Abstract- An important aspect of deploying scientific sensors in the deep sea is reliable underwater communication. We have developed an optical communication system that complements and integrates with an acoustic system to provide underwater communications that is capable of high data-rates and low latency in clear water combined with long range and robustness in the presence of high turbidity. This combined optical/acoustic telemetry technology was recently tested at a CORK (Circulation Obviation Retrofit Kit) borehole observatory in the deep ocean of northeast Pacific. A CORK is a seafloor system to seal a borehole from the overlying ocean to allow the subsea floor hydrologic regime within the sediments and volcanic basement to retain its pre-drilling pressure state. CORKs are instrumented with downhole thermistor strings and pressure sensors and are typically visited on a semi-regular basis by submersible for downloading data and for collecting physical samples of subsurface fluids. We deployed the Optical Telemetry System (OTS) at the Hole 857D CORK in 2420 m water depth using the submersible ALVIN in July, 2010. The OTS was plugged into the existing underwater connector on the CORK to provide not only an optical and acoustic communication interface but also additional data storage and battery power for the CORK to sample at an increased 1 Hz data-rate. Using a CTD-mounted OTS similar to the seafloor unit we were able to establish an optical communication link at a range of 100 meters at rates of 1, 5 and 10 mega bits per second (Mbps) with no bit errors. Subsequent tests were done to establish the optical range of the various data rates and the optical power of the system. After approximately 1 week we repeated the CTD-OTS experiment and downloaded 20 Mb of data over a 5 Mbps link at a range of 80 m. The CORK-OTS will remain installed at the CORK for a year.

Our Optical Telemetry System (OTS) enables faster data rates to be employed for in situ measurements that were previously limited by data download times from a submersible. The OTS also permits non submersible-equipped vessels to interrogate the CORK borehole observatory on a more frequent basis using a receiver lowered by wire from a ship of opportunity. In the future, autonomous vehicles could interrogate such seafloor observatories in a “data-mule” configuration and then dock at a seafloor cabled node to download data. While borehole observatories may ultimately be linked into underwater cables relaying real-time data back to shore they represent a superb opportunity to test free water optical communication methods. This application of seafloor optical communication could be used for a number of other types of seafloor sensors that may not be linked into a cabled network. The lessons learned from our CORK development efforts will go a long way towards establishing the viability of underwater optical communications for a host of autonomous seafloor sensor systems in the future.

I. INTRODUCTION

Science sensors in the ocean form a key part of any observing system and a critical component of any installed sensor system is underwater communication. While the recent plans for underwater cabled networks will allow sensors to be connected directly to power and data communications [Ocean Observing Initiative - Final Network Design, 2010], there are many situations where sensors are not within the range of a cabled network and will need to operate autonomously. These sensor systems need to be serviced for power and data retrieval if they are to remain installed over any significant time period of a year or more. While power issues are relatively straightforward to address, the methods for underwater communication remain limited especially for high data rate sensor systems. Direct connection requires an underwater wet-mateable (UWM) connection and a submarine vehicle to visit each sensor site. Non-contact communications has primarily been via acoustic methods i.e. acoustic modems. Such systems, while effective over long ranges, have an inherent limitation in terms of bandwidth, typically limited to about 57 Kbaud. Optical communications is an attractive alternative to acoustics providing high bandwidth and relatively modest power requirements, albeit over shorter ranges of 0-200 meters. This range, however, is operationally amenable to either remote submarine vehicle communication or via surface deployment from a ship-based optical communication system lowered on a wire.

