Wireless Data Harvesting Using the AUV *Sentry* and WHOI Optical Modem

Clifford Pontbriand, Norm Farr, Johanna Hansen,
James C. Kinsey, Leo-Paul Pelletier, Jonathan Ware
Advanced Ocean Physics and Engineering Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543 USA
cpontbriand@whoi.edu

Dehann Fourie
MIT-WHOI Joint Program in Oceanography/
Applied Ocean Science & Engineering
CSAIL, Cambridge, MA 02139 USA

***Abstract*—The optical communications group at Woods Hole Oceanographic Institution has demonstrated wireless optical transmission of data from a seafloor node to the *Sentry* AUV. This effort is based on the latest version of the optical modem under continual development at WHOI, and it builds on fieldwork conducted in 2012 and 2013 during which we successfully transferred data from seafloor-deployed optical modem systems using a wire-lowered optical modem from a ship. While our previous work used a high-bandwidth optical modem for the data uplink and an acoustic modem "backlink" to control the file transfer, the optical modem described in this paper supports fully bidirectional optical communication—essentially subsea WiFi. A subordinate objective of our work was to literally map the operational space for an AUV-bottom node optical link. Armed with this spatial map, we can plan for future "connected" AUV operations in support of data mule, inspection, manipulation, and other underwater semi-autonomous tasks.**

Keywords—underwater optical communications; freespace; optical modem; underwater wireless communications; AUV; data mule

I. INTRODUCTION

Underwater wireless communication plays a crucial role in the expanding field of AUV robotic science, especially for long-term deployments of these vehicles for survey, inspection, and service of deep ocean observatories. The ability to exfiltrate data from deep submerged infrastructure is critical to scientific fieldwork (e.g., long-term monitoring), military operations, and commercial subsea survey for the oil and gas industry. Existing sensor platforms are either cabled to shore or to a surface expression, or they are physically recovered for data extraction [1, 2]. Our optical modem data mule concept allows routine near-real-time access to data from subsea platforms which will not only save expense and improve performance over the complete life cycle of deployment but will also extend the reach of existing infrastructure. A key technology for this application is a high-rate wireless communications interface at Mbps (or higher) rates with low power consumption and sufficient range capability.

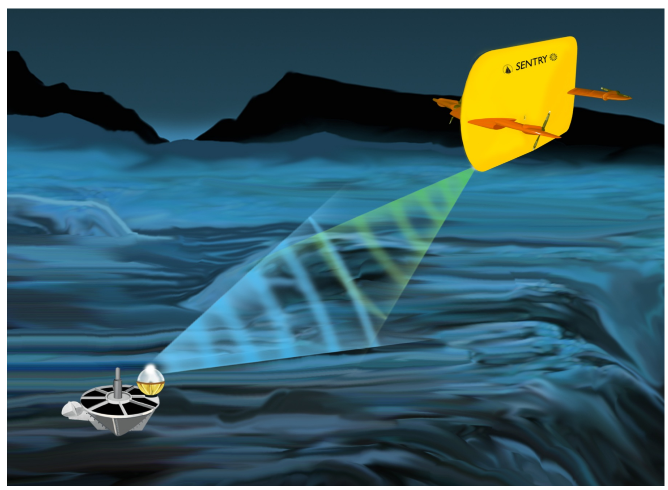

Figure 1. Data mule concept showing *Sentry* and a CORK borehole instrument. The blue and green shading indicates bidirectional optical communication; both node and AUV use the same color of light but share time in the optical channel (TDM).

