A Smart Sensor Web for Ocean Observation: System Design, Architecture, and Performance

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***Abstract* – Much of the cost and effort of new ocean observatories will be in the infrastructure that directly supports sensors, such as moorings and mobile platforms, which in turn connect to a "backbone" infrastructure. Four elements of this sensor network infrastructure are in various stages of development, presented here: (1) a cable-connected mooring system with a profiler under real-time control with inductive battery charging; (2) a glider with integrated acoustic communications and broadband receiving capability; (3) an integrated acoustic navigation and communication network with tomography on various scales; and (4) a satellite uplink and feedback system. We also present initial results from field experiments, as well as from studies on communication performance of the underwater sensor network system under development.**

I. Introduction

Over half the world's population lives within 200 km of a coastline. Improving our physical understanding in coastal zones and ultimately having a predictive capability would have huge societal and economical impacts. Despite the recent success of NASA satellite missions in global weather and climate research, satellite data remain underutilized in coastal areas. Our NASA sponsored work aims to demonstrate the use and benefits of satellite data in prototyping a dynamic sensor web system in the coastal environment to improve our understanding and enable predictions. Both mobile and fixed underwater assets are combined in a loop with a suite of NASA satellites to establish an integrated sensor web with reconfiguration capabilities. While satellite observations provide a global perspective, in-situ underwater sensors provide a continuous 3D presence in the local water column. Two-way interactions are established between the integrated sensor web system and predictive models. The sensor web data is first assimilated into predictive models with a goal to fill in the gaps where and when there are no measurements, and to reduce uncertainties of the model simulation and predictions. The assimilated model is then used to guide the future observing strategy (or adaptive sampling), thus closing the loop of an end-to-end autonomous sensor web from measurement to predictive modeling (see Fig. 1).

As part of the Earth Observing System (EOS), several satellite missions have been providing systematic measurements that are directly related to our work. They include MODIS (Terra and Aqua), TRMM, AVHRR, QuikSCAT/SeaWinds, AIRS, and Jason-1. The Jason-2/OSTM (Ocean Surface Topography Mission) mission, planned for launch in 2008, will provide a continuous measurement of sea surface height after Jason-1. In addition, the Aquarius mission, as part of the Earth System Science Pathfinder (ESSP) exploratory missions, will be launched in March 2009 and will provide the ocean surface salinity measurements that are required to close the water budget over the ocean.

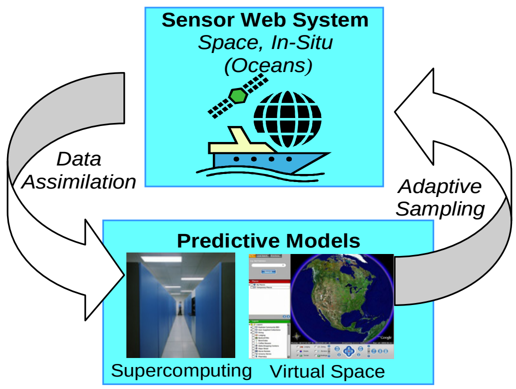

Figure 1: A semi-closed loop dynamic smart ocean sensor web architecture.

There is currently much activity within the oceanographic community to develop many types of underwater sensor networks: mobile, fixed, autonomous, and cabled. Our ocean-observing smart sensor web is composed of both mobile and fixed underwater assets, with EOS satellite data providing larger-scale context. After an overview of design challenges for wide area ocean networks (Section II), we report on the development of various network elements (Section III). These include a fixed mooring system, with a vertical profiler, cabled to shore, modem-equipped mobile Seagliders, and satellite networking [1-3]. Results from three field experiments as well as initial simulation studies on acoustic communication system performance are then described (Section IV). Two of these components – the mooring and Seaglider – are using acoustics to provide a unifying framework to connect fixed and mobile systems [4-6]. The components, together with satellite networking, and validation and calibration of predictive data models, form a dynamic sensor web for ocean observation incorporating integrated precise timing, navigation, and communications, combined with science. Future directions are given in Section V.