We report here on the successful deployment of an optical telemetry system installed at underwater observatory site 857D – a CORK borehole observatory on the flanks of the Juan de Fuca ridge in the northeast Pacific Ocean. A CORK (Circulation Obviation Retrofit Kit) borehole observatory is a seafloor system to seal a borehole from the overlying ocean to allow the subsea floor hydrologic system to return to its equilibrium pre-drill state [Becker and Davis, 1998]. CORKs were first installed at a series of boreholes drilled on the flanks of the Juan de Fuca ridge in the northeast Pacific as part of an Ocean Drilling Program (ODP) initiative [Becker and Davis, 2005]. These CORKs are instrumented with downhole thermistor strings and pressure sensors at various depths in the
subsurface formations and are visited on a semi-regular basis for downloading data and for collecting physical samples of subsurface fluids. Typical CORK measurements have provided important insight into the fundamental properties of the crustal hydrologic system including the permeability of the ocean crust, the overlying sediment layers, and the hydraulic connectivity of oceanic basement. These measurements have, for example, allowed for constraints to be put on the timescale of flow between the ocean and crust [Wheat et al., 2003] as well as the extent of microbial activity at depth [Cowen et al., 2003]. CORK pressure measurements reveal broadband forcing of fluid flow ranging from D.C. buoyancy forces to crustal strain, ocean tidal loading, tsunamis, infragravity waves and seismic body and surface waves. For example, the magnitude 9.1 2004 Sumatran earthquake and subsequent tsunami were both recorded by the 1026B CORK observatory in the northeast pacific despite a limited 15 sec data rate [E. Davis pers. comm.]. A more local seafloor earthquake was detected in 2001 at the 857D CORK and produced a dramatic drop in the borehole pressure regime, which was modeled as the fluid response to a dilatational crustal spreading event [Davis et al., 2004]. The pressure drop was equal to about 20% of the buoyancy pressure that drives nearby hydrothermal venting demonstrating that such events can clearly modulate hydrothermal activity at these locations.

The limited sampling resolution of the CORK data using serial UWM connection and submersible download times have precipitated the need to collect data at higher data rates and to improve the rates of data download. Optical communication methods provide a good solution to this problem and the CORK observatory infrastructure provides a unique opportunity for deploying and testing an optical communications node in relatively controlled conditions. Below, we describe an Optical Telemetry System (OTS) that enables faster data rates to be employed for in situ measurements. The OTS permits non submersible-equipped vessels to interrogate the CORK borehole observatory on a more frequent basis using a receiver lowered by wire from a ship of opportunity. We deployed the OTS system using the submersible ALVIN in July 2010 at the 857D CORK in the Middle Valley region of the Juan de Fuca Ridge in the Northeast Pacific (48° 26.5086’N 128° 42.6512’W). The 857D CORK was the first CORK to be installed [Davis et al., 1992] and thus the OTS installation represents a major upgrade to its data gathering potential. We tested the CORK-OTS both in situ with ALVIN and also with an optical receiver/acoustic transmitter system installed on a CTD wire and using a symmetric digital subscriber line (SDSL) communication link over the CTD wire [Swartz, 2009]. Data was downloaded over an optical link from the CTD to the CORK at various rates from 1 Mbps to 10 Mbps over ranges of 100 m and greater. The tests and results are described below and demonstrate the applicability of optical communications over the important “last 100 meter” range that is critical to the future success of autonomous underwater vehicle interrogation of seafloor sensors. While borehole observatories may ultimately be linked into undersea cables relaying real-time data back to shore, borehole observatories represent a superb opportunity to test free water optical communication methods and approaches that could be used for a number of other types of seafloor sensors that may not be linked into a cabled network.

Figure 1. 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

II. IMPLEMENTATION

A. System overview

The WHOI optical telemetry system (OTS) is a reliable communications system for offloading data from a seafloor CORK observatory to a surface vessel or submarine vessel (Fig. 4). In addition to allowing for data retrieval without the use of a submersible, the high bandwidth of the optical system, 1 to 10 mbps, plus additional power and data storage, allows more data to be accumulated and transferred. The sampling frequency was increased from one sample per minute to one sample per second, dramatically increasing the amount of data to be transferred.