Optical modem equipment developed by the Optical Communications Group at Woods Hole Oceanographic Institution (WHOI) has been used to wirelessly control an AUV [3] and to wirelessly offload data from moorings and seafloor instruments [4]. In August 2014 aboard the R/V *Atlantis*, we used the National Deep Submergence Facility's *Sentry* AUV to autonomously offload data from a seafloor node. This demonstration took place in approximately 2400 meters of water on the Juan de Fuca

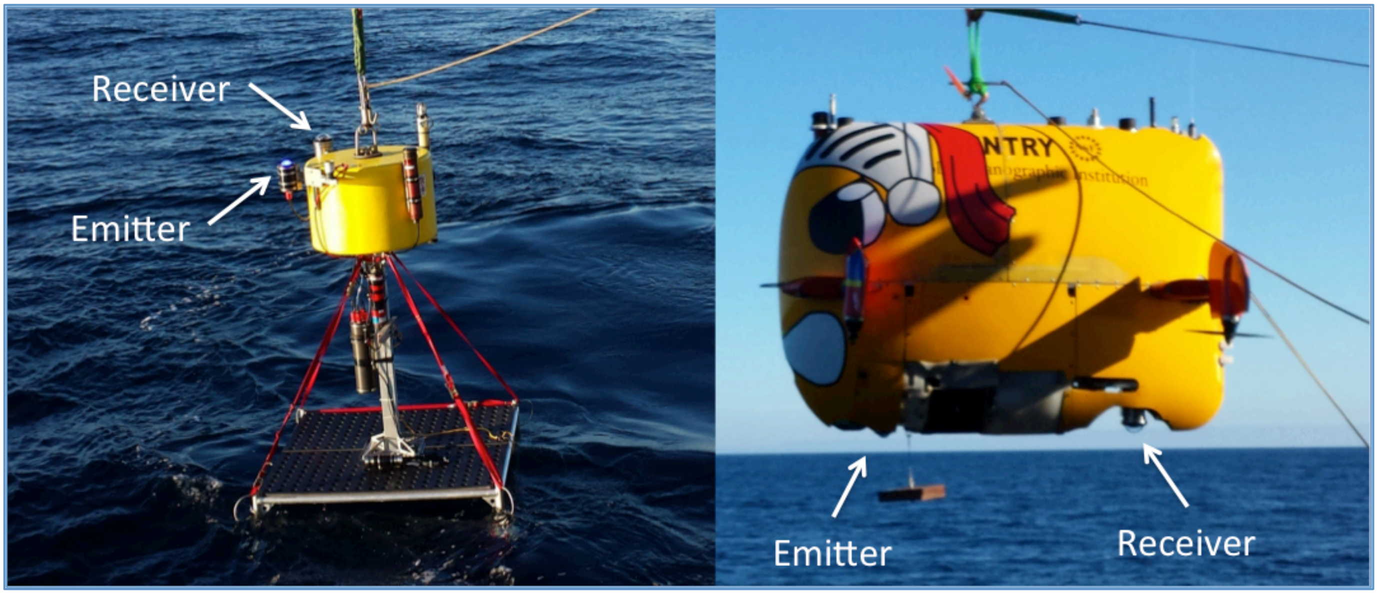

Figure 2. Test node (left) and *Sentry* (right) with optical modem emitter and receiver locations labeled.

plate and made use of our latest generation optical modem equipment. The technology harnesses LEDs to allow for a 5 – 20 Mega-bits per second (Mbps) data transfer rate over relatively long ranges (~100m in clear, dark water) without the need to align the transmitter and receiver. Our optical modem exhibits fully bidirectional optical communications by use of time-division multiplexing (TDM). Here we detail our recent work using *Sentry* to autonomously and wirelessly offload data from a seafloor node—a data mule mission. This demonstration is the result of close collaboration between the *Sentry* group and the Optical Communications group. Since the optical modem transparently supports bi-directional Ethernet traffic, we were able to use a TCP-based file transfer protocol (Rsync), which made the problem of managing the file transfer more tractable (no custom file transfer protocol required). The WHOI optical modem should be viewed as an appliance—ready and capable for deployment on many platforms.

II. Concept of Operations

Building on the Optical Communications Group's body of work using our WHOI-developed optical modem for ship-based wireless data offload of geophysical data from a seafloor node [4], we present results of a field demonstration of node-to-AUV data transfer. Using an AUV instead of a lowered receiver node is the next logical step, as it enables efficient, multi-node data offload; frees expensive ship time; and requires no surface expression. See Section V for quantitative discussion of the benefits of the wireless optical data mule.

