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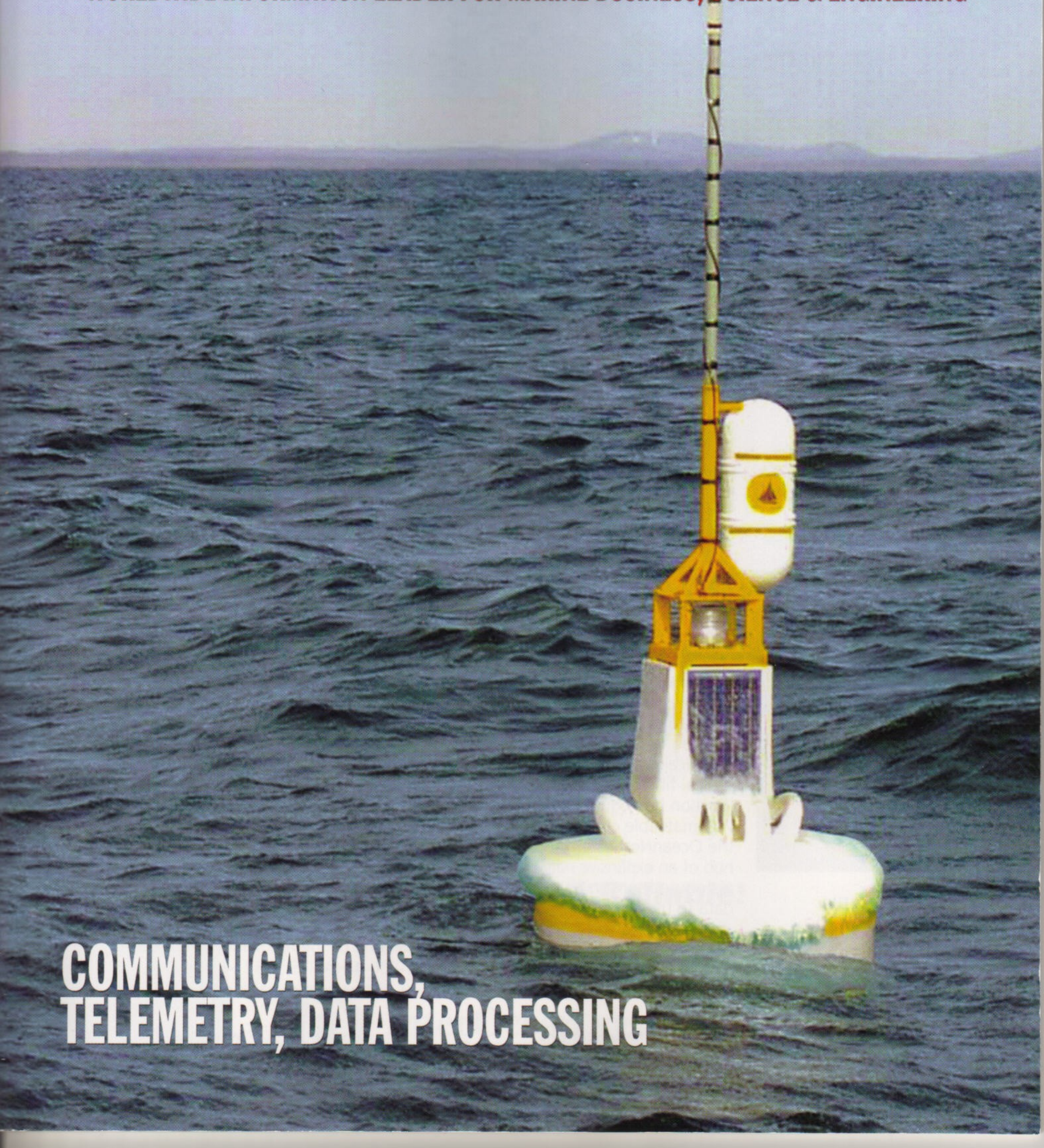
SEA TECHNOLOGY

