Acoustic Communication in Very Shallow Water: Results from the 1999 AUV Fest

Lee Freitag, Matt Grund, Sandipa Singh and Mark Johnson

Woods Hole Oceanographic Institution
86 Water Street
Woods Hole, MA 02543

***Abstract*—The 1999 AUVFest was held near Gulfport, Mississippi in a shallow-water area with depths between 3 and 8 meters. The acoustic channel was characterized by multipath spanning up to 20 msec and high noise levels from snapping shrimp. Acoustic communication testing was performed with the REMUS AUV transmitting both known test data and real-time status information. In addition, a series of ship-to-ship tests were performed in order to characterize stationary performance at ranges of one to five kilometers. Data rates of 60-5000 bits per second were transmitted and, despite the very shallow water conditions, the communication link was reliable at ranges up to 5 km at all data rates.**

I. INTRODUCTION

Acoustic communication with unmanned underwater vehicles in very shallow water (VSW) is important for both civilian and Naval applications. The US Navy defines very shallow water as less than 40 feet (12.2 meters), and has recently focussed on this water depth due to its importance for coastal Mine Countermeasure (MCM) operations. However, acoustic communication with autonomous vehicles in VSW is challenging, and the maximum range and data rate of the link are a complicated function of the propagation conditions. Thus, performance evaluation of acoustic communication systems under realistic field conditions is needed so that effective command and control systems may be developed for near-shore AUV operations.

Very shallow water MCM surveys have a variety of data communication requirements which depend upon the configuration of the underwater vehicle and its mission. In addition, minimizing source level or the average transmitted duty cycle may also be important, requiring the communication system to reduce data rate as source level is reduced in order to maintain reliable operation. This multiple rate capability also maximizes efficiency with respect to range because as the signal-to-noise ratio (SNR) at the receiver changes, the system can increase or decrease throughput accordingly.

A further need for VSW MCM operations is a multi-user capability, providing either centrally-controlled supervision or multi-vehicle cooperation. One method for providing multi-user underwater acoustic communication is code-division multiplexing. In code-division multiple-access (CDMA) each users' signal is spread with a unique code so as to reduce interference from other users. This has the effect of reducing throughput for a given bandwidth, but the coding gain increases the link margin at a constant source level.

There were two main goals for this particular test. The first was to demonstrate phase-coherent acoustic communication from an autonomous underwater vehicle in VSW during a typical MCM mission. The second was to determine the reliability and throughput possible in VSW at different ranges using a number of signaling strategies.

The paper is organized as follows. Section II describes the signaling methods and algorithms used for processing. Section III details the test equipment, while the fourth section summarizes the results for the REMUS vehicle and for the stationary ship-to-ship tests.

II. SIGNAL AND RECEIVER DESCRIPTIONS

The system uses phase-coherent signaling and a variety of coding methods. The aggregate data rate ranges from approximately 60 to 5000 bits per second. While the high-rate signals are intended for single-user applications, the low-rate signals are designed for multi-user or very low SNR situations.

A. Single-User Modulation and Reception

The two highest rate signals utilize QPSK and BPSK modulation and a concatenated error-correction coding method. A high-rate Reed-Solomon code is used for the outer layer, while a block code is used for the inner layer. The data rate is varied by selecting different block codes as listed in Table I.

The receiver is the multi-channel decision-feedback equalizer (DFE) with phase-locked loop [8][9]. The equalizer reduces the effect of multipath and the phase-locked loop tracks carrier drift which occurs when there is source or receiver motion. In order to allow the DFE to take advantage of the gain from the inner block code, the receiver uses a delayed filter update. The delay, which is the length of an inner

This work was supported by the Office of Naval Research under Grants N00014-99-1-0287 and N00014-95-1-1316. Email: lfreitag@whoi.edu.

TABLE I MODULATION AND CODING SUMMARY

	Single-User Rates		Multi-User Rates	
Specification	High Rate	Low Rate	DS-15 Low	DS-31 V. Low
Modulation Methods	QPSK	BPSK	BPSK	BPSK
Reed Solomon Code Rate	0.9	0.9	0.9	0.9
Inner Code Type	BCH	BCH	Conv.	Conv
Inner Code Rate	11/16	10/63	1/2	1/2
Total Rate (bits per sec)	4950	570	120	58
Packet Size (bits)	24576	2048	512	256

Table 1. Summary of modulation methods and error-correction coding used for the different packets during the test. BCH codes are a well-known family of block codes [10]. The convolutional code has constraint length 9 and is used for the IS-95 digital telephony standard.