II. Wide Area Ocean Networks

A. Network Overview

Architectural issues underlying the conceptualization and design of underwater oceanic networks are of increasing importance due to imminent and planned deployment of sensors in the ocean for a variety of purposes. These include ocean observatories driven by scientific considerations such as NEPTUNE [7-14] or mission-oriented networks addressing commercial or security concerns such as SeaWeb [15]. Network design in such circumstances must contend with a variety of (conflicting) dimensions such as node mobility, coverage area/volume requirements, energy constraints, and communications link budget considerations [16-20]. Contending design methodologies can be compared within an overall cost-benefit analysis framework since wide-area ocean exploration remains a costly enterprise. Clearly, network nodes/resources should be located close to the anticipated pockets of interest in terms of scientific phenomena. Hence, if ocean floor exploration is the primary driver, a suitable architecture is to proliferate cabled seabed networks – whereby a set of nodes tethered by cables provide the power and communications infrastructure – such as the proposed NEPTUNE backbone. Similarly, for exploration of ocean sub-surface bulk phenomena, the presence of surface elements such as buoys and moored profilers is desirable, as indicated in Fig. 2 that shows a conceptual moored observatory combined with mobile nodes and satellite networking.

While such an architecture solves the issues of power and bandwidth availability at critical node points, it incurs costly capital expenditures and cannot scale for large area/volume coverage. One way to achieve wide-area coverage at reasonable cost is the deployment of a network that employs autonomous underwater vehicles (AUVs) which are battery powered, self-propelled (mobile) nodes. Such nodes provide many other advantages besides cost, including the flexibility to dynamically reconfigure network topology to localized events of interest as they occur. However, the current state-of-art in AUV design determines the limits of range and data transfer capabilities achievable and will dictate the density of AUVs needed for coverage.

The type of wide-area oceanic network under development here is comprised of (see Fig. 2):

a) A network topology and architecture which will evolve out of a cabled backbone (that will eventually provide DC power on the order of 10 kW, and high-speed connectivity such as 1 or 10 Gbps Ethernet) along the ocean floor (at depths of 1-5 km), emanating from an on-shore gateway.
b) A mooring system with junction nodes at the top and bottom that support a vertical profiler. This has limited power (periodically charged when docked at its end points), gathers continuous data and is outfitted with an inductively coupled modem for real-time data transmission to shore.
c) A set of junction boxes on the seafloor and moored in the water column constituting the network's 1st-tier nodes. These boxes are powered and contain acoustic transceivers; they will be sparsely positioned (approx. 100 km separation) along the backbone cable. Each junction box can act as a hub for connecting wired sensors as well as wireless sensors via 1-hop to form a local area network. For many lower power sensors, a wireless connection is the more economical.
d) Powered underwater unmanned vehicles (Seagliders) that will primarily function as range extenders for volumetric coverage beyond the 1-hop radius of 1st-tier nodes; several of these can collaborate and reconfigure their formation to perform optimized environmental sampling and/or passive acoustic monitoring missions on an on-demand basis.
e) Satellite networking for data assimilation, calibration, predictive model formation, and fine tuning measurements made from space, increasing their accuracy and timeliness.

Topologically speaking, the core network will evolve as a rooted tree with (shore-based) gateways acting as a root node, and potentially multi-hop transmission of data from remote Seagliders to the root node (via 1st-tier junction boxes) using other collaborating nodes in the vicinity (other Seagliders). The largely static nodes with power tether will either reside on the sea-bed or float on the ocean surface (surface buoys) and serve as egress points for observed data to a shore station (either directly or via an intermediate satellite station). The mobile AUVs on the other hand are lightweight, battery powered and capable of autonomous exploration.

