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1. Ocean Observing Systems (Clark, page 6)
2. Ocean Energy (White, page 9)
4. Surface Craft (Bash, page 21)
5. Manned Underwater Vehicles (Kohnen, page 26)
6. Remotely Operated Vehicles (Cohan, page 38)
7. Autonomous Underwater Vehicles
   (Nicholson and Healey, page 44)
8. Underwater Optical Imaging (Kocak et al., page 52)
9. Acoustic Imaging (Potter, page 68)
10. Biogeochemical Sensing (Moore, page 75)
11. Physical Ocean Sensing (Luther et al., page 84)
12. Optical Communications (Lacovara, page 93)
13. Acoustic Communications (Chitre et al., page 103)

On the Cover: Artist’s conception of some of the technology advances described in this issue. Image courtesy of Maritime Communication Services, HARRIS Corporation.
Dear Readers,

Since the last MTS Journal State of Technology update in 2005, many advances have been made spanning the spectrum of our society. Our goal in this issue is to assemble leading technologists and researchers in their fields to present these innovations in a single, “coffee-table” issue. An overview of the topics, authors and their papers is presented here.

For the past decade, in journal articles and special issues for which he has served as Guest Editor, Past MTS President Andrew Clark has provided detailed accounting of the state of the art in ocean observing systems. In this commentary, he updates the reader on recent advances, progress and lack thereof in this rapidly emerging field—one that encompasses most if not all the technologies reported throughout this issue.

In today's economy, empowered by the movement to “go green” and become less reliant on imported and non-renewable fuel sources, the prospect of harnessing sustainable energy from the oceans is an alluring one. In the next commentary, Daniel White, Marine Technology Fellow and founder/organizer of the Energy Ocean Conference, discusses recent policies and practices that govern this nascent stage of ocean energy technology. Although the future of this technology is not yet clear, legislation appears to be opening the door for its development.

Continuing with this “global” perspective, our next commentary features the state of technology in remote sensing. Herbert Ripley, Fellow of the Remote Sensing and Photogrammetry Society and Chair of the MTS Committee on Remote Sensing, discusses recent changes that have enhanced sensor system capabilities used to capture both the inner and outer dimensions of our oceans. He also provides a brief overview of the technology's history and offers the reader a listing of satellite and airborne systems in use today.

Our first paper begins at the ocean's surface where we find new (and sometimes not so traditionally appearing) advances in surface craft. John Bash describes how specific economic, environmental, security, safety, geopolitical, and mission considerations are driving the design of today's research, commercial and military surface vessels. Illustrations of several cutting-edge vessels are shown and a preview is given of alternate energy systems that we can look for in future developments.

The next three papers take us beneath the surface to describe new technologies in manned, remotely operated and autonomous underwater vehicles (ROVs and AUVs). In the first of these papers, William Kohnen, Chair of the MTS Manned Underwater Vehicles Committee, provides a listing and status update of the most active, non-military, manned submersibles in operation around the world today. In the next paper, Steve Cohan describes trends in ROV development—focusing on the capabilities of digital video, model-based control techniques for operations, and sophisticated remote diagnostic capabilities. Finally, in our third paper, John Nicholson and Anthony Healey review the state of the art of AUV technology. These authors key-in on emerging design features and sensor technologies that are most critical in advancing the state of the art.

continued on page 5
Having reached the depths of the ocean, the next set of papers explores recent advances in a number of *in situ* sensing technologies. First, leading researchers, including Fraser Dalgleish, Frank Caimi and Yoav Schechner, focus on recent advances in underwater optical imaging. They look at a number of methods for “seeing” 2-D and 3-D representations of the environment and review techniques researchers are now using to extend in-water optical vision capability. Next, John Potter reviews some of the new developments emerging in underwater acoustic imaging that are helping to “listen” through the clutter in both deep and shallow waters. The third paper in this series “sniffs out” what is new in biogeochemical sensing. Casey Moore provides a review of the state of the art in sensors and technologies that are now being adopted in ocean exploration and observation. Lastly, the fourth paper gives us a “feel” for *in situ* sensing of physical ocean parameters. In this paper, Mark Luther, Sherryl Gilbert and Mario Tamburri discuss recent activity and technologies emerging from the Alliance for Coastal Technologies.

Finally, having reviewed the advances in technologies required to gather information from the ocean’s depths, the next two papers provide a thorough review of some optical and acoustic communications methods employed to transmit this information to the user. In the first paper, Philip Lacovara discusses advances in free-space optics and includes a comparison of this technology to acoustics, radio frequency electromagnetic waves, and fiber optics technologies. In the second paper, Mandar Chitre, Shiraz Shahabudeen and Milica Stojanovic present a complete review of recent developments in acoustic communications and networking. Although both of these communications methods are ultimately limited by the physics of their environment, they are both likely to progress even further in the coming years as enabling technologies move forward.

We hope you will enjoy reading this as much as we have enjoyed putting this issue together for you!

Sincerely,

Donna M. Kocak, Chair of the MTS Underwater Imaging Committee  
Richard Crout, Chair of the MTS Physical Oceanography/Meteorology Committee
The state of technology enabling ocean observing systems has been reported in special issues of this Journal (Winter 1999, Fall 2003) in articles that provided inventories of existing observatories and the technologies they employ to collect and transmit data back to users on shore. While there may not be many new technological breakthroughs occurring since that most recent publication on which to report, there have nonetheless been continued incremental improvements to and maturation of some of the tools and techniques worth noting here. The need for new long-term unattended, in situ sensors, particularly those that monitor chemical and biological processes, is perennially identified as critical to the viability of ocean observing systems. Appearing elsewhere in this issue (Moore, Luther et al.) are other articles describing some of the recent advances in this area.

Another area vital to ocean observing that has benefited from continued use in the field and resulting maturation is that of unmanned gliders as described by Nicholson and Healey in this issue. Notwithstanding a lack of major advances in the technology that enables ocean observing systems, there have been some notable changes on which to report since the last journal issue devoted to this subject.

The ocean observing efforts previously described are still underway, so rather than repeat an inventory of individual observatories, this article attempts to update the reader on some of the major ocean observing initiatives in the U.S. and abroad. Perhaps not surprising, in each case a common theme that has either fostered or encumbered progress has been funding (or the lack thereof)—particularly from government sources. Another recurring thread that emerges among these various initiatives, and one seen by some as a potential means to help mitigate the financial obstacle, is the need for an increased role in ocean observing by the international industrial sector.

In the U.S. there are two national ocean observing initiatives backed by the federal government, the Integrated Ocean Observing System (IOOS) and the Ocean Observatories Initiative (OOI). The IOOS, a multi-agency undertaking, strives to maximize the usefulness and effectiveness of the data generated by its member agencies and is, therefore, oriented toward the development of data products, services and operations. The OOI, a National Science Foundation (NSF) effort, is oriented toward research and providing the instruments necessary to answer effectively the most important research questions facing society. In recognition of its criticality to success, a symposium titled “IOOS and OOI; The Role of Industry” was convened by NSF in 2007 in an attempt to create an environment conducive to establishing this vital public-private partnership.

The OOI is a major infrastructure effort to deploy long-term coastal, regional and global ocean observatories. A detailed accounting of the goals and objectives for OOI was described in the referenced 2003 MTS Journal issue (Volume 37, Number 3). At that time, a request on the order of $300 million had been made to fund four major components: a cabled regional scale observatory, a coastal and a global scale...
observatory, and the “cyberinfrastructure” that would be necessary to tie them all together. The OOI program office had then been established at the Joint Oceanographic Institutions (JOI) to administer the funds and oversee its development (www.oceanleadership.org/ocean_observating). In 2007, a competitive process was conducted to fund several “implementing organizations,” one to head the development of each of the major components: University of Washington was awarded the contract to lead the regional observatories effort, University of California San Diego the cyberinfrastructure, and the coastal and global observatories were rolled into one contract that was awarded to Woods Hole Oceanographic Institution.

Industry's role in managing the OOI was established early on. Only non-profit education or research institutions were eligible to bid on these contracts to lead the implementing organizations. In spite of this limitation, there have been some early signs of industry's willingness to participate, contributing their resources and expertise and receiving in return the opportunity to acquire new knowledge with the ultimate intent of achieving a competitive advantage in the marketplace. One such example is the extended draft platform (EDP; see Figure 1) being developed by Technip of France for use in the exploration and production of offshore oil. In preliminary designs for the OOI, Technip offered, upon completion of its initial deployment and testing, to turn their scale EDP platform over to the OOI for use within the global scale ocean observing system. Not only would this represent a large-scale and truly transformative tool benefiting the NSF initiative, its further utilization by OOI would provide Technip with additional operational, seakeeping and performance data. Unfortunately, recent descoping efforts required to match budget constraints led to the elimination of the Mid-Atlantic site, where the EDP would have been deployed.

In terms of funding, OOI has fared better than other major ocean observing initiatives but is still not out of the woods. All planning efforts conducted thus far have required using NSF's limited research dollars. The OOI was listed as a new start in 2007, with a $331 million spending profile; however, the FY09 budget eliminated out-year funding for the OOI. A successful Preliminary Design Review was conducted in late 2007 but allocation of funds for actual construction is pending the results of a Final Design Review to be completed in late 2008.

The other major U.S. initiative reported on in the 2003 MTS Journal issue devoted to Ocean Observing Systems was the IOOS. Unlike the research focused OOI, IOOS represents the effort to bring together the data and products generated by individual observatories and observing efforts in a synergistic manner that is accessible to individual users. Another salient difference between them is that while OOI is owned by a single federal agency, IOOS is a collaborative effort among more than a dozen agencies, not just to seek common ground among themselves, but in the process to also engage state and local governments, universities and the private sector, including industry. Ocean.US, staffed by scientists, engineers and managers from government, academia and industry was established to serve as a central planning office for IOOS but does not administer funds as does the OOI program office (www.ocean.us). This daunting task, coupled with federal funding at levels only fractional to what has been determined necessary, have conspired to set the pace of progress for IOOS. However, since that previous Journal issue, some progress is now underway.

The National Oceanic and Atmospheric Administration (NOAA) was designated to serve as the lead federal agency and has subsequently stood up an internal IOOS program office focused upon execution. On the funding front, IOOS made it into the President’s request for the first time in FY 2008 and, though Congress was nearly twice as generous (see Table 1), these levels of funding still fall an order of magnitude short of the need projected by the U.S. Commission on Ocean Policy as reported in the 2003 Journal special issue. The FY 2009 Congressional appropriation will not be known until fall 2008, with another potential delay due to a change in administration, regardless of the outcome of the presidential election.

As with OOI, there have been some successful examples of IOOS partnering with industry. One that may represent a model for mitigating some of the potential financial strain while benefiting end users is cited here. Earlier this year, NOAA and Shell Oil Company signed a Collaborative Agreement to enhance meteorological and oceanographic observations in the Gulf of Mexico. In this partnership, Shell will purchase and install instrumentation on five off-shore platforms and three near-shore stations. In turn, NOAA will provide technical expertise in High Frequency Radar (HFR), data formatting, data distribution, data quality assurance and control. This partnership is envisioned as a long-term collaboration for the collection, processing and distribution of atmospheric and oceanographic data as part of the ongoing development of the U.S. IOOS. The goal of this partnership is to advance observational quantity, quality and diversity to meet shared interests in improving operational forecasts and understanding of the Gulf of Mexico environment.

Together, IOOS and OOI represent the United States' contribution to the international Global Ocean Observing System (GOOS), which is, in turn, the

**TABLE 1**

Federal Funding Profile for IOOS. Courtesy of the National Federation of Regional Associations (www.usnfra.org).

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An oceanic component of the Global Earth Observation System of Systems (GEOSS). Also reported upon in the previous Journal issue were a number of international ocean observing activities in Asia and Europe. One was a component of MedGOOS (the Mediterranean contribution to GOOS) and the others NEAR-GOOS (North-East Asia Regional). These coalitions of member institutions might be likened to the Regional Associations that make up the U.S. IOOS.

A recent development worthy of noting in this update is the launch of a pan-European seafloor observatory initiative, the European Multidisciplinary Seafloor Observatories research infrastructure (EMSO) (www.esonet-emso.org). As with the U.S. IOOS, EMSO intends to tie together existing independent observatories into an integrated system. A network of observatories around Europe would undoubtedly lead to unprecedented scientific advances in knowledge of submarine geology, the ecosystem and the aquatic environment. Such an operational network could also play a key role in the assessment and monitoring of geo-hazards, as the coasts off southern Europe comprise many of Earth’s most seismogenic zones.

Real-time recording and reporting afforded by cabled observatories facilitate rapid reaction to episodic events, such as earthquakes and tsunamis, as suggested by UNESCO-IOC in the recommendations of the “Intergovernmental Coordination Group for the Tsunami Early Warning System in the North Eastern Atlantic, the Mediterranean and Connected Seas (ICG/NEAMTWS)” launched at its 1st Session held in Rome (November, 2005).

As a subset of the international GEOSS initiative, EMSO will coordinate closely with other similar efforts such as the French-led European Seas Observatory Network of Excellence (ESONET-NoE). Projected cost estimates for implementing EMSO and ESONET-NoE, including conducting cable route surveys, procuring cables and junction boxes and deploying them, are on the order of $500 million, in line with the USCOPE estimate for implementing the U.S. IOOS. Essential to the EMSO concept is a synergic collaboration between the academic community and industry. Mutually beneficial consortia are being actively sought with both large industrial partners as well as with SMEs (Small and Medium-sized Enterprises).

The examples of industry partnerships cited in this article for the U.S. ocean observing initiatives were both related to the offshore oil and gas industry. It stands to reason that the offshore energy industry also represents fertile ground for private–public partnership overseas. CSnet, International is an SME, established recently to deploy and operate international seafloor networks that can both serve the scientific community as well as provide a communication backbone to support the enterprise of offshore hydrocarbon exploration and production. In the Shell Oil Co.–IOOS partnership, sensor packages will be deployed on platforms that are installed and operating offshore. While this program is aimed at collecting and reporting real-time current and environmental data during drilling and production operations, a recent U.S. Marine Minerals Service (MMS) Notice To Lessees (NTL) also calls for the collection of year-long environmental data records from certain offshore leases prior to commencement of some operations. European Union requirements are no less rigorous, thus creating a potential market: commercially operated offshore communication backbones (OCBs) that can both be utilized by the scientific community while supporting the offshore energy enterprise from pre-exploitation environmental base-lining through exploration, drilling, production and finally decommissioning. CSnet, International is initially focusing on sites off Africa, the Middle East and Europe where the combination of offshore hydrocarbons and scientific interests coincide. In regions such as the eastern Mediterranean, there is also the very immediate advantage of an OCB serving as a geo-hazard-tsunami early warning network, thereby representing another potential public–private partnership.

It would appear that it has been recognized universally, both in the U.S. and abroad, that success of these major and technology-intensive ocean observing systems will require true partnering between the research and industrial communities. Forums like the symposium sponsored last year by NSF will be essential to help identify these opportunities and to bring potential partners together.

**FIGURE 2**
Conceptual CSnet Environmental Monitoring Network and Offshore Communication Backbone for Industry and Science
Introduction

Worldwide, ocean energy is emerging as a viable source of electricity, water and fuel (hydrogen). However, for the U.S. this could be years away. Most groups agree that utility-scale electricity-producing devices, such as wave energy conversion (WEC), instream tidal flow energy conversion (TISECS), ocean thermal energy conversion (OTEC), and offshore wind, will be providing power to the grid by 2010 and beyond. Offshore wind is included as an ocean renewable because it falls within the same regulations and permitting processes as other forms of ocean energy, and may lend itself to hybrid systems (e.g. wind/tidal, wind/wave, etc.).

This commentary will focus on the current state of ocean energy and the factors driving the implementation of the technology, while touching on a few of the more promising technology developments likely to be connected to the grid in the foreseeable future.

The New Energy Bill

On December 19, 2007, President Bush signed into law the Energy Independence and Security Act of 2007, which focuses primarily on fuel economy standards. Unfortunately it removed all renewable energy tax incentives and a four-year extension of tax credits for renewable electricity projects, representing a cost of $6.6 billion over the next decade and a setback for ocean energy.

That said, the new energy act does call for accelerated research and development of renewable energy technologies, although all the provisions are subject to congressional appropriations of funds.

President Bush did approve an omnibus appropriations act on December 26, 2007, that provides a 17% increase in funds for the Department of Energy’s (DOE) Office of Energy Efficiency and Renewable Energy (EERE). The new act appropriates over $1.7 billion for EERE. The appropriations act does not provide a breakdown of funds by program, but mandates that any change in program implementation be submitted for congressional approval.

Part of the Act includes the Marine and Hydrokinetic Renewable Energy Research and Development Act, which includes wave, tidal, current and OTEC, as well as energy produced from flowing rivers, lakes, streams and manmade channels. Traditional hydropower generated by dams, diversionary structures or impounds are excluded. The Act authorizes an appropriation of $50 million to the Secretary of Energy for each of the fiscal years from 2008 to 2012. The money is intended to support two major initiatives:

- Establishment of a research and development program within DOE, in consultation with the Department of the Interior (DOI) and the National Oceanic and Atmospheric Administration (NOAA).
- Provision of grants to universities for the establishment of “National Marine Renewable Energy Research, Development, and Demonstration Centers” that will advance research and development into the commercial application of marine renewable energy.

At the time of this writing, the U.S. House of Representatives passed HR 5351 that could shift $18 billion in tax breaks from major oil companies to alternative and renewable energy projects and conservation and energy efficiency programs.
Ocean Energy—What Took So Long?

While the rest of the world has been busy developing ocean renewables, the U.S. has been moving along at a painfully slow pace because the U.S. government, in particular the U.S. Department of Energy (DOE), has not formally recognized ocean energy as a source of power—until now. Unlike wind energy, which faced this battle some 20 years ago, ocean renewables have just begun the long path to acceptance.

In a report published in March of 2007 by the ABS Energy Research (www.researchandmarkets.com), 2006 was a year in which the development of ocean energy made a leap forward. The report looked at the market development and provided a comprehensive overview of ocean energy looking at the advantages and disadvantages of tidal, wave, ocean and marine energy. According to the report, wave and tidal energy together represent a global market of US$250 million, with US$180 million earned in the U.K. While committed tidal projects are primarily off the East Asian Pacific coasts of Korea and China, the bulk of wave energy projects are being developed in Europe. The U.K. and Portugal are the countries with the most current activity. Other key findings were that between 2004 and 2008 it was estimated that the world capital expenditure (CAPEX) on wave energy will be US$140 million, with almost 50% of this in the U.K. In the same period, it has been estimated that the world CAPEX on tidal projects will be around US$110 million, with almost 90% of this being related to the U.K. market.

In the last year, there has been an advance in the progress of tidal energy, with one barrage already under construction on the Korean coast, the 254 MW Shihwa tidal power plant, and a contract agreed for a second 300 MW tidal lagoon power plant in China. Both are larger than the barrage at La Rance in France, presently the largest in the world.

Several events have helped ocean renewables move forward:

- Commitments by European and Canadian governments to generate 10% of electricity from renewable sources by 2010 have spurred significant growth in the renewable energy sector.
- Demand for green energy sources has increased due to the desire for secure energy supplies and the use of renewables as a hedge against volatile fuel prices.
- Use of renewable energy has increased because of lower production costs and an increasing awareness about global warming.
- Legislated Renewable Portfolio Standards (RPS) will help to establish ocean energy in the U.S. An RPS is a state policy that requires electricity providers to obtain a minimum percentage of their power from renewable energy resources by a certain date. Currently there are 20 or more states that have RPS policies in place. Together these states account for more than 52% of the electricity sales in the United States.
- Organizations have lobbied for ocean renewables to be recognized in the recent U.S. energy bill, allowing the U.S. Department of Energy to establish a formal ocean energy program in 2008.
- The Electric Power Research Institute (EPRI) has completed several studies on the wave and tidal resource in the U.S., quantifying the potential to meet a significant portion of the nation’s demand.
- Conferences, such as EnergyOcean (www.EnergyOcean.com), have brought technologists together with government agencies, financial institutions, environmentalists and power companies.
- Renewables have moved into the mainstream, creating greater financing opportunities from investment banks.
- Several U.S. developers have had successes (and failures) with demonstration projects, proving the technologies, power-generating capabilities and the need for sound ocean engineering to resist the ocean’s relentless attack on equipment put in its path.

At the end of 2007, the U.S. Secretary of the Interior released the Final Programmatic Environmental Impact Statement (FPEIS) for the Outer Continental Shelf (OCS) Alternative Energy and Alternate Use (AEAU) Program and announced an interim policy for authorization of the installation off offshore data collection and technology testing in federal waters.

Now with some MMS and FERC in some form of agreement on how to implement these ocean energy technologies offshore, things appear to be moving ahead.

As of February 4, 2008, 47 permits had been issued for ocean wave and tidal projects and 41 were pending. In-river permits totaled 40 with 55 more pending.

Utilities—The Missing Piece to the Puzzle

Now with utilities like Pacific Gas & Electric (PG&E) actively looking at sites and technologies for wave and tidal energy, the puzzle is finally coming together. With utilities looking to meet the RPS policies, renewables are being pushed to the forefront. In states such as Alaska, California, Hawaii and Oregon, ocean energy is a prime consideration.

The Governor of Florida wants the state to produce 20% of its power through renewable energy, which is currently at 2%. The Governor of Hawaii has set its goal at 70% by 2030. Oregon has established the Oregon Wave Energy Trust, a nonprofit association that expects to receive funds of $4.2 million over the next two years to reach its goal of installing 500 MW of commercial wave energy projects by 2025.

FIGURE 2

Seagen, courtesy of Marine Current Turbines (MCT)
PG&E provides energy to nearly 1 in 20 people in the U.S. with 5.2 million electric and 4.2 million gas customer accounts. PG&E is also funding studies and projects that will help it reach its goals for the inclusion of ocean energy. Today, PG&E is working towards and expects ocean energy to begin contributing power to the grid post-2010.

Pacific Gas and Electric has applied for permits to operate two California wave energy sites off the coast of Mendicino and Humboldt counties. PG&E also signed a long-term, 2 MW commercial wave energy purchasing agreement (PPA) with Finavera Renewables Inc. Finavera is developing the Humboldt County Offshore Wave Energy Plant about 2.5 miles off the Northern California coast, and is expected to begin generating electricity in 2012. The agreement calls for 3,854 MWhrs of electricity to be delivered annually to PG&E over the term of the contract.

The Sonoma County Water Agency in California has applied for a permit from FERC for exclusive rights to study and develop wave energy technology along the entire 41-mile-long coastline of the county and out 12 miles. The permit gives it three years to study and test technologies, after which it can apply for an operating license.

The Cost of Electricity (CoE)

Over two decades ago, as wind technology was beginning its emergence into the commercial marketplace, the Cost of Electricity (CoE) was in excess of 20 cents/kWhr (in 2006 dollars). Over 75,000 MW of wind has now been installed worldwide and the technology has experienced an 82% learning curve (i.e., the cost is reduced by 18% for each doubling of cumulative installed capacity) and the CoE is about 6 cents/kWhr (in 2006 dollars with no incentives) for an average 30% capacity factor plant.

According to experts like EPRI and others, it is generally believed that the leveled cost of electricity for ocean energy devices needs to be less than 7 cents/KWh and closer to 5 cents/KWh to be feasible. Initially, wave and tidal systems may produce electricity at costs of 13 cents/KWh or higher until the development costs are spread over many units.

EPRI looked at areas around San Francisco, California, that could support both a tidal and a wave energy project. By building either of these plants in the area, EPRI determined that the cost of electricity (CoE) would be in the range of 5-9 cents/kWh for tidal power and 8-16 cents/kWh for wave power.

How Much Do They Cost to Build?

There are a few data points on the costs of these systems. A comparison of two different companies using different tidal power technologies shows they correspond almost identically in the cost per MW installed:

- The tidal project off Pembrokeshire, South Wales, will consist of eight MW Lunar Energy turbines, estimated to cost of about $20 million. That’s about $2.5 million per MW installed.
- Verdant Power is targeting costs around $2,500 per kW installed or $2.5 million per MW for future projects.
- Oceanlinx (Australia) has signed an agreement to provide 2.7 MW of power to Maui Electric Company from 2-3 floating wave energy platforms. The cost of the project was estimated at $20 million.

The global market for renewables reached $38 billion in 2006, 25% higher than 2005. The market for ocean renewables will increase dramatically as utilities are convinced to buy this type of power.

Commercial WEC systems will range from 150 kW to 1 MW each (150-500kW for buoy types) and installed in large offshore areas designated as wave farms.

To put this into perspective, the total U.S. wave resource (according to EPRI) is

Florida Power & Light Co. (subsidiary of FPL Group) will issue an RFP for renewables, including ocean energy. Proposals are due in June. FPL provides power to 4.5 million Floridians and has projects in 25 states. It has invested heavily in renewables, including solar and wind.

Many U.S. utilities have been educated about bringing on renewables to the grid through land-based wind power. Offshore wind, unbelievable as it seems, looks like it will not be the first ocean renewable to come online in the U.S. In fact, there is already a tidal system demonstration project installed in the East River connected to the grid.

FIGURE 3

PowerBuoy, courtesy of Ocean Power Technologies (OPT)
2,100 TWh/yr. The total U.S. consumption of electricity is about 4,000 TWh/yr. Assuming that only 1/4 of this wave resource could be harnessed at about 50% efficiency (262 TWh/yr) of wave power, it could still provide about 6.5% of the national requirement. Harnessing this energy would take at least 60,000-500 kW WEC devices—thus creating a very large market for WEC systems in the U.S. alone.

With regard to tidal river and ocean currents, EPRI estimates they could provide about 125 TWh per year in the U.S.

Overall, the potential wave and tidal resource for installed wave and tidal projects in the U.S. could support $172 billion in projects over the next 15-20 years.

Regarding OTEC, there have been some estimates of the cost of a 10 MW plant ranging from about $30 to $50 million.

**The Wave Hub Concept**

A concept known as a Wave Hub has been proposed in several areas around the world. It is a streamlined way to get developers' pilot projects tested and on the grid.

A wave hub can be built by a utility, allowing several developers to connect and provide electricity while proving the technology to the utility. If the utility feels that the technology is sound and will provide reliable power, the developer may be allowed to add full-scale systems in the form of a wave farm. There can be several developers and wave farms attached to a single hub. This concept is likely to work best in the U.S., as the utility will have streamlined the process to get wave power to the grid.

The Pacific Northwest Generating Cooperative (PNGC Power) plans to develop the Reedsport wave farm in Douglas County, Oregon, teaming with Ocean Power Technologies (OPT). Initially, the power generated will be 2 MW, but FERC has granted OPT a preliminary permit for up to a 50 MW connection. PNGC Power will provide expertise regarding grid connection and meeting the standards of the Bonneville Power Administration, which operates much of the region's power system.

PG&E applied for permits to operate two California wave energy sites off the coast of Mendocino and Humboldt counties in 2007. The hubs, called Wave Connect, would allow multiple WEC device manufacturers to demonstrate their systems at a common site. If fully developed, each site could provide up to 40 MW of electricity.

The European Marine Energy Center (EMEC), located in the Orkney Isles in Northern Scotland, is grid connected. This is a test facility, which allows developers to test WEC devices in real conditions. This concept provides an easy way for a developer to test his WEC and prove it to the industry while providing power to the region. EMEC has also established tidal sites for testing tidal energy devices.

A large-scale Wave Hub is underway off the Southwest of England and could generate £76 million a year for the regional economy. It would create at least 170 jobs and possibly hundreds more by creating a new wave power industry in Southwest England. The Wave Hub could generate enough electricity for 7,500 homes, which would support Southwest England's target for generating 15% of the region's power from renewable sources by 2010. Four companies have been chosen for installations at the hub that are sufficiently advanced with their devices and have the resources to deliver their projects, including Pelamis, PowerBuoy and Oceanlinx's Oscillating Water Column (OWC) device.

**U.S. Centers of Excellence and R&D**

The American Marine Energy Center, proposed to be established in the next few years, is located at a research/demonstration site in Newport, Lincoln County, Oregon, where land-based facilities would be integrated with the ongoing activities at the Oregon State University (OSU) Hatfield Marine Science Center (HMSC). The main elements of the facility would be similar to that at EMEC. The National Center will advance wave energy developments through a number of initiatives, such as testing existing ocean energy extraction technologies, research and development of advanced systems, investigation of reliable integration with the utility grid and intermittency issues and development of wave energy power measurement standards.

The Oregon Wave Energy Trust, which received its first $1 million of a promised $4.2 million over the next two years, plans to study the potential ecological effects of wave energy developments and will work with existing ocean users to come up with ways to best share Oregon's wave resource. Six wave energy projects have applied for permits off of Oregon's coast so far.

The Advanced Technology Manufacturing Center at the University of Massachusetts, Dartmouth, will host the Marine Renewable Energy Consortium aimed at organizing a network of technologists, entrepreneurs, and investors around ocean wave, tidal, current, and wind energy projects.

Last year, Florida Atlantic University was awarded $5 million to establish a Center of Excellence in Ocean Energy Technology. Utilizing the Navy's offshore test range, FAU, in partnership with academia, industry and government, will foster the research and development of cutting-edge ocean energy technologies.

**FIGURE 4**

FAU's concept of a Gulf Stream current farm. Courtesy of the FAU Florida Center for Electronic Communications.
including ocean current, thermal, wave and tidal-based energy.

In 2007, the Rockland, Maine, Ocean Energy Institute was established. The Institute has welcomed a limited number of researchers and is developing a research agenda around the most promising technologies. Eventually the institute may include on-site housing for visiting researchers, large meeting spaces for conferences, and a demonstration tidal power plant, and may function as a grant-making and investment body supporting a variety of ocean energy projects.

The State of the Technology

Installation of ocean energy systems in the U.S. won’t necessarily involve devices built by U.S. companies. Most of the development work on WEC and instream (tidal and current) devices has been accomplished in Europe and Australia, and these companies are actively marketing their systems in the U.S.

Several companies have developed successful designs that have been proven in demonstration projects. The interesting thing here is that they all take somewhat different approaches to harnessing energy from the ocean.

The following are intended as examples of the more significant projects planned, underway or completed in the U.S.

Wave Power

There are four basic types of wave energy devices and a few systems that are proven to be utility or near-utility-scale devices:

- Point Absorber: Ocean Power Technologies’ (OPT) PowerBuoy; Finavera Renewables’ AquaBuOY; Wavebob Limited’s Wavebob
- Attenuator: Pelamis Wave Power’s (PWP) Pelamis
- Oscillating Water Column (OWC): Oceanlinx’s OWC; Wavegen’s Limpet
- Overtopping: Wave Dragon Ltd.’s Wave Dragon

All of these technologies offer advantages and are considered viable ways to harness wave energy. In the U.S., several of the devices mentioned are in use or planned for installation off U.S. coastlines.

According to a DOE-funded study, there are 150,000 sites for wave energy development in the U.S.

Currently, there only a few utility-scale WEC devices installed off U.S. coastlines. Finavera Renewables Ocean Energy, Ltd., until very recently, had an AquaBuOY 2.0 installed off the Oregon coast. Just hours before completion of the test phase, the device flooded and sank. The good news is FERC issued a license to Finavera, in January of 2008, for the installation of four 250 kW WEC buoys, a 3.7-mile-long, DC underwater transmission cable, a shore station and a 12 kV transmission line to connect the shore station to the existing Clallam County Public Utility District distribution line. The project is called the Makah Bay Offshore Wave Pilot Project and is located off Washington State.

Most recently, Finavera has been issued a preliminary permit from FERC for its proposed 100MW Humboldt County, California, wave energy project.

OPT has one PowerBuoy installed offshore New Jersey and one off Kaneohe Bay, Hawaii, adjacent to the Marine base. A second PowerBuoy has been funded by the U.S. Navy’s Office of Naval Research (ONR) to continue the effort.

As mentioned above, Oceanlinx Limited and Pelamis Wave Power have planned installations off Oregon, and an Irish company—Wavebob—has signed an agreement with Chevron Technology Ventures (Houston, TX) to provide technical consulting services with regard to the conversion of wave energy into useful power.

Oceanlinx has very recently signed an agreement to provide up to 2.7MW of wave energy to Maui Electric Company from 2-3 floating platforms located less than a mile due north of Pauwela Point on the northeast coast of Maui. The project, to be completed by the end of 2009, is estimated at $20 million and will be paid for by Oceanlinx and its investors. This follows the signing of an agreement between the U.S. DOE and the State of Hawaii, establishing the Hawaii Clean Energy Initiative (HCEI), aimed at using renewable energy and energy-efficient technologies to supply 70% of its energy needs using clean energy by 2030.

Tidal and Current Power

In the U.S., tidal power is underway, even though there are only a few sites deemed suitable for tidal projects. Alaska, Washington, and Maine to Massachusetts have excellent tidal resources, while local areas such as San Francisco Bay could be used as tidal power sources. Many short-term tests have been completed, but to date, only one long-term test has been accomplished in the U.S.

Verdant Power claims to be the first tidal energy device to be connected to the U.S. grid and providing energy to an end-use customer. The company has successfully installed six Free Flow™ turbines in New York’s East River, along the eastern shore of Roosevelt Island. The project, Roosevelt Island Tidal Energy (RITE), has delivered power to a supermarket and parking garage as part of the demonstration. The turbines were shut down after it was discovered that the blades were not robust enough for the more severe conditions. A redesign of the blades solved the problem giving Verdant valuable information for the next phase. The project plan is to proceed from six turbines to 100-300 turbines generating up to 10 MW of power.

Florida Atlantic University’s Center of Excellence in Ocean Energy Technology, and partners, plan to demonstrate the power that can be generated long-term from the current of the Florida Gulf Stream using an open blade turbine. The site will be in 300 meters of water within the U.S. Navy’s South Florida Testing Facility.

Maryland-based UEK Corporation has been selected by the Nova Scotia government to participate in the Bay of Fundy Tidal Energy Project where it will deploy a twin turbine unit in 2009. Two other companies, one from Ireland and one from Canada, will participate as well. The host facility will be built at Minas Basin Pulp and Power.
Ocean Thermal Energy Conversion (OTEC)

OTEC had a short-lived success in the late 1970s and early 1980s, but the millions of dollars invested in OTEC research quickly ended around 1982 when the price of oil fell drastically.

With oil prices reaching the $100 per barrel mark on January 2, 2008, OTEC is again being looked at seriously. One company with a great deal of OTEC knowledge claims to be working on the first full-scale, modern OTEC plant in the U.S. The company will be working on the detail design in 2008, but has not made a formal announcement at this time. Other companies have proposed full-scale OTEC plants in areas such as Puerto Rico, the Kwajalein Atoll, Diego Garcia, and Hawaii, but no awards have yet to be made. This also suggests that the first OTEC plants may be built on military bases.

Offshore Wind

Offshore wind, it seemed, would be quick to follow its land-based success in the U.S. This quickly proved to be an incorrect assumption. Offshore wind has been proposed in many areas off the U.S. coastline, in places like Texas, Louisiana, Massachusetts, New York, New Jersey and even in the Great Lakes. However, none have yet to get strong support and many seemed to be unwilling to begin a fight like the one the Cape Wind project off Nantucket Sound has been trying to win for several years.

In February, 2007, Cape Wind filed its Draft Environmental Impact Report with the Commonwealth of Massachusetts. Previously, in November, 2004, the Corps of Engineers issued a 3,800 page Draft Environmental Impact Statement (DEIS) on Cape Wind that found substantial benefits and few impacts of the project. An open public comment period ran until February 24, 2005 and about 5,000 written comments were submitted and four public hearings occurred. The next stage in the process will be the Final Environmental Impact Statement. In May, 2005, the Massachusetts Energy Facilities Siting Board issued a permit for Cape Wind to interconnect its electric cables with the electric transmission system in Massachusetts. Other Massachusetts agencies are awaiting the preparation and completion of the Final Environmental Impact Review to complete their reviews. If approved, the Cape Wind Energy Project would be comprised of 130 wind turbine generators that could generate a maximum electric output of approximately 180 MW.

To date, no offshore wind farms exist off any U.S. coasts and most planned installations have been abandoned, with the exception of the Cape Wind project and a proposed wind farm off Galveston, Texas. Wind farms off Texas and Louisiana have a couple of things going for them. State waters extend 10 miles offshore, versus three for the East and West coasts, and these states are accustomed to seeing structures (oil & gas platforms) offshore.

Most believe that offshore wind is more predictable and reliable than land-based wind farms, and better matches the load requirements of utilities.

The latest attempt has been made by New Jersey, where Fisherman’s Energy of New Jersey, LLC (FERN) has submitted a proposal to the New Jersey Board of Public Utilities to build a two-phase 350MW offshore wind energy facility off Cape May. At the same time, PSEG Renewable Generation and Winergy Power Holdings have submitted a proposal to the New Jersey Office of Clean Energy (OCE) to build a 350MW wind farm 16 miles off the shore of South Jersey. The proposal shoots for a 2013 date to be fully operational.

The Future

Ocean Energy ultimately will be used to supplement power to the grid, providing clean, renewable and sustainable energy to the world. How much is yet to be seen. Both DOE and EPRI have stated that ocean energy has the potential to meet 10% of the U.S. demand—that’s nearly 400 TWh/yr.

Each day the oceans absorb thermal energy (heat) from the sun equal to the thermal energy contained in 250 billion barrels of oil.

One must wonder where the world would be today if it had long ago begun harnessing the largest sustainable energy source on the planet…its oceans.
Remote Sensing—State of the Art

Introduction

The past several years have seen what may be looked back upon as the greatest expansion in remote sensing sensor capability in the short history of our technology. Whether you are a proponent of airborne or satellite systems, each has benefited from an increase in platforms, the introduction of new and better sensor systems and greatly improved ancillary equipment.

This commentary will attempt to address many of these changes and to provide information about the various sensors and their capabilities. As the sensor suite is constantly changing, please excuse any omissions that may have been made.

Included with this review are two tables that show current satellite systems and airborne systems. Specific details on wavelength, number of bands, spectral sensitivity and so on are included. Additionally, the tables show what specific applications these sensors are thought best suited for.

Background

Remote sensing, as we know it today, has been on the scene for only roughly 50-60 years. The term remote sensing was first used by the U.S. military to describe a type of aerial surveillance that went beyond the use of photography into the use of parts of the electromagnetic spectrum other than the visible, such as the infrared and the microwave parts (Morley, L.W., 1993. Remote sensing then and now. Ottawa: CCRS).

The Geospatial Resource Portal defines remote sensing as the science and art of acquiring information (spectral, spatial, temporal) about material objects, area, or phenomenon, without coming into physical contact with the objects, or area, or phenomenon under investigation. Without direct contact, some means of transferring information through space must be utilized. In remote sensing, information transfer is accomplished by use of electromagnetic radiation (EMR). EMR is a form of energy that reveals its presence by the observable effects it produces when it strikes the matter. EMR is considered to span the spectrum of wavelengths from 10-10 mm to cosmic rays up to 1010 mm, the broadcast wavelengths, which extend from 0.30-15 mm.

Types of Energy Resources

- Passive Remote Sensing: Makes use of sensors that detect the reflected or emitted electro-magnetic radiation from natural sources.
- Active remote Sensing: Makes use of sensors that detect reflected responses from objects that are irradiated from artificially-generated energy sources, such as radar.

Types of Wavelength Regions

Remote Sensing is classified into three types of wavelength regions:
- Visible and Reflective Infrared Remote Sensing
- Thermal Infrared Remote Sensing
- Microwave Remote Sensing

Evolution

Aerial photography only first started to be routinely used for spatial mapping purposes during the 1930s. The need for detailed information for military planning purposes during WWII gave a major push to the technology. A perfect example of this is the development of infrared film as a means to identify camouflaged military vehicles. As we all know, the use of infrared film and the basic technology has gone on to become a backbone of modern day remote sensing.

The 1960s saw another major armed military conflict, Vietnam. As so often happens, another branch of airborne remote sensing that had military roots, thermal infrared imaging, became known and started being used in civilian remote sensing. In fact, there were many restricted technologies in use by the U.S. military at that time. The break came in 1963 when the Environmental Research Institute of Michigan obtained permission from the U.S. Department of Defense to hold an open conference on remote sensing. A wide variety of both operational and experimental sensors, ranging from infrared and multispectral scanners, to side-looking radar and passive microwave imaging devices, scatterometers and laser sensors, were discussed (Morley, 1993).

The 1960s and 70s were an exciting period that saw the conception, design and deployment of our first earth observation satellites. The move to satellite platforms created a need to develop new sensors for use on these satellites. These new sensors resulted in a move away from analogue technology and brought on the use of digital technology for data capture and storage. As is often the case when developing space-borne sensors, the systems are first tested on airborne platforms, and this serves to drive development in airborne remote sensing as well.

Computing Power

The development of remote sensing has been very closely linked to the development of computer systems and also to the development of data recording technology. As recently as twenty years ago we were still using mini computers and 9 track tape drives on aircraft platforms to capture and record
airborne remote sensing data. Fifteen years ago, 200 MB hard drives were selling at more than $1,000. The speed of computer architecture and the related speed of computer-based recording systems have been a defining factor in things such as spatial resolution and the quantity of spectral bands that can be recorded. As computers have advanced, so has the ability to record smaller and smaller pixel resolutions while increasing the number of bands that are recorded.

The recording media used to store data has also played a significant role in the advancement of remote sensing technology and subsequently its usage. Twenty years ago, 9 track tape drives were state of the art. These were gradually replaced by much smaller and faster tape drives such as Exabyte, which, in turn, were replaced by the availability of larger and larger hard drives at lower and lower prices. The $1,300 that could purchase a 210 megabyte hard drive in the early 1990s will now buy approximately 13 – 300 gigabyte hard drives today.

Resolution
Resolution, particularly spatial, is of prime interest to most remote sensing data users. However, often overlooked are spectral resolution and dynamic range. All have seen significant improvements in the last several years, resulting in much more powerful remotely sensed data.

Spatial Resolution
Spatial resolution is normally a combination of across track resolution and along track resolution. Across track resolution is generally a function of the type and size lens used on a sensor combined with how high above the Earth’s surface the sensor is flown. Adjusting these two variables will produce varying spatial pixel sizes. Along track resolution is controlled by how fast the platform on which a sensor is being operated is moving along its track of flight and how quickly can the data that is being collected be recorded. A general rule of thumb is that the more data you try to collect, the longer the along track pixel size will need to be.

Spectral Resolution
The ability to discern smaller parts of the spectrum has been a welcome outcome of the improvements that have been made in CCD arrays combined with faster computers and improved sensor optics. Improved signal-to-noise capabilities of sensors have also allowed sensor manufacturers to develop systems with smaller and smaller bands. It is now becoming routine to have airborne sensors that record spectral bandwidths that are as narrow as 2-3 nanometers and satellite platforms with bands measured in 10s of nanometers.

Dynamic Range
This is one of the resolutions often overlooked during a discussion of resolution. Dynamic range is the ability to detect small variations in light levels in a very bright scene. Earlier sensors and even some of today’s sensors are 8 bit devices. An 8 bit device will divide the light it receives into 256 portions. The usual problem with 8 bit sensors is over-saturation as well as difficulty in separating features with similar coloring. Most of the sensors now in use have been improved to either 12 bit or 14 bit. A 12 bit device has 16 times the dynamic range of an 8 bit system. 14 bit sensors have 4 times more range than a 12 bit system and 64 times the range of an 8 bit device. The greater the dynamic range, the more likely it is that a sensor will separate very small variances in color and therefore data analysis will have much greater detail.