The typical concept of operations for a data mule mission consists of: (1) vehicle deployment, (2) seafloor node position acquisition and retention, (3) data offload and integrity check, (4) putting node into low-power sleep mode, and (5) transit to the next data node, with (6) eventual vehicle recovery or docking. Figure 1 illustrates this concept. Details such as navigation routines for steps (2-3) and fail-out behavior are mission- and platform-dependent. Feeding optical link quality data (in particular received signal power and bit error rate) into the mission controller allows for corrections in offsets in the node position and allows the AUV to minimize its standoff distance from the node, thereby maximizing data transfer speed (see Section V, below).

III. Optical Modem Hardware Description

Our optical modem hardware used in this demonstration is capable of bi-directional communication at data transfer rates of up to 10 *Mbps* with loose directionality requirements: when within range, the only constraint is that the relative hemisphere be known (i.e., the node must be deeper than the AUV). Once an optical link is established, the AUV has a generous watch circle of operation, typically 25 to 75 meters radius, depending on data rate and altitude. One distinct advantage of our wideangle optical communications approach is the very fast link acquisition time, usually hundreds of microseconds. This fast acquisition time gives flexibly in data offload patterns, indicates a robust communication link, and facilitates multiple-node data mule missions (low overhead). The deployed hardware is shown in Figure 3.

Figure 3. Optical modem, 4500 meter-rated. The receiver (top) and emitter (bottom) form one half of an optical modem system. This set was installed on *Sentry*, and a similar set was installed on the node. The receiver housing has a 6 inch outer diameter.

An alternate optical signal source (i.e., laser) would enable transfer rates up to 50 *Mbps*, while much higher transfer rates above 500 *Mbps* can be achieved with specialized hardware. Table 1 summarizes the current technological capabilities of the Optical Communications Group.

Rate	Range (meters)	Angle	Technology (receiver/source)
1 Mbps	138	Hemisphere	PMT / LED
10 Mbps	108	Hemisphere	PMT / LED
15 Mbps	80	Hemisphere	PMT / LED
> 400 Mbps	4	+/- 7 degrees	PMT / Laser
10 Gbps	Contact	+/- 2 degrees	Photodiode / Laser

Table 1. Optical Modem Group-fielded systems produced the rates and ranges shown above. These are not maximum ranges but rather ranges within which reliable transfer of large data files were performed.

IV. METHODS

In August 2014, we used the National Deep Submergence Facility's *Sentry* AUV to demonstrate autonomous data offload from a seafloor node. The vehicle and a seafloor node were both equipped with bidirectional 3^{rd} generation WHOI optical modem hardware and Sonardyne AvTrak 6 acoustic modems. Integration of the optical modem with *Sentry* required mechanical mounting brackets and 60W power and 10/100 Ethernet connections (1 cable). The remainder of integration involved data handling on *Sentry* to parse the optical link status information (signal power, error rate, etc.). The navigation and planning aspects of the mission were essentially separate from the file transfer process, which ran in parallel with the mission controller [5]. Figure 2 shows the node and *Sentry*, with mounting locations of optical modem equipment labeled. Although the photomultiplier receiver is tolerant of optical backscatter, we followed the best practice of selecting mounting locations to minimize common volume for the emitter and receiver. *Sentry's* receiver and emitter were mounted in the tail and nose, respectively, achieving 1.5 meter separation. Equipment on the seafloor node was mounted around the perimeter of the syntactic foam float, achieving separation between the emitter and receiver of 1 meter.

The demonstration began with a free-fall deployment of the battery-powered test node from the ship. With the node installed on the seafloor and acoustically located, the AUV was launched with mission plans to map the optical power field and to offload test data from the node. When the AUV passed close enough to the node to make an error-free optical link (as indicated in the optical modem status message to *Sentry*), the *Sentry* data transfer process automatically initiated transfer of a 100 MB file from the node to the AUV via the optical modem. This process was repeated for the duration of the dive. Three separate dives were completed using different methods for homing on the node: acoustic homing, dead reckoning, and optical signal power [5]. During one 4.5 hour mapping dive more than 5 GB of data was wirelessly transferred. Figure 4 shows example vehicle track lines with measured optical signal power overlay.

