THE INDUSTRY'S RECOGNIZED AUTHORITY FOR DESIGN, ENGINEERING AND APPLICATION OF EQUIPMENT AND SERVICES IN THE GLOBAL OCEAN COMMUNITY

MAY 2006

SINGLE ISSUE PRICE $4.50

Reprint www.sea-technology.com

SEA TECHNOLOGY

WORLDWIDE INFORMATION LEADER FOR MARINE BUSINESS, SCIENCE & ENGINEERING

COMMUNICATIONS
TELEMETRY
DATA PROCESSING

Through-the-Hull Acoustic Communication Technology

Ships Hulls as a Wireless Medium for Networking and Data Transfer Among Spatially Distributed Sensors

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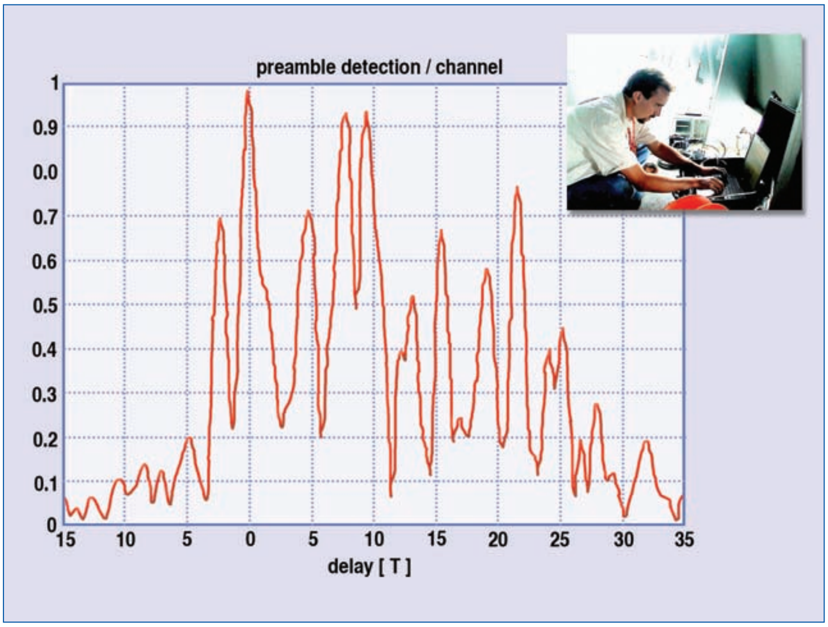
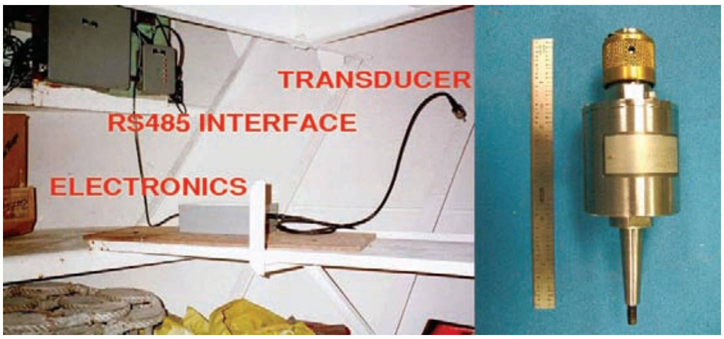


Establishing ad-hoc data communication inside the hull of an oceangoing vessel can pose a significant challenge. This lesson was learned during the installation of Improved Meteorology (IMET) modules on volunteer observing ships (VOS) in merchant fleets. IMET modules are sensor clusters developed by Woods Hole Oceanographic Institution (WHOI) as part of the World Ocean Circulation Experiment.[1] In the program, reliable sea surface temperature (SST) from sensors mounted near the waterline needed to be recorded. Ships that travel the same route are excellent platforms for measuring different data sets over the same areas of the ocean. Such ships, however, are in port for such a minimum amount of time, that it does not allow for the elaborate installation of cables to network the instruments. Since VOSs are frequently replaced to meet contracted load needs, the option of running a wire through bulkheads from the SST area to the main deck is impractical and expensive.