B. Design Challenges

From the above description, several system aspects are seen to be of immediate significance from the network design perspective:

- What are the geometrical considerations and traffic characterization for a 1-hop sensor network – i.e. network radius and node locations; how many sensor nodes and their respective traffic profiles (mean rates, max and min deviations, storage and processing capabilities etc)? Of particular interest will be modeling the profiler for data rate as a function of time if near real-time operation is a driving consideration.
- What are the capabilities of the Seagliders – i.e. maximum radius of operation and associated link performance; particularly what is the design for the physical and media access control (MAC) layers? An important component of this will involve modeling energy consumption as an integrated function of their navigation and communication suites, to suggest how efficiencies in both areas may be achieved.
- In what ways can the sensor network be reconfigured, expanded, or otherwise modified without a loss in performance? What configurations, topologies, and network routing schemes are conducive to scalability in terms of power and bandwidth usage, congestion control, and overall network robustness to disruptions?
- Successful sensor network design (topology, protocol stack and associated algorithms), must incorporate credible link models. It is well-known that the impact of unreliable links manifests itself at the physical layer, and higher layers, specifically on the MAC and routing protocols, significantly impacting aggregate sensor network performance. Specifically, one will have to characterize a) the channel rate vs. range/Doppler profiles as a function of frequency, bandwidth, transmit-receive geometry, ocean acoustic parameters etc., and b) theoretical upper bounds on link capacity to explore important trade-offs: since both available bandwidth and channel attenuation increase with frequency, an optimum frequency band/signal bandwidth for our environment can be computed.

III. Network Elements

A. Mooring System

The moored profiler[1] is a University of Washington/Applied Physics Laboratory (UW/APL) design for use with seafloor observatories with power and communications provided by a connection to shore via electro-optical cable [21-24]. This system addresses the challenge of sampling the ocean with both high temporal and vertical resolution. The mooring consists of three main components (Fig. 2): a near-surface float at a depth of 165 meters with a secondary node (junction box – J-Box) and suite of sensors; an instrumented motorized moored vertical profiler moving between the seafloor and the float that will mate with a docking station on the float for battery charging; and a secondary node (J-Box) on the seafloor with a suite of sensors. Both secondary nodes will have remotely operated vehicle (ROV) mateable connectors available for guest instrumentation. The profiler will have real-time communications with the network via an inductive modem that will provide remote control functions to allow the sampling and measurement capabilities to be focused on the scientific features of greatest interest.

The moored profiler system being developed connects to a cabled observatory node, thereby removing power as the major constraining factor [21-24]. The profiler's docking station with an inductive coupler will transfer 200W to the profiler, enabling a 95% duty cycle (Fig. 3). Furthermore, two-way inductive communications will be used to offload profiler data at modest rates in real time as well as transfer adaptive sampling commands. Secondary junction boxes on the subsurface float (Fig. 4) and on the seafloor (Fig. 5) will provide several hundred watts, 100 Mb/s Ethernet, and precise time to users, and be ROV-serviceable. Instrument packages (e.g., Fig. 4) can be added on the subsurface float, such as a winched profiling system to carry point and remote sensors through the mixed layer to the surface.

The mooring system is considered a prototype, as called for in the planning for the ORION NEPTUNE regional cabled observatory project in the northeast Pacific [7-14]. This particular mooring will be tested in Spring and Summer of 2007 in Puget Sound, Washington, and deployed on the MARS cabled observatory system in Monterey Bay, California, in 900 m of water in November 2007 [25]. At the time of this writing, a simple node has been installed at the UW/APL/OSC Marine Technology Seahurst Observatory in Puget Sound, just west of Sea-Tac International Airport. This node and associated sensors will be used for testing.

B. Acoustic Seaglider

Mobile acoustic nodes are essential elements of an ocean observing/surveillance system. These nodes are necessary to provide precise time, navigation, and communications infrastructure services [26]. Further, the acoustic receiving capability can serve multiple purposes: tactical sensing, tomography, and ambient sound recording (seismics, wind, rain, marine mammals). These will be useful tools for basic and applied research on temporal and spatial signal and noise coherence and coherent processing.