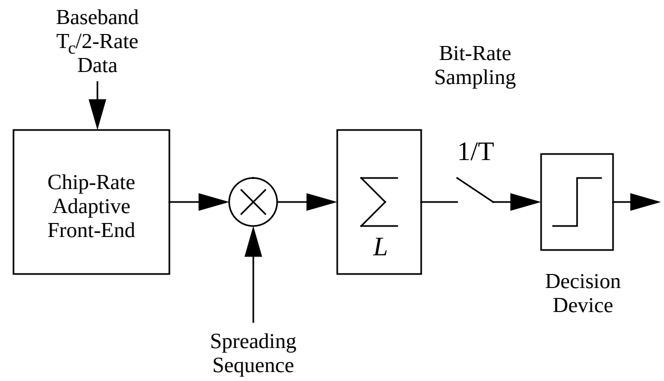

Fig. 1. Spread spectrum receiver with chip-rate adaptive front-end which includes phase-tracking and Doppler compensation prior to decorrelation.

code, allows feedback of corrected decisions, improving performance at low SNR. The phase-locked loop is operated without feedback delay because it is less sensitive to occasional decision errors.

B. Multi-User Modulation and Reception

The low-rate multi-user communications signals [1] use direct-sequence spread-spectrum (DSSS) modulation [2]. Direct sequence spread spectrum communications utilizes a family of k L-length codes [7], which are transmitted at the chip rate $1/T_c = B$, where B is the maximum bandwidth. The link rate is then B/L bits per second. The system described here uses 15- and 31-chip Gold codes [6].

The conventional direct-sequence receiver [2] uses the desired user’s code to de-correlate the modulated signal and recover the transmitted data. While this receiver is used for many RF applications, its performance is limited in the underwater channel due to phase variations and time-varying multipath. However, several DSSS systems have been proposed for use underwater. The system described in [3] utilized 10 kHz of bandwidth and short spreading codes in order to combat fading effects in shallow water, and in [4] and [5] long-range communications and multi-user access using DS codes are discussed.

A drawback of the conventional DS receiver is that the spreading code must be longer than the multipath delay in order to avoid intersymbol interference at the output of the decorrelator. However, to achieve the spreading code gain L, the channel must be stationary over the period of the code. In the non-stationary underwater environment, channel variation over the L-chip data bit period will reduce the achievable spreading gain at the receiver.

In order to combat these effects and increase the reliability of underwater DS systems with moving vehicles, an adaptive receiver structure [8] which mitigates these effects is used (Fig. 1). The adaptive front-end reduces multipath and performs Doppler correction [9] at the chip level (before de-correlation). While the adaptive receiver is more complex than the conventional receiver, it provides a significant increase in performance in a dynamic multipath environment.

An equally important feature of the adaptive receiver is its ability to reduce interference from other users. The filter taps are adapted using a minimum mean-square error criterion, which in the presence of interfering users converges to a solution which reduces their impact.

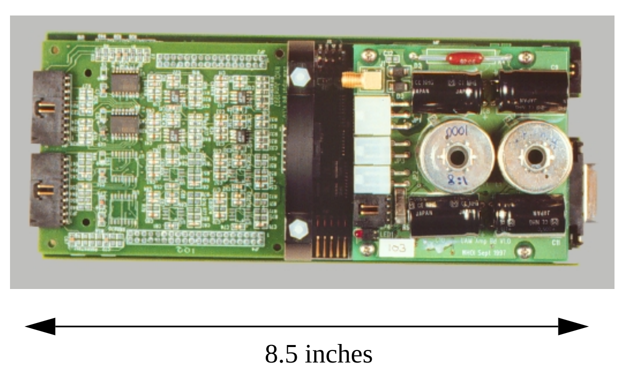

Fig. 2. Utility Acoustic Modem electronics (top view). The board set measures just 8.5 by 3.5 inches and weighs 1.2 pounds. A variety of different acoustic transducers, both transmit and receive, may be used with the modem. The modem draws 3 Watts when receiving and approximately 30 Watts while transmitting.