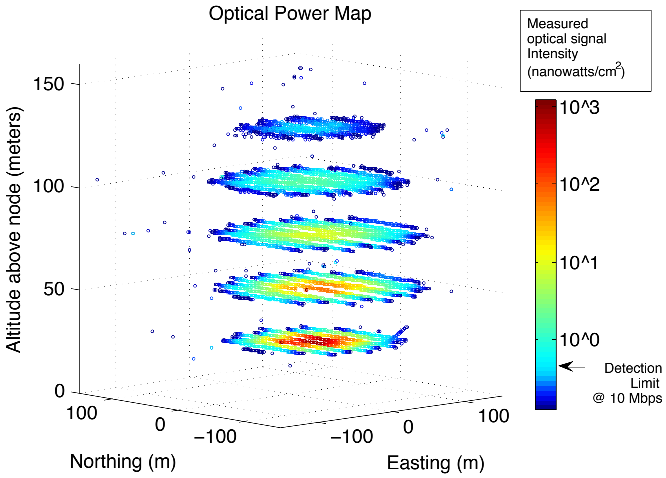

Figure 4. Spatial plot of survey track lines with optical power overlay. *Sentry* completed a lawn-mowing survey while receiving optical data. The tracks above are at 5 different altitudes above the seafloor: 25m, 50m, 75m, 100m, and 125m.

V. RESULTS

On the combined optical power survey/data transfer mission, the seafloor node acquisition was initially performed using inertial navigation; once in close proximity, inertial navigation was aided by ultra-short baseline (USBL) acoustics. After the vehicle was within optical communications range (generally <100 meters), a constant-depth grid survey pattern was initiated both to mimic a "fly-by" data offload and to measure the optical signal power over the node in order to generate an emitted power map (Figure 3). During this grid survey, a parallel data transfer application running on the *Sentry*-embedded computer initiated repeated wireless optical data offload of 100 MB sample files from the test node. The automated data transfer application used acoustic range and optical signal level as inputs to initiate this data offload portion of the mission. This survey pattern was repeated at altitudes of 25, 50, 75, 100, and 125 meters above the test node. Mission progress was monitored via acoustic modem messages between *Sentry* and the *Atlantis*. While this is standard operating procedure, the messaging was passive to the mission, proving the feasibility of an unattended data mule. The optical signal power map resulting from the survey is shown in Figure 4. This figure represents the times when a valid optical link was maintained and shows the Lambertian beam pattern of the emitters. Both the emitted signal beam pattern and the signal threshold to successfully transmit data are similar to results from our previous field deployments [4]. Figure 5 compares the constant-power signal envelope measured from the *Jason* ROV in 2012 with the same envelope generated from our recent survey. The performance envelope for the 2014 survey is 10 meters greater than the 2012 deployment because emitter optical power was doubled from 3 W to 6 W. The shape of the envelope is similar in both cases.

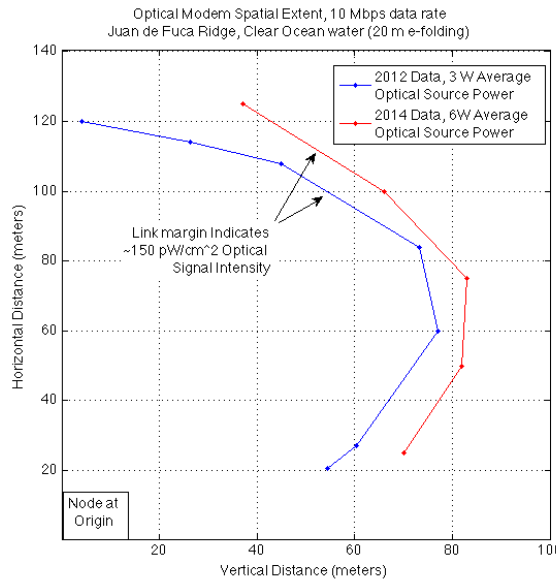

Figure 5. Comparison of 2012 measured emitted optical signal (blue) with 2014 survey data (red).

