m, which is probably concrete filled. The edges of the cube have a stronger signature at low frequencies than at high frequencies. This might be for two reasons: the LF SAS has a larger beamwidth and illuminates the target at more angles, and the low frequency has longer wavelength, which means that the object surfaces become smoother (measured in acoustic wavelengths). Note also the texture difference

FIGURE 10

HF (left) and LF (right) SAS images taken of the same scene.



between HF and LF in the seabed in the lower left corner, compared to other areas. This indicates that the seabed composition is different in this region compared to the area around.

Current State of Technology

There is a desire for more accurate knowledge about the ocean environment, with an increased need for high-resolution documentation of the seabed in many applications such as geophysical exploration and underwater mining, installation of offshore structures (before, during, and after), inspection of underwater structures and pipelines, offshore windmill farms, underwater archaeology, undersea sites with radioactive or toxic waste, marine habitat for marine life, and coral reefs. In many of these applications, there is a desire for high-resolution accurate images and maps, maybe collected autonomously and repeatedly. In some of these applications, the trend goes towards deeper operations (offshore oil and gas in particular).

Recent Developments That Affect the Future of SAS

The current state of the technology and the trend in high-resolution sonar imaging are affected by several recent technological developments and achievements in other fields:

- Development of high-performance computing resources with small footprints, both in field-programmable gate arrays, digital signal processors, standard CPUs, and more specialized parallel computing units such as graphics processing units. This development allows for more advanced array signal processing and higher data throughput without using costly, power-hungry, large computers. SAS is very computationally heavy due to the extra required processing per pixel and the large throughput (number of pixels per second).
- New composite material technology used in transducers provides more bandwidth and thereby higher resolution and larger frequency agility in the sonar design.
- AUVs have matured substantially during the last decade and are regularly used in many different applications. AUVs are slow-moving platforms that typically travel close to the seabed and are very stable. This makes them the perfect platforms for SAS.
- Underwater navigation on small platforms such as AUVs has improved over the last couple of decades. Navigation accuracy is a critical component for successful SAS processing. Today, advanced aided INS provides a much better starting point for advanced imaging sensors such as SAS.
- Significant improvements in SAS processing techniques have improved SAS performance while decreasing transducer fabrication costs and, thus, overall system-level costs.

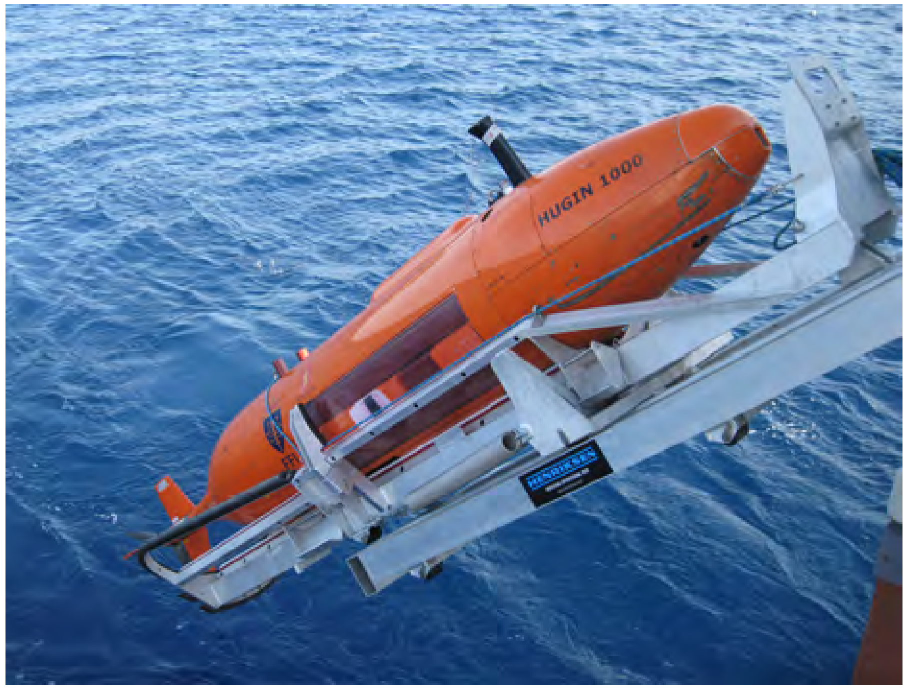
Current Sonar Systems

There are many interesting design choices in the current state-of-the-art in high-resolution sonar imaging. In sidescan sonar, noticeable systems are the Sonardyne solstice (www.sonardyne.com), which is a 32-channel phased array multibeam sonar operating at 760-kHz frequency with near-field imaging (dynamic focus) and swath bathymetry using a shorter array for interferometry with 18 wavelengths baseline; the Edgetech littoral mine countermeasure sonar (www.edgetech.com), which is a dual-frequency multipulse sidescan sonar operating at 600 and 1600 kHz, including dynamic focusing; and the L-3 Klein 5900 (www.l-3klein.com), which is a 600-kHz multibeam sonar with 1.5-m-long array, with an option to combine the sonar with swath bathymetry by interferometry on an additional sonar at 455 kHz. All of these use modern pulse forms and pulse compression to obtain longer range while maintaining high signal energy level (as all SAS systems do).

In SAS, there are also many different design philosophies in the available systems. Here, we list a few to show the variety in the systems. In Bellettini and Pinto (2009), the SAS system is specifically designed to obtain good shallow water performance. The center frequency is 300 kHz, and the array length is 1.2 m giving 200-m range at 2-m/s speed. Larsen et al. (2010) describe a system from Raytheon Applied Signal Technology (www.appsig.com) where the primary design goal is long range. The system has a center frequency of 60 kHz, and the receiver array is 4.3 m with 32 elements giving a maximum range of 1500 m at 1-m/s speed. The Ixsea (www.ixsea.com) system described in Jean (2008) has a center frequency of 100 kHz, a receiver array of length 2 m with 24 elements giving a maximum range of 300 m at 2.5-m/s speed. The Atlas Elektronik (www.atlas-elektronik.com) system described in Glover and Campbell (2010) is a dual-frequency SAS at 17.5 and 150 kHz with a receiver array of 0.6 m in length and 24 receiver elements. This gives a maximum range of 100 m at 2-m/s speed. A new SAS manufacturer, Kraken sonar (www.krakensonar.com), has a design very similar to Bellettini and Pinto (2009). The HISAS 1030 system from Kongsberg Maritime (www.kongsberg.com) from which we show all the images in this paper (Hagen et al., 2008) has a programmable center frequency, typically 100 kHz. The receiver length is 1.2 m with 32 elements giving 200 m range at 2-m/s speed. Figure 11 shows a photograph of the sensor mounted on a HUGIN AUV during launch from NATO Research vessel Alliance in Italy, October 2012.

FIGURE 11

HUGIN AUV equipped with the HISAS 1030 interferometric SAS. The SAS system is extended with LF and HF bands and real-time processing capabilities.



Similar Technologies

When forecasting future trends in sonar and SAS, it is fruitful to glance at the recent development and the current trends in other similar areas such as ultrasound, seismics, and radar.

The development of SAR has taken enormous steps since the early days of SAR in the 1950s (Wiley, 1985) to today. Examples of state-of-the-art in SAR are tomographic (three-dimensional) imaging using repeated passes (Zhu & Bamler, 2012), mapping of the earth's surface with spaceborne SAR on two satellites in formation flying (Krieger et al., 2010), airborne SAR imaging of urban areas with subdecimeter resolution (Brenner & Roessing, 2008), and bistatic SAR using a satellite SAR system as transmitter and an airborne SAR receiver (Rodriguez-Cassola et al., 2010).

Medical ultrasound imaging is a large field with a lot of research activity, very similar to sonar imaging technology-wise. Current state-of-the-art (Eklöf et al., 2012) includes large bandwidth near-field focused imaging in three spatial dimensions with Doppler velocity estimation. Harmonic imaging is an interesting technology that is widespread in medical ultrasound. The principle is to transmit on one frequency and receive on a higher harmonic of the frequency, allowing nonlinear effects in the medium to form the transition from fundamental frequency to harmonic frequencies. The potential gain is higher resolution and less aberration (distortion) of the signal. A new interesting technology is elastography or the estimation of the elastic properties of the medium through speckle tracking. The trend includes also miniaturization and portable scanners and very high frequencies above 20 MHz (Shung, 2011). Synthetic aperture processing is also shown to have applications in ultrasound imaging (Nikolov et al., 2010).

The link between SAR/SAS and seismic signal processing is very strong. Modern wavenumber-frequency-based imaging algorithms in SAR and SAS (Franceschetti & Lanari, 1999) originates from the Stolt migration technique developed for processing of seismic data (Stolt, 1978). The basic principle of seismic exploration is to transmit sound pulses through inhomogeneous layered media and use the recorded data to estimate the layering structure and properties of the media. Current state-of-the-art in seismic exploration includes massive sensor systems with more than 100,000 receivers and physics-based inversion (Blacquière, 2009). Also noticeable is the so-called 4-D seismic monitoring, which is the comparison of changes in 3-D seismic surveys as a function of the fourth dimension, time.

Future Trends in SAS

Up until recently, the major topic in SAS development was to make sure the SAS processing was successful in producing sharp images. The next steps in the development of SAS technology for seabed imaging and mapping will include the following:

- Calibrated sonars: There are very few imaging sonars today providing calibrated backscattering strengths in their images. Absolute backscatter calibration includes estimating all the terms in the sonar equation such that the sonar image will show estimated target strength (Ainslie, 2010; Lurton, 2010). This is a very valuable parameter for seabed and target characterization. Most SAR systems (spaceborne particularly) are calibrated and use the backscatter values heavily in their applications (Massonnet & Souyris, 2008).
- Frequency agility: A major benefit of SAS is the ability to produce high-resolution images independent of frequency. Frequency selective information about the seabed may be very important in seabed characterization for various applications and in target recognition.
- Robustness and autonomy: In challenging environments such as rough terrain and multipath limited environments, robustness of SAS is still a major issue. The future will include more environmentally adaptive sonar systems where the platform and the sensor automatically adapt to the actual environment and the signal processing of the data is adapted such that the best possible quality is obtained.
- Resolution: Although resolution is very high already on many SAS systems today (on the order of 1 × 1 inch resolution), certain applications will demand even higher resolution. Experimental work at several universities has significantly increased the resolution of SAS systems, however, at a price of significantly decreasing system range. Another benefit of very high-resolution images is the potential to trade geometrical resolution against target strength (radiometric) accuracy by despeckling (Oliver & Quegan, 1998).
- Mapping accuracy: In certain applications, very high-resolution maps with high accuracy are required. SAS interferometry has the potential to produce very high-resolution maps in the same footprint as the SAS image, giving large area coverage rate while maintaining high resolution. The technological development will follow the development in SAR, and more sophisticated interferometry processing will be developed. Fundamental issues such as multiple scattering, layover, and shadow will be explored. A particular challenge in the underwater domain is to estimate and correct the estimated bathymetry for acoustic ray curvatures caused by variable sound speed.
- Repeat pass processing: Following the trend in SAR, repeat pass processing for interferometry, tomography, and change detection is likely to be developed for SAS too and find its ways to different applications. There are technological challenges in SAS that are not present as strongly in SAR, one of them being the lack of absolute positioning of the platform in SAS. A critical success factor for repeat pass processing is accurate data acquisition and control, which again imposes strict requirements on vehicle control and navigation accuracy. Another critical success factor is data-driven coregistration of the SAS images in repeated passes (Midtgaard et al., 2011; Sæbø et al., 2011; Sternlicht et al., 2012).

Active Research Areas

There are several trends in the sonar and radar community that may become important in SAS. Compressed sensing (Ender, 2010) is a new technique that explores sparsity in the signal to obtain certain properties. It has gained certain popularity in radar/SAR. Multiple-input multiple-output (Haimovich et al., 2008) has widespread applications in wireless radio communications and radar. This technology includes interesting design choices in solving the spatial undersampling problem. In sonar, a popular topic in many years has been bio-inspired sonar with advanced and adapted pulse forms in combination with multioctave transmissions, which has been used (Capus et al., 2007). A partly overlapping technology is waveform diversity (Calderbank et al., 2009), which has become a research field in radar. A fairly new trend in radar is knowledge-based radar (Gini & Rangaswamy, 2008) or cognitive radar (Guerci, 2010), which essentially is to adapt the sensor to the environment and the task in hand and to adapt the signal processing for optimum signal detection. The principles for this have been known for a long time (Gjessing, 1986), but it is only recently that the sufficient computing power has become available for the principles to be implemented. In sonar, bistatic and multistatic concepts have for a while been explored, especially for military applications. Synthetic aperture processing may as well be applied in this field.

Summary

SAS has the potential for high resolution and long range at the same time, unmatched by any other sonar imaging technique. SAS technology has matured substantially during the last decade, and today, the technology is available for numerous applications. In this paper, we have given a brief review of SAS technology and shown example applications. The future in SAS development includes more sophistication in both the platforms, the sonar technology, and the signal processing.