Sensing Systems Today

Passive Systems

High Spatial Resolution
Many modern sensor systems, both airborne and spaceborne, have been developed placing a major emphasis on very high spatial resolution. Satellite sensors such as Ikonos, Quickbird and Kompsat have the capability for less than 1 m resolution in panchromatic and between 2-4 m resolution in 4 band multispectral mode. This high resolution, combined with a very high re-visit rate, (2-3 days in most cases), means that detailed mapping and very quick change detection studies can be easily undertaken. This class of satellite/sensor is extremely useful for quick impact mapping following major weather events, such as hurricanes and tornados. These sensors are also very powerful tools for mapping coastal land features, mapping change in coastal features, and mapping coastal vegetation and determining its health.

Airborne digital camera systems were first used in the agricultural sector less than ten years ago. The initial cameras were 8 bit devices and 4 bands. Their major strengths were the very high spatial resolutions that were possible, in the order of 0.25 m and ranging up to 1 m, and the ability to process the imagery within hours of being acquired. Digital camera systems have now been used for many other applications and have shown they are powerful tools in the marine/coastal sector. They are ideal tools for mapping coastal change, mapping coastal vegetation and mapping nearshore benthic habitat. More recent airborne camera systems have 12 bit capabilities and can acquire up to 8 spectral bands. This will make them very key systems for a number of applications.

Spectral Resolution
In the satellite sector, there has been an obvious movement towards placing sensor systems in orbit that have increased spectral sensitivity and that have the ability to record more spectral bands. Sensor systems such as Hyperion, Modis and Meris all have expanded spectral band capability and are capable of collecting between 15 to 220 individual bands. Generally the tradeoff for satellite systems with increased band capability is having lower spatial resolution.

Airborne sensors have been increasing in capability and are able to record considerable numbers of bands. Hyperspectral imagers such as Casi, Aviris, Aisa, Hymap and Probe are all capable now of collecting between 20 – 288 bands of spectral data. Many of these sensors also have the ability to record very narrow bands, sometimes as small as 2 nanometers in width.
### TABLE 1  AQUATIC FEATURES FROM SATELLITES
(see page 19 for Glossary and Websites)

<table>
<thead>
<tr>
<th>MULTISPECTRAL/HYPERSPECTRAL</th>
<th>THERMAL/IR</th>
<th>PASSIVE MICROWAVE</th>
<th>RADAR - ALTIMETER</th>
<th>RADAR - SAR</th>
<th>RADAR-SCATTEROMETER</th>
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</thead>
<tbody>
<tr>
<td>SATELLITE</td>
<td>NOAA</td>
<td>ERS-2</td>
<td>DMSP</td>
<td>ERS-2</td>
<td>ERS-2</td>
</tr>
<tr>
<td>SENSOR</td>
<td>AVHRR</td>
<td>ATSR</td>
<td>TMI</td>
<td>TOPEX/Poseidon</td>
<td>GFO</td>
</tr>
<tr>
<td>Country</td>
<td>USA</td>
<td>U.K.</td>
<td>Japan</td>
<td>USA</td>
<td>Canada</td>
</tr>
<tr>
<td>Spatial resolution (km)</td>
<td>1100 &amp; 4000</td>
<td>1000</td>
<td>25000</td>
<td>25000</td>
<td>30</td>
</tr>
<tr>
<td>North (km)</td>
<td>120</td>
<td>15</td>
<td>2350</td>
<td>2800 &amp; 1500</td>
<td>36</td>
</tr>
<tr>
<td>No bands</td>
<td>36</td>
<td>8</td>
<td>36</td>
<td>8</td>
<td>13</td>
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<tr>
<td>Web Site</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
</tr>
</tbody>
</table>

#### FEATURE

- Coastal vegetation: •
- Colored DOM: 0
- Flooding & storm surge: •
- Fronts & currents: •
- Ice: 0
- Phytoplankton (chlorophyll): •
- Plumes (turbidity): 0
- Seafloor mapping (coastal): 0
- Ships: 0
- Slicks: 0
- Surface temperature: 0
- Waves (surf): 0
- Waves (internal): 0

(Solid circle represents a developed application; open circle represents an application under development or thought to be suited for development.)
### TABLE 2 AQUATIC FEATURES FROM AIRCRAFT (see page 19 for Glossary and Websites)

<table>
<thead>
<tr>
<th>VISIBLE/MULTISPECTRAL/HYPERSONSPECTRAL</th>
<th>THERMAL</th>
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<tbody>
<tr>
<td><strong>SENSOR</strong></td>
<td><strong>AISA EAGLE</strong></td>
</tr>
<tr>
<td><strong>Country</strong></td>
<td>Finland</td>
</tr>
<tr>
<td><strong>Spatial Resolution (m)</strong></td>
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</tr>
<tr>
<td><strong>Spectral Range</strong></td>
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</tr>
<tr>
<td><strong>No Bands</strong></td>
<td>288</td>
</tr>
<tr>
<td><strong>Web Site</strong></td>
<td>1</td>
</tr>
</tbody>
</table>

**FEATURE.** This table outlines current airborne sensors that observe aquatic features. All sensors have limitations. A sensor/feature identified with a blue dot indicates this type of sensor is suited to observe the feature. Check the sensor’s website for further details. Please report any errors or omissions in the table to herby@hyperspectralmap.com

Bathymetry | • | • | • | • | • | • | • | • | • | • |
Coral reefs | • | • | • | • | • | • | • | • | • | • |
Coastal plumes | • | • | • | • | • | • | • | • | • | • |
Coastline | • | • | • | • | • | • | • | • | • | • |
Currents & fronts | • | • | • | • | • | • | • | • | • | • |
Flooding | • | • | • | • | • | • | • | • | • | • |
Gelissofice | • | • | • | • | • | • | • | • | • | • |
Ice | • | • | • | • | • | • | • | • | • | • |
Phytoplankton | • | • | • | • | • | • | • | • | • | • |
Salinity | • | • | • | • | • | • | • | • | • | • |
Ships | • | • | • | • | • | • | • | • | • | • |
Sticks | • | • | • | • | • | • | • | • | • | • |
Surface temp | • | • | • | • | • | • | • | • | • | • |
Topography | • | • | • | • | • | • | • | • | • | • |
Waves (surface) | • | • | • | • | • | • | • | • | • | • |
Waves (internal) | • | • | • | • | • | • | • | • | • | • |
Wetlands | • | • | • | • | • | • | • | • | • | • |

### LIDAR

<table>
<thead>
<tr>
<th><strong>SENSOR</strong></th>
<th><strong>ALTM</strong></th>
<th><strong>LADS MKII</strong></th>
<th><strong>SHOALS</strong></th>
<th><strong>PALS</strong></th>
<th><strong>SLFMR</strong></th>
<th><strong>EMISAR</strong></th>
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<td>4 to 8</td>
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<td>5 to 10</td>
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<td>L</td>
<td>L, C</td>
<td>L, C, P</td>
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</tbody>
</table>

**FEATURE.**

Bathymetry | • | • | • |
Coral reefs | • | • | • |
Coastal plumes | • | • | • |
Coastline | • | • | • |
Currents & fronts | • | • | • |
Flooding | • | • | • |
Gelissofice | • | • | • |
Ice | • | • | • |
Phytoplankton | • | • | • |
Salinity | • | • | • |
Ships | • | • | • |
Sticks | • | • | • |
Surface temp | • | • | • |
Topography | • | • | • |
Waves (surface) | • | • | • |
Waves (internal) | • | • | • |
Wetlands | • | • | • |
Winds | • | • | • |
TABLE 1  

TABLE 2  

Active Systems

Lidar

Perhaps one of the greatest jumps has taken place in both the capability and use of lidar systems. In a very few years terrestrial lidar systems have increased significantly in power. This jump in power has had a resulting major improvement in the “cloud of data points” that the sensors can acquire and this, in turn, translates into much more accurate terrain measurements. Coincidental with this increased capability has been a marked increase in the number of users of the technology and in the number of service providers. Marine lidar systems have also made significant technical advancements in the past few years. More systems are available and more and more projects are being undertaken with these systems.

Radar

Radar systems continue to hold a strong position in the remote sensing field. Airborne radar use has had a long history, dating back over forty years. Sensor systems have improved greatly over that period and have become much more powerful and capable of providing better and better resolutions. Satellite systems also have made major inroads over the past decade. Radarsat I and ERS-2 both have proven that space-borne radars have many uses. The launch of Radarsat II in 2006 brought significant new capabilities to this emerging sector.

Spatial Accuracy

Complementing the advancements made in the spectral and spatial characteristics of modern day sensor systems has been the remarkable improvement in the ability to obtain very high x,y spatial mapping accuracies. GPS systems have been available in the airborne remote sensing sector for approaching twenty years. Over this period they have improved in capability and dropped significantly in cost. Modern day GPS systems and the advanced processing software make it possible to record centimeter or better positional accuracy.

However, simply having a high-end GPS on an aircraft does not translate into very good x,y accuracies. The difficulty lies in the fact that aircraft are constantly in motion along three primary axes. So as imagery is being recorded, this variable movement creates distortions in the image data, which translates into large errors in positional accuracy.

About fifteen years ago, the first Inertial Measurement Units (IMUs) were placed on aircraft in order to measure this aircraft motion. IMUs are military technology that has moved over into the civilian sector and these three axis systems measure aircraft motion very accurately and very rapidly. The use of IMUs in airborne data collection
was initially slowed by the high cost of the early IMU systems. In recent years these costs have dropped considerably and most airborne systems now employ IMUs. The advent of IMUs has meant that x,y spatial accuracies that were measured previously with 30–50 meter errors have dropped to the order of 1-3 meter errors.

**Summary**

The opportunity to obtain highly specialized remote sensing data, whether from airborne or spaceborne sources, has never been better. The variety of sensor systems available for use and their powerful capabilities mean more specialized applications are being developed and employed in operational use. The future is bright as a significant number of new systems and satellites are being planned and will soon be in operation.
Introduction

Changes in ship technology have been slow to evolve. Commercial boat and ship designs have advanced over time by adapting to local conditions and trading requirements. Ships, as instruments of war, made a major change when the British advanced the concept of fighting at sea from the movement of fortified castles, such as the Spanish Armada, to instruments of battle capable of rapid maneuvering. New designs followed resulting in hull and sail improvements. The introduction of the steam engine again caused a major shift in propulsion-related design. This proved to cause a change in geopolitical posturing as countries needed to secure coaling stations worldwide to support ocean trade and colonization. The ironclad added yet another factor to ship design. Ships became heavier and more lethal. However dramatic the changes seemed at the time, they were mostly adapting to changing conditions and not to significant shifts in design.

CATAMARAN/SWATH DESIGNS

The catamaran design has been around for hundreds of years in the Pacific. In the latter half of the 20th century, power was added allowing for a faster and more stable platform. The Small Waterplane Area Thin Hull (SWATH) design grew out of this in the 1970s. Both the catamaran and SWATH concept are used for high-speed ferries and other applications requiring both speed and comfort. Ever larger ships of this design are being built.

In 2005, the U.S. Navy christened a 262-foot Catamaran, Littoral Surface Craft (Figure 1) referred to as the X-Craft Sea Fighter (FSF-1). This ship can operate in shallow water and is capable of 50 knots with a full payload. It is powered by two MTU diesel engines and two LM2500 gas turbines. The huge deck allows for helicopter operation and the huge cargo bay allows for a dozen 20-foot mission modules. It will be operated with a miniscule crew, by navy standards, of 26. Missions anticipated include: battle force protection, mine countermeasures, anti-submarine warfare, amphibious assault support, and assistance with humanitarian aid. The ship is essentially an empty box until mission-specific vans are placed aboard. This design reflects several drivers including speed, multi-mission, reduced crewing, ride comfort (human factor), and that it is required to operate in relatively shallow waters.

ABSTRACT

The ship building industry is experiencing a wave of new ship technology and design. Historically, ship design has been slow to change. For example, the mono-hull design has been around for centuries. Propulsion has evolved as technology advanced but we see ship owners as very conservative in embracing new advances. In the past 20 years this trend has shifted as new designs begin to appear. This article explores some of these changes and the drivers that are causing this shift. Clearly, as technology advances and uses for ships expand, the ship building industry design is evolving. New issues have come to the fore and have accelerated the design change. These drivers include fuel costs, reduced crewing, speed, security issues, pollution regulations, stealth needs, human factors, safety, geopolitical changes, multi-mission requirements, and acoustic quietness. Examples of military, commercial, and research ships are discussed.
A radical takeoff from this design has been developed. The designation given to this new ship is Wave Adaptive Modular Vessel or WAM-V (Figure 2). This experimental spider-like craft is an ultra-light flexible catamaran modularly designed to allow for multi-missions and projects. The supporting pontoons are capable of moving in relation to one another. They are outfitted with springs, shock absorbers, and ball joints to allow articulation of the vessel, which results in a mitigation of stress to the structure, payload, and crew. Two engine pods, containing the propulsion and ancillary systems, are secured to the hull with special hinges that keep the propellers in the water at all times. The modularity of this ship allows for different payloads and missions.

Research vessels have been venturing into the catamaran and SWATH design concept. The University of Miami placed F. G. Walton Smith (Figure 3) into service in 2000. This catamaran design allows for a shallow draft of 5½ ft to accommodate the oceanographic research missions of Southern Florida waters, a large operation platform, and a generous 800 sq. ft. laboratory for its 96-foot length. The design provides a stable ride and the ability to accommodate 20 persons on scientific missions.

The University of Hawaii selected a SWATH design for their newest research vessel, RV Kilo Moana (Figure 4). This world-ranging ship is 185 feet long and displaces over 2500 tons. A stabilized working environment for rough sea oceanographic operations is a major plus for this ship. The ship can remain at sea for 50 days, operate at a maximum speed of 15 knots and carry a large scientific party of 28 with a crew of 20. The large deck and laboratories allow for multi-mission operations for this versatile ship.

Acoustic Drivers

While the catamaran and SWATH designs satisfy the missions for the Universities of Miami and Hawaii, other ship characteristics have driven research vessel designs. The University of Delaware was interested in the acoustic profile of its new ship Hugh R. Sharp (Figure 5). Scientific missions are depending more on acoustic equipment to sample the ocean and noisy ship hull and propulsion systems inhibit the operation of these sensitive instruments. Sharp was built to operate quietly following the International Convention for Exploration of the Seas (ICES) standards.

The National Oceanic & Atmospheric Administration (NOAA) has recently commissioned three fishery research ships with superior acoustic characteristics and a fourth ship is under construction and scheduled for delivery in 2009. The first three ships: Oscar Dyson, Henry Bigelow (Figure 6), and Pisces were designed to meet the tough ICES standards. This
opens a new window for fisheries research, permitting the ship’s acoustical equipment to count fish and assess the size, health, and behavior of fish stock. This technique provides a faster assessment process that translates into more cost-effective sampling. The process is non-destructive to the fish stock providing another plus. Clearly, acoustic concerns have been the driver in the NOAA design planning. Acoustic quietness, however, comes with a significant additional construction cost.

**Speed**

A new group of smaller research vessels has taken another design approach. Naval architect Roger Long has designed a Challenger Class research vessel that is focused on speed. Three ships in this class include RV Gulf Challenger (UNH) (Figure 7), RV Tioga (WHOI), and RV Fay Stover (ODU). A high-speed design of up to 20 knots allows a smaller vessel to quickly get to its operating area and return with a 6-8-hour mission profile. It also provides for the option to run from approaching weather allowing the small 50-foot vessel to stay on station longer and then “run for the barn.” The high operating success of Gulf Challenger stimulated the second two ships of this class.

Speed has also been a driving design consideration in a plethora of new Navy and commercial vessels. The U.S. Navy has contracted for twelve M2-35 catamaran patrol boats. Moose Boats is constructing the aluminum hull catamarans powered by twin Cummins 380 hp turbo diesels and propelled by Hamilton 292 water jets. The boats draw less than 3 feet and have a service speed of 27 knots and a top speed of 35 knots.

The Navy’s arsenal is being augmented by more high-speed boats. Kvichak Marine Industries is constructing four MPF 40-foot utility boats to support Marine amphibious assault missions. These landing craft vessels have a loaded cruising speed of 25 knots and a lightened flank speed of 40 knots. Twin Cummins QSM11 engines rated for 660 hp at 2300 rpm make up the propulsion package.

A 40 knot Commander class 27-foot patrol vessel has been delivered by Sea Ark Marine Inc. to the Bossier Sheriff’s Office in Benton, LA. The vessel is a deep-vee variable dead-rise aluminum hull that produces a smooth, dry and stable ride designed for patrol/security, surveillance and search/rescue.

As seen above, the Navy, oceanographic community, as well as commercial ship design have emphasized speed. These designs were developed before the recent dramatic increase in fuel prices. Unless the price of fuel takes a dramatic about-face, it is hard to see how this design feature can prevail in the future.

**Superior Stability**

The Lake Charles Pilots, operating on the Calcasieu ship channel in southwest Louisiana, have ordered their third pilot boat from Gladding-Hearn Shipbuilding, Duclos Corporation. They need a stable boarding boat with a deep V hull that can operate continuously to the outermost sea buoy, 30 miles off the coast. The all-aluminum vessel is 75.8 ft. overall with a 20.6 ft. beam and 6.8 ft. draft. Twin Cummins QSK38M diesel engines of 1350 bhp provide a top speed of 27 knots. The engines will be equipped with a Cummins’ Centinel lube-oil management system, adding fresh oil as needed to replace oil burned through the fuel system. The boat will be driven by 5-blade Bruntons propellers. Special consideration was given for bridge noise abatement; limiting noise levels by about 75 decibels. Again we see consideration given to the “human factor.”

A high-speed ferry, Alakai, has been delivered to Hawaii Superferry with a second catamaran of this class under construction. Four MTU 20V 8200 M70 main engines with a top speed of 35 knots power the ship. It is capable of carrying 866 passengers and 282 cars. Many environment-friendly features are included, such as hulls with a non-toxic coating and on-board storage of wastewater, refuse, and other solid waste. Environmental considerations and an energy-efficient design permit this catamaran to meet or exceed government standards for protecting Hawaii’s islands and ocean. This is the largest aluminum catamaran ever built in the U.S.

**The Environment**

Environmental issues are clearly driving new ship design and equipment selection. The House Transportation and Infrastructure Committee approved legislation to reduce global warming through greater transportation efficiencies and conservation initiatives. The major freight goods move-
ment components of House Resolution (HR) 2701, the Transportation Energy Security and Climate Change Mitigation Act of 2007, will integrate the marine highway into the nation’s overall intermodal transportation system. Title IV of this bill will establish a new program to promote short sea shipping to move cargo on the Great Lakes and along the sea coasts. Loan guarantees will help marine operators and shippers construct a new class of cargo vessels suitable for short sea shipping. Senator Boxer and Representative Solis of California introduced the Marine Vessel Emissions Reduction Act of 2007 in companion versions to amend the Clean Air Act to reduce air pollution from marine vessels.

The Environmental Protection Agency (EPA) issued a direct final rule extending through December 17, 2009, the date for adoption of a rulemaking to address the control of emissions from new marine compression-ignition engines at or above 30 liters per cylinder.

Emission reduction efforts have already begun in the ports of Seattle, Tacoma, and Vancouver (Canada) where they have proposed performance goals to reduce particulate matter by 70 percent from ships at berth and 30 percent from cargo-handling equipment. This aggressive goal has been scheduled to be met by 2010.

The first hybrid tug is being built to support the San Pedro Bay Ports Clean Air Action Plan in California. This tug will be designed to reduce gas emissions, such as nitrogen oxide and carbon dioxide, and should exceed the EPA’s Tier 2 emission requirement for marine vessels. The drive unit design will be powered by batteries and diesel generators and will have the horsepower of an average tug. The vessel is scheduled for delivery in 2008.

“Going green” is becoming the goal of the Offshore Industry. Public pressure is driving this effort according to Neil Patterson, managing director of IMT Marine Consultants. The effort is spreading worldwide. Diesel-electric propulsion provides about a 40 percent reduction in fuel usage and is an effective tool to work towards this goal. Norway is addressing the emissions problem by switching to liquefied natural gas (LNG). Five new ferries have entered service and have been fitted with Rolls-Royce gas fueled engines. Just as with acoustic quieting environmental upgrades, going green comes with increased cost.

Security

Security and terrorist attacks provided the impetus for the Navy to install the first Shipboard Protection System (SPS). The system will allow the ship’s commander to conduct surveillance, track, and evaluate identified threats and respond appropriately beginning with a non-lethal response and progressing to lethal defensive action as necessary. The system is an integrated package of command and control software, sensors, tactical decision aids, warning devices and weapons to provide a full range of defensive capabilities. Similar port security systems are going into operation around the world. Mandatory requirement for Automatic Identification Systems (AIS) also falls within the security changes.

Hazardous Mission Vehicles

As the Navy’s Littoral Warfare plans unfold, we have seen the need for the high-speed landing craft. A new generation of unmanned vessels is being developed where hazardous missions are involved—Unmanned Sea Surface Vessels (USSVs) (Figure 8). USSVs allow for decreased operator workload (reduced manning); increased personnel safety; robust, stealth, and higher reliability operations due to reduced communications requirements and enhanced operational range. Missions include mine countermeasures, Anti-Submarine Warfare (ASW), surface warfare, Expanded Maritime Interception Operations (EMIO), electronic warfare and supply delivery in adverse conditions. These vessels will be able to work in a high sea state environment and will have an obstacle detection and collision avoidance system for autonomous navigation in littoral and cluttered environments.

Solar Powered Ships

With the price of oil going continually skyward, could the future be with solar powered ships? New York City ferry operator Circle Line is contracting a solar and wind powered ferry to join the Statue of Liberty and Ellis Island fleet (Figure 10). The ship is being built by an Australian Company, Solar Sailor Holdings Ltd. It incorporates both solar and wind with a hybrid engine that can shift to conventional fuel. This radical design collects solar power that recharges a huge battery bank. Like the hybrid car, when high speeds are required it shifts to fossil fuel. It also has the capability to recharge the batteries at night by plugging into the

FIGURE 9

An Owl MK II Unmanned Surface Vehicle cuts through the waters of Mile Hammock Bay, New River, N.C. The remotely controlled Owl MK II is being developed by Navtec, Inc. for the Office of Naval Research. DoD photo by Lance Cpl. T.A. Pope, U.S. Marine Corps.

USSVs are optimized for at-sea launch and recovery. One such vessel is the Navtec, Inc. Owl MK II (Figure 9). The Owl MK II is considered a semi-autonomous/autonomous marine craft for real-time data collection and is built with a modular design enabling easy installation of sensor packages or technologies to meet the mission needs. With speed ranges up to 30 knots, this 10-foot 3-inch unmanned vehicle can be crammed full of mission technology. Again we see speed, stealth, multi-mission, and safety being design drivers.
grid. This catamaran design can operate at 13 knots when under conventional power. While operating with the solar sail, it emits essentially no noise, vibrations or fumes. This is truly a green ship incorporating a high-speed, stable design that is environmentally friendly and fuel efficient.

The Future

Looking ahead to new design and technology advances for ships, we see progress on the high-temperature superconductors (HTS) for all-electric ships. Siemens has developed the world’s first HTS generator rated at four megawatts. The HTS produces 30 times higher torque compared with the standard generator and is smaller and lighter than conventional electric propeller motors. As we see electric propulsion capturing the Naval, commercial and research propulsion needs, the HTS is a welcome advance.

Fuel cells offer another advance for marine power generation. Used already in the submarine world, the fuel cell is making a bid for other marine applications. Fuel cell power offers many advantages: environmentally clean power source, more fuel-efficient than internal combustion engines, low maintenance, and acoustically quiet operations. The problem to date has been finding an optimal fuel source for the needed hydrogen. The Navy’s efforts seem to be focused on a molten carbonate fuel cell (MCFC) capable of running on Jet Propellant (JP-8). This fuel must be reformed before use to remove harmful sulfur from the fuel, which adds considerable size, weight and cost to the system.

FuelCell Energy Inc. is developing a next generation high temperature, diesel fueled, fuel cell for marine service. This Solid Oxide Fuel Cell (SOFC) can range in size from 250 kilowatts to 2.4 megawatts. Voller Energy Portable Fuel Cells has developed a Proton Exchange Membrane (PEM) fuel cell for operation on yachts. This fuel cell operates at low temperature and is fueled by liquefied natural gas (LNG) or propane. This 1kW power source is small, quiet and environmentally friendly.

As the fuel cell industry continues to move forward with technical advances and cost reduction progress, we will see more and more of this technology move into the marine business. Small power requirements and auxiliary applications will come first followed by main propulsion fuel cells. These advances will parallel terrestrial fuel cell development for busses, rail and automotive applications. Fuel cells are currently competitive in the forklift world; other applications will soon follow.

Conclusion

Change occurs when government, industry, and society are stimulated by new events, new technology, economics and geopolitical maneuvering. We have seen many such “drivers” for ship design. Environmental and security considerations have become the newest design drivers. Economics have caused reduced crewing and more efficient hull forms and propulsion equipment. Economics have also caused the need to have multi-mission hulls. Reduced crewing has caused concern for crew fatigue providing impetus for more stable platforms with better movement characteristics. More human cargo with ferries and cruise ships also demand more comfortable ships. Technological advances in acoustics have provided useful tools for scientists at sea as well as safety equipment in all ships requiring reduced noise in hull and engine design. These drivers seem to have accelerated in the recent past causing major advances in ship design and technology.
2007 MTS Overview of Manned Underwater Vehicle Activity

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ABSTRACT
There are approximately 100 active manned submersibles in operation around the world; in this overview we refer to all non-military manned underwater vehicles that are used for scientific, research, tourism, and commercial diving applications, as well as personal leisure craft. The Marine Technology Society committee on Manned Underwater Vehicles (MUV) maintains the only comprehensive database of active submersibles operating around the world and endeavors to continually bring together the international community of manned submersible operators, manufacturers and industry professionals. The database is maintained through contact with manufacturers, operators and owners through the Manned Submersible program held yearly at the Underwater Intervention conference.

The most comprehensive and detailed overview of this industry is given during the UI conference, and this article cannot cover all developments within the allocated space; therefore our focus is on a compendium of activity provided from the most dynamic submersible builders, operators and research organizations that contribute to the industry and who share their latest information through the MTS committee. This article presents a short overview of submersible activity in 2007, including new submersible construction, operation and regulatory activity of research, tourism, commercial diving and recreational applications. The scope of this article is limited to active atmospheric submersibles, and does not include historical, ambient pressure, or laid-up submersibles, which would be an entire article on its own. For a complete overview that includes submersibles not covered in this article, readers are invited to peruse the MTS Manned Underwater Vehicle online database at the committee's website (www.mtsmuv.org).

Introduction
The year 2007 did not herald a great number of new manned submersible deployments, although the industry has experienced significant momentum. Submersibles continue to find new applications in tourism, science and research, commercial and recreational work; the biggest progress coming from the least likely source, namely the leisure markets. The year’s most sensational news was unquestionably achieved by two Russian submersibles, MIR 1 and MIR 2, with their voyage to the bottom of the North Pole. Scientists from the PP Shirshov Institute of Oceanology duly recorded the event and planted a Russian flag there, sparking an international debate over the ownership of the North Pole. Other news stories reported submersibles used for drug trafficking in South America, creating stereotypes that feed the population’s imagination with yarns of old submarines used in dangerous applications.

In reality however, ocean sciences have been heavily curtailed due to reductions in the U.S. federal budgets. The Alvin replacement HOV project, funded through the National Science Foundation (NSF) and led by the Woods Hole Oceanographic Institution (WHOI), is in its fourth year with a scheduled delivery in 2010 (Dietrich, 2008). The effort to deliver a new 6500 m vehicle on schedule and on budget is an ongoing challenge amidst tight budgetary guidelines. Overseas, however, budgets are burgeoning. China is making steady progress in the completion and testing of a 7000 m-rated deep submergence vehicle (DSV) projecting their sea trials for 2008; neighboring Japan claims the deepest operating DSV, the Shinkai 6500; and the latest entrance to the deep submergence club, India, has issued a public RFP for a 4000 m manned submersible. Led by the National Institute of Ocean Technology, the Indian government has already commissioned a 104 m Ocean Research Vessel, the Sagar Nidhii, which was delivered in January 2008.

No segment of the industry introduces more people to the underwater world than the numerous tourism operators around the globe. There are approximately 35-40 tourism submersibles operating worldwide. The vast majority of passengers are toured by a few operators of large 44-64 passenger submersibles that typically dive to depths ranging between 100-150 feet, and perform from 2000 to 5000 dives each year. A lesser number of people tour the oceans in smaller submersibles. The tremendous tourism growth experienced in the 1990s has leveled out, leading to a stable fleet of submersibles. The excellent safety record is a testament to the high quality guidelines and regulations that have been generated over the past 25 years by classing agencies such as the American Bureau of Shipping (ABS), Det Norske Veritas (DNV), Cayman Island Shipping Registry (CISR) and Lloyds Register (LR), as well as flag state government agencies.

Most of the new submersible builds belong in the market segment for private leisure use. While regulatory adherence is fully established in classic commercial applications such as tourism and research, there are few formal requirements for private vehicles. This has the advantage of facilitating modifications of existing design guidelines...
as well as the establishing new ones, but lay owners are at a strict disadvantage to objectively evaluate concepts and operating procedures of these complex systems.

The luxury yachting market is growing at a swift pace. In 1993, there were fewer than 700 yachts worldwide larger than 80 ft; today there are more than 700 new orders on the books for yachts 80 feet or more. When all delivered, there will be more than 6000 yachts in operation, many of them between 150 ft and 250 ft long, large enough to carry private submersibles. The trend has not escaped the notice of large yacht management firms around the world (Boggs, 2008). To foster an exchange of technical information, a preliminary dialogue between the yachting and submersible industry was initiated at the 5th Annual MTS Manned Submersible program at the Underwater Intervention conference in January 2008. The response was very positive and the effort is likely to make a significant impact in the mainstream deployment of private submersibles for the public yachting market.

The biggest technology advancements in the field of subsea tools and instruments come from Remotely Operated Vehicles (ROVs), spurred in large part by the oil industry, and in battery technologies from the Autonomous Underwater Vehicle (AUV) industry. Unique to all submersibles is the need for autonomous power and high capacity batteries. The major push today is in the development of lithium-ion-based batteries that provide a significant increase in energy density. More testing and regulatory approval is in the works to make this commonly available. The biggest changes, however, are seen in the wide variety of high resolution underwater imaging systems that are offered by a growing number of manufacturers, and the emergence of high power LED light technology. The latest developments are one of the areas addressed through the MTS MUV yearly program during the Underwater Intervention conference.

The following is a brief summary of activity, presented in simple alphabetical order of the submersibles.

1. Alvin
Alvin started the 2007 season in February by completing 9 cruises for a total of 77 dives, ranging from EPR 9N, SoCal, JdF, OR Margin, Guaymas. The submersible was on layup from February to June for overhaul work and to install new pieces of equipment to be tested. These included new LED lights, a precision clock for navigation and Frangibolt emergency releases.

Alvin dove to an average of 2100 m with submerged times averaging 7.6 hours and 5 hours of bottom time (www.whoi.edu). The majority of the dives were for Biology science (29 dives) followed by Biochemistry (22), Geo Chemistry (19) and Geology (12). Alvin did perform two engineering dives in June to verify the function of the new equipment, and also to support the Lockheed Martin engineering team that was awarded the contract in Summer 2007 for the design and fabrication of the RHOV. Four team members experienced diving a deep submergence submersible. Alvin is operated by Woods Hole Oceanographic Institution, designated as the National Facility Operator. Alvin is presently rated to 4500 meters by the U.S. Navy (Brown, 2006). The RHOV scheduled to replace Alvin will be rated to a maximum depth of 6500 m and will be classed by the American Bureau of Shipping, Southwest Research Institute is under contract for the design and fabrication of the manned pressure vessel, to be delivered to Lockheed Martin for integration into the vehicle.

2. Antipodes
Hoffmann Submarines completed the final stages of the overhaul and ABS classification of the submersible Antipodes. Antipodes’ present configuration was created from the pilot compartment and conning tower from a modular sub originally known as the Perry PC-1501 and built for service in the oil fields of the North Sea (Hoffmann, 2008).

Antipodes is a five-person submersible with unusually large diameter 58” hemispherical viewports both bow and stern. Each viewport has a 46”-wide seat for two and uses a unique feature where the pilot can move about with the handheld remote control. The submersible is equipped with vectored thrusters for precise control. It is classed to a maximum depth of 1000 feet by the American Bureau of Shipping (ABS) for both private use and passengers for hire. Hoffmann Yacht sales has been involved with this sub since 1988, and has performed all major modifications and upgrades in 1997 to integrate it into a 150’ yacht, and later to operate as a tourism submersible in the deep Fiords of New Zealand’s South Island.

3. Atlantis Submarines
Atlantis Adventures operates a family of 11 submersibles in nine locations worldwide. The main achievement in 2007 has been to keep all locations operating safely and steadily, a true exception in an industry
that is marked by irregular business cycles. All of the submersibles are classed by the American Bureau of Shipping and the U.S. Coast Guard for U.S. Operations. The submersibles operate daily touring passengers to depths of 100 to 150 feet. No new Atlantis submersibles have been added or retired and all 11 submersibles are operating in the same locations. Started in 1985, Atlantis has taken more than 10 million passengers on more than 352,000 dives and continues to foster interest in the underwater world and its technologies (Kohnen, W., 2007).

4. BS600/BS1100

Blue Safari Submarine is based out of Grand Bay, in the Republic of Mauritius, and operates two tourism submersibles (www.blue-safari.com). The company operates what it calls “The Little” BS600, which carries 5 passengers, and “The Big” BS1100, which carries 10 passengers. The BS1100 was built in Finland and is rated to a maximum depth of 80 meters (260 ft). The BS600 is based on a Bureau Veritas classed PS700 design, manufactured in France by Personal Submarine Industries (Onofri, 2008). The BS1100 is based on the DNV classed SM100 design, which offers large flat windows to passengers and a large hemispherical bow window for the pilot. Both submersibles are certified by the Indian Register of Shipping (IRS) and operate from a support ship called the “Betty des Mascareignes.” The company started operation in 1998 and estimates having carried more than 60,000 passengers underwater. BS600 completed a major overhaul in 2007, which replaced its large acrylic cylindrical viewport as it had reached its 10 year service life limit as set by IRS.

5. Carolyn

In September and October of 2007, Dr. George F. Bass aboard SEAmobile Carolyn continued its superb record of enabling the Institute of Nautical Archaeology (INA) to locate ancient shipwrecks in the Aegean Sea (Bass, 2008). When weather and visibility cooperated, INA was finding a new wreck about every other day in the vicinity of Çe me, Turkey. Of greatest interest were a Hellenistic wreck of the third century B.C. and a Byzantine wreck of the fourth-to-sixth century A.D., both worthy of future excavation. Carolyn was transported, launched, and retrieved from the 45-ft catamaran Millawanda, in use since 2000. The submersible is maintained and operated by staff members of the Institute of Nautical Archaeology located in Bodrum, Turkey. The submersible is inspected yearly by the Turkish Coast Guard and overseen by the INA head office at Texas A&M University.

6. Deep Flight Challenger

The first winged submersible was unveiled by Hawkes Ocean Technologies (H.O.T) in the late 1990s with Deep Flight I and II, Wet Flight and Deep Flight 502. Graham Hawkes is developing a full ocean depth (37,000 feet) version, the Deep Flight Challenger, also with wings and funded by the late Steve Fossett (Hawkes, 2008). The project is based on a single-person pressure hull, with the pilot in a prone position looking out through an acrylic spherical segment viewport. Other plans are well underway to build high utility, modular manned vehicles that can hover and be twinned to take passengers/mission specialists and carry the tools needed for science and industry.


DeepOcean Quest reports that the MV Alucia (previously the RV Nadir) is in the final stages of a two-year, $25M refit that has seen her transformed into a highly functional expedition vessel. The ship retains her roots as a sub-support ship and will carry the two Deep Rover submersibles (DR01 and DR02), and a Dual Deep Worker 2000 (DDW2000).

The two Deep Rovers provide full acrylic spherical cabins that accommodate one pilot and one observer. The Deep Rovers are rated for a depth of 1000 m (3280 ft) and were built by Deep Ocean Engineering in 1994. The Deep Rovers were purchased in 2002, underwent substantial rebuilding of the electronics and a full classification review to achieve ABS Class. Commissioned in 2001, DOQ also took delivery of its first Dual-DeepWorker submersible (DDW2000), manufactured by Nuytco Research Ltd., in Vancouver, Canada. The submersible holds a pilot and one observer, is rated to a maximum depth of 600 m (2000 ft), and was built and certified to Lloyds Register of Shipping. The MV Alucia is scheduled for its first expedition in July/August 2008 (McCallum, 2008). Deep Ocean Quest is a privately owned science-based research entity that conducts science and exploration missions worldwide.
8. DeepSee

DeepSee is a three-person, 1500-ft-rated full acrylic hull, ABS classed submersible operated in Costa Rica by Undersea Hunter, a diving expedition company specializing in expedition tours to the remote dive sites of Cocos Islands and Malpello. Launched in 2005 and manufactured by SEAmagine Hydrospace Corporation, DeepSee has completed a total of 580 dives, with 230 dives logged in 2007 (Kohnen, C., 2008). Equipped with an array of 10 high efficiency HID lights and a custom HD camera housing mounted on a Pan & Tilt mechanism, the company has explored and recorded the deep reefs and abundant sea life around Cocos Island, much of it for the first time. The submersible is equipped with USBL tracking and Doppler Velocity Log (DVL) navigation permitting complete and safe access to the deep walls and canyons around Cocos Island. The submersible was featured in two television productions on deep marine life in Cocos for the BBC in the UK and NHK in Japan.

DeepSee Submersible

In 2007, the company purchased and is refitting a dedicated ship for Deepsee to extend its range and reach out into the far oceans. Named the “Argos,” the new ship is equipped with a large crane and A-Frame and will be launched in early spring. This will coincide with the installation of a new manipulator arm, which will extend the submersible’s versatility for scientific, biological and archaeological applications.

9. Deepstar/Sirena

The original Sirena submersible was the first W-sub tourist submarine built in Finland in 1986, with a capacity of 48 passengers, designated as Mariea I, and delivered to Saipan in 1987. In 2007, she was decommissioned after an incredible service period of 20 years for Pacific Subsea Saipan Inc., a company engaged in the tourist business at Saipan, in the Northern Mariana Islands. In 2001, the company acquired a second 48 passenger submersible, “Deepstar,” which was added to work at Phuket Thailand (McClure, 2008). The project was short lived due to the tsunami that struck the area. In 2007, Deepstar was relocated to Saipan where it operates today as a U.S.A. flagged tourism submersible under the control of the American Bureau of Shipping (ABS) and the U.S. Coast Guard. Sirena was sold to a U.S. business group for consideration in a tourism operation in Key West, Florida. Pacific Subsea Saipan Inc. is one of the few companies in the world that has managed to maintain and sustain a successful level of operations over an extended period of time.

10. Deepworker and Dual Deepworker

The Deepworker 2000 is Lloyds Register classed, single occupant submersible built by Nuytco Research Ltd. and is rated to a depth of 2000 feet. The design offers a small package submersible, easily portable aboard a wide array of support ships. In 2000, the company designed and developed a two-person version named the Dual Deepworker, also rated to 2000 ft, to enable a trained pilot to take a novice underwater safely in the single atmospheric pressure of the cabin. Over the years, a great number of these submersibles, nearly twenty vessels in total, have been built for filming, research, exploration and commercial diving applications.

The main expedition in 2007 involved a voyage into the Bering Sea to investigate the Pribilof canyon, the largest single species fishing grounds in the world (Nuytten, 2008). The submersibles were mainly used to perform a detailed seafloor habitat exploration. The Deepworkers were also used in the investigation in British Columbia of a barge that sunk with a 1200 gallon fuel tanker truck aboard. The submersible investigation confirmed that the truck had remained intact and facilitated controlled recovery of the fuel. The company continues to operate a number of Deepworkers along with the original Deep Rover, a single occupant 3000-ft rated submersible built in 1984, and the Aquarius submersible, a three occupant vehicle rated to a depth of 1000 feet. The Aquarius remains a popular submersible for filming, especially since it enables an observer to dive to depth along with a pilot. In addition to these submersibles, Nuytco is also designing two new submersibles: one, a five passenger tourism submersible to be operated on the island of Curacao, and the other, a re-design of the Deepflight Aviator, which will undergo a number of changes and be renamed the Orca Sub.

Nuytco’s progress on the Exosuit continues as well. A new generation of atmospheric dive suits, the full dexterity ADS system, is designed for a maximum depth of 100 or 200 m and will include specially designed fins that allow the diver to literally swim. The company is on a parallel development of a prehensile hand manipulator named the “Prehensor.” The goal is to replicate the capability of the human hand, so the design features fully dexterous fingers but also a fully functioning opposable thumb. Operated from inside the Exosuit, this will allow divers to work underwater with the benefit of the full productivity of two hands.

11. Delta

Delta Oceanographics operates the two-person, ABS classed Delta submersible from Camarillo, California. The submersible has a long history with a total of 6978 completed dives by the end of 2007. The company experienced some changes but continues the diving work, with three expeditions scheduled for 2008. DELTA made a total of 246 dives in 2007, piloted by Joe Lilly and Chris Ijames (Ijames, 2008).
The sub and its support equipment were shipped to Juneau, Alaska, in July to work on a two-week contract with the Alaska Department of Fish and Game. The submersible was mobilized aboard the ADF&G Research Vessel Medea and used to collect density estimates of fishes in an area between Sitka and Cape Omaney. Over a period of eleven dive days, Delta performed 42 dives. Starting in Seattle onboard the Velero Four, Delta proceeded to Monterey to begin 50 days of diving. The dives were used to study fish, invertebrates and habitats. The dives included work by the San Jose State Research Foundation to study Marine Protected Areas in Monterey Bay and south as far as Big Creek. Finally, the submersible studied fish assemblages on the oil platforms in the Santa Barbara Channel. Delta made a total of 204 dives during the 50 days expedition.

12. Deep Marine Technology

Deep Marine Technology owns four Deepworker submersibles to complement its commercial diving work in the Gulf of Mexico. The Deepworker 2000 is a one-person submersible, built by Nuytco Research Ltd., rated to a maximum depth of 2000 ft and classed by Lloyds Registry. Two of the submersibles are presently being refitted for a one-year research expedition to the island of Palau (Kohnen, W., 2008). The work is being performed by DOER Marine, which is upgrading the manipulator, lights and video equipment. Deep Marine Technology recently announced entering in a one-year contract with the Coral Reef Research Foundation (CRRF) in Palau. Scheduled to arrive on the island in early 2008, the submersibles will be used for the collection of deep water marine samples for the National Cancer Institute’s research program. Palau is the home base for the program, which ranges throughout the Indo-Pacific region. It is part of a worldwide effort to find cures for cancer and AIDS from deep ocean organisms.

13. Deep Ocean Engineering Research (DOER)

During 2006 and 2007, DOER has continued to expand its integration and engineering services to submersible owners/operators. With its core engineering team and full in-house machine capability, the company offers custom, one off and limited production capability for a broad range of subsea equipment, including pressure housings, valve packs, manifolds, mounts, adapters, and more.

In addition to work with several multi-passenger crafts, DOER performed a major refit of two 2000-ft-rated one-person submersibles owned by Deep See LLC, returning them to full operational class (Lloyds Register) after a prolonged layup (Taylor, 2008). The submersibles were refitted with HD video cameras, video decks and DOER HMI lamps. In addition, a DOER Sea Mantis manipulator was customized to support positioning of the HD Camera. The submersibles are on track for major projects this year in Belize and points south. A second set of submersibles owned by Deep Marine Technology came to DOER for integration services prior to a long-term deployment for science and film applications in Palau. In addition to adding dual Sea Mantis 5 function manipulators, a number of upgrades and integrations were accomplished ensuring reliability in a remote location.

