Undersea Acoustic Communications Signals

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Abstract-- **A diverse collection of underwater signaling waveforms provided by four acoustic modem developers was tested in the April ModemEx'99 experiment 6 km southwest of San Diego in 200-m water. These waveforms and a variety of probe signals were bidirectionally transmitted between a surface ship and an autonomous, bottom-deployed instrument called the telesonar testbed. The intent of this test was to relate communications performance in a variety of channels to signal design, decoding method, and the channel response. To reduce the number of free parameters, all waveforms were transmitted, received and digitized using a common suite of electronics. Although a complete waveform set could not be transmitted within the channel coherence time, they were all subjected to approximately the same channel geometries and noise. This paper describes the experimental design for ModemEx'99.**

I. INTRODUCTION

Prior underwater acoustic communications research and experimentation have concentrated on developing modem signaling techniques that target specific capabilities, such as covertness, robustness, high bit-rate, and multi-acess. Multi-mode signaling research will lead to a versatile, reliable modem that uses the channel efficiently as the channel conditions or mission requirements change. Operationally, this multi-mode modem will use probe signals to categorize the prevailing channel [1]. Theoretical and empirical studies will determine what mix of channel parameter values should constitute a channel category and identify effective signaling techniques for each category. Other constraints such as covertness, reliability, power efficiency, and speed will also influence the selection of an appropriate signaling method for the estimated channel.

At this time, however, we lack quantitative relationships between parameters for effective signaling (coding, modulation, equalization, etc.) and measured channel parameters. ModemEx'99 is the first in a series of experiments intended to relate signaling performance to the scattering function of the channel. As the database of signal performance in a wide variety of ocean channels grows, so will our ability to create broad channel classifications and identify signaling techniques that perform well within each.

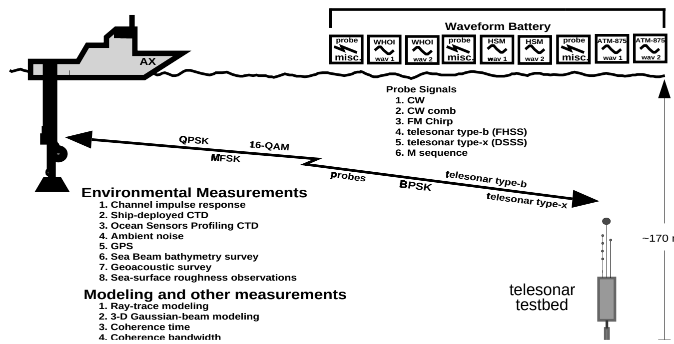

Fig. 1. A medley of communication waveforms and probe signals were transmitted (half-duplex) between a surface ship and the telesonar testbed. Environmental measurements, modeling, and probe signals will aid in interpreting signaling performance in various channels.

II. APPROACH

There have been many independent acoustic telemetry experiments conducted by numerous modem designers in a variety of environments. Typically, very few underwater signaling schemes are tested in any one experiment. It would be cost effective to simply compile data taken during these and future experiments, and relate signaling performance to the channel conditions. This information could then be used to make comparisons among the various signaling methods. Unfortunately, this is impossible for four reasons. First, the underwater communication channel varies from one experiment to the next. Second, standard techniques for characterizing channel properties do not exist. Third, measurements of environmental conditions during these experiments are typically not rigorously performed. Fourth, the hardware, (matching networks, amplifiers, receive circuitry, etc.) varies from one modem to the next making fundamental comparison of signaling methods difficult.