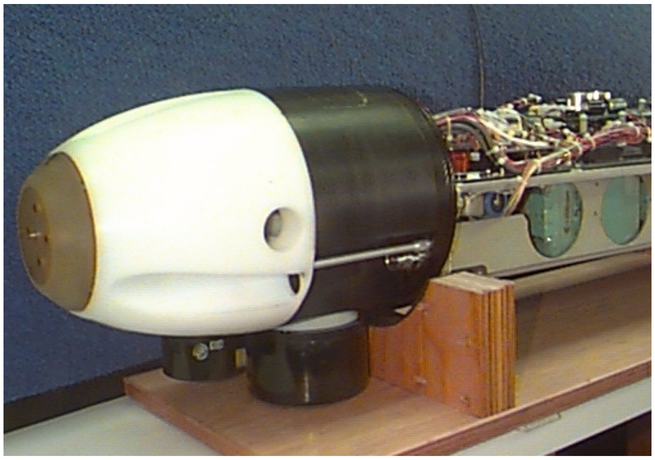

Fig. 3. REMUS nose-cone showing the forward-looking homing transducer (front), 25 kHz tracking transducer (bottom, forward), and 10 kHz communications transducer (bottom, aft). The modem electronics are mounted in the dry volume above the batteries.

III. Systems Description

The communication system includes a compact assembly installed on the REMUS vehicle and a larger set of equipment aboard the receiver vessel. The Utility Acoustic Modem (UAM) installed on REMUS consists of an electronics package (Fig. 2) and a 10 kHz underwater acoustic projector mounted on the bottom of the vehicle just behind the nose-cone (Fig. 3). This frequency was selected to avoid interference with existing tracking systems between 20 and 30 kHz. The modem may utilize almost any frequency between 10 and 30 kHz depending upon the user's requirements. Specifications for the modem as installed and configured for this test are listed in Table II.

The modem is based around the TI TMS320C44 digital signal processor and it uses a flexible operating system which allows reconfiguration based on mission requirements. The modem transmits using an efficient class-D amplifier which allows high sources levels to be delivered while minimizing power consumption. For this particular test the UAM was used as a transmitter only.

Mission status data was provided by the vehicle controller to the modem every thirty seconds using an RS-232 interface. In order to make the most of the available link bandwidth the REMUS vehicle controller packs the data to use the minimum number of bits necessary as shown in Table III. For the compact vehicle status messages (32 bytes), the lowest rate acoustic communications shown in Table I was used.

The receiver consisted of a 2-m 16 element vertical array with DSP-based packet detection and digital down-conversion. A near real-time multi-processor system performed the equalization and error-correction described in Section II. A variable number of channels was used by the receiver, usually ranging from one to six. After equalization, the decoded information was sent to the REMUS topside tracking display for plotting. The display plots the vehicle position determined by its acoustic navigation system as well as various sensor and status data.

Table II REMUS Modem Transmit Specifications

Symbol Rate	4000 symbols per second
Bandwidth	4000 Hz
Carrier Frequency	10 kHz
Source Level	185 dB re uPa.
Beampattern	Omni (Horizontal)

Table III Data Transmitted by REMUS Over the Acoustic Modem in One Packet

Data Unit	Bits Used
Mode	8
Message Number	8
Latitude	24
Longitude	24
Time	32
Heading	8
Vehicle Depth	8
Status Word (Faults)	32
Battery Voltage	8
Mission Leg	8
Estimated Velocity	8
Age of Navigation Fix	8
Conductivity	8
Temperature	8
CTD Depth	8
Sound Speed	8
CTD Data Point Latitude	24
CTD Data Point Longitude	24

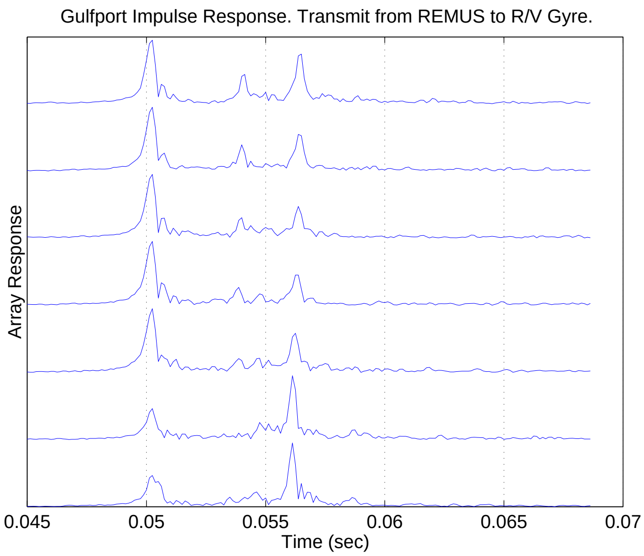

Fig. 4. Example of the multipath observed on the acoustic array suspended from the R/V Gyre during a REMUS communications test. The array spans 2 m and significant variability with respect to depth is present.