To address a growing need for submersible “self rescue” operations, DOER combined the flexible open frame design of its Ocean Explorer 1000 m ROV with the power of hydraulic ROVs resulting in the DOER Thug, a series of modular, all hydraulic 25–75 HP ROVs. Compact and powerful, these ROVs provide security for submersible owners while doubling as a highly stable film platform for depths to 3000 m.

DOER was also engaged by both vessel management firms and private parties to develop and implement training and maintenance programs for both manned and unmanned systems. The company continues to expand its ability to support submersible owners for integrated shipboard applications as well as ship of opportunity deployment.

14. GSE Trieste

Nautilus Underwater Systems is a company based in Fort Lauderdale, Florida, specializing in diving systems on yachts. They are the worldwide sales agent for GSE Trieste in Italy, manufacturers of the VAS diver lockout submersibles. GSE Trieste is headed by Mr. Giunio Santi, an industry expert in the construction of spe-
cial manned vehicles for various military applications. The company is currently in the final stages of completion of a five-person private submersible to be installed on a new 74-meter yacht in 2009 (Dooley, 2008). GSE Trieste also announced the development of a 10-meter, eight-person diver lockout submersible that would feature a 2-meter interior diameter, three acrylic viewpoints on each side, with an estimated speed of 8 knots.

15. Hyper-Sub

In 2007, Marion Hyper-Submersible Powerboat Design, LLC began testing a novel proof-of-concept prototype submarine. The concept incorporates a 1 ATM pressure hull that is also capable of planing powerboat performance on the surface. The Hyper-Sub is intended as a general-purpose small submarine, offering independence from the need of a support ship, along with both a long surface travel range and a high weight carrying capacity. The vehicle is designed to be configurable as a multiple crew mission. Surfaced, the submarine is an autonomous, seafaring 40-foot boat with self-recharge capacity, 800 horsepower diesel engines and diesel stores for deployment over a range of 500 miles. Submerged, production models will be rated to either 600 or 1200 feet. Subsurface propulsion is battery-powered, and the vessel projects a significant horizontal range with over 136 KWh battery capacity.

The prototype underwent significant testing in 2007, logging 21 complete dives and over 20 hours submerged carrying crews of up to 3 (Marion, 2008). The vessel also operated in surface boat mode where it initiated each dive after charging its own dive systems. The prototype was tested to a maximum depth of 30 feet and traversed courses of 1.0 to 1.3 miles long at speeds of up to 2.5 knots. All testing was conducted within the confines of an inland lake, at an average depth of 15 feet. With the prototype having completed its service as the test bed for the concept, work on an ABS classed production model is underway for 2008.

16. Idabel

Idabel is built by Stanley submarines, which operates the unique three-person tourism submersible in Roatan, Honduras. Named in honor of the town in Oklahoma where the submersible was constructed, the design uses three separate spherical steel pressure hulls, joined so as to provide room for the pilot and two observers. Although not a formally classed design, the company rates the submersible to a maximum depth of 900 meters (3000 ft). The design offers a large 30-inch diameter viewport for its passengers, plus nine separate viewpoints for the pilot. The submersible operates near Half Moon Bay, in Roatan. Situated near deep underwater canyons, the operation does not require a surface support ship and operates independently. The submersible was completed in 2002 and operation in Roatan started in 2003 (Stanley, 2008). In 2007, the submersible completed its 500th dive with its deepest voyage to 2400 ft. Idabel was in layup for two months for its first complete overhaul.

17. JAGO

JAGO is a two-person, 400-meter-rated, GL Classed submersible built by the Max Planck Institute and presently operating from the IFM GEOMAR research institute in Kiel, Germany. During March/April the submersible was mobilized to the west coast of Namibia. Aboard the South African research vessel FRS Algoa, JAGO performed geological survey and ground truthing with geologists, engineers, and technical personnel of De Beers Marine Namibia within the offshore diamond mining area Atlantic 1, off the Orange River mouth (Hissmann, 2008).

JAGO returned north to Norway in June, heading out aboard the German Research vessel RV Polarstern for cold water coral reefs study. This diving campaign was part of the EU project HERMES (Hotspot Ecosystem Research on the Margins of European Seas). Dives took place at several reefs at the continental shelf break near the Lofoten Islands, which includes one of the largest known cold water coral reef complexes, where corals grow along the back wall of a giant submarine slide at water depths between 300 and 400 m. The reef complex is about 40 km long. Scientists measured physical and chemical parameters within the reefs, took samples for genetic and microbial analyses, and collected sponges associated with the reefs.

In September 2007, JAGO headed to Spain, in the northeast Mediterranean, to continue the cold coral reef research. The team participated in a diving campaign, part of the EU project HERMES, exploring the Cap de Creus Canyon in the Gulf of Lion. Scientists confirmed the patchy occurrence of cold water corals and a divers’ benthic fauna along the canyon margins. Different species of reef-building corals were observed to grow within the canyons that do not form complex reefs like in
Norway. JAGO ended the year in October/November 2007 in Toplitzsee, Austria, taking German and Dutch microbiologists to explore the deep Alpine lake (103 m), which is anoxic below 20 m.

18. Johnson Sea Link

The Johnson Sea Link I and II are two-person, 1000-m-deep-rated, ABS classed submersibles operated by the Harbor Branch Oceanographic Institutions (HBOI) in Ft. Pierce, Florida, since the early 1970s. During 2007, the JSL II conducted operations in the Florida Straights, the Florida Keys, and the Bahamas, supporting Marine Scientists studying: 1) The Deep Lophelia Coral Reefs in 1800 to 3000 feet of water, 2) the ecosystems of the Florida Offshore Sinkholes, and 3) The Fluorescence, Bioluminescence and Neurophysiology of benthic crustaceans. On December 31, 2007, Harbor Branch Oceanographic Institution, Inc. joined Florida Atlantic University (www.fau.edu) as a stand-alone research institute (Liberatore, 2008). The new institute’s name, mission, and organizational structure remain unchanged. Dr. Shirley Pomponi, who was president and CEO of HBOI, continues to lead the organization as Executive Director of Harbor Branch Oceanographic Institute, Inc. The Foundation also commissioned the construction of a new support ship, the “Ada Rebikoff,” a 16 m motor catamaran, scheduled for delivery to the Azores in early 2008.

19. Lula

The autonomous submarine Lula (Portuguese for squid) is a three-person submarine, built in 2000 and capable of diving to a maximum depth of 500 meters. The submarine incorporates both a diesel combustion engine (24Kw) for surface travel and an electric propulsion system (8Kw) when diving. Operated by the Foundation Rebikoff-Niggeler (FRN), based in the Azores, Lula is classed +A1 by ABS and is subject to yearly inspections by the naval authority (Jacobsen, 2008). During 2007, Lula participated in a three-year bio-erosion project with the German University of Erlangen/Institute of Palaeontology. 2007 was the second year of cooperation and the submersible was used to recover several experimental panels that had been deployed by Lula last year in several locations, at depths of 60, 150 and 500 meters. Samples of deepwater corals and deepwater giant oysters of a yet unnamed species were also collected. Finally, Lula actively participated in the archaeological project called “Underwater Archaeological Map of the Azores” with the Azorean Government, which is running for 4 years from 2005 to 2008 (www.rebikoff.org/html/arqueology.html). The Foundation also commissioned the construction of a new support ship, the “Ada Rebikoff,” a 16 m motor catamaran, scheduled for delivery to the Azores in early 2008.

20. MIR

The MIR-1 and MIR-2 submersibles are both three-person, deep submergence vehicles rated to a maximum depth of 6000 m, class by Germanischer Lloyds. The submersibles are operated by the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO RAS), which is the oldest and the largest Russian research center in the field of oceanology. The submersibles were constructed in 1987 and operate from the mothership R/V Akademik Mstislav Keldysh. The MIR submersibles are famous for their extensive survey of the HMS Titanic. The media event of 2007 was the North Pole expedition (Sagalevich, 2008). On August 2nd, MIR-1 and MIR-2 made two dives to the point of Geographic North Pole at a maximum depth of 4300 meters. The dives were performed through a narrow breach in the ice, created by the accompanying ice breaker. The hole was no larger than 100 m x 50 m-wide, surrounded with an ice cover of 2-2.5 m-thick. The submersibles were transferred and stowed in the hold of R/V Akademik Fedorov, which served as the support vessel for the MIRs, which followed the nuclear icebreaker Rossia, which broke ice to pave the way. Navigation under the ice was very unusual and supported by various hydroacoustical means, like LBL and USBL navigation special directional systems. The submersibles both dove to the designated point, took video and still photography, and deposited a titanium flag of Russia along with a small time capsule to mark the event. Both submersibles returned safely to surface and the crew learned a great deal about the complexity of navigation methods under thick ice. After the expedition, both MIR submersibles, equipment and crew returned to their normal support ship, the R/V Mstislav Keldysh.

21. Nautilien

The Nautilien is a three-person manned submarine designed for observing and operating at depths reaching 6000 meters. Maintained and operated by the French research institute IFREMER, the Nautilien was commissioned in 1984 and had logged
a total of 1682 dives by the end of 2007. In 2007, Nautile participated in three major expeditions with six missions in the Mediterranean and the Atlantic Ocean (Lev- eque, 2008). Three of the missions were for engineering and technology evaluation purposes and three for scientific studies. The season started in April 2007 in the Mediterranean Sea with three technology evaluation dives followed by two scientific missions. The Nautile operated in April, May, and June, completing a total of 36 scientific dives for the ATANAUT – MBNA and MARNAUT missions. During the month of July, the team headed to the Atlantic Ocean, performing an additional 11 dives as part of the MoMarDreamNAUT mission for the study of deep-sea macrofauna, to depths reaching 3000 m, with the aim to use biological means of evaluating the stress response of these fauna resulting from sampling at depth. Nautile is in layup as of December 1, 2007, completely disassembled for a 5-month detailed inspection. The inspection is mostly focused on maintenance, with replacement installations for older computers and video systems. Engineering dives are planned for May 2008; no science projects are planned as yet for the 2008 season.

22. Nemo – Australia

Nemo is a completely autonomous, one atmosphere submersible currently based in Fremantle, Australia. Together with its 40 ton support ship Maniki III, it is capable of a multitude of tasks within a three hundred mile radius of port. Launched in 2004, NEMO is a two-person submersible rated to a maximum depth of 90 meters. Manufactured by SEAmagine Hydrospace Corp., the submersible is easily integrated into the 70–ft support ship. One of Nemo’s major design features is its ease of deployment. It can be lowered (unmanned) into the sea, avoiding the requirement of a ‘man rated’ crane. Once on the sea’s surface, its hyperlon pontoons create a stable platform allowing the cabin to be opened and closed without fear of water intrusion. This feature gives Nemo the ability to submerge with different passengers repeatedly during the day without the need for the sub’s retrieval aboard Maniki. During 2007, Nemo and Maniki traveled all along the Western Australia coast, covering in excess of 5000 km, diving on shipwrecks near Albany in the Southwest to volcanic islands near Broome in the Northwest (Kohnen, C., 2008). Back in Perth, the submersible continues to be used in a historical documentary project of U.S. warships and military hardware scuttled off Rottnest Island at the end of WWII.

23. OceanWorks

OceanWorks International is a Canadian manufacturer of international military and commercial Atmospheric Diving Systems (ADS). These include sophisticated one-person dive suits such as the Hardsuit™, rated to depths of 365 m (1200 ft) or 610 m (2000 ft), to full submarine rescue systems. The OceanWorks’ ADS technology was released in 1986 and has evolved into the Hardsuit™ Quantum. This latest suit represents the state of the art in atmospheric diving systems, with almost double the thrust performance of previous ADS systems, including the latest generation of electronics and instrumentation. Commercial ADS applications in the offshore oil and gas industry have expanded and include projects involving platform inspection and subsea field development installation, maintenance, and infrastructure remediation. These are currently used in operations in the Gulf of Mexico as well as the South China Sea (English, 2008).

Military ADS applications include submarine ventilation & decompression, ELSS Pod posting, submarine escape hatch clearing for rescue operations, search and salvage, and aircraft and weapons recovery. Hardsuits™ continue to support international submarine rescue exercises such as Sorbet Royale (Mediterranean), Pacific Reach (Asia Pacific) and Bold Monarch (North Sea). Navies that currently own and operate Hardsuit™ ADS systems include the United States, Russian, French, Italian, and the Turkish navies.

November 2007 saw OceanWorks International deliver the U.S. Navy’s next-generation submarine rescue capability; the “Pressurized Rescue Module System” (PRMS), to the Deep Submergence Unit in San Diego, CA. The new tethered rescue vehicle has a capacity of 18 people; with 230 HP of hydraulic thrust it achieves speeds of 3+ knots. Unique features include a bottom hatch opening into a Transfer Skirt, incorporating rotating joints that allow omni-directional approach into a current and mating to a DISSUB at angles up to 45 degrees, while maintaining a normal horizontal vehicle attitude. The vehicle is rated to 6 ATA internal pressure and includes an end hatch for Transfer Under Pressure (TUP) to Surface Decompression Chambers. The vehicle is controlled from a topside van using a state-of-the-art fiber optic redundant telemetry system, advanced auto controls and navigation capability. The PRMS represents a quantum step forward in submarine rescue capability to a depth of 2000 ft and up to sea state 4 surface conditions.

24. PC1201

PC1201 is one of the PC-12 series of submersibles built by Perry Submarine Builders in the mid 1970s and represents a class of submersibles with tremendous diving heritage worldwide and an unblemished
safety record. PC1201 was fully overhauled and refurbished by Deep Sea Adventures in Florida, and ABS classed to a depth of 1000 feet (304 m). PC1201 will participate in the DEEP REEF project in 2008, which is a partnership between the Cape Eleuthera Institute, The Island School and Deep Sea Adventures LLC of West Palm Beach, Florida. The site selected is on the very tip of Cape Eleuthera, on the southwestern end of the Bahamian Island of Eleuthera (Wicklund, 2007).

25. PC8B

PC8 is a two-person Perry Submersible launched in 1979 that is presently operated by the Institute of Oceanology, Bulgarian Academy of Sciences, located in Varna, Bulgaria. The submersible was designed for maximum depth of 250 m (800 ft) and was the first Perry submersible to use an acrylic bow window. The 140-degree window provides a downward view of approximately 13 degrees from the horizontal, a concept that was extended to all the Perry models thereafter. PC8B started operation in Bulgaria in 1987. The submersible is equipped with scientific instruments, still photo and video cameras, a manipulator, sampling devices, and is supported by the R/V Akademik mother ship. Dr. Ilya Shitirkov, director of the Institute of Oceanology, attended the MTS MUV program at UI2008 and reported personally that the Institute is being funded for research work through the European Union and that they plan to perform a full high-resolution scan of the Black Sea shores of Bulgaria (Shitirkov, 2008). The Institute acquired a Klein multibeam sonar and the submersible is planned to visit various detected anomalies. This is seen as a long-term project and the Institute is eager to participate in future MTS MUV programs.

26. Pisces IV and Pisces V

The Hawaii Undersea Research Lab (HURL) is part of the University of Hawaii’s School of Ocean and Earth Science Technology. It operates two ABS classed submersibles: Pisces IV, rated to 1980 meters (6500 ft) and Pisces V, rated to 1915 meters (6280 ft). By the end of 2007, HURL has accumulated a total of 911 dives on its two manned submersibles; PISCES IV with 201 logged dives and PISCES V with 710 dives. PISCES IV was acquired and put into operation in 2000 and performed a total of 10 dives in 2007 (Kirby, 2008). While PISCES IV was being upgraded with science and operational gear that included a new robotic manipulator, the vehicles performed three test and training dives plus a series of seven exploration dives, along with PISCES V for the deep investigation of Mauna Kea (3 dives) and of the deep coral reefs (4 dives). PISCES V, in operation at HURL since 1987, logged a total of 32 dives in 2007. This included five dives for test and training, and actively participated in nine different investigation projects. Among them, PISCES V made six dives for the investigation of climate variability from deep sea corals in the Central North Pacific Gyre. An additional six dives were made for the study of ageing and growth validation of the deep Gold Coral, plus seven dives for the study of megafauna of deep seamounts and ridges in Hawaii’s Papahanaumokuakea Marine National Monument.

The two submersibles are operated from the R/V Ka‘imi‘kai-o-kamloa (R/V KoK) mothership, a 70-meter-long, 2000 ton research vessel. The R/V KoK is fully equipped for long expeditions and provides 24-hour capability for its submersibles and ROV operations and is also equipped with full multibeam mapping capability. HURL’s objectives are to continue the upgrade of their two submersibles in scientific equipment with a goal to make the two vessels as identical as possible with a complete set of spares. The two vessels afford the added safety of providing complete self-rescue capability and full versatility for a broad range of research projects.

27. ProMare S201

ProMare, based in Houston, Texas, drafted a concept design in mid-2005 for the construction of a small, manned submarine with a specific focus on submerged endurance significantly in excess of other manned submersibles of similar size (Phaneuf, 2007). The 2-person submersible is designed to a maximum depth rating of 1000 ft. The design is based on a large 1.65 m diameter hull, with a total length of 9.0 m and a displacement of 9 tons. In an effort to push the envelope of technology, adherence to classification rules was set aside and the MARIAN S201 was built by MSubs Ltd. in the United Kingdom. The vehicle was completed in late 2006 and ready for testing in the early spring of 2007. The submersible was operated under contract to the U.S. Navy in support of R&D projects managed by the Office of
Naval Research Laboratory and the Special Operations Command and in concert with private corporations. The main feature of the design integrates lithium-ion batteries that are aimed at providing a speed in excess of 6.0 knots for a range of 225 miles. The vehicle is designed as a test platform that allows rapid integration of commercially available and proprietary instruments to be evaluated by the United States Navy.

In 2007, the submersible accumulated more than 100 dives to a maximum depth of 200 ft, the majority of the research programs being focused in the littoral zone. In 2008, S201 will continue working with the U.S. Navy as a large-diameter Unmanned Underwater Vehicle surrogate, and also serves as a test platform for the internal development of ProMare’s next submersible system, S301, to be launched in the fall of 2008. Plans for 2009 include modification of the S201 to integrate a new hybrid lithium-ion battery fuel cell power system for extended testing at sea and development of a larger and deeper submersible, S401, in 2010.

28. Russian AS-37

A new deep submergence vehicle was delivered to the Russian navy in St. Petersburg in Spring 2007. Designated as the AS-37, the submersible is rated to a maximum depth of 6000 m and resembles closely the two MIR submersibles, operated by the PP Shirshov Institute of Oceanology, Russian Academy of Sciences, in Moscow. From the published news, the main pressure hull holds three occupants and, unlike the Maraging steel hulls used on the MIR submersibles, the AS-37 uses a titanium hull, like Nautil, Shinkai 6500 and the new Alvin RHOV. Total reported weight of the submersible is 25 tons. The official delivery was made at the Kousnetsov Marine Academie in St. Petersburg in February 2007. The third generation Rus AS-37 submersible was designed by the Malakhit Design Bureau of St. Petersburg and constructed at the Admiralty Shipyards (Novosti, 2007).

29. SEAmagine VII

In August 2007, SEAmagine Hydrospace Corporation delivered Hull #7, anABS classed two-person Ocean Pearl model rated to a depth of 300 ft. The submersible is the first of a series to be integrated onto a megayacht, which sails in the Mediterranean Sea. The vehicle is stowed and operated from a shadow ship that follows the main 85 m yacht. The submersible was integrated onto the support ship in Barcelona while it was undergoing a refit (Kohnen, C., 2008). During this overhaul period, SEAmagine personnel trained the crew in handling of the submersible for Launch & Recovery operations, as well as maintenance and operation of the vehicle. The Ocean Pearl model is equipped with underwater lights, acoustic and RF communications, sonar navigation and USBL surface tracking equipment.

The company also upgraded its design for the three-person Triumph model for a maximum depth of 3000 ft. This would provide a unique scientific capability that can carry a pilot and two scientists to a significant scientific depth, similar to the Deep Rovers and the Johnson Sea Link but with 50% more room. A joint effort in 2007 with Marine Pollution Control (MPC), an oil spill recovery specialist, used the SEAmobile I submersible as the primary control platform for underwater oil recovery operations (Usher, 2008). Certain oils are heavier than water and will sink to the seafloor. Although recovery of submerged oil can be accomplished using diver-assisted pumping techniques, these operations are costly, time consuming and inherently dangerous to perform. Due to the simplicity of the diving logistics and safety factors, the simulated spill recovery was very successful.

SEAmagine also responded to the RFP for the construction of a 4000 m research submersible for the Indian government. The design is a much more classical form and provides room for a pilot and two observers. The international competition included firms from Russia, Canada (International Submarine Engineering) and USA (Lockheed Martin).

30. Shinkai 6500

The Japan Agency for Marine-Earth Science Technology (JAMSTEC) operates today’s deepest diving manned submersible, the Shinkai 6500. Rated to a maximum depth of 6500 m (21,325 ft) the submersible weighs 25.8 tons and has a crew of 2 pilots and 1 researcher. In 2004, the submersible was refit with new batteries, exchanging its silver-zinc for pressure compensated lithium-ion batteries (Komuku, 2006). The submersible reports excellent performance, and, in particular, the crew is very satisfied with the easier maintenance procedures. Shinkai 6500 is the only submersible presently operating regular research dives with the lithium battery technology. Much progress has been made in this field, especially for applications in AUVs, and the American Bureau of Shipping is working on regulatory language to certify these types of batteries for manned underwater vehicles.

31. Thetis

Thetis is a two-person acrylic hull submersible owned and operated by the Hellenic Center for Marine Research (HCMR), based in Athens, Greece. Built by COMEX in France in 1997, Thetis
is rated to a maximum depth of 2000 ft. (Volonakis, 2007) Thetis participated in a number of projects of HCMR, the most important among them was the scientific project #8220 and Nautil #8221, under the supervision of the Institute of Oceanography. In this project, Thetis performed a number of dives in areas of high scientific interest in the Aegean Sea. These areas contained red corals, geothermic areas, and underwater fresh water springs. In the field of underwater archaeology, Thetis also participated in the search for ancient Minoan wrecks south of Crete under the supervision of the Hellenic Ministry of Culture in cooperation with Professor Shelley Wachsman of the University of Texas. In the area of technical development, the Thetis submersible participated in live search and rescue exercises designed to train and familiarize personnel with these operations. The scenario included various distress conditions of Thetis. The final exercise was the recovery of Thetis with the use of the ROV MAX Rover, which was the first time this exercise was executed. The Hellenic Navy participated with observers (Volonakis, 2008).

32. Triton 1000

In 2007, U.S. Submarines, which has for many years offered a wide range of submarines and submersible designs and consulted for the luxury yachting market, completed construction of its first submersible. Called the Triton 1000, this new submersible model uses a full acrylic hyper-hemisphere design as cabin for its two occupants, and is rated to a maximum depth of 1000 feet. The Triton is designed in a catamaran configuration which provides both the surface stability and freeboard to allow passengers easy and safe boarding while at surface. The full acrylic cabin, with a diameter of 57 inches, provides exceptional visibility for both pilot and observer. For control, a digital joystick provides full maneuverability with a speed of 2-2.5 knots (Lahey, 2007). The submersible is compact with a length of just under 10 feet (3.0m) and a weight of 3.3 tons. The submersible was completed in 2007 with testing performed in Florida and the Caribbean. The design is ABS classed and the submersible completed its sea trials, operating from aboard the 164-ft yacht Mine Games. The submersible is also equipped with a full complement of lights, underwater video recording equipment and navigation instruments.

Conclusion

The manned submersible industry is growing and developing vehicles with new capabilities based on numerous technologies that have been primarily commercialized by the ROV and AUV markets. Beyond the ultimate benefit of in situ observation provided by manned vehicles, these new technologies greatly enhance the real-time analytic capabilities and productivity of the submersibles for research, commercial and security applications, as well as increasing the safety of operators. The technologies include navigation instruments, lighting, video recording, robotic manipulators and high energy density batteries. For all applications, this raises the level of safety features available.

Applications remain as diverse as the ocean itself, as evidenced from this review. The Marine Technology Society committee on Manned Underwater Vehicles (MUV) continues to maintain its database of active submersibles and provides the latest information on operation, construction, regulation and technology development for the benefit of operators, enthusiasts and manufacturers alike. Although this paper cannot claim it is a complete overview, it does capture the majority of recent manned vehicle activity. For reasons of space, the scope of this article was limited to active atmospheric submersibles, leaving out a number of historical, ambient pressure, or laid up submersibles. For a complete overview that includes submersibles not included in this article, readers are invited to the MTS Manned Underwater Vehicle online database at the committee's website (www.mtsmuv.org).

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Trends in ROV Development

Introduction

Recent trends in offshore industries (primarily offshore oil and gas) are currently driving changes in how remotely operated vehicles (ROVs) are used. In particular, the movement of offshore operations into deeper water and the movement of processing functions to the seafloor have required ROVs to become more efficient and better able to perform a wide range of tasks. These requirements are in turn driving changes in ROV technology.

This paper discusses three trends in ROV technology that are now feasible because innovations (such as Ethernet communications and sophisticated data gathering and data modeling techniques) have been adapted from use in other industries to applications in subsea intervention. These trends are:

- Treating video imagery as simply another form of data that can be searched, organized, and merged with other data in sophisticated digital asset management systems
- Using model-based control to plan, simulate, and then automatically execute difficult ROV intervention tasks
- Greatly expanding the data available to diagnostic experts who perform remote troubleshooting for ROV field repairs

The means to implement these tools and techniques comes not from the subsea intervention industry but from other related fields. These other fields share with ROV operations the fact that by applying advanced hardware and software to increasingly automate operations, gains are realized in productivity and in the economic value of products and services.

Digital Video

Underwater imagery is a key output for most ROV operations. In particular, video is almost always critical to operations, and in some cases, it is the ROV operator’s deliverable product. Video’s utility increases substantially when it is combined with other data (such as time and position information) because associating such data with video images enables users to search, organize, and deliver video that is packaged to optimize its utility to customers. For example, an ROV operator’s customer may be interested in observing all sections of a surveyed pipeline in which the pipeline location deviates from its previously surveyed route by more than a given number of meters. Being able to associate “built-in” position data with the video would make it easy to deliver this product.

Taking this reasoning one step further, video imagery can be considered as simply another form of data, akin to data from the multitude of other sensors aboard an ROV. Ideally, video could be combined, visualized, and merged with other data (via processes that are transparent to the operator), providing a rich visual window into an operation’s state.

Currently, however, video images are seldom transparently combined with other data since conventional analog video formats do not mix directly with sensor data received over ROV telemetry networks. Ironically, the video data is generally traveling over the same media, but current techniques for managing and processing video data complicate its combination with sensor data. To combine video and sensor data, users must supply and interconnect additional components and interfaces for data, as illustrated in Figure 1. The figure shows that the video switcher routes some of the feeds into an overlay unit, which in turn receives sensor data such as depth and heading over a separate data channel. The overlay output is then routed to other destinations, including a tiling unit that combines several video feeds into a single display. The tiling unit also chromakeys a “heads-up display” background over the combined video display, using sensor data obtained over yet another channel. Such a system also needs additional control signals to manage the switcher, overlay unit, and tiler.

As illustrated in Figure 2, digital video has the potential to move freely between digitally enabled devices without inter-
mediate conversions to analog form and without traversing extra physical interfaces with their inherent requirements for cabling, power, and configuration. In the system shown in Figure 2, all devices that produce or consume video interface to an Ethernet-based local area network (LAN) (Stanley, 2007). The system's other sensor data and state data traverse the LAN and are available to all entities that perform data processing, display, and storage functions.

As illustrated in Figure 3, devices that do not typically include native Ethernet interfaces, such as displays and cameras (other than IP cameras), can be augmented with electronics and software that transform between the device's native format and compressed packetized video.

Techniques for digital video compression, transmission and recording are technically well established and commercially available (Axis Communications, 2007; Force Incorporated, 2005). These techniques and standards make it feasible to have sophisticated digital asset management systems that provide their users with powerful tools to associate different types of data; to store, catalog, and retrieve large quantities of video content; and to distribute it to their customers (Virage Autonomy Systems, 2007; Artesia Digital Media Group, 2007).

Such systems are the state of the art for broadcast, security, and video production (VisualSoft Ltd., 2004). They eliminate difficulties such as managing large volumes of physical media (for example, tapes and disks) and provide much more efficient means to retrieve content of interest via nonlinear editing capabilities.

**Video analytics** encompasses an even more advanced set of techniques in which specialized algorithms extract very specific information from a video data set by analyzing trends and patterns (Siemens...)

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**FIGURE 1**
Combining video and sensor data currently requires additional components and interfaces.

**FIGURE 2**
HD video travels with other data over an Ethernet system.

**FIGURE 3**
Devices that do not typically include native Ethernet interfaces can be equipped to transform between the device's native format and compressed packetized video.
While many of today’s commercial offerings in video analytics are geared toward security applications, ROV operations-oriented tasks that require video capture are also candidates for automation through video analytics.

Important digital video attributes for ROV use include bandwidth requirements, time latency, and storage requirements. Because bandwidth in general (and in ROV telemetry systems in particular) is a finite resource, techniques that are bandwidth-hungry drive tradeoffs in cost and complexity. Low-latency displays are imperative for teleoperation since ROV maneuvers and manipulator operations are degraded if images are delayed by more than approximately 100 ms. The H.264 digital video compression standard in particular offers streaming high-definition (HD) video that has sufficient compression to make its network bandwidth and storage requirements reasonable for ROV applications. There are now product offerings on the market designed to transmit HD video (1920 X 1080, interlaced or progressive) over Ethernet networks with both low latency (less than 100 ms) and low bandwidth (less than 30 mbps) (4i2i Communications, 2007; HaiVision Systems, 2006). The H.264 standard’s popularity also ensures that a multitude of devices and software will be available to display, manage, and deliver the video.

In the near term, it will be practical to deliver high-quality HD video systems that have a reasonable cost, that meet ROV telemetry system requirements, and that can combine data in ways unconstrained by conventional video management techniques. Such systems will let ROV operators further enhance the value of their end products by using content management tools that are now standard in the broadcast and video production industries.

**Model-Based Control**

Today’s computer-aided design and engineering systems provide detailed geometric (and sometimes physical) models of components and systems, and these data are typically used beyond the design stage in manufacturing, quality assurance, and technical documentation. Such models can also be used in various ways by organizations and people who install, commission, and operate subsea installations and equipment. Planning for intervention and operations is one use for such models. Using simulation software, inspections and interventions can be designed and rehearsed, yielding useful products like work flow analyses, contingency plans, and training scenarios for the pilots and technicians who will perform the tasks.

Task execution is a natural progression from task planning, and if the steps for a task have been simulated, refined, and then stored in a manner that is interpretable by the system executing the task, the task can be automatically executed by interpreting and replaying those steps. The user’s input is needed to define the environment and the task (modeling), and to verify that what has been modeled will be effective (simulation). Automated systems then have the potential to either assist in or autonomously perform task execution.

Many processes in various disciplines already use the details in a model to execute tasks in the physical world. For example, rapid prototyping technologies for creating prototype machined parts are widely available (Castle Island, 2007). These systems typically “grow” a model by building up two-dimensional cross-sections of a computer-assisted design (CAD) model (Figure 4).

For many years, computer-assisted surgery has used models derived from medical images to plan and then execute complex neurologic and orthopedic surgical procedures. More recently, these techniques have facilitated minimally invasive spinal fusion...
and joint replacement procedures (Nolte, 1999). In the operating room, the surgeon “registers” the patient’s anatomy with the image data (that is, he or she matches up particular points on the patient’s body with the same points on the model of the patient’s body) as shown in Figure 5. In some cases, the procedure can then be executed autonomously by a robotic device (Taylor, 1994). Alternatively, the surgeon can use an image guidance system in which software provides navigational displays that guide the surgeon in placing and orienting instruments relative to the patient’s body.

Model-based control conceptually maps over to ROV tasks for operations such as hot stab placement since this task requires proper position and orientation of the hot stab tool relative to the hot stab receptacle. As this task is currently performed by ROV operators, the lack of three-dimensional information and the large number of degrees of freedom can make it difficult to move the ROV and manipulator to the proper location. The operator must determine how to best partition the task among these many degrees of freedom (ROV motion, manipulator, camera views), which can be a difficult process requiring skill and experience.

Augmenting the hot stab operation with model-based control, however, has the potential to simplify the operation. Ideally, an existing model of the installation would be the starting point. This model would then be registered with the actual installation’s position and orientation, allowing the pilot to specify locations of interest on the model. At this point, the ROV control system could assist the pilot in moving to these locations. If the ROV were equipped with DP and/or navigation capability, it could move autonomously to the desired locations so that the manipulator workspace would be well placed for the hot stab.

It is possible to envision tasks that require a manipulator-mounted sensor to be moved along a path that is defined relative to the modeled installation, such as inspecting a structural joint in nondestructive testing. By using a model of the component, the manipulator control system could move the tool in the required spatial path while maintaining proper distance from the surface under inspection.

A key requirement for successful model-based control is that objects be mapped into the relevant coordinate system for control with sufficient accuracy for the task to be executed. Accurate mapping in turn depends on accuracy of the data input to the registration procedure, i.e., the procedure that calculates the transformation between the coordinate system where the work is planned (the “model” coordinate system) and an available and useful coordinate system at the worksite. One technique for finding this transformation is to obtain the coordinates of a set of “fiducial” points (that is, points used as a standard reference) in both coordinate systems. Once these fiducial points have been determined, planners can calculate the transformation between these coordinate systems using either direct geometric methods or “least squares” methods. With the latter method, adding extra fiducial points reduces the error and therefore increases the accuracy of the transformation (Umeyama, 1991). While the fiducial technique is mathematically simple and has an analytical solution, it can be difficult in the subsea environment to find a good set of fiducial points that are easily measured.

A more sophisticated method is to collect a relatively large set of points (called a point cloud) from a surface in the work environment that is easily represented mathematically in the model, and then find the coordinate transformation that minimizes the point cloud’s distance from the modeled surface. The advantage of this solution is that it does not require that specific points in the work environment be measured, but only a set of points in a region of interest.

Regardless of the method used, coordinates of points in the work environment must be determined. One method is to locate the ROV and all fiducial points using conventional acoustic measurement techniques. A shortcoming of this approach is the variable (and not very high) accuracy inherent in acoustic positioning, which depends on factors such as local environmental conditions (which affect sound velocity) and the accuracy and layout of the transponder array. Significant effort is also required to set up the array, and the number of transponders required and the effort to survey them could add unacceptable cost and complexity.

An alternative approach is using an ROV-based position sensor to collect either fiducial coordinates or point clouds from the work region. For example, a properly calibrated manipulator can serve as a “portable coordinate measuring machine,” quickly digitizing multiple points in its workspace. In this case, the collected points are transformed from the manipulator or ROV coordinate frame to the model coordinates. For this approach to work, the ROV/manipulator platform must remain stationary relative to the environment. In theory, once the registration has been obtained, an ROV with DP and/or navigation capability could update the registration as the ROV moves (at least over small distances), eliminating the requirement for the intervention to take place in a completely stationary state.

Another promising approach involves using a measurement technology that does not involve contact (such as multibeam sonar) to digitize the local environment and provide three-dimensional data. This approach would be much more automated and efficient than using a device such as a manipulator. However, various tradeoffs in range, power, and precision and accuracy must be considered in developing a feasible multibeam sonar approach.

Ideally, during task execution under model-based control, pilots would be relieved from low-level path planning decisions and would be able to think of operations in terms of “macro” steps, such as moving along a path or into a receptacle. The payoff for developing, refining, and commercializing model-based control capability is the automation of various ROV intervention tasks, with potential benefits of greater productivity, reduced operator load, and increased capability for complex interventions.
Remote Diagnostics

ROV manufacturers strive to make highly reliable systems that have minimal maintenance requirements. However, as ROV systems become more capable and feature rich, system complexity inevitably increases. Well-designed systems can mask complexity by presenting users with simple interfaces and intuitive workflows. When problems occur, however, it is sometimes necessary to remove the covers and investigate the system’s internals.

ROV pilot/technicians frequently have to perform in-field diagnostics and repairs, particularly on mechanical, hydraulic, and electronic systems. Given access to drawings, schematics, and training, they can deal with most failures and can conduct preventive maintenance. However, as systems become more complex (with many components and interfaces), troubleshooting also becomes more complex. When ROV manufacturers deploy new functions, particularly software-intensive ones, pilot/technicians must simultaneously learn these new capabilities, train others, and solve problems in the offshore environment. To succeed in this situation, they need quick access to information and expert advice. Remote diagnostics capability can provide this assistance.

Remote diagnostics in the most basic form could be a telephone or instant messaging connection between a knowledgeable troubleshooter at the manufacturer’s facility and the technician at the equipment site who serves as eyes and ears for the expert. For all but the simplest problems, this approach results in a slow, painstaking, error-prone process. To make the process efficient, the expert must have the data and equipment controls available at his or her location.

Various industrial and medical systems now feature remote diagnostics capability (GE Energy, 2007; Delphi Medical Systems, 2007). In addition to diagnosing and repairing malfunctions, these systems gather operational data that enables their manufacturers to recommend preventative maintenance; to suggest upgrades, complementary products, or training based on usage trends; and even to re-supply customers with consumables. Remote support is also widely available for software users, from PC consumers to purchasers of complex business systems.

Obviously, connectivity is required to implement remote diagnostic functionality. Such connectivity is widely available today via satellite links; although at sea, bandwidth availability varies and may not be on par with similar services using land-based networks. Still, available bandwidth as low as DSL or dial-up levels can support services such as Windows Remote Desktop when tuned properly (Russel, 2001). Under this limitation, it is important to use the available bandwidth to transport the most salient information to the expert. Given that ROV control systems have basic Internet connectivity, there are several options for organizing internal system state data so that it is useful to an expert.

One option is to provide a duplicate pilot station at the remote support site. This option is feasible if the control system architecture is sufficiently modular and abstract (that is, if the additional pilot station is simply another instance of a general pilot station and can be driven by available data channels). The expert then has the same view and same set of diagnostic tools that are available to the pilot/technician. This arrangement is useful when the regular operational user interface can provide the required diagnostic information (for example, when sufficient information to solve the problem is available, but the pilot/technician lacks the experience needed to solve the problem quickly). This method can also provide a training opportunity; assuming that time zone differences can be accommodated and voice/video communications are available, the expert can guide the pilot/technician through the troubleshooting process as he is performing it.

A disadvantage of the duplicate pilot station option is that solving the current problem may require data that is not available at the pilot station. The ability to “dig deeper” is critical to maximizing the expert’s impact. Software tools that are unavailable at the standard pilot station (such as capabilities for advanced plotting, statistical analysis, and simulation) could be available at the support location and could be used to solve the current problem.

In general, it is best for troubleshooters to have access to all internal state data so that regardless of the problem, all data that might be relevant are available for examination and analysis. In the approach illustrated in Figure 6, a dedicated software function captures and transmits data representing a system’s full internal state and communicates this data over a channel dedicated to this purpose. In this fairly typical arrangement, the capture-and-transmit function gathers data from predetermined internal sources and transmits it outside the system. The data’s remote user does not have general access to arbitrary data traversing the control system.

**FIGURE 7**
The Publish/Subscribe architecture enables data gathering as an inherent part of inter-process communications.
Implementing this approach presents significant challenges, however. Brute-force transmission of all relevant data may become bandwidth-intensive, and the data items of value in any particular situation are not weighted any differently than other data items. In cases of limited bandwidth, it would be useful to have a data capture system in which the expert performing the diagnosis could select the data items to be sent from the remote system.

Another challenge in this architecture is managing change. When new functionalities are deployed, data channel contents must be updated to handle the new data associated with these functions. If this update is not automatic (that is, inherently part of the system update), sustaining full diagnostic functionality becomes a manual maintenance task and thus subject to error.

A more sophisticated approach would enable the expert to query the remote system about which data items are available. The expert could then request these items as needed, adding new data items when required and deleting those that are not useful in a particular situation. Such an approach has several advantages:

- Since it is not necessary to decide *a priori* which data items will be made available, network bandwidth can be used optimally in each situation.
- When necessary, high-priority data can be favored over low-priority data.
- The data’s presence in the system makes it inherently available for transmission to the expert conducting the diagnosis.

The Publish-Subscribe architecture is an inter-process communications architecture that supports this flexible data-gathering functionality (Matteucci, 2003). In this architecture, a “broker” manages communications and data flow between different entities and components as illustrated in Figure 7. Producers of data items register them with the broker, along with other information such as data format and the frequency of data updates. Producers then “publish” data to the broker as the data are updated. Data consumers also register with the broker for specific data items of interest to them, providing additional information such as frequency at which updates are desired. After data consumers have registered, the broker transmits fresh data updates to them as updates become available.

Using this Publish-Subscribe data architecture, the “capture and transmit” function in Figures 6 and 7 can ensure that the most relevant parameters are brought over from the remote system (taking available bandwidth into account). Such a system also largely eliminates the need to update the diagnostic software each time that the remote system’s software is updated. For example, if a new software release for the remote system includes data items that were not previously gathered, the diagnostic software does not need to be updated explicitly to recognize the new data. Instead, the diagnostic software can simply query the remote system to determine which data items are available, and can select those items for capture and transmission.

This kind of flexibility would provide experts performing troubleshooting with access to the most important data when they need it, allowing faster response and better results for pilot/technicians and ROV end users.

**References**


I. Introduction

Development and application of AUV technology has grown steadily over the last few decades, with particularly rapid growth in the last decade. This growth is fueled by the increasing number of missions made possible by advances in technology and growing awareness of these capabilities by potential AUV customers. As capabilities became feasible, and seemed close enough to feasibility to warrant research efforts, and as customers bought in to the advantages of such systems, the number of customers, systems and system developers grew quickly. Although it started with a few players in the oceanographic, military and academic fields, today’s AUV community is a robust group that includes these and several commercial players. And although applications and technologies have reached a fair level of maturity, AUVs have not yet reached their full potential for utility and continue to be an active area of research.

This paper surveys the present state of AUVs, as viewed by the authors, by addressing present applications and technologies. It focuses on what a present-day operator can expect from typical AUV systems, rather than ongoing research, which does not yet significantly influence AUV operations.

II. Present AUV Applications

Present-day AUVs are particularly useful as unmanned survey platforms, carrying sensor payloads along pre-programmed trajectories to gather data for a variety of applications. The typical AUV operates in “flight” mode, translating along segmented linear trajectories that lie largely in the horizontal plane, attempting to efficiently survey as large an area as possibly subject to vehicle performance constraints. Some specific applications are exceptions to this operating profile in that they involve significant navigation in the vertical direction, for example, in shallow/deep water ocean data gathering and sampling.

A. Hydrographic Survey

An early stimulus for AUV development was to improve the ability to conduct oceanographic survey and mapping (Bildberg, 2001). AUV mobility enables spatial and temporal sampling along desired trajectories, a significant advantage over other methods such as the sparse number of static oceanographic moorings or free-drifting floats. Manned platforms with towed instruments also provide mobility, but placing instrumentation on an AUV separates the instrument from the noisy sea surface. Surveys are more efficient when compared to towed instruments because AUV turns are tighter and take less time than a surface vessel with a long tow line. Also, the initial and daily operating cost of a manned vessel usually exceeds the costs of an AUV with similar capabilities. For the same cost, an AUV-based survey potentially can use more sensor platforms and covers a larger area than a manned platform (MacNaughton et al., 2003). AUV mobility also enables measurements in inaccessible or hard-to-access areas such as under the polar ice (Bellingham et al., 1993; WHOI, 2007). Mobility also enables optimized sampling strategies, positioning a limited quantity of sampling platforms in the regions of greatest interest, significance, or variability; e.g., ocean fronts (Curtin et al., 1993), as depicted in Figure 1.