ModemEx'99 was designed to overcome these shortcomings by transmitting a wide variety of communication and probe signals through a common well-parameterized channel using

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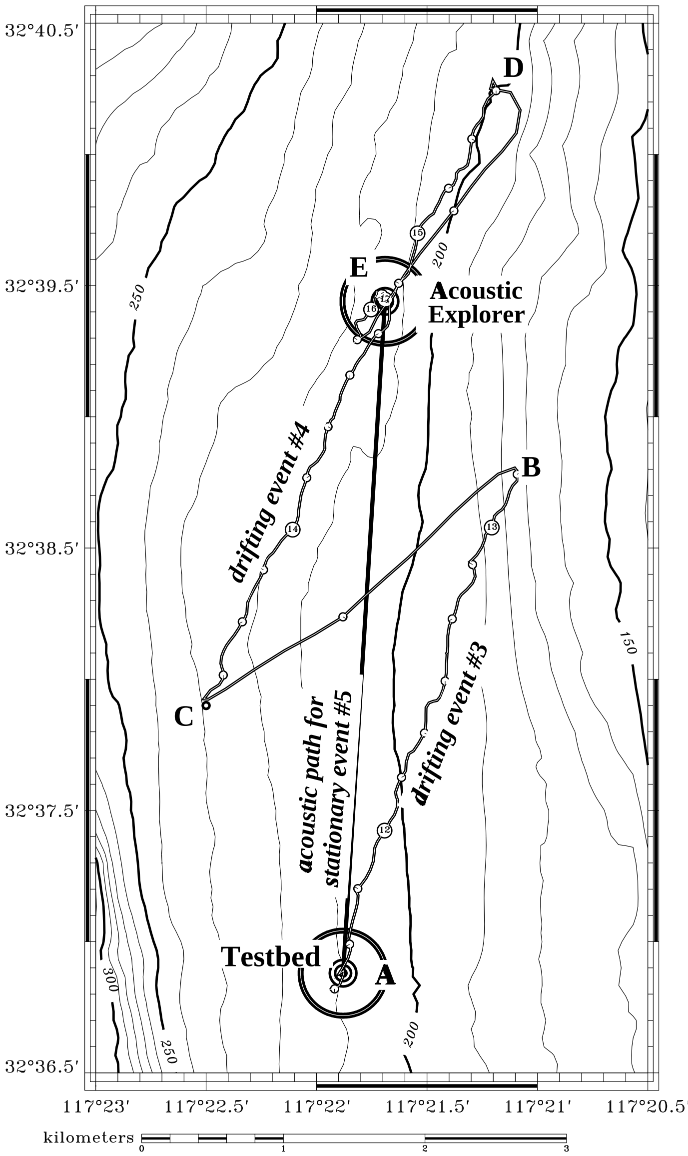
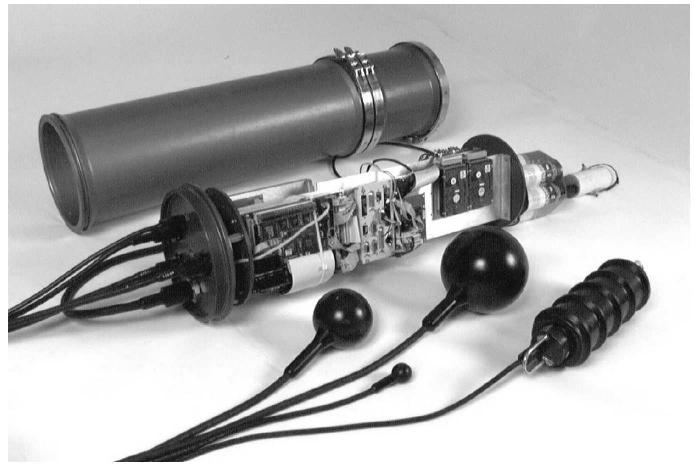


A. Overvi

ModemEx'99 occurred 6 km southwest of San Diego in 200-m water. A collection of communication and probe signals, constituting a waveform battery (see section D below), was sent repeatedly for six hours in a half-duplex manner between two platforms, the R/V Acoustic Explorer (AX) and an autonomous, bottom-mounted instrument called the telesonar testbed [2]. During the two-day test, the distance between the two platforms varied from approximately 0.2 to 6 km. Events

environment (Fig. 2). For event 5, the range between the AX and testbed (Fig. 3) was fixed at 4.75 km.