The comprehensive field map in Figure 4 highlights a significant difference in achievable offload speeds between the ship-based and AUV-based methods for retrieving data. For vessels without dynamic positioning, the optimal altitude for data offload is 75 meters from the bottom, which provides a watch circle with a radius of more than 75 meters. This arrangement provides adequate signal for 5 or 10 *Mbps* data offload. AUVs such as REMUS typically operate closer to the bottom where much more power is received, which can support faster data offload speeds. The 25-meter altitude survey of the field mapped by *Sentry* is shown in Figure 6. Measured optical signal vs. slant range is shown on the left of Figure 6; while expected watch circles for 5, 20 and 50 *Mbps* are shown on the right, highlighting the efficiency improvement of using an AUV-based vs. a ship-based data mule. Our optical modem operated at 10 Mbps during the survey.

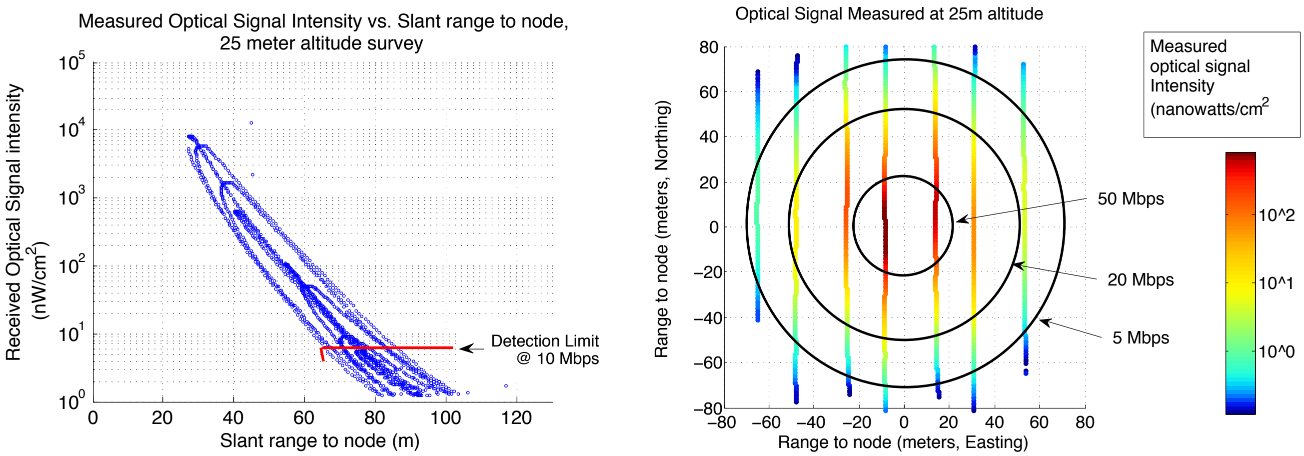

Figure 6. ***Left*** **- Optical power vs. slant range (m) from the seafloor node at 25m-altitude.** ***Right*** **- A detail of the 25m-altitude track line. Survey data was gathered with a 10Mbps optical modem. The black circles show predicted operating space for three data rates based on our measurements of optical signal power. This defines the size of the loiter circle that a vehicle needs to maintain for a given data rate.**

VI. Impact

Having demonstrated the optical modem technology, it is appropriate to make the case for adoption of the AUV data mule. There are two tiers to this argument: (1) cases where a data mule is a key enabling technology (no clear alternatives), and (2) cases where there is a compelling economic or performance increase based on this technology. The former case is evident: ship-free missions such as long-range AUV deployments, docked AUV data harvesting, etc. Fortunately, those applications are on the horizon.