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PAPER

Extended-Range Undersea Laser Imaging: Current Research Status and a Glimpse at Future Technologies

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ABSTRACT

Recent advancements in obtaining visibility of undersea objects at extended ranges in coastal and oceanic waters are reviewed for the years 2009 to present. The paper focuses on the latest techniques that are utilized to reduce the undesirable effects of scattering, mainly due to suspended particulate within the imaging volume, leading to the loss of contrast and blurring characteristic of undersea optical images produced over long ranges. Several recent sets of experimental results obtained using both benchtop laboratory development systems as well as field-deployable prototypes of new system concepts are presented, with observed performance attributes being discussed. Simulation studies that make use of accurate radiative transfer physical models to enable design and operation of new system concepts within a turbid water environment are also presented. Finally, this paper includes a description and results from an extended-range laser system that has reached a level of packaging and automation necessary to be available as a commercial product.

Keywords: laser imaging, lidar, underwater optics, modulation, compressive sensing

Introduction

The challenges associated with detecting and viewing objects at long distances have been difficult to overcome due to the absorptive and scattering nature of seawater. Mitigating these effects has been the focus of the underwater imaging community for decades, but recent advancements in hardware, software, modeling, and algorithmic methods have led to new sensor architectures being proposed, as well as some older concepts being revisited, equipped with the latest tools and technology. This paper has the aim of describing recent research trends in extended-range underwater laser imaging, where extended range refers to greater than 4 beam attenuation lengths (i.e., optical thicknesses) one-way between the imager and the scene.

Structure of Paper

The paper firstly summarizes the main principles of extended-range underwater laser imaging and how these principles have guided the most recent imager developments. The discussion then proceeds to describe recent work in the following categories:

1. Next generation serial lidar imaging systems:
   a. transmits temporally modulated bursts of nanosecond pulses towards scene, with gated coherent radio frequency (RF) demodulation detection stage to form each image pixel in a serial scan mode
   b. transmits single nanosecond pulses towards scene, with multiple telescopic photon collectors and a multichannel pulse deconvolution detection stage to form each image pixel in a serial scan mode
2. Spatially modulated laser imaging systems:
   a. transmits spatially modulated multiple beam patterns over entire scene, with single element detection and sequential full scene image reconstruction assisted by knowledge of point spreading within the construct of the compressive sensing (CS) paradigm
   b. transmits spatially modulated multiple beam patterns over entire scene, with confocal camera detection optics using the same modulation pattern as a mask to sequentially construct a full scene image
3. Distributed laser serial imaging systems: imaging and communications system architectures that employ multiple platforms to distribute serial scanning laser transmitters and wider angle photon collectors in bistatic and multistatic geometries
4. Commercially available flash lidar: commercially available system that transmits spatially broadened nanosecond pulse over entire scene and uses high-speed gated camera with automated features including

- polarization and variable gate delay, packaged as a portable, hand-held unit

Background

To summarize the main principals that are generally adhered to when designing extended-range underwater imagers, it is useful to consider a conventional lamp and camera system, which is by far the most commonly used imager configuration. These systems are typically contrast limited in turbid water performance after 2–3 beam attenuation lengths, which can be defined as the dimensionless product of the one-way distance between the imager and the scene in meters and the beam attenuation coefficient c in inverse meters (m^{-1}).

It can be seen from Figure 1 that the effect of scattering within the common volume can result in photons that have not interacted with the target region being accepted into the aperture of the camera (red dashed line). This is known as *backscatter* and does not contain any target information, instead leading to the characteristic loss of contrast typical with underwater images when operating in turbid water. In order to mitigate the effects of backscatter without restricting the field of view (FOV) of the imager, it is possible to increase the separation between the lamp and camera, thereby reducing the common volume formed between them. Another possibility is to use a very short pulse of light, of the order of 5 ns or less, and to precisely control the camera integration time so that photons from the backscatter region do not enter the aperture during this time. This is known as *range gating* and is the main principal behind the flash lidar system concept, which is shown in Figure 2 (left) and the commercial system described in the Example of a Commercially Available Flash Lidar section.

Referring back to Figure 1, the purple dashed line represents a portion of the transmitted light energy, which does interact with the target but before and/or after reflecting from the target region is scattered in the forward direction at a small angle, so that at the image plane, this energy is captured and recorded in a position slightly offset to where the reflectance information it carries originated. This is known as forward scattering and is typically the reason why long range underwater images appear blurred even in relatively clear water, where refractive index microstructure caused by the mixing of water masses with differing densities can lead to observable fuzziness due to multiple small-angle forward scattering. In more turbid water, with significant concentrations of suspended particles, forward scattering appears as a glow, particularly around bright target objects. In order to reduce the undesirable collection of small-angle blur-glow forward scattering, it is necessary to reduce the FOV of the detector, to restrict collection of forward scatter from adjacent regions of the target, and also to restrict scattered light from entering the FOV on the return path.

In order to restrict the FOV without sacrificing the total swath, it is necessary to employ a serial scan imaging techniques, such as laser line scan (LLS) (shown in Figure 2, right). LLS was proposed to partially mitigate the collection of both backscattering and forward scattering by means of spatially restricting the detector FOV, hence common volume and using a narrow collimated beam to maximize photon density on each target element, while optical scanning in a synchronous fashion over a wide total swath (70–120°), generating one image element at a time. The combination of telescopic detector optics with good collection efficiency and a very sensitive detector, such as a photomultiplier tube (PMT), commonly used in LLS are designed to maximize sensing of resolution element photons.

Although LLS is widely regarded as one of the optimal technologies for extended-range underwater optical imaging, researchers have established the main mechanisms responsible for the technique becoming limited in certain conditions, and operators have found the system to perform successfully within quite a narrow range of conditions, with additional reliability issues due to the hardware-centric nature of the

FIGURE 1

Left: typical underwater image reduced in contrast and resolution by volumetric scattering. Right: diagram of conventional lamp and camera underwater imaging system, showing direct, backscatter and forward scatter paths. (Color versions of figures are available online at: http://www.ingentaconnect.com/content/mts/mtsj/2013/00000047/00000005.)

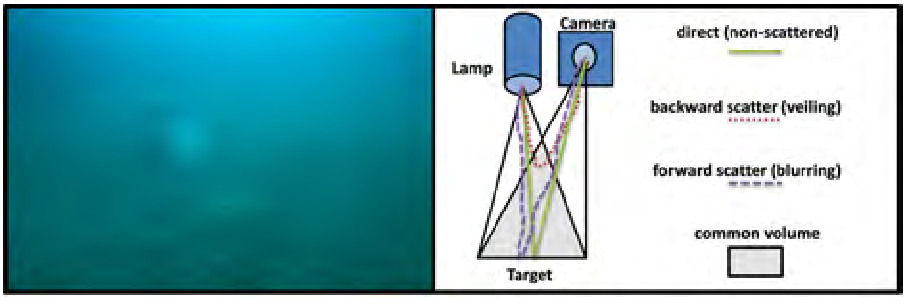
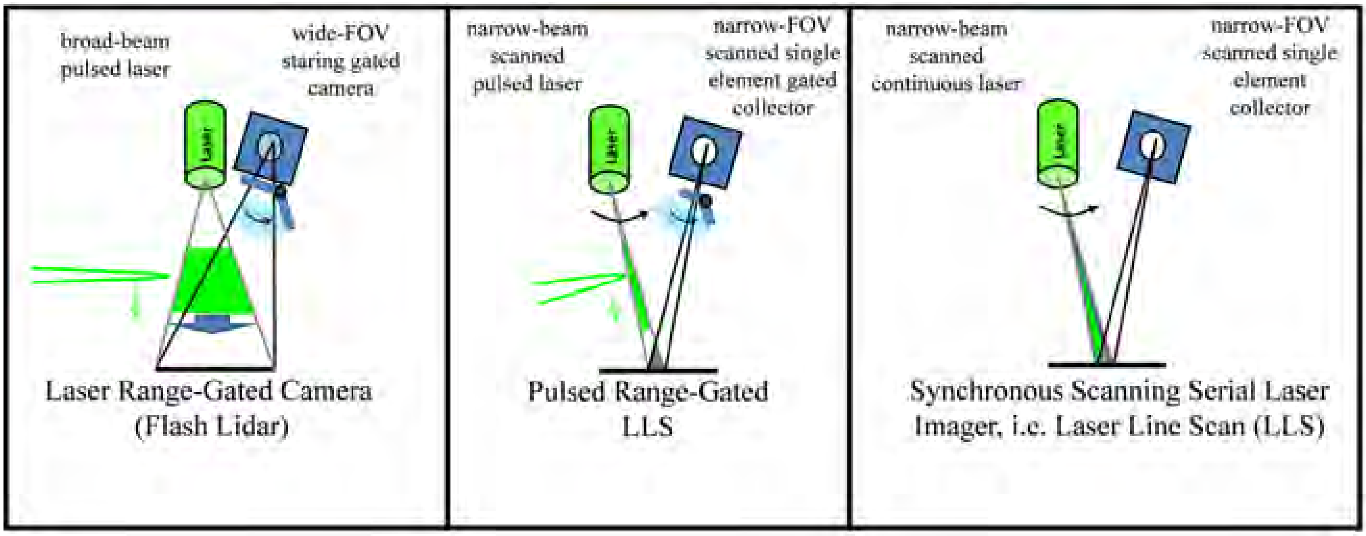


FIGURE 2

Laser range gated (LRG) and LLS general classes of extended-range underwater laser imaging systems, which have the main objectives of reducing the collection of nonimage resolution photons, while maximizing the collection of image-bearing photons.



sensor, particularly a number of complex moving parts. From a performance perspective, Strand (1998) has shown that LLS imagery produced in typical coastal conditions (c = 1.0 m^{-1} at 4.6-m range) when using a continuous wave (CW) laser source and wide separation distance between the source and receiver (0.5 m), depicted in Figure 2 (right) is limited in contrast and resolution by common volume backscatter and small-angle blur-glow forward scatter. Dalgleish et al. (2009a) have shown that when one considers more compact versions of LLS, amenable to packaging on an unmanned underwater vehicle (UUV), depicted in Figure 2 (center), there is a performance benefit in rejecting the multiple backscattered component at the formation stage for each image element by employing a pulsed laser and gated detection scheme. The use of such schemes is also advantageous with respect to reducing overall system package size, providing three-dimensional (3D) information via time of flight, and is also effective at reducing the average photodetector current and associated shot noise produced due to near field multiple backscatter and solar illumination. The challenge for the pulsed source/gated receiver approach is to turn the optical receiver on with sufficient speed and with low noise so that only light within the round trip time to and from the object is detected. This is especially difficult when the sensor is close to the object of interest since the receiver must turn on and reach a constant sensitivity within tens of nanoseconds. Mullen et al. (2004) have previously shown that amplitude modulated CW laser sources together with a coherent RF demodulator at the receiver can help reduce the collection of unwanted backscatter.

When one considers that the primary objective of the classes of imagers shown in Figures 2 is to only capture photons that traveled directly to each element of the scene, transferring image information directly back to the detector, they are known as line-of-sight (LOS) imagers and are typically deployed in near-monostatic configurations on the same deployment platform. In the Distributed Laser Serial Imaging Systems section, we examine bistatic imaging concepts that attempt to limit scattering effects by using extreme separation, where the laser transmitter is deployed on one platform positioned closer to the target and the photon collector/s is deployed on another, more distant from the target. These distributed systems are consequently known as non-line-of-sight (NLOS) imagers because they attempt to capture all the photons emitted by the transmitter in order to reconstruct an image using scattered light.

In addition to introducing the most important principles in extended-range undersea laser imaging and attempting to classify the previous and latest approaches, the intent of the sections that follow is to give the reader an insight into several recent research advances in extended-range laser imaging that could form the basis of future commercial systems and also to give an example of a compact commercial system already available.

Next Generation Serial Imaging Lidars

Background

A new approach is currently being investigated that combines the advantages of the modulated CW and pulsed range-gated approaches. This modulated pulse system, the concept behind which is depicted in Figure 3 (left) uses high-frequency (>0.5 GHz) intensity modulation within a 10–20 ns macro pulse. Unlike the previous approach implemented with a CW source (Mullen et al., 2004), the modulated pulse approach enables the receiver to be gated to attenuate strong near-field backscatter, which can otherwise reduce dynamic range, increase shot noise current, device saturation and even component damage. Furthermore, the receiver gate requirements (extinction and rise time) are less stringent for the modulated pulse receiver due to the fact that the high-frequency modulation within the pulse already provides a way to discriminate against backscatter. This has enabled a tradeoff between the gate extinction and rise time to minimize the additional noise that typically arises from gating an optical detector. Furthermore, results from tests conducted to measure the propagation of light modulated at frequencies >0.1 GHz show that these high modulation frequencies can also potentially be used to discriminate against small-angle blur-glow forward scatter (Mullen et al., 2009a).