Extended AUV missions are the domain of underwater gliders, low-power AUVs using wings and buoyancy changes for propulsion in a manner analogous to glider aircraft. This is an efficient method of propulsion, albeit at speeds on the order of one knot. For large area ocean survey...
missions, gliders have proven particularly useful providing the ability to perform vertical zigzag maneuvers with little energy consumption. They can last in the ocean for many days, and some up to a month or more where obtaining temperature and salinity measurements as a function of depth are of key interest. Naturally this leads to sound speed profiles for prediction of ocean acoustic propagation in deep water. Gliders have demonstrated such long-distance operations as a 600-mile transit from Massachusetts to Bermuda (Nevala, 2005). The Spray glider used in this experiment and in other research has been made commercially available by Bluefin Robotics. The Seaglider, developed at the University of Washington, has been used for oceanographic work and is being considered for naval missions as well (Doughman, 2008). Another glider frequently used in oceanographic research is Webb Research Corporation’s SLOCUM glider, shown in Figure 2. The electric version, which uses battery power to vary its buoyancy for glide propulsion, is similar to the other gliders. However, the thermal version uses a unique propulsion system based on the phase change of a working fluid caused by ocean temperature variation with depth to vary its ballast. The environmental energy harvested by this method reduces battery power requirements and significantly extends mission duration (Webb et al., 2001).

Most commercially available AUVs feature hydrographic instrumentation as standard equipment or an option. Both Hydroid (Hydroid, 2007) and Bluefin Robotics (Bluefin, 2007) offer vehicles with conductivity-temperature-depth (CTD) instruments as standard equipment, and most AUV manufacturers offer as optional equipment a basic CTD or more advanced oceanographic instrumentation such as pH meters, oxygen analyzers, fluorometers, and spectrometers. Most commercially available AUVs also provide the ability to collect bathymetric data, usually by depth sounders or as one output of a Doppler velocity log (DVL), although swath bathymetry system modules for rapid survey of bottom topography are also available. Given the well established ability of AUVs to follow a survey pattern, their usefulness as hydrographic tools is largely driven by the capabilities of hydrographic sensors available to be carried as payloads.

SECFIGURE 2
SLOCUM Glider (Photo courtesy Webb Research Corporation).

B. Undersea Oil/Gas Production

One specific hydrographic application of AUV technology is undersea exploration and production of oil and gas. Undersea surveys to locate deposits have recently used Maridan and Hugins AUVs in the North Sea and Gulf of Mexico respectively, with exceptional results in characterizing the bottom and sub-bottom (Bingham, 2002). The inherent mobility of AUVs in this application results in time savings of 60% or better when compared to less-maneuverable towed systems (Morr, 2003). Savings increase with surveys in deeper waters, which are becoming increasing common as shallow water production fields are depleted. AUVs have also been used for undersea pipeline inspection once the field has been established. This trend in exploration and production points to an increasing future usefulness of AUVs in this application.

C. Hull inspection

Recent attention to the security of shipping and ports has motivated development of methods to inspect both cargo and the vessels carrying it, including the difficult to survey underwater hull. One tool for this application is a hull inspection AUV, car-
rying sensors over the contours of the hull to search for devices such as limpet mines. This new mission has been demonstrated by vehicles such as the CETUS II (Trimble, 2002) or the Bluefin HAUV (Vaganay, 2006). The hull inspection mission is significantly different from other AUV missions in that the vehicle must follow a three-dimensional trajectory roughly conforming to the three-dimensional surface defined by the ship's hull, a significant difference from the straight-line flight-mode trajectories typical of other AUV missions. Hull inspections may be performed using optical or acoustic imaging sensors.

D. Military Applications

A significant driver of AUV research and development has been military applications, which benefit from the covert nature of AUVs, the elimination of risk to manned vessels, as well as other benefits of AUVs discussed above. Much of today’s successful AUV technology was initially government funded for military applications.

A significant military application is mine warfare, which makes good use of AUV characteristics to provide covert, rapid, controlled, and efficient survey of a potential minefield without risking a human operator. AUVs are particularly useful for very shallow water minehunting and were used during Operation Iraqi Freedom in 2003, the first opportunity to use AUVs for mine warfare operations since the development of this capability. During this operation, a system based on Hydroid’s REMUS 100 AUV, shown in Figure 3, was used by the U.S. Navy in mine clearance operations in Umm Qasr Harbor (Ryan, 2003).

Other AUVs with military applications are being acquired by the U.S. Navy. The Surface Mine Countermeasures Unmanned Underwater Vehicle Increment 2 (SMCM/UUV-2) is undergoing development for installation on MCM-1 class mine countermeasures ships (Wilcox, 2007). It is a 12.75 inch vehicle, larger than REMUS 100 and designed for deeper water. The Battlespace Preparation AUV (BPAUV), shown in Figure 4, is a 21” vehicle being developed as part of a mine warfare mission module for the U.S. Navy’s littoral combat ship (Morral, 2003). Both these AUVs are also capable of covertly conducting hydrographic surveys. Submarine-launched AUVs are also under development, including the long-term mine reconnaissance system (LMRS) and its successor the mission reconfigurable UUV (MRUUV). The latter will carry a variety of sensors ranging from mine countermeasures and hydrographic sensors to above-water surveillance cameras and electronic warfare antennas/receivers, thereby expanding the range of military missions assigned to AUVs (Whitman, 2002). Other countries are similarly investing in AUVs for military applications, such as the Talisman built by BAE in the United Kingdom, and Hugins built by Kongsberg in Norway.

The utility of AUVs in these military missions, and their future utility as technology progresses, points to their increasing role in military operations. The guidance for future development and applications is contained in the U.S. Navy’s UUV Master Plan (U.S. Navy, 2004), which lays out a fifty-year vision of military AUV applications, and the Office of the Secretary of Defense’s Unmanned Systems Roadmap 2007-2032 (OSD, 2007). These documents lay out a long-range vision of military AUV applications, many not yet feasible with current technology. As such, fulfilling these missions will involve significant research in the coming years.

III. AUV Design and Technologies

Present AUV capabilities are defined and limited by the design and maturity of the various technologies that equip the vehicle. This section reviews the state of AUV development from the perspective of these technologies, all of which are currently evolving.
A. Modular Design

An easily reconfigurable AUV design is advantageous for several reasons. The configuration of an AUV tends to vary over time as technology upgrades and changing missions result in software and hardware changes, which are easier to accomplish in a modular design. Also, system costs can be reduced significantly if a single AUV can carry one of many different sensor packages to perform various missions; when compared to the cost of multiple single-purpose vehicles or one larger vehicle carrying a variety of mission hardware. Finally, modular batteries permit reduced system down time for battery replenishment by permitting rapid replacement of depleted batteries instead of recharging installed batteries. As such, modularity is increasingly addressed in AUV design and is becoming evident in commercial products. The Gavia AUV from the Icelandic manufacturer Hafmynd ehf is of highly modular design; the basic vehicle consisting of nosecone, battery, control and communication, and propulsion and servo modules. The modules connect end-to-end, using mechanical and electrical connections that can be made by hand in the field, to form a torpedo-shaped hull. A variety of modules are available to allow equipping the AUV with various camera, sonar, and hydrographic sensors; navigation instruments; communications devices; and additional batteries (Gavia, 2007). Other AUVs with some modular design features include the Bluefin 9, with a replaceable battery module for rapid vehicle turnaround (Bluefin, 2007); and the REMUS 100 and 600 vehicles, with a modular front end capable of being reconfigured for various sensors (Hydroid, 2007).

B. Navigation

The underwater operating environment does not permit continuous access to GPS signals, causing AUV designers to pursue other navigation methods. Most AUVs use one of two predominant approaches. Because acoustic energy propagates further in water than other forms of energy, it is the basis of many navigation systems. In a typical acoustic system the vehicle interrogates an array of acoustic transponders, which are moored at known positions, whose responses are timed to determine vehicle position relative to the known absolute transponder locations. Such systems provide frequent fixes, although they require the presence of transponders which must be deployed in locations known to the vehicle prior to operations. Long-, medium-, and short-baseline acoustic navigation systems are variants of this approach. Hydroid’s REMUS vehicles mostly use acoustic beacon navigation.

A second predominant method, which eliminates the need to deploy transponders, is to obtain GPS fixes by surfacing periodically. Because surfacing for a fix represents an undesirable interruption of the vehicle’s mission, fixes are infrequent. Navigating during the long intervals between fixes is done with inertial navigation systems, usually assisted by other instruments. An example is the Bluefin-21 BPAUV, which surfaces periodically for GPS fixes and uses an attitude and heading reference system (AHRS) inertial sensor to measure vehicle attitude and heading and a Doppler velocity log (DVL) to measure vehicle velocity to navigate between GPS fixes. Bluefin’s use of post-mission renavigation to GPS-correct data gathered during dead-reckoned portions of the mission reduces overall navigation errors in recorder data (Bluefin, 2007).

In general, AUVs with either of the above navigation systems employ DVLs, which provide measurements of velocity and altitude above bottom. DVLs also provide measurements of water current direction and magnitude as a function and depth when used in the acoustic Doppler current profiler (ADCP) mode, making it a hydrographic instrument as well as a navigation instrument. Vehicles of all types almost universally carry some form of heading reference as well, either inertial or magnetic. Magnetic sensors, usually electronic compass modules, are most common but are susceptible to magnetic disturbances from the vehicle or the environment. Inertial sensors are not susceptible to such disturbances, but drift over time. Some vehicles, such as the Hydroid REMUS, use both types of heading sensors in a complementary manner (Hydroid, 2007).

The fusion of several navigation instruments can minimize navigation error in a package small enough to be carried by larger AUVs. The Kearfott SEA Devil is an example of a GPS-INS-DVL navigation system that provides exceptional navigation accuracy for AUVs through the integration of these precision navigation instruments. Navigation accuracy of 0.05% of total distance traveled has been demonstrated when DVL bottom-lock is maintained (Kirkwood, 2005) More highly accurate inertial sensors may be obtained if survey accuracy requires but the cost is greater and not always justified.

C. Communications

Although AUV operations generally involve minimal or no communications, some communication is desirable for data download, mission updates, or status monitoring. The underwater environment imposes many of the same electro-magnetic constraints on communications that it does to navigation. As a result, in most instances AUV communications options are limited to either intermittent use of radio methods, available only when the AUV surfaces to expose an antenna, or to acoustic methods which have limited range and very limited data rate. Optical and laser-based communications systems have shorts ranges in water and require complex systems to provide motion stabilization because of the narrow beams involved. As a result, with other more practical means available, these are not commonly used for communications between moving platforms.

As a result of the desire to keep antenna size reasonable, most AUV radio systems use carrier frequencies of approximately 1 GHz or more. Common systems include 900 MHz wireless modems or 2.4 GHz 802.11 wireless networks for line-of-sight operations when operating AUVs near shore or support craft. Longer distance radio links make use of satellite circuits such as Iridium. Because radio communi-
communications can only commence after the AUV has exposed an antenna above the surface, an operator cannot command an AUV to the surface to initiate such communications. Communications opportunities are therefore determined by the AUV.

When more continuous communications are needed, or the AUV must be contacted while submerged, acoustic means are generally employed. Acoustic modems modulate data as acoustic energy for transmission through the water, but the water medium has several disadvantages such as limited range and bandwidth. Communications are also highly variable and dependent on factors such as depth, bottom type, temperature, salinity, and sea state. A summary of acoustic modem capabilities is the subject of Kilfoyle (2000). Common acoustic modems include the Benthos Telesonar® system, which is capable of kilobit-per second data rates at ranges on the order of a kilometer (Green, 2002); LinkQuest modems, which have been used in offshore petroleum work; and the Woods Hole Oceanographic Institution (WHOI) modem, which has been widely used in AUV research and is the basis of the Hydroid REMUS acoustic modem (Grund, 2006).

A hybrid communications option is the use of a surface buoy employing an acoustic modem below the surface and a radio transceiver above. Radio communications between the controlling station and the buoy are converted to acoustic communications that are sent through the water between the AUV and the buoy. Doing so allows a controlling station to be many miles away (within radio range of the buoy) from the AUV. The AUV must be within acoustic communications range of the buoy to complete the communications link to the controlling station, which is compatible with missions requiring AUVs to remain in a particular geographic area such as an intensive survey mission; or missions with communications periods during which the AUV closes within acoustic communications range of the buoy. An example of such a buoy is the Hydroid Paradigm/Gateway system (Hydroid Gateway, 2007).

D. Power

Because they operate underwater, isolated from the atmosphere, the vast majority of AUVs use batteries as their air-independent power source. Since battery capacity limits AUV endurance, improved battery technologies have been rapidly adopted for AUV use. Lithium batteries, widely used in demanding applications such as photography, cellular phones, and laptop computers, are common in AUVs. Rechargeable, or “secondary”, lithium-ion batteries are used in REMUS and Gavia vehicles, and similar lithium-polymer batteries are used in Bluefin vehicles. Such power systems provide mission duration on the order of a day at speeds on the order of a few knots. One design feature which mitigates short battery life is that in some REMUS and Bluefin vehicles is swappable batteries, allowing rapid vehicle turnaround by battery replacement instead of battery charging. Another means of extending mission duration is the use of non-rechargeable “primary” lithium batteries, which allow longer mission duration, at the significant cost of having to dispose of and replace them once discharged. Such an option is available for the Gavia vehicle (Gavia, 2007).

Mission duration of battery-powered vehicles can be extended by periodically recharging vehicle batteries during a mission, usually by docking with an underwater charging station. Such stations, which have seen limited use to date, may supply power from their own batteries, from cabled connections to a power source, or from environmental energy sources. These require an AUV capable of accurately navigating into the dock and establish electrical connections, either directly or inductively. Several have been tested in recent years and are described in Podder (2004).

The use of solar power has been demonstrated in the Solar AUV (SAUV), a unique vehicle developed by Falmouth Scientific Inc. and the Autonomous Undersea Systems Institute. The SAUV is equipped with a solar cell array and lithium ion batteries, designed for long-duration missions during which cells charge during daylight hours while the vehicle remains on the surface; and discharge during submerged operations. Long-endurance solar-powered operations have been demonstrated during a 30-day simulated mission (Crimmins, 2006). Fuel cells have been used to a limited degree as a replacement for batteries in a few AUVs (Tsukioka, 2004), however they are relatively complex compared to battery power sources, involve the handling of reactant gases or chemicals, and are roughly equivalent to primary lithium batteries in expense and performance (Griffiths, 2005). As a result, their adoption to date has been limited.

E. Sensors

As discussed previously, AUVs are particularly well suited as sensor platforms due to their mobility and autonomous operation, and commercial models frequently feature basic oceanographic instrumentation as standard or optional equipment. Because they are generally compact, almost any oceanographic instrument is suitable for deployment onboard an AUV.

Imaging sensors are also standard equipment on many AUVs. Side scan sonar is the most common high-resolution underwater imaging sensor, and is available on most AUVs. Figure 5 shows analysis of side scan sonar imagery collected by the REMUS AUV. Synthetic aperture sonar, another high-resolution acoustic imaging sensor with the potential for improved range, resolution, and ability to detect buried objects, has been under development for a few years (Fernandez, 2004). AUVs are particularly suited to carrying this sensor because the imaging process requires precise vehicle navigation along an underwater path, although vehicle position and attitude must be more tightly controlled than for other sonar systems. Sub-bottom profilers have been carried by AUVs to image geological features beneath the seafloor for use such as oil exploration, and multi-beam sonar for swath bathymetry seafloor mapping (Henthorn, 2006). Acoustic cameras such as the dual-frequency identification sonar (DIDSON) have been carried by several AUVs for demanding imaging applica-
tions such as hull inspection (Son-Choe, 2006). The submerged use of optical cameras is limited by water clarity, which is generally on the order of a few feet, but they can also be mounted on an AUV mast to observe conditions above the surface at long distances (Allen, 2006).

Examples of other sensors carried by AUVs include magnetometers (Wynn, 2002), chemical and biological sensors (Farrell et al, 2003), and 100-meter-long vector sensor arrays capable of acoustically detecting and tracking other vessels (Benjamin, 2007). In general, most sensors are compatible with an AUV, unless the sensor's physical size, power requirement, or desired period of deployment exceeds that of the host AUV.

F. Autonomy

Bandwidth limitations and other difficulties with underwater communications place a large premium on AUV autonomous operations. Limited opportunities for telemetry of sensor data or vehicle status and for follow-on human intervention requires the vehicle be more autonomous that unmanned ground, aerial, or space vehicles. The enabling technology is autonomy. As progress is made in this area, and as confidence grows that the vehicle's autonomous actions enhance mission performance without endangering it, AUVs become more useful and capable.

Most present-day missions involve a very low level of autonomy in that they are either pre-programmed as a series of waypoints, or pre-programmed and later modified mid-mission through exchange of data and orders with a human operator. Autonomy in such missions consists largely of automatic control of vehicle position, velocity, and attitude while passing through a sequence of waypoints. Payload and communications functions occur continuously or at pre-determined times or positions. This level of autonomy is satisfactory for applications such as surveying.
An incrementally higher level of autonomy is represented by vehicles whose default operations are as described above, but which have the additional capability to momentarily and reactively depart from preprogrammed operation in response to specific, clearly defined stimuli. An example is obstacle detection and avoidance, shown in Figure 6, whereby the vehicle momentarily departs from its pre-programmed trajectory to maneuver around a sensed obstacle and later returns to its pre-programmed track (Horner, 2005; Healey, 2006). Work underway at Naval Postgraduate School focuses on the use of a small blazed array from BlueView Technologies, Inc. to detect underwater obstacles in both vertical and horizontal directions linked to vehicle avoidance response as demonstrated in Healey and Horner (2006) and Horner and Yakimenko (2007). Such extensions of autonomy potentially reduce risk to the vehicle when avoiding hazards, while adding minimal additional risk from unpredictable vehicle behavior in that the vehicle eventually returns to pre-programmed behavior.

Higher levels of autonomy would enable such high-level activities as reliably classifying detected objects or transmissions; reliably detecting, classifying, tracking or avoiding other vehicles; diagnosing and taking corrective action for vehicle hardware/software faults; or autonomously replanning vehicle trajectories to optimize sensor performance based on in situ measurements. Such activities are presently too demanding to be performed reliably in an autonomous manner, leading to much research in this area. One reasonably mature example of this level of autonomy is the automated computer-aided detection/computer-aided classification (CAD/CAC) of mine-like objects detected in AUV sidescan sonar images (Ciani, 2002).

The two most significant technological challenges, which if overcome would most advance the utility of AUVs, are power and autonomy. Present power sources limit the duration and spatial extent of AUV missions and therefore the amount of data gathered per deployment. Just as nuclear power unleashed the potential of manned submarines, a significant breakthrough in powering AUVs would greatly enhance their capabilities. Present autonomy limits the degree to which AUVs may be left unattended by human operators; thereby raising their operating costs, limiting the types of missions they may perform without human presence, and exposing them to underway hazards that they cannot autonomously avoid. One example of improved autonomy would be a long-duration military AUV surveillance mission in which the AUV’s sensors and processing enable it to classify and interpret sensor data, determine and execute optimal positioning for further data gathering, decide which events warrant reporting, identify risks of collision or counter-detection, and execute evasive maneuvers. Given the strong motivation to overcome these challenges and replace vulnerable and increasingly expensive manned systems with their relatively inexpensive unmanned counterparts, and given the difficult nature of these challenges, much effort on further developments can be expected for the foreseeable future.

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A Focus on Recent Developments and Trends in Underwater Imaging

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Abstract
Advances in the field of underwater optical imaging are reviewed for the years 2005 to present. A synopsis of research and technical innovations is presented, organized in much the same way as the previous report (Kocak and Caimi, 2005). Several recent applications of novel systems are shown as examples, and trends in emerging underwater imaging research and development are briefly summarized.

- Compact, efficient and easy to program digital signal processors execute algorithms once too computationally expensive for real-time applications.
- Modeling and simulation programs more accurately predict the effects that physical ocean parameters have on the performance of imaging systems under different geometric configurations.
- Image processing algorithms that handle data from multiple synchronous sources and that can extract and match feature points from each such source derive accurate 3-D scene information.
- Digital compression schemes provide high-quality standardizations for increased data transfer rates (i.e. streaming video) and reduced storage requirements.

This paper reports developments over the past three years in the following topics:

- Extended range imaging techniques;
- Image formation and image processing methods;
- Compact, efficient and easy to program digital signal processors execute algorithms once too computationally expensive for real-time applications.
- Modeling and simulation programs more accurately predict the effects that physical ocean parameters have on the performance of imaging systems under different geometric configurations.
- Image processing algorithms that handle data from multiple synchronous sources and that can extract and match feature points from each such source derive accurate 3-D scene information.
- Digital compression schemes provide high-quality standardizations for increased data transfer rates (i.e. streaming video) and reduced storage requirements.

FIGURE 1
The EITS camera system deployed at Gouldings Cay in the Bahamas at a depth of 488 m. Inset: An unidentified squid recorded by the EITS while the system was deployed in the Gulf of Mexico on the edge of the NR-1 brine pool. This unusual squid, with its short muscular tentacles that lack an obvious club, cannot be assigned to any known scientific family. (Courtesy Edith Widder)
Imaging using spatial coherency (e.g. holography); and

Multiple-dimensional image acquisition and image processing.

Along with leading advancements in each of these areas, a few newly applied vision systems are presented. Lastly, trends for future systems are briefly touched upon.

Image Formation and Image Processing Methods

Cameras and Lighting for Underwater Observing

Described in the 2005 State of Technology issue (Kocak and Caimi), the Eye-in-the-Sea (EITS) camera was deployed on the seafloor several times over the past three years and will soon become a part of the Monterey Accelerated Research System (MARS) ocean observatory sensor suite (Widder, 2007). A photograph of the system and a captured image (inset) are shown in Figure 1. The system differs somewhat from the FOVAR (Field of View And Ranging) system developed by HBOI (Tustling and Lee, 1989) for autonomously recording still images of sea life as triggered by far-red wavelength illuminators and photoreceptor. The newer system utilizes a video camera that records footage at scheduled intervals or when bioluminescent light is detected by a photomultiplier tube (PMT). Far-red illumination (680 nm light-emitting diodes with cut-off filters below 625 nm) is used since this wavelength is invisible to most deep-sea inhabitants, and an intensified video camera compensates for the reduced illumination and permits recordings of bioluminescence.

Another recent camera system has been set up to monitor coral reef communities in marine parks (Lam et al., 2007). This system collects 10 minutes of video footage each hour on a year-round basis, during the day and night. Unlike the “stealth” EITS camera system, this system uses two high intensity bulbs that are switched on and off automatically at timed intervals during the night. The benefit of this is being able to capture high resolution color video images that provide sufficient information to identify fish species and invertebrates.

Animal-Borne Imaging

Not all cameras deployed in the sea are stationary or mounted to underwater vehicles. Since mid-1980, animals have become imaging platforms to record in situ data from the animal’s point of view. Today, in addition to video and still images, audio, environmental, and positioning data are logged on systems worn by manatees, sea turtles, sharks, whales, seals, penguins and many others. Animal-borne systems are the focus of the winter 2007/2008 issue of the Marine Technology Society Journal. In a previous issue, Marshall et al. (2007) describe how advances in smaller, more ruggedized cameras and solid state recording media have benefited the new generation (“GenV”) CRITTERCAM. Where the first Hi-8 CRITTERCAM system was 10.2 cm outside diameter (OD), 31.6 cm in length (L) and weighted 2.4 kg; GenV is 7.6 cm OD, 21.1 cm L and weighs 1.1 kg. This is no doubt a substantial relief for smaller bearers. Whereas Hi-8 videotape recording times allow up to 6 hours, GenV recording times allow up to 10 hours using an 8 GB compact flash and MPEG-2 program streams (PS) at low resolution (352x240 pixels). Even better news is larger compact flash cards (16, 24 and 48 GB) will soon be available and will allow even greater amounts of storage (Murph, 2008). At 75 minutes/GB, a 48 GB card will allow up to 60 hours of video. In addition, solid state memory is non-volatile and contains no moving parts, making it indifferent to loss of power and mechanical shocks.

Image Processing Methods to Simulate Visual Acuity and Perception

In addition to recording from the animal’s perspective, researchers are developing image processing techniques that simulate the visual acuity and perception of the animal (Johnsen et al., 2004). Animals living in the dark depths must trade visual acuity for increased sensitivity by pooling the light from a large number of photoreceptors to increase photon counts to detectable levels, much the same way as in dark-adapted human vision. This is similar to using a bigger F-stop and is referred to as spatial summation. Also of interest is temporal summation, where the integration time of the photoreceptor is increased (i.e. holding a shutter open longer) so that signals are able to integrate over a longer period of time to increase sensitivity. Figure 2 illustrates how the sea urchin (Echinometra lucunter) in (B) would perceive itself (or another sea urchin) in (C). The spatial and temporal resolutions needed to simulate the reduced visual acuity image are dependent on how the animal processes the reflected and absorbed light shown in (A). Techniques to determine the animal’s visual acuity and perception are described in Belvins and Johnsen (2004), Frank (2003), and Marshall et al. (2003).

High Definition (HD) Video

High resolution and quality offered by high definition (HD) video can benefit security and surveillance, inspection, mapping and precision photomosaics, photo

Figure 2

(A) Test of E. lucunter with two spines. Off-angle light (gray arrows) is absorbed and reflected by the spines. Light within the acceptance angle, (white arrow), reaches the body wall between the spines and is detected. (B) E. lucunter in a typical shelter. (C) Simulated view of B showing how the species would see itself.
excavation and historical documentation, basic work functions, online video for broadcast, education and discovery, cinematography, and many more underwater applications. Current high-end technology is capable of capturing images at 24/25/30 fps progressive or 50/60 fps interlaced at a resolution of 1920 x 1080 pixels. The Sony HDW-F900H CineAlta, for example, utilizes a 2.2 MegaPixel, 1” optical format frame-interline-transfer (FIT) charge coupled device (CCD) and is equipped with various gamma curves for improved image quality. Dual filter wheels (neutral density and color temperature) and comprehensive software adjustment parameters afford user control of the image. The FIT imager is a 2/3”, 2,200,000-pixel sensor that provides high resolution images having a 16 (horizontal) by 9 (vertical) aspect ratio. In its standard configuration, the camera can continuously record up to 50 minutes in 24P mode (24 fps with “pulldown” to create 29.97 fps video). Many of the newer cameras utilize the H.264 video-processing LSI codec (Compressor/DECompressor) for the advanced digital signal processor (ADSP), which provides real-time compression/decompression from video stream to display without degradation; smaller size and low power consumption by combining logic and low-power DRAM (FCRAM) on a single-chip; improvement in picture quality and stability using proprietary compression/image-enhancement technology that is optimized for human vision; and improved operational reliability (Fujitsu, 2007).

A recent undertaking involves deploying a HD video camera on VENUS (Victoria Experimental Network Under the Sea) and NEPTUNE (North East Pacific Time-Series Undersea Networked Experiments) (Roston et al., 2007). In a joint effort by McGill University and the University of Victoria, the system is designed to transmit live, full broadcast standard HD video (1280 x 720 pixels in 10-bit color at 60 Hz) over a 1 Gbps network using ultra-videoconferencing software. Rather than decimating the image (e.g., cropping or using 8-bit color), run-length encoding (RLE) is implemented to reduce bandwidth overhead to approximately 830 Mbps—equivalent to about 75% data compression (Lucas, 2008). The system uses a commercial camera having three 2/3” CCDs, a zoom of 44x, and a sensitivity of about 80 lux at F2. The video transmission will be available over the Web and control software will allow a single user to change internal camera settings, lens magnification, the illumination source (arc lamp or light-emitting diode [LED] based), on/off status of three parallel reference lasers, and pan/tilt parameters. The user interface allows scientists to define “change parameters” within a particular region of the image for notification of events of interest. The user interface and system architecture make this system unique.

**HD Video Compression Formats**

HD obviously provides a larger and much sharper image than standard video but requires much greater bandwidth and storage; something that is not always feasible in underwater applications where electronic “real estate” is limited. Recent image compression formats such as HDV, MPEG-4 AVC/H.264 and VC-1 reduce these demands by allowing reductions of the data rate or memory requirements by up to a factor of nearly 50 (Jones, 2007; Sauer, 2006). This helps make HD a viable option in many underwater applications. The HDV (High Definition Video) format was introduced in 2004 as the first practical implementation available in low-cost cameras. Where 1 hour of uncompressed 1080i HD video requires 432 GB of storage, 1 hour of 1080i HDV video only requires 12GB. HDV applies anamorphic stretching but compression is accomplished using the H.264 codec, which is able to compress to half the size of MPEG-2 (using -3 times fewer bits) without degradation of visual quality. This is up to twice as efficient as conventional MPEG-4. Once again, the disadvantage of AVC is the computational time required to unpack the files for editing.

VC-1 compression is based on Microsoft’s Windows Media 9. The codec is part of the MPEG-4 definition but is generally considered to be more efficient, though not necessarily more so than AVC. VC-1 is an acceptable standard for both Blu-ray and HD-DVD formats.

**Extended Range Techniques**

A primary goal of extended range underwater imaging is to improve image contrast and resolution at greater distances than what is possible with a conventional camera and underwater lighting. In recent years, several advancements have been made in this field. In general, the techniques used can be categorized into six areas:

- Time discrimination/range-gated methods;
- Spatial discrimination/laser line scan (LLS) methods;
Imaging using structured lighting; Scattered light rejection using modulation/demodulation techniques; Polarization discrimination; and Multiple perspective image construction.

A recent emphasis has been on designing wide swath imagers with the potential to be implemented on the common classes of autonomous underwater vehicles (AUVs). In fact, there are currently only a few design strategies for underwater laser imaging systems that have led to practical field systems. These are: (i) synchronously scanned continuous wave (CW) beam and photomultiplier tube (PMT), as implemented in the Raytheon LS4096 and the Northrop Grumman LLS systems; (ii) scanned laser beam and high speed linear CCD camera, as implemented in LBath system (Moore et al., 2000); (iii) pulsed fan beam with time-resolved signal detection using streak tube, as implemented in the Arete STIL system; and (iv) CW fan beam structured lighting system with a CCD camera, as recently implemented in a Bluefin12 AUV by the University of South Florida (USF) and SRI International.

All of the approaches provide intensity reflectance maps of the seafloor and targets, while the latter three also provide 3-D topographic information, either via time-of-flight or triangulation. Each of these systems has limitations or operational challenges that result from the design choices. Such limitations and challenges include: limited depth of field, which leads to difficulty in 'focusing' the system over the variable terrain; large size; high input power requirement; and limited range versatility. The deficiencies vary from system to system, but overall the operational community requires a system that combines reduced operational complexity (size, power, etc.) with enhanced performance.

Recently, Howland (2006) describes the development of a class of imager suitable for medium range imaging in clear water. Utilizing an array of high-power cyan LEDs centered at 500 nm and pulsed via a trigger signal from a high dynamic range, 12-bit high resolution CCD, the system is being designed for the benthic imaging payload of the Woods Hole Oceanographic hybrid remotely operated vehicle (HROV).

**Time Discrimination/Range-Gated Methods**

Range-gated systems traditionally use low repetition rate (< ~100 Hz) green pulsed laser sources, and have the aim of improving image contrast by rejecting most of the backscattered light between the source and the target. Previous and recent implemented bench top configurations (Fournier et al., 1993; McLean et al., 1995; Seet and He, 2005) use a spatially broadened laser pulse as the illuminating source and a non-scanning gated intensified camera as the detector allowing for the acquisition of a thin temporal slice of the entire (global) scene, over perhaps a 40 degree FOV. Utilizing suitably high sampling rates, these systems can also allow for 3-D image reconstruction from many short time slices (Busck et al., 2005).

More recently, an evolved implementation of this variety of system, the LUCIE2 (Laser Underwater Camera Imaging Enhancer) (Weidemann et al., 2005) has been packaged for use onboard a remotely operated vehicle (ROV) and deployed in very turbid water with encouraging results. The tested configuration allows for propeller blade inspection at 5 attenuation lengths. Ongoing system improvements include optical polarization control to implement polarization difference techniques to further enhance target contrast. A more compact third generation diver-held version of the system is currently under development. Other techniques to extend the performance range and retrieve optical properties of the environment are described in (Hou et al., 2007).

**Spatial Discrimination/Laser Line Scan (LLS) Methods**

Laser Line Scan (LLS) underwater imaging is a serial imaging technique that involves the optical scanning of a narrow instantaneous field of view (IFOV) receiver in a synchronous fashion with a highly collimated laser source over a wide swath. It has been widely regarded as the optimal technology for extended range underwater optical imaging. Indeed, it can be shown by deriving the optical transfer function of such systems that the achievable image resolution is near the diffraction limit (Jaffe, 2005a).

Although somewhat effective at spatially rejecting scattered light, LLS systems, which traditionally use a CW laser at a blue-green wavelength, are usually limited by receiver shot noise resulting from the temporal overlap between the target return and that of the scattering volume, from both laser and solar illumination. To maximize operational range, LLS systems use increased source-receiver separation that reduces the detrimental effect of near field multiple scattered light. However, this can lead to bulky systems which are not compatible with the smaller form factor UUV platforms.

Computer models of such systems have been studied for several years (Gibby et al., 1993; Giddings et al., 2005) and indicate that images can be obtained at up to 6 attenuation lengths in turbid seawater. Indeed, tested configurations, either in the field or lab-based demonstrators, have become cost limited at around this distance. To reject much of the undesirable scattered light and therefore enhance the performance of the LLS class of imager, it has been suggested to replace the CW laser source with a pulsed laser source and to replace the always 'on' receiver with a gated receiver. The pulsed laser line scan (PLLs) imager has been proven in simulation to be effective at over 7 attenuation lengths, but until recently was determined impossible to implement due to technological constraints, in particular the availability of suitable laser sources. The use of a pulsed laser and gated receiver also offers the capability to reduce the form factor of such systems, which leads to more compact and easier to implement systems.

Due to the availability of suitable benchtop laser sources in the last few years, modelers have been concentrating on synoptic model development to avert the computational burden of Monte-Carlo ray trace methods and to allow system de-
velopers to consider the trade-off of system parameters (Shirron and Giddings, 2006). Indeed, recent studies have shown that the use of a pulsed laser makes it possible to temporally separate the volume scatter and target signals and estimate the energy returning from the target alone, thereby offering the potential to improve the image contrast and possibly the successful operational range of the system (Dalgleish et al., 2006b; Caimi et al., 2007).

However, it is well known that in turbid water the backscatter signal at the receiver becomes much larger than the target return signal as the source-receiver separation is reduced. This large backscatter signal can lead to dynamic range limitations, device or amplifier saturation and even component damage, and it has been found that electronic gating is advantageous particularly at a smaller source receiver separation (Dalgleish et al., 2007).

The use of time-gated pulses within a LLS framework for extended range underwater imaging has been demonstrated by researchers at Harbor Branch Oceanographic Institution (HBOI), who have developed prototype hardware utilizing both custom and off-the-shelf gated-PMT assemblies and a custom high repetition rate (357 kHz), high power green pulsed laser (6-7 ns full width at half maximum Gaussian pulses). The test tank reflectance image comparison in Figure 3 shows a drastic contrast and signal-to-noise ratio (SNR) improvement of the time-gated PLLS over CW LLS in precisely controlled artificial turbidity environment under near-identical system and operational conditions. As the source-receiver separation is reduced, the performance of the time-gated PLLS is expected to be maintained, whereas the CW LLS will become contrast limited at a reduced stand-off distance.

At the limit of detection of the time-gated PLLS, several possibilities exist to extend the performance. The integration of multiple pulses will increase the SNR, albeit with a sacrifice to the achievable image resolution; physically increasing the size of the receiver aperture can also increase the SNR; likewise the use of coded pulses and coherent detection has also been shown to potentially further extend imaging capabilities (Mullen, 1996; Contarino, 1998).

**Imaging Using Structured Lighting**

**Distance-compensated Structured Light**

When using structured light, a narrow laser beam or plane is typically projected onto the scene, off the center axis of the camera. This configuration significantly reduces backscatter in the raw data and enables recovery of the scene’s 3-D structure by means of triangulation (Dalgleish et al., 2005; Carder et al., 2005). Narasimhan et al. (2005) present two innovative additions to this method. First, unlike synchronous scanning systems, scanning is performed without any major moving parts and is instead controlled by a spatial light modulator using a digital light processing (DLP) projector. Second, compensation is made for the attenuation of the water when recovering the object radiance. The attenuation depends on the distance of each object point, where distance is recovered using triangulation. The attenuation is parameterized by the attenuation coefficient of the water, where the parameter is recovered by a method based on the raw frames taken in the scene. This method also recovers a...
parameter that estimates the phase function of the water. An experimental example of the system output is shown in Figure 4.

**Synthetic Aperture Illumination**

A method for separating a background object from its foreground backscatter has been developed by Levoy et al. (2004). While most methods of structured light are based on illumination from a single direction, the method proposed here is based on a constellation of illumination sources, each irradiating the scene from a unique position and direction. Moreover, the illumination from each source is structured in the form of multiple bright patches. Figure 5 illustrates an experimental setup in a large water tank and some example images.

In this technique, multiple frames are acquired while different sets of illumination sources are active, where each combination produces a different illumination pattern. The acquired frames contain backscatter similar to that obtained by floodlighting. When the data is post-processed, the backscatter field is estimated based on the set of frames and then the backscatter component is compensated for to enhance the image quality. Two contrast enhanced test target examples are shown, where (b) uses only a floodlight and (c) uses multiple sources as shown in (a). The results in (c) show a dramatic improvement in the SNR. In this example, the attenuation length was about 8 inches and the range to the target was 4 feet or about 6 attenuation lengths.

**FIGURE 5**

(a) Experimental setup and test target examples in very turbid water acquired using (b) single floodlit illumination and (c) multiple illumination sources. (Courtesy Marc Levoy)

(b) Floodlit
(c) Multiple Sources

**Scattered Light Rejection using Modulation/Demodulation Techniques**

In the underwater imaging community, it is well known that coherent modulation/demodulation methods at optical frequencies fall apart due to the high dispersion in the sea water path (Swanson, 1992). Therefore, intensity modulation of the laser carrier is the only realizable choice in the design of coherent imaging architectures for extended range underwater use.

Earlier underwater coherent detection demonstrations have usually used a CW laser radiating an amplitude modulated beam of light to illuminate a target underwater from an airborne platform or underwater vehicle. A PMT then integrates the backscatter and the target photons together, and by demodulating the AM signal, partially rejects the scattered light signal enabling ranging to the shot noise limit of the receiver.

It has also been recognized that the non-coherent signal detection methods used by earlier LLS systems might also be improved by using sub-carrier coherent detection at the receiver to separate the temporally dispersive scattered light from the target return and to produce target profile or range information. One such system has been developed by NAVAIR to image targets underwater from an airborne platform or underwater vehicle (Mullen et al., 2004, 2007). This system uses a 3W CW laser sinusoid modulated at up to 100 MHz, with complex (IQ) demodulation to recover magnitude and phase information for enhanced contrast and range imaging capabilities. The system has also been demonstrated as having the potential for hybrid imaging/communications capabilities (Cochenour et al., 2007).

Another recent modulated CW imaging demonstration (Bartolini et al., 2005) utilized a 20 mW single mode laser at 405 nm amplitude modulated at 36.7 MHz via control of the current, and scanned in steps by a miniaturized piezoactuator. In laboratory tests at ENEA Research Center, submillimeter range accuracy was reported at a 1.5 meter stand-off distance in clear water. The diode laser wavelength matches the minimum of the pure water absorption spectrum, and hence this system has been designed for (eventual) long range 3-D imaging in relatively clear water.

The main limitation of these previous efforts were not demonstrating the systems using a full scale test range or with a real-time scanning architecture. However, in
2007, the NAVAIR system was tested with the HBOI benchtop LLS system (Dalgleish et al., 2006a). The results, which demonstrated a noticeable reduction in backscatter and hence improvement in image contrast when compared to CW LLS in turbid water (shown in Figure 6), were reported in a recent poster (Mullen et al., 2008).

It has been proven in simulation that the use of modulated-pulses, as described by Mullen et al. (1996, 1998), as the hybrid LIDAR-radar technique has the potential to further extend the operational range of LLS systems. The simplest method is to impress a high frequency sinusoidal amplitude modulation on the laser pulse. This in turn makes it possible to reject the lower frequency components of backscatter and ambient light, further increasing the range capability of the system. This type of system has previously been investigated by various research laboratories (Mullen et al., 1996; Pellen et al., 2002) and has been the subject of recent simulations using Metron’s radiative transfer solver (Shirron and Giddings, 2006) and other radiative transfer codes developed specifically for pulsed underwater laser imaging systems (Liang et al., 2006).

Within the last few years, the required hardware sub-systems have been under development. In particular, two recent NAVAIR SBIR topics address the development of both high power green modulated-pulsed lasers, and high timing resolution demodulating receivers for this class of advanced underwater imager.

These techniques can offer improvement in the recovered SNR on a pixel-by-pixel basis and consequently can provide better image quality at the range limits of the system. Improved simulation capability and hardware advancements will determine the potential limits of using coherent detection to reject noise and scattered light impairments to the image quality, and this will be investigated over the coming years.

**Polarization Discrimination**

An image enhancement technique proposed by Treibitz and Schechner (2006) combines an optical step during image acquisition along with digital post-processing. The optical step uses wide-field polarized light to irradiate the scene, while viewing the scene via an additional polarizer. Two wide-field frames are taken in mutually orthogonal polarization states. Backscatter exists in both polarization states (frames) but in different amounts; hence the optical step modulates the backscatter.

Next, a mathematical process is applied using the two raw frames as input. The process extracts the backscatter field and then estimates the background free of backscatter. This work generalizes the earlier work to scenarios where the illumination is artificial rather than natural (Schechner and Karpel, 2005). Several oceanic experiments were conducted to demonstrate this technique and are described in the 2006 paper. Figure 7 demonstrates the “unveiling” of a turbid Mediterranean underwater scene under artificial illumination using this polarization-based technique.

**Multiple Perspective Image Construction**

Imagery of a scene collected from different locations is commonly used to derive size and depth measurements, photo-mosaics, and 3-D reconstructions. This can be accomplished by performing high resolution optical reconnaissance sweeps of a desired area using a single imaging system, or using multiple imaging systems that perform the sweeps in a fraction of the time. When a multiple system technique is employed that separates the illumination from the image formation process, images can be captured at greater distances due to a reduction of the backscatter component. Jaffe (2007)
has shown this by simulating different configurations of lights and cameras (Figure 8a), where inputs consist of 3-D locations, pointing angles, characteristics of the lights and cameras, and a reflectance map with an arbitrary reflectance profile. Lighting is modeled as monochromatic or wide band, with its output pattern being a narrow sheet-like beam or a wide beam with theta and phi beam widths and an arbitrary radial dependent intensity pattern. The camera parameters include the f-stop, focal length and number of resolution elements. The inset in Figure 8a illustrates two potential geometries—a single vehicle system (Vehicle 1) equipped with a camera and light (Light 1); and a two-vehicle system where one vehicle (Vehicle 1) is equipped with a camera and a second vehicle (Vehicle 2) is equipped with a light (Light 2). Standoff and separation distances are shown. Simulation results show that the single vehicle configuration provided no useful information from the simulated scene (Figure 8b), whereas the two vehicle configuration provided a clear image (Figure 8c).

Woods Hole Oceanographic Institution researchers are using two AUVs to cooperatively characterize the Arctic seafloor (Woods Hole, 2007). Unlike the approach described by Jaffe, the two AUVs are launched sequentially with unique tasks in mind. The first AUV, Puma or “plume mapper,” is launched to localize chemical and temperature signals given off by hydrothermal vents; while the second AUV, Jaguar, is sent to those locations to use high-resolution cameras and bottom-mapping sonar to image the seafloor.

