An integrated, underwater optical /acoustic communications system

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Abstract- **Communication underwater is severely limited when compared to communications in air because water is essentially opaque to electromagnetic radiation except in the visible band. Even in the visible band, light penetrates only a few hundred meters in the clearest waters and much less in waters made turbid by suspended sediment or high concentrations of marine life. Consequently, acoustic techniques have been developed for underwater communication systems and now represent a relatively mature and robust technology. Acoustic systems are capable of long range communication, but offer limited data rates and significant latency (due to the speed of sound in water). We are developing an optical communication system that complements and integrates with existing acoustic systems resulting in an underwater communications capability offering high data rates and low latency when within optical range combined with long range and robustness of acoustics when outside of optical range. Amongst a wide array of applications, this combination of capabilities will make it possible to operate self-powered ROVs from support vessels or platforms without requiring a physical connection to the ROV. Such a capability will help simplify operations and potentially reduce costs through the use of less capable surface vessels. New deployment strategies may offer game-changing opportunities within all areas of undersea activities. For example, rapid event response will be enhanced and repair and maintenance of the emerging ocean observatory infrastructure will become more cost effective. Such through-water communications will likewise enable exchange of large data files from fixed sensors using AUVs (or ROVs) as data mules, shuttling real-time video from untethered vehicles for inspection, identification, and other related operations. Interconnectivity for dense arrays of underwater sensors without the need for expensive and difficult to install undersea cables is also possible. An unmanned battery operated vehicle, dedicated to a subsea node, that can be wirelessly operated though a combination of acoustic and optical communications, will be an important asset for both scientific exploration and commercial applications.**

We have demonstrated robust multi-point, low power omnidirectional optical communications over ranges of 100 meters at data rates up to 10 mega bits per second using a few tens of Watts of battery power with small, inexpensive transmitters and receivers. During the next few years, we will be exploring applications of this new technology directly in support of ongoing science and engineering programs.

High-speed underwater optical communication is an enabling technology that has many potential applications in a range of environments from the deep sea to coastal waters. This development effort will enhance infrastructure for scientific research and commercial use by providing technology to efficiently communicate between surface vessels, underwater vehicles and seafloor infrastructure.

I. INTRODUCTION

Robust, high speed communication is ubiquitous in modern science, but is still very much a technical limit in underwater applications. In air, RF communications operate over long distances at high data rates while using modest power. This is not feasible in water due to the high absorption of electromagnetic signals at radio frequencies. Optical fibers are used for high data rate links in fixed undersea applications, such as telecommunication cables, but are too expensive for use in most science applications, and are not appropriate for mobile assets. The primary issue related to underwater wireless communication is data rate as a function of power consumption (Table 1). Acoustic modems generally operate between about 100 and 5000 bits per second (bps) over moderate ranges and potentially higher rates for some specialized, short range systems [1]. At these speeds, large data files take a long time to transfer and real-time video transmission is not feasible. These issues currently limit the retrieval of real-time data from ocean sensors and usually require an instrument to be recovered in order to download the full resolution data set.

The ocean is modestly transparent in the visible light spectrum. Thus, the best alternative to acoustic links lies with the development of optical links where high data rates (10 Mbps or more) are achievable. The e-folding scale (i.e., the distance over which light intensity decreases by 1/e ~ 0.37) in the blue-green band (400-500 nm) is ~20-50 m in clear ocean water. Communication can be carried out over ranges of ten or more e-folding scales (at these data rates), thus the working range of underwater optical modems is on the order of 100-200 m, and up to 300m in the clearest of water. The energy required for optical data transmission is much less than acoustics when considered on a bits per Joule basis, which translates into modest battery usage for large data transfers.

Telemetry Method	Range	Data Rate	Efficiency
Acoustic	Several km	1 kbps	*100 bits/Joule*
Optical	100 meters	1 Mbps	*30,000 bits/Joule*