[1] See http://alohamooring.apl.washington.edu

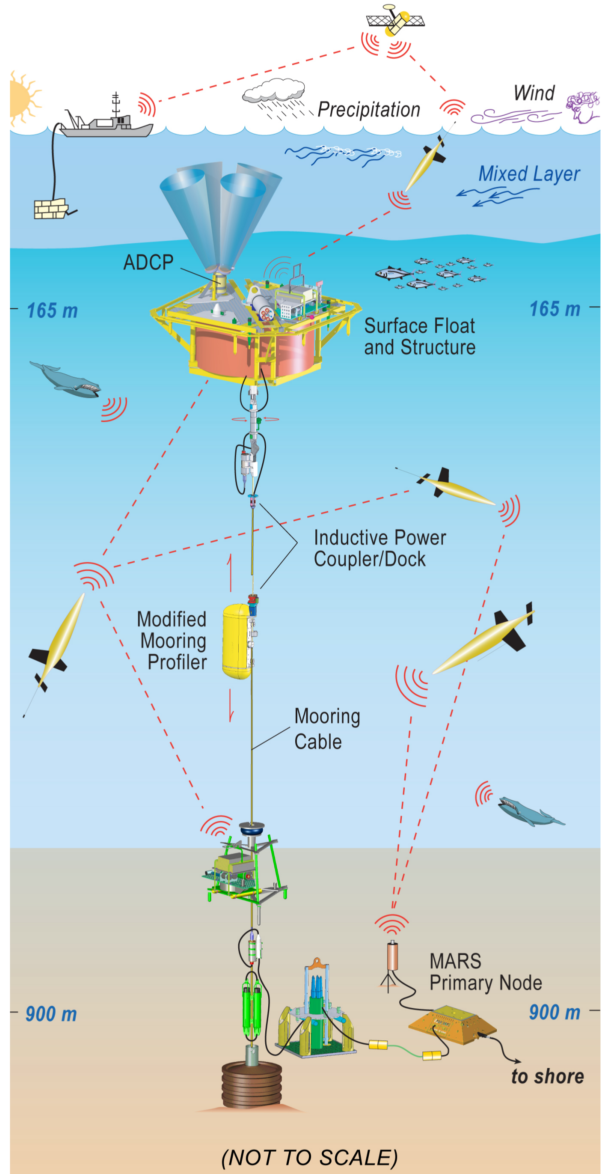

Figure 2: An Ocean observing sensor web system.

The acoustic Seaglider (Fig. 6) is an APL developed autonomous vehicle, 1.8 meters long and weighing 52 kg with low hydrodynamic drag shape [4]. Seagliders are buoyancy-driven, relying on battery powered hydraulic pumps to bring about changes in buoyancy for generating thrust for propulsion. Typically, they move slowly through the water to conserve energy and achieve desired range or mission durations. Designed to operate at depths up to 1,000 meters, the hull compresses as it sinks, matching the compressibility of seawater (Fig. 2).

Seagliders can travel at varied angles – from gentle (e.g. 1:5) to steep (3:1). At gentle glide slopes the vehicle transits most efficiently in terms of battery consumption, while steeper slopes are used to maintain position and act as a "virtual mooring". Seagliders can gather conductivity-temperature-depth (CTD) data from the ocean for months at a time and transmit it to shore in near-real time via satellite data telemetry. Seagliders make oceanographic measurements traditionally collected by research vessels or moored instruments, but at a fraction of the cost. A power budget analysis of Seagliders is given in [27]. Seagliders can survey along a transect, profile at a fixed location, and can be commanded to alter their sampling strategies throughout a mission (Fig. 3).

Figure 3: The inductive power system coupler

Figure 4: The subsurface float and secondary node, with instrument package and an Acoustic Doppler Current Profiler (ADCP).

Figure 5: The seafloor secondary node

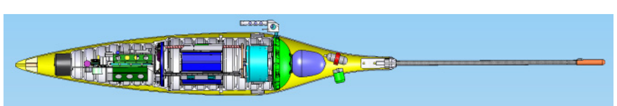

Figure 6: Schematic of the acoustic Seaglider with the hydrophone and modem in the tail.