Spatial Coherency Techniques

Holography is a technique that necessitates post-processing and a tailored optical process. The raw data recorded in holograms is not a projection of the object as in standard photography. Instead, the hologram represents the intensity of an interference between waves propagating from the object and a reference wave—usually at optical frequencies. The physical acquisition resembles a transform: waves evolve from the object according to wave-propagation rules (diffraction); the diffracted waves interfere with a reference wave, creating a combined wave amplitude; and the intensity at the detector plane is a nonlinear version of this amplitude (its squared modulus). In order to recover the object from this transformed data, a hologram reconstruction is necessary. Traditionally, reconstruction is done by optically irradiating a slide encompassing the recorded hologram; i.e., in an analog manner.

Today it is possible for the reconstruction to be done digitally, by mathematically applying the rules of diffraction on the hologram input data. In digital holography, an electronic hologram is recorded directly onto a CCD (charge coupled device) or CMOS (complementary-symmetry metal oxide semiconductor) and then numerically reconstructed. As a result, 3-D information and a fourth dimension, time, form electronic holographic 3-D videos of living organisms and particles in their natural environment, recorded unbeknownst to the subject.
This principle is used by submersible digital holographic systems, as described in Watson et al. (2004), Sun et al. (2007), and Pfitsch et al. (2005 and 2007), to record plankton and other millimeter-sized marine organisms. An example is shown in Figure 9a. (Jaffe [2005] provides a good review of acoustic and optical imaging technologies used for sensing plankton.) The systems mentioned here operate at stand-off distances of about 0.1 mm to several millimeters. When recording over such a small volume there are no significant backscatter or attenuation effects. One might question the benefit of using this approach, rather than conventional underwater microscopy. Microscopy is essentially a projection of the object on the detector plane, and is thus simpler to obtain. However, in standard microscopy, the depth-of-field of each frame is narrow. Hence, for 3-D volumetric information, many frames must be scanned to capture the axial focus settings. In the described holographic systems, a single hologram (a single frame) can provide 3-D information using the aforementioned digital post-processing.

The captured water volume in systems referenced above have a cross section of about 1-squared cm. In the system described by Pfitsch et al., two holograms of the same volume are simultaneously acquired, from orthogonal directions. This improves the axial resolution of the recovered objects. The ocean water freely flows in and around the inspected volume. To view the dynamics of an organism for a relatively long time, the system drifts freely during the holographic acquisition. The system described by Sun et al., eHoloCam shown in Figure 9b, is towed through the water by a boat. Motion blur is avoided by using a pulsed Nd:YAG laser that has the capability of very short exposure times. Recent work pertaining to eHoloCam has focused on reducing the aberrations in the holographic images using an off-axis scheme with normal incidence of the object beam (Dyomin et al., 2007), similar to Pfitsch et al. Such a technique has an advantage at the reconstruction stage since no extra means of compensation is required.

Digital holographic systems offer another advantage as compared to non-digital (analog) systems such as HoloMar (Hobson and Watson, 2001)—the ability to develop and seamlessly integrate custom image processing algorithms like those used to extract 3-D regions of interest (Li et al., 2007) or those used to classify binary plankton images (Tang et al., 2006).

Methods using coherency of spatial gratings formed by structured lighting methods, such as proposed some years ago by Blatt and Caimi have not been investigated due to practical implementation problems (Bailey et al., 2003; Caimi et al., 1998).

FIGURE 9

(a) Reconstructed holographic image of a calanoid copepod at a standoff distance of 62 mm
(b) eHoloCam

Multi-dimensional Methods in Image Space

Hyperspectral Images and Perception

The work of Chiao et al. (2000a) sought an explanation for the number of types of color-sensitive visual cones in the eye of marine animals and the response of these cones. For this purpose, they built an underwater multispectral imaging system. In this system a variable interference filter was mounted on a CCD camera. Motion of this filter changed the sensed spectral band per pixel. Across the visible band, the system yielded 40 sub-bands, each having an effective bandwidth of about 15 nm. The wavelength band and its corresponding exposure setting were controlled by a portable computer operated from a surface boat. The collected image data revealed two findings. First, it was found that almost all the variance of underwater object spectra can be expressed using three principal components (Chiao et al. 2000b). This may suggest that a visual system composed
of three cone types can capture efficiently almost all the spectral variance. Then, this group proceeded to study a dichromatic model, where only two cone types may exist. Based on the underwater hyperspectral images, they sought a ratio between two cone types, which would optimize underwater scene discrimination. They found that the actual ratio in coral reef fishes appears to yield discrimination which is near optimal.

**Optical-Acoustic (Hybrid) Imaging**

Methods that combine Dual frequency IDentification SONar (DIDSON) and stereo imagery are being investigated for multiple-view 3-D reconstruction of scenes (Negahdaripour et al., in prep; Negahdaripour, 2007, 2008). The intent is to use the sonar to enhance reconstruction in poor visibility conditions, where visual cues become less informative. DIDSON uses high-frequency sonar (1-2 MHz) to produce range and azimuth 2-D measurements that are acquired in a polar coordinate system. Even in turbid water, near optical-quality 2-D video can be acquired at operational ranges of 10 to 20 meters. Since the geometry of “acoustic cameras” differs drastically from those of pinhole cameras, the greatest challenge in combining sonar and stereo images is calibrating the system to ensure data model consistency (Negahdaripour, 2005; Kim et al., 2005). Not only do the sensors have different areas of coverage, a pixel in polar coordinates maps to a collection of pixels in the Cartesian coordinate system, which further complicates searching and matching of feature points in successive images. Other challenges specific to DIDSON include limited resolution, low SNR, and limited range of sight. Kim et al. (2006) developed an algorithm to enhance sonar video sequences by incorporating knowledge of the target object obtained in previously observed frames. This approach involves inter-frame registration, linearization of image intensity, identification of a target object, and determining the “maximum posteriori fusion of images” in the video sequence.

DIDSON as a stand-alone sensor offers numerous advantages. In high-frequency mode, images from the sound beams can show the outline, shape and features of a target object. A common application is fisheries management and assessment, where fish behaviors such as spawning, feeding and migration can be non-invasively monitored and recorded even in low visibility conditions (Moursund et al., 2003; Baumgartner et al., 2006; NOAA, 2006). In many cases, even fin details of the target fish can be recovered. In Moursund’s application, fish were observed in real-time at a 12 m distance in zero-visibility conditions using 1.8 MHz high-frequency mode, where 96 beams covered a 29-degree FOV. DIDSON also provides the ability to count and measure fish (or target objects) automatically, as a software feature. Limitations of DIDSON, however, were apparent in a recent deployment to observe groundfish near the mouth of a trawl (Matteson et al., 2006). DIDSON alone did not provide enough information to reliably identify the fish species and fish above the seafloor were difficult to distinguish when both the sonar and fish were in motion. A better solution in these situations is to combine DIDSON and a video camera, stereo camera system (as in Shortis et al., 2007) or other optical imaging system. Figure 10 shows one such ROV-mounted system that combines DIDSON, a video camera and parallel lasers for fish stock assessments and quantification (Yamanaka et al., 2008; Yamanaka, 2005). Other applications well suited to using DIDSON (and optionally a conventional camera system) include close-range inspection of manmade structures such as dock and bridge pilings (Kloske, 2005) (see Figure 11), ship hulls (Negahdaripour and Firoozfam, 2006; Kloske, 2005) (see Figure 12) and oil pipelines to name a few.

Another system that combines sonar and video, reported in the 2005 technology update, is J-QUEST—Japan Quantitative Echo-sounder and stereo TV-camera system (Takahashi et al., 2004; Sawada et al., 2004). One of J-QUEST’s recent applications provided *in situ* measurements of target strength, tilt angle and swimming speed of *Boreopacific gonate* squid at depths approaching 300 m (Sawada et al., 2006). This system uses commercial analysis software to measure the echo levels (TSAN, Kaijo Sonic Corp.).

**FIGURE 10**

Canadian Fisheries Phantom HD2+2 ROV equipped with DIDSON, video camera and parallel lasers for abundance estimation and fish behavior analysis. (Photo by George Cronkite)
Recent Applications of Vision System Technology

Fish-Pond Monitor

A new domain in which underwater imaging is employed is agricultural fish ponds. The work of Zion et al. (2007) describes a computer vision system for automatically classifying, sorting and directing live fish in such places. In this work, fish in the pond are trained by feeding habits to voluntarily pass through a narrow channel made of transparent glass. The channel’s narrow width effectively allows only a single fish at a time to pass through. As the fish swims through the channel, it is photographed, classified and measured by a computer-vision system. When there is no fish in the channel, the image is bright. As a fish passes through the channel, the illumination is blocked and a dark silhouette is cast. The silhouette of the fish provides a very high contrast image that is somewhat preserved even in the presence of a large degree of multiple forward scatter. This enables simple feature extraction (on the outer body) followed by classification of the fish. Consequently, the fate of the fish is automatically determined: once it is out of the channel, the fish is either redirected to its habitat or redirected into a fishnet.

Bed-Sediment Microscope

An additional domain of underwater research is rivers. Geologists are interested in the study of sediments in river beds, particularly those of grain size. According to Rubin et al. (2007), sediments would traditionally be taken out of the water and measured in a lab. To enable fast measurements and tracking of changes over time, the authors developed a method to measure the sediments in situ. They describe microscopes whose camera and optics are enclosed in a flat viewport housing. The viewport rests directly over the bed area to be sampled to minimize image degradation caused by water turbidity. The optics are pre-focused on the external port plane. Such a setup was integrated into several systems; particularly a video system lowered from a river boat and a hand-held system based on a digital still camera. In addition, versions for marine use were developed, where the microscope served also as one of the legs in a tripod.

Hand-Held Stereocam

Stereo vision is a major technique in computer vision, and has long been studied underwater. Typically, stereo vision systems are mounted on underwater vehicles. In the work described by Hogue and Jenkin (2006), the track of stereo hardware development is done in parallel to development of the robotic platform. The authors intend to integrate a compact amphibious robot, called AQUA, with a stereo vision system. AQUA is able to maneuver in open water by swimming, as well as on soil by crawling and walking. As its stereo-vision system is gradually developing, hand-held versions are being built. The hand-held stereo rig is designed to be compact, easy to carry and easy to operate by a diver. The prototypes are based on machine-vision cameras using Firewire™ interfaces that connect...
directly to a computer. VGA-quality data is streamed at video frame rates. Their recent implementation eliminates many cabling and tethering problems. The stereo head is compact and enclosed in a small hand-held compartment, which is easy to operate and control by a single diver. A cable connects this compartment to a separate housing, which includes the computer and associated electronics. Finally, the computer housing can be harnessed directly to the diver, alleviating a need for connection with surface support personnel.

Future Trends

Several areas of technology development are particularly notable when anticipating future advancements in underwater imaging technology. Compact high power light sources, data compression and management, and energy storage, and realistic recreation of the image space continue to be areas where major strides are being made.

LED Technology

White light and single wavelength LEDs have made rapid advancements in the past few years with respect to electrical to optical conversion efficacy and wattage. Single package units are available that can produce output of several hundred lumens—equivalent to 60-watt incandescent sources, but at a fraction of the power. A measure of the output normalized to the wattage is the “luminous efficacy.” This can range from 50 lumens per watt to 70 lumens per watt for fluorescent lamps, and as much as 50 and 150 lumens per watt for arc light and HMI sources, respectively. White light LEDs promise efficiencies of 150 lumens per watt (or greater) and can be powered from low voltage sources without expensive or bulky ballasts. This makes them particularly useful for battery powered applications such as dive lights, small AUVs or other vehicles. As the technology advances, higher power units will become available and will ultimately replace lamps that currently are rated at hundreds of watts or more.

Laser Technology Advancement

New developments in laser technology have achieved short pulses at blue-green wavelengths offering stable, high repetition rate (> 300 kHz) and average power (> 2W) laser sources (Q-Peak Inc., Aculight Corp.). In an LLS system, this technology enables temporal separation of the backscatter from the reflected target signal and allows primarily the integration of the target photons during the detection process. This tends to increase the SNR allowing a greater distance for detection/imaging of the target. Further refinements in laser technology will be higher speed modulation capability and greater uniformity of pulse-to-pulse energy stability, as well as increases in power, efficiency, and compactness. This will allow more advanced laser imaging systems to be developed and integrated onto small platforms.

Data Management

Managing data from multiple disparate sensors as well as sensors that produce vast amounts of data is currently a challenge and will continue to be so as technology continues to advance. Data management involves storing, cataloguing, searching, retrieving, interpreting (human in the loop), sharing, editing, reusing, distributing, archiving and thinning. Though specialized systems will need to be developed for custom data types, rich media management and Digital Asset Management (DAM) software for high definition video (for example) and its related data is commercially available (Virage, 2007; Artesia, 2008; Digital News Direct, 2008). These packages include features such as automatically capturing, encoding and indexing TV, video and audio content from any source dynamically; automatically generating a comprehensive range of metadata that is immediately fully searchable and accessible by any user; and full screen streaming of HD video content at reduced costs. There is no doubt that these systems and others will continue to evolve for this challenge. A paper by Leslie et al. (2007) presents considerations for assuring high quality software for large-scale data management.

Fuel Cell Camera

Fuel cell power systems are making their way into the imaging field, led by a wireless system referred to as EnerOptix, shown in Figure 13 (EnerFuel, 2007). EnerOptix captures images using four day/night vision cameras that transmit data over a Code Division Multiple Access (CDMA) cellular network. Real-time control of the camera and retrieval of archived photos can be performed via secured Internet portals. By using a fuel cell, the camera is able to operate for extremely long periods of time without recharging or requiring battery swap (typically > 6 months), making it a promising technology for remote surveillance applications such as port, harbor,
ship, and buoy security and also for ocean observing applications. Fuel cell technology has several desirable attributes that make it suitable for “top-side” ocean operation (e.g., not corrosive, works well in humid conditions, and environmentally friendly), and designs have also recently been proposed capable of long duration underwater performance (e.g., Dow et al., 2005).

Three-Dimensional Television (3DTV)

A study undertaken by European researchers is exploring the feasibility of 3-D television (3DTV) (Kunter, 2006). Although broadcasting 3-D TV signals is beyond today’s capabilities, many recent technological advances (some already in use in underwater imaging systems) may help make this “futuristic idea” a reality. As an example, developers of eHoloCam are lending their expertise in holographic imaging to this cause (Benzie, 2007a; Kovachev, 2007). In another example, deformable meshes and other generic 3-D motion object representation tools found in computer graphics technology provide almost all of the tools necessary for 3-D scene representation. Once 3DTV is developed, its use in underwater filming could be a natural progression.

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Underwater Sonar: Plenty of New Twists to an Old Tale

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With sonar development historically being driven almost exclusively by military interests and the number of investment dollars sunk into underwater acoustics during half a century of war (both hot and cold) reaching into the billions, now (two decades later) one might be forgiven for expecting the pace of underwater acoustics technology advance to have slackened. Not a bit of it. While traditional funding sources have shifted focus, the diversity of applications and new discoveries continue to expand pace. In this commentary we explore some recent innovations and trends in interest, from vector sensors to distributed systems, from remote focusing to communications, long-range reverberation to Megahertz imaging. While the ocean still remains the last great unexplored region on Earth (the seabed being less well-mapped than both the dark side of our moon and Mars) acoustic tools are becoming more sophisticated, smaller, lighter, and more widely applied to beating back the curtains of darkness that shroud the unknown deep (and shallow) waters of our planet.

Just 40 years ago, “Computers were in glass rooms tended to by a core of monks that knew how to do the proper incantations.” (Gordon Moore, co-founder of INTEL)

**Time Reversal Mirror Acoustics**

Time Reversal Mirror (TRM) acoustics is based on the property of the linear wave equation in that it deals only with the second derivatives of time and space and is hence invariant to the arrow of time and reversal in space. Its power lies in using the ocean as an analogue computer to calculate the channel impulse response and include it automatically in a transmission scheme to focus energy at some range and depth. A key advantage of TRM is that it requires no a priori knowledge of the propagation environment. Furthermore, the method is not only applicable to areas with multiple scattering, variable ocean bathymetry, and range-dependent sound speed, it positively thrives on environmental complexity. Broadband time-reversal operator decomposition (known as DORT, an acronym derived from the French name for this process) is a related processing technique that decomposes contributions to the acoustic signal from separate scatterers.

TRM has been investigated for acoustic waves in the ocean for more than a decade, but the field (excuse the pun) is now rapidly diversifying into new and exciting areas, including applications for Passive Phase Conjugation (PPC), which is a powerful means of channel characterization for communications, and Green’s function estimation from the cross-correlation of ambient noise measurements. The latter technique has already been applied by Heat Light and Sound in the U.S. to sub-bottom profiling using a vertical array. In principle, only two hydrophones are required, though the field must be sampled over a very long time to adequately sample the geometric space. By combining the cross correlations of all hydrophone pairs in a vertical array, a much stronger result can be obtained, greatly reducing the required acquisition time. A drifting vertical array can then be used to determine both bathymetry and ocean sub-bottom features along its track purely from processing passively-received ambient noise in the waveguide.

TRM systems typically consist of an array of collocated source and receiver elements known as a Source Receiver Array (SRA), with perhaps a ‘probe source’ with one or more receivers at a separate location. Several groups have demonstrated iterative schemes by which some features of a received signal arising from particular directions can be suppressed while others are enhanced. In active sonar, a target return can be enhanced by iteratively focusing an active virtual source on the target, greatly reducing signal spreading losses by exploiting the multi-path coherence of the channel. This is a particularly powerful technique in shallow water, where active sonars are reverberation limited.

Such techniques might equally be used to do the opposite; enhance reverberation signals of interest against other features in the received signal. The Naval Research Laboratory (NRL) and NATO Undersea Research Centre (NURC) have explored how a TRM that is focused near the seafloor can be used to remotely construct a map of the azimuthal variation in bathymetry. The idea is to transmit a TRM signal from an axi-symmetric vertical array that forms a focal virtual source ring at the range of the probe source. If the bathymetry has a smooth azimuthal variation, this range will be shifted at different bearings. Backscattered reverberation is then time shifted on reception at the TRM and the round-trip time can be used to calculate the shifted focal range and hence infer bathymetric trends at each bearing. The NRL in the U.S. has acquired an SRA that they are using to test many such ideas, including echo enhancement and other properties of interest such as DORT processing to generate a directed ‘searchlight’ beam to probe the seabed for partially-buried mines. Similar approaches could perhaps be applied to the long-range reverberation
imaging currently being investigated at MIT to image large fish stocks at long range (see later sections).

In principle, TRM shows particular promise for shallow water applications, where the propagation is complicated by strong interactions with both the surface and the bottom, leading to extended multipath echoes. Provided the channel is sufficiently stable (over the time taken for the transmission, time reversal and re-transmission of a signal), these interactions increase the effective virtual aperture of a TRM SRA. While attenuation degrades TRM effectiveness to some degree, the real enemy is the temporal coherence limitations of the ocean. Scripps Institution of Oceanography (SIO) and NURC have shown that the temporal coherence for TRM ranges from many hours for frequencies below 1 kHz in deep water to tens of minutes at 3.5 kHz. More recent results from the National University of Singapore paint a more worrying picture for shallow tropical waters, with temporal coherence down to tens of milliseconds at 8 kHz. While this appears to prohibit some uses of TRM, it does not invalidate approaches such as PCC that, together with MIMO processing, may be the best hope for reliable, high-bandwidth shallow water communications.

Sensor Technologies
Ceramics

The history of piezoelectric ceramics goes back to the beginning of underwater acoustics and would take a book to describe, yet the development story is far from over. Single crystal lead magnesium niobate/lead titanate PMN/PT compounds are showing considerable promise thanks to their high electromechanical coupling factor and high energy density. The high coupling factor (0.9) allows the usable bandwidth of a transmitter to be extended well beyond what is achievable with polycrystalline lead zirconate titanate PZT transducers. PMN/PT ceramics are also being used in the smallest vector sensors now being produced, as described in a later section.

The Armament Research & Development Establishment (ARDE) in India has developed PMN-PT ceramics for actuator and sensor applications. It has been developed and tested by the National Physical Oceanography Laboratory as part of a sonar development project. ARDE has also developed Porous Piezo-composites for hydrophones. Porous Piezo-composites are useful for hydrophone applications because of low acoustic impedance, high figure of merit, hydrostatic coefficients, and hydrostatic sensitivity.

As the interest in high-power Low-Frequency Active (LFA) sonar intensifies as the best defense against increasingly quiet anaerobic submarines, there has been a consequent increase in interest in the development of efficient low-frequency high-power transducers. Most LFA systems are very large and cannot be operated from smaller vessels or aircraft. LFA projectors are generally massive flextensional devices, typically constructed from aluminum, steel, fiberglass and graphite composites (though these are expensive). Graphite composites are desirable because of their relatively light weight for strength and high tensional stiffness. A lighter, cheaper and broader-band class of LFA transducers would be of great interest. Increased acoustic power densities have been demonstrated for LFA by slotted cylinder projectors configured with lead magnesium niobate ceramic materials. Greater LFA projector power densities translate into larger detection ranges, increased bandwidth, size, weight and cost reductions. BAE in the UK has extended the idea of sloting a cylinder to a light-weight openwork honeycomb projector shell that is claimed to increase bandwidth while reducing weight and cost.

Fibre-Optic Sensors

Fibre-optic (FO) hydrophones have been in the pipeline for three decades, ever since it was recognized that Bragg scattering in optical fibers had the potential to provide an effective solution for large-scale arrays of that could be interrogated over large distances without the various noise and loss problems associated with analogue and digital electrical signals. Both the United Kingdom and United States navies have extensively funded the development of FO sonar technology to the point that it is now deployed on submarines and as seabed arrays. The basic design of a FO hydrophone has changed little since its conception, consisting of a coil of optical fiber wound on a mandrel, interrogated using interferometric techniques. Although other approaches are being investigated, including the development of fiber-laser hydrophones, the interferometric approach remains the easiest and most efficient way to create large arrays of acoustic sensors at a distance. Such hydrophones are now being used not only by navies, but by such diverse groups as high-energy physicists (who are looking for neutrino impacts at the bottom of the ocean) and the offshore oil and gas industry, who want large arrays of seabed-mounted FO sensors allied with 3-axis geophones for geotechnical studies. This has given new impetus to the development of the sensors and the associated interrogation systems which has led to the technology being adopted for other commercial uses. It remains to find a way to reduce the size of current mandrel-wound FO sensors to smaller sizes so that the applications in high-density arrays can be realized, a goal to which many millions of dollars have been dedicated. While the ‘holy grail’ of a FO sensor no thicker than fishing line is as yet still out of reach, the National University of Singapore has successfully employed longitudinal noise power averaging to build very low inertia thin arrays (of 8-10 mm diameter) from strings of tiny cylindrical ceramics that can be towed by small autonomous vehicles at up to 4 knots with self-noise levels remaining below sea state 0 ambient. Having proven the application, the motivation to perfect a thin FO acoustic sensor is strong.

QinetiQ has developed a range of ‘OptaMarine’ FO-based surveillance networks. Physically, their FO hydrophone array consists of a lightweight cable that can be deployed from a small vessel. Based on an optical architecture of time and wavelength multiplexed interferometric hydrophones, the system is generally made up
of two or more sub-arrays. In one example, the underwater section comprises two arrays each of 48 hydrophones separated by a 3 km fiber-optic link, connected to a shore station with 40 km of single-mode optical fiber. QinetiQ claims that the system self-noise levels are typically 10 dB lower than the ambient acoustic noise experienced in their sea trials with array gains close to the theoretical maximum. In principle, the use of multiple sub-arrays (none of which require electrical power) allows extended perimeters to be built over many tens of km and interrogated via a long (~ 50 km) optical fiber data link.

Thales Underwater Systems has placed a contract with a division of the QinetiQ to carry out a feasibility study on the deployment of reelable thin line towed sonar arrays for the Barracuda class submarine, a new nuclear attack submarine due to enter French service in 2017.

Vector Sensors

Directional sensors can selectively reject noise emitted from discrete interfering noise sources and localize targets, even from a single sensor. Acoustic vector sensors measure acoustic pressure and each of the three orthogonal components of particle motion in a single unit with a common center of detection. Such four-component vector sensors effectively buy up to 11 dB gain over individual omni-directional pressure sensors, in addition to resolving the port-starboard ambiguity of linear arrays. Vector sensors are normally constructed from three accelerometers plus a pressure sensor. They have been demonstrated to be effective in free field applications but there remain problems with their application to conformal flank arrays (where vibration is an issue) and in their use in towed arrays (where their current size and buoyancy are a burden). The motivation to pursue smaller vector sensors is driven by the property that vector sensors allow narrower beams to be generated with a smaller number of sensors over a smaller footprint than can be obtained from simple pressure-sensing hydrophones. This is particularly attractive for their use in towed arrays.

Small vector sensors (suitable for towed arrays) have traditionally suffered from poor signal-to-noise ratio, excessively positive buoyancy and fragility. While micro-machined sensors like the Microflown have been developed for use in air, no such design has yet appeared for underwater use. Wilcoxon Research, Inc. have taken a more traditional approach and, with the use of a new piezoelectric material (PMN-PT crystals), a patented electromechanical sensing mechanism and specialized low-noise signal amplification, they have succeeded in reducing the size of underwater vector sensors by about a factor of 2 in all directions while meeting U.S. Navy standards for towed arrays. Their new sensor is potted into a cylinder with hemispherical end caps, some 66 mm long and 36 mm in diameter; it is also neutrally buoyant in water, weighing just under 60 grams. This sensor is primed as almost a simple swap-out for existing Navy towed array sensors, although there remains considerable work to be done in the signal processing domain to develop optimal beamforming and other processing algorithms comparable to the considerable body of theory that supports current pressure-sensing array processing.

Large-Scale, Broadband and Multi-static

It is no longer news that modern sonars need to be broadband and multi-static to achieve the best results in long-range scenarios. An obvious example is the class of LFA sonars now being developed and deployed in several countries, all of which exploit both of these advantages. There have also been some non-military uses that have sprung up, sometimes from unexpected sources.

In work intended to map out the reverberation structure of the sub-bottom for improved clutter rejection in coastal long-range military sonar, MIT stumbled on a curious and very important result; that they could image large schools of fish using a bistatic active sonar. This discovery provides a means to conduct an almost instantaneous fisheries population census (and presumably also to plan more efficient capture of fish in large net operations). Continental shelf environments are traditionally monitored using line-transect methods that are slow and provide only local data, seriously undersampling the medium in both time and space. This leads to an incomplete and ambiguous record of abundance and behavior. MIT has shown that fish populations can be instantaneously imaged over thousands of square kilometers over the continental shelf and continuously monitored by simply imaging the backscattered signal of a bistatic active sonar system, as received on a horizontal line array. The technique has revealed the instantaneous horizontal structural characteristics and volatile short-term behavior of fish schools containing O(10^7) fish spread over O(10^2) km^2.

Synthetic Aperture Sonar

If not moving to multi-static, then another way to create a leap in performance over a traditional monostatic active sonar is to go to Synthetic Aperture Sonar (SAS) processing. A primary difficulty in realizing the theoretical advantages of SAS has been in estimating the sensor positions with sufficient accuracy to maintain phase coherence. Some combination of direct measurement, autofocusing based on the cross-correlation of overlapping phase centers and phase gradient autofocus is now often employed together with a dynamic model of the system (AUV plus array) often tracked by a Kalman filter to provide a robust motion estimation scheme. SAS is now maturing and has found a natural synergy with AUVs, which are less susceptible to surface motion disturbance than surface vessels. Several commercial AUV systems are coming onto the marketplace, notably the SAS AUV sonar from Thales (who are now designing their own AUV; The Asemar project includes ECA and IXSEA and the research laboratories of Ensight, Ecole Navale, ISEN and UBO), in addition to QinetiQ’s AUV-based broadband SAS being supplied to Saab Underwater Systems in Sweden; part
of an underwater capability that Saab are developing for FMV, the Swedish Defense Material Administration. QinetiQ’s SAS is claimed to achieve a 25 mm azimuth resolution at ranges of over 200 m from an underwater vehicle moving at up to 4 knots, with Thales’ system turning in similar performance figures.

**Doppler Sonar Developments**

Major advances continue to drive the development of Doppler sonars for current profiling and surface wave spectra estimation, in addition to side-scan Doppler systems for surface wave, ship wake and Langmuir cell research. The development of broadband coded pulses for improved sonar precision and orthogonality, together with the development of phased array Doppler sonar is enabling the 3-D imaging of flow fields at scales from tens of mm to km and the accurate navigation of underwater vehicles using either beacons or bottom-lock tracking. Doppler sonars usually operate at relatively high frequencies, 250 kHz - 3 MHz being typical, and can therefore be made very compact, rendering them suitable for a variety of applications and easy deployment. Recent developments include moves at Benthos/Teledyne to integrate acoustic modems with ADCPs to provide a single compact unit that requires no external cabling to operate autonomously, reporting its results via orthogonal acoustic modem coded signals.

As an example, LinkQuest’s NavQuest 600 Micro Doppler Velocity Log (DVL) is perhaps the world’s smallest and lightest DVL in its performance band. In its standard configuration with pressure housing it measures about 126 mm in diameter x 170 mm in length. The minimum altitude can be as low as 0.3 m, allowing users to operate much closer to the bottom than before. Applications include both deep and shallow water AUV navigation, ROV station keeping, manned submersible and diver navigation. It has a maximum range of about 100 m, a significant improvement over older systems.

**COTS-Based Systems and the Impact of Increased Computational Power**

Sonar system design continues to migrate from custom silicon technology with unique one-off software and firmware to COTS (commercial off-the-shelf) hardware with open source firmware and software operating environments, employing FPGAs (field-programmable gate arrays) and other intermediate customizable elements to obtain the necessary high throughput demanded by newer sonar systems. This is particularly the case for broadband sonars. The value of moving from narrow-band to broadband processing has been known for some time, but now multiple distributed COTS processors with highly configurable and capable FPGA support can finally provide the computational power required to make broadband sonars that are compact and relatively low-cost both to build and to maintain.

The cost of electronics has come down so sharply in recent years that expendable mine-destructors are now an economic option. One example is the German Navy’s Seefuchs, which has been adapted by STN Atlas and Lockheed Martin as the Seafox element of its Airborne Mine Neutralization System (AMNS). It has its own acquisition, homing and classification sonar, capable of horizontal mechanical scanning, with resolution down to 0.9 degrees.

So even for military uses, the trend is increasingly to convert older systems and bring new ones to market using COTS-based subsystems. Another example is provided by the Low Cost Conformal Array (LCCA) team (with contributors from Lockheed Martin, ARL Texas, NUWC and Stanley Associates); an industry team that recently received the U.S. Navy’s “Program Executive Office Integrated Warfare Systems (PEO IWS) Excellence in Engineering Award” for developing a new sail-mounted acoustic sonar system that provides enhanced tactical control for operations in coastal waters. The timeline from concept to prototype was only three years. The LCCA work adds to the Acoustic Rapid COTS Insertion (ARCI) system, which is intended to provide significant acoustic processing upgrades to the U.S. submarine fleet.

**Diver Portable Sonar**

Adding to the established 3D imaging sonars already proven in the marketplace and fitted to small surface vessels, AUVs and ROVs such as the Farsounder, Didson and Echoscope products, there is a new diver-operable sonar from Shark Marine that integrates a BlueView multibeam sonar into a lightweight, portable package with diver software support to give a real time image of a search area, and a means to log all underwater activity. The Navigator weighs only about 1 kg in water, including the front mounted scanning sonar. The sonar image is displayed on a 130 mm LCD screen and controlled by the diver through a GUI. The Windows XP-based unit can be operated while wearing gloves and during low visibility conditions. The LCD screen provides enough illumination to make a dive light unnecessary. Options include a WAAS GPS Receiver for shallow-water applications, digital camera, and DVL for diver navigation. It is envisioned that the Navigator will find applications in Mine Countermeasures, Underwater Archaeology, Search and Recovery, Diver Guidance and Surveillance.
The BlueView multibeam sonars come in two frequencies (450KHz & 900 KHz) and are modular swappable plug and play units that are finding applications with several customers such as the U.S. Navy, Port Authorities, Law Enforcement, Oil & Gas, and Dive operations. The platform flexibility and ease of integration of such COTS modular products has been proven in a wide variety of applications including boat mounted, ROV, AUV/UUV and diver hand-held systems allowing users to accomplish previously difficult or impossible missions such as inspections, detection, and navigation work in zero-visibility conditions.

Long-Range Satellite-Enabled Gateway Buoys

In another COTS leapfrogging of technology from the domestic to the military arena, Raytheon (together with RKK Technologies and Ultra Electronics Maritime Systems) is developing a gateway buoy communications system called ‘Deep Siren’ that includes expendable buoys 130 mm in diameter and about 1m long with antennas that receive Iridium satellite phone signals and convert them to 2 Hz coded and doppler-tolerant acoustic signals in the water that can be received and decoded up to ranges of approximately 175 nm by submarines traveling at up to 30 kts. The buoys are designed to stay afloat for up to three days and can be ejected out of a trash disposal unit so submarines can set up their own acoustic networks without the need to come to periscope depth and tow an antenna. In addition, land-based commanders can order Deep Siren gateway buoys to be air deployed in an operational area and transmit information without the usual waiting period for a patrolling submarine to come to communications depth or resorting to Ultra Low Frequency EM transmissions.

Acoustic Positioning and the Emergence of Underwater GPS

Over the last 10 years satellite navigation systems like GPS have transformed positioning and surveying in ways far outside the military uses envisioned in its design. Differential GPS (DGPS) has now consigned radio-based navigation systems to history by providing accurate positioning and tracking solutions in applications from geologic fault zone spreading to container ship offloading. While the GPS system has matured rapidly in the terrestrial and above-water arenas, there is as yet no such standard for positioning underwater. The offshore survey and construction market has grown substantially over the last 20 years and the future focus of operations in deeper waters, particularly with oil prices now exceeding $100/barrel as this commentary is written, is prompting strong renewed interest in the further development of underwater positioning systems.

The processing power required to perform signal processing and code correlation made receivers and decoders bulky and power-hungry, but now (thanks to Moore’s Law) we are seeing compact DSPs and FPGAs of unprecedented power and efficiency that can easily handle the most complex spread-spectrum orthogonal coding schemes in real time. This has empowered the shift from analogue circuits and simple pulsed narrowband CW signals to much more effective orthogonal coded signals and sophisticated digital processing. Finally the benefits of orthogonality (to avoid signal interference) and pulse compression (to obtain greatly superior time resolution and signal strength from cross-correlations) are available and are being incorporated into products.

Sonardyne has developed the Fusion range of flexible hardware platforms using modern DSP technology to support both traditional “tone burst” and broadband signals. This has been extensively operated over the last two years in an extreme range of environments from the icy waters of the Grand Banks to the straits of Singapore, no mean feat when the diverse nature of both the ambient noise and propagation channel characteristics are considered.

Deepwater oil field developments require highly accurate seabed positioning. The necessary positional accuracy on the seabed is not achievable with narrowband signals in deepwater operations as the high frequencies necessary to attain the required temporal resolution are attenuated too severely over the vertical propagation range to the surface ship in deep waters. The increased precision offered by broadband signals allows positional accuracies at mid-frequencies that were previously obtainable only at extremely high frequencies.

Sonardyne has also developed a robust high-speed broadband telemetry scheme with forward error correction that is de-
signed for real-time transfer of the relatively short data packets commonly associated with subsea navigation. In contrast to the schemes employed in many acoustic modem products, it does not require the overhead of a training sequence, which reduces the latency associated with the data. This makes it more appropriate to real-time monitoring applications such as the acoustic telemetry of gyrocompass and attitude data for navigation.

The orthogonal properties of coded broadband signal architectures largely resolves the interference problems that were common with conventional acoustic positioning systems, allowing the use of multiple simultaneous positioning operations within the same frequency band and within interference range. This has significant implications in deepwater oil field exploitation where acoustic systems have an increasingly important role to play, with both drilling and seabed installation vessels often working in the same area, with multiple ROVs using both LBL and Ultra-Short BaseLine (USBL) acoustic positioning systems, linked to atmospheric DGPS groundtruthing. This is effectively the birth of underwater GPS, without the standards that heralded the arrival of GPS and the ability to independently build GPS receivers.

Sonardyne has released their AvTrak 2 broadband acoustic navigation and communications system. A good example of functional integration, it combines the functions of transponder, transceiver and telemetry link in one low power device. It is also compatible with Sonardyne's family of LBL and USBL survey quality navigation systems. The command language allows an AUV to conduct simultaneous LBL ranging, USBL tracking via a surface vessel, and robust and high-speed telemetry both for AUV-to-vessel and for AUV-to-AUV communications.

Meanwhile Linkquest’s TrackLink 5000 and 10000 systems, also based on broadband spread spectrum coding and modern DSP technology, have gained acceptance from some highly regarded clients worldwide, including NOAA, which is installing a TrackLink 10000 system on its research vessel Okeanos Explorer, capable of reaching a range of 11 km, used to track an ultra-deepwater ROV and its TMS system. Like the Sonardyne AvTrak 2, this system has an integrated acoustic modem function that can be used to send commands to and receive data from an AUV. The National Oceanography Centre (NOCs), in the UK has ordered a second TrackLink 10000 system which will be used for AUV tracking and communication. Their first system is installed on the Autosub 6000 AUV. Other clients include the University of Hawaii, which uses a TrackLink to track deepwater towed systems and the deepwater manned submersibles, Pisces V and Pisces IV.

**System Integration and GUI**

The power of computing has advanced so rapidly and relentlessly that it has now outrun our ability to display and comprehend the gathered data. While data mining has a relatively long history of development, the degree of software integration and sophistication of display interfaces has not yet caught up with the real-time task of effectively conveying important information to the user. There is now a flurry of activity in the marketplace, offering modular and integrated software display packages, and some of these are now being generated by the hardware manufacturers themselves, rather than being offered by independent software engineering companies working at the margins.

SRD have developed a multibeam seabed visualization, measurement and control system for De Beers by integrating transducer arrays from its SVS3 range of real time digital sonar acquisition equipment with its own 3-D visualization software. The system will be used on De Beers’ new mining vessel “Peace in Africa,” which will be equipped with the largest crawler ever developed for harvesting diamond bearing material from the seabed. It generates real-time 3-D images of the underwater environment and gives the crawler’s cutting depth and the volume of material being removed. This will enable De Beers to mine the seabed efficiently and reduce the risk of any over or under mining of the diamond bearing layer.

Kongsberg, Nautilus Marine Group & ASI Group have combined their expertise to do the first three-dimensional model of an underwater structure based on real-time data acquisition. This is the first step in developing three-dimensional modeling applications that integrate 3-D sonar returns with GPS in a way that allows underwater images to be connected to above-water images. This allows clients to see structures both above and below the waterline. All data collected below the waterline is tied into the above portion of the structure with GPS RTK.

**AUV Sensor Systems**

As discussed earlier in this commentary, SAS has already made its way onto AUVs, one example of how the range and complexity of available sensors for AUVs continues to expand relentlessly as the AUV technology is increasingly perceived as having matured. Furthermore, the size of competent AUVs is being reduced, moving the cost down to levels at which mass-production advantages in production cost might soon be realized. The maturation of the AUV market is revealing itself in the classic consolidation phase as this is being written, with mergers and buy-outs prevalent in the AUV marketplace.

A version of the Gavia, a man-portable AUV, has been fitted with a GeoSwath Plus 500 kHz wide swath sonar capable of...
collecting bathymetry data for chart use. So far it has been used to profile sea ice cover in the arctic, deployed from the APL Ice Station 2007 (APLIS07) in the Beaufort Sea approximately 300 miles North of Alaska. The ability of the GeoSwath sonar to generate a 3-D digital terrain map of the underside of the ice is a unique contribution to understanding sea ice formation and evolution. The research is aimed at corroborating airborne ice thickness measurements and investigating the accuracy in areas with complex cracking and ridging. This could have a significant impact on the accuracy of parameter estimates used in climate change modeling, which is now widely thought to be a highly non-linear process. The Gavia also has an RDI DVL and a Kearfott inertial navigation system in addition to the Gavia's standard GPS, Iridium phone, wireless link, obstacle avoidance sonar, pressure depth sensor and mini sound velocity sensor. The Gavia has a diameter of 200 mm and is fully modular, expanding to about 2.6m long in this configuration.

Diver Detection Systems

The focus of naval attention continues to burn into littoral water operations with increasing interest in protecting vulnerable assets from attack from small groups of special forces. One of the most probable platforms of attack is considered to be divers. The response from the commercial naval defense giants has been quite rapid, though to date based on low-technological risk traditional technology, rather than, for instance, a barrier formed from TRM part network or from patrolling AUVs. Given the requirement of relatively high frequency operation to resolve small targets and the range limitations this imposes, particularly in highly-reverberant and multiply-scattering shallow waters, individual units cannot be expected to cover the entire region of interest. As a result, such systems generally operate on the principle of overlapping coverage from several identical units.

Sonardyne’s Sentinel is a compact self-contained diver sonar system that is relatively lightweight and can be rapidly deployed, having a sonar head 300 mm in diameter and of 400 mm height. This is a 360-degree sonar that can operate as a stand-alone portable system or as a member of a cluster of heads that are networked together to provide wide area coverage. The next step, presumably, is to allow the heads to detect each other’s signals, thus forming a net of multi-static active sonars. While the system presently lacks such advanced features, it does have an automatic target detection, classification and tracking capability similar to that used in radars that removes the need for continuous manual operation. Threat warnings can be communicated over Ethernet to a host command and control centre.

QinetiQ’s Cerberus is a similar, though much heavier, 360-degree active swimmer detection sonar with a range of about 800 m, again with intelligent detection, classification and tracking ability options. It is deployed and operated in much the same way as the Sonardyne Sentinel, and can be used in clusters to provide overlapping coverage. It is interesting to note that this swimmer detection sonar is the first to be used in a non-military application, having been deployed to protect the harbor entrance and waterways during the America’s Cup in 2006-2007.

Conclusions

The major new sonar developments making their way into the marketplace are currently being enabled by improvements in computational and sensing hardware, where the focus on shallow waters and higher resolutions are encouraging sonar sensing systems to become smaller, lighter and more easily deployed and recovered. Further into the future we can expect such systems to become more intelligent and autonomous, forming ad-hoc networks of co-operating assets. Meanwhile, upstream discoveries in signal processing and the fundamental physics of propagation are opening up new and exciting means of environmental sensing using, for example, ambient noise, that can be expected to fuel downstream applications in the future.

“The future is already here. It’s just not very evenly distributed.” (William Gibson)
Using Fundamental Optical Property Sensors for Characterization of Biogeochemical Materials and Processes in Marine Waters

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ABSTRACT
Over the past ten years, efforts to characterize the optical properties of Earth’s natural waters have largely merged with the need to better understand underlying biological and chemical processes. Fundamental optical properties such as light level, absorption, scattering and fluorescence are now being utilized with increasing effectiveness to specify particulate and dissolved in-water components in a wide range of applications, including detection of harmful algal blooms, studying ecosystem dynamics, monitoring the effect of industrial and agricultural pollutants, and understanding carbon sequestration processes in the oceans. A diverse offering of commercial optical sensing products capable for research, routine measurements, and in some cases, operational monitoring are now available. These technologies have provided the scientific community with a set of tools for developing, testing, and placing into practice analytical and semi-analytical methods to infer specific biogeochemical parameters and processes. As a result, new, more specialized sensors are now emerging. New sensors couple basic optical property measurements with processing algorithms to provide specific indicators for Harmful Algal Bloom (HAB) identification, carbon products, nutrients, and particle size distributions. The basic measurement methods are described and examples of devices incorporating them are provided to illustrate their use in modern oceanographic research and monitoring.