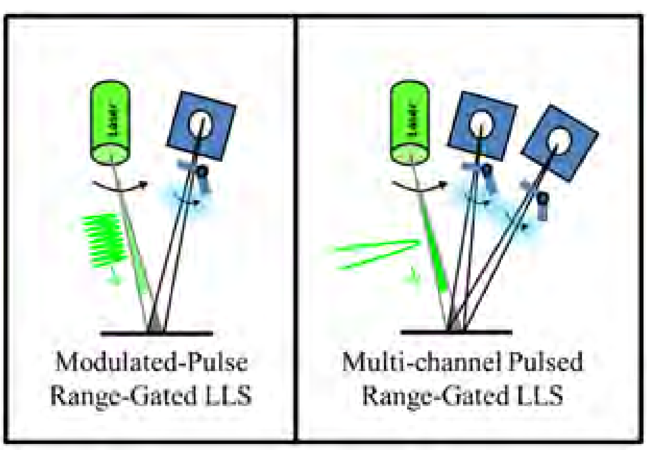
Initial work was focused on evaluating the effectiveness of the modulated pulse approach in a static, nonimaging geometry. Results showed that the use of both single tone and coded waveforms within the pulse provide an effective way to discriminate against unwanted backscatter (Mullen et al., 2011; Cochenour et al., 2011). More recently, hardware has become available to permit testing of the modulated pulse approach in a dynamic, imaging geometry, with results demonstrating the removal of common volume backscatter and small-angle blur-glow forward scatter in turbid water imagery (Mullen et al., 2013).

Somewhat conversely to the multiple pulse/single detector configuration, another approach that uses single pulses/multiple overlapping detectors (i.e., multichannel) has recently been explored as an alternative to further enhancing the image quality performance of pulsed range-gated LLS. Such a configuration offers the potential to maximize collection of resolution element photons while still minimizing the collection of nonimage resolution photons. The system concept is depicted in Figure 3 (right).

A benchtop experiment was recently performed (Ouyang et al., 2012) in which the objective was to study the application of multichannel deconvolution (MCD) to exploit the advantage of this architecture in improving resolution element photon reception and reducing small-angle blur-glow scattering effects at each image element. The use of bilateral pulse shaping was applied to improve signal-to-noise ratio (SNR) for target return pulses and the use of a time-dependent radiative transfer model, which predicts pulse spreading in a known geometry and environmental conditions, was used at the multichannel pulse deconvolution stage. Although computationally intense, this method has been shown to restore acceptable contrast and resolution for pulsed range-gated LLS images that are severely degraded due to forward scattering and attenuation.

FIGURE 3

New approaches to time-resolved LLS underwater imaging.



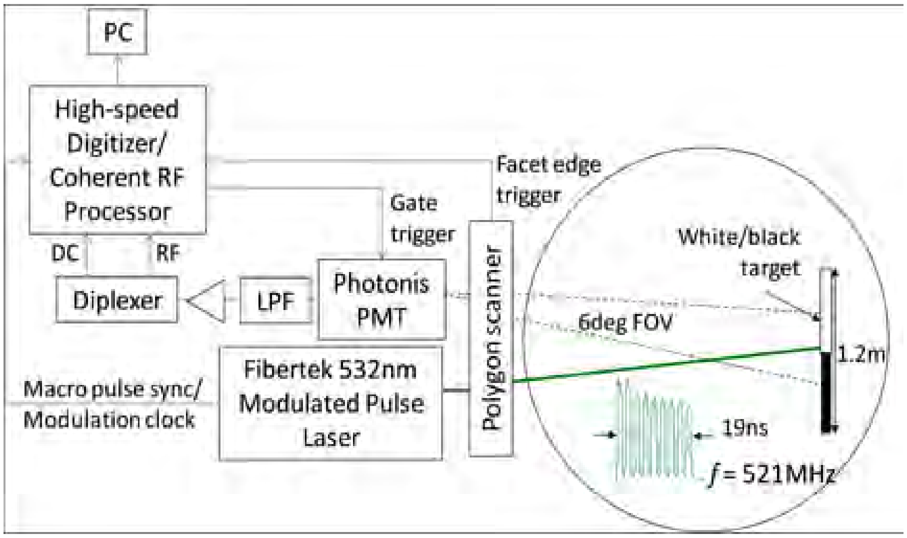
Modulated Pulse

The bench-top modulated pulse laser imaging system prototype consists of a modulated pulse transmitter, synchronous optical scanner, wide bandwidth, gated optical receiver, and the high-speed digital coherent RF processor. A block diagram showing how these components are interfaced in the bench-top system is shown in Figure 4. The general system concept is depicted in Figure 3 (left).

As shown in Figure 4, the 532-nm laser was operating with 19 ns macro pulse width, 521 MHz amplitude

FIGURE 4

Block diagram of the bench-top modulated pulse system (Mullen et al., 2013).



modulation, 500 kHz macro pulse repetition rate, and 2 W average power. A custom laser developed by Fibertek Inc. (Herndon, VA) was used to generate modulated pulses and also provided the necessary timing signals to synchronize and phase lock the digitizer/coherent RF processor.

The synchronous scanner design was similar to the pulsed range-gated LLS imager previously demonstrated (Dalgleish et al., 2009b), which consists of a six-faceted polygon that rotated at a rate of 500–4000 RPM and scanned the beam at 50–400 lines per second over a 60° FOV. A pair of symmetrical folding mirrors on either side of the polygon was used to overlap the laser beam path and telescopic receiver FOV at the desired target range. The system is described in more detail in US Patent 11/857,039 (Dalgleish et al., 2011), with a comparison to other synchronous line scanners in (Dalgleish & Caimi, 2011).

The gated optical receiver consisted of an adjustable telescope placed in front of the gated PMT, producing a 5.1° full angle FOV. The gate delay and length were controlled by timing signals provided by the high-speed digitizer/coherent RF processor to a custom-gating circuit, which functioned by swinging the voltage applied to one of the dynodes so that the sensitivity of the PMT changed by 10 dB within 50 ns.

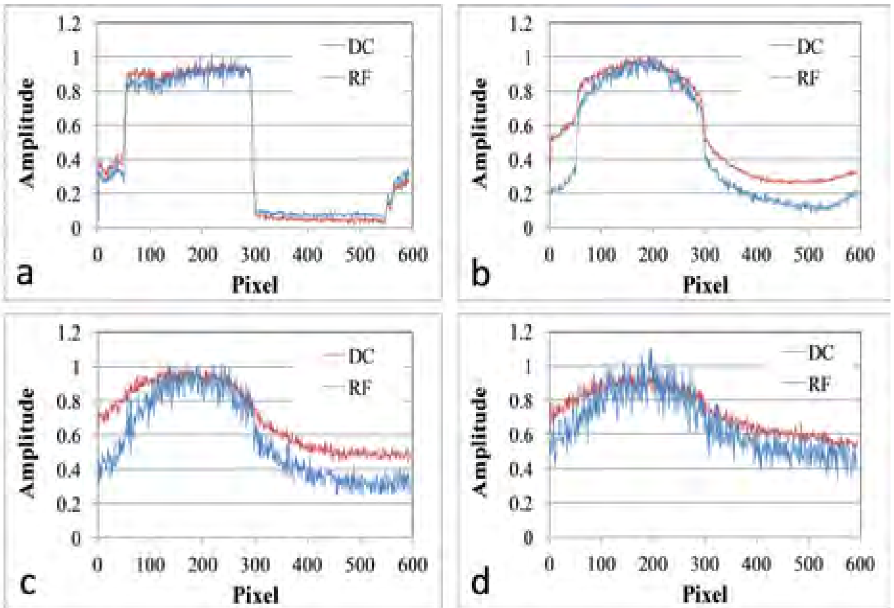
The digitizer clock of the high-speed digitizer/coherent RF processor was locked to the RF modulation signal that was generated from the laser, allowing digitization of the PMT signal to be performed at exactly four times the RF modulation frequency, so that the RF signal could be digitally demodulated into its in-phase and quadrature-phase components, also ensuring phase coherency between the transmitter and receiver. The output of the PMT was also low pass filtered and amplified via a high-speed, low-noise amplifier. The signals were then split into high-frequency (RF) and low-frequency (DC) components via a diplexer, to be synchronously sampled by the digitizer. A PC running LabView connected to the high-speed digitizer/coherent RF processor was used to control the various timing delays and collect, process, and then display the imagery data.

The entire system was mounted in front of an access window at one end of a 7.2-m diameter water tank. A 1.2-m black (3% reflectance) and white (95% reflectance) split target was submerged and placed on the opposite side of the access window with a propagation distance of d = 7 m. Maalox antacid was added to the tank to vary the water turbidity, and a WetLabs C-Star transmissometer was used to measure the beam attenuation coefficient, c (m^{-1}), at 532 nm. Data were acquired with and without gating the PMT. When the PMT was gated, the gate trigger timing was adjusted so that it was applied approximately 50 ns prior to the anticipated target return signal. As previously determined (Dalgleish et al., 2009b), image contrast and dynamic range were improved by removing the near-field backscatter signal using the gated detector.

However, the results shown in Figure 5 show the additional advantage of forming images via digital coherent RF demodulation, which attempts to further improve image quality by removing small-angle blur-glow forward scatter. The curves represent a 600-pixel line generated as the laser and detector are synchronously scanned over the white to black portions of the target. The red curve represents the low-frequency (DC) image, which is the equivalent of a line from a pulsed-gated LLS image, while the blue curve represents the same line from the modulated pulse-gated LLS (RF) image, which has been demodulated to reduce the small-angle blur-glow signal. Therefore, despite both cases gating out the backscatter, there is an additional enhancement in contrast apparent in the RF line images. These results

FIGURE 5

"DC" and "RF" line images obtained with a gated PMT by integrating the "DC" and "RF mag" waveforms for each scanner position across the target scene. The images correspond to 0.56 (a), 3.78 (b), 5.18 (c), and 6.09 (d) attenuation lengths between the system and the underwater target (Mullen et al., 2013).



indicate that the modulated pulse approach has the potential to enhance both the contrast and resolution of underwater images in turbid water environments.

However, perhaps the greatest advantage of this approach, particularly in very turbid water over shorter ranges, is a relaxation of the presently hardware-limited requirement of gating the detector into a stable "on" state in a very short period of time, since the common volume backscatter can instead be removed via the RF processing stage. The system is also able to recover phase and hence target range (distance), although such results are not shown. A more detailed system description together with 2D/3D imaging performance analysis will be provided in future literature by Linda Mullen and Brandon Cochenour from NAVAIR.

We now examine another recent approach to enhancing performance of the serial imaging lidar, which utilizes a single short pulse and multiple detectors rather than multiple short pulses and a single detector. The concept for this system is depicted in Figure 3 (right).

Multichannel Pulse Deconvolution

A prototype LLS/lidar receiver has been developed at Harbor Branch to support ongoing undersea laser imaging and communications research activities. The receiver consists of an array of multiple, small, low-cost detectors operable in a variety of configurations within a glass dome (Figure 6).

A pulsed LLS system consisting of a multielement receiver can be modeled as a single input–multiple output (SIMO) architecture as shown in Figure 6 (right). Ouyang et al. (2012) studied the application of the MCD to exploit the advantage of this architecture to enhance underwater laser reflectance and range images. Figure 7 (top) shows the MCD processing flow.

In this approach, a nearest neighbor bilateral pulse shaping is first applied to improve SNR for all pulses, MCD is performed in the time domain to further enhance the pulse reflectance signal for each individual pixel. The final intensity image is then reconstructed using the enhanced pulses. In the current nonblind deconvolution implementation, the Electro-Optic Detection and Simulation radiative transfer models (EODES) developed by Metron Inc. (Reston, VA) (Giddings & Shirron, 2009) was used to predict the point spread function (PSF) with given inherent optical properties (IOPs) and system conditions. The channel weight factor is determined per pixel via the normalized correlation coefficients between the pulses for each channel and that of the reference channel (i.e., channel with lowest average pulse noise floor), shown in Figure 7 (top). Further improvement to the technique that adaptively enhances the image, the PSF and the channel weight factors in a semiblind fashion is under investigation. While not studied within the scope of this work, this postprocessing centric technique can be readily integrated with other emerging technologies such as the modulated pulse system.

