SignalEx: Linking Environmental Acoustics with the Signaling Schemes

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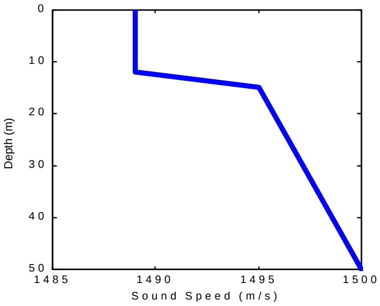
Abstract- **Although work on digital underwater acoustic communications dates back to the early 70's, the last 5 years have seen a strong renewed interest. The signaling schemes include a variety of noncoherent and coherent schemes including MFSK, DPSK, and QAM and a variety of manufacturers provide such modems 'off-the-shelf'. Meanwhile, the R&D community has demonstrated the impressive potential of the modems as the key connector in undersea networks. While the signaling schemes have become much more sophisticated, the role of the ocean environment on their performance remains poorly understood. As a corollary, predictive models of modem performance are not readily available. The SignalEx tests are designed to address specifically these issues, drawing upon the significant navy experience with acoustic propagation models originally developed largely for ASW applications. A variety of different test sites have been selected with the goal of understanding better how modems respond to multipath and variability induced by a changing ocean. This paper will summarize the lessons learned from recent SignalEx tests conducted on the Loma Shelf near San Diego and on the New England Shelf near Long Island.**

I. INTRODUCTION

A compelling example of the role of the ocean channel on modem performance was provided in engineering tests for the FRONT (Front-Resolving Observatory with Networked Telemetry) oceanographic network. The oceanographic conditions in the area are both interesting and complicated as fresh river runoff interacts with the tides to generate a persistent front. The sound speed profile in the area shows a somewhat unusual, strongly upward-refracting profile shown in Fig. 1.



Fig, 1: Sound speed profile during the Front engineering test.

A transmission loss plot (show in Fig. 2) shows the anticipated upward refraction for a communications node (serving as the projector) located on the ocean bottom.

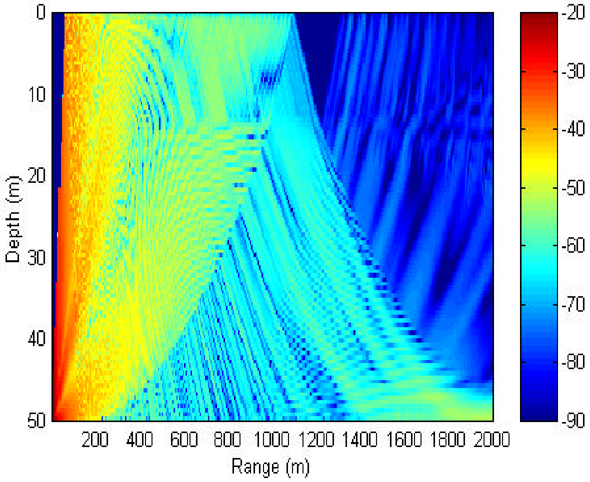


Fig. 2: Predicted transmission loss during the Front engineering test.

During the course of the network deployment, there were periods with strong winds followed by relatively calm conditions as may be seen in the wind speed plot in Fig. 3a. As the wind speed increases, wave action drives up the ambient noise. At the same time, the choppiness of the surface makes it a poor acoustic reflector so the signal level drops. The combination of the two factors drives the SNR at the bottom-mounted receiver (Fig. 3b). This in turn drives the overall modem performance as measured by the bit-error rate (Fig. 3c). In summary, high winds caused network outages.

This is the simplest of mechanisms driving modem performance. Even with strong SNR, a modem that relies on a tap-delay line for adaptive equalization may fail as the multipath spread becomes long. Similarly, a modem may fail to track Doppler changes, which is yet another dimension to the parameter space affecting modem performance.

To understand more fully these processes, the U.S. Navy has embarked on a systematic program called SignalEx, for comparing modem performance and relating it to the propagation conditions.