Table 1. Performance comparison of acoustic and optical telemetry

II. CONCEPT

Free-water optical communication (i.e. free-space optical communications using water as the transmission medium) provides the potential for high speed data rates over intermediate ranges. The recent improvements in LED technology have enabled low cost, power efficient optical transmitters to be developed that offer high levels of light intensity, fast switching speeds, high efficiency, and optimal wavelengths for underwater light transmission. The optical communications system we are developing was conceived from the outset to operate on mobile platforms to allow real-time interactive operation. Under our initial funding, we evaluated the trade-offs between wide-angle and aimed collimated transmitter/receiver pairs, LED and laser diode sources, and avalanche diode and photomultiplier tube (PMT) receivers. We have developed a prototype system employing omni-directional links that are optimized for mobile applications as well as stationary platforms. To operate on mobile platforms, an optical link must provide sufficient bandwidth to downlink (from the vehicle) compressed high-resolution video, allow nearly unrestricted motion on the part of the vehicle, and work at ranges of at least 100 m. Cost, size, power consumption, and compatibility with other optical systems (for example, camera lighting) all bear on the design and consequentially on the technical issues and engineering trades. The key system trade studies and design choices are fully described in [2][9]. These studies involve 1) selection of an aiming and tracking strategy, 2) selection of a transmitter light source, 3) selection of a detector for the receiver, and 4) selection of a modulation method.

While the majority of the electromagnetic spectrum is highly attenuated by water, there is minimum intrinsic attenuation in the blue-green band (400-500 nm) [12]. In addition to attenuation, scattering of visible light limits the data rate due to the propagation path difference between direct and scattered components. Fortunately, water clarity at depth is high so the amount of forward-scattered light is typically small. Further, the required bit rate (~10 Mbps) allows bit signaling intervals of the order of 100 ns, which are long compared with the delay associated with the path difference resulting from typical scattering 10-20° out of plane.

III. TESTING TO DATE

The first deep water test of the system with real time data encode/decode processing was performed on the *Alvin* submersible in August of 2008. A dock test with the Hybrid Remotely Operated Vehicle *Nereus* (HROV), demonstrated the potential for real-time vehicle control by transferring high rate video.

Small Aperture Test on Alvin with Real-Time Decoding

A test of range-vs-rate of the optical system was demonstrated in clear, deep water using the HOV *Alvin*. An emitter was positioned on the sea floor and the receiver on *Alvin*, which was slowly backed away until the communication signal was lost. This system configuration consisted of a small receiver and processor enclosed in a cylindrical housing. All sub-systems including receiver, amplifier, digitizer, demodulator, and error correction block were enclosed in one 12 cm diameter by 50 cm housing. This configuration, which was smaller than that used for previous tests, traded receiver sensitivity for a form factor compatible with an underwater vehicle and had the added capability to demodulate received signals in real-time. The small aperture system was tested on two dives on the HOV *Alvin* in August 2008 near borehole sites 1301A, 1301B and 1026B on the Juan de Fuca ridge in 2400 meters of water. In this experiment, test data were transmitted at 1 Mbps from the seafloor package to the receiver mounted on *Alvin*'s light bar facing forward. *Alvin* was moved to a series of stations and error rate data were collected. Water clarity was measured to be 20 meters e-folding length. Error free transmissions at 1 Mbps were achieved at a range of more than 100 meters and these results are plotted in Figure 1.

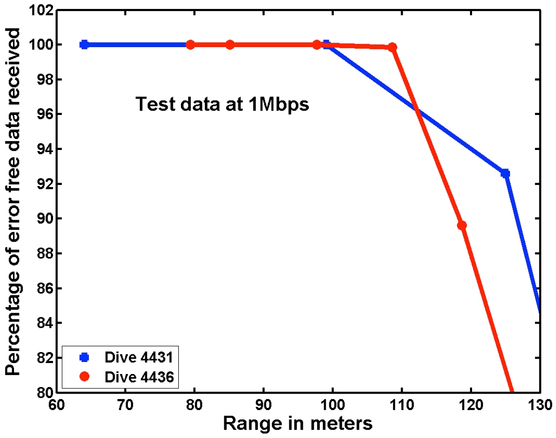

Figure 1. Deep water *Alvin* system test results showing error free data vs. range (m)

Dock Trial with HROV Nereus Demonstrating Transmission of Video Data

A demonstration of the potential of the system used during the *Alvin* test was performed using the HROV *Nereus* at the Woods Hole Oceanographic Institution (WHOI) dock. *Nereus* is a self-powered ROV with light intervention capabilities to a depth of 11,000 meters [10]. The point of the demonstration was to establish the viability of an optical link to enable real-time control of a vehicle, particularly direct human control during the highly interactive process of performing complex, unstructured manipulations subsea. In this configuration a full-duplex optical link was implemented, consisting of a pair of receiver/transmitters communicating via separate optical wavelength channels. Real-time video data was optically transmitted and decoded for the first time (Figure 2). This was a proof of concept test, using a full-duplex optical link to show the viability of untethered vehicle control using optical links. Separation between the two systems was approximately 15 meters and the vehicle's video lights were on during the demonstration.