The experiment was conducted in Harbor Branch large electro-optics tank, a 13-m controlled turbidity test facility. The laser used in the experiment was a 30-µJ 1-ns pulsed green laser with a 500-Hz repetition rate. A 1-GHz bandwidth PMT with 50-mm diameter telescopic optics forming a 4° full angle FOV was used as the receiver in the experiment. The target was mounted on a linear drive capable of horizontal/vertical motion to simulate scanning. The target distance was

FIGURE 6

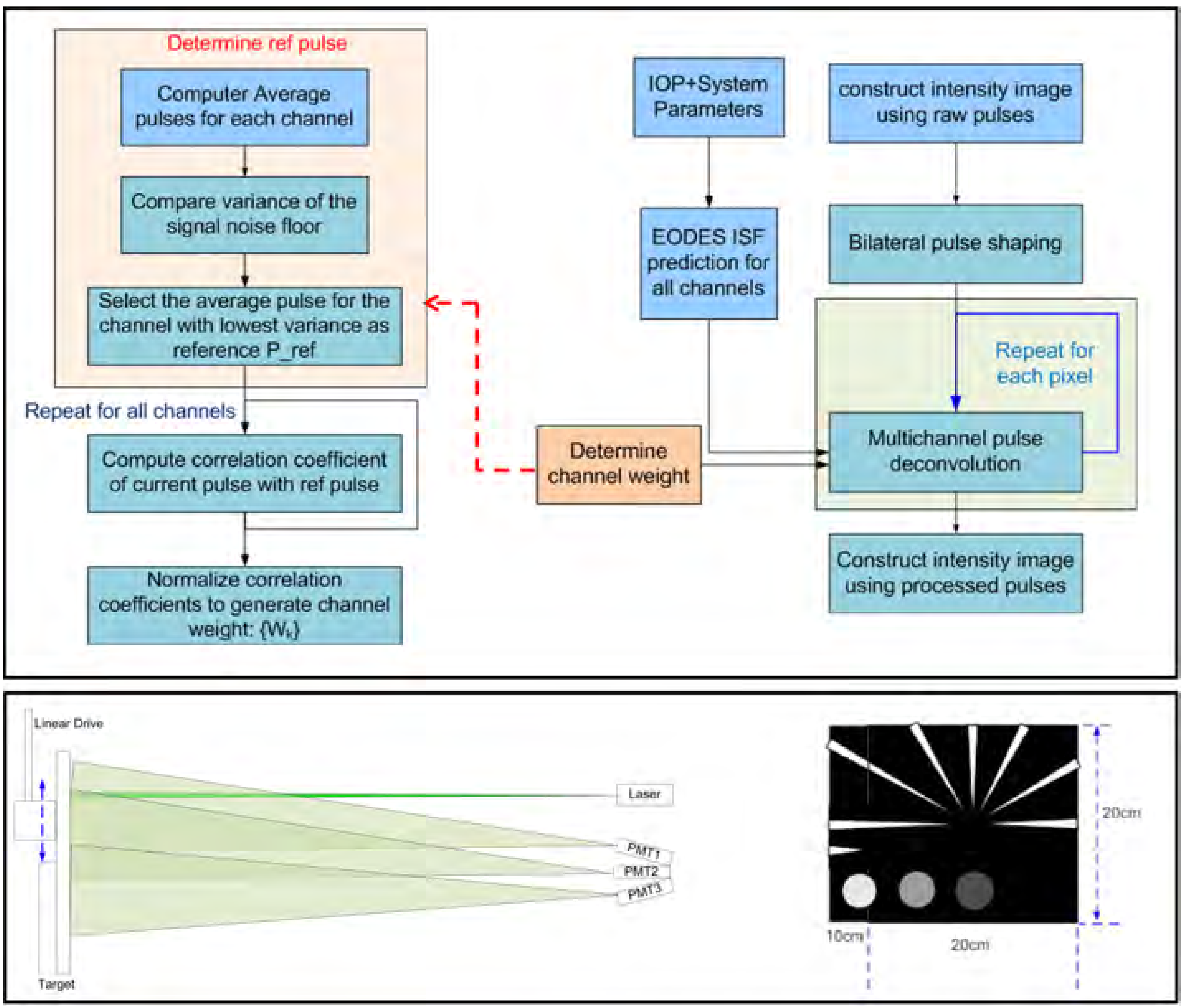
Left: multiple-element LLS/lidar receiver. Right: LLS system concept with multiple-element receiver (Ouyang et al., 2012).

10.56 m. Arizona test dust was used to change water turbidity (total of four different turbidities), and a WetLabs ac-9 transmissometer was used to measure beam attenuation and absorption coefficients at 532 nm.

At each turbidity increment, backscatter and target return waveforms were acquired at 3 PMT offset angles (0, ±3°). The separation between the

FIGURE 7

Top: Multichannel processing flow. Bottom left: Multichannel pulsed-LLS experiment setup. Bottom right: Test target with dimensions. Adapted from Ouyang et al. (2012).



laser and PMT was 0.32 m. A target with a dimension of 30 cm × 20 cm was used in the experiment. The top part of the target consisted of a start chart; three calibrated Spectralon™ 40-mm diameter medallions were mounted at the bottom (Figure 7, bottom right).

Figure 8 shows the experimental and processing results using the above setup. The images acquired were all at a resolution of 30 × 20 and are scaled up to enable better examination. The results show that multichannel processing resulted in enhanced image quality, especially at high-turbidity cases. The most interesting result is that meaningful imagery was obtained in the MCD processed image at 8.8 beam attenuation lengths, which was well above the normal operational limit of 5–7 beam attenuation length for a pulse-gated LLS system (Dalgleish et al., 2009b). It should be noted, however, that the target Spectralon™ medallions were 50%, 75%, and 99% reflectance, which is much higher than a natural seabed object. The laser pulse energy of 30 μJ, which is the equivalent of 15 W average power (at the 500 kHz pulse repetition rate that was utilized in the previously described modulated-pulse demonstration) is a factor of seven times higher in average power than the laser used in the modulated pulse tests.

Spatially Modulated Laser Imaging Systems

Background

A new system concept for extended-range underwater imaging, which has the goal to reduce hardware complexity and hence overall system cost, is the spatially modulated serial laser imager (Ouyang et al., 2013a), which can be considered a hybrid flash-serial system (shown conceptually in Figure 9, left). This system employs a solid state spatial light modulation device such as the digital micromirror device (DMD) to project a matrix of laser beams in certain patterns or measurement matrices onto the scene and uses a serial imaging architecture (i.e., a wide aperture "bucket" photon collector with a very sensitive single element detector). The theoretical foundation of the system is the CS theory (Donoho, 2006; Candes & Tao, 2006) that exploits the signal sparsity in the underwater electro-optical images, which increases with increasing water turbidity, in order to reduce the amount of data required to reconstruct a sufficiently high-quality image. A line sensing lidar version of the system using patterned fan beam is also under development (Ouyang et al., 2013b).

Similarly motivated by the need for a compact, more reliable system, a structured illumination and ranged gated camera (SIRGC) technique was recently described by Jaffe (2010). DMD-based confocal optics were used to spatially modulate a laser pulse into multiple beams that were separated by a predefined distance at the target plane. Such separation ensured that there was less overlap between beams after spreading in turbid water. The target reflection was modulated by the same DMD pattern and focused onto a range-gated camera via confocal optical design. This general system concept, which can also be described as a spatially modulated flash lidar, is depicted in Figure 9 (right). In this section, a radiative transfer image simulation study is presented to compare expected performance of these two spatially modulated system concepts.

FIGURE 8

Multichannel denconvolution PLLS experiment results.

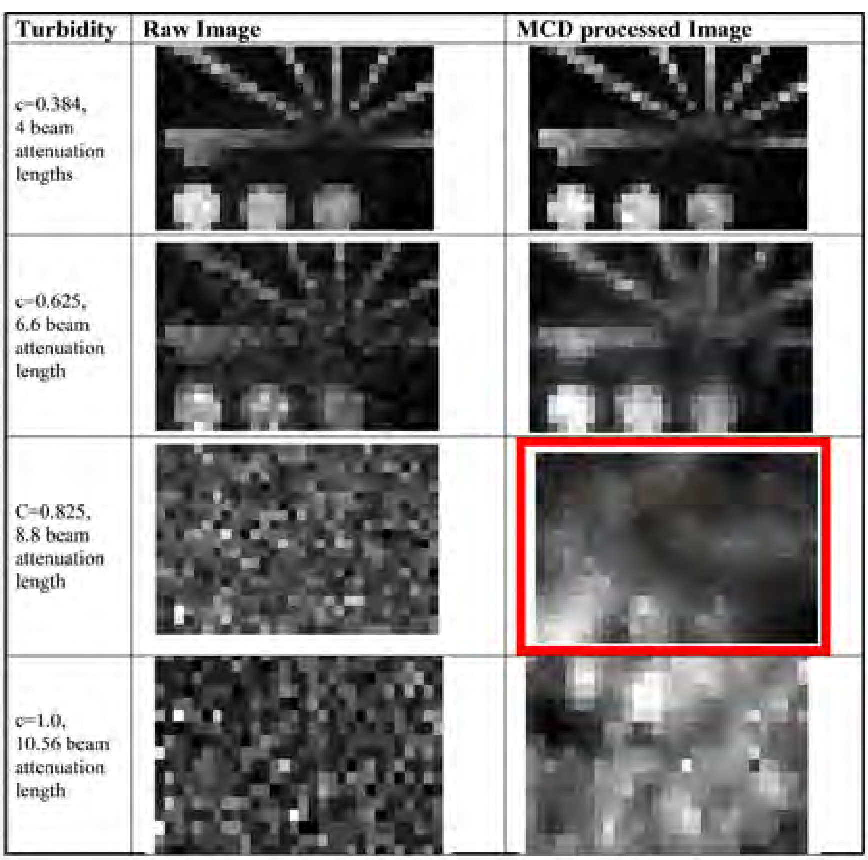
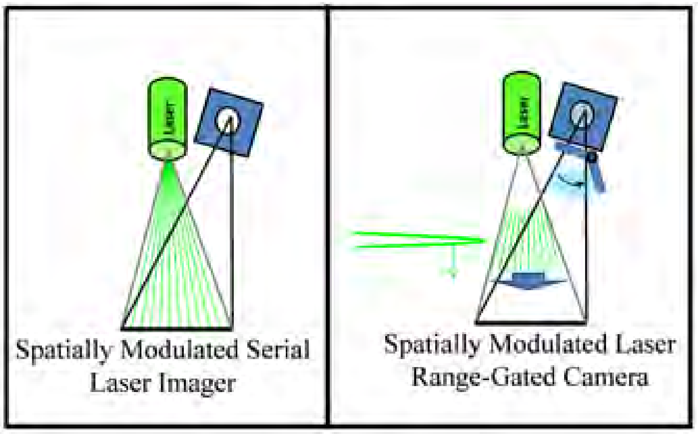


FIGURE 9

New approaches with spatially modulated underwater laser imaging (left: hydrid flash serial imager, right: spatially modulated flash lidar).



CS Hybrid Serial-Flash Laser Imager

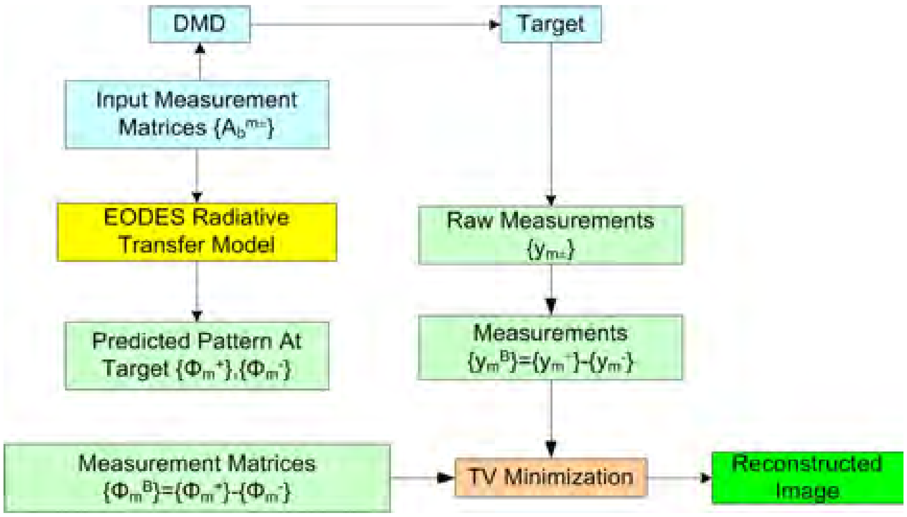
Motivated by the need to simplify optics, electronics, reduce unnecessary data volumes and be more immune to motion artifacts, while also exploiting the fact that underwater electro-optical images do become more sparse with increasing turbidity, Ouyang et al. (2013a) has proposed a CS underwater laser imager, which can be considered as a hybrid of a flash lidar and the serial LLS system. During the sensing process, the illuminating laser is focused onto the DMD loaded with binary illumination patterns, which are rapidly projected onto the target surface in a predefined sequence. At the receiver, as with the LLS system, a single element "bucket" collector focuses collected light onto a sensitive detector such as a PMT to measure the total photon flux in response to the modulation of each pattern with the target plane. The illumination patterns and these corresponding PMT measurements are then provided as inputs to an optimization process that reconstructs the image. The transmitter and receiver can be colocated, such as the near monostatic LLS system or on different platforms like the distributed laser serial imaging (described in the Distributed Laser Serial Imaging Systems section). Such an algorithm-centric design also has the potential to be more adaptive to the changing environment and/or task requirements.