MAY 2004
SINGLE ISSUE PRICE $4.50

WORLDWIDE INFORMATION LEADER FOR MARINE BUSINESS, SCIENCE & ENGINEERING



COMMUNICATIONS, TELEMETRY, DATA PROCESSING

Experiments Study Underwater Acoustic Communications

Series of Experiments, Combined with Computer Simulations, Unravel Environmental Factors Leading to Variable Performance

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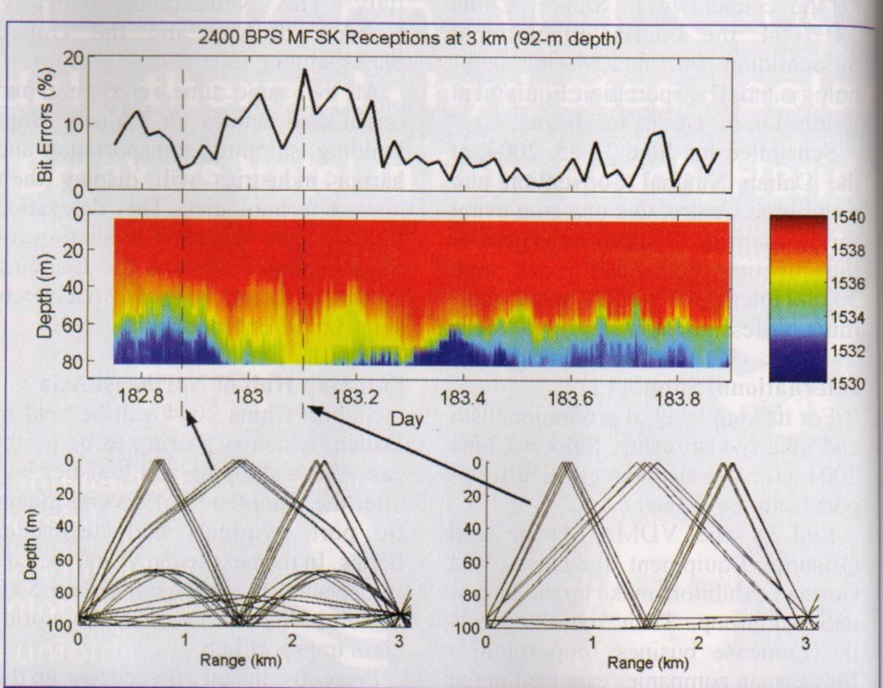
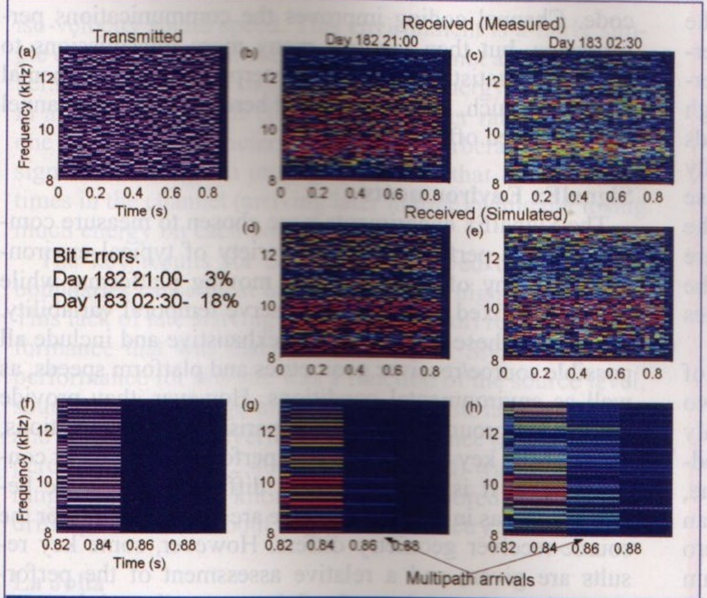


Results from the Kauai: Top panel shows the bit errors on a hydrophone at 92 meters depth, middle panel shows the corresponding sound speed profile, and the lower panels are the ray traces for day 182 at 21:30 (three percent bit errors) and day 183 at 02:30 (18 percent bit errors).