(Top) Data collection on TS Enterprise *main deck (inset). Acoustic channel response at 100 feet.*

(Bottom) Typical installation of the modem inside the hull of a ship (left). Close-up of the acoustic transducer (right).

While most of the data from the topside sensors could be collected at the vessel's bridge by conventional radio frequency (RF) modem, obtaining the data from the SST sensor proved to be a special challenge. The SST sensor is located well inside the hull so that the metal structure significantly attenuates the electromagnetic energy radiated by the RF modem antenna (similar to the operation of a Faraday cage). This was confirmed in the wireless feasibility study conducted at WHOI.[1] Three approaches for data transfer were tried in the study: RF modems, power line coupling and acoustic modems.

The RF modems worked well only within line of sight. Data transmitted by coupling 120-kilohertz pulses to a 60-hertz, 120-volt AC power line were prone to interference from fluorescent lights. Moreover, it assumes the existence of a common power line between two points of communication, which is not

> *"Ships that travel the same route are excellent platforms for measuring different data sets over the same areas of the ocean."*

always true in a ship. Ultimately, acoustic modems remained as the final choice.

Acoustic Modems

The through-the-hull acoustic communication technology, developed by Harris Acoustic Products, provided the most promising solution. As a result, a product named HullCom was developed for the IMET VOS program. The system consists of two sets of equipment. A local acoustic modem unit (AMU-L) is in a location that is easily accessible—such as the bridge, main deck, etc. The second unit is the remote AMU (AMU-R). This unit is placed next to the SST instrument. Each HullCom AMU consists of an acoustic transducer, acoustic transmit and receive electronics, and a power control and communications interface board. The electronics are contained within a watertight package. The transducer can be installed in any part of the ship's hull structure. It installs quickly using a single #10-32 mounting hole and does not necessitate any dry-docking.

The acoustic modem can communicate with the ship's data acquisition computer at 9,600 bits per second. Communications can be either RS232 or RS485. An internal battery is available in the AMUs, and battery power is parallel with the external power and maintains the system in the event of a disruption in ship's power. The AMU-R communicates with the SST unit by RS485 at 9,600 baud. Typically though, the ship's power is not available and batteries are necessary.

In order to expedite product development, simple amplitude shift keying was employed in the AMUs—where ones are marked by a short acoustic pulse and the absence of a pulse indicates a zero. Acoustic reverberations in the ship's hull can last on the order of tens of milliseconds. To allow the reverberations to decay, the ones are defined as acoustic pulses that are five milliseconds long, followed by a silence of 45 milliseconds. This scheme provides a low data rate of 20 bits per second over a distance of approximately 50 feet. While modest in terms of data rate and range, this was sufficient for the application requiring temperature information once every hour. At 20 bits per second, a complete temperature message is transmitted in less than five seconds. The electronics board provides power control, interfaces to the temperature sensor, and receives and passes on the data at 9,600 bits per second, but it interfaces to the acoustic transducer at 20 bits per second due to above-mentioned reasons.

This system has been tested on the WHOI vessel *Oceanus*, on the National Oceanic and Atmospheric Administration ship *Ronald H. Brown* and has been installed in a few merchant ships as part of the VOS-IMET program.