Most of the time, the OTS is in a low power sleep mode, collecting data from the CORK and always listening for an acoustic wake-up request to prepare for data offload. This is
accomplished by using an acoustic modem with a relatively low power listening mode attached to a very low power microprocessor (PIC). The system power consumption in the low power mode is roughly 60mW. Data and command and control signals from the surface are transmitted through the CTD cable to the lowered optical modem via an SDSL 400K bps continuous link. The link between the lowered optical modem and the sea floor unit (downlink) is acoustic down to the CORK allowing for long range wake up and control as well as the ability to acquire range. The high speed data link from the CORK up to the lowered system (uplink) is fully optical.

B. Hardware description

The hardware deployed on the CORK (Fig. 5) consists of a power/data storage housing, which contains batteries, a single board computer (SBC) and acoustic modems, an optical receiver housing, containing the optical modem hardware and two emitter housings containing the optical transmitter and associated driver boards. An ODI underwater wet mateable connector is used to connect the OTS with the CORK. The battery pack consists of 54 Lithium D cells for powering the OTS and 9 Lithium D cells, which are used as supplemental power for the CORK in order to support the 1 Hz sampling rate.

C. Software Architecture

The optical modem software architecture consists of a distributed processing design that uses UDP messaging to communicate. The sub-systems of the OTS can be broken down into six different categories including optical, acoustic, instrumentation, file transfer, power management and system control. This design allows the applications to be run on multiple processors or in parallel for redundancy purposes. Commands can be sent between the master and remote system using either the acoustic or optical paths. In the case of the lowered CTD-OTS unit, all commands from the master (CTD) are sent acoustically and data is sent optically from the remote (CORK) unit.

Operation of the master unit requires a data link that ensures a reliable IP connection greater than or equal to 115200 baud. In cases where a typical Ethernet connection is not possible PPP over serial or SDSL technology can be used. Existing ALVIN wiring will not support an Ethernet connection, so PPP over a RS422 serial connection was used on the submersible during the CORK-OTS deployment.

III. INSTALLATION AND TESTING

A. Deployment with ALVIN

HOV ALVIN was fitted with the equivalent of a lowered OTS with the receiver mounted to the center of the submersible light bar, pointing forward, above the pilots viewport (Fig. 4). Optical emitters were mounted about 0.75 meters to either side of the receiver also on the light bar. An acoustic modem comprises the final component of the system. Power and data were wired through the hull from the optical receiver to an internal computer used for installation, configuration and data storage. The CORK OTS was loaded onto ALVIN’s basket for transport to the seafloor and its subsequent installation. The CORK OTS is a standalone unit
with internal batteries, acoustic modem and an ODI underwater wet mateable connector for connection to the existing CORK system. Also on ALVIN’s basket was a second ODI connector to connect directly to the CORK to download data, and to check the system integrity and configuration prior to plugging in the optical system.

Figure 4. HOV ALVIN ready for launch with an optical receiver and two emitters mounted to the light bar (three small yellow circles, top) and the to-be-deployed seafloor CORK-OTS on the basket (large yellow circle, bottom). The emitters mounted to the light bar are shown on emitting violet light.

ALVIN was launched and then descended to the site of CORK 857D. Upon arrival, the ALVIN ODI was plugged into the CORK and serial communication was verified. Then, the OTS ODI connector was plugged into the CORK and the system was put to sleep to allow time for data to accumulate before it was activated again by an acoustic command sent to the OTS. A bi-directional optical link was established and the data from the CORK was displayed on the submersible computer to verify the correct configuration of communication parameters. Once these settings were verified and the data were correct, the seafloor OTS was deployed on the CORK platform and ALVIN returned to the surface (Fig. 5).

Figure 5. Seafloor CORK OTS installed on top of wellhead 857D next to CORK datalogger (lower left)

B. Testing with lowered link on CTD wire

The lowered OTS was installed on the bottom of a CTD carousel along with a Sonardyne AvTrak USBL transponder. The USBL allowed us to navigate the lowered CTD carousel close to the seafloor OTS at CORK 857D. For the first test, we lowered the carousel to within 75 m of the bottom and an acoustic command was sent to wake up the seafloor OTS. An optical link was established and a data file was transferred to the lowered OTS at 1 Mbps. The CTD carousel was then hauled in until the optical link was broken, at approximately 170 m range. The objective of this first lowered test was to verify the correct operation of the entire system.