In the last few years, an experimental study has been underway to answer questions about why underwater acoustic modem performance varies significantly at different locations and why this variability is so difficult to predict. These questions are of current interest because the need for reliable underwater communications is increasing as applications emerge for autonomous underwater vehicles (AUVs) and autonomous instrumentation.

Performance in the ocean's shallow-water environments is often the hardest to predict since these sites can be highly reverberant and the channel characteristics can change over time. One of the reasons the ocean channel is challenging for acoustic communications is the large number of multipath arrivals. Multipath is caused by propagation paths that are reflected and refracted between the source and receiver and, therefore, arrive at different times, causing echoes of the transmit signal. Unless compensated for, these echoes can cause intersymbol interference (the reception of previous symbols that arrive at the same time as the current symbol making it difficult to correctly detect what information the current symbol was intended to convey, causing bit errors). In some ocean channels, performance is dominated simply by a signal-to-noise ratio (SNR), while more often, it depends on the multipath interference and its time variability. In all cases, source and receiver motion further complicate the situation as each multipath arrival has a different Doppler shift for which the decoding algorithm may need to compensate.

Observations have shown drastic differences in the performance of underwater acoustic communications at different locations. Even for deployments at the same location, performance can show a large time variability. The reasons for these performance differences are often not well understood. For example, do strong winds lead to increased bit errors due to rougher sea-surface conditions and increased ambient noise level? Or, do strong winds lead to decreased bit errors because surface reflections have high scattering losses and, therefore, reduce the multipath arrivals? Or, for example, what environmental factors can cause bit errors to increase from



Panel (a) shows the transmitted waveform and in (b) the reception is shown for day 182 at 21:00 (three percent bit errors) and in (c) for day 183 at 02:30 (18 percent bit errors). The middle panels (d) and (e) show simulations using measured sound-speed profiles for the same time periods. Lower panels (f), (g) and (h) are zoomed-in views.

zero to 20 to 30 percent in just a few hours, while the winds remain constant and the source and receiver are not moving? Answers to these types of questions are the motivation for the SignalEx program started in 2000.[1]

The purpose of SignalEx is to measure a variety of underwater communications signals in many locations and develop an understanding of the mechanisms that impact performance. While these measurements may have been performed only in particular environments and times using a limited set of possible configurations, the ultimate goal is to be able to extrapolate these results to the full range of possible environmental conditions (e.g., as the weather and season changes), for all possible source and receiver geometries, and for the full suite of modulation schemes, such as multi-frequency shift keying (MFSK), phase shift keying, orthogonal frequency division multiplexing, etc. This will enable reliable mission planning for acoustic communications.

To achieve this goal, we have developed sophisticated modeling tools to synthesize realistic ocean channels and the communications signals that would be observed by receivers in any given geometry, with platform motion and channel dynamics included. This modeling is based on the current understanding of the physical phenomena that contribute to the channel dynamics, such as surface waves, bottom roughness and water column variability. We are in the process of validating these models using data measured during the SignalEx experiments. The key is to have simultaneous measurements of environmental parameters (e.g., wind speed, sound speed and bottom type) while acoustic communications signals are being transmitted and recorded.

The first stage in the process is to verify that the channel simulator precisely reproduces both the multipath structure and the communications performance in the SignalEx tests. Then, the channel simulator can serve as a basis for virtual experiments for any desired environment or configuration. For instance, suppose an AUV mission is planned for an area that had previously shown good communications performance for source and receivers moored near the seabed. The AUV is, of course, a moving platform operating at different depths and possibly in a different season. The mission planning software must then extrapolate the communications performance to consider those differences. Demonstrating accurate predictions of acoustic communications performance for the conditions when the SignalEx data were recorded builds confidence in being able to predict performance in new situations where acoustic communications tests have not been done. The environmental information needed for these simulations can often be found in existing Navy databases, and if the models are sufficiently reliable, these can be used to anticipate and optimize performance.