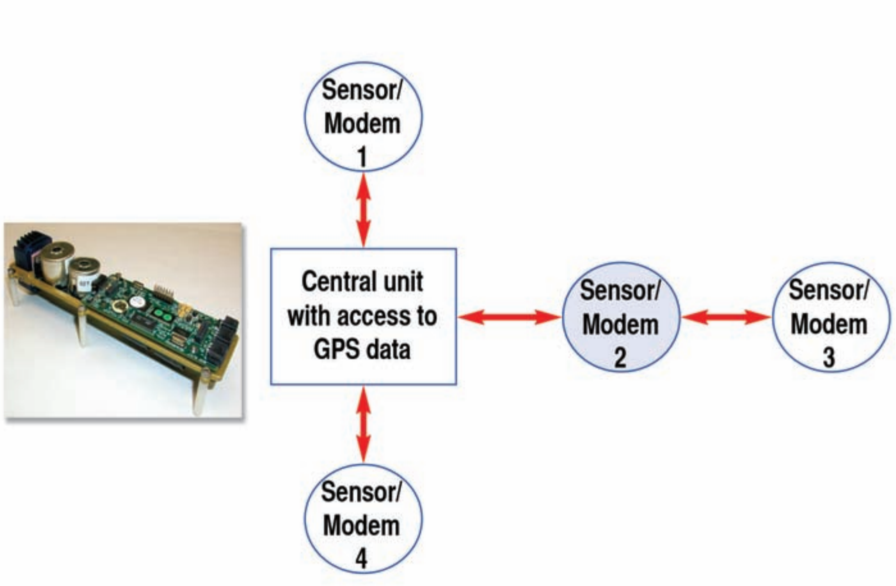
Digital Development

Research to improve the range and data rate of through-the-hull acoustic communication is ongoing. Initial attempts to improve the data rate using other non-coherent communication schemes—such as frequency shift keying, differential phase shift keying and minimum shift keying—proved to be bounded by an upper limit of 80 bits per second due to the multi-paths.

Simulations with real-channel responses indicated the possibility of using phase-coherent detection and equalization of bandwidth-efficient, linearly modulated signals to achieve higher bit rates.[2] A series of experiments were conducted onboard the Massachusetts Maritime Academy's *TS Enterprise*. Candidate signal sets were designed. The modulation methods included binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-PSK and 16-quadrature amplitude modulation. The signals were transmitted from the aft of the vessel on the main deck and were received at different stations along the same deck. The different receiver configurations included a linear and decision feedback equalizer (DFE) with symbol-spaced or fractionally spaced feed-forward filtering.

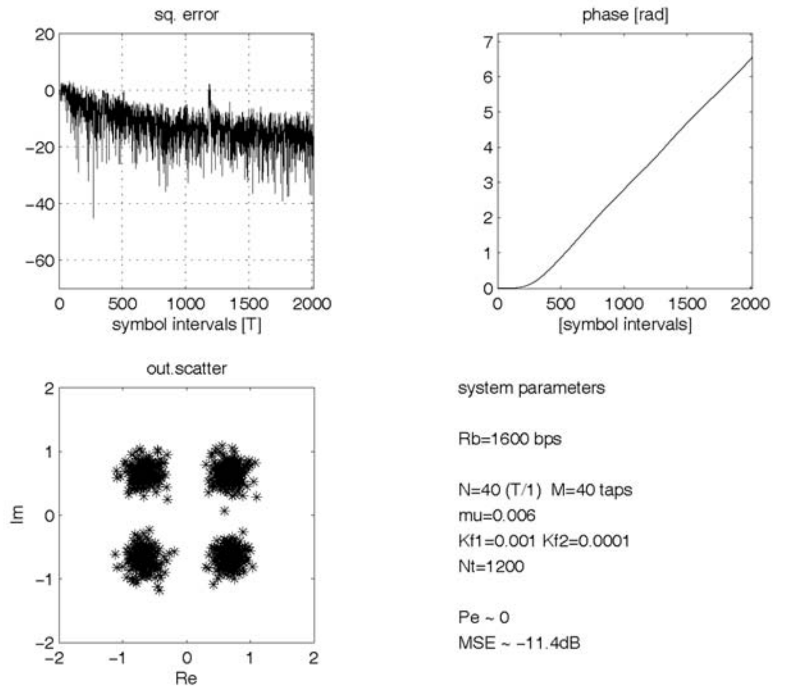
Excellent results were obtained for all of the modulation schemes for a distance of 50 feet. The signals were successfully recorded and processed at the rate of 800 symbols per second, and bit rates of 800, 1,600, 2,400 and 3,200 bits per second were achieved corresponding to the varying modulation levels (two, four, eight, 16).