B. Experiment Preparation

Each modem developer provided encoded, modulated signals in the 8- to 16-kHz octave that were sampled at 48 kS/s. Not all waveforms took advantage of the full 8-kHz bandwidth. The testbed transmitted all waveforms through a common D/A, amplifier, matching network, and omnidirectional transducer. All signals received by the four-channel testbed array underwent the same signal conditioning before digitization (Fig. 4). The testbed was essentially duplicated

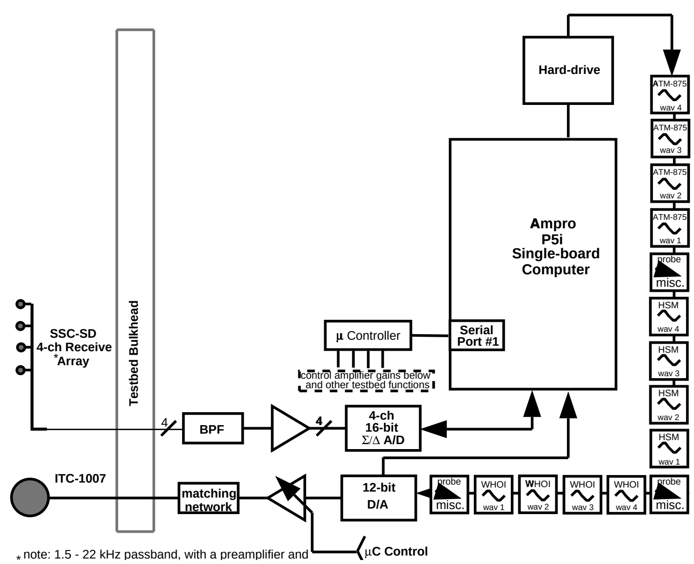
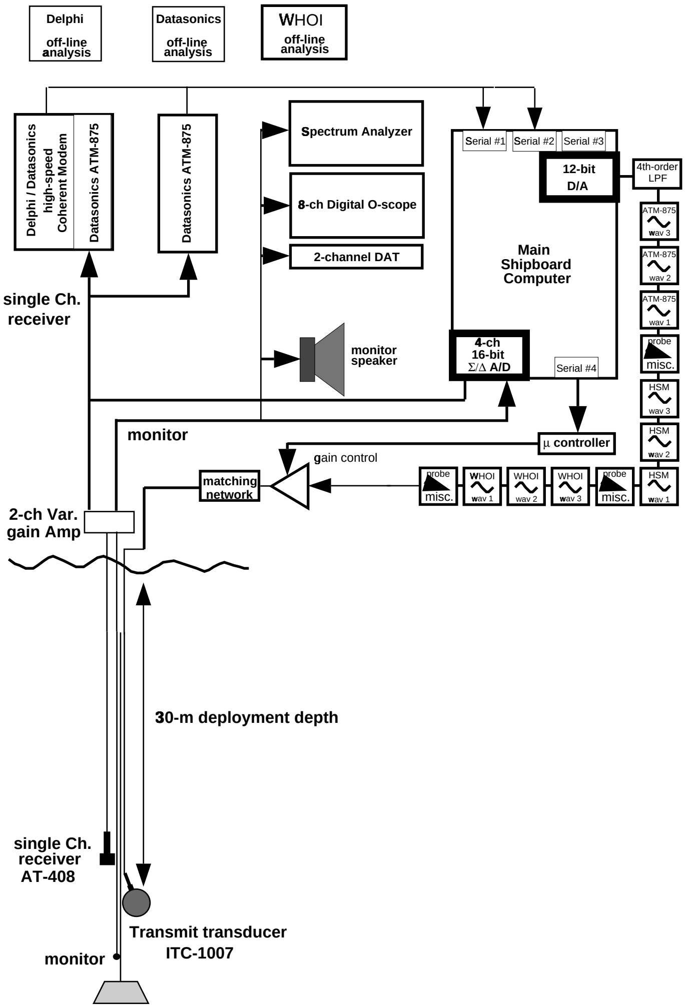
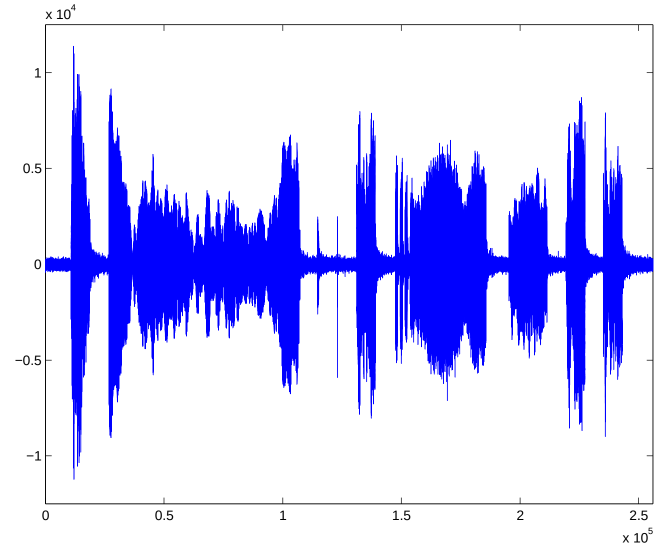