MFSK Signals

Coherent and non-coherent signals are two general categories of communications. The non-coherent methods exploit the energy of the signal, which makes them relatively robust and simple to implement. The coherent methods exploit the phase of the signal, which offers a more efficient use of bandwidth, providing higher data rates for a given spectral band. However, the increased bandwidth efficiency requires a much more complicated system since the phase is highly sensitive to the channel characteristics and source and receiver motion. Currently, most commercially available modems use non-coherent methods, since many applications will readily trade-off increased reliability for lower data rates.

During the SignalEx tests, a suite of both coherent and non-coherent signals were transmitted, however, for the analysis presented here, we focus on the non-coherent

MFSK. In addition to being valuable in its own right, the simple and robust nature of MFSK signaling makes its performance a highly valuable yardstick for comparing different environments and other signaling methods. Although the MFSK signals were transmitted in different bands between eight and 50 kilohertz, we will discuss results only in the eight to 13.2-kilohertz band. These MFSK signals use 128 frequency components spaced 40 hertz apart. The upper and lower four frequency bins in each band are reserved for pilot tones to compensate for Doppler. The information is passed using a subset of the 128 frequencies that can be modified every 0.025 seconds.

One detail of the modulation scheme is the use of one of four coding. This means four tones are used to encode two bits of data. The advantage of this is that in decoding, only a decision about which of the four tones is loudest is needed to determine if the transmission is a zero,zero, zero,one, one,zero or one,one. This method is less problematic than having the decoder decide if a tone is a one (on) or zero (off). Based on the frequency band used here, the maximum data rate in each band is 60 bits in 25 milliseconds, or 2,400 bits per second. To transmit at lower data rates, the time duration of the tones is increased (e.g., 1,200 bits per second is achieved by holding the tones on for 50 milliseconds). Achieving higher data rates requires more bandwidth. Preceding the MFSK transmissions is a marker pulse used to determine the signal start. A spectrogram is then taken of the MFSK portion of the time series using a non-overlapping boxcar window of 25-millisecond duration. The highest tone in each block of four tones is then determined. Practical systems inevitably use so-called "channel coding," which may be thought of as a sort of parity check code. Channel coding improves the communications performance, but then requires many more transmissions to collect the statistics required to interpret the environmental effects. As such, results presented here are with the channel coding turned off.

SignalEx Environments

The SignalEx experiments were chosen to measure communications performance in a variety of typical environments.[2] Many of the tests used moving platforms, while some used fixed moorings to observe temporal variability. Obviously, these tests cannot be exhaustive and include all possible source/receiver geometries and platform speeds, as well as environmental conditions. However, they provide the needed ground-truth for comparisons with simulations, which is the key to extrapolating performance to other configurations. It is also somewhat difficult to compare between sites, as in some cases there are fewer statistics or the source-receiver geometry differs. However, some key results are given, and a relative assessment of the performance is presented for each of six tests—all used the same transmitter equipment with a nearly flat spectrum in the eight to 16-kilohertz band with a source level of 185 decibels referenced to one micro Pascal at one meter.[3]

Ship Island

The Ship Island tests were in October 2001, off the coast of Mississippi, in the Gulf of Mexico. This area is very shallow (four to five meters water depth) and has a seabed with sediments that are lossy and not very reflective to acoustic signals. The test was in the fall and the windy conditions caused the water column to be fully mixed, leading to an

iso-velocity sound speed. This environment is a fairly simple one to understand and predict. This is not a highly reverberant channel since most of the signal energy arrives within a few milliseconds (for source-receiver ranges of about one to seven kilometers). Longer reverberation requires significant energy in propagation paths that bounce many times in the channel (arriving later in time) while not losing much energy on each bounce.

The key results for Ship Island showed that the lossy boundaries cause most late arrivals to be highly attenuated. This lack of late arriving echoes (multipath) resulted in performance that was mainly a function of SNR. Therefore, performance for this site was a function of the source level, source-receiver range and wind speed (surface roughness and ambient noise level). Good performance (fewer than 10 percent bit errors at 2,400 bits per second) was observed at ranges beyond five kilometers for a moored receiver and drifting source (at about 0.5 knots) geometry.