C. WHOI MicroModem

This modem (Fig. 7) developed at the Woods Hole Oceanographic Institution will be used in our network backbone, deployed on Seagliders, as well as on seafloor and moored nodes (See [28] and http://acomms.whoi.edu). As a firmware upgradeable modem, this is a simple, yet powerful device, enabling data rates of 80-5400 bps and a good level of control via software, such as

- Acknowledgement of individual data packets/frames.
- Ability to measure travel time to specific units or determine if they are in range.
- Remote control of hardware output lines on the modem (e.g. to drop a weight).
- Low power operation modes.
- interface to on-board A/D converter.
- Tracking of relative Doppler between source/receiver.
- Built-in data FIFO flash buffer for data storage prior to transmission.
- Multiple transmit rates using frequency, or phase shift keying, and one receive data rate. Frame integrity is protected with a cyclic-redundancy check (CRC).
- Reporting of real-time clock time, start/end of packet transmission, and ACK that a frame has been received correctly by another unit.
- Transponder navigation capability.

Seagliders have been recently equipped with a broadband hydrophone (5 Hz–30 kHz) acoustic receiver system (ARS) and the MicroModem, operating in this case at 25 kHz. The ARS can store raw data on a 60-GB disc as well as send back computed power spectra. The ARS is synchronized to GPS when at the surface, with 1 ms accuracy maintained during dive cycles. When on the surface, the glider communicates with shore-based pilots using the Iridium satellite system.

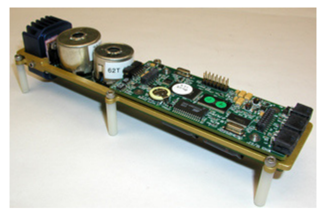

Figure 7: The WHOI MicroModem

D. Satellite Networking and Models

Two-way communications from the Seagliders to satellite and shore are accomplished using two Motorola 9522 satellite modems via the Iridium network. Iridium modems use a direct-dial connection to a Linux workstation through a POTS telephone line or a backup Iridium modem. The connection speed for the Iridium modems is 2400 baud. Once a connection is made, PPP (point-to-point protocol) is used to run IP (Internet Protocol) allowing the use of standard networking tools for communication and file transfer.

The primary Iridium unit contains an integrated GPS receiver and is turned off when not in use. The secondary unit is powered at all times and will accept incoming connections. Simultaneous connections are possible and the controller supports multiple PPP connections when increased bandwidth is required. Each modem, along with its power converter and antenna are mounted in waterproof housing on the Seaglider.

Satellites are used in three ways within our sensor web system: 1) for uploading data gathered locally to scientist workstations, i.e., as communication network node relays, 2) for downloading mission profiles from shore or ship to the Seaglider, and 3) most importantly for end-to-end integration of in-situ underwater sensor network driven models with satellite data, and their assimilation into a Regional Ocean Modeling System (ROMS) to realize the goal of adaptive sampling. In-situ calibration of satellite data will also be possible. In this sense, while underwater sensors provide a continuous 3D presence in the local water column, satellite observations provide a global perspective, and combination of both of these views into a unified modeling and prediction system enables new science as well as new sensing capabilities.

IV. Experiments and Simulation Studies

Much needs to be done to integrate the above elements in both hardware and software, to enable the ocean observing sensor web vision and concept. We are currently at the preliminary stages of deploying various network elements in the field, simulating communication system performance offline, and porting initial network protocols for the Media Access Layer (MAC) and network layer into hardware/software for field testing.

When the mooring is deployed in Monterey Bay, several WHOI MicroModems will be deployed with it and on the seafloor. Several gliders with modems will fly around the mooring, all communicating with one another, to test and demonstrate acoustic communications network protocols, designed to operate with multiple units communicating at the same time in an environment with large latency and delays (Fig. 2). This is one step toward using gliders (and other mobile platforms) as communications gateways, transporting data and commands between subsea platforms and shore via Iridium, as well as for integrating multi-scale navigation and acoustic tomography in such systems [29-34]. We report here on initial results from Seaglider experiments, as well as preliminary results from simulation studies of underwater communications.