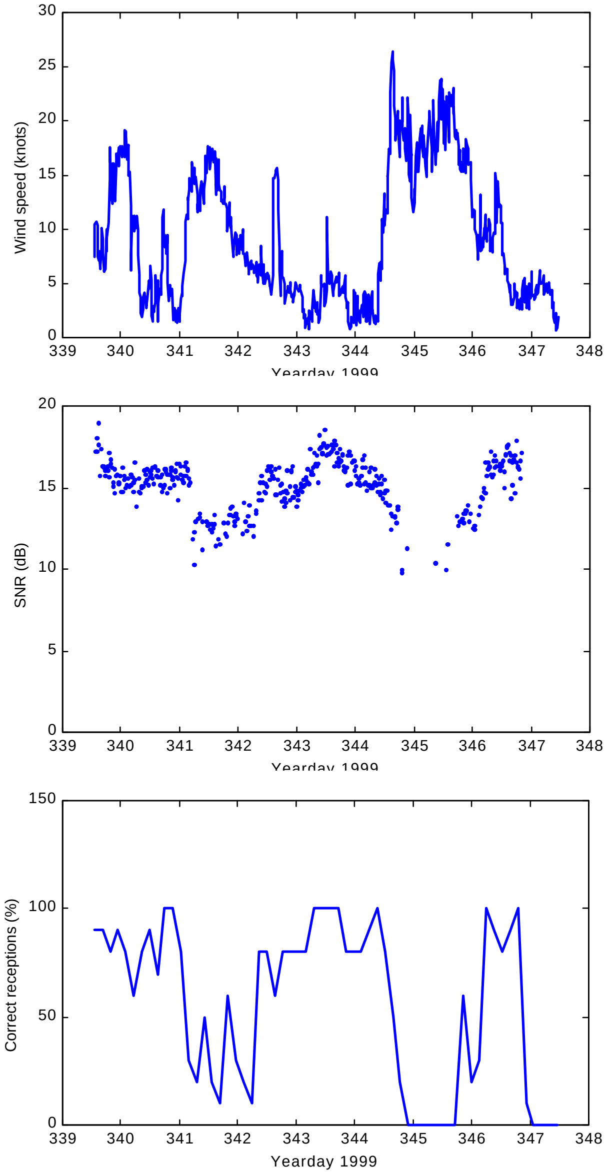


Fig. 3: During the Front network engineering test, the wind speed varied considerably (a). The wind speed affects both the ambient noise and the surface reflectivity which both drive the SNR at the receiver (b). Variations in SNR in turn drive the performance of the modem (c).

The experiments involve participation from a large number of institutions, whose waveforms are transmitted and received through a pair of common telesonar testbeds. The use of a common set of hardware eliminates the ambiguity associated with variations in such features as projector and receiver sensitivity. Along with the modem performance measurements, a complete set of probe signals is transmitted to provide detailed measurements of the environmental conditions.

II. APPROACH

The Space and Naval Warfare Systems Center has developed a set of 'telesonar testbeds' for SignalEx testing. These are compact units consisting of a single-board Pentium II computer together with a projector, 4-hydrophone receiver, high-speed DSP and a Benthos ATM885 modem (Fig. 4). A versatile real-time operating system is used to control the system while maintaining the efficiency required for digitizing and storing the multi-channel acoustic data sampled at 48 kHz.

Currently, the modems are used in a non-interactive mode in which modem developers simply provide waveforms that are received on another tested and stored to disk for subsequent processing. However, the integral Benthos modem allows real-time decoding of the popular MFSK scheme and the on-board testbed DSP, a TI C6701, will be used for real-time decoding of new modem schemes under development.