Fig. 4. Communication waveforms from 4 modem developers were transmitted and received using common electronics allowing controlled analysis of fundamental signaling issues.

(Fig. 5). This setup allows analysis to focus on signal design and decoding methods without experimental errors introduced by non-common components associated with each

Fig. 3. The telesonar testbed is an autonomous, high-fidelity instrument for





C. Composite Probe Signal

The objective of ModemEx'99 is to relate the performance of various signaling methods with prevailing channel conditions. As a means to this end, a suite of probe signals or a composite probe (Table 1) was sent four times within each waveform battery. Each composite probe was sent just before each set of test signals provided by the four participating modem developers: Datasonics Inc., Delphi Communications Systems Corp., Northeastern University (NEU), and Woods Hole Oceanographic Institute (WHOI). Figure 6 shows a time series of the composite probe received by the testbed at a range of approximately 1.7 km from the AX.

Although the various probes within the composite probe may generate redundant information, they were transmitted for several reasons. First, comparisons can be made among the processed probes to determine how well they correlate. Second, some of the probe signals were specially designed to measure a particular characteristic of the channel (for example, the 10-second long, 10-kHz sinusoid was included in the composite probe to provide high spectral resolution for determining frequency spreading and/or shifting). Third, the LFM was repeated four times within the composite probe to see how the channel changes on a time scale of seconds. Fourth, a 500-µs 10-kHz pulse was transmitted to provide real data for a 3-D Gaussian-beam model [3] that uses a

Table 1. Composite probe description

Probe Signal	Duration	Notes
LFM	1 seconds	8 - 16 kHz
Long CW	10 seconds	10 kHz
Short CW	40 ms	10 kHz
Very Short CW	500 µs	10 kHz
LFM	1 second	8 - 16 kHz
DS-DPSK	5 seconds	
Comb	2 seconds	16 tones in 8 - 16 kHz band, spaced at 500 Hz
FM	1 second	8 - 16 kHz
FM	...ond	8 - 16 kHz

...veform-Battery

...vaveform battery (Fig. 7) was ... by placing a ...osite probe signal before each modem developer's ...unication signals. We asked each developer to provide ...l test waveforms, varying a single parameter (such as ...rate or convolutional coding length) from waveform to ...orm. This would allow the isolation of an effect due to ...le variable change assuming that the channel remained ... during the transmission of successive waveforms ... ...gnal ... ...ond for channel ...

...di... were interested in assessing the dependence ...

Fig. 6. Probe signal received on one element of the tesbed's 4-ch receive array. The range between the transmitter on board the AX and the testbed is approximately 1.7 km.

level achievable from each platform. The AX and testbed were capable of transmitting a tonal at 186 and 180 dB re 1 µPa at 1 meter respectively. Table 2 lists all the test waveforms. Figure 8 shows the close-range reception of an entire waveform battery at high SNR.