La Jolla

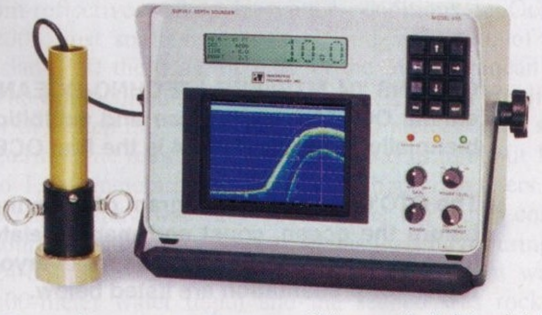
The La Jolla experiment was conducted over a medium-reflective seabed in 80-meter water off the coast of San Diego, California, and took place in summer conditions in May 2002. Using a string of thermistor sensors, the water column temperature structure was monitored over the time of the experiment (water temperature has the greatest impact on sound speed) and showed a very shallow layer of mixed water (i.e., iso-speed) and below, a thermocline that changed the sound speed from about 1,507 meters per second to 1,490 meters per second over 20 meters of water depth. The oceanography was variable with the upper part of the water column changing over the course of minutes. However, the thermocline was contained in the upper 10 to 40 meters, and the source was towed at about 25 meters depth and receiver was moored about five meters off the bottom (both well below thermocline depth, which minimized its impact). Sediment maps show the La Jolla site to have a sand/silt surficial layer with sound speed of 1,527 to 1,555 meters per second, which is slightly higher than the water column and leads to a seabed with medium reflectivity.

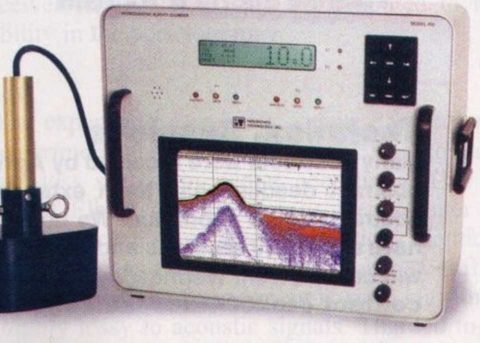
The key results for this experiment showed that the seabed reflectivity gave rise to multipath arrivals that lasted about 50 milliseconds (or about twice the MFSK symbol duration). This led to significant bit errors, even when the SNR was high. Bit-error rates varied from zero to 15 percent (2,400 bits per second) and relatively high SNR was observed for a moored receiver and drifting source (at about 0.5 knots) to about six kilometers.

Coronado

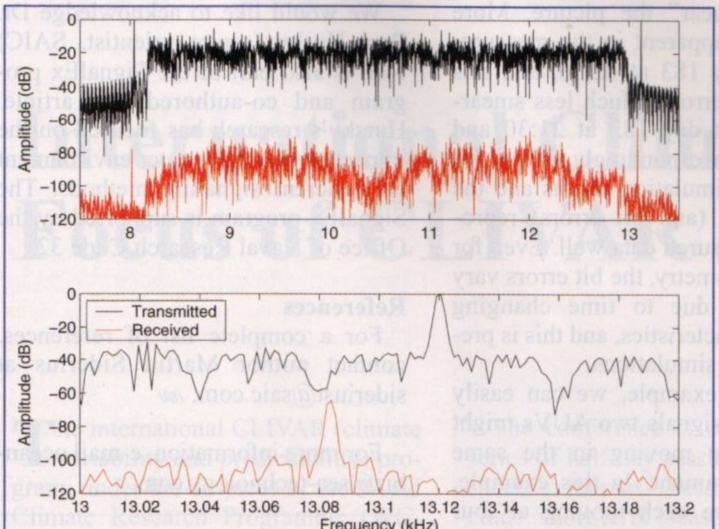
The Coronado experiment was conducted over a highly reflective seabed in 150-meter water depth off the coast of San Diego, California. This was also done in summer conditions, within a few days of the La Jolla experiment in May 2002, and had approximately the same water column sound speed structure. Source and receiver configuration was similar to the La Jolla experiment. Sediment maps show a more reflective seabed with sound speeds greater than 1,700 meters per second. The seabed reflectivity gave rise to even more multipath arrivals than for the La Jolla site.