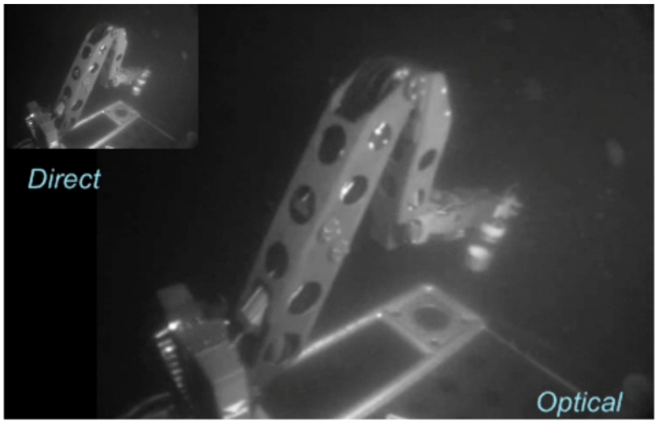

Figure 2. Screen capture of real-time *Nereus* video transmitted via the optical link demonstrating the potential for real-time vehicle control and manipulation in a tetherless vehicle.

IV. APPLICATION: UNTETHERED ROV (UTROV)

The recent development and successful testing of the HROV *Nereus [11]* paves the way for a derivative vehicle-type, able to perform a variety of useful tasks such as rapid event response, deployment from ships of opportunity, time-series Ocean Observatory maintenance, and exploration at increasingly high latitudes, including beneath polar ice. Next generation battery-powered vehicles like *Nereus*, will be able to perform tasks that might otherwise require a conventional remotely operated vehicle (ROV) like Jason II. Further, these tasks, when performed by UTROV, could be accomplished at much lower potential costs as their streamlined launch and recovery systems would allow for deployment by smaller operational teams from a wider range of Ocean and Regional-class ships. The integration of through-water optical and acoustic communications coupled with a suitable control system capable of *adaptive* autonomy enables such vehicles to be considered.

A concept of operations for UTROV is outlined in figure 3. The left pane shows the vehicle working within a low bandwidth acoustic communications and positioning network, performing typical autonomous survey and reconnaissance tasks. The center and right-hand panes show the UTROV communicating via an optical communications channel through either a small ship-based relay or fixed infrastructure on the seafloor.

The *Nereus* vehicle tests described in section III above clearly confirm the concept of a virtually tethered ROV with real intervention capabilities. The unique, integrated combination of advancements in both acoustic and optical communications, coupled with the successful realization of a battery powered ROV, positions Woods Hole Oceanographic's scientists and engineers to make broad and important contributions to the evolution of undersea robotic vehicles in the years to come.

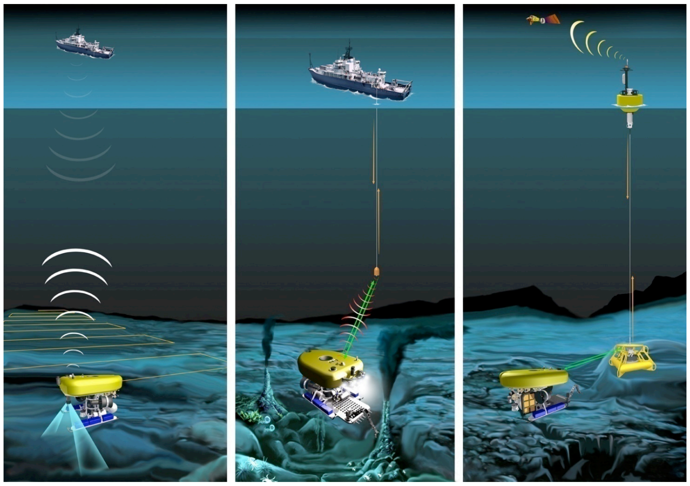

Figure 3. UTROV concept of operations. On the left, UTROV is performing a typical AUV mission using low bandwidth acoustic communications. In the center and right hand views, UTROV is utilizing an optical communications path provided from either a ship-mounted relay (center) or associated with subsea infrastructure (right)

V. APPLICATION: DATA MULE

Movement of information in the ocean environment continues to be an ongoing challenge. The optical modem in its various forms will emerge as a new tool offering improved strategies to facilitate data exchange in a variety of settings. There is a wide array of applications where optically-based data transfer may provide new opportunities enabling distributed sensing networks. As with the application of high-bandwidth optical communications for un-tethered intervention vehicles discussed in the previous section, it is also entirely feasible to consider how such communications might offer sensing systems designers a new means of interconnecting widely distributed networks by utilizing the higher bandwidths available in tandem with mobile relay points in the form of autonomous underwater vehicles. Figure 4 illustrates how a vehicle such as WHOI's REMUS AUV could be used as the first step towards this objective by acting as a relay mechanism or "data mule".