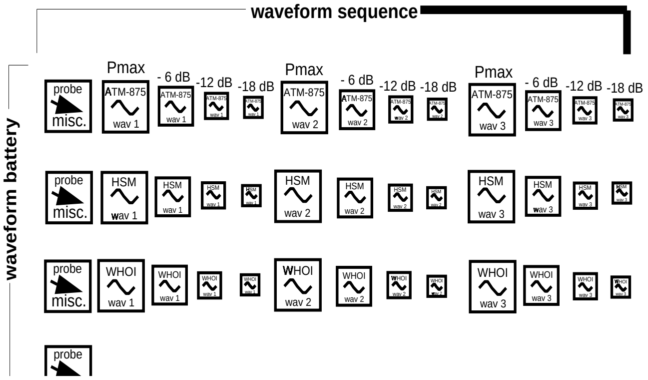
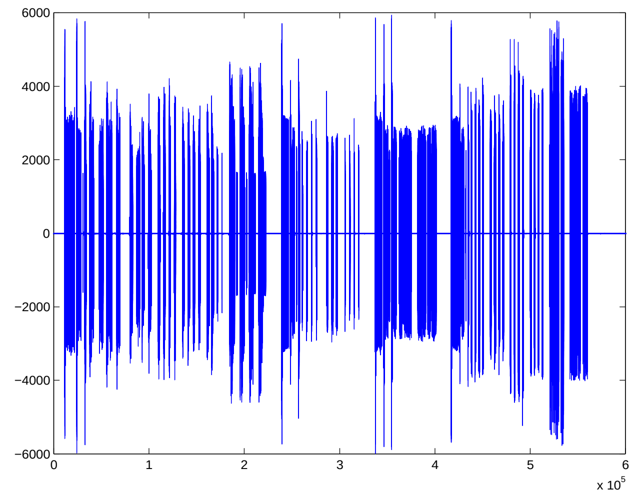


Fig. 7. The waveform battery consists of a concatenation of many communication waveforms and composite probe signals. Source-level reduction as shown, exposes failure modes in the demodulation and decoding process.



Organization	Signaling	Notes
Datasonics	MFSK	150 bits/s, Hadamard, 1/2 rate convolutional coding, doppler tolerant, 25 ms guard band
Datasonics	MFSK	300 bits/s
Datasonics	MFSK	600 bits/s
Datasonics	MFSK	1200 bits/s
Datasonics	MFSK	2400 bits/s, (1 of 4)
Datasonics	FH-MFSK	
Delphi	QPSK	f_c = 12 kHz, bandwidth = 4 kHz
Delphi/ Datasonics	BPSK	f_c = 12 kHz, bandwidth = 4 kHz
Delphi/ Datasonics	16-QAM	f_c = 12 kHz, bandwidth = 4 kHz
NEU	DS-DPSK	10 bits/s
NEU	DS-DPSK	100 bits/s
WHOI	QPSK	pseudo-random data sequence, and 12/23 Golay code for all of WHOI signals. Each group of two signaling types occupied different frequency bands: 9.5 to 14.5 kHz and 8 to 16 kHz.
WHOI	QPSK	
WHOI	MFSK	
WHOI	MFSK	
WHOI	FH-MFSK	
WHOI	FH-MFSK	

E. Experiment Execution

Ideally all communication signals should be subjected to a wide variety of scattering functions, time variability, and noise fields. This can be accomplished by testing in several environments and/or testing in a single environment for an extended period. For ModemEx'99 we were limited to a single site 6 km off the coast of San Diego and two days of testing during the week-long SubLink'99 exercise. Nevertheless, we planned on establishing several distinct multipath conditions: 1) dominant, direct-path arrival with minimal multipath spread, 2) complex, extended multipath structure with a non-dominant direct path (phase-minimum channel), and 3) no direct path with indistinguishable, multipath arrivals indicating highly-scattered received energy.

Before the experiment the 3-D Gaussian-beam model predicted responses for several candidate geometries. During the experiment on-site CTD data was used as input to the model to refine the best positions of the platforms to obtain

The first day of testing was used to prepare equipment, and obtain high-SNR recordings of the waveform battery. Datasonics Inc. and Delphi Communications Corp. provided modems and personnel onboard the AX for real-time decoding of received waveforms. Their ability to decode the received waveforms at low signal level with no errors validated the sampled waveforms as well as the design of the transmit and receive systems.