At 100 feet, successful detection was achieved with BPSK and QPSK. The major distortion observed in the system was the inter-symbol interference (ISI). The ISI was caused by the multi-path propagation, and the delay spread observed in the experiments was between 25 and 50 milliseconds, resulting in severe ISI that spanned multiple symbol intervals. To overcome the ISI, use of the DFE proved essential, and a symbol-spaced DFE operating under the least mean squares algorithm was found to offer the minimum complexity solution up to a distance of 100 feet. Detection at longer ranges is currently limited by the band-



Micro-Modem motherboard (inset). Conceptual diagram of sensor-modem network. Message relay will increase ranges beyond the direct path limit.

Results from QPSK data detection performance at 100 feet.



width of the transducer and the acoustic power level. Research is ongoing for an improved transducer. The algorithms will be ported to a low-power proven digital signal processor, the Micro-Modem, that was developed at WHOI for underwater communications.

The extended range of 100 feet, and the higher data rate of 1,600 bits per second already mark a significant improvement—double the range and 80 times the data rate—over older versions of the modems. The ranges can be further extended by putting the modems in a networked configuration. These improvements open up the possibility of applying the technology to a number of other emerging areas.

Application Areas

One of the possible new application areas will be the automatic monitoring of ballast water discharge compliance. The increase of sea-borne commerce over the last century has increased the vulnerability of native ecosystems and the associated local economy and public health. Threats come from the release of non-indigenous species into new environments from the ballast water discharge of the ships. To reduce the threat, the U.S. Congress passed the National Invasive Species Act of 1996 that requires ships entering U.S. waters from outside the Exclusive Economic Zone to report ballast water management practices. There are different ways to manage ballast water to reduce the threats from aquatic nuisance species. These methods include isolation (discharging water in special reception facilities or returning water to its original location), treatment (mechanical, physical or chemical treatment of the water before discharging) and exchange (flushing the tanks in deep water by empty-refill or flow-through techniques).

Of the three main possibilities, only ballast water exchange is the most economical at present, and is the focus of the U.S. Coast Guard. The new mandatory ballast water management (BWM) reporting program is applicable to all transoceanic ships visiting a U.S. port.[3] Currently, ship operators achieve BWM compliance by manually filling out a Coast Guard form, which is difficult to verify for accuracy and integrity. The need to reduce the burden of paperwork for ship operators, while providing verifiable information to the authorities, will grow in the future. Countries such as New Zealand and Australia already have national BWM rules. The International Maritime Organization has also adopted a convention for comprehensive BWM among all the participating countries.

Since ballast tanks are located in various parts of a ship, collecting the sensor data that monitors the water levels or flows from those tanks in a cost-effective manner can be a significant challenge. The higher data rate acoustic modems can be used to create an inexpensive network of ballast tank sensors, and automated, tamper-proof reports can be generated when needed.

Other potential application areas include the monitoring of wastewater discharge, tank gauging, water ingress monitoring in bulk carriers, independent fuel consumption monitoring in chartered vessels and data communication for marine black boxes.

Acknowledgements

The material in this article is based in part upon work supported by the National Science Foundation under grant numbers DMI-0450355 and DMI-0319497.

Any opinions, findings, conclusions or recommendations expressed in this article's material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

The authors will like to thank David Hosom from WHOI for his support toward the HullCom development, the officials at Maritime Administration for permission to be onboard the *TS Enterprise* and the captain and the crew of the vessel for their support. /st/

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Lee Freitag holds B.S. and M.S. degrees in electrical engineering from the University of Alaska, Fairbanks, which he received in 1986 and 1987, respectively. He is currently a senior engineer at the Woods Hole Oceanographic Institution, where he has worked on projects related to underwater acoustics for 15 years. Freitag's research programs focus on underwater acoustic communication and navigation, with a strong focus on unmanned underwater vehicles, sensors and submarine systems.