The key results for this experiment were similar to the La Jolla test, but the bit errors were even greater as the duration of the multipath was about twice that for La Jolla (around 100 milliseconds). There was good SNR out to





Performance of MFSK Signals Analyzed at 2,400 Bits per Second at Six of the SignalEx Test Sites.						
	Ship Island	Coronado	La Jolla	Kauai	Capraia	Elba
Performance	Very Good	Fair-Poor	Fair	Fair-Poor	Good	Very Good



Top panel is the simulated signal transmitted from one AUV (black line) and received by another (red line). The AUVs are moving towards each other at four knots. The lower panel is a zoomed-in view of the pilot tone that is Doppler shifted.

ranges of about six kilometers and bit-error rates varied from zero to 20 percent (2,400 bits per second).

Kauai

The Kauai experiment was conducted off the coast of Kauai, Hawaii, in the summer conditions of June and July of 2003, over a medium-reflective seabed with a high degree of ocean variability. Measurements were taken over many days to observe the temporal variability on performance. The site had a flat bathymetry of 100 meters depth. Communications signals were transmitted between both fixed and moving platforms. The water column sound speed generally showed a mixed layer near the surface that was caused by the often windy conditions. The mixed region was iso-velocity and below that was a thermocline that produced sound speed that reduced from about 1,538 meters per second to 1,530 meters per second. The depth where the mixed layer ended and the thermocline began varied greatly with location and time. The seabed was sand and was, therefore, of medium reflectivity. There was observed multipath of 50 to 100 milliseconds for ranges of one to seven kilometers.

The key results for this experiment showed that oceanography plays an important role at this location, causing the bit-error rate to fluctuate over time. Performance improved for source and receivers near the seabed, as this is below the thermocline (most of the time) and this part of the water column has many acoustic paths that do not interact with the sea-surface and can, therefore, carry significant energy.

For one set of data with source and receiver near the seabed and separated by three kilometers, the bit errors varied from zero to 20 percent (2,400 bits per second) over time, depending on the depth of the thermocline. The results show increasing bit errors that coincide with the thermocline disappearing and the water column mixing.

Capraia Island

The Capraia experiment was conducted over a medium-reflective seabed in winter conditions in October 2003, just south of Capraia Island and north of Elba Island, off the coast of Italy in the Mediterranean Sea. The water column was typical for early winter conditions with a deep mixed layer at about 70 meters and a slight thermocline reducing the sound speed from about 1,520 to 1,510 meters per second over about 10 meters. The oceanography was fairly benign, as the water column sound speed did not appear to change much during the 24-hour measurement period. The experiment was in 100-meter water depth and the seabed was rock and sand, which has medium reflectivity and the estimated seabed sound speed is 1,560 meters per second. These conditions gave rise to multipath that lasted about 100 milliseconds from about one to seven-kilometer source-receiver separation. The key results for this experiment showed this site had a multipath duration of a length similar to the Kauai site (around 100 milliseconds) and a similar water column sound speed profile, but the bit errors were significantly reduced (from zero to two percent at 2,400 bits per second). The significantly lower bit errors observed when comparing a similar geometry and source-receiver range with Kauai are attributed to much less variability in the oceanography.

Elba Island

The Elba experiment was just a few days after the Capraia experiment in October 2003, and was conducted over a high-loss seabed in winter conditions. This took place south of Elba Island in slightly deeper water (120 meters) with the ocean sound speed conditions identical to those at Capraia. The seabed, however, was very different from Capraia, consisting of a sediment layer of clay and silt which is highly lossy to acoustic signals. This led to very few multipath arrivals (as was the case for Ship Island, but for much deeper water). The key results for this experiment showed that this site was dominated by the direct acoustic path (weak multipath arrivals). Performance was even better than for the Capraia site. This site had the lowest bit errors when comparing similar geometries against the Capraia and Kauai sites.

The results show trends that can be useful for determining how acoustic communications systems will perform in different areas. However, this does not tell the whole story and it is difficult to draw too many conclusions. Many factors other than SNR come into play, such as weather, time of year and source-receiver geometry. However, there are some general observations that can be drawn.