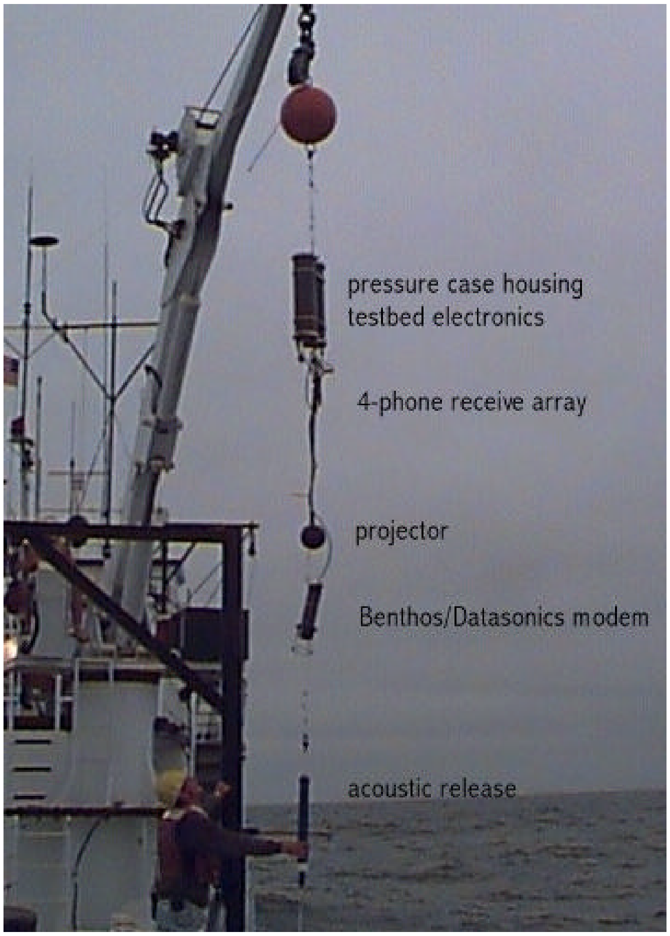


Fig. 4: Testbed configuration.

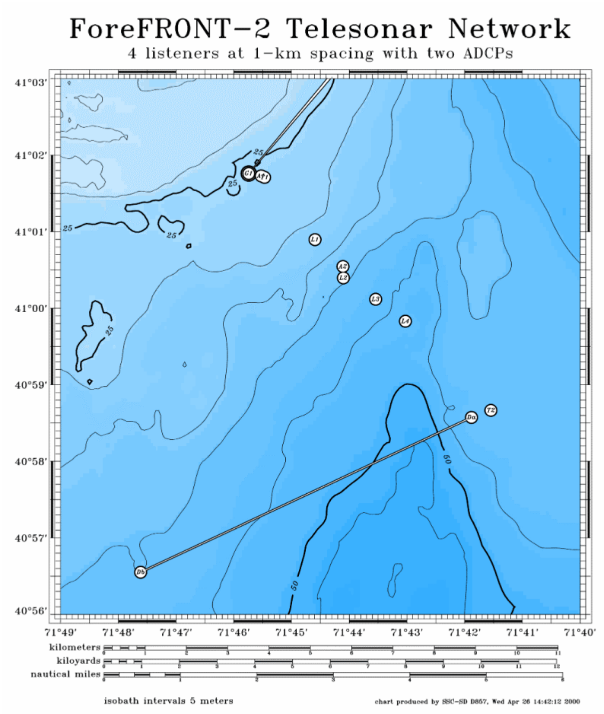


Fig. 4: Bathymetry and drift track during SignalEx-B.

III. SIGNALEX-B (NEW-ENGLAND SHELF)

The new telesonar testbeds were tested first in an experiment over the New England Shelf during April 2000 in the area where the above ForeFRONT-2 experiment was conducted (Fig. 5). The testbed was deployed on the ocean bottom in about 30 m of water and recorded waveforms transmitted from the R/V Connecticut as it drifted west, southwest of the testbed. The source was an over-the-side projector located at a depth of about 20 m.

Probe signals were sent every 5 minutes to measure both the Doppler shift/spread and the multipath spread (in effect, the channel scattering function). The impulse response was estimated using a sequence of 40 LFM chirps in the 8-16 kHz band--- the same band used by the communication waveforms. After doing the usual matched-filter technique one obtains the replica correlogram, which is shown in Fig. 6. The impulse-responses were then aligned by a leading edge. (This process does not always capture the same arrival resulting in occasional anomalies in the plots.)

As there are few published examples of these measurements of the impulse response for communications frequencies, there are several properties of interest. During the first hour of the experiment, the multipath spread increases. This sort of behavior has also been noted in previous low-frequency experiments. A somewhat simplified explanation is that the bottom may be treated as a homogeneous halfspace leading to a critical angle; this causes strong absorption for ray paths with angles steeper than that critical angle. Thus the rays can only propagate within a fan up to the critical angle. With this angle fixed, the number of eigenrays that can reach a receiver increases as range increases.