Introduction: From Optical Property Measurements to Ocean Biology and Chemistry
Throughout most of the last half of the twentieth century, the field of optical oceanography was largely backed by the Navy in support of anti-submarine warfare and other military applications. The small group of scientists and engineers engaged in the field were interested in fundamental questions relating to optical radiation transfer in water, and in developing methods and sensors to measure basic in-water optical properties. These properties include two broad classes of parameters: those that convolve natural sunlight into the signal to provide apparent optical properties (AOP); and those that addressed the intrinsic or inherent optical properties (IOP) of the water itself. Researchers designed new sensors and instrument systems within their laboratories and explored the oceans seeking to understand the fate of light through the sea. Hand in hand with these efforts they also sought to determine how particulates and dissolved matter in the water impacted these optical signals.

The end of the Cold War and the advent of ocean color satellites ushered in a new era of endeavor—understanding ocean color from space. Measurement of ocean color now implied determination of near surface chlorophyll concentrations. Scientists began to address questions of global biomass, carbon sequestration by the ocean and the associated implications of climate change. This period also saw the advent of a new generation of commercial AOP and IOP tools for performing in situ water measurements of the ocean color-related parameters. The in-water measurements were required to provide calibration points for water leaving radiances used by satellites to determine ocean color, and also necessary to interpolate optical signals through the vertical water column. While many of the early satellite calibration and validation efforts focused upon the open ocean, more recent studies began to focus on understanding ocean color in coastal environments. Understanding the coastal oceans introduced a new set of requirements, in that colored dissolved organic materials (CDOM), suspended sediments and other coloration materials became significant components of the signal. These once again needed complimentary in-water measurements in order to “truth” and interpolate the data.

Using optical measurements to obtain information about matter in the water was always a natural component of these seminal eras, but the new century ushered in a new set of requirements for an ongoing and permanent monitoring infrastructure to address societal needs. Detection of harmful algal blooms (HABs), water eutrophication coupled with hypoxic events, tracking of pollutants, and understanding anthropomorphic and climate impacts upon our coastal resources and habitats drew more attention. With this emerged a new emphasis in driving the optical measurement technologies—understanding water biology and chemistry through the use of optical measurements.

The emerging requirements also drove a “coming of age” in many of the fundamental AOP and IOP-related technologies. The same set of basic measurement techniques that helped scientists understand optical radiation processes in the water...
were now being more directly employed in understanding the biological and chemical variability and identification in the waters. This leads us to the current era. While still in the early stages of development as a field, scientists and engineers are rapidly progressing in developing new sensors, new methods for inversion and in producing more specialized tools.

This article reviews this set of measurements and tools and attempts to highlight some of the significant accomplishments, state-of-the-art products, and promising new technologies associated with these methods. At the onset it should be noted that it does not attempt to review many emerging optical technologies that fall outside the classical AOP and IOP. It rather attempts to show how scientists and engineers have built upon the study of optical processes in the ocean and their associated measurements to provide a valuable set of tools for monitoring Earth’s natural waters.

Understanding Light in Water—Apparent and Inherent Optical Properties

In order to describe the technologies involved in optical property measurements it is necessary to provide a brief overview of the study of light propagating in the ocean. This introduction is only meant to generally acquaint readers to what is a rich and complex field of study. Numerous texts provide excellent treatments of modern optical oceanography. Readers seeking a more extensive background in the theory, methods of measurement, and applications of ocean optics are encouraged to read Kirk (1994), Mobley (1994), or Jerlov (1976).

When light propagates through a given volume of sea water, one of several things happens: Some of the light passes through the volume unimpeded; some of the light is scattered by suspended materials in the water and the water molecules; and some of the light is absorbed by dissolved and particulate matter in the water and the water itself. When light is absorbed by phytoplankton containing chlorophyll, most of the energy is either transferred into chemical energy (via photosynthetic pathways) or into heat. However, a significant amount of absorbed energy can re-emit or fluoresce into the water at longer wavelengths (Figure 1). Other ancillary chlorophyll pigments also fluoresce as well as some dissolved organic material. The amount of scattered, absorbed, and fluoresced light all vary with material concentrations, composition, size, shape, physiological state, and anatomical “packaging” of the cellular structure. Modern optical sensors are based on detecting these relatively simple physical processes (scattering, absorption, fluorescence) over wide spectral ranges and through different angular scattering regions to aid in discriminating the composition and concentration of components of natural waters.

The first efforts in quantifying optical properties of natural water bodies were based on measurements of the propagation of sunlight through the water. By determination of the optical flux in specific directions over defined angular and spectral regions, one can derive specific radiometric parameters. These parameters are known collectively as the apparent optical properties (AOP). Primary AOP include the down-welling irradiance, the upwelling radiance and the scalar irradiance. The down-welling irradiance measurement attempts to capture all light propagating in the water in a general downward direction across a unit area. The radiometer detector “sees” direct light from the sun and scattered light that is still propagating in the general downward direction. When these measurements are obtained at different depths the differences obtained provides the basis for deriving the diffuse attenuation coefficient ($k_d$). This parameter provides an indication of the penetration depth of light in the water. Similarly, albeit with an opposite sign, upward radiating light is measured by an upwelling radiometer. In this measurement, the acceptance angle of the detector is limited to accept only light propagating in the upward (sometimes referred to as nadir) direction. Downward irradiance and upward radiance measurements are often conducted in tandem, as their ratio provides information as to the water leaving radiance or alternatively, the reflectance. Most modern radiometer systems measure light at multiple wavelengths. The spectral measurement convolves water absorption and scattering with the absorption and scattering of phytoplankton, CDOM and other materials in the water column. Spectral radiometers also detect the spectral shifts resulting from secondary effects such as chlorophyll fluorescence, which increases the photon flux in the

![Figure 1](image-url)

Water, particles and dissolved compounds absorb light in water. Water and particles also scatter light. These interactions are quantified by the absorption coefficient ($a$), the scattering coefficient ($b$), and the attenuation coefficient ($c$) where $c = a + b$. Phytoplankton containing chlorophyll and some colored dissolved organic materials re-emit or fluoresce some of the absorbed energy.
red portion of the spectrum centered around 690 nm. Scalar irradiance collects light in the water from all directions. This measurement is often embodied by using a diffuse spherical collector coupled to a photodetector. PAR, or photosynthetically available radiation is commonly determined from scalar irradiance. This radiometric measurement provides an indicator of the light available to plants for energy conversion, and hence an indicator of potential phytoplankton growth.

By replacing sunlight with a source of known intensity, angular distribution, and spectral bandwidth, the source variability is removed. This in turn allows one to obtain absolute coefficients of water optical transfer properties. These parameters are collectively known as the inherent optical properties (IOP). IOP parameters include: the beam attenuation coefficient (indicating total light lost to scattering and absorption over a given path of travel in the water); the absorption coefficient (indicating light lost to absorbing particles and dissolved matter); and several important parameters relating to scattering. Stimulated fluorescence is also considered an IOP parameter in that it uses a known excitation source to create an emitted signal. While designs for devices that measure IOPs differ, they fall into two broad groups: devices that determine transmittance losses through a fixed path or volume of light, and devices that rely upon coupling of a source emitter and a receiver detector set at opposing angles that have a defined volume of intersection (Figure 3). IOP devices range in complexity, from single wavelength scattering sensors for estimating particulate matter concentrations to multi-angle and multi-spectral (and hyperspectral) devices that provide broad characterization capability for dissolved and particulate components of the water.

Both AOP and IOP sensor technologies and associated methods hold advantages and limitations, but fundamentally the two systems of measurement are complementary and synergistic. AOP measurements provide a direct indication of the distribution of solar radiances of the water and relate directly to what is seen by many ocean color satellites. IOP measurements provide absolute coefficients of fundamental optical properties at time and space scales compatible with measured physical processes. These measurements are tightly interrelated and tell two distinct but overlapping parts of the story.

While in situ sensors that provide basic optical properties are uniquely designed and engineered to perform in natural waters, the optical measurement of liquids hardly constitutes a new field. In fact the measurements IOP parameters are similar to basic laboratory spectrophotometric and spectral fluorometric techniques, widely used in biomedical, industrial and other fields of endeavor. By analytical inversion (and use of other semi-analytical and empirical techniques) of these specific optical

FIGURE 2
Basic AOP configurations include down-welling irradiance (a), upwelling radiance (b), and scalar irradiance, (c).

FIGURE 3
Typical IOP sensor configurations for attenuation measurement (a), reflective tube absorption measurement (b), scattering sensor (c), and fluorescence sensor (d).
parameters, one can detect and identify specific dissolved and particulate components in water. Modern field sensors, in effect, merge fundamental in-water optical measurements with the analytical techniques developed in the laboratory.

The Need for \textit{In situ} Optical Property Sensors in Modern Ocean Research and Monitoring

The use of laboratory instrumentation is still a popular alternative in quantifying biological and chemical materials in water. By obtaining water samples and processing them in the lab one can derive information from discreet points within the water column. Laboratory instruments are not held to the constraints and requirements of in-water instruments. Size, power requirements, ruggedness, and ability to withstand immersion to depth, are not an issue for most bench-top devices, and samples can be pre-treated to minimize interference and concentrate analytes of interests. That said, in order to fully understand the critical linkage of matter to the dynamic changes occurring in the water, biology and chemistry must be sampled at the same time and space scales as the underlying physical processes. Moreover, to understand relationships between local biological and remotely sensed information from satellites and other platforms, data density in time and space must provide adequate coverage to provide meaningful correlation. While the extent of spatial and temporal scales are highly dependent on the underlying physical and biogeochemical processes, scientists acknowledge that these critical measurement scales must extend from centimeters to kilometers, and that temporal coverage must capture periodic cycling from tides to annual variability (Dickey, 2005). In many coastal systems, the complexity of the hydraulic setting and temporal forcing functions results in significant variability in the particle and dissolved fields on time and space scales that would be simply impossible to measure with discreet sampling. Finally, it should be noted that discreet sampling and related laboratory methodologies often create their own artifacts and errors. Ultimately the \textit{in situ} measurements promise the highest resolution, greatest coverage scales, and fewest artifacts.

Spectrophotometry

Modern \textit{in situ} spectral absorption and spectral beam attenuation meters are analogous to laboratory spectrophotometers. In oceans and lakes, phytoplankton, some dissolved organic dissolved materials, nitrates, bromides, and particles all can be seen, and in many cases identified, by these types of devices. Laboratory and in-water spectrophotometers operate upon similar principles, but the \textit{in situ} instruments are held to special constraints. They must work underwater, over wide swings in temperature and pressure, and they must accurately and reproducibly detect the low concentration levels found in nature. Absorption-based devices must also efficiently collect scattered light in order to isolate absorptive-based losses, due to the relative abundance of scattering components in natural waters. There are several different spectrophotometers now available—some are general purpose tools and some are designed for specific applications.

Spectral Absorption Meters and Spectral Beam Attenuation Meters—These sensors are commercially available (sometimes within a single instrument) and are gaining broader acceptance within the community. They are most commonly used in
a variety of applications under the general umbrella of ocean color validation. In situ absorption and beam attenuation meters are particularly capable at discerning the distribution of particulates and dissolved matter within the water at relatively fine space and time scales. In coastal systems, biology and chemistry are often not distributed uniformly and sometimes exist in very stratified layers with complex dynamics. The spectrophotometric tools not only determine general particle and biology concentrations but further isolate and distinguish different dominant particle populations in the water. This makes them particularly valuable for HAB monitoring (Johnson et al., 2002), and in understanding ecosystem dynamics. As an example shown in Figure 4, three spectra encompassing a dominant particle layer in Monterey Bay show distinct phytoplankton distribution within and surrounding the layer—the primary signature within the layer matching the identified dominant species (Donaghay and Rines, 2005).

Breve-Buster – The breve-buster spectrophotometer system serves a dedicated purpose in detection of HABs. The breve-buster combines a high-resolution spectral absorption measurement with a fourth derivative deconvolution technique to identify Karenia brevis, an organism that causes prevalent harmful algal blooms off the coast of Florida (Kirkpatrick, 2006). Built for operation upon autonomous underwater gliders (AUVs), the breve-buster is transcending from a research device to a monitoring tool.

ISUS – Designed to determine spectral absorption in UV, the ISUS uses a unique spectral difference technique to separate nitrate from a background of various salts and organic matter (Johnson et al., 2002). The processing algorithm applies a multi-wavelength differential method to separate nitrate from the background of bromides and CDOM. A commercial version of this device is now available and used both in real-time and extended monitoring applications throughout the world.

Particles and Scattering

Perhaps the most ubiquitous of all in-water optical sensors are those which measure particulate scattering. When light is scattered by a particle it propagates in all directions. The relative distribution of light throughout the various angles of scattering is defined by the Volume Scattering Function (VSF). The relative magnitude and distribution of the VSF is, in turn, influenced by the concentration, size, composition and shape of the particles. Inversely, devices are designed and manufactured to measure certain angular regions of the VSF to infer these particle attributes.

Turbidity Sensors – Optical Turbidity sensors form the biggest family of commercial scattering sensors. Turbidity sensors provide an indication of scattering generally centered around 90 degrees from the primary beam axis of propagation. These sensors play an increasingly important role in operational oceanographic monitoring. Turbidity sensors are calibrated against a secondary standards solution (e.g., formazin) and output is expressed in units relative to the standard. They come in a variety of configurations and these differences tend to lead to different responses in different water masses (due to measuring of different parts of the VSF and potential absorption effects). There are numerous standard methods and configuration standards (e.g., ISO 7027) for turbidity sensors. Turbidity sensors are widely available and commonly used in many monitoring programs. While these sensors can indicate a first-order estimate of suspended sediment concentrations in the water, the potential use of scattering in discerning particle composition, size distribution, and shape, and in validating ocean color remote sensing data is far greater.

Backscattering Sensors – While the underlying measurements are similar, backscattering sensors used for ocean color studies provide output in absolute coefficients related to the portion of the VSF they observe. Scattering is the dominant interaction mechanism between light and particles in most natural waters, and light scattered between 90-180 degrees (typically referred to as the backwards direction) is proportional to the signal seen by satellites. Scientists have extensively modeled backscattering to approximate light interacting with the particle field and have developed numerous biogeochemical inversions using this information (Zaneveld et al., 2002). Single angle optical backscattering sensors are configured for measurement typically between 115 degrees and 145 degrees. (Some special configurations center closer to 180 degrees.) These sensors are calibrated in absolute terms relating to the angular region defined by the source-receiver interaction volume and response to particles with a known VSF (Mueller et al., 2003). Usually the coefficients are for the scattering at a specific angle or are extrapolated to estimate coefficients for scattering in the entire backward region (90-180 degrees). Currently within the United States two manufacturers produce these sensors—both come in multi-spectral configurations. These sensors are most widely used in applications focused upon validating ocean color measurements from satellite data.

Beam Attenuation and Scattering – Total scattering is generally inferred through use of a transmissometer which is a 1-3 wavelength beam attenuation meter. Using wavebands in subject to minimal absorption by dissolved organic materials and particulates, the derived attenuation coefficient and scattering coefficient are close to equal in magnitude. Transmissometers are widely available and applied to a variety of applications—from use as turbidity sensors, to providing particulate organic carbon estimates in the open ocean (Bishop, 1999).

VSF and Particle Size – Scattering sensors are configured to span both spectrum and angle. Multiple angle scattering devices can infer more specific and accurate information about the particle field. One of the angular regions of highest scattering variability lies in angles less than 1 degree in the near-for-
ward direction. By determining scattering at multiple angles within this region one can estimate the near forward VSF. This in turn can provide an estimation of the particle size distribution. Produced by one manufacturer in the U.S., this type sensor provides powerful capability for monitoring sediment transport processes throughout the water column (Agrawal, 2005).

Complete VSF – Complete characterization of the VSF in natural waters has proven to be a rare phenomenon. Until recently the ocean optics community was almost entirely dependent upon a data set collected by Petzold (1972) from a small group of measurements performed at representative ocean locations. In 2002 scientists and engineers from the Ukraine partnering with Canadian and American scientists introduced a new device for VSF determination. The sensor measures scattering at 0.3 degree resolution from 0.6 degree in the near forward to 177.3 degree in the backward direction. (Lee and Lewis, 2006). Seminal results using this device (Chami et al., 2006) challenge common assertions about particle scattering in coastal waters and will likely dramatically improve the ability to discern particle populations.

Advanced Fluorescence Tools

As with spectrophotometers, fluorometers that incorporate spectral excitation and/or emission provide a much greater potential for specific identification of biologic species and chemical compounds. Several manufactures now provide multi-spectral fluorometers for detection of chlorophyll and some of its ancillary pigments as well as CDOM. These systems tend to match excitation-emission wavelengths to provide optimal fluorescence response for given photo-reactive pigments and other organic compounds. In ecosystems in which there are characteristic species, this information can, in turn, be used to infer taxonomic composition. Using multiple spectral excitation and emission bands to produce identifying signatures is carried to the next step in some recently developed research prototypes. These sensors couple single or multi-excitation sources with spectrometer-based emission receivers. Cowles et al. (1993) developed one of the first of this class of device. Since then both the component technologies and final products have evolved.

**Advanced Laser Fluorometer (ALF)** – The ALF couples two excitation lasers with a grating-based spectrograph receiver to produce high resolution emission spectra (Chekalyuk et al., 2006). The accompanying software automatically deconvolves emission spectra to separate CDOM and the chlorophyll-related pigments. These in turn provide signatures for identification of certain species. ALF currently operates as an onboard, underway system (Figure 5).

**eXcitation-eMission Fluorometer (XMF)** – The XMF couples high resolution spectrograph emission data with 10 nm resolution excitation pulses to produce 3-dimensional excitation-emission matrices. Exciting over 16 wavelengths, primarily in the UV region of the spectrum, the XMF measures emission spectra extending from 250 nm to 800 nm. The excitation-emission matrices provided by the XMF can be interrogated using a parallel factor analysis (PARAFAC) to separate specific hydrocarbon and CDOM compounds (Moore et al., 2004). As most crude oils and natural CDOM compounds have unique chemistry and fluorescence signatures based upon origin or refinement processes, the XMF can potentially be used to track these signals to their inputs.

**Excitation-Relaxation Fluorometers** – In addition to serving as an identification tool, fluorescence can also be used as a method for determining primary photosynthetic productivity of phytoplankton. Primary productivity is a vital parameter for understanding the ocean’s sequestration of carbon from the atmosphere, and also is a key to understanding the dynamics of ecosystems in the ocean. By providing an initial excitation pulse followed by a rapid sequence of additional pulses, and monitoring the de-
Optical Sensors in Operational Monitoring

As the capabilities and applications for optical-based sensors have grown, some sensors have begun to transcend from research-based use to more routine applications. This has not only been in response to growing need, but also a result of development of standard protocols for use and calibration, independent evaluations, and improvements in sensor performance—especially over extended durations. These factors have culminated in a limited but growing class of tools—the operational optical sensors.

**MOBY**—Since 1996 scientists from NOAA have engaged in an ongoing vicarious calibration effort for a suite of satellite sensors. Located approximately 16 kilometers off the coast of Lanai, Hawaii, the MOBY mooring (Flora et al., 2007) provides a primary calibration point of water leaving radiances. The MOBY mooring has supplied calibration and validation data for a series of international ocean color satellites.

The primary optical detectors for MOBY are a group of high-resolution hyperspectral radiometers known as the Marine Optical System (MOS). These detectors are spaced at 1.5 m, 5 m, and 9 m depths, as well as at the surface for above-water down-welling irradiance. Working towards the overall goal to reduce uncertainties of the measured water leaving radiances to within 5%, the MOBY team has worked to incrementally improve system performance since the initial deployment. The NIST traceable MOS sensors have been shown to hold stability to 1%; and to date, the MOBY system has obtained well over 8000 measurements.

The MOBY project is one of the first, as well as probably the most demanding, applications of operational optical measurements of the ocean. While MOBY is not used to estimate biogeochemical parameters per se, it has provided the vicarious calibration of satellite sensors, the critical link in translating satellite data sets to in-water measurements of specific properties. The success of the MOBY system has also helped to fuel a new generation of high precision commercial radiometric sensors.

Now, researchers are starting to use the much less expensive commercial equipment to expand on the MOBY single point data set while retaining the high quality of the calibration (e.g., Antoine et al., 2006). Furthermore, commercial radiometers are now commonly involved in ongoing sampling programs to tie optical signals with periodic and episodic events (e.g., Chang et al., 2006). The new sensors are used for profiling and moored operations and are available in both multi-spectral and hyperspectral configurations, extending from the UV through the visible spectrum.

**Commercial Monitoring Tools**—The primary challenges in applying sensors into routine extended monitoring programs are in making them resilient to fouling and corrosion (NRC, 2003). By 1999, the first of the new generation of optical sensors were beginning to be successfully tested and folded into active research and monitoring efforts (Morel et al., 2000; Chavez et al., 2000). These systems included radiometers, but more predominantly fluorometers and backscattering sensors. The work presented in a milestone paper (Manov et al., 2001) demonstrated that coherent optical measurements could be generated in situ from a year-long deployment of radiometers and fluorometers. Fluorometer and scattering sensors (often provided as turbidity meters) are now increasing, if not routinely, added to the measurement suites on monitoring platforms.

In 2005 and 2006, the NOAA Alliance of Coastal Technologies evaluated fluorometers and turbidity sensors (Tambouri, 2005, 2006), respectively, providing the first broad based, unbiased assessment of commercial optical sensors performing in various coastal conditions. Now these sensors continue to gain acceptance from the marine monitoring community and are used to provide indicators of biological variability and abundance, water clarity, storm related outflows, and use of biological signals as a proxies for nutrient availability.

**Advanced Methods, Simple Tools**—While most monitoring sensors range between one to six channels of measurement, as their use grows more ubiquitous, scientists learn more and more how these simple parameters provide indicators for ongoing environmental processes. Examples include:

- Washington Department of Ecology used fluorometer data over year-long timescales to accurately predict seasonal biological productivity (Newton et al., 2002); and
- Researchers at University of South Florida developed excellent correlations between Karenia brevis populations responsible for red tides off the West Florida coast by incorporating a simple ratiometric relationship of backscattering and fluorescence (Cannizzaro et al., 2007); and
- Scientists used data from backscattering meters, transmissometers, and fluorometers to track water mass movement and separate organic and inorganic particle populations at the Rutgers LEO-15 observatory (Boss et al., 2004).

As researchers and monitoring agencies transition these optical tools into operational monitoring systems, they are elucidating new means to use these optical measurements to understand and describe the biogeochemical variability observed in the oceans.

**Looking Forward**

The examples of technologies and applications provided in this article are illustrative but by no means comprehensive. Many scientists from around the world
are dedicating their efforts towards building more effective algorithms and models for using optical sensors to better discern materials and processes occurring in natural waters. Meanwhile, the technology development moves forward and government agencies continue to focus support and establish protocols for effective biogeochemical validation.

The current set of commercial optical property products is really the first generation marketed to operational ocean monitoring and research. These devices are just now gaining acceptance and widespread use in programmatic marine monitoring efforts. Evaluation and protocol efforts are now underway to evaluate more advanced spectral IOP and AOP tools for operational biogeochemical validation of ocean color satellites (Hooker et al., 2007). This portends broader capabilities, usage and acceptance for underwater spectral radiometers, spectrophotometers, and scattering sensors.

Bulk-phase AOP and IOP measurements by no means define the extent of modern optical methods for assessing biogeochemical state of the oceans. As needs for biogeochemical monitoring have increased, the trend of applying optical techniques that “take the laboratory into the water” has gained momentum. In-water flow-cytometers that measure scattering and fluorescence of individual organisms are now seeing use in ocean observing systems (e.g., Sosik et al., 2003). Selective membranes coupled with fluorescence and absorption measurements are now available for detection of dissolved oxygen (Tengberg, 2004), pCO₂, methane, and other dissolved gases. In situ analyzers that combine optics with reaction chemistry to measure nutrients, metals, and pH are another growing class of commercial tools (e.g., Hanson et al., 2004; Rawlinson, 2000; Seidel et al., 2007). Raman spectroscopy, surface plasmon resonance, and doped fibers all provide promising paths for detectors with high levels of specificity. Environmental researchers continue to look to the biomedical and other technology-driven arenas for new improved methods to adapt to the ocean.

While these new approaches hold great promise and will undoubtedly prove invaluable in the future, the development of methods and measurements for the fundamental optical properties will likely continue to play a growing and important role in ocean monitoring. Not only will the AOP and IOP technologies improve in their own right, but they will stand upon a field of science which by its very nature, links the sun, the earth’s oceans, and a broad set of dynamic processes essential for life on this planet.

References


Status of Sensors for Physical Oceanographic Measurements

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Abstract
This paper draws from recent workshops held by the Alliance for Coastal Technologies to summarize the present status of sensors and sensor platforms for making physical oceanographic observations. Technologies reviewed include those for current measurements, HF Radar, wave sensors, drifting buoys, profiling floats, surface meteorological observations, and automated vessel-based systems, as well as related issues of data telemetry and biofouling.

Introduction
The U.S. is implementing an Integrated Ocean Observing System (IOOS) to meet a wide range of the nation’s marine product and information service needs. The seven societal goals of IOOS are to:
- Improve the safety and efficiency of marine operations
- Improve homeland security
- Mitigate effects of natural hazards more effectively
- Improve predictions of climate change and their effects
- Minimize public health risks
- Protect and restore healthy coastal marine ecosystems
- Sustain living marine resources

The successful implementation of the IOOS will require parallel efforts in instrument development and validation so that promising new technologies will be available to make the transition from research/development to operational status when needed. To foster new sensor development and transition to operations, the Alliance for Coastal Technologies (ACT) was established as a partnership of research institutions, state and regional coastal decision makers, and private sector companies interested in developing and applying sensor and sensor platform technologies for monitoring and studying coastal systems. ACT is designed to serve as:
- An unbiased, third-party testbed for evaluating new and developing coastal sensor and sensor platform technologies,
- A comprehensive data and information clearinghouse on coastal technologies, and
- A forum for consensus and capacity building through a series of annual workshops on specific technologies or topics.

The ACT workshops are designed to aid decision makers, coastal scientists, and private sector companies by identifying and discussing the current status, standardization, potential advancements, and obstacles in the development and use of new sensors and sensor platforms for monitoring, studying, and predicting the state of coastal waters. The workshop goals are both to help build consensus on the steps needed to develop and adopt useful tools, while also facilitating the critical communications between the various groups of technology developers, manufacturers, and end-users. ACT workshops seek to identify the present status and likely near-term advances in the technology, to identify impediments to the implementation of the technology as a component of an operational coastal ocean observing system, and to recommend specific, achievable actions to overcome these impediments.

ACT Workshop Reports are summaries of the discussions that take place between participants during the workshops. The reports also emphasize advantages and limitations of current technologies while making recommendations for both ACT and the broader community on the steps needed for technology advancement in the particular topic area. Workshop organizers draft the individual reports with input from workshop participants. ACT is committed to exploring the application of new technologies for monitoring coastal ecosystems and studying environmental stressors that are increasingly prevalent worldwide. For more information, please visit http://www.act-us.info/.

Although this publication focuses only on those workshops that discussed physical oceanographic parameters, ACT has hosted many that focus on biogeochemical sensors, with 38 workshops held to date.

Current Measurement
Many types of current meters are commercially available and are utilized for a wide spectrum of activities in academic research, resource management and industrial applications (ACT, 2005a). Each of the available current meter technologies has advantages and disadvantages related to initial costs, application restrictions (shallow water, surface current resolution), biofouling and interference by marine life, mooring and deployment requirements, maintenance and calibration issues (e.g., longevity of batteries, calibration of compasses), and data interpretation.

Rotor and vane vector averaging current meters measure at a discrete depth in the water column and provide measurements of current speed and direction. Though rotor-vane current meters are less frequently produced today, many are still in use. Rotor-vane current meters are capable of
Acoustic travel-time sensors measure current velocity in a moderate sized volume of water between pairs of acoustic transducers. These instruments use the phase shift/angle difference between the forward and reverse pulses along multiple paths to compute estimates of velocity in 2 or 3 component directions. They do not rely on the presence of scatterers, as the sound propagation speed between the two transducers is little affected by bubbles or suspended materials. Acoustic travel time sensors sample short path lengths (~1.0 cm), which yield restricted volume current estimates, making sampling near boundaries (near surface and bottom) achievable. These instruments exhibit both high sensitivity and precision; however, the measurements near the transducer can be affected by flow obstruction from the mooring device. Fouling of the transducer can negatively affect the measurements as fouling impedes the volume flow between the transducers emitting and receiving the signal. Being that this technology requires a well defined start and end signal, any fouling could produce more noise in the data and may result in erroneous absolute velocity estimates.

Acoustic point Doppler velocimeters measure two or three flow velocity components at a specific location in the water column using the phase shift between a pair of pulses that are separated by a time lag. Adjusting these time lags changes the maximum measurable velocity that the velocimeter can measure. Each pulse relies on scattered sound from particles in the water column. Acoustic Doppler velocimeters are bistatic sensors with the transmitter separate from the receivers. They transmit and receive signals at high frequencies, and are designed to provide accurate measurements in a small volumes of water, in the range of about 1-2 cm³. They are well suited for turbulence measurements, measurements in the surface boundary layer, and are used frequently in controlled laboratory experiments. The lack of moving parts make them resistant to mechanical fouling, and acoustic point Doppler velocimeters are insensitive to water quality issues. Fouling on the transducer can potentially lower acoustic signals and result in noisier data (reduced signal-to-noise ratio [SNR]). This type of current meter operates at a lowered SNR, thus fouling can become a problem if severe. If biofouling dimensionally exceeds the blanking distance away from the transducer, it may cause a flow disturbance in the remote volume where the current measurements are made, resulting in erroneous measurements. These systems are the least power efficient of all the technologies. To achieve the high level of accuracy, acoustic Doppler velocimeters require averaging of many acoustic pings in a short period of time, often sampling at rates greater than 25 Hz. Even during longer sampling intervals, or where less accuracy is required for an experiment, acoustic Doppler velocimeters still sample at greater than 25 Hz. The inability of these instruments to ‘sleep between pings’, or for users to control ping rates, contributes significantly to power consumption.

Acoustic Doppler current meters and profilers use the frequency shift (Doppler effect) of scattered sound off particles to estimate current speed and direction (Figure 1). Discrete-depth acoustic Doppplers measure velocity in a single volume of fixed/known size (a single depth cell), whereas acoustic Doppler profilers are capable of sampling a profile of horizontal velocity. The vector velocity profile from a single profiling instrument is based on range gating, and the instruments can be oriented vertically or horizontally. Acoustic Doppler current meters and profilers are monostatic sensors, using a single transmitter-receiver that transmits a signal at a given frequency, and receives the reflected signal, which is Doppler shifted. Pulse-coherent profilers combine acoustic Doppler velocimeter precision with Doppler profiling capability, and are useful for measuring in boundary layers or in low-flow environments.

Measurement ranges vary for acoustic Doppler profilers and are frequency dependent. Long-range (> 1000 m) profilers transmit at lower frequencies over larger depth bins in order to penetrate the entire water column. They also have larger dimensions to accommodate the power supply required to transmit and receive...
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Signals over a deeper water column. Smaller profiler units, designed for coastal waters, transmit at higher frequencies over smaller depth bins (1-5 m) and are ideal for water depths on the order of 5-200 m. Bottom-mounted shallow water profilers can also give directional wave measurements (see below). Downward looking profilers record bottom reflection, which is a necessary parameter for bottom tracking while collecting current profiles from a moving platform. Bottom tracking is used to remove the vehicle motion from the observed current velocities.

Doppler current meters and profiler measurements are correct at zero velocity and do not require an offset, while the volume sensed is remote from the transducer. Accuracy and precision depend on the sampling scheme and is determined by the combination of sampling frequency, averaging periods, and bin sizes. Auxiliary sensors integrated into the acoustic Doppler current meters are typically pressure and temperature. Despite fouling on the transducer faces, which can reduce the signal-to-noise ratio, acoustic Doppler current meters and profilers can still record accurate records of current velocities, even when fouling is severe (e.g., mussel growth). However, when instruments become buried under sediment, acoustic attenuation and loss of transmission can compromise data coverage (range) and quality. Higher frequency acoustic Doppler profilers are compromised more by severe biofouling or sedimentation than the lower frequency instruments, typically resulting in reduced water column range. One disadvantage of using any Doppler current meter or profiler is that they require scatterers to be present in the water column. A necessary assumption is that these scatterers move at the same horizontal velocity as the water, which requires the scatterers to be largely free-floating (i.e., non-swimming).

Surface Current Mapping with HF Radar

Surface currents are an identified high priority product for coastal ocean observing systems (ACT, 2004b). Surface Current Mappers (SCMs) that broadcast and then observe back-scattered radio signals from the ocean’s surface are now an operational technology that has been implemented in numerous locations worldwide. SCM technologies, using the same back-scattered radio signals, have also produced useful surface wave and vessel-tracking data in research applications. A nested network of SCMs installed along the coast of the United States, and used in conjunction with other observations and data-assimilative forecast models, will address issues critical to the goals of IOOS (Paduan et al., 2004).

Most (but not all) commercially available SCM systems operate in the high frequency (HF) radio band. Such systems include CODAR and WERA (commonly referred to as HF Radar or surface current radar) and could be used in SCM implementation. Other short-range systems operate in the X-band of the radio spectrum while some systems utilize multiple frequency bands. This summary focuses on systems operating in the HF band, as these systems are in most widespread use.

SCM networks currently require transmit and receive antennae at each site (Figure 2). Direction-finding implementations have a small number of antennae placed tens of meters apart and look both directions along a beach. Phased-array designs utilize more widely spaced antennae (~100 m) and look in one direction along a beach. Ideal locations for both types of systems are shoreward of open beaches. Because of the compact footprint, direction finding systems are convenient to deploy on headlands or in heavily populated areas where space is premium. The basic measurements provided by all systems are maps of radial currents. Vector currents are available for the region of overlapping coverage from two or more individual sites.

Approximately 100 individual SCM systems are presently operated in U.S. EEZ waters by research institutions or state agencies (http://cordc.ucsd.edu/projects/mapping/maps/). Many systems are long-range, as described above, while others are more regional-scale (30-60 km), higher resolution systems. Mostly, HF radar system products are closely aligned with the framework for a national backbone SCM.
network proposed for the IOOS. HF radar systems are capable of generating several different products. They span a range from mapping scales of highest resolution, lowest range implementations to lower resolution, long-range systems. SCM technologies are used to identify surface current fields (tidal, etc.), from which trajectories of passive bodies can be computed, waves and wave heights, and atlas products of current and wave statistics. Operational products, such as NOWCOAST, have been developed for currents and waves. Examples that serve the public include real-time velocities (U and V components), trajectories for search and rescue or hazardous material spill mitigation, wave observations, and short term forecasts of current and wave conditions.

SCM technology is under development and more needs to be done to further its application. Uncertainties in measurements of surface currents and waves need to be identified in the form of confidence limits or errors. Further work also is required to refine vessel detection and tracking capabilities of HF radar systems. Subsurface currents and bathymetry, directional wave information, and winds are examples of developmental applications. Trial support by government agencies most likely to benefit from this technology is needed to explore these applications and is especially desired for currents.

Finding and gaining access to potential sites for location of HF radar antennae pose both short and long term difficulties inhibiting the implementation of HF radar on a national and regional level. The permitting process requires cooperation from multiple governing agencies on the federal, state, and local levels. Instead of viewing these governing agencies as roadblocks, collaborations among agencies should be encouraged. For example, lighthouses could be used as HF radar sites if U.S. Coast Guard headquarters made this a priority. Other examples of potential sites include state parks, coastal NPDES discharges and lakes, and offshore transmission sites. Products produced from HF radar data should be explained to the above mentioned governing agencies, emphasizing the utility of the SCM products, although some benefits may not be obvious now. Insurance and liability must be taken into account when inquiring about siting permissions. Additionally, visual impacts may cause denial or delay in obtaining permits (antenna and ancillary equipment, solar cells, generators, etc.). Therefore, the physical installation, including electronics housings, should be aesthetically pleasing. Radio frequency safety education materials should be supplied to the governing agencies, academia, and the public, explaining the operating principles of HF radar to avoid fears of human health impacts from radio frequency energy.

The frequency band useful for surface current mapping operations is constrained by oceanic wavelengths. As the number of oceanographic surface current mapping systems increases there will be increasing competition for frequency allocations in the limited part of the electromagnetic spectrum available for these observations. Consequently, competition will be increased between surface current mapping systems and other users of the HF band. Better coordination is needed to contend with frequency allocation issues. Data from all HF radar systems are similar, as are the requirements for installing and maintaining the instruments. Hence, establishing a systematic network for data management represents one component of IOOS in which centralized coordination and training is beneficial.

Wave Sensor Technologies

Waves consistently are ranked as a critical variable for numerous coastal issues, from maritime transportation to beach erosion to habitat restoration (ACT, 2007). The focus here is on measuring “wind waves” (i.e., waves on the water surface, generated by the wind, restored by gravity and existing between approximately 3 and 30-second periods), although it is recognized that a wide range of both forced and free waves exist on and in the oceans. The emphasis here is on the near-shore application of wave measurements; however, the discussion is relevant equally to open ocean surface wave measurement.

Presently, wave measurement systems can be classified into two large categories: in situ instrumentation and remote sensing methods. In situ sensors include submerged pressure sensors, buoys, acoustic sensors (with and without pressure) for measuring wave orbital velocities, non-acoustic sensors for measuring wave orbital velocities, wave staffs, and subsurface arrays of pressure sensors. Remote sensing technologies include marine radar (non-coherent and coherent), high frequency radar, lidar, satellites, optical sensors, and altimeters. A brief description of each technology class follows.

Submerged pressure sensors are mounted at fixed positions underwater. These instruments measure pressure fluctuations associated with the changing height of the water column above the sensor indicating passing waves. These pressure time series can be converted to sea surface elevations and wave frequency spectra.

Buoys measure motions of the water surface, such as accelerations or slopes of the water surface. Wave heights and periods are obtained from the vertical motions, and wave directions may be obtained from the orbital motions or wave slopes. Buoys are
useful for measuring waves far offshore or at remote locations because they do not require a fixed platform, such as a pier or other structure. Data are transmitted via satellite or radio link. Buoys that measure $x$, $y$, $z$, are called “translational,” or “particle following,” buoys, and buoys that measure $z$ and sea surface slopes $dz/dy$, and $dz/dx$ are called “pitch-roll” buoys.

For the PUV Method, there are several instruments that measure wave subsurface pressure ($P$) and the two horizontal orbital velocity components ($U$ and $V$). The PUV method utilizes the velocity and pressure time series to determine wave non-directional and directional information. This method assumes that waves in each frequency band are coming from one primary direction.

More recently, acoustics have been used to measure the surface position in an effort to make wave measurements from bottom mounted devices. These systems can be considered as inverted echo-sounders. Functioning in much the same way as a depth sounder measures distance from a boat to the sea bottom, an upward looking acoustic device can measure distance from the sea bottom to the sea surface. By making these measurements rapidly and accurately, a time series of the surface position can be measured, and non-directional wave parameters can be calculated.

Some instruments directly measure components of the wave orbital velocity. A typical transit-time flow measurement system utilizes two ultrasonic transducers that function as both ultrasonic transmitter and receiver. This is called UWV (Ultrasonic Wave Velocity). The flow meter operates by alternately transmitting and receiving a burst of sound energy between the two transducers and measuring the transit time that it takes for sound to travel between the two transducers. The difference in the transit time measured is directly and exactly related to the velocity of the water.

Wave heights are measured by analyzing radar echoes from the sea surface by marine radar. The radar sea-echo amplitude is dependent on the wind generated “roughness” of the sea surface. Gravity waves and currents form images on the radar display because they modulate the sea surface radar cross section by angular modulation, hydrodynamic interaction and shadowing. By the use of proper algorithms, a full three dimensional wave spectrum and the magnitude and direction of near surface currents may be calculated on the basis of digitized radar images. Marine navigation radars utilize only the non-coherent radar back-scatter modulation. The navigation radar is an indirect wave sensor because there is no direct relation between wave height and radar backscatter modulation amplitude. The calculated wave spectrum is basically un-scaled with respect to wave energy. Additional measurement of the non-directional wave spectrum may be required for calibration purposes or an empirical method of calibration, relating some parameter derived from the measured data to the real wave height, may be employed. Coherent radars measure Doppler-modulation, as well as amplitude modulation, while non-coherent radars only measure amplitude modulation. (http://www.miros.no)

HF radar is well established as a powerful tool for sea current measurements at ranges of 30 to 200 km as described above. It operates in the 3 to 50 MHz frequency band corresponding to a radio wavelength in the range of 10 to 100 m. The Doppler shift of the first order Bragg lines of the radar echo is used to derive sea current estimates. For wave measurements, a more complex second order mechanism of backscatter is used. Although it has been claimed that HF radars can measure wave spectra at very long ranges, their success as wave sensors has been limited. A disadvantage of many HF radars is the size of their antennas. Attempts have been made to make the antennas smaller but probably at the cost of greatly reduced antenna efficiency.

Microwave altimeters emit microwave FM chirp signals and receive reflections from the water surface. The propagation delay of the electromagnetic signal, due to the distance between the antenna and the water surface, causes a beat signal in the receiver. By means of advanced frequency domain filtering, the beat signal is converted to an accurate distance estimate. The altimeter has a built-in reference to compensate for any long term drift. Microwave altimeters have been shown to also provide valid non-directional wave observations.

Laser altimeters are small and lightweight and operate in the infrared (IR) frequency band. They normally use pulsed waveforms and perform direct measurements of sea surface elevation, which can be converted easily to wave amplitude. The laser beam is very narrow and almost non-dispersive. The footprint is small and almost independent of range. Originally it was thought that due to the high frequency of operation, laser altimeters are prone to interference from natural sources of IR emission. Salt and soot deposits on the optical window can greatly deteriorate the measurement performance. However, recent tests of lasers for use as redundant air gap sensors have demonstrated that they are surprisingly robust. Altimeters deployed as long as 5 months can still work well with no lens maintenance. Laser altimeters have also been shown to provide valid wave directions (Irish et al., 2000).

Some issues associated with making real-time wave measurements have to do with the different user requirements. There are two principal user groups of real-time wave data: those interested mostly in a few parameters of the wave field that describe the dominant waves and those interested in the underlying component waves or wave events. The “dominant wave” users typically look at the significant wave height, $H_s$, peak wave period (also called dominant wave period), $T_p$, and the mean wave direction at the peak wave period, $Dm \oplus T_p$. There are likely few, if any, directional wave instruments currently in use that cannot adequately satisfy this user base. The “component wave” users are more interested in observing the individual wave events in a region. Instrument accuracy is crucial to component wave users, and the selection of directional wave instrumentation requires a more careful evaluation of its performance.
Drifters and Profiling Floats

Lagrangian drifting buoys are used for mapping surface or near surface currents and can be used in search and rescue and for tracking fish larvae, ice bergs, pollutants and oil slicks (ACT, 2005b). They can be used as well for gathering data on ocean temperature, salinity, and atmospheric pressure to better enable scientists to model the ocean environment and associated climate. In addition to Lagrangian buoys, floating buoys are used in cases when it is not required to follow a moving parcel of water. These buoys do not necessarily follow the current, but are deployed and allowed to move with the wind while collecting data.

Although drifting buoys have been used to study the ocean environment dating back to the Challenger Expedition in 1872, their usefulness was limited by the inability to accurately track the buoys for great distances. In the 1970s the implementation of the ARGOS satellite system helped solve this problem. The ARGOS instrument, located aboard the NOAA Polar-orbiting Operational Environmental Satellites (POES), can receive data transmitted by the buoys and relay that data to ground stations around the world. This system has made it possible to easily track the movements of a great number of buoys scattered over a large area. This technological development paved the way for two of the more ambitious ocean circulation programs that are gathering a large collection of data on the world's oceans. As these programs developed so did the variety of drifting buoys available.