Due to circumstances that arose during the experiment, three days of planned signal transmissions were decreased to one. Thus, time was not available to methodically construct the three multipath conditions discussed above. Instead, the testbed was positioned such that the prevailing winds would permit the AX to drift out in range across a range-independent region providing a continuum of multipath conditions.

The second day of testing was dedicated to six hours of half-duplex transmission of waveform batteries between the AX-based system and the deployed, autonomous testbed. During this period approximately 105 composite probe signals and 7140 underwater communication messages were transmitted and recorded for post-experimental analysis. The testbed was deployed at station A and the AX drifted from station A to B then repositioned and drifted again from C to D (Fig. 2). Although these data are interesting, it limits direct comparisons between signaling techniques since the channel is changing significantly throughout a 10-minute waveform battery transmission. During the two drifting events, real-time decoding by Datasonics demonstrated that they were able to decode their message at low SNR with zero errors at a range of approximately 4500 meters. We selected this zone for more extensive measurements of the signaling methods from fixed platforms. Thus the AX moored at station E (Fig. 2) and Stationary Event 5 was performed for one and a half hours.

F. Sources of Experimental Error

To determine the effect that a single parameter has on a complex system, it is desirable to hold all other parameters and conditions of the system constant. However, there are

Multipath spread and structure can be controlled in a rough sense by manipulation of the source and receiver geometry. Control over the fine structure and temporal variation of the multipath is not possible, however. Furthermore, the motion of the tesbed and shipboard-deployed transducers affects the multipath spread in a manner not easily measurable. (Future experiments performing side-by-side comparisons will use two autonomously deployed testbeds with fixed transducer positions.)

Careful planning and design can eliminate or minimize most sources of error. However during this experiment, the channel coherence time is most certainly less than the time needed to transmit the 10-minute battery of signals. Thus, communication waveforms within the battery may be subject to different channel characteristics; whether these differences are significant to signaling performance is a question that should be kept in mind. Keeping test messages as short as possible mitigates this problem. However, it is impossible to test as many signals as were tested in ModemEx’99 within the coherence time of the channel. Nevertheless, if each organization’s signals are transmitted enough in a statistical sense, then even though the channel may not remain stable while transmitting a battery of signals, there should be a qualitative indication of the relative performance of each type of signaling scheme for a given geometry. In other words, if a statistically significant signal set from each organization is transmitted for each established geometry, then the channel on average will not prejudice a particular signaling technique.

IV. PRELIMINARY DATA

As mentioned above, the objective of ModemEx'99 is to understand how the ocean channel affects the performance of various modems. In particular, we would like to relate observed bit-error-rates to features of the channel such as shadow zones or areas characterized by many or few multipaths.

shown by the solid lines. Other regions are ensonified by SRBR (surface-reflected, bottom-reflected) paths shown by the dashed lines. Finally, there are shadow zones such as the near-surface region over the range from about 1000 to 2000 m. (this region would actually receive a weak reflection from

Fig. 9. Ray trace from the R/V Acoustic Explorer.

As a result, the testbed with a receiver located near the ocean bottom at a range of about 1400 m sees an echo pattern with the associated eigenrays shown in Fig. 10. Notice that at this range there are 8 rays seen by the receiver The first 4 arrivals are D (direct), B (bottom), S (surface), and SB (surface-bottom) which arrive with a small time-separation. The next 4 arrivals are BS, BSB, SBS, and SBSB with surface and bottom reflections adding to the path length in relation to the separation of the source below the surface and the receiver above the bottom.