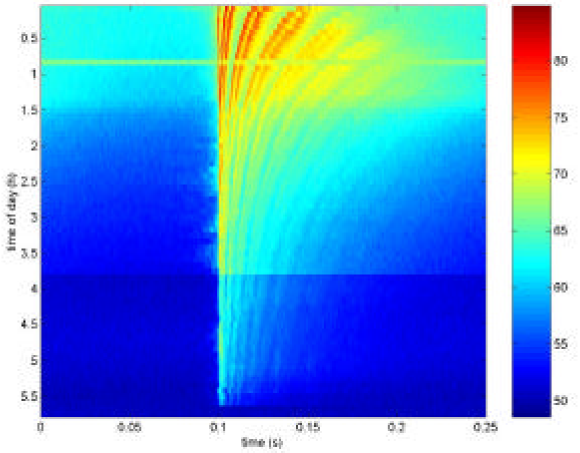


Fig. 5: Measured channel impulse response during the 6-hour drift.

Interestingly, after the first hour where range increases beyond about 1 km, the multipath spread starts to decrease again. Here the mechanism is that the loss per bounce becomes a strong effect (this is an exponential loss compared to the 1/r law of cylindrical spreading).

This overall behavior of the impulse response is important for the design of most modem schemes since the multipath spread drives tone duration and/or clearing times for FSK schemes and the length of the tap-delay line used for schemes that use channel equalization. As a result, long-range communications may often be easier than short-range communications. Also of note is the reverberation, which causes fill-in between the multipaths. However, the overall clarity of the 'echoes' is noteworthy.

IV. SIGNALEX-C (POINT LOMA)

SignalEx-C was conducted shortly after Signal-B, in an area just west of Point Loma shown in Fig. 7. By this time, 2 telesonar testbeds had been produced. The first was deployed on the bottom in about 200 m of water. The second was deployed at fixed positions 3, 5, and 7 km directly to the north (and along an isobath). Each deployment lasted for about 6 hours.

In addition, the Dolphin research submarine participated in the experiment executing a sort of racetrack pattern indicated by the north-south parallel lines. These data will be used to study the role of Doppler; however, as the waveforms received by the Dolphin are still being processed, the rest of our discussion will focus on the testbed-to-testbed signals.

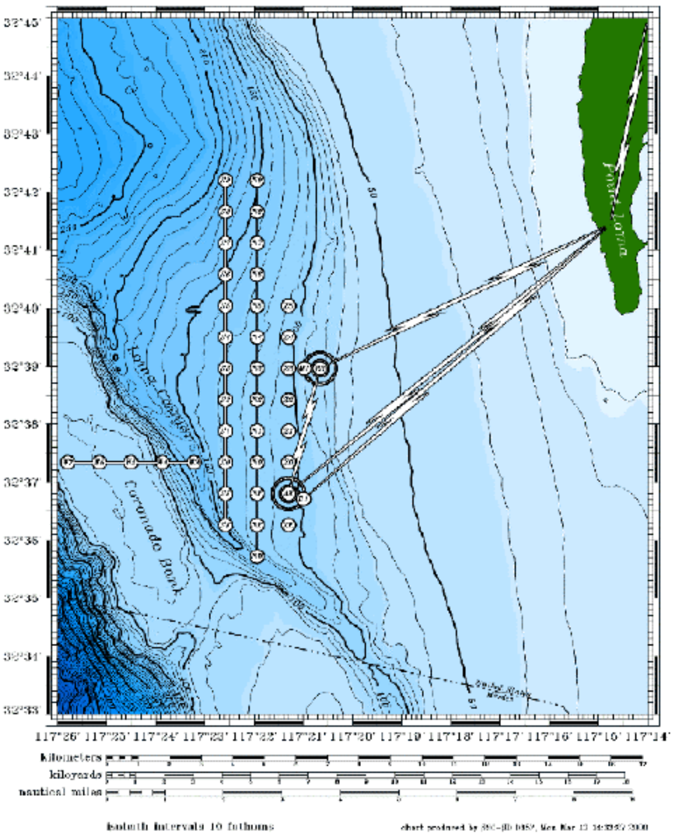


Fig. 6: SignalEx-C bathymetry and stations.