A. Initial Seaglider Experiments

The Seagliders have so far been used in three experiments [35]:

1. LWAD-06 [29–30 July 2006, Seaglider SG022, 14 dives]: Measured signal transmission loss as a function of range, made ambient sound and temperature/salinity measurements in the Philippine Sea. Low-frequency signals transmitted by a nearby ship as well as signals from a distant ship/source were received clearly.
2. MB06 [12–25 August 2006, three gliders (number of dives), Seaglider SG022 (61), Seaglider SG023 (83), Seaglider SG106 (131)]: In this major multi-project experiment in Monterey Bay, the acoustic Seaglider served as a communications gateway for subsea assets “talking” with shore via acoustic modem and satellite links. This was an important demonstration for the concept of undersea persistent surveillance. Glider SG106 relayed commands successfully from shore to a bottom-mounted University of Texas/ARL array and relayed associated status messages from the array back to shore. Ranges up to around 4 km were achieved in around 100 meters of water depth with a small bias to deeper depths due to the downward refracting sound speed profile (Fig. 8). The “Lubell” source [2] was received and Doppler measured during this experiment. In addition, one glider was tracked by MIT kayaks.
3. Kauai [31 August–8 October 2006, Seaglider SG023, 143 dives]: Listened to the NPAL/ATOC 75-Hz source as a function of range and depth to demonstrate tomography signal reception, study signal coherence, long-range communication capability, and to collect ambient sound data. Off Kauai, the NPAL/ATOC transmissions at 75 Hz were received; coherent processing was possible (with 10 dB of gain) with the glider moving 136 m horizontally, 33 m vertically, and over a 12-minute period. Figure 9 shows relative travel time increasing by 3.8 ms (5.5 m)/27.28 s block, equivalent to 0.20 m/s, consistent with measured Doppler shift.

It should be noted that oceanographic data (temperature and salinity) and ambient sound, many from marine mammals, are also routinely collected, and for MB06, assimilated into ocean models (ROMS, Harvard and JPL) in near real time.

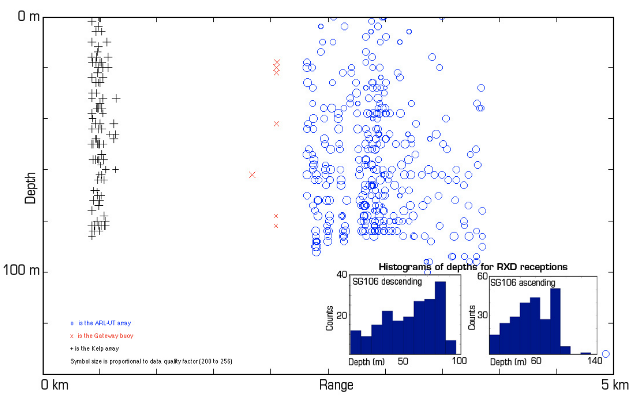

Figure 8: Depth and range positions where modem communications occurred.

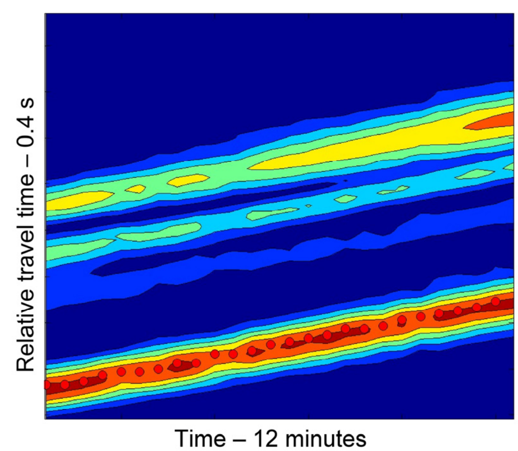

Figure 9: ATOC/NPAL acoustic transmissions received on the acoustic Seaglider.

B. Initial Communication System Simulation

The difficulties of the underwater acoustic communications channel are well-known: overall bandwidth is limited due to acoustic absorption that increases with frequency, and typical shallow water regions where communications are desired have high degrees of spatial and temporal variability.