Figure 6. Lowered OTS installed on the bottom of a CTD carousel. The optical receiver is mounted near the base of the CTD at the center (visible by its glass dome). To the left and right of the receiver are the two emitters.

The objective of the second CTD-OTS lowering was to quantify the optical range, power and data transfer capabilities of the installed CORK-OTS. The ship was navigated such that the CTD-OTS was at a location 200 meters south of the CORK. The CTD-OTS was lowered to an altitude of ~75 m
from the bottom and a transect was driven to the north at 0.2 kts. Optical power, and received errors were recorded continuously at a rate of 5 Mbps for the transect. The ship then navigated to a position directly above the CORK and a vertical cast was performed collecting the same data as was collected during the horizontal cast. The CTD-OTS was then lowered to a series of altitudes beginning at 108 m and ending at 138 m where data file transfers were attempted at data rates of 1, 5 and 10 Mbps. Table-1 shows the results of the data file transfers at these various rates and ranges.

Table 1. Data file transfer rates vs transmit range

<table>
<thead>
<tr>
<th>Range (meters)</th>
<th>Data transfer rate (Mbps)</th>
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<tbody>
<tr>
<td>108</td>
<td>1, 5, 10</td>
</tr>
<tr>
<td>118</td>
<td>1, 5</td>
</tr>
<tr>
<td>128</td>
<td>1, 5</td>
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<td>138</td>
<td>1</td>
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</tbody>
</table>

Figure 7. Spatial track of the CTD-OTS near the CORK-OTS. The data shading depicts the amplitude of optical power received and correlates to achievable data transfer rates.

Figure 7 shows the path traversed by the CTD graphically with the axes being altitude from the sea floor in meters and horizontal distance from the CORK. The shading of the data represents received power, which falls in the range of nano Watts to a micro Watt over most of the transect. The amplitude of received power correlates well with data transfer rates: i.e. approximately twice the power is required for a 10 Mbps transfer as for a 5 Mbps transfer.

Optical power versus range follows approximately an inverse exponential relationship, as depicted in Figure 8. While the actual radiative transfer in our system is a complex and variable combination of spreading losses, absorption, and multiple scattering, which depends on water quality, the end result is a steep fall-off in signal at extreme range [Pontbriand et al., 2008]. The linear tradeoff between required average signal power and data rate does not compensate for the logarithmic decrease in received power at the edge of the optical link. Reducing the data rate will increase robustness in the 120-140 meter range, but it will not extend the link appreciably in distance.

Figure 8. Optical power received at CTD-OTS vs range to CORK-OTS; approximately 15-20 Watts source power

IV. SUMMARY

We successfully deployed and characterized the Optical Telemetry System (OTS) at the Hole 857D CORK in 2420 m water in the north Pacific. This operation involved the use of the ALVIN manned submersible to install and configure the OTS equipment, and a standard shipboard CTD rosette outfitted with an OTS to retrieve data from the CORK via a free water optical link of 1 to 10 Mbps raw data rate.

An SDSL modem permitted high speed communication from the ship to the CTD-OTS over the CTD wire and a shipboard USBL navigation system helped to locate the CTD-OTS accurately over the CORK-OTS.

We showed that it is possible to establish an optical data link over ranges in excess of 120 meters in clear, deep ocean water, and that this was easily maintained in a sea state of 3-4 with the CTD-OTS during this deployment.
This size of the watch circle (200 m diameter) is promising for other data mule implementations using autonomous underwater vehicles, less capable vessels (i.e. no dynamic positioning) or lower precision navigation techniques. Our high bandwidth, optical telemetry system enables wireless underwater data links over the range of 0 to 100 meters, which will allow more frequent data retrieval from optically equipped remotely installed seafloor sensors in the future. This technology also has the advantage of freeing up valuable resources, such as the HOV ALVIN, for more appropriate manipulation intensive missions.

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