The ARGOS positioning system is accurate from 150 to 1000 m, a resolution that is sufficient for the large scale ocean currents, but cannot accurately portray the finer motions within the coastal zone. Coastal drifters use Global Position System (GPS) location with cellular or satellite telemetry (see below). This method demonstrates an accuracy of 10 m, a fine enough resolution for modeling the coastal and estuarine environment.

Since 1988 over 2,500 Lagrangian drifters have been deployed as part of the Surface Velocity Program (SVP) of the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere Program (TOGA), and then of Global Drifter Program. On September 18, 2005, the Global Drifter Program reached its goal of 1,250 buoys in sustained service. Buoy #1250 was recovered on Feb 21, 2007, at Brest, France, after a 521 day journey across the Atlantic Ocean from its launch in Halifax, Nova Scotia. Both SST and Barometric pressure sensors were reporting good data until its recovery (http://www.aoml.noaa.gov/phod/dac/gdp_information.html). This program, a component of the Global Ocean Observing System, provides mixed layer velocity and sea surface temperature observations in all major ocean basins. In 1991 the buoys deployed for this program were standardized to the surface velocity profile (SVP) drifter. The SVP consists of a spherical hulled surface buoy containing the ARGOS antennae, electronics, and sensors, a subsurface sphere at about 3 m to reduce the wave motion effects on the drogue, and a holey-sock drogue centered at a depth of 15 m. The data from these buoys are distributed in real time onto the Global Telecommunications System (GTS) and to the Drifting Buoy Data Assembly Center.

Profiling floats alter their buoyancy by transferring oil between internal and external bladders to move vertically through the water column, making profile measurements of temperature, conductivity, and depth, along with other parameters such as dissolved oxygen and chlorophyll fluorescence, as they rise and fall. The Argo program maintains an array of 3,000 autonomous profiling floats deployed in 3 degree spacing reporting 100,000 profiles per year (http://wo.jcommops.org/cgi-bin/WebObjects/Argo). Argo floats (Figure 3) collect water column profile data from the upper 2,000 meters of ice free ocean. Once deployed from aircraft or ships of opportunity, the floats submerge to approximately 2,000 meters. Every 10 days they slowly rise to the surface collecting profile data as they rise. Once on the surface, the float transfers its data to shore via satellite then submerges to repeat this cycle. Data are transferred via GTS and made public within 24 hours of collection. The floats are expendable and are designed for approximately 150 cycles over a four year period.

Numerous projects using a variety of drifting buoy technologies are ongoing at this time, many of which occur in the coastal and estuarine environment. The open ocean design of the drifting buoys used in the used in the Global Drifting and Argo programs must be adjusted for the higher traffic, shallower waters, as well as the smaller spatial and temporal scales occurring in the coastal estuarine environment. For example, the Bottom Stationed Ocean Profiler (BSOP) developed at the University of South Florida is similar to the Argo float but rests on the bottom in continental shelf waters between cycles (http://ogcweb.marine.usf.edu/BSOP/bsop_index.shtml).

Marine Meteorological Observations

Employing technologies associated with atmospheric observing systems in the marine environment continues to pose challenges (ACT, 2006b). Most of the national and regional observing systems that deploy environmental moorings include
sensors that measure some or all of the near surface variables of wind speed and direction, barometric pressure, humidity and air temperature, whether or not the primary purpose of the moorings is to acquire atmospheric observations (Figure 4). Surface meteorological measurements are high priority core variables required to achieve the goals of the IOOS, particularly those that involve public safety, marine navigation, and climate.

Anemometers used for measuring marine wind speed and direction generally fall into one of two categories, mechanical or sonic. In the mechanical types, wind speed is sensed by the rotation of cups mounted symmetrically on a vertical spindle or a propeller that is oriented into the wind by an attached vane. An AC generator or an interrupted light beam and photocell convert rotation rate to an electrical signal for processing. Wind direction is sensed by vane angle and a potentiometer produces a voltage proportional to vane angle from 0 to 360 degrees. With all the moving parts, exposure to the highly corrosive marine environment is the most common problem. Some manufacturers have developed marine versions with special bearings, seals and lubricants. Required dynamic response and detection thresholds depend on application and are governed by a compromise between the employment of lightweight materials and the need for ruggedness to withstand high wind speeds.

Sonic anemometers were designed to eliminate many of the problems associated with mechanical anemometers by eliminating moving parts. They operate on the principle that the time for a sound wave to travel over a distance is altered by wind speed. They have a sufficient number of sonic transducers mounted about a central axis to resolve wind velocity into its eastward and northward components. Sonic anemometers historically have been more costly than mechanical types, but cost has been decreasing. They may be even more susceptible to the effects of birds than mechanical types since there are no moving parts to deter roosting. For both types of anemometers, moored buoy applications are made a bit more complicated than on land since a compass is required to reference wind direction to magnetic north. This produces another point of potential failure.

Most sensors that measure atmospheric pressure in marine applications employ a circuit whose capacitance changes proportionally with pressure. Two closely spaced metallic surfaces, one of which is allowed to flex under pressure, create the variable capacitance, which is used to produce an electrical signal for processing. Ventilation to the atmosphere must be provided while protecting the sensor from water or salt contamination and preventing dynamic pressure fluctuations associated with wind speed to be confused with barometric pressure variability. Mounting the sensor within the buoy hull and venting with a tube equipped with a reverse flow check valve and terminated in an external port such as that designed by Gill is effective at preventing contamination.

Temperature sensors are generally of two types, resistive thermal devices (RTDs) or thermistors. RTDs rely on resistance change in a metal, with the resistance rising more or less linearly with temperature. Thermistors are based on resistance change in a ceramic semiconductor; wherein the resistance drops nonlinearly with temperature rise. Temperature sensors must be shielded from direct or secondary solar radiation. Good airflow through the shield housing is essential for accurate readings. In applications where power is not an issue, a motor driven aspirator can be used to ventilate the shield housing; however, due to limited power availability on moorings, offshore towers, and many marine land-based stations, the use of an aspirated shield is normally not possible. Multi-plate passive radiation shields are recommended, though even with these, false readings in low wind and strong sunlight conditions do occur.

A thin film capacitive sensor is most commonly used to measure relative humidity. This type of sensor measures humidity through the change in capacitance of a thin polymer as it is exposed to variations of water vapor. A gas permeable membrane protects the electronic parts from spray and particulate matter but allows air to enter the instrument housing. The measurement of relative humidity is temperature sensitive and the sensor may incorporate a temperature probe to determine dew point, thus a housing to shield against solar radiation is required. False high humidity readings can be obtained, particularly after periods of saturation, when conditions within the shield may lag ambient conditions. Water and salt adhering to or being held by the shield may also cause errors; rewetting salt particles can create salt solution droplets with vapor pressure different than ambient. It should therefore be constructed of hydrophobic, slick material and shaped so water flows off easily and particulates do not adhere.

Instrument survivability is the greatest challenge to taking meteorological measurements in the marine environment. Sensor degradation or failure as a result of saltwater intrusion and corrosion, biofouling by birds, and theft and vandalism are all factors that reduced sensor survivability. High cost, both in terms of capital investment and maintenance, is another serious challenge. Not only is there the initial cost of the equipment, but ship time to maintain offshore stations is quite expensive, particularly if high reliability is sought. Managing sensor power requirements with the limited power typically available on a...
Integrated Sensor Systems for Vessels of Opportunity

The use of self-contained, low-maintenance sensor systems installed on commercial vessels is becoming an important monitoring and scientific tool in many regions around the world (ACT, 2006a). These systems integrate data from meteorological and water quality sensors with GPS data into a data stream that is automatically transferred from ship to shore. Most integrated sensor systems consist of both meteorological and subsurface sensors. Within the meteorological suite, the sensors or parameters that are most prevalent are wind speed and direction, temperature, relative humidity, barometric pressure, GPS positioning, solar radiation (short and long wave), and ceilometry. Within the subsurface suite, the sensors or parameters that are presently on most integrated systems are sea surface temperature (SST), sea surface salinity (SSS), chlorophyll, dissolved oxygen (DO), pH, partial pressure of carbon dioxide, nutrient sensors (nitrate and phosphate), blue green pigment, silicate, and turbidity. Other potential sensors or parameters for potential integration include shipboard weather radar, waves, surface current, acoustic Doppler current profiling, biomass, colored dissolved organic matter (CDOM), optical plankton instruments, continuous plankton recorders, towed sensors, expendable probes, and collection of discrete samples for use in quality control.

While several research groups around the world have developed custom integrated sensor packages, there are currently three commercially available systems in use: 4H Jena Engineering, Chelsea Technologies Group, and The International Seakeepers Society (Figure 5). For summaries of these three commercial systems see Appendix B of the full workshop report (ACT, 2006a).

Some limitations (e.g., cost, calibration, maintenance, data quality) of present integrated sensor systems for vessels of opportunity include system maintenance, initial installation and/or retrofit cost, downtime, calibration frequency/cost, sensor reliability, biofouling, debubbling (residence times, sampling intervals), compatibility/interoperability, access to sensors, vertical/horizontal scale profiling, sustained funding, and QA/QC of data. Other limitations and pertinent issues include the creation of incentives for ship owners, labor, socioeconomics, and sensor/technology maturity (reliability, maintenance requirements, etc.).

Hardware interface issues are a major hurdle further complicated by the issue of proprietary technology that prevents companies from integrating their connections and software. The concept of “plug and play” is seen as an ideal adaptation to these integrated systems; however, this can be costly with respect to developing unifying programs that are able to standardize the input displayed by the various integrated sensors contained in one package. It would be difficult to standardize the interfacing of all instruments due to the multitude of manufacturers involved. The other issue concerning this standardization approach to integrated sensor systems is that users may prefer a particular instrument that may not be adaptable for an integrated suite due to software or power requirements.

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Standard protocols for monitoring are welcomed by many agencies and are, in some cases, a basic requirement. Most of the Volunteer Observing Ship (VOS) systems that are currently operated are being done so by academic or research institutions rather than operational agencies. As a consequence, strict protocols have yet to be developed. In Europe, the European Union-funded project “FerryBox” has developed standard data reporting procedures and produced a coordinated review of the procedures employed by the eight different organizations running VOS lines within the project.

One obstacle associated with the implementation of standard protocols is that many countries do not readily grant permission to monitor in restricted waters due to defense and/or natural resource (including artifacts and fisheries) protection issues. In some countries, it could take up to six months before being granted permission into these restricted areas.
Conclusion

Observing technologies for physical state variables in the ocean are relatively mature, with recent advances in those for currents and surface waves. Operations and maintenance costs and long-term instrument survivability continue to be impediments to deployment of these sensors as components of an operational observing system. We have focused herein on physical variables; however, rapid advances are being made in sensor technologies for biological and geochemical parameters. Continued improvement of existing technologies and development of new observing capabilities are critical to implementation of IOOS and to address its goals.

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References


High-Bandwidth Underwater Communications

ABSTRACT

The rapid exchange of data with underwater sensors and systems is increasingly valuable for oceanography, oil exploration and other investigations of undersea phenomena. This paper reviews the potential, as well as the limitations, of acoustic, radio-frequency electromagnetic, fiber-optical and free-space optical techniques for high-bandwidth, undersea communication. In particular, we discuss the environmental and hardware attributes that bound the performance of free-space optical communications in a variety of undersea scenarios. Free-space optical approaches are capable of providing data bandwidths approaching $10^6$ bits per second (bps) under suitable environmental conditions. More commonly, $10-100 \times 10^6$ bps can be achieved over ranges approaching 100 meters. Turbid water and high-ambient light conditions (primarily from downwelling sunlight) pose a serious challenge to performance at moderate and long ranges.

Introduction

The sea, the primary conduit of international commerce and a critical element of the global biosphere and climate system, is the subject of continual study and exploitation. As more sophisticated sensors and other subsea devices are deployed, the mass of data to be handled and the accompanying data rate requirement continues to rise. In response, new methods of transmitting this undersea data have been developed. This article will briefly survey the challenges, status and potential of high-data-rate (here defined as greater than 100 kbps) underwater communications, with an emphasis on applications where both ends of the communications channel are submerged; i.e., we will not consider air-to-subsurface communications, nor will we discuss the use of surface buoys. We will review the limitations the undersea environment places on transmitter-receiver (transceiver) performance and discuss technical approaches for improving performance.

Underwater Communications Methods

Underwater data communications requires two essential characteristics: the modulation (at a transmitter) and demodulation (at a receiver) of a carrier wave used to transport the data symbols; and an environment that will support propagation of the carrier wave with low enough attenuation and background noise and high enough temporal fidelity that the carrier wave can be successfully demodulated in the receiver. Shannon’s Theorem (Shannon, 1948) states that the maximum bit rate that can be supported on a channel with a finite signal-to-noise ratio is

$$BR_{\text{max}} = \Delta v \log \left(1 + \frac{S}{N}\right)$$

where $\Delta v$ is the frequency bandwidth of the channel, $S$ is the signal power at the receiver and $N$ is the noise power at the receiver (from all sources). Inspection of equation 1 shows that high-data-rate communication requires high bandwidth, and high signal-to-noise ratio (SNR); in other words, channels that feature high loss and/or cannot support high carrier frequencies will be poor candidates for high-bandwidth communications.

Shannon’s Theorem is independent of the method of encoding the data symbols; rather, it establishes the maximum possible data rate for any transmission scheme. To achieve performance at the theorem limit generally requires complex modulation schemes. For example, the most common modulation scheme used in fiber-optics uses on-off keying to provide on the order of one bit per Hz of waveform bandwidth. In bandwidth-limited wireless RF communications more sophisticated “n-ary” (quaternary, etc.) modulation techniques are widely used to divide a single time-slot into multiple levels, frequency shifts, etc., to increase the bandwidth utilization. Shannon’s Theorem also only addresses noise-induced inter-symbol interference (ISI). Effects such as multi-path propagation in low-loss environments greatly limit practical data bandwidth, by allowing multiple out-of-phase data waveforms to arrive at the receiver, frustrating demodulation of the original data stream. These processes can drive the actual performance of a communications system well below Shannon’s limit.

In addition to bandwidth, noise and interference, a practical communications system must consider other elements, such as: link initiation; transmitter acquisition, pointing and tracking (if needed); network and/or handshaking protocols; detection and correction of errors and lost data, etc. As we now consider different approaches for high-data-rate communications in more detail, these issues will be addressed in specific context.

Acoustics

Given the ease with which sound propagates in the ocean, acoustics is by far the most common method for undersea sensing and data transmission and it comprises the benchmark against which...
all other methods of undersea data transmission must be compared. Modulation of acoustic transceivers is typically performed as a frequency shift with respect to the carrier baseline frequency, with multiple shifts possible in order to obtain high bandwidth efficiency. We will not discuss the details of acoustic communications here (see the Chitre et al. article in this issue), but will briefly touch on the challenge of utilizing acoustics for high-bandwidth communications. First, consider the attenuation of sounds waves in the ocean. The attenuation is dominated at lower frequencies by molecular absorption of dissolved compounds such as boric acid and magnesium carbonate, and at higher frequencies by viscous absorption (Apel, 1987). As such, the attenuation varies somewhat with changes in temperature, salinity and pressure, but the nominal attenuation as a function of frequency is shown in Figure 1. As is well known, the loss is low enough at frequencies up to a few tens of kHz that long-range propagation is possible. On the other hand, the relatively low loss at these frequencies enables multipath propagation, which occurs when transmitted sound waves reach the receiver via more than one route due to refraction in the volume, reflections from the bottom, surface, etc. The result of this multipath propagation can be severe ISI as phase-shifted (time-delayed) versions of the data stream interfere at the receiver. These and other restrictions have limited acoustic communications to fairly low data rates at long ranges (a few kbps over distances of a few tens of kilometers) (Kilfoyle, 2000), or higher rates over very short, acoustically homogeneous channels (150 kbps over distances of a few tens of meters) (Pelekanakis, 2003).

Radio Frequency Electromagnetic Waves

Our 21st century world is populated with ubiquitous Radio-Frequency (RF) communications, from broadcast radio and television to Bluetooth, Wi-Fi and cellular phones. A natural approach, then, is to try to extend some elements of RF communications technology to the undersea environment. Immediately a challenge emerges, since, unlike the terrestrial atmosphere, seawater is an electrical conductor, with a nominal conductivity of 4.3 siemens m$^{-1}$ (Apel, 1987) (the conductivity of natural fresh water varies widely but is generally 2 or 3 orders of magnitude smaller). While this is less than a ten-millionth the conductivity of copper, it still has a profound effect on the propagation of electro-magnetic (EM) radiation in the sea. Solving Maxwell’s equations for the propagation of EM radiation in a uniform conductor shows that the EM field decays exponentially with distance. Using the above value for the average conductivity of the ocean the attenuation coefficient (the inverse of the distance over which the electromagnetic field decays to 1/e of its initial strength) for EM waves is given by

$$\alpha = \sqrt{\pi \mu_0 \sigma \nu} \approx \frac{\sqrt{\nu}}{243} \text{m}^{-1} \quad (2)$$

where $\mu_0$ is the permeability of free space, $\sigma$ is the seawater conductivity, and $\nu$ is the frequency of the EM wave in Hertz. Using this calculation for $\alpha$, the attenuation is plotted in Figure 2 over a range of frequencies.

Note that the attenuation here is in dB-m$^{-1}$, rather than dB-km$^{-1}$ in the case of acoustics. It is obvious that long-range propagation of high-frequency RF carriers in the ocean is not realistic, hence the decades of work on very-low-frequency (nominally 3-30 kHz) transmission systems for contact with submerged submarines. From Figure 2
and equation 1, it is clear that at any significant depth these very-low-frequency systems will be SNR limited and have extremely low bit rates. On the other hand, at shorter ranges (a few meters) modern, low-noise electronics and signal-processing techniques enable practical communication at the rates of a few hundred kbps (Engineering and Technology, 2007). Because of the high loss and high propagation speeds (compared to the bit rate), this technology is relatively unaffected by ISI, with the data rate limited for a given modulation scheme by the achievable bandwidth and SNR (very nearby electrical noise sources may lower the SNR). At sub-meter ranges RF is capable of Mbps rates, making it an attractive approach for high-bandwidth, non-penetrating data interface with captive autonomous underwater vehicles (AUVs). Besides choice of operating frequency and data coding, relative antenna placement is a significant design consideration (Al-Shamma’a, 2004).

Fiber Optics

Of all methods to be discussed for high-bandwidth underwater transmission, optical fiber has by far the greatest capability for supporting high bandwidths over long distances. The use of light transmitted through glass fibers has the benefit of a very high carrier frequency ($10^{14}$ to $10^{15}$ Hz), enabling very high data rates even with simple modulation schemes. The development of glass optical fibers with extremely low scattering and absorption loss, along with suitable semiconductor lasers for operating in glass fiber’s near-infrared transmission maximum or dispersion minimum, led to the demonstration of submarine fibers capable of spanning intercontinental distances with Gbps (10^9 bits per second) bandwidths with only occasional electronic regeneration of the signal. More recently, the use of multiple data-carrying wavelengths transmitted simultaneously in the same fiber (wavelength-division multiplexing, or WDM), along with the development of broadband, low-noise optical amplifiers, means that a single fiber can now transmit Tbps (10^{12} bits per second) over multi-hundred kilometer ranges before regeneration is required. This, of course, greatly exceeds any undersea requirement short of connecting continents (Mohs, 2005). On the other hand, static undersea sensor arrays such as Neptune (Maffei, 2001) will use fiber-optic cable to provide robust, high-bandwidth connections among fixed, seafloor sensors via gigabit-Ethernet. With low-loss fiber the range of a fiber-optic connection can be determined as much by protocol-latency limitations than by loss of signal.

Other fiber-optic applications include high-bandwidth connection of tethered ROVs, where the small diameter of a fiber-optic “microcable” allows thousands of meters of tether to be coiled and handled with small (sub-meter-sized) winches and cable-handling equipment (Webster, 2003). The small diameter of the microcable also reduces viscous drag incurred on the cable due to ocean currents and vehicle motion. Ultimately, the constraints on microcable use stem from the limited tensile strength of the microcable, about 450 N, and the vulnerability of the thin cable sheath to damage from sea life and other mechanical intrusions. Compared to more conventional, heavier-walled cables containing optical fibers, these limit the speed or maneuverability of vehicles tethered using fiber-optic microcable and the long-term endurance in fixed installations.

Another challenge for undersea use of fiber optics is the making and breaking of episodic connections between transceivers, such as between a surface ship and a submerged sensor, or between an AUV and a sensor. While waterproof, wet-mateable fiber-optic connectors are available, they require close angular and transverse alignment and considerable insertion force. An approach has been demonstrated using a very small ROV tethered to a fiber-optic microcable that swims into a “basket,” with the cm-scale last distance between the fixed platform transceiver and that on the ROV bridged by a low-power free-space optical link (Fletcher, 1999). Another approach is the use of fixed free-space optical connections between the ends of respective fiber-optic connections (Lacovara, 2006).

Free-Space Optics

Free-space optical (FSO) communications combines the benefits of a high-frequency, optical carrier with the flexibility of un-tethered operation by propagating the optical carrier directly in the seawater medium. Development of terrestrial, point-to-point FSO systems accelerated during the recent telecom boom, where the flexibility and low-deployment costs proved attractive for some applications (Killinger, 2002). Unlike fiber-optic communications, FSO performance can be severely affected by ambient environmental conditions, with heavy rain and fog severely limiting range compared to clear air. In the essentially lossless environment of space, FSO has been demonstrated over multi-hundred kilometer satellite-to-satellite distances, and considerable work is now going into the development of interplanetary FSO links for high-bandwidth communication with distant planet-observing satellites (Hemmati, 2007). By contrast, in the ocean we can be faced with an even higher signal loss per unit distance than in heavy fog, so the undersea environment will play the dominant role in FSO performance. In the next section we examine the optical properties of the undersea environment.

The Undersea Optical Environment

The preceding discussion highlights the fact that free-space data communications is strongly dependent on the properties of the environment. For FSO we must consider the transmission of light, potential mechanisms for multipath propagation, and ambient background noise.

Compared to RF radiation, the very high frequencies of light (nominally 10^{12} to 10^{16} Hz) result in very different propagation properties in the ocean. At these high frequencies the effect of ionic conductivity in seawater is negligible; instead, energy is lost to the propagating transmitter light via different mechanisms in the water and its dissolved materials (Apel, 1987). The intrinsic absorption and molecular scattering of pure water create a transmission-maxi-
mum in the blue-green region of the optical spectrum, with the short wavelength side dominated by Rayleigh scattering and the long-wavelength side dominated by the absorption tail from overtone and combination bands extending from the infrared. In addition to this pure-water behavior, optical transmission in seawater strongly depends on the amount of organic and inorganic scatterers, and on absorption by chlorophyll and decaying organic matter. These materials generate widely varying scattering and absorption properties among the world’s bodies of water, but for convenience Jerlov (1976) grouped them into individual “water types” that have roughly the same optical properties. Rather than the “diffuse attenuation coefficient” or “K” used by oceanographers to model radiative transfer in the sea, we must use the “beam attenuation coefficient” (“c”), which measures the amount of light lost from a narrow-angle (collimated) beam of light and which can be measured directly with an appropriate transmissometer or calculated from K. Figure 3 shows the attenuation of a light beam for a few general Jerlov water types calculated using K data and general relationships between c and K. As with pure water, the lowest attenuation is in the blue-green, and the “Jerlov minimum” shifts to longer wavelengths as the water becomes more turbid. As in Figure 2, the attenuation in Figure 3 is plotted in dB-m\(^{-1}\) and one can see that the optical attenuation is considerably greater than for sound waves, but much lower than for any but the lowest-frequency EM waves. A body of work (Zaneveld, 1973; Smart, 2005) shows that for many open-ocean regions c decreases below the euphotic layer (typically below 60-140 m depth) to values usually less than 0.125 m\(^{-1}\), although moderate to strong current over a silty bottom can cause the attenuation to rise again near the sea floor.

A finite-sized laser beam propagating in the ocean spreads with a divergence that depends on the scale and density of both suspended particles and water refractive-index variations. To first order the effect of beam spread on the intensity of the transmitter beam on axis is accounted for in the measurement and use of the beam attenuation coefficient. The exact calculation of the radiance distributions as a function of distance is fairly complicated and strongly dependent on the environmental parameters, but a qualitative estimate of the spreading is fairly simple. For most Jerlov water types, where scattering is dominated by suspended particles, the far-field half angle of the propagating beam approaches the value

\[ \theta_f = \theta_{sa} \left[ \frac{z}{R_c} \right]^{1/2} = \theta_{sa} (zb)^{1/2} \]  

where \( \theta_{sa} \) is the mean single-scattering angle, \( z \) is the propagation distance and \( R_c \) is the mean distance between scattering events, which is the inverse of the scattering coefficient b (Yura, 1973). A plot of this function for nominal clear and coastal waters with suspended scatterers of 10-micron average size is shown in Figure 4. Note that the figure is an example of the spreading effect for a specific case; other environments will exhibit qualitatively similar but quantitatively different results.

In addition to attenuation and broadening of the transmitter beam, scattering has a temporal effect caused by the range of angles, and therefore distances, photons travel as they pass from transmitter to receiver. Optical scattering in the ocean is highly peaked in the forward direction (because of the small mean scattering angle), but depending on the receiver field of view (FOV), a finite amount of scattered light can arrive at the receiver detector out of phase with the direct or “ballistic” light. Figure 5 shows a calculation (Stotts, 1978; see also McLean, 1987) of the temporal spread due to the difference of photon arrival times at a receiver with a wide FOV in fairly clear seawater.
To some degree the temporal effects of scattered light can be mitigated by limiting the receiver FOV and using polarization to discriminate against depolarized, scattered light, but practical limits on transmitter/receiver pointing, tracking and alignment can make this challenging for a real system. Pulse spreading represents a potential limitation for very high-bandwidth FSO operation (regardless of modulation method) due to ISI, but no experiment has yet reached a data rate or range where scattering-induced ISI is a demonstrated limitation (Snow, 1992; Cochenour, 2006; Hanson, 2007). We are currently investigating these effects using a prototype ~1Gbps transceiver.

Background optical noise can be a significant limitation to undersea FSO operation. From the surface to a few hundred meters depth background light stems mainly from sunlight or moonlight propagating in the water column, although full moonlight irradiance at the sea surface is less than $3 \times 10^{-8}$ of the downwelling value. Representative calculations of the sidewelling irradiance at solar noon for clear-ocean, and moderately turbid coastal water are shown in Figures 6 and 7.

Notice that the spectrum of the background light "sharpens" as it propagates deeper into the volume as a result of the spectral dependence of the diffuse attenuation coefficient.

At much greater depths, where sunlight has been attenuated by passage through the volume, bioluminescence, as well as Cherenkov radiation from cosmic rays, will dominate sunlight (Farr, 2006); however, the effective radiance at the receiver as a result of these effects is orders of magnitude below the threshold transmitter-signal levels required for low-error, high-bandwidth communications and for these purposes the deep ocean can be considered dark.

Transceiver Components

An undersea FSO transceiver consists of an optical transmitter and an optical receiver. The transmitter requires an electronic interface to the data stream to decode the incoming data and encode it in the modulation format desired for the FSO segment. The transmitter then generates an optical carrier from a laser or other source that can be modulated and transmitted through optics that tailor the beam size, FOV and
direction for transmission through the seawater. Beam pointing may include additional electro-mechanical components internal to the transceiver or may be accomplished by steering the platform (such as an AUV). The receiver provides the reverse functions, with electro-mechanical components for pointing the receiver FOV (if needed), light-collecting and spectral-filtering optics, a detector that converts the received light into an electronic signal that is pre-amplified and processed to determine the symbol stream, and interface electronics to restore the FSO-transmitted data into a format required for the receiving platform. On the receive side, there may be additional optical detectors and electronics to determine the presence and position of the remote transmitter. While much of the success or failure of an undersea FSO system derives from the electronic and electro-mechanical functions, for brevity we will focus mainly on the optical and electro-optical components of amplitude-modulated (on-off-keyed or pulse-position-modulated) transceivers.

Transmitters

The high optical attenuation in seawater means that even with very high transmitter powers, the distances achievable using undersea FSO are fairly short (much less than a kilometer); thus, subject to other system parameters, useful transmitter powers will be in the approximate range of 10 mW to 10 W. Except for very small attenuation coefficients, there is little useful increase in communication range even for very high transmitter powers. Practical concerns, such as available space and electrical power, will limit the transmitter power to these values for most undersea applications.

Compared even to the near infrared, nature and technology provide relatively few choices for blue-green lasers. The argon-ion laser can generate multi-watt outputs at a variety of blue-green wavelengths, but these lasers are much too inefficient (less than 0.1% electrical-to-optical conversion efficiency) to be practical. For the last few decades, blue-green transmitters for undersea applications have frequently employed the frequency-doubled (green) output of near-infrared lasers, such as neodymium-doped yttrium-aluminum garnet (Nd: YAG). These lasers operate with output powers from milliwatts to tens of watts at 532 nm and with overall electrical-to-optical efficiencies of a few percent. Newer Nd: YAG lasers with semiconductor-diode (versus flashlamp) pumping are considerably smaller and more efficient. Q-switching (modulating the laser internal cavity loss to generate a short, very intense output pulse) can be used to generate pulses; but, because of laser dynamics, this method is practical only for the very lowest data rates (Hz to kHz) at the very longest ranges.

For higher data rates and greater flexibility, either a mode-locked or continuous-wave laser can be used with an external optical modulator. This mode of operation expands the laser choices somewhat to include diode-pumped neodymium or ytterbium-doped, frequency-doubled fiber lasers, which like the Nd:YAG laser are scalable to tens of watts in output power with overall efficiencies around 10%. Unlike the case for near-infrared (1550-nm) terrestrial FSO, low-power integrated-optical modulators are not available for use in the blue-green; on the other hand, equivalent devices can be used to modulate fiber or fiber-coupled infrared lasers that are subsequently frequency doubled. Note that the power consumption of the modulator and other electronics must be included with the laser and cooler power consumption when estimating transceiver power requirements.

Since external modulators add complexity, volume, power-consumption, and potential performance limitations in transceiver design, one might consider direct modulation of the laser via the pump source. Nonlinearities in the laser dynamics cause relaxation oscillations and other distortions that prevent the use of direct modulation for typical optically pumped solid-state lasers. On the other hand, the optical output of a semiconductor device, because of its much higher gain, and shorter cavity length, is better able to follow the waveform of the injection cur-
Higher data-rate operation will require the use of InGaN lasers rather than LEDs. These devices rely on technology developed for high-density optical data storage (Blu-Ray and HD-DVD) for operation at 405 nm. While this wavelength propagates reasonably well in clear water, longer-wavelength devices are currently available around 450 nm and 470 nm, albeit with output powers of a few tens of mW compared to a few hundreds of mW currently available at 405 nm. The short carrier-relaxation time in the laser active region means that these devices should have rise and fall times of less than a nanosecond. We have verified these properties and built and tested a transmitter using InGaN lasers that operates at 700 Mbps. InGaN lasers also have much narrower spectral bandwidth, typically less than 1 nm. While the receiver filter must accommodate any temperature-caused shift in the laser wavelength, the bandwidth can be considerably narrower than for LEDs with the accompanying reduction in received background light. Disadvantages of InGaN lasers compared to LEDs include their much higher price (currently about 100 times higher per unit output power), as well as increased system complexity and susceptibility to over-current damage, so lower-bandwidth (10 Mbps and below) transceivers may be more practically built using LEDs.

Receivers

The receiver must provide enough sensitivity for high SNR at the maximum practical limiting range, with the least input energy per bit; this requires the largest-possible collecting area for transmitter photons. On the other hand, etendue (conservation of brightness) limits how large the collecting area can be for a given detector active area and FOV without the detector being overfilled. In the blue green, detector choices include: semiconductor devices such as PIN-photodiodes, which are capable of fast response times but have no internal gain, and avalanche photodiodes, which add internal gains ~100; and photomultiplier tubes (PMTs), vacuum tubes encompassing a photoemissive surface (the photocathode) followed by an electron-multiplying structure. For PIN and avalanche photodiodes, risetimes generally exceed 20 ns as their width exceeds about 5 mm due to increasing shunt capacitance, while PMTs offer few-nanosecond risetimes even for photocathode diameters of a few centimeters. In addition, PMTs provide low-noise, high-bandwidth current gains of $10^6$ to $10^7$, orders of magnitude greater than provided by avalanche gain or simple electronic amplifiers. On the other hand, PMTs require high voltage for operation and are larger, more expensive, less rugged, and more easily damaged from exposure to bright light.

We have successfully built receivers using PIN and avalanche photodiodes, as well as PMTs. The choice of detector for a given application will depend on volume available for the transceiver, transmitter power, range requirements, etc. In general, short range requirements can usually be met using semiconductor photodiodes, while longer ranges will benefit from the use of PMTs. Since the noise-equivalent power of a well-designed receiver can be less than a pW, background light can limit performance at the shallowest depths and the clearest waters, depending on the receiver aperture (entrance pupil), FOV and bandpass-filter selectivity. The bandpass-filter selectivity may depend strongly on FOV and the development of moderate-to-wide FOV spectral filters with narrow bandwidth and high out-of-band rejection continues to be a challenge for background-light limited applications (Zhang, 2001; Gelbwachs, 1988).

**Acquisition, Pointing, and Tracking**

While the transmitter beam remains peaked in the forward direction, the blurring of an initially well-defined beam reduces the contrast for a tracking system, placing a practical lower limit on transmitter and receiver FOV that will depend on the specific environment and range. For deep and dark operation, maximum transmitter FOV can be limited by the noise-limited range required and the receiver FOV set by etendue limitations for a given detector size, as well as any pulse-broadening concerns discussed above. In general, operation in a high-ambient light environment will drive both FOVs much narrower. The challenge of narrow FOVs will be particularly severe when there is relative motion between the platforms, such as the case with a maneuvering AUV. For example, a 3-knot AUV passing a fixed node 50 meters distant represents a 30 mrad-s$^{-1}$ angular rate; at 10 meters it is nearly 150 mrad-s$^{-1}$. These rates put a premium on rapid acquisition and low-jitter tracking, both of which depend on obtaining high-enough SNR in their respective optical receivers. An acoustic system could be used to provide initial acquisition and coarse tracking, but fine tracking will almost certainly need to be performed using optics.

**Transceiver Performance**

Given the wide trade-space among transceiver properties (transmitter power, beamwidth, wavelength, and data rate, receiver collecting area, FOV, sensitivity, etc.) and operating conditions (range, water clarity, ambient light, etc.), a fairly wide range of transceiver performance can be obtained depending on the specific scenario. It is outside the scope of this paper to review the details of SNR calculations for an underwater transceiver, since the complete calculation must include not only attenuation and divergence of the transmitter beam and its capture by the receiver, but also details of the receiver electronics and decision circuit (Alexander, 1997). Because of this complexity it is usual to calculate the SNR at the input of a preamplifier that follows the detector and precedes the decision circuit. A simplified expression for the SNR that illustrates the physical scaling is

$$SNR = \frac{I_p}{(2\Delta f)^2 \Delta V^2 \left( e^{NF} \left( I_p + I_s + I_d \right) + NF \frac{2kT}{R_G^2} \right)^{1/2}}$$

where $\Delta f$ is the analog bandwidth of the receiver, $e$ is the charge of the electron, $NF_d$
is the excess noise factor for the detector, $N_{fa}$ is the amplifier excess noise factor, $k$ is Boltzmann's constant, $T$ is the temperature of the load resistor, $R_l$ is the load resistance, $G$ is the detector gain (if any), and $I_{ps}$, $I_{d}$, and $I_{s}$ are the average signal photocurrent, the background photocurrent and the detector dark current, respectively, all measured at the cathode for the case of a PMT. $I_{ps}$ is given by

$$I_{ps} = \frac{\lambda e P \epsilon A \eta}{hc \pi (z \tan \theta_t)^2} e^{-kz} \tag{5}$$

where $\lambda$ is the transmitter wavelength, $h$ is Plank's constant, $c$ is the speed of light, $P$ is the average transmitter output power, $\epsilon$ is the transmission of the transmitter optics, including any windows, $\epsilon_t$ is the transmission of the receiver optics, including any filters and windows, $A$ is the effective collecting area of the receiver, $\eta$ is the detector quantum efficiency, $z$ is the distance between the transmitter and receiver, $\theta_t$ is the transmission half-angle (in the water) and $k$ is the wavelength-dependent attenuation coefficient “c” that includes absorption and scattering. The square-root term in the denominator of equation 4, multiplied by the square-root of the analog bandwidth $\Delta \nu$, represents the “shot-noise” contribution that derives from the statistics of the arrival of photons at the receiver. Intuitively, it corresponds to fluctuations in the number of photons received per bit time, hence the inverse bandwidth dependence (for the same average received transmitter power a shorter bit time means fewer photons per bit). The shot-noise contribution is fundamental to the photon-detection process and can only by minimized by increasing the signal photocurrent through increased received transmitter power, increased detector quantum efficiency, longer bit-time or decreased analog bandwidth, etc., as guided by equation 5. The background photocurrent $I_b$ is

$$I_b = \frac{e}{hc} \pi A \sin^2 \theta_t \int_{\lambda_s}^{\lambda} R(\lambda) \epsilon(\lambda) \eta(\lambda) \lambda d\lambda. \tag{6}$$

where $\theta_t$ is the receiver FOV half angle, $R(\lambda)$ is the background spectral radiance, and $\epsilon(\lambda)$ and $\eta(\lambda)$ express the wavelength dependence of the receiver optics (filter) transmission and the detector quantum efficiency. The integration interval can be chosen based on the wavelength dependence of the filter transmission, quantum efficiency and background. The dark current $I_s$ results from thermal activation of charge carriers in the detector active region (semiconductor junction or PMT photocathode) and will vary with detector active area, temperature and gain (if any) (Keyes, 1980).

It is clear from equation 6 that in the presence of significant background radiance, SNR can be maximized by limiting the receiver FOV, consistent with pointing and tracking limitations, as well as the receiver spectral pass-bandwidth, consistent with the bandwidth of the transmitter and any accompanying spectral drifts. An example can be seen in Figure 9, where we have calculated SNR versus distance for the same system under shot-noise limited and background limited conditions. The model system uses a 1W transmitter with +/- 3 degree transmitter beamwidth and a 10 cm diameter receiver with similar FOV and a 25 nm filter bandwidth. The water beam attenuation coefficient was 0.12 m$^{-1}$ and background spectral radiance was 1.3 x 10$^7$ W cm$^{-2}$ str$^{-1}$ nm$^{-1}$.

At the shortest ranges the SNR is limited by the dynamic range of the receiver, although the SNR is already so high that the dynamic-range limit is not a problem. Since a perfect receiver requires an SNR of about 20 to achieve a bit-error rate of 10$^{-9}$ (Alexander, 1997), it is clear that for this case the background-limited range is almost 20 m shorter compared to the shot-noise limit.

The presence of the receiver analog bandwidth in the denominator of equation 4 suggests that, even in the absence of scattering-induced pulse broadening, the transceiver performance at a given range is more challenging at higher data rates compared to lower rates. A typical calculation shows approximately a factor of 2 shorter SNR-limited range for a 1Gbps transceiver compared to a transceiver with identical parameters operating at 100kbps. Needless to say, operation approaching Gbps data rates is challenged by all aspects of transmitter and receiver temporal performance, including laser/modulator and detector rise and fall times, and receiver decision-circuit jitter.

There is relatively little at-sea data in the literature about high-bandwidth undersea FSO, and virtually nothing about the transmission of real data vice simulated data waveforms. Measurements in clear Caribbean water (Longacre, 1990; Snow, 1993) using externally modulated argon-ion and frequency-doubled Nd:YAG lasers demonstrated transmission of high-bandwidth (up to 50 Mbps) simulated data waveforms over ranges up to 28 m and 11 equivalent attenuation lengths. More recent published work (Farr, 2006) reports transmission of 5 MHz simulated data waveforms over a 10 meter ocean path using a broad-angle LED-based transmitter. The waveforms
recorded appear to show a fairly slow rise and fall time associated with the large-area LEDs used in the transmitter.

In unpublished work in 2003, we demonstrated 10Mbps, full-duplex (bi-directional) operation over an 8 meter range in a harbor environment \((c \sim 0.4 \text{ m}^{-1})\) using a 1-W, LED-based transceiver with a +/- 5 degree transmitter angle. Actual data files as large as 50 Mbytes were transmitted, with a sustained one-way data transfer rate of 4.6 Mbps (which included the TCP/IP and Ethernet overhead). This represented the first known use of TCP/IP at normal Ethernet rates in undersea communications. For this test the transmitter and receiver were each packaged in pressure vessels measuring 10 cm diameter by approximately 30 cm long. More recent demonstrations (Lacovara, 2006) have shown 10 Mbps simplex communication between 2 submerged buoys over 42 meter range in an open-ocean environment \((c \sim 0.08 \text{ m}^{-1})\). The transmitter used multiple low-power \((-80 \text{ mW})\) LED arrays, each with a +/-5 degree transmitter angle, spanning an azimuthal field of regard of 120 degrees, allowing non-mechanical scanning of the transmitter beam. The large-aperture \((-150 \text{ cm}^{-2})\), iso-azimuthal, PMT-based receiver was considerably more sensitive than the receiver used in the 2003 demonstration. Autonomous acquisition, pointing and tracking of the transmitter, shown in Figure 10, was demonstrated in which the transmitter searched for the receiver, and then optimized transmitter-receiver alignment. Handshaking was performed at low bandwidth using a simulated acoustic link \((2.4 \text{ kbps serial communication over optical fiber})\), and overall power consumption at each end was less than 1.5 W. Even with the relatively wide transmitter beam and receiver field of view, wave-induced motion of the shallow-submerged test buoys sometimes caused data dropouts, as the motion exceeded the bandwidth of the pointing/tracking subsystem.

Channel Fading Effects

The short range for FSO and the use of an incoherent receiver means that multipath and other effects that cause interference among multiple received beams in terrestrial RF or undersea acoustic systems do not cause rapid or sustained fades. On the other hand, because of the directionality of the optical transmitter beam and the receiver FOV, tracking errors and the passage of biologics through the propagation path can lead to gross fades lasting over many bits (Lacovara, 2006). This places a premium on error detection and correction, with our current work using the packet-loss detection and retransmission features of TCP/IP. As undersea FSO systems are further optimized it is not clear that that TCP/IP will remain the optimum approach for dealing with the fade statistics of the undersea environment; however, more field measurements are needed to establish fade statistics over a variety of environments. A protocol with optimized error sensing and correction that can control packet size depending on fade statistics would provide higher overall throughput than a static send and retransmit model.

We are also currently investigating the use of forward error correction codes to improve undersea FSO performance.

Conclusion

The properties of the ocean environment create different choices for high-bandwidth data communications compared to terrestrial applications, each with their own capabilities in range, data rate and operability. Most notably, ubiquitous RF communications over long ranges is not possible, with limited-bandwidth acoustics used in its place. Optical fiber provides a capability for high-bandwidth communication over long ranges, but with limited operational flexibility. Free-space optics provides a capability for high-bandwidth communications over short to moderate ranges (10 to more than 100 meters) with considerable operational flexibility, limited primarily by turbidity and ambient background light. Figure 11 provides a semi-quantitative view of the operating regimes for different, practical, underwater communications technologies.

Future developments will likely expand the edges of these regions of applicability somewhat, with the use of improved signal processing in acoustic, RF and FSO trans-

![Figure 10](image)

*Figure 10:* Underwater transceiver with autonomous pointing and tracking.