IV. Experimental Results

The tests were conducted in November 1999 offshore Gulfport, Mississippi in a shallow-water area just north of Ship Island. The bottom is mostly mud and sand, and the sound speed is nearly constant from the surface to the bottom. The measured channel impulse response varied with range and location of the source, however most of the time the channel included at least several rays with delay spreads of 5 to 20 msec. A typical example of the impulse response measured using the frequency-modulated probe which starts each packet is shown in Fig. 3. This figure shows the impulse response at each of 7 hydrophones in the array spaced approximately 0.2 m apart. Several arrivals are visible and the total span is about 7 msec. Significant channel-to-channel variation is present across the array.

Two main noise sources were experienced during the test: snapping shrimp which create large amplitude but very short-duration impulses, and outboard motors from small boats which supported the various vehicle tests and provided shuttle service. While the error-correction coding methods provide immunity to impulsive noise as from snapping shrimp, the continuous noise from outboard engines approaching the receive vessel would sometimes preclude communications for a few minutes. Other than temporary outages due to small boats, the system was very reliable.

A. AUV Fest Results

Missions with the modem-equipped vehicle were conducted almost every day of the experiment. Each mission was several hours long and ranges of up to 4 km were tested. Depending on the vehicle's survey area, the water depth varied from as low as 3 m to about 8 m.

The modem was operated at a low duty cycle: the vehicle status packet, a three second transmission, was broadcast every thirty seconds. This rate was sufficient for the vehicle operator to determine mission progress, identify error conditions and sample environmental data such as water temperature and conductivity. A low transmit duty cycle is used to minimize the power consumption of the modem on the vehicle as well as interference with other acoustic systems.

Figures 4 through 6 show the test tracks and the locations where acoustic transmissions were made from the REMUS vehicle for three different missions. In Fig. 4 the results from a mission with range up to 3 km is shown.The mission starts and ends with a transit to a point about 1.25 km from the receive vessel and the maximum range of the vehicle is slightly over 3 km. Four survey legs of 1.75 km are performed. Each point in the plot represents a position where a communications packet was transmitted. The survey extends into water that is 5-6 meters deep and while the SNR is reduced

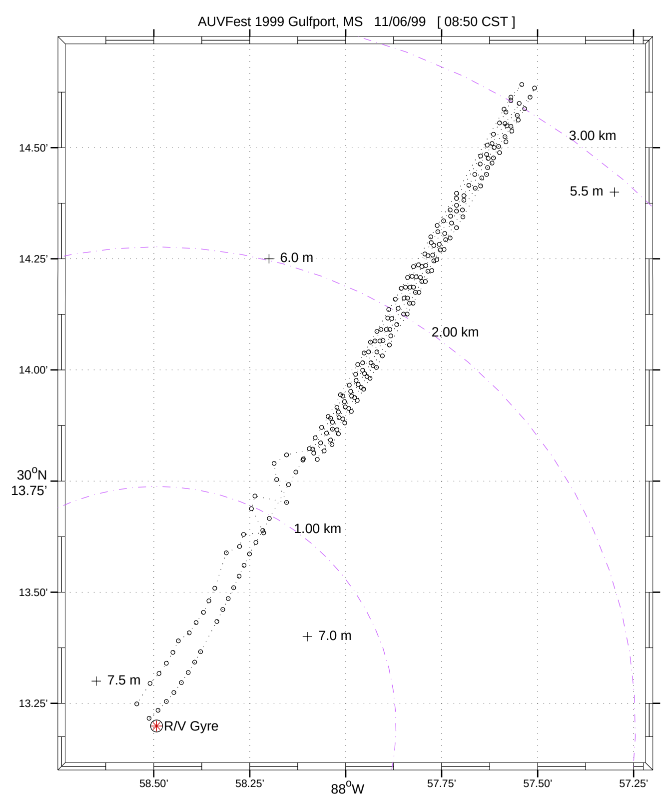

Fig. 4. REMUS mission with four closely spaced survey legs between 1.2 and 3 km range.