Designing an underwater network is often considered a constraint imposed on other system optimization considerations whose metrics are derived from the intended

[2] This is a piezoelectric transducer delivering 197 dB/uPA/1 m at 600 Hz (80 V rms). Its main advantage is its size and weight for a useful band of 400 Hz – 8 kHz.

mission of the sensing nodes. Therefore, nodes should be deployed such that the overall sensing mission will be successful, but mission success may also depend on information being passed between nodes through the communications network. The networking schemes will likely be *ad hoc* in nature if moving vehicles comprise some subset of the nodes. Although specific requirements may differ among applications, one fundamental requirement is usually some basic level of connectivity between nodes. Successful design of a network configuration then depends on the ability to predict the likelihood of communications packets being successfully received.

We are developing a methodology for modeling acoustic communications performance based on high-fidelity acoustic time series modeling and acoustic modem processing emulation [36]. In this effort we utilize the Woods Hole MicroModem and a software package that emulates its transmit signal generation and receive signal processing and demodulation process. Furthermore, in order to accurately model the effects of acoustic propagation through the ocean between potentially moving sources and receivers, the Sonar Simulation Toolset (SST) [37] is being used.

SST allows a user to specify an ocean environment with a wide variety of parameters relevant to acoustic signal propagation and reception: sound speed profile, bathymetry, surface/bottom characteristics, ambient noise levels, and others. The user can also specify locations and trajectories of acoustic sources and receivers within that environment, and signals to be transmitted by the sources. SST then uses acoustic propagation models and time series simulation techniques to produce properly calibrated digital time series of the signals that would be “heard” by the receivers. These time series can then be operated on by signal processing algorithms, such as the MicroModem emulator mentioned above.

An example of the simulation procedures can be found in Figs. 10 and 11. Figure 10 shows a conventional transmission loss (TL) plot in a vertical slice of the ocean computed using a Gaussian ray bundle approach [38]. The narrow panel on the left shows the sound speed profile as a function of depth, and the larger panel on the right shows the loss of sound pressure level (relative to the source level) in dB as a function of range and depth for a source transmitting a 10 kHz signal from 70 m depth. Note the very high loss values for receivers above the thermocline.

SST uses the same basic information about ray paths used to generate the TL information for Fig. 10 in generating actual time series realizations for receivers at various locations in that vertical slice of the simulated ocean. Figure 11 shows the results of generating such data and using the MicroModem emulation software to demodulate the results. The top panel of Fig. 11 shows the number of raw bit errors (out of 640 transmitted) that occur for a grid of hypothesized receiver locations. The bottom panel shows the number of bit errors at the receiver locations after the built-in error correction of the modem is used. In the lower panel, red indicates that a data packet was not successfully received. Note that there is no communications performance for receivers above the thermocline, and rather complicated spatial patterns of performance exist below the thermocline for ranges greater than 10 km.

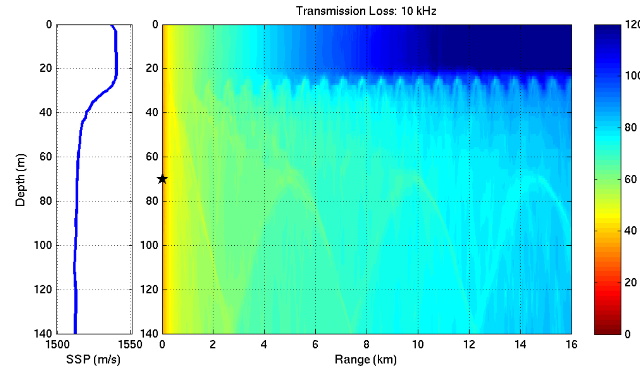

Figure 10: Transmission loss (dB) at 10 kHz for a source at 70m depth.

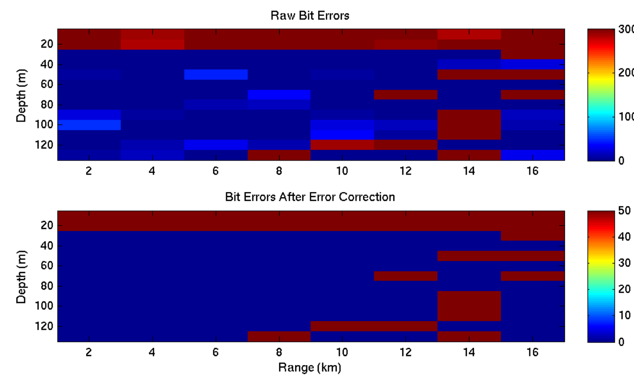

Figure 11: Bit errors as a function of receiver location: raw bit errors in top panel, bit errors after error correction in lower panel. Red in the lower panel indicates failed packet delivery.