The La Jolla and Coronado experiments occurred in the same oceanographic conditions, but with different seabed types and that shows up in the errors. This, again, is shown for the data collected at the Capraia and Elba sites. Another observation is the higher errors at Kauai, La Jolla and Coronado compared with Ship Island, Capraia and Elba. At Ship Island, the low errors are mainly attributed to the lack of multipath. The low bit errors at Capraia are due to the very stable oceanographic conditions. The Elba site had both benign oceanography and low multipath arrivals.

Communications Simulator

Conclusions about experimental results carry more meaning if they can be duplicated in simulation. In recent years, advances have been made in using physics-based propagation modeling to simulate the channel impulse response and communications performance. However, there have been very few experiments with simultaneous acoustic and environmental measurements similar to those taken during the SignalEx program. The simulation tool used for comparing with SignalEx data is based on the Gaussian beam tracing code bellhop, with modifications to allow for moving platforms (i.e., Doppler effects).[4] This model can be used to simulate any type of communications signal in environments that vary both in range and depth. That is, variable bathymetry and depth-dependent water column sound speed and seabed properties can be included for both coherent and non-coherent simulated transmissions.

As an example, consider the environment for the Kauai experiment. The source is located at 95 meters depth and the receiver three kilometers away at a depth of 92 meters (i.e., a fixed source and fixed receiver geometry). A perfect reception would have a spectrogram similar to the transmit signal, but late arriving multipath tends to "smear" the picture. More smearing is apparent in the measurements on day 183 at 02:30, and this has high bit errors. Much less smearing occurs at day 182 at 21:30 and there are correspondingly lower bit errors. The simulation results and the spectrograms (and bit errors) reproduce the measured data well. Even for this fixed geometry, the bit errors vary significantly due to time changing channel characteristics, and this is predicted by the simulations.

In a final example, we can easily consider the signals two AUVs might receive while moving in the same Kauai environment. In this example, the AUVs are each moving at four knots towards each other. The transmitted and received spectra illustrate both the fading and the Doppler effects. In this example, the Doppler shift of around 36 hertz is clear. While the main Doppler shift can be corrected before decoding, the simulation mimics reality with each arrival Doppler shifted by a different amount. This leads to a Doppler spread that is more difficult for the decoding algorithms to compensate for.

Acknowledgments

We would like to acknowledge Dr. Paul Husky (senior scientist, SAIC) who is also part of the SignalEx program and co-authored this article. Hursky's research has focused on the impact of the underwater environment on coherent signaling methods. The SignalEx program is supported by the Office of Naval Research Code 32.

References

For a complete list of references, contact author Martin Siderius at sideriust@saic.com. */st/*

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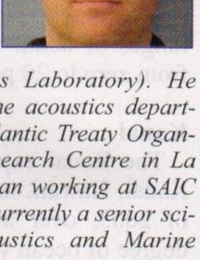
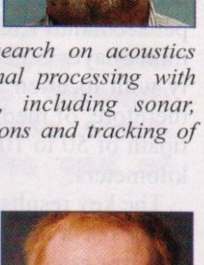


Dr. Martin Siderius received his M.S. in electrical engineering in 1992 and his Ph.D. in electrical engineering in 1996, both from the University of Washington (Applied Physics Laboratory). He spent five years in the acoustics department at the North Atlantic Treaty Organization Undersea Research Centre in La Spezia, Italy, and began working at SAIC in 2001, where he is currently a senior scientist with the Acoustics and Marine Systems Operation.



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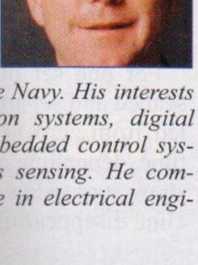

Vincent K. McDonald primarily designs underwater sensor systems for the United States Navy. He also conducts underwater acoustic communication research for the Navy. His interests include communication systems, digital signal processing, embedded control systems and autonomous sensing. He completed an M.S. degree in electrical engineering this year.