The overall system is summarized in the flowchart of Figure 10. The same binary matrices that are projected onto the scene are also processed through a radiative transfer model to predict the measurement matrices at the target plane once subjected to the small-angle blur-glow scattering process. As the PMT records the total optical return signal, the difference between polarity-flipped pairs of measurement matrices (predicted with opposite polarity binary patterns in an attempt to cancel out volumetric scattering) constitutes one input to the reconstruction process, and the difference between their corresponding PMT measurements constitutes the other input to the reconstruction process. In the current implementation, total variance (TV) minimization under a quadratic constraint is adopted for the image reconstruction process. Extensive simulations were conducted to evaluate the proposed technique and compare the performance of the proposed technique with that of LLS sensors and a spatially modulated camera-based imager. Initial proof-of-concept tests were also conducted in the Harbor Branch electro-optics test tank. Some simulation results are reproduced below. More details describing the mathematical approach and the simulation and experimental results can be found in Ouyang et al. (2013a).

In the CS, PLLS, and SIRGC simulation results that follow, the laser and receiver (PMT or range gated camera) separation was set to 0.4 m throughout. The target scene was 1.2 m × 1.2 m and was located 7 m away from the illuminator-receiver assembly. The resolution of the image and the sensing patterns was 64 × 64 pixels. The average laser power for all three systems was set to 4 W. For the CS system, the DMD refresh rate was 4 kHz, and for SIRGC, the refresh rate was 100 Hz. The laser divergence angle for all three systems was 2 mrad, whereas the full angle receiver apertures were set to 1° for PLLS system, 5.3° for the CS system, and 30° for the SIRGC system. For both PLLS and SIRGC, perfect gating is assumed. Receiver device noise was introduced to the measurements to capture the effects of shot noise and random variations in PMT gain using a PMT noise model developed by Metron Inc. and Harbor Branch (Rashkin et al., 2012). The comparison of model-assisted reconstructions with and without polarity flipping, as well as reconstructions using binary matrices (with polarity flipping), at 7 beam attenuation lengths over 7 m stand-off distance ($c = 1.0\ m^{-1}$) were evaluated using the Star Chart (Figure 11). When no polarity flipping was used, the measurements and measurement matrices were converted

FIGURE 10

CS-based hybrid serial flash laser imager system flow chart (Ouyang et al., 2013a).

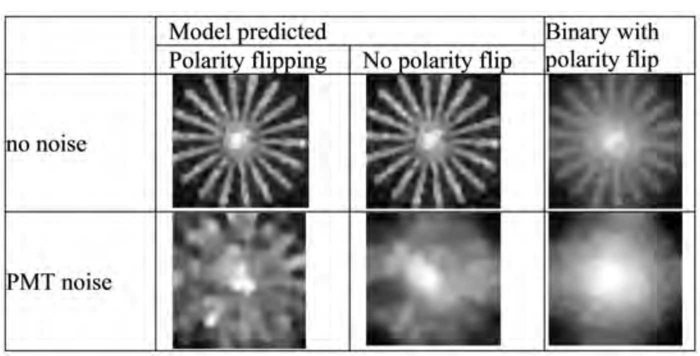


to bipolar signals by subtracting the mean of all measurements and measurement matrices before normalizing to unit amplitude. When there was no noise added, better contrast and resolution were achieved using model predicted measurement matrices as opposed to using the binary illumination patterns. It was found that there was no significant difference when polarity flipping was employed in the absence of noise. However, when noise was added, better image resolution seemed to result when polarity flipping was engaged.

Figures 12 demonstrates CS imager performance against various test images at different turbidities. These images consisted of both test patterns (star chart and geometry patterns) and images taken in underwater environments (coral, fish, and diver), therefore with typically varying contrast and levels of detail.

FIGURE 11

Simulated reconstructed images at 7 beam attenuation lengths, showing the impact of radiative transfer model-predicted and polarity flipping measurement matrix implementations, with and without PMT noise (Ouyang et al., 2013a).



Spatially Modulated Confocal Flash Lidar Imager

A spatially modulated flash lidar system concept, known as SIRGC technique, was recently described by Jaffe (2010). DMD-based confocal optics were used to spatially modulate a laser pulse into multiple beams that were separated by a predefined distance at the target plane. Such separation ensured that there was less overlap between beams after spreading in turbid water. On return from the target, the collected pattern was spatially modulated by a DMD and focused onto a range-gated camera via confocal optics. Finally, an image synthesis process was proposed to reconstruct the uncompressed image using all of the subimages, as shown in Figure 13 (top).

The CS hybrid flash-serial imagery performance was compared in simulation to the SIRGC. To verify the simulation integrity, when there was no noise added, the SIRGC results, shown in Figure 13 (bottom), were in good agreement with those reported in (Jaffe, 2010).

Figure 14 shows the results when noise was added in the simulation. To improve the SNR in the SIRGC simulation, each subpattern was imaged 50 times and averaged, so the pulsed laser repetition rate was effectively 5 kHz, with DMD updating at 100 Hz. At the higher turbidity (7 beam attenuation lengths), the SIRGC image was dominated by noise. This can be explained by observing that, for both CS and SIRGC imagers, only a small fraction of energy reached/reflected from each target element; however, for the CS imager the total reflected photons were used in image reconstruction, whereas with SIRGC, the camera needed to discern the intensity for each individual target element.

FIGURE 12

Simulated reconstructed images using model-predicted measurement matrices with polarity flipping at different turbidities. PMT noise is also added (Ouyang et al., 2013a).

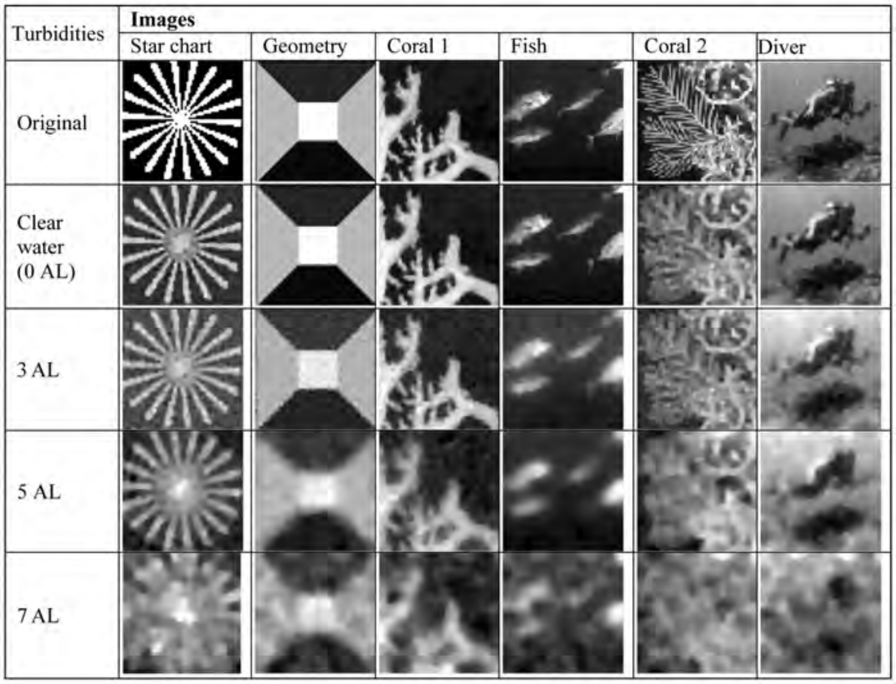
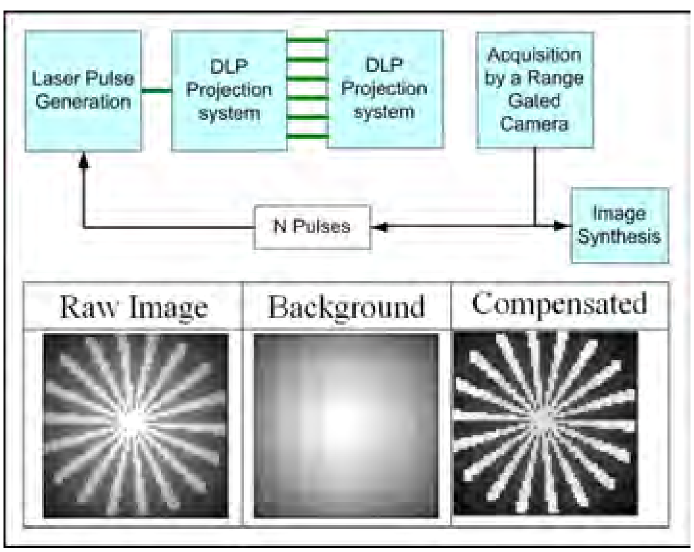


FIGURE 13

Top: Process flow for structured illumination-based imager (SIRGC). Bottom: SIRGC at 3 beam attenuation lengths with no added detector noise. Adapted from Ouyang et al. (2013a).



At 3 beam attenuation lengths, while the SIRGC image was noisy, it appeared to retain good image resolution. However, the SIRGC simulation results warrant some additional comments. First, in SIRGC, in addition to generating the illumination patterns, the DMD also serves as the receiver mask in front of the camera image plane. As in most confocal imaging applications, such a pinhole mask helps to achieve the balance of the light intensity and sharpness. By adopting the same single-pixel mask as in (Jaffe, 2010), the simulation assumed the smallest pinhole and therefore maximum sharpness; however, the impact on the noise performance due to the photon loss from such a small pinhole was not considered in the simulation. Secondly, adopting the PMT noise model in the simulation for each camera element also improved the noise performance since a PMT in general provides superior low light signal to noise than the charge-coupled device (CCD) used in the camera. On the other hand, while in simulation, each subpattern was imaged 50 times to improve the signal to noise of the SIRGC system, high-speed cameras capable of thousands of frames per second are now commercially available. However, a thorough study of the performance of the SIRGC concept needs to consider the tradeoffs among all of these factors.

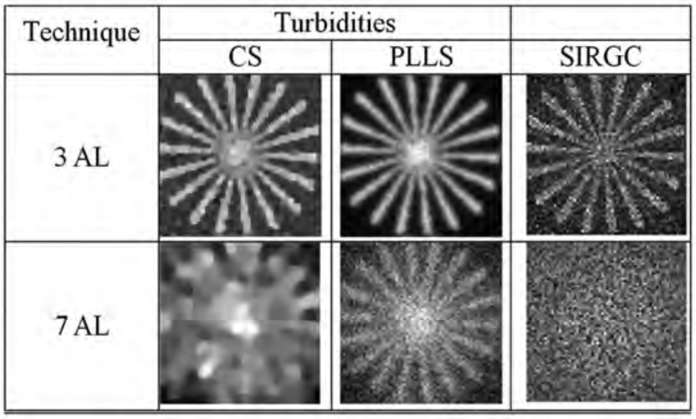
Distributed Laser Serial Imaging Systems

Background

Other recent serial imaging approaches that specifically rely on multiple platforms to greatly extended imaging range and also the range of conditions over which image reception is possible are presented in this section. These systems are somewhat unusual in that the laser source and detector subsystems are mounted on separated underwater platforms. Such a system concept, which attempts to remove the effect of nonimage resolution element photons by employing large separation distances between the source and receiver (tens of meters in coastal

FIGURE 14

Simulated image comparisons among CS, PLLS, and SIRGC (Ouyang et al., 2013a).



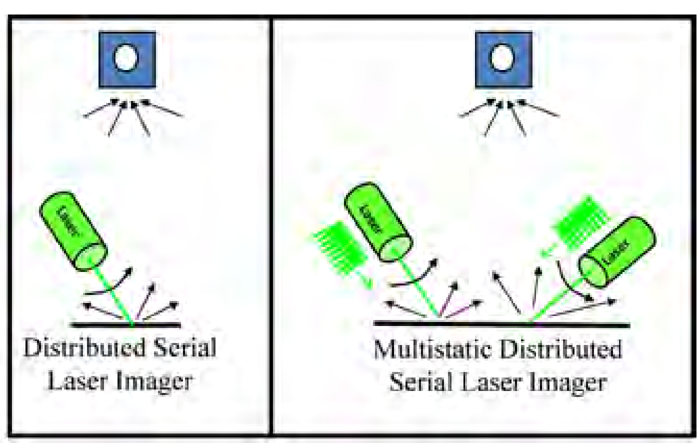
waters), was introduced a long time ago by Duntley et al. (1974) and was known as time-varying intensity (TVI). This system concept also limits development of small-angle blur-glow forward scatter by reducing the distance between the laser source and the target, with the immediate drawback that image swath or coverage is reduced. Complementary approaches by two research groups have recently resulted in fieldable prototypes being tested in various littoral and coastal conditions and results from each are presented.