Again, a sequence of LFM pulses was transmitted to measure the channel impulse response: the results for ranges of 3, 5, and 7 km are shown in Fig. 8. The multipath structure is evidently quite different from that seen in the New England Shelf. At all the ranges there are only a few clusters of arrivals and the multipath spread is always less than 20 msecs (by any reasonable measure). This is a result of the four-fold increase in the water depth.

Also of interest is the 'ghosting' in the second cluster of multipaths in Fig. 8a. This is probably due to a reflection from a subbottom layer.

Variation in the multipath structure occurs on a spectrum of time scales with accordingly different physical mechanisms. Variations on the longest time scale may be directly measured in the environment as seen in the CTD casts in Fig. 9. There is evident variability in the time-evolution of the upper ocean layer, which accounts for the long-term trends seen in the data.

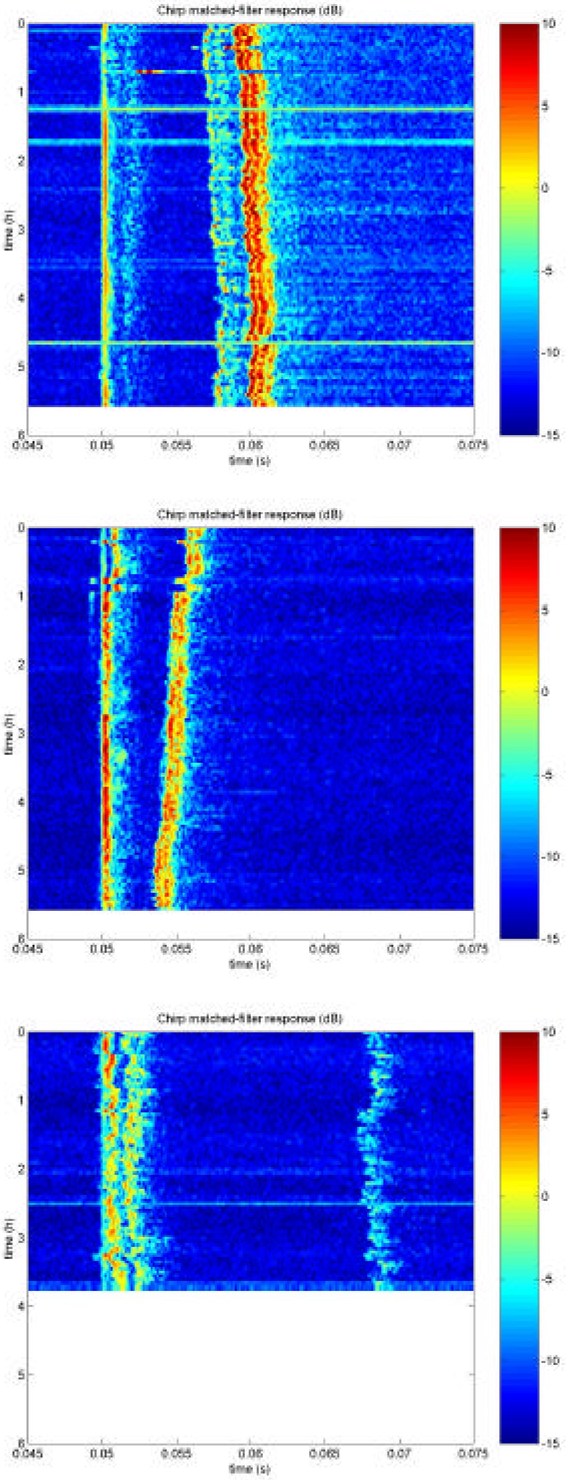


Fig. 7: Estimated impulse response for a range of a) 3 km, b) 5 km , c) 7 km.