For the latter case, improved economics or efficiency, demonstration of the efficiency gains of the optical data mule over other data transfer methods is needed. As an example, the case of offloading the data generated by an array of 100 hydrophones is considered. If the array is operating in a continuous mode, the data generation rate is 5-50 *Mbps*. A six-hour collection period will result in 100 Gbit to 1 Tbit data volumes. Offloading this data over a 20-minute access period requires communication rates between 100 – 1,000 *Mbps*. Moving large amounts of data in real-time or during short access periods is challenging due to limited power capacity for undersea systems. Compared to acoustic modems, optical communication systems can provide significant improvements in prime power efficiency (bits-per-Joule). For example, compare the WHOI 300-kbit/J 10-Mbps undersea optical modem used in this demonstration and the Benthos 1-kbit/J undersea 5-kbps acoustic modem. Acoustic technology will not work for this data payload since the data rate is too low (i.e., 5 kbps vs. 5 Mbps) and the energy is excessive (i.e., 30 kW-hr to move a single 100 Gbit data volume over a 6,000-hour access period). The optical modem, on the other hand, both meets the communication need (i.e., 10 Mbps) and significantly reduces the energy requirement (i.e., 0.1 kW-hr to move a single 100 Gbit data volume in a 3-hour access period). Improvement in AUV station-keeping would yield an order of magnitude increase in data offload speed while decreasing the access period to minutes. Soft docking would yield an additional order of magnitude transfer rate increase, which would allow for transfer of larger data volumes (see Table 1).

Wireless data mule operations, as we have demonstrated here, will both extend the deployment duration of underwater sensors and enable intermediate data exfiltration. AUV-based data mule operations will save ship time and efficiently transit between nodes in a multi-drop application. Wireless optical data mule offload speeds are rivaled only by fiber optic cabled nodes and physical recovery of platforms.

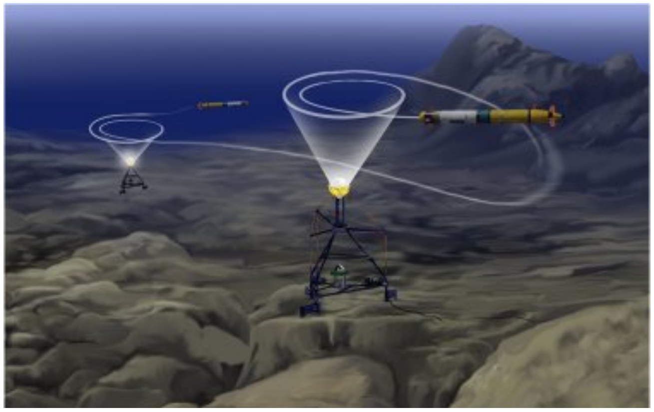

Figure 7. Data mule concept with multiple nodes and REMUS AUV engaging in back-to-back exfiltration using a loitering mode. Both node and AUV are equipped with a bi-directional optical modem (transmitter and receiver on both platforms).

VII. Conclusion

The latest generation of the bi-directional wireless underwater communications system, the WHOI optical modem, was deployed on a seafloor test node and on the AUV *Sentry*. A complete optical field map of the signal emitted from the seafloor node was generated while demonstrating an autonomous data mule mission. Test data was successfully transferred from the node to *Sentry* over the wireless optical modem from 20 to 150 meters slant range at data rates of 5 and 10 *Mbps*. Moving to an AUV platform elevates the capability of data mule operations to autonomously recover data from a seafloor observatory with minimal human intervention. Future work with the hover-capable *Sentry* AUV could demonstrate short-range (<5 meter) ultra-high-bandwidth (>400 *Mbps*) data harvesting. Other possible directions of research include data transfer between non-stationary platforms (AUV-AUV). Wireless optical underwater networking is a reality for many relevant applications.

VIII. ACKNOWLEDGMENTS

We thank the captain and crew of the R/V *Atlantis* and the *Sentry* AUV team (Z. Berkowitz and J. Fujii, among others) for their field operations support. We also would like to thank M. Heintz and M. Fernandez from The Deep Submergence Laboratory (DSL), who provided the test lander platform used in this expedition. This work was funded by the National Science Foundation through funding for optical modem development (OCE-0942835) with additional funding from OCE-0926849 and OCE-1036843.

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