![Figure 11](image)

*Figure 11:* Applicability of underwater communications techniques, including fiber optics (FO), free-space optics (FSO), radio-frequency electromagnetic radiations (RF) and acoustics.
ceivers, as well as better optical filters and the exploitation of coherent sources and receivers in FSO. But the general forms are defined by the physics of the ocean environment; RF and acoustics are unlikely to reach Gbps speeds over any useful range, and FSO is unlikely to reach kilometer ranges with any useful data rate.

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Underwater Acoustic Communications and Networking: Recent Advances and Future Challenges

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Abstract
The past 30 years have seen a growing interest in underwater acoustic communications because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry and defense. Continued research over the years has resulted in improved performance and robustness as compared to the initial communication systems. In this paper, we aim to provide an overview of the key developments in point-to-point communication techniques as well as underwater networking protocols since the beginning of this decade. We also provide an insight into some of the open problems and challenges facing researchers in this field in the near future.

I. Introduction
The past three decades have seen a growing interest in underwater acoustic communications because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry and defense. Continued research over the years has resulted in improved performance and robustness as compared to the initial communication systems. A series of review papers provides an excellent history of the development of the field until the end of the last decade (Baggeroer, 1984; Catipovic, 1990; Stojanovic, 1996; Kilfoyle and Baggeroer, 2000). In this paper, we aim to provide an overview of the key developments in the field since the beginning of this decade. We also hope to provide an insight into some of the open problems and challenges facing researchers in this field in the near future.

This paper is divided into two main sections—one on underwater communications and another on underwater networking. Section II concentrates on research on point-to-point communication issues such as channel modeling, modulation, coding and equalization. Key advances in these areas have enabled us to establish reliable high-speed underwater communication links. Using these links as a foundation, underwater networks can be established. Section III focuses on research on algorithms and protocols for such networks. In this paper, we do not attempt to provide an exhaustive survey of all research in the field, but instead concentrate on ideas and developments that are likely to be the keystone of future underwater communication networks.

II. Underwater Communications
High-speed communication in the underwater acoustic channel has been challenging because of limited bandwidth, extended multipath, refractive properties of the medium, severe fading, rapid time variation and large Doppler shifts. In the initial years, rapid progress was made in deep water communication, but the shallow water channel was considered difficult. In the past decade, significant advances have been made in shallow water communication.

A. Channel Equalization
The shallow water acoustic communication channel exhibits a long delay spread because of numerous multipath arrivals resulting from surface and bottom interactions. Movement of transducers, ocean surface, and internal waves lead to rapid time variation and, consequently, a high Doppler spread in the channel. Coherent modulation schemes such as phase shift keying (PSK) along with adaptive decision feedback equalizers (DFE) and spatial diversity combining have been shown to be an effective way of communication in such channels (Stojanovic et al., 1993). However, the long delay spread (often hundreds of symbols) and rapid time variation of the channel often makes this approach computationally too complex for real-time implementations.

FIGURE 1
Basic structure of a turbo DFE
Although the underwater channel has a long impulse response, the multipath arrivals are often discrete. This opens up the possibility of using a **sparse equalizer** with tap placement based on the actual channel response. This can potentially dramatically reduce the number of required taps and hence lead to a lower complexity, faster channel tracking and an enhanced performance. In Stojanovic et al. (1999), the authors proposed an algorithm to track the channel explicitly and determine the tap placement for the DFE based on this channel estimate. The equalizer and the channel estimator are separately updated throughout the packet. The channel estimator can update either the whole estimate or a set of selected channel coefficients at one time, depending on computational and channel considerations. The algorithm uses spatial diversity by multi-channel combining before equalization.

Another algorithm for robust automated DFE tap placement in sparse channels is presented in Lopez and Singer (2001). The algorithm alternates between tap placement for the feedforward and feedback filters in the DFE. A stopping criterion is defined in terms of the estimated mean square error (MSE) rather than a fixed number of taps. As increased model order leads to increased estimation noise, a model order penalty is imposed in the optimization. When used with multiple receivers for exploiting spatial diversity, the algorithm uses the same number of taps in each receiver. An empirically tuned version of the algorithm was successfully demonstrated in an experiment using a 4-hydrophone receiver array. The algorithm placed an average of 10 feedforward taps and 25 feedback taps; this is a significantly smaller number than the number of taps required in a conventional DFE for shallow water communication.

In Weichang and Preisig (2007), the authors develop a sparse channel estimation technique based on the delay-Doppler-spread function representation of the channel. As this representation is an approximation of a rapidly time-varying channel, it captures the channel structure and its dynamics simultaneously. In the paper, the authors compare the performance of recursive least square (RLS) estimation, sparse channel impulse response estimation and the proposed method.

Sparse partial response equalizers (sPRE) exploit the sparse nature of the underwater channel to shorten the impulse response of the channel. When combined with a low-complexity belief propagation (BP) detector, the residual inter-symbol interference (ISI) from the sPRE can be used for multipath diversity. Data collected during an experiment in Kauai was used to demonstrate a communication scheme based on a sPRE with a BP detector (Roy et al., 2006).

Conventional equalization techniques require a training period during which the equalizer converges. However, blind equalization techniques use only the statistical properties of the signal and do not require an explicit training sequence. They typically converge slower than training based methods and therefore their use has been limited to long or continuous data streams. In Labat et al. (2003), the authors show that a blind DFE, when combined with an appropriate iterative procedure, provides good performance on short data bursts.

DFE structures suffer from error propagation due to the feedback of erroneous decisions in the loop. Hence powerful forward error correction (FEC) codes are needed to ensure low bit error rate (BER) communication. Turbo codes are a class of powerful codes that utilize iterative information exchange between two decoders to correct errors. Inspired by this idea, researchers have developed turbo equalization techniques where iterative interactions between the equalizer and a decoder result in joint estimation, equalization and decoding (Sozer et al., 2001). The data to be transmitted is encoded, interleaved and transmitted. The receiver treats the combination of the encoder, interleaver and channel as a serial concatenated code. A maximum a posteriori probability (MAP) equalizer is used along with a decoder as the two components of the turbo decoder. The turbo decoder’s output is used in the feedback loop of the DFE to reduce errors. Although MAP equalization is computationally intensive, per-survivor processing (PSP) helps reduce the number of trellis states used in channel equalization. Experimental testing at 1 km range in very shallow waters with a vertical 8-hydrophone receiver array showed that the algorithm performed significantly better than DFE. The algorithm however had some difficulty with sparse channels; future work combining sparse equalization techniques with turbo equalization may help address this difficulty.

The computational complexity of MAP equalization increases exponentially with channel length. Even with PSP, this complexity can be too high for practical implementation. In Blackmon et al. (2002), the authors propose a soft-input DFE structure to replace the MAP algorithm in the turbo equalizer. The data from multiple receivers can be combined to gain spatial diversity. A joint DFE is optimal for such multichannel combining, but is often too complex. The authors considered alternatives with separate DFE for each receiver and found that a set of DFE with a log-likelihood ratio (LLR) output yields good performance. To avoid error propagation problems with DFE, some researchers have successfully used a linear equalizer instead of the DFE in the turbo equalizer structure (Oberg et al., 2006).

Many conventional receivers have difficulty in shallow water channels due to the large Doppler spread induced by rapid channel variation. In a two-part paper, Eggen et al. (2000, 2001) use a channel tracker with a linear decoder to combat large Doppler spread. The tracker uses a modified RLS algorithm and frequency domain filters known as Doppler lines to estimate channel coefficients. The decoder makes use of the channel tracker coefficients in order to perform minimum mean square error (MMSE) decoding.

The use of direct sequence code division multiple access (DS-CDMA) has some benefits such as multi-user access and low probability of detection (LPD). In Stojanovic and Freitag (2006), the authors explored the use of a DFE to combat ISI in DS-CDMA.
systems. A symbol decisions feedback (SDF) DFE uses the symbol decisions after de-spreading on the feedback path. As the symbols in a DS-CDMA system are relatively long, a DFE using SDF is not able to track rapidly varying channels. For such channels, a chip hypothesis feedback (CHF) can help track the channel at the chip rate rather than the symbol rate. For M-ary signal constellations, the complexity of the CHF is at least M times higher than the SFD as M different hypotheses have to be tracked. However, the advantage of a CHF was clearly demonstrated at high spreading factors during a shallow water experiment in Italy. The authors expect that the performance difference would be more apparent in a mobile environment as one would expect the channel to change more rapidly.

If the statistics of the errors in channel estimation are known, DFE or linear equalizer performance can be estimated (Preisig, 2005). The error estimate can be split into the minimum achievable error and the excess error. The excess error component is strongly affected by rough sea conditions. Through a scattering function analysis, it was also shown that the rate of change of propagation path length for the surface bounced arrival is a primary contributor to the error. This suggests that the ability to effectively track the surface bounced arrival may provide an improved equalizer performance.

B. Phase Conjugation

Due to the symmetry of the linear wave equation, if the sound transmitted from one location is received at other locations, reversed and retransmitted, it focuses back at the original source location. This is the principle behind time reversal mirrors (TRM) or its frequency domain equivalent—active phase conjugation. The temporal compression effect of TRM reduces the delay spread of the channel while the spatial focusing effect improves signal-to-noise ratio (SNR) and reduces fading. An experiment conducted in 1999 demonstrated such a TRM communication system in shallow waters (Edelmann et al., 2002). The larger the number of transmitters, the better the TRM focus. Thus, TRM based communication systems effectively utilize spatial diversity at the transmitter rather than the receiver. In fact, the spatial focusing precludes the use of multiple receivers for spatial diversity, but opens up the possibility of spatial multiplexing and low probability of intercept (LPI) communications. Although TRM helps reduce delay spread of the channel, it does not eliminate ISI completely. By implementing a DFE at a TRM receiver, the communication performance can be further improved (Edelmann et al., 2005). In a TRM-based communication system, a probe signal has to be first transmitted from the receiver to the transmitter. The transmitter then uses a time-reversed version of this signal to convey information. As the channel changes over time, the probe signal has to be retransmitted to sample the channel but decoherence times up to several tens of minutes were observed at frequencies of 3.5 kHz during experiments.

Since TRM does not eliminate ISI completely, it is ISI-limited at high signal strengths. In Stojanovic (2005), the author presents a detailed analysis of several solutions to deal with the ISI in a TRM system if the channel response is known. By introducing optimal filters at the transmitter and receiver, ISI can be completely eliminated. However, this is prohibitively complex and requires channel knowledge at both ends. An excellent trade-off between complexity and performance can be found by limiting filter adjustment to the array-side of the communication system. The paper presents strong analytical results and upper bounds on system performance, but the ideas have yet to be experimentally tested. Imperfect channel estimation resulting from noise may limit the performance of the algorithms described in the paper.

A closely related idea—passive phase conjugation (PPC)—uses the cross-correlation of two consecutive signals transmitted from the transmitter to the receiver to convey information. In Hursky et al. (2001), the authors describe one such system which uses pulse position modulation (PPM) with PPC for communication. The spacing between a linear frequency modulated (LFM) signal and its mirror image is used to encode the data. PPC requires that the spacing between signals is more than the delay spread of the channel. Although this results in relatively low symbol rates, the use of PPM allows many bits to be packed in each symbol. The use of LFM signals also enables low-complexity Doppler correction. The authors present results from a successful PPC communication experiment at ranges of up to 10 km using a single transmitter and receiver. Another communication system using PPC is described in Rouseff et al. (2001). This system uses a probe signal followed by several data-carrying PSK symbols. The system was successfully demonstrated at ranges up to 5 km using a single transmitter and a 14-hydrophone receiver-array. More recently, Gomes et al. (2006) presents results from an experiment off the west coast of Portugal where the authors compare the performance of several methods including equalization, PPC and combinations of both methods. In Song et al. (2006), the authors study the benefits of spatial diversity in PPC communications. They also show that adaptive equalization can be effectively combined with PPC to estimate and eliminate residual ISI. In the experimental results presented, gains of up to 5 dB were obtained through equalization in the case of a fixed transmitter/receiver. When the transmitter was moving, the channel varied more rapidly and the gain from equalization increased to 13 dB. In another experiment, it was found that continuous channel updates and Doppler tracking are required before time reversal in order to achieve acceptable performance in the presence of ocean variability (Song et al., 2008). This ocean variability was shown to be primarily a result of interaction of the acoustic field with the dynamic ocean surface.

The computational simplicity of phase conjugation-based communication systems makes them extremely attractive. However, the use of such systems is constrained by the quasi-static channel requirement that is fundamental to the idea. The quasi-static constraint may be somewhat relaxed in cases where an adaptive equalizer is used in conjunction with a phase conjugation scheme. Rapidly changing channels result.
ing from moving communication nodes may limit the use of phase conjugation in mobile applications.

C. Channel Modeling

A good understanding of the communications channel is important in the design and simulation of a communication system. A good review of channel modeling work prior to the year 2000 has been presented in Bjerrum-Niese and Lutzen (2000).

At high frequencies appropriate for shallow water communications, ray theory provides the framework for determining the coarse multipath structure of the channel. However, such a model does not encapsulate the time-varying nature of the channel. By augmenting this model with a time-varying surface model, a shallow water channel can be simulated (Bjerrum-Niese et al., 1996). As acknowledged by the authors, the primary limitation of such a channel model is the availability of an accurate and calibrated surface time-variation model. Moreover the time-variation in the channel is not limited to surface reflected arrivals.

If the received signal is a sum of a large number of multipath arrivals, each of which are modeled as a complex Gaussian stochastic processes, the resulting model is the well-known Rayleigh fading channel. Some researchers model the shallow water channel as a Rayleigh fading channel but others challenge that assumption, especially when discrete arrivals can clearly be seen in the channel response. There has been no consensus among researchers on the model applicable in shallow waters. Recently, a ray theory-based multipath model, where the individual multipath arrivals are modeled as Rayleigh stochastic processes, has been shown to describe the medium range very shallow water channel accurately (Chitre, 2007). The physics resulting in the time-variation of each arrival is not fully understood, but it may result from micro-multipath or internal waves. Theoretical and experimental studies of acoustic propagation through anisotropic shallow water environments in the presence of internal waves (Badiey et al., 2007) may form the basis of further physics-based channel modeling research in the future.

Channel modeling in the surf zone is especially difficult because of the large impact of the rapidly time-varying surface on the acoustics. The scattering of acoustic signals off shoaling surface gravity waves results in a time-varying channel impulse response and occasional caustics characterized by intense, rapidly fluctuating arrivals (Preisig and Deane, 2004). Through a combination of experimental measurements and propagation modeling, the authors showed that the high intensity arrivals were often due to focusing by surface gravity waves and caustic formation. Hence most channel impulse response algorithms have difficulty coping with surf zones. Further work in this area is needed to help improve performance of communication systems in surf zones.

An additive Gaussian noise assumption is used commonly in the development of most signal processing and communication techniques. Although this assumption is valid in many environments, some underwater channels exhibit highly impulsive noise. Signal detection (Chitre et al., 2006) and Viterbi decoding (Chitre et al., 2007) techniques developed for impulsive noise models such as the symmetric $\alpha$-stable noise have been shown to perform better in warm shallow waters dominated by snapping shrimp noise.

D. Multi-carrier Modulation

Multi-carrier modulation is an attractive alternative to a broadband single-carrier communication system. By dividing the available bandwidth into a number of narrower bands, orthogonal frequency division multiplexing (OFDM) systems can perform equalization in frequency domain, thus eliminating the need for complex time-domain equalizers. OFDM modulation and de-modulation can easily be implemented using fast Fourier transforms (FFT). In shallow waters in the Mediterranean sea, an experiment was conducted to compare the performance of OFDM with direct sequence spread spectrum (DSSS), both using differential PSK modulation (Frassati et al., 2005). The authors reported good OFDM performance (BER $< 2 \times 10^{-3}$) at ranges up to 6 km. At the same ranges, the DSSS performance was found to be significantly poorer.

OFDM equalization is simplified greatly if a guard interval longer than the delay spread is allowed between consecutive OFDM symbols. This guard period is usually implemented as a cyclic prefix to maintain orthogonality of the sub-carriers. However, when the delay spread is long, the prefix length can become undesirably long and affect the efficiency of transmission significantly. In Morozov and Preisig (2006), the authors explore the use of maximum likelihood sequence detection (MLSD) on individual sub-carriers when the symbol period is smaller than the delay spread. An algorithm to perform joint channel estimation and MLSD using a low complexity PSP was proposed and experimentally demonstrated in the paper. Channel shortening techniques such as sPRE may also be used in future OFDM systems to reduce the prefix length and improve bandwidth efficiency.

To conserve energy, the cyclic prefix can be replaced by a zero prefix (ZP). Optimal de-modulation of ZP-OFDM requires a computationally intensive matrix inversion operation. In Li et al. (2006), the authors use pilot-based channel estimation with a low complexity overlap-add de-modulation to implement an OFDM system. By using maximum-ratio combining over the data from multiple receivers, the authors utilize the spatial diversity available to further increase the robustness of the system.

When using coded OFDM, consecutive symbols are often striped across sub-carriers to reduce the error correlation resulting from fading. However, impulse noise present in some environments can affect multiple sub-carriers simultaneously and hence generate correlated errors. The use of a channel interleaver with coded OFDM allows symbols to be distributed over a frequency-time plane, thus allowing the code to make maximal use of frequency and time diversity offered by OFDM (Chitre et al., 2005). The knowledge of error correlation resulting from impulsive noise could
be used in future decoding algorithms to improve decoding performance.

The narrowband sub-carriers in an OFDM system make the system very sensitive to Doppler shift. As the carrier frequency in underwater acoustic systems is low as compared to typical Doppler shift experienced as a result of movement, the communication systems have to cope with wideband Doppler. In the case of OFDM, this results in non-uniform Doppler shift across sub-carriers. As a maximum likelihood solution for Doppler compensation is computationally far too expensive to be practical, a simpler solution is needed. In Stojanovic (2006), the author presents an algorithm for non-uniform Doppler compensation in OFDM systems based on a single adaptively estimated parameter. The algorithm was tested on experimental data from a ZP-OFDM system with multiple receivers to correct a Doppler shift of about 7 Hz (0.02%). By adaptive MMSE combining of data from a minimum of 3 receivers, the author was able to successfully demonstrate the proposed algorithm. In Sharif et al. (2000), the authors present a preprocessor that estimates Doppler shift by measuring the time between two known signals and removes the Doppler shift using a computationally efficient linear interpolator. Being a preprocessor, the technique can be used with any type of modulation and equalization. The technique was tested in the North Sea using a prototype communication system and demonstrated to work well at speeds of 2.6 m/s and accelerations of 0.9 m/s². The authors expect the technique to work at higher speeds and accelerations.

E. Spatial Modulation

Information theoretic studies have shown that the capacity of a channel increases linearly with the minimum of the number of transmit and receive antennas. This increase in capacity translates to a corresponding increase in achievable data rate through the use of multiple input multiple output (MIMO) processing techniques and space-time coding. The computational complexity of optimal detection techniques such as MAP and maximum likelihood sequence estimation (MLSE) grows exponentially with the number of transmit antennas. In Roy et al. (2004), the authors explore the use of space-time trellis codes (STTC) and layered space-time codes (LSTC) with various sub-optimal decoding techniques. For STTC, the proposed receiver consists of explicit phase tracking and timing recovery loops which are jointly optimized with a MIMO DFE. The equalization and decoding is jointly performed using the powerful trellis structure of STTC. This limits the error propagation that is inherent in DFE. For LSTC, the equalization is performed iteratively (turbo equalization). The authors demonstrated the benefits of MIMO over single-input single-output (SISO) underwater communication systems through a successful experiment in the Mediterranean Sea using 2 transmit projectors for STTC and 4 transmit projectors for LSTC.

In another set of experiments with 6 transmit projectors, a spatial modulation scheme with an outer block code, interleaver and an inner trellis-coded modulation (TCM) was demonstrated (Kilfoyle et al., 2005). A joint DFE and phase-locked loop (PLL) was used for each data stream at the receiver. Low latency soft decisions were released to support the DFE. The experiments demonstrated that with the proposed spatial modulation scheme offered increased bandwidth and power efficiency as compared to signals constrained to temporal modulation. For ISI-limited channels, spatial modulation offers a unique and effective means to increase data rates when simply increasing transmission power does not. Recently, results from a MIMO-OFDM experimental data obtained during the AUV Fest in Panama City, Florida in 2007 have been presented (Li et al., 2007). Nearly error-free performance was achieved with a 2-transmitter 4-receiver setup at ranges up to 1.5 km using a ½-rate low-density parity check (LDPC) codes at a coded data rate of 12 kbps.

In Nordenvaad and Oberg (2006), the authors consider the channel as a 1-rate code and use turbo decoding framework to decode the MIMO signals. A widely linear model of the Alamouti code was used for joint equalization and decoding, with a linear equalizer chosen for its low complexity. The Alamouti code uses two transmit antennas and multiple receive antennas to achieve spatial diversity gains without a direct increase in data throughput. Although this algorithm was successfully tested in a trial in the Baltic Sea, the gains resulting from MIMO processing were questionable in the trial as a single dominant path with very slow fading was observed in most of the data.

To achieve the promise of increased throughput and spatial diversity in practical MIMO systems, the transducers in transmit and receive arrays must be placed with spacing larger than the spatial coherence scale at the frequency of interest. In Yang (2007), the author theoretically and experimentally studies the gain from spatial diversity given parameters such as the number of transducers and the spacing between them. Further research is needed to be conducted to better understand issues surrounding transducer locations, especially as their placement may be constrained in mobile systems such as autonomous underwater vehicles (AUV).

F. Summary

Robust incoherent techniques have been well studied in the past. Although they still play a significant role in low data rate communication applications that demand robust and low-complexity solutions, most of the new advances in the past decade have been in the area of coherent communications. Advances in DFE algorithms have resulted in robust algorithms that can be used to equalize underwater communication channels. Channel characteristics (such as sparseness) or channel models may be used to reduce noise in channel estimates. When combined with error correction coding and iterative (turbo) algorithms, DFE algorithms can benefit from the higher reliability of the feedback loop. In OFDM systems, equalization or partial equalization may be used to reduce the effective channel delay spread and im-
prove performance. OFDM systems suffer from high sensitivity to Doppler shift. As new algorithms for wideband Doppler compensation for OFDM systems develop, we expect that success of OFDM in wireless networks could be replicated in underwater networks. Although phase conjugation provides an innovative low complexity solution to equalization problems, constraints on channel variation may limit the use of algorithms based on phase conjugation.

The use of multiple receivers for spatial diversity gains is becoming common in underwater communication systems. With MIMO processing techniques, we expect that more communication systems will include multiple transmitters as well and derive benefits from the increased theoretical channel capacity. As researchers master the techniques required for point-to-point communication links in the next 5-10 years, we expect that the research emphasis on underwater networking will increase.

III. Underwater Networking

A recent survey on research in underwater protocol development presents a good overview of the subject (Akyildiz et al., 2006). The state of the art in current underwater networking technology is oriented towards a setup as shown in Figure 2. The network consists of a set of underwater local area networks (UW-LAN, also known as clusters or cells), connected to each other via gateway nodes. A gateway node provides administration, security and routing between multiple UW-LANs and other wireless or wired networks.

In a cluster, the exact choice of physical layer protocol may depend on factors such as specific channel conditions, security reasons, processing capability, data rate requirements and energy efficiency. In view of the limited bandwidth underwater, a high level of cross layer optimizations or transcending of traditional layer boundaries may be needed to provide high data rates. We now review some of the recent work and future challenges. The key focus of our review will be on the data link layer (DLL) and network topology.

G. Datalink Layer

Key differences between terrestrial radio wireless networking and underwater acoustic networking are the large propagation delay of sound, extremely low point-to-point data rates and high raw BER. Thus it is often proposed that media access control (MAC) protocols for underwater networks be developed ground up and not directly adopt existing terrestrial protocols (Jiejun et al., 2005; Heidemann et al., 2006). MAC protocols can be typically be classified into contention-based (non-orthogonal) and contention-free (scheduled, orthogonal or deterministic) protocols. Some of the simpler contention-based protocols include half duplex ALOHA, ALOHA with acknowledgements (ACK) and retries, medium access collision avoidance (MACA)-based half duplex protocol using RTS/CTS handshaking (Sozer et al., 2000). The traditional contention-free MAC protocols include time division multiple access (TDMA), frequency division multiple access (FDMA), CDMA and space division multiple access (SDMA).

In contention-based protocols the key protocol family is based on MACA originally proposed for terrestrial networks (Karn, 1990). Such protocols use RTS, CTS, DATA, ACK sequences, as illustrated in Figure 3. These protocols were shown to be effective for underwater use compared with scheduled protocols early on in the Seaweb project (Rice et al., 2000). The authors observe that in the physical and MAC layers, adaptive modulation and power control are the keys to maximizing both channel capacity and channel efficiency. Handshaking permits addressing, ranging, channel estimation, adaptive modulation, and power control. RTS/CTS exchanges channel measurement so that the DATA frame can be sent using optimal parameters. In Sozer et al. (2000), the authors review MAC protocols such as ALOHA and MACA and present results on throughput and delay performance. MACA-based protocols are found to be highly suited in many scenarios underwater where scalability is important and time-synchronization is not available (Kebkal et al., 2005; Heidemann et al., 2006; Molins and Stojanovic, 2006; Xie and Cui, 2006). However in some sensor networks, RTS/CTS mechanisms could perform poorly due to latency issues and inefficiency for small payload packets (Turgay and Erdal, 2006).

Protocol extensions and enhancements of MACA have been investigated to suit them better to underwater channel. For example, a WAIT command extension has been investigated in Sozer et al. (2000) and
Doukkali et al. (2006). A WAIT command is sent back by the receiver if it is currently busy and intends to send a CTS later on. In Rice et al. (2000), instead of using ACK packets, selective ARQ is initiated by the recipient should it not receive packets in a specified time. Guo et al. (2006) proposed to counter the wasted bandwidth of using RTS, CTS, DATA, ACK resulting from the high propagation delay, through a new protocol called PCAP. It requires accurate time synchronization. They propose to pipeline other actions while waiting for CTS from receiver. Packet trains can greatly improve the performance of protocols such as MACA (Garcia-Luna-Aceves and Fullmer, 1998; Molins and Stojanovic, 2006; Shahabudeen et al., 2007). By dividing the DATA segment into packets, RTS/CTS collisions only affects a small number of packets and do not result in complete retransmission of the DATA, as shown in Figure 3. Floor acquisition multiple access (FAMA), a family of protocols of which MACA is a variant, was originally proposed for terrestrial networks. Control of the channel is assigned to at most one station in the network at any given time and uses carrier sensing (absent in MACA) and puts restrictions on RTS/CTS time durations.

FIGURE 3
Packet trains in MACA protocol

Although the effectiveness of carrier sensing is limited by long propagation delays in underwater networks, it can nevertheless provide some collision avoidance against nearby nodes. Time-slotted schemes can also be implemented to enhance performance (Fullmer and Garcia-Luna-Aceves, 1995). FAMA in its original form is quite unsuited to underwater networks, but with enhancements such as slotted, it can be used underwater effectively (Molins and Stojanovic, 2006). Distance aware-collision avoidance protocol (DACAP) is based on MACA (Peleato and Stojanovic, 2006). It adds a warning message if a RTS is overheard while waiting for a reply to its own RTS. While waiting for reply, if another CTS or a warning is heard, a random back off is used. Optimal power control for DACAP is studied in Dolc and Stojanovic (2007). The optimal power is found to be that which minimizes connectivity. A RTS/CTS-based handshaking scheme can be expected to perform well in dynamic mobile AUV networks, too, since during the delay of at most a few seconds between RTS and CTS, typical AUV velocities and distances imply little change in geometry and consequently appropriate power levels. However, DATA packet trains long enough for the AUVs to travel significant distances may render the power setting inappropriate.

Among contention-free protocols, there seems to be general consensus that FDMA is inefficient for underwater applications (Rice et al., 2000). TDMA is better than FDMA but requires good time synchronization in nodes. In some publications, CDMA is favored over TDMA and FDMA (Proakis et al., 2001), and over MACA based protocols (Jun-Hong et al., 2006; Chan and Motani, 2007). PCLS, a loosely synchronized form of TDMA with non-overlapping timeslots, has been proposed for low capacity sensor networks (Turgay and Erdal, 2006).

Some analytical results are presented for a variant called FAMA-CF (Collision Free) that applies only to a centralized topology in (Kebkal et al., 2005). Mathematical analysis for slotted-FAMA is presented in Molins and Stojanovic (2006). Xie and Cui (2006) compare random access protocols such as ALOHA with collision avoidance handshaking scheme such as MACA and present some mathematical analysis. Gibson et al. (2007) present one of the first analyses of contention-based protocols in a multi-hop string network.

Contention-based and contention-free protocols are both being used in many underwater networks today. The choice is driven by the exact constraints and requirements such as time synchronization, delay-tolerance, time criticality and reliability in messaging, ad-hoc network establishment, number of expected nodes, nature of traffic (continuous or bursty), sleep-wake schedules in sensors and mobility. In the future, more rigorous analytical results and accurate simulations are needed to further verify the many ideas put forward for underwater DLL and MAC.

DLL/MAC aspects such as energy conservation have also been looked into recently. PCLS as discussed earlier (Turgay and Erdal, 2006) incorporates a power control and sleep-wake scheme. Another example on energy minimization (Rodoplu and Min Kyoung, 2005) shows an ultra-low duty cycle MAC protocol focusing on energy conservation and not data rate.
The paper makes some over-simplifying assumptions that the propagation delay is constant and there is no clock drift. Nodes transmit sporadically and each transmission includes a preamble that specifies the next intended transmission. Listeners decide their wakeup times based on this preamble and sleep till packets are expected from transmitters. The objective is to minimize the fraction of energy wasted in collisions. For a transmit duty cycle of 0.4%, a 3% loss due to collisions is obtained. Assuming no loss due to bit errors, a physical layer data rate of 5 kbps only yields an effective data rate per node of $5 \times 0.4\% \times 97\% = 19.4$ bps. A sensor wakeup scheme—adaptive wakeup schedule function (AWSF), suitable for underwater sensor systems uses a time cyclic wakeup schedule for each node such that at any one time only a few nodes are active. Time asynchronous situations also work with AWSF except for a loss and change in neighborhood connectivity (Wong et al., 2006). In general, sleep and wakeup schemes focus on energy savings at the cost of bandwidth efficiency due to the usage of wakeup preamble signals and time delays required to switch modes. The improvements in energy efficiency are therefore at the expense of data rate. Such schemes are meant for long term underwater deployments that can cope with extremely low data rates and very long latencies.

One essential service choice offered by DLL to higher layers is reliability. In protocols such as MACA with packet trains, this involves ACKs and negative ACKs (NACK) that indicate received or lost data and retries for lost data. Packet size or train/group size adaptation is required to optimize performance. Analytical results for optimal packet size as a function of the acoustic link parameters (transmission rate, link distance, and error probability) and the train or group size have been presented in Stojanovic (2005). An alternative novel approach to provide reliable data transfer uses rate-less codes, a class of erasure correcting codes where the source data packets are converted into virtually an infinite stream and can be reconstructed from received data, provided it contains a minimum number of packets (Chitre and Motani, 2007). This allows a file transfer protocol to be designed where the individual packets do not have to be acknowledged and is suited for large file transfers. The sender can stop transmitting after it has decided that the probability that the receiver has not received enough packets is smaller than a preset threshold or the receiver can acknowledge complete delivery.

For optimal performance, the DLL needs to adapt packet size, batch size and timers based on measured link metrics. Reply timeout can be adapted for MACA RTS based on inter-node distance (Doukkali et al., 2006). Inter-node distances can be known through direct exchange of position information or through acoustic ranging techniques implemented in many modems. For optimal performance, the DLL could help adapt the FEC code rate at the physical layer.

**H. Clustered and Cellular Topologies**

Fully connected peer-to-peer topologies without the need for routing were commonly used earlier (Proakis et al., 2001), but such networks suffer from near-far power problems. A clustered network topology helps extend and scale the network and easily accommodates connectivity to other networks. One CDMA code per cluster and spatial re-use of codes is considered in Salva-Garau and Stojanovic (2003). TDMA is used within each cluster. Nodes are assumed to be able to handle multiple CDMA codes simultaneously. Similar scheme in which clusters are allocated with certain CDMA codes is found in Casari et al. (2007). Within each cluster TDMA is used but it is not clear how the inter-cluster communications are handled. The protocol called FAMA-CF in Kebkal et al. (2005) uses MACA-like RTS, RTS, CTS, DATA, ACK handshaking to communicate with the central node. The central node initiates the request for RTS (RRTS) to its peer nodes. Both analytical and experimental results are presented in the paper. Algorithms for cluster formation and dynamic changes are presented in Salva-Garau and Stojanovic (2003).

An underwater acoustic cellular network is an extension of the cluster topology and analysis of frequency re-use between adjacent clusters and optimal cell-radius selection criteria has been carried out recently (Stojanovic, 2007). A related work on channel allocation and scheduling protocol for cellular networks is presented in Peleato and Stojanovic (2007). An interesting example of a gateway node is the smart buoy where a surface raft that can maintain its position is equipped with global positioning system (GPS), surface radio and acoustic modems (Curcio et al., 2006).

**I. Network Layer and Routing**

A review of underwater network protocols until the year 2000 can be found in Sozer et al. (2000). Routing overheads for underwater networks should be kept as minimal as possible due to the extremely low data rates. In a typical clustered topology, the nodes communicate to a gateway node using a single hop while the gateway node handles all routing. In Xie and Gibson (2001), the authors present a similar topology assuming full-duplex modems. The gateway node manages route discovery through the use of probe messages to its neighbors. Route information is cached unless errors are reported in future relaying. In Foo et al. (2004) AODV-based routing together with MACAW is proposed. AODV is reactive and routing is initiated only when requested. The authors modify the standard AODV to use reverse link pointers by assuming bi-directionally symmetric links. Carlson et al. (2006) discuss location aware source routing for dynamic AUV networks, a modification from the DSR protocol originally designed for terrestrial networks. It uses TDMA and known TDMA frame timings to compute ranges based on propagation delay. Ranges are used to estimate local topology to determine routes. The authors suggest the use of a recursive state-estimation filter algorithm, but have not implemented it in their study.
Cross layer optimization of the routing algorithms with the DLL is required for optimal performance; much work remains to be done in this area. The Delay Tolerant Networking Research Group (http://www.dtnrg.org) has developed an architecture (known as DTN) that focuses on unreliable networks that uses store and forward techniques and future developments in underwater network layer can benefit from this. In Pompili et al. (2006), the authors propose routing algorithms for delay-sensitive and delay-tolerant networks. In the delay-tolerant case links are chosen based on energy minimization. In the delay-sensitive case, the algorithm is further constrained by avoiding retransmissions of corrupted packets at the DLL. Thus effectively implements cross-layer optimization by involving the DLL in the networking problem.

The idea of mixing data at intermediate nodes in a network is at the root of network coding, a technique introduced in a seminal paper in the year 2000 and gaining popularity since (Ahlsweide et al., 2000). In a recent paper, network coding schemes for underwater networks are considered (Lucani et al., 2007). In a concatenated relay network, the authors compare via simulation two routing schemes based on end-to-end acknowledgements, two based on link-by-link acknowledgements and two based on network coding. At high loads, the transmission delays in network-coded schemes were much better than in the other schemes. At low loads, the transmission delays in all schemes were similar; however, the network-coded schemes had lower power consumption as compared to the other schemes. Network coding with implicit acknowledgements has the lowest power consumption per node while providing low transmission delays. The use of network coding in underwater networks is being explored only recently and remains a promising open research area.

J. AUV Networking

As a result of the increasing applications of AUVs, networking of mobile assets is currently a very active area of research. The mobility and ad-hoc requirements for such networks pose many challenges. Stojanovic et al. (2002) describe a TDMA protocol for AUVs. Exchanged packets contain position information for localization. Simulated results from a FAMA-based MAC for an AUV network were presented in Molins and Stojanovic (2006).

AUVs are sometimes equipped with multiple modems or a single modem with multiple frequency band transducers (Freitag et al., 2005). The effective use of multiple modems optimized for different ranges in an AUV network using random access protocols is explored in Shahabudeen et al. (2007). As AUVs move around during a collaborative mission, the inter-node separations may vary from few tens of meters to several kilometers and different modems are used at different ranges based on exchanged position information. Such multi-channel or multi-modem nodes will also be needed in clustered or cellular topologies (to act as gateway nodes) and this is an exciting area for future research. Efficient multi-hop and ad-hoc packet routing protocols for AUV networks also are in their infancy and a potential research area for the future (Jiejun et al., 2005).

K. Simulation Studies

Simulations using appropriate software have been norm in underwater network research even more so than in terrestrial networks, because of the difficulty and cost in setting up sea trials and lack of direct access to the physical layers of commercial modems. Simulations provide a quick assessment of performance for new and modified protocols before an actual implementation. Mathematical analysis often offers limited and very loose bounds on complex network performance measures. The network simulator needs a base software platform, an appropriate channel simulator and a physical layer simulator.

Base software platforms include commercial network software such as Opnet used in Xie et al. (2006), open-source network software such as NS2 in Harris and Zorzi (2007), discrete event simulation packages such as Omnet++ used in Shahabudeen et al. (2007), or custom simulation software written in languages such as C++ (Carlson et al., 2004). The simulated channel needs to account for propagation delay and path loss. Spherical spreading model provides a first level approximation. More complicated models could be implemented depending on the accuracy needed (Raysin et al., 1999; Chitre, 2007). Computationally efficient physics-based underwater channel models have been developed (Xie et al., 2006). The physical layer is typically assumed to be a half duplex system as it is usually the case in many commercial acoustic modems. A simple physical layer model that computes BER and packet loss using received SNR can be used. Direct BER against range curves could be used if empirical data for a channel is available. Packets may also be lost due to collisions. AUV networking studies requires motion modeling (Carlson et al., 2004).

Some authors explicitly state the limitations of the simulators they used (Carlson and Beaujean et al., 2004) but often none are reported. The accuracy of simulations has to be addressed in the future. It is important to move towards standardized open-source simulation frameworks in the underwater network research community.

L. Standardization

The underwater networking research community can benefit hugely from standardization. Standardized protocols for gateway access from external networks and routing would allow applications to access underwater nodes easily. As a first step towards this goal, the common control language (CCL) specifications for AUV networks outline a TCP/IP based protocol for access to a CCL gateway (Stokey et al., 2005). Landline and GSM modems typically use the “AT” command set to allow applications to communicate with them. The WHOI micro-modem supports a NMEA 0183 protocol (Freitag et al., 2005). Most other commercial modems today provide support only for proprietary protocols. Standardization on communications to acoustic modems would enable applications to be easily integrated with various modems.
Modems’ internal stacks can be developed adhering to standardized inter-layer interfaces that allow interoperability and portability of stack software from different researchers. These can be used in real implementations as well as simulation studies. The inter-layer interfaces may expose optional settings such as FEC code-rates, power control, etc, to enable interoperable cross-layer optimization. Modem vendors may choose to expose some of these application programming interfaces (APIs) to the user to enable them to access lower layer functionality directly. Some initiatives towards this goal have started. In one initiative an underwater network architecture (UNA) for modem network layers was proposed to standardize inter-layer messages (Chitre et al., 2006). Figure 4 shows the recommended interfaces for each layer, with request, response, and notification messages between layers. The UNA specifications include an optional framework application programming interface (FAPI) to eliminate direct coupling between layers though the use of a messaging framework, to abstract hardware and operating system functionality and to help make layers easily portable. The CCL specifications also propose an application layer protocol for AUV networks (Stokey et al., 2005).

The use of standardized open-source simulation frameworks in the underwater network research community will help provide results that can easily be reproduced by others. Simulations from various research groups can run on common simulation platforms, if the simulation frameworks are written conforming to standard layer interfaces. This will also enable the use of the software used in simulation to be plugged in directly to the actual modem hardware that uses the same standard interfaces.

An important aspect of standardization is the physical layer implementation to enable greater interoperability between modems made by different vendors. The standards should allow for the existence of different technology families such as CDMA, OFDM, PSK, etc, with the option of using control information to convey which modulation scheme is being used. The physical layer of the WHOI micro-modem was published as a standard (Freitag and Singh, 2000) and a commercial modem maker Benthos implemented compatible modems (Freitag et al., 2005).

A related body of work on software radio, a structured and modular concept for modem implementation, has been proposed for use in underwater modems (Jones, 2007). In software radio, the bulk of the signal processing happens in software on DSPs and FPGAs. A software communications architecture (SCA) initiated by U.S. Department of Defense allows defining software components descriptors in extensible markup language (XML). The components are mapped on to hardware through device package and device configuration descriptor files.

Standardization in underwater networking is still very much in its infancy. A summary of interfaces and protocols that could be standardized is shown in Figure 5. Lack of technology is not the bottleneck for standardization, as most of the architectural components have proprietary implementations in many projects around the world. Setting up an underwater network will be just as easy as setting up a terrestrial WiFi network once standardization takes place and users have choice of alternative components from different vendors.
M. Summary

MACA-based contention protocols and TDMA or CDMA-based contention-free protocols can be used in a UW-LAN depending on the exact requirements and constraints. Multi-modem adaptive MAC protocols for AUV networks have been proposed to provide a unified interface to higher layers. AODV and DSR-based lightweight routing protocols have been proposed for underwater use. Efficient routing for ad-hoc mobile underwater networks still remains an open research challenge. Standardization for underwater networking is required to provide interoperability and ease of operation and help accelerate the research in the field.

List of Abbreviations

| API | Application programming interface | MACA | Medium access collision avoidance |
| AUV | Autonomous underwater vehicle | MAP | Maximum a posteriori probability |
| AWSF | Adaptive wakeup schedule function | MIMO | Multiple input multiple output |
| BER | Bit error rate | MLSD | Maximum likelihood sequence detection |
| BP | Belief propagation | MLSE | Maximum likelihood sequence estimation |
| CCL | Common control language | MMSE | Minimum mean square error |
| CHF | Chip hypothesis feedback | MSE | Mean square error |
| CTS | Clear to send | OFDM | Orthogonal frequency division multiplexing |
| DACAP | Distance aware-collision avoidance protocol | PCM | Phase-locked loop |
| DFE | Decision feedback equalizers | PPC | Passive phase conjugation |
| DLL | Data link layer | PPM | Pulse position modulation |
| DS-CDMA | Direct sequence code division multiple access | PSK | Phase shift keying |
| DSSS | Direct sequence spread spectrum | PST | Per-survivor processing |
| DTN | Delay tolerant network | RLS | Recursive least square |
| FAMA | Floor acquisition multiple access | RTS | Request to send |
| FAMA-CF | Floor acquisition multiple access (collision free) | SCA | Software communications architecture |
| FAPI | Framework application programming interface | SDF | Symbol decisions feedback |
| FDMA | Frequency division multiple access | SDMA | Space division multiple access |
| FEC | Forward error correction | SISO | Single-input single-output |
| FFT | Fast Fourier transform | SNR | Signal-to-noise ratio |
| GPS | Global positioning system | sPRE | Sparse partial response equalizers |
| GSM | Global system for mobile communications | SSTC | Space-time trellis codes |
| ISI | Inter-symbol interference | TCM | Trellis-coded modulation |
| LDPC | Low-density parity check | TCP/IP | Transmission control protocol/Internet protocol |
| LFM | Linear frequency modulated | TDMA | Time division multiple access |
| LLR | Log-likelihood ratio | TRM | Time reversal mirror |
| LPD | Low probability of detection | UNA | Underwater network architecture |
| LPI | Low probability of intercept | UW-LAN | Underwater local area network |
| LSTC | Layered space-time codes | XML | Extensible markup language |
| MAC | Media access control | ZP | Zero prefix |

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