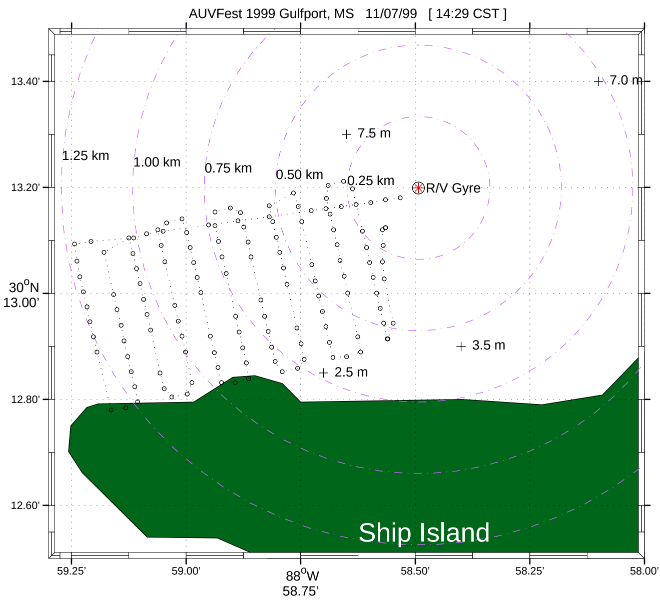

Fig. 5. REMUS tracks during a test in water as shallow as 2.5 meters near Ship Island. Each dot represents a point where REMUS transmitted a data packet. Despite the shallow depth the link operated very reliably. Note that the outline of Ship Is. is approximate.

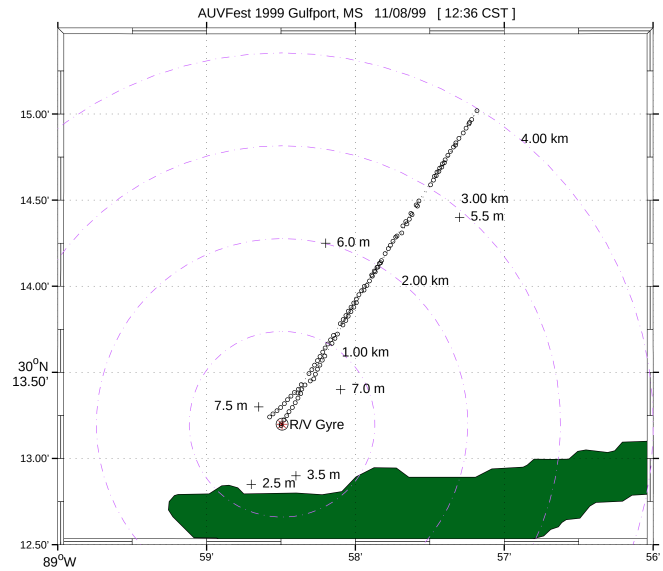

Fig. 6. REMUS tracks during a 4 km range test showing locations where the vehicle transmitted a status information packet back to the R/V Gyre.

at the long ranges, the link remains reliable and almost all packets were received error-free.

In Fig. 5 a short survey into even shallower water is shown. Here the mission runs in toward the beach where the water shoals to approximately 3 meters depth. The link is very reliable even close to shore. In Fig. 6 the track of a longer mission is shown. The track is simply a transit out to 4 km range and then back. The link is again very reliable with only a few data packets lost during the entire survey.

B. ModemFest Results

During AUVFest several research organizations collaborated to perform acoustic modem testing under controlled conditions. This experiment, called ModemFest, was conducted during two evening periods. A second vessel was used for the transmit platform and it was anchored at five different ranges, three to the East of the receiver on the first night and two to the West on the second as shown in Fig. 7.

At the R/V Gyre the same receiver setup was used, while on the source vessel a battery-powered transmitter generated the test signals from digital audio tape. The specifications for the source used during this test are listed in Table IV.

The four different data rates listed in Table I were transmitted sequentially in order to compare relative performance. Each was equalized using the adaptive receiver and the success rate was very high, nearly 100%, as shown in Table V. A total of 189 packets were received and all but one were decoded with no bit errors after the concatenated error-correction is applied. The resulting packet success rate is very high, demonstrating the communication in very shallow water is not only feasible, but can be very reliable as well.

V. Conclusion and Ongoing Work

The results presented here demonstrate that communication with autonomous vehicles is feasible in very shallow water (less than 12 meters). This capability is made possible through use of a sophisticated adaptive receiver algorithm with modulation and coding selected to achieve the desired throughput and reliability.

The tests performed during AUV and ModemFest were one-way and relied upon some laboratory equipment for processing. However, the variable-rate, phase-coherent receiver has now been ported to the Utility Acoustic Modem and it is undergoing additional trials in the REMUS vehicle and on buoys in both shallow and very shallow water environments.