The acoustic model can also be used to predict the impulse response in the channel as shown in Figure 11. In this calculation a brief ping is propagated through the model yielding a series of peaks delayed in accordance with the

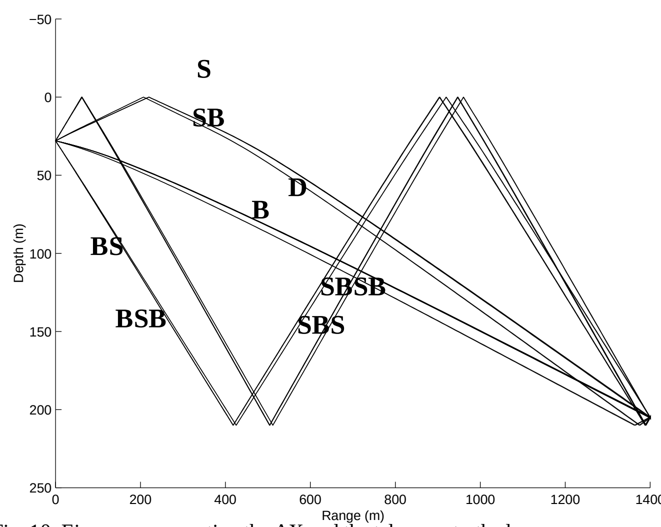
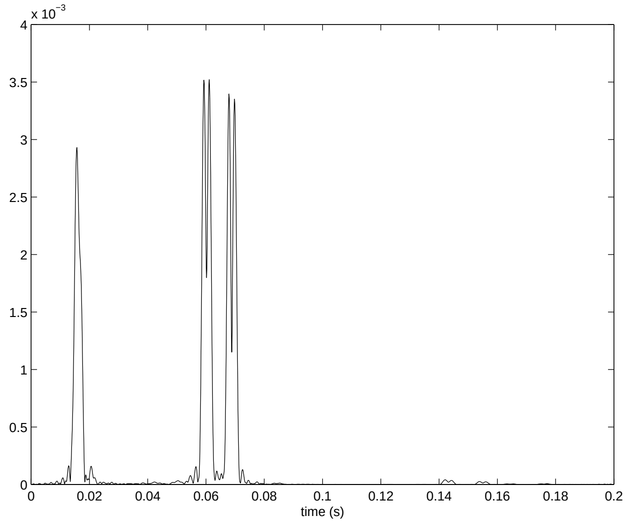


Fig. 10. Eigenrays connecting the AX and the telesonar testbed.

travel time. The first 4 paths are not resolved and appear as a single peak in the echo repsonse. The BS and BSB paths are separated by about 5 ms representing the path length required for an extra bottom reflection for the receiver 5 m above the bottom. Similarly the BS and SBS paths are separated by about 20 ms representing the path length for an extra surface reflection for the source 30 meters below the surface.



The above results (Fig. 11) were calculated using a normal-mode model that is accurate but becomes computationally expensive at high-frequencies. As an alternative, we have been developing a 3D Gaussian-beam model for telesonar applications. Figure 12 shows the 3-D Gaussian-beam results at the 4.75-km range where AX was stationed during Event 5 (plotted here on a dB scale). At these larger ranges there are additional multipaths representing additional surface and bottom reflections. The peak-width in both models is a function of the source bandwidth. At these longer ranges we have chosen to use a sharper pulse to distinguish more clearly the individual arrivals.

To assess the validity of this theoretical view of the propagation conditions we can use the ModemEx'99 data to directly measure the channel response. During the experiment, LFM chirps were transmitted sweeping the 8-16 kHz band over a 1-second period. Theoretically, the impulse response is a combination of these chirps delayed in time according to their path length and attenuated according to volume absorption and reflection loss at the boundaries.

To review briefly the ideas of pulse compression: the correlation of the chirp with itself is a sharply peaked function (a sinc pulse). Similarly the correlation of the full received time-series with the chirp yields a series of impulses corresponding to the multipath structure. The result for Event 3 is shown in Figure 13. We can clearly see the predicted pattern of arrivals in the data. As the ship drifts to greater ranges the groups of paths described above become less separated in time. We can also see the faint outline of higher-order multipaths at later times (the 10-minute gap starting at about 12.7 hours is a period where no data was collected). This clear multipath structure has been seen throughout the experiment and will provide an excellent basis for interpreting the performance of the various signaling schemes.