Present sensing networks requiring real-time external connectivity rely on either fixed cabling or acoustic means. Each of these methods has limitations, which could be mitigated by the presence of a dynamic and controllable means of shuttling information using autonomous vehicles and short-range optical communications. A simple but valuable example will be the download of data and potential reprogramming of an array of widely distributed scientific sensors. The potential of such an approach is significant. For example, it is possible that by using such techniques we can avoid physically recovering instruments to download data – a typically expensive and time consuming task. Utilizing an AUV to perform such a task will either reduce or potentially eliminate the need for expensive surface vessels or specialized vehicles and docking systems.

Aside from such easily imagined uses for a data mule, more sophisticated applications likely exist. As sensing and surveillance networks increase in their complexity and expand their coverage, systems designers may consider including adaptive response modalities enabled by appropriately equipped AUVs. Communication strategies such as the medium range, optically based systems described here will offer important new technological choices, with significant impacts on both scientific and commercial operations in the deep sea.

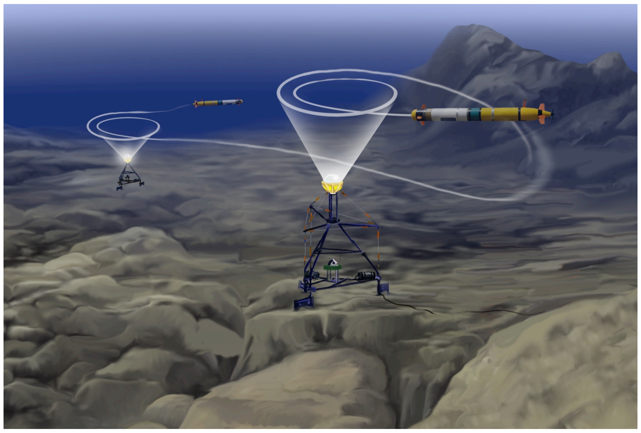

Figure 4. Rendering showing a simple data mule AUV approach to interrogating and downloading data from a widely distributed network of seafloor sensors using optical communication methods. No complex docking maneuvers or infrastructure is needed in this realization.

VI. A FIRST DATA MULE TEST: REMOTE DATA OFFLOAD FROM A SEAFLOOR BOREHOLE OBSERVATORY (CORK)

Over the past several years the Ocean Drilling Program (ODP) has drilled multiple boreholes into the volcanic basement rock off the west coast of the US on the flanks of the Juan de Fuca Ridge in order to investigate the hydrological structure of oceanic crust and the pathways of fluid flow through the crust. These holes have been instrumented with thermistor strings and pressure sensors to measure the long-term variations in subcrustal fluid properties and various oceanographic phenomena from tides to earthquake generated tsunamis. This seafloor borehole instrumentation is more commonly known as a CORK (Circulation Obviation Retrofit Kit), which, as the name implies, is a system that seals the borehole from open flow from the overlying open ocean allowing for in situ measurements of fluids and physical properties to be obtained [3]. The CORK program has been remarkably successful in demonstrating the feasibility of operating and maintaining a long-term seafloor observatory. It has provided important new scientific insight into many aspects of fluid flow within oceanic crust [4][5][6][7][8], arguably one of the most important processes involved in the transfer of mass and energy between the ocean and solid earth.

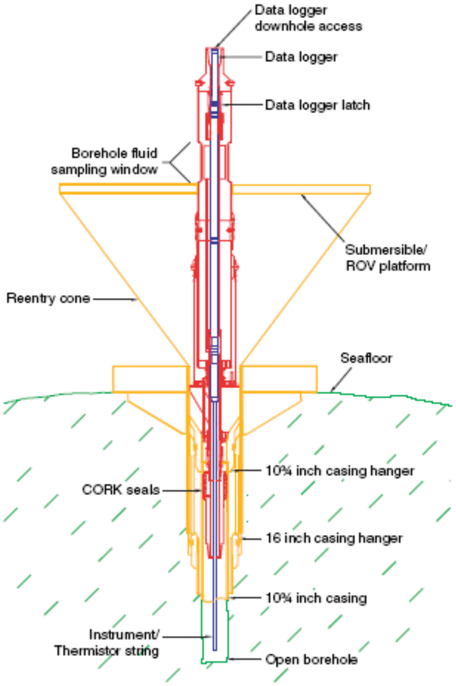

Figure 5. Diagram of a typical single-seal CORK installation. Red is the CORK body, blue is the scientific instrument string and orange is the drill hole and reentry cone super-structure. From Becker and Davis, [2005].