Table IV AUVFest Modem Transmit Specifications

Symbol Rate	4000 symbols per second
Bandwidth	4000 Hz
Carrier Frequency	13.5 kHz
Source Level	183 dB re uPa
Beampattern	Omni (Horizontal) 60 deg (Vertical)

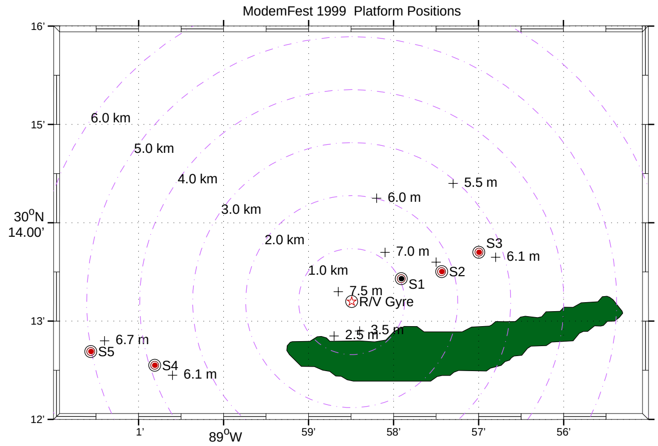

Fig. 7. Platform positions for the ModemFest testing performed in conjunction with AUVFest. The R/V Gyre was the receiver platform for all of the tests. The source vessel was anchored at each of the five stations (S1-S5) during two evenings of testing.

TABLE V NUMBER OF GOOD PACKETS/TOTAL RECEIVED

	Single-User Rates		Multi-User Rates	
Station/ Range	High Rate	Low Rate	DS-15 Low	DS-31 V. Low
S1 - 1 km	10/10	9/9	10/10	8/8
S2 - 1.8 km	13/13	12/12	9/9	12/12
S3 - 2.6 km	10/10	10/10	8/8	9/9
S4 - 4 km	9*/10	10/10	9/9	10/10
S5 - 5 km	6/6	8/8	9/9	7/7

Results from the tests performed at five different ranges during fixed ship to ship testing. Of the 189 packets received during the test there were errors in only one packet. The single bad packet (*) was at the high rate at 4 km range and it had 212 bit errors out of 24576 bits in the packet.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the work and assistance of the REMUS development and operations team: Chris von Alt, Tom Austin, Roger Stokey, Ben Allen and Ned Forrester. AUVFest was sponsored by ONR (Dr. Tom Curtin) and organized by NAVOCEANO (Kevin Schexnayder). The authors would also like to thank the Captain and crew of the R/V Gyre and the NAVOCEANO small boat staff which provided excellent support.

REFERENCES

[1] R. L. Peterson, R. E. Ziemer and D. E. Borth, *Introduction to Spread-Spectrum Systems*, NJ: Prentice Hall, 1995.

[2] S. Glisic and B. Vucetic, *Spread-Spectrum CDMA Systems for Wireless Communication*, Boston: Artech House, 1997.

[3] J. H. Fischer, R. Kendrick, et. al, “A high data rate, underwater acoustic data-communication transceiver,” *Proc. Oceans ‘92*, Newport, RI.

[4] G. Loubet, V. Capellano and R. Filipiak, “Underwater spread-spectrum communications,” *Proc. Oceans ‘97*, Halifax, Nova Scotia.

[5] C. Boulanger, G. Loubet and J. Lequepeys, “Spreading sequences for underwater multiple access communications,” *Proc. Oceans ‘98*, Nice France.

[6] P. Fan and M. Darnell, *Sequence Design for Communications Applications*, Hertfordshire, UK: Research Studies Press, 1996.

[7] D. V. Sarwate and M. B. Pursley, “Crosscorrelation properties of pseudorandom and related sequences,” *Proc. IEEE*, vol. 68, pp. 593-619, 1980.

[8] M. Stojanovic, J. Catipovic and J. Proakis, “Phase coherent digital communications for underwater acoustic channels”, *IEEE J. Oceanic Eng.*, Vol. OE-16, pp 100-111, Jan. 1994.

[9] M. Johnson, L. Freitag and M. Stojanovic, “Improved Doppler Tracking and Correction for Underwater Acoustic Communication,” in Proc. *ICASSP’97*, vol 1, pp. 575-578, Munich, Germany, April, 1997.

[10] J. Proakis, *Digital Communications,3rd Edition*, New York: McGraw Hill, 1995.