V. FUTURE WORK

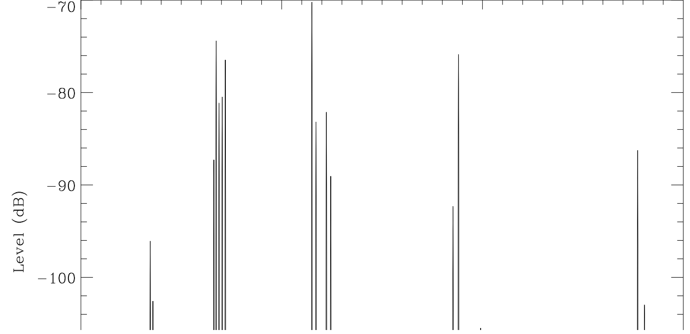
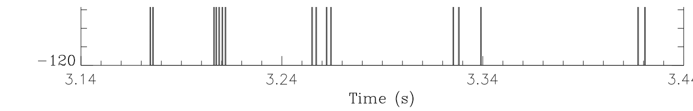


Fig. 12. Predicted impulse response by 3-D Gaussian-beam model for a source/receiver separation of 4.75 km..



These testbeds will be smaller and lighter weight, and thus easier to deploy than their predecessors. These added features will allow measurements to be made in as many environments possible. Future ModemEx tests will seek even tighter control over experimental conditions, and study how various signaling techniques are affected by jamming signals. The number of participating modem developers will increase from four to as many as eight.

Finally, another series of complimentary experiments beginning this calendar year called ModemFest will be coordinated by SSC-SD. ModemFest will showcase currently available, fully-integrated, modem technology. Each modem will be tested in a set of common channels, monitored with

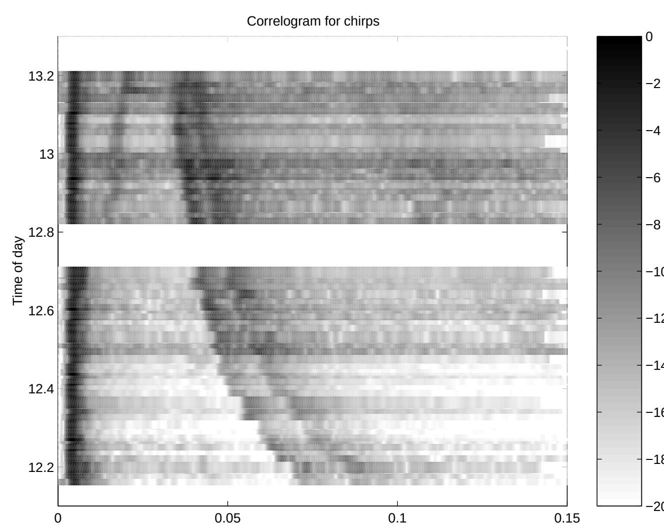


Fig. 13. Correlogram showing the impulse response over a period of 1 hour. Every ten minutes the signaling direction changes, and the above time history concatenates these reciprocal transmissions.

common equipment, and be constrained by a common set of rules thus making comparisons possible in a head-to-head competition among modem developers.

Although ModemEx and ModemFest are significantly different in design and intent, a strong synergism exists. While ModemFest will suggest which currently available modems worked best in a particular event, fundamental signaling research conducted under ModemEx may enable us to determine exactly why they succeed or fail. Furthermore, ModemEx will encourage modem developers to improve their

VI. CONCLUSIONS

ModemEx'99 was an important first step in relating the performance of a diverse set of underwater, acoustic signaling methods to the impulse response of the channel. A rich data set is now being analyzed. Future ModemEx experiments will build on the experimental techniques developed thus far.

Emphasis was and will continue to be focused on isolating the coding, modulation, and decoding by fixing as many parameters as possible through the use of common transmit and receive circuitry, fixed transducers, and a common channel. This work ultimately will provide the enabling technology for modems to adapt their signaling based upon the response of the channel and mission requirements.

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