The problem of wirelessly synchronizing the distant laser transmitter and receiver platforms has been addressed using communications approaches and robust image links have even been demonstrated through the water to air interface (Alley et al., 2012). In test tank testing using low-power lasers, the bistatic serial-scan laser imaging approach (Figure 15, left) has been shown to offer a significant range and image quality improvement over single-platform techniques in both CW and pulsed configurations (Mullen et al., 2009b; Dalgleish et al., 2009b) and is operable through a wide range of environmental conditions with low-cost, low-power laser transmitters; to counter the undesirable attribute of reduced swath, multistatic distributed architectures (Figure 15, right) have been demonstrated using a frequency division multiple access communication technique (Caimi & Dalgleish, 2013), also with the application of a light field rendering technique to produce photorealistic 3D imagery and synthetic aperture imagery in turbid water (Ouyang et al., 2013c).

These systems are also known as NLOS imagers because they attempt to capture all the photons emitted by the transmitter in order to reconstruct an image. The original TVI system that was conceived by Duntley et al. (1974) resulted in a coastal demonstration using a diver-held laser transmitter with a receiver at the surface. Line synchronization between the transmitter and receiver was accomplished with an additional strobe. The approach by the authors (Harbor Branch) and program partners Metron Inc. (Reston, VA) had the objectives of developing a time-resolved radiative transfer model for accurately predicting the physical layer channel frequency response and developing an image performance prediction tool that can be applied through a wide range of geometries and optical environments for the distributed serial imaging and communications system concept. This involved developing a prototype bistatic serial laser system apparatus that includes interchangeable two-axis scanned CW and pulsed laser transmitters in separate 19 cm diameter housings and a four-channel high-speed receiver housed within a 32-cm diameter glass sphere housing, which is compatible with both the CW and pulsed modes of operation. The receiver was configured such that there was an angle of 35° between the center axis of the downward

FIGURE 15

New approaches in distributed laser serial imaging.



staring PMT assembly and the center axis of the three outer staring PMT assemblies, which are separated radially by 120°. Each PMT assembly has a flat-top angular response over a total FOV of 12°. Therefore, each photon collector is staring into a unique solid angle with no direct overlap between adjacent collector apertures. This was determined to be a useful way to generate at-sea test data to demonstrate relaxation in pointing accuracy and which could also be used in the validation of the newly developed simulation tools for laser imaging and communications. A drawing and photos of the transmitter and receiver are shown in Figure 16.

The signals from the PMTs were acquired on the vessel via a laptop connected to a digitizer. A custom GUI was used to acquire and display data and images in near real time and also to acoustically communicate with the microcontroller within the transmitter housing on the seabed. During coastal tests, the lander, which sits on three folding legs for stability and to keep it above loose sediments, is placed onto the seabed and an acoustic positioning system is also used to track the lander position relative to the surface vessel.

FIGURE 16

Four-element high-speed optical receiver.

The two-axis scanned CW laser transmitter housing consists of a variable power (20–800 mW) single-mode low-noise OEM 532 nm laser and a 5-mm two-axis galvanometer scanner with fast axis scan speeds of up to 500 lines per second and a total optical scan angle of 60° in both axes. For

FIGURE 17

Self-powered lander with laser transmitter, sensors, and technical target mounting.

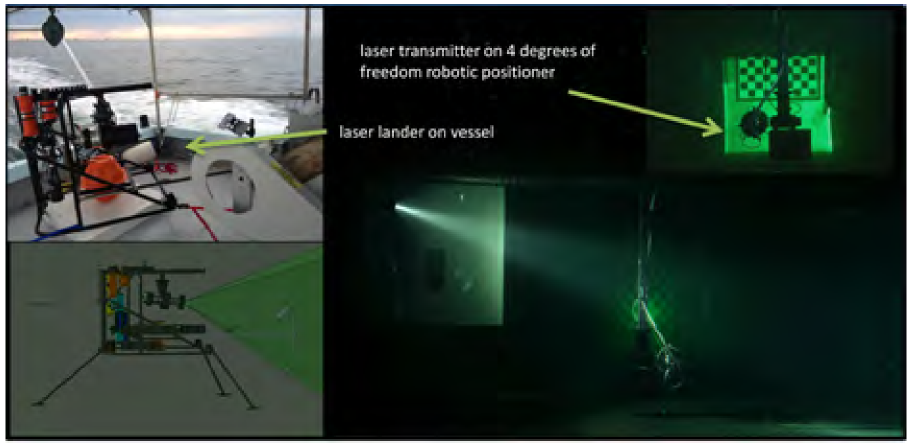
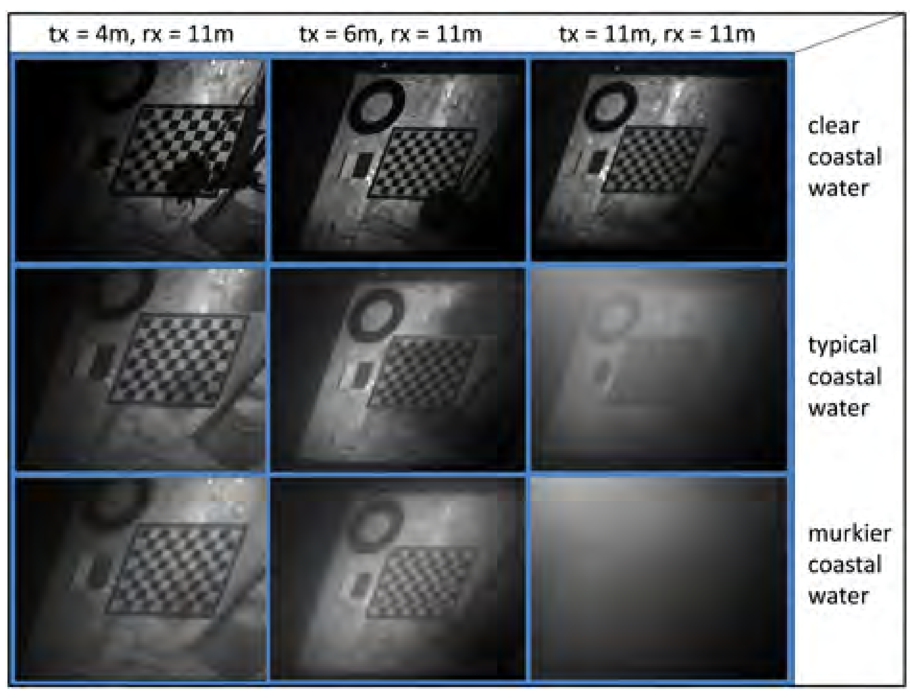


FIGURE 18

2D serial laser images of 2.5 m × 2.5 m target assembly within the HBOI-OVOL electro-optic testing facility. Upper row: c(532 nm) = 0.15 m^{-1}, middle row: c(532 nm) = 0.37 m^{-1}, lower row: c(532 nm) = 0.49 m^{-1}. Right-hand column: near monostatic case at 11 m stand-off distance, 0.5 m separation between laser source and receiver. Middle column: Scanned laser transmitter has been moved to within 6 m of target plane, receiver at 11 m. Left column: Scanned laser transmitter has been moved to within 4 m of target plane, receiver at 11 m. Receiver FOV is 12° full angle (Dalgleish et al., 2012b).



the results presented, scan speeds of 500 lines per second, which are realistic for mobile platforms, were used. For the pulsed laser channel characterization tests (not shown), the transmitter consists of a two-axis scanned pulsed laser (532 nm Q-switched laser, 25 μJ, 500 ps FWHM, 500 Hz repetition rate). During operations, the transmitters are deployed on the self-powered profiling lander that comprises the laser transmitter mounted on a pan-tilt unit and a suite of optical sensors for IOPs and radiometry characterization. The system can be controlled by acoustic modem from the support vessel to turn laser transmitter on and off, modify scan job and laser power, adjust transmit pointing arrangement (via the pan-tilt unit) and also to retrieve sensor samples. The surface vessel is piloted to perform a series of passes over the lander during which the operator can view in real time the PMT signals being acquired and waterfall images. A drawing of the lander package together with a photo taken during a recent test tank test is shown in Figure 17. More information about the system can be found in Dalgleish et al. (2012b).

Experiments were initially conducted with the newly developed prototype distributed serial laser imager, within the large electro-optic turbidity test tank at Harbor Branch using a robotic positioning system to move the transmitter within the test tank (Figure 17, right).

For these tests, the scanned laser housing is initially placed beside the receiver (i.e., near-monostatic) at 11 m distance from the target (right column of Figure 18), then 5 m in front of the receiver (distance from laser to target was 6 m), shown in the middle column, and then 7 m in front of the receiver (distance from laser to target was 4 m) shown in the left column. One important observation from these tests was that, in the clear water case (upper row), the shadow of the in-water laser transmitter (19 cm diameter glass housing) is visible on the lower portion of the checker pattern for the two bistatic geometries (left and middle columns), but as the scattering coefficient increases, the shadow is seen to diminish with the image being clearly visible in its entirely. Since this shadow could equally have been created by a small UUV being used to deploy the transmitter, these results show that there will not be a significant problem with self-shading even in fairly clear water.

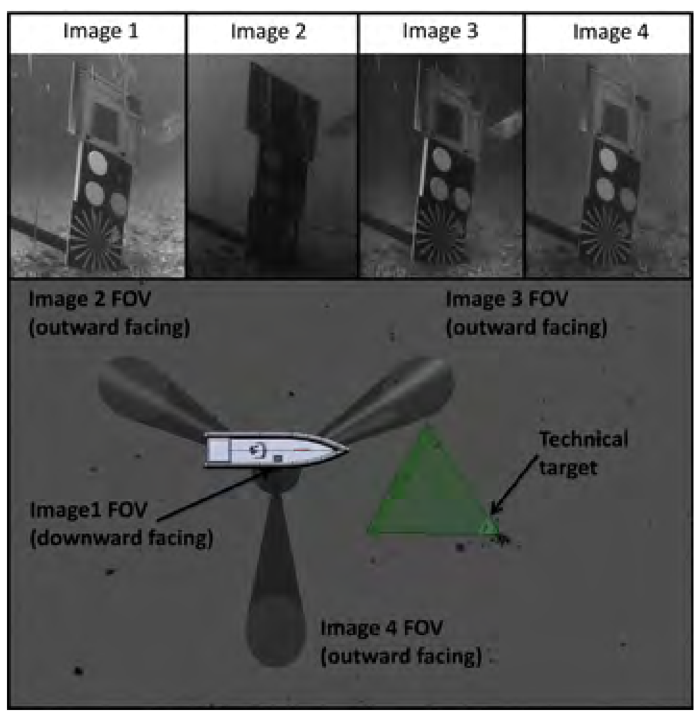
The coastal Atlantic ocean tests were performed in 18-m water depth, 8 miles off Fort Pierce, FL. A series of passes were made over the lander to exercise orientation and distance between the transmitter and the receiver in the horizontal axis while continuously acquiring four-channel images until reaching the detection limit in order to determine the range at which imagery was possible.

In addition to ensuring that the sensor parameters and system log of events were accurately synchronized, great care was taken to accurately measure the static and dynamic aspects of the test geometry and relevant environmental parameters (IOPs) during the experiments so that the results can be used as test cases in the validation of the new radiative transfer code.

For the multichannel imaging results shown in Figure 19, which were taken at dusk on September 20, 2012, the slant-range between the target and the vessel-mounted receiver was 32 m. This corresponds to almost 30 beam attenuation lengths between the target

FIGURE 19

Cropped system images from 18 m water depth coastal ocean tests, $c(532\text{ nm}) = 0.9\text{ m}^{-1}$, $a(532\text{ nm}) = 0.2\text{ m}^{-1}$ showing Spectralon™ reflectance standards (2%, 50%, 75%, 99%) and a wheel spoke target. Laser to target distance was 1 m. Target to receiver distance was 32 m. Laser output power was 800 mW. Scan rate: 500 lines per second.



and the receiver. The left-hand side image (Image 1) was formed from the PMT assembly, which was pointing in the downward direction, albeit with no direct overlap with the lander where the laser transmitter and technical target was located. The pointing orientation and relative geometry between the laser transmitter and the other PMT assemblies are illustrated in Figure 19 with images exhibiting various levels of contrast between the near-field and far-field image depending on the orientation of the lander and pointing direction of the PMT assembly. However, the main observation is that, despite the fact that the PMT assemblies were pointing away from the laser lander, discernible reflectance data were still being transferred through the multiple scattering channel, with enough signal content to allow asynchronous image reconstruction, a process which only requires knowledge of the number of samples per line (Dalgleish et al., 2012a).