The results shown in Fig. 11 are for a single realization of the ocean channel. In fact, the channel should be considered in a random sense, both due to the additive ambient noise and to variations of sea surface and bottom roughness. SST can be run with different random number seeds in order to generate distinct realizations of an ocean channel with the same statistics. The mean and standard deviation bit errors over 30 realizations are shown in Figs. 12 and 13, respectively. Notice that there are areas with relatively low mean bit error rates, but high variability, such as at range 12 km and depth 120 m. This variability could be due to closely spaced multipath arrivals that, depending on the specific characteristics of the random reflecting surfaces, may interfere in such a way as to cause communications signal acquisition to fail. Taking this type of variability into account could be crucial to designing a robust *ad hoc* network.

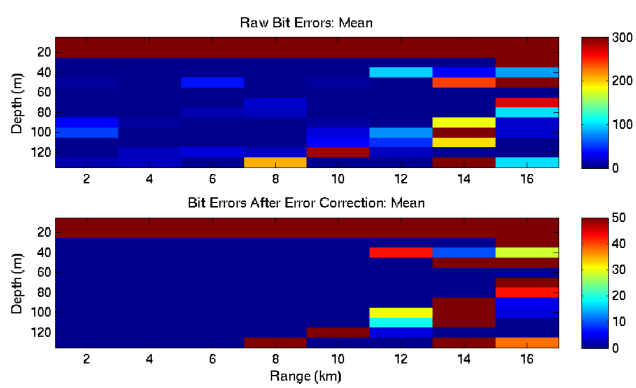

Figure 12: Mean values of bit error results over 30 realizations.

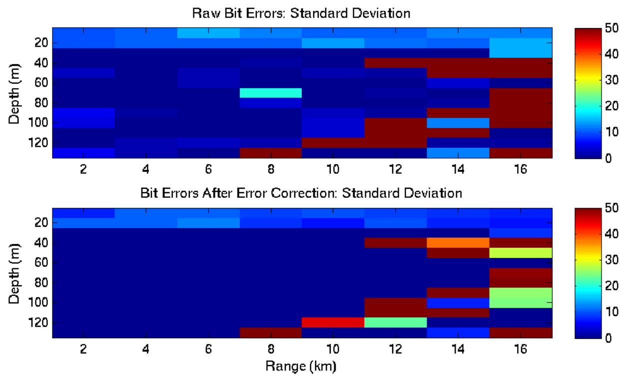

Figure 13: Standard deviations of bit error results over 30 realizations.

V. CONCLUDING REMARKS

These sensor network infrastructure developments enable a wide range of new sensing modalities with fixed and mobile systems. On the mooring, one can put easily-serviced winch systems to sample the upper ocean, as well as complex instruments such as mass spectrometers, environmental sampling processors, acoustic imaging and tomography systems, etc. In addition to conventional ocean sampling, the mobile platforms can serve as data trucks, launched from a pier, going to remote areas (e.g., Southern Ocean) to retrieve data from long-lasting robust instrumentation.

Our goal in this work is to design, develop, and test an integrated satellite and underwater acoustic communications and navigation sensor network infrastructure and a semi-closed loop dynamic sensor network for ocean observation and modeling. This first-of-its-kind sensor network will incorporate features such as reconfiguration of sensor assets, adaptive sampling and autonomous event detection, targeted observation, location-aware sensing, built-in navigation on Seagliders, and high-bandwidth, high-power observation on mooring systems with vertical profilers. Many challenges in communication network design for the underwater channel and data assimilation remain, which will be addressed over the next three years. Our work continues efforts to provide essential infrastructure elements throughout the ocean volume – power, precise timing, communications, and navigation – necessary for any and all ocean observing efforts.

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