A CORK installation (Fig. 5) includes a sensor instrumentation package that typically consists of a data logger, batteries, a thermistor string, one or more pressure gauges at various formational levels, and a reference pressure gauge at the seafloor. External connection to the data logger is provided by an underwater mateable connector for an ROV or submersible to download data. Typical data rates (1 Hz to once per hour) are limited by several factors that include data storage capacity and power, but download data communication rate is the most limiting factor along with the need for an in situ visit with a submersible or ROV for download [E. Davis, pers. comm. 2009]. The CORKs in the northeast Pacific are an example of a widely distributed network of sensors. Currently, a submersible visits the CORKs on an annual basis, but often this can become multi-year periods between downloads for CORKs located in more distant areas. If a higher download rate could be employed along with a method to download data from any platform of opportunity (e.g. a ship or ROV/AUV/HOV) then higher sampling rates for the sensor could be employed to collect unaliased pressure/tidal data and the data could be retrieved on a more consistent basis.

The concept of using free-water optical communication technology at a CORK observatory site provides a real-world demonstration of the ability of optical communications to enhance and broaden the ability of standalone seafloor observatories. A CORK optical telemetry system (CORK-OTS) provides a high speed communication interface, extra data storage capacity, and enables data downloading without the requirement of an in situ visit by submersible or ROV. The CORK-OTS is being designed to be portable for use on either a submersible or ROV but also for use from a surface vessel on a lowered cable (Fig. 6). A ship-based lowered system would save valuable time and money in the CORK operational costs by using a platform of opportunity.

The components of the CORK-OTS consist of a self-powered bi-directional optical communication system utilizing blue-green emitters and a small receiver. The target design specification will be for a 1-10 Mbit/s transfer rate. For the lowered system, an acoustic modem will be integrated with the optical system to wake up the seafloor installation. An automatic data transfer function will be developed for applications where communication with the surface is not possible. A field program is scheduled for the summer of 2010 with a visit to the CORK installed at Hole 1025C in the northeast Pacific using the submersible *Alvin*. An optical communication interface will be installed and tested and will remain in place for one year. A return visit will be made in 2011 using an ROV to check the status, re-battery, and evaluate performance.

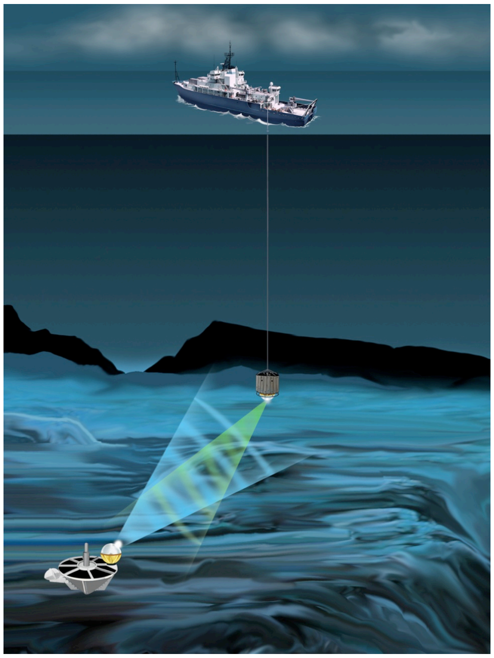

Figure 6. Rendering of the CORK optical telemetry system (OTS) being interrogated by a surface vessel using a lowered optical modem. Different wavelengths are used for bidirectional communication.

VII. SUMMARY

The technology described above encourages transformational opportunities in a range of important potential applications. Rapid development and application of this technology is underway at WHOI and is expected to make both short and long term impacts similar to those of acoustic communications over a decade ago. From enabling designers to consider new means of tethering vehicles, to important evolutions in sensing networks, optical communications in the ocean appears to be a promising, potentially game changing technology.

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