Researchers at Naval Air Systems command (NAVAIR) have also developed a distributed laser serial imaging system. To capture the fact that these systems do not require an accurately pointing receiver in order to collect quality imagery, it is termed as NLOS imaging system. An innovative wireless communication paradigm has been developed where coded information about the laser source scanning sequence is transmitted via photons scattered from the target and the medium between target and receiver. The receiver is then able to collect the information from multiply scattered light to reconstruct the scanning sequence, resulting in high-resolution imagery at greater than 20 beam attenuation lengths. Field experiments were recently conducted with the bistatic, NLOS imager to evaluate the effect of system and environmental variables on its performance. The receiver must be able to discriminate this scan information from the time-varying intensity of the detected signal that contains the object reflectivity information. Therefore, the illuminator scan information cannot be encoded via intensity changes in the transmitted light since these variations will be indistinguishable from the intensity variations due to changes in the underwater object reflectivity. An alternate scheme is one that uses frequency variations (such as frequency shift keying) in the signal that modulates the laser illuminator. At the receiver, changes in the modulation frequency are decoded to obtain the scan information that is then used to create an image from changes in the amplitude of the modulated light. Using a modulated optical source also helps reduce the sensitivity of the receiver to changes in the ambient light illumination. This is due to the fact that the center frequency of the receiver is located far away from the low frequencies associated with variations in the solar ambient level.

A block diagram of the modulated laser scanning transmitter developed entirely with commercial off-the-shelf components is shown in Figure 20

FIGURE 20

Top: diagram of the NLOS modulated laser illuminator showing blue (488 nm) and green (530 nm) lasers. Bottom: block diagram of the optical receiver and RF processing components of the NLOS imager. Image courtesy of Linda Mullen.

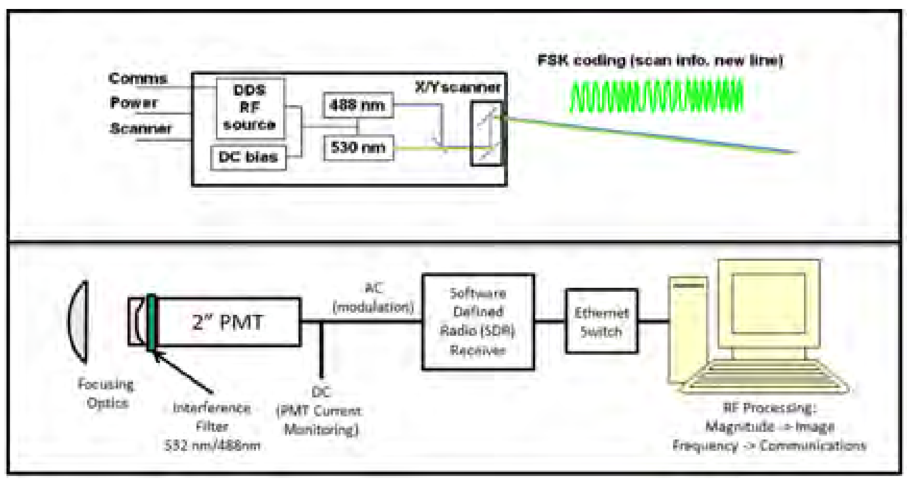
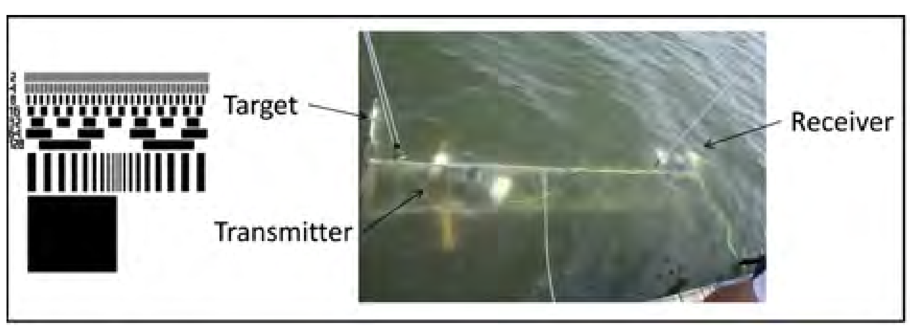


FIGURE 21

NLOS modulated bistatic serial imager experimental setup. Image courtesy of Linda Mullen.



(top). The communications information is encoded on the laser via a direct digital synthesis (DDS) source that can easily be reconfigured via software to accommodate different operational scenarios. The output of the DDS source modulates the current of both blue (488 nm) and green (530 nm) low-power laser sources. The choice of which laser to use depends on whether the system is operated in clear, open ocean (488 nm) or shallow, coastal water (530 nm) environments. The scanner control signals are synchronized with the modulation signal so that the modulation frequency is changed at the beginning of each scanned line. The receiver uses these frequency changes (along with the communicated scan information) to reconstruct images from scattered light.

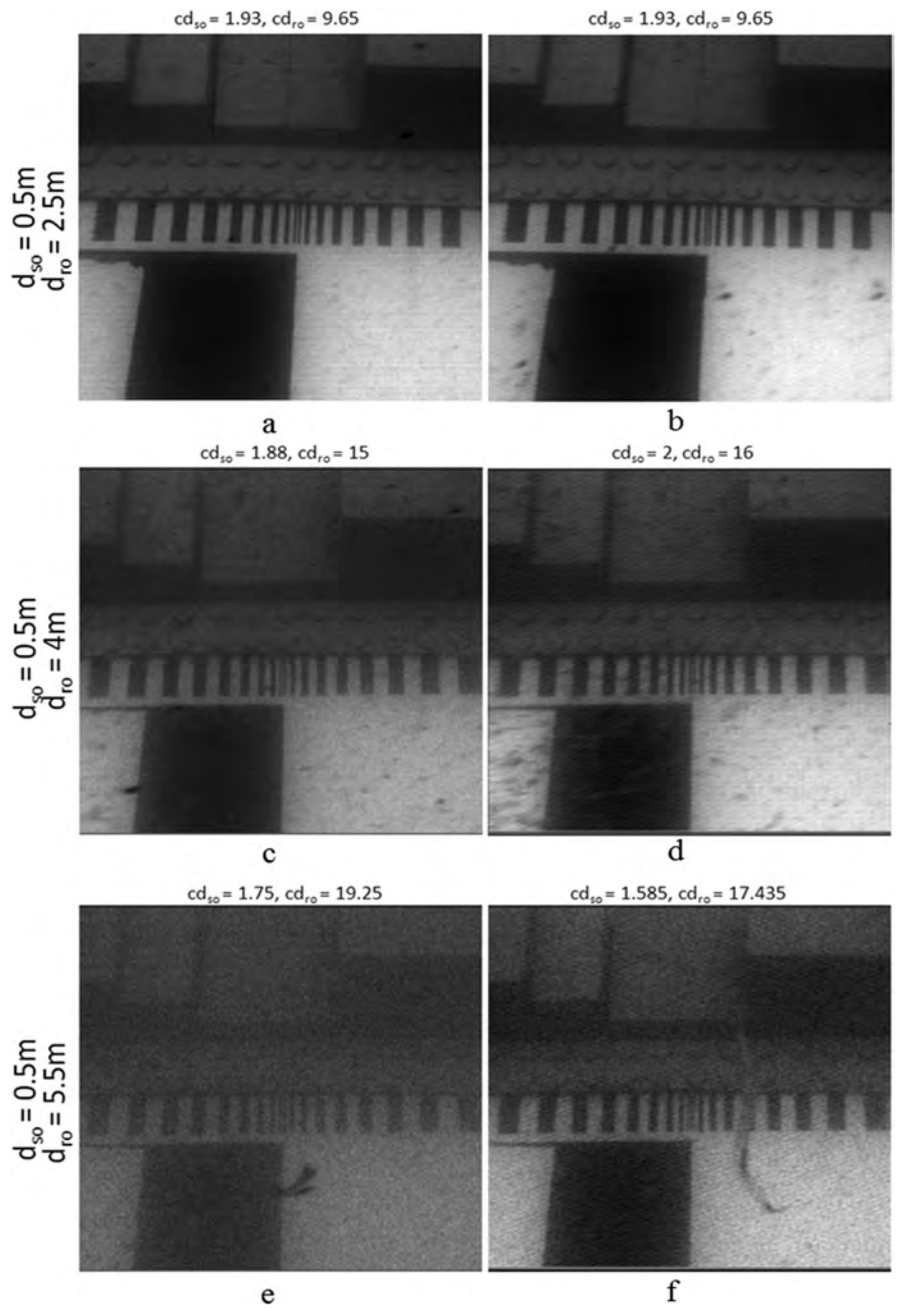
A block diagram of the optical receiver is also shown in Figure 20 (bottom). The receiver is a 50-mm diameter PMT with a 105-mm focusing lens to increase the collection aperture. The RF signal processing component is also shown in Figure 20 (bottom). The output of the optical receiver is split into its AC and DC components. The DC component is used to monitor the average current output of the PMT to make sure that it is operating in the linear portion of its dynamic range. The AC component is digitally demodulated by a software defined radio (SDR) receiver. The resulting baseband I and Q samples are then packetized and sent to a computer via Ethernet where a LabVIEW™ program calculates frequency and amplitude from the I and Q samples. The frequency data contain the wireless communication signal sent from the source, and the amplitude signal contains reflectivity information about the target.

The focus of recent work was to test the system in a more realistic, *in situ* environment. The test site was a pier in the Patuxent River at the Chesapeake Biological Laboratory at Solomons Island, MD. The test setup is shown in Figure 21.

The imagery shown in Figure 22 was collected at night and illustrates the ability of the system to produce high-quality imagery up to 20 attenuation

FIGURE 22

Underwater images obtained during night testing with the 530 nm laser. The images in the left column (a, c, e) were obtained with the high data rate, wide bandwidth configuration, and the images in the right column (b, d, f) were obtained with the low data rate, narrow bandwidth configuration. The system geometry is noted on the left, and the number of attenuation lengths between the source and object (cd_{SO}) and between the receiver and object (cd_{RO}) is shown at the top of each image. Images courtesy of Linda Mullen.



lengths between the object and the receiver. The images were taken at two receiver RF bandwidths to evaluate the effect of the bandwidth on SNR and resolution. The labels on top of each image indicate the number of attenuation lengths between the source and object (cd_{so}) and between the receiver and object (cd_{ro}). The receiver FOV was 12° (full angle) for the 10-nm filter used during night tests.

As shown in the right-hand column of Figure 22, reducing the bandwidth of the SDR receiver limited the amount of noise from ambient light and other sources and enhanced the image SNR. Although using a lower receiver bandwidth results in a corresponding decrease in the number of pixels per image line, the spatial information of the target used in the experiments is still preserved. Several more tests have been performed with the NLOS bistatic serial laser imager, demonstrating successful collection of imagery during both day and night, and also through the water-air interface, without the surface-induced distortions by which airborne systems can be significantly impacted.

Example of a Commercially Available Flash Lidar

The last section of this paper briefly describes the latest version of the LUCIE-3 flash lidar sensor, which is now available as a commercial product in a hand-held package from Neptec Technologies Corporation (Ontario, Canada). The system uses a high repetition rate pulsed laser with variable gate delay to rapidly image slices of the scene in turbid conditions. In certain challenging conditions, multiple frame averaging can also be employed to improve noisy imagery. Originally reported by Fournier et al. (1993), the second generation Laser Underwater Camera Image Enhancer (LUCIE-2) had previously been packaged for use onboard a remotely operated vehicle (ROV) and deployed in very turbid water with high contrast images being acquired at 5 beam attenuation lengths (Weidemann et al., 2005). Hou et al. (2007) reported ongoing system improvements to include optical polarization control in order to implement polarization difference techniques that showed promise in further enhancing target contrast. These additions have now been implemented, as part of the more compact third generation hand-held version of the system, the LUCIE-3, with all operations automated for optimized imaging (Figure 23).

The eye-safe LUCIE-3 unit, which is 25 cm long, 20 cm wide, and 10 cm high, can be operated continuously for 90 min. The system uses a 600-mW average power 532-nm pulsed Nd:YVO4 laser with a variable gate delay intensified camera that can be operated over 3 ns in 100 ps increments, allowing for centimeter-scale slices to be viewed sequentially. Figure 23 shows some recent results taken in a turbid pond with the hand-held version of the system. A comparison with a high-quality underwater camera, which has reached a contrast limit, is also shown.

Conclusions

The paper firstly summarizes the main principles of extended-range underwater laser imaging and how these

FIGURE 23

Top: LUCIE-3 hand-held version showing diver viewing port on the left and front view of system on the right. Middle: System testing setup. Lower left: Image of chair with high-quality underwater camera showing contrast limit. Lower middle: LUCIE-3 image of chair with gate time setting selected to view frame of chair. Lower right: LUCIE-3 image with gate time setting selected to view lattice of chair. Images courtesy of Neptec Technologies Corporation (Ontario, Canada).