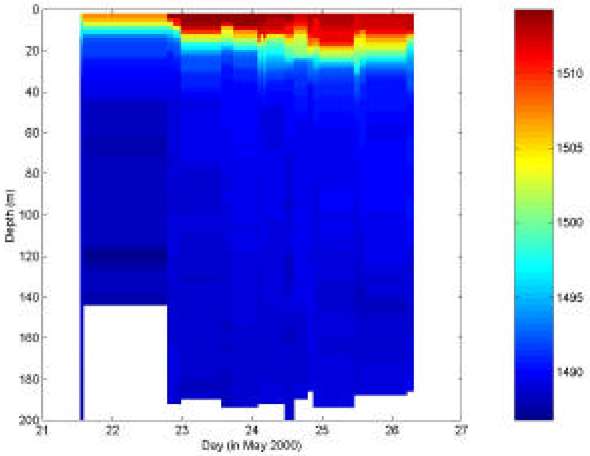


Fig. 8: Evolution of the ocean sound speed structure during SignalEx-C, derived from CTD casts.

V. Modem Performance

A large number of modem schemes were tested during these two SignalEx tests and many of the developers are still processing data to produce statistical results. Here we focus on two schemes in particular, that are distinguished by being specifically designed to provide a multi-access capability for use in the SeaWeb network.

The two signaling schemes are FH-FSK (frequency-hopped, frequency-shift keyed) [4] and DPSK (differential phase-shift keyed) scheme. In the MFSK scheme, mutli-access is provided by assigning each user a different hopping sequence. In the DPSK scheme, each user's data sequence is convolved with a different Gold sequence, which provides a unique key for decoding. This approach is closely related to a common CDMA standard for wireless phone communications.

A comparison of the bit-error rates for the two signaling schemes is shown in Table. 1. A waveform for each scheme was transmitted once every 30 minutes yielding a total of 11 datasets during the 5.5 hours of the experiment. The FH-FSK scheme involved a 200 bit transmission which after channel coding expanded to 268 bits. The DPSK transmission contained 400 bits and no channel coding.

While these results are only preliminary, there are several interesting aspects. First, both methods performed well during the test. Here it is important to emphasize that the error rates are presented as channel errors, i.e. before the error correction that results from the channel coding: This allows us to separate the channel coding from the fundamental physics affecting modem performance. After implementing the channel coding the FH-FSK scheme showed *zero* errors and a similar improvement is anticipated in the DPSK scheme.

Secondly, we see that the two methods had quite different error statistics. Often the DPSK method had exactly zero errors; however, on some of the datasets the error rate goes up significantly. We may say that the FH-FSK was more predictable. The reason for this is still being explored but it may reflect a shortcoming of the DPSK acquisition process rather than the data decoding itself.

Thirdly, and in stark contrast to the Front engineering test described above, neither of the methods shows sensitivity to the strongly changing propagation conditions (and in particular to the multipath duration).

TABLE I
Bit-error rates (percent) for FH-FSK and DPSK schemes in SignalEx-B.

Dataset	FH-FSK (30 bps)	DPSK (10 bps)	DPSK (50 bps)	DPSK (100 bps)
1	7.0	1.5	2.5	47.5
2	2.5	0	0.3	5.6
3	2.7	0	27.5	5.8
4	2.4	44.3	31.5	10.5
5	0.3	0	0	0
6	1.5	0	0	0
7	1.5	0	0	0
8	1.1	0	0	2.5
9	2.2	0.3	0.5	50
10	1.5	0	0.3	1.8
11	0.5	48.8	54	1

VI. Conclusions

The SignalEx tests are unique in bringing together a variety of different signaling schemes together for testing under comparable conditions (identical projectors, receivers, etc. and under essentially identical environmental conditions). The hardware itself has performed admirably with stunning clarity of analog (music) transmissions received out to 6 km in range. Similarly, the probe signals have provided valuable insights about the acoustic propagation conditions.

The analysis and interpretation of the statistical measures of performance is however extremely challenging. Each signaling scheme is sensitive to different factors (Doppler spread, multipath spread) and most of the methods have parameters that can affect which factors they are sensitive to. For instance, an FSK scheme with a long tone-duration becomes quite insensitive to multipath spread. In addition, most of the schemes involve both an acquisition and a decoding phase and problems in the acquisition must be separated. Nevertheless, the comparison of these methods under common conditions will provide valuable insights.

ACKNOWLEDGMENTS

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