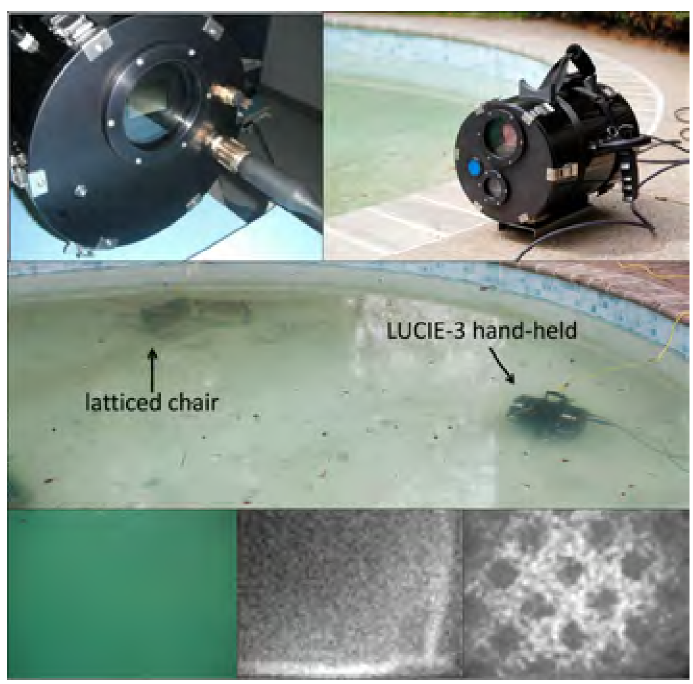


TABLE 1

Alternate system summary and relative performance and selection attribute comparison table.

		Lidar Serial-Scan		Spatially-Modulated		
	Distributed Serial-Scan	Modulated-Pulse	MCD-Pulse	Hybrid Flash-Serial	Confocal Flash	Flash-Lidar
Imaging Method	Serial-scan	Serial-scan-gated	Serial-scan-gated	Sequential full scene or line pattern illumination	Sequential full scene or line pattern illumination	Full scene illumination
	Non line-of-sight	Line-of-sight, 3-D	Line-of-sight, 3-D	Line-of-sight or	Line-of-sight, 3-D	Line-of-sight, 3-D
	Wide FOV staring photon collector	Scanning telescopic photon collector	Staring overlapping photon collectors	Non Line-of-sight, 3-D	Gated high speed camera with mask	Gated high speed camera
	3D visualization			Wide FOV staring photon collector		
Hardware Cost/ Complexity	Low	High	Moderate	Low	Moderate	Moderate
Scene Coverage	Low, but offers multistatic	High	High	Moderate	Moderate	Moderate
Motion Tolerance	High	High	High	Low	Low	Moderate
Ambient Light Tolerance	Low, unless gated or modulated	High	High	Low, unless gated or modulated	High	High
Processing Requirements	Low	Moderate	High	High	High	Moderate
Photon Efficiency	High	Moderate	High	Moderate	Low	Low
Needs a priori environmental data	Low	Low	High	High	Moderate	Low

principles have guided the most recent imager developments. Several areas of research and technology development are described to inform the reader about ongoing and future advancements in underwater imaging technology, which are mainly motivated by the need to view underwater scenes in 2D and 3D in order to perform a variety of turbid water inspection and intervention tasks at stand-off distances greater than what is possible with a conventional camera and lamp. For diver and UUV applications, the availability of compact, automated extended-range systems that can be operated for several hours on one set of batteries is needed, and the Example of a Commercially Available Flash Lidar section describes one such hand-held commercial system. For ROV and towed applications, where available power is not so limited, enhanced laser scene visualization systems are required for piloting, manipulation activities, change detection and seabed survey in challenging optical conditions and also to provide millimeter-scale resolution 2D/3D inspection data.

Newly developed laser transmitters are allowing researchers to evaluate the effectiveness of lidar-radar modulation and certain coding schemes for 2D/3D underwater imaging, the concepts behind which are conceived using the various radiative transfer imaging tools, which have been under development for several decades. New approaches to improving image quality that involve estimating environmental parameters in near real time through-the-sensor and using accurate radiative transfer models to effectively "remove" the blurring effects of scattering during image formation with an additional digital processing stage have also been explored and show potential to reduce hardware complexity and enhance performance for extended-range imagers. A radiative transfer image simulation study is also presented in the Spatially Modulated Laser Imaging Systems section to compare the performance of alternate implementations of a new class of extended-range laser imager that uses the latest optical MEMS devices to project spatially modulated laser beam patterns onto the scene.

Several system concepts are described in this paper, and recent results demonstrate that high contrast imagery is obtainable at greater than 4 beam attenuation lengths (optical thicknesses) for the near-monostatic (co-located) transmitter/receiver configurations, with some system configurations involving few moving parts, with very low bill of material (BOM) hardware costs. The bistatic and multistatic serial imaging and communications approaches described in the Distributed Laser Serial Imaging Systems section demonstrate that high-resolution imagery can be transmitted over more than 20 optical thicknesses between the target object and the receiver using relatively simple, off-the-shelf hardware, with the drawback of reduced area coverage and added challenges of operating multiple platforms in a collaborative, coordinated fashion to create and sustain the imaging link. Table 1 summarizes various benefits and limitations of the alternate system configurations discussed in this paper, although more research, development, testing, and evaluation activities will be essential in fully understanding the potential of these undersea imaging technologies.

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COMMENTARY

A View Through the Waves

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When using the term *underwater imaging*, what is underwater? Is it the camera? Is it the imaged object, or the light source? In most studies and engineered systems, the camera, object, and light source are all submerged. However, there may be exceptions in systems designed to operate in shallow waters, where part of the setup is above the water's surface or where natural illumination is needed from above the surface. Significantly less research and development has been conducted to image objects through a "wavy" water-air interface, where either the camera or the object is underwater, *but not both*. This commentary seeks to shed more light on this emerging domain, referred to as *intermedia imaging*.

Refracted View

Being less studied, there is a lot of room for significant innovation in intermedia imaging. You may wonder why it is important to view objects through the surface. To answer this, there are both biological and engineering drivers. Some animals must take this view to survive. While being submerged, the archer fish visually detects and localizes airborne prey (flies) and shoots them down using a water jet (shown in Figure 1), where the water jet takes an airborne parabolic trajectory (Mokeichev et al., 2010).

Analogously, while being airborne, many aquatic birds visually detect and localize submerged fish and then dive for the kill. Underwater viewpoints such as these also give a defensive advantage where fish, seals, and other underwater creatures may keep their distance from perceived predators on shore. A submerged box jellyfish (Figure 2) navigates and controls its position close to shore using eyes specifically tuned to view objects on land (Garm et al., 2011). Box jellyfish have 24 eyes of four different types, including a set dedicated to survey the airborne scene.

There are various technological applications utilizing these same viewpoints. Submerged objects can more easily be viewed looking downward through the surface from airborne or spaceborne camera platforms (Schechner et al., 2011), as compared to being viewed from cameras located on the surface. This principle is exploited in airborne lidar bathymetry. Conversely, viewing upwards from a submerged camera can facilitate a *virtual periscope* where the surrounding area around a vehicle or diver can be scouted without a salient physical probe (Alterman et al., 2013a). Figure 3 provides a good example of the periscope effect. In the image, the strong random distortion changes in both space and time. Computational vision methods can be designed to operate in the presence of these distortions, as if a virtual periscope is used.

Applications such as these are well addressed when the water surface is flat, for which the optical distortion model is deterministic. However, as we are all well aware, the water's surface is usually rather wavy or uneven, which creates image distortions that are random in space and time. This strongly inhibits high definition imaging

FIGURE 1

An Archer Fish shooting a water jet in the lab (courtesy of Ohad Ben-Shahar and Ronen Segev).

FIGURE 2

A box jellyfish where the enlarged region reveals one of its upward-looking eyes (courtesy of Jan Bielecki and Anders Lydik Garm).

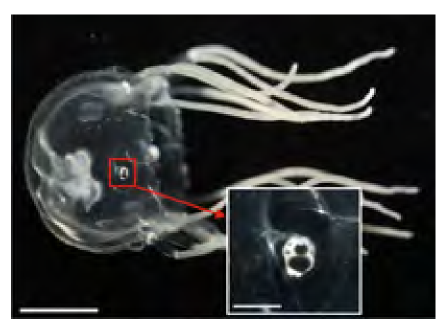


FIGURE 3

An airborne scene captured by a submerged camcorder (Alterman et al., 2013a).

through the medium as was shown in Figure 3. Consequently, applying standard deterministic imaging models and recovery methods will result in very large errors.

Rather than adhering to standard image processing approaches, there are other principles that can help. One principle incorporates the said randomness into the imaging model. This leads to *stochastic* inverse methods coupled to multiple, independent image measurements in a sequence. Methods based on this principle do not claim to achieve precise, true results but rather achieve *highly likely* results (Alterman et al., 2013b). To date, researchers have applied only a fraction of the processing and statistical tools that are available, including machine learning (Tian & Narasimhan, 2012). There is a lot of room for innovative algorithms.

Another helpful principle is that the random wavy surface can be measured. If the water surface topography is mapped while images are taken through this surface, then image distortion can be deterministically derived and inverted. In such cases, there is less need for complex algorithms. Physical measurements of the surface take the burden off the computer and transfer it to the measurement optics. Ingenious ideas have been suggested to measure water surface topography that affects images (Baglio et al., 1998; Milder et al., 2006; Schultz & Corrada-Emmanuel, 2007). Techniques include analysis of reflected sky radiance and polarization, sun-glint, laser specularities, and wave self-occlusion. These preliminary and creative methods demonstrate the richness of cues from which the wave structure can be inferred.

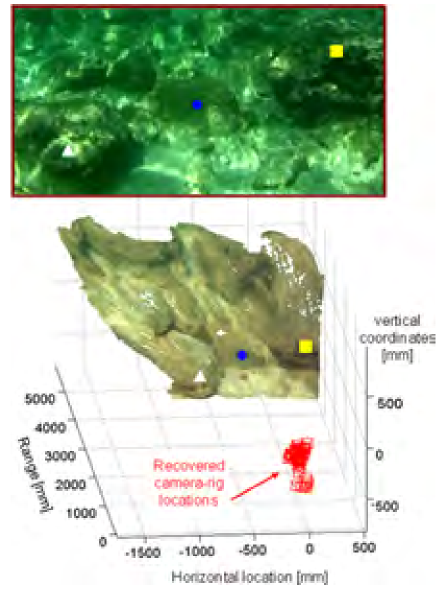
Refracted Lighting

Even if both the camera and object are submerged, the surface waves can still strongly affect images. The spatiotemporal variations of the water surface modulate sunlight refracted into the water. Natural illumination thus has a spatiotemporal random pattern, termed *sunlight flicker* or *caustic network*. The illumination modulation is so strong and fast that it often overwhelms spatial variations created by object albedo, as shown in Figure 4. This is contrary to scenes captured in air where illumination variations are typically of low frequency in space and time. It appears as if vision in the presence of caustic networks is inherently difficult; however, facts may point to the contrary. In a recent publication, Swirski and Schechner (2013) show that this effect actually eases the 3-D recovery of the underwater scene, while recovering motion of the rig carrying the camera (Figure 4).

For decades, most computer vision methods have been developed for out-of-water scenes. Hence, most computer vision methods were developed under the assumption that illumination variations consist of low frequencies, while strong changes are attributed to albedo variations. Due to sunlight flicker, these assumptions

FIGURE 4

Sunlight flicker creates a strong spatiotemporal illumination pattern on the seafloor and submerged objects (images courtesy of Yohay Swirski).



become invalid beneath the water's surface. This poses a problem when traditional, in-air computer vision methods are applied to underwater applications.

However, many shallow water marine animals have a small visual cortex and thrive in this environment. This indicates that biological vision in the presence of flickering caustics is not overwhelmingly complex if visual processing is done in way that is tuned to the flicker. Some tasks may even be made easier by this effect. To realize this, we need to bypass old notions that stem from traditional computer vision algorithms and rather think afresh on visual tasks and how caustics can be useful for them.

Consider range triangulation by stereoscopic vision, which requires determination of correspondence between image points in different locations. In air, this is usually a difficult problem. However, the spatiotemporal caustic illumination pattern very effectively establishes stereo correspondences. Thus, use of this effect has recently been termed *CauStereo* (Swirski et al., 2011). The temporal radiance variations due to flicker are unique to each object point, thus disambiguating the correspondence with very simple calculations. Hence, the random flicker actually helps to recover the 3-D scene structure like that shown in Figure 4. Moreover, being illumination invariant, the 3-D shape can be used to recognize objects or recover motion of the platform carrying the cameras (Swirski & Schechner, 2013). Furthermore, since flicker eases range recovery, it also helps in retrieving and correcting for range-dependent scattering effects.

To summarize, systems are up and running for scenarios in which both the camera and object are submerged in a fixed medium where the illumination is constant. It may be time to think more creatively for novel solutions to the difficult yet rewarding problem of random intermedium imaging.

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- April 18, 2014 — Authors receive proofs
- April 25, 2014 — Authors return final corrections
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