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AUV COMMUNICATIONS SYSTEM EVALUATION

FINAL REPORT

Contract No. MDA972-90-K-003

MSEL REPORT #91-13

REVIEW OF THIS MATERIAL DOES NOT IMPLY DEPARTMENT OF DEFENSE INDORSEMENT OF FACTUAL ACCURACY OR OPINION.

UNMANNED UNTETHERED SUBMERSIBLE TECHNOLOGY

Prepared by: Marine Systems Engineering Laboratory
University of New Hampshire
Marine Program Building
Durham, NH 03824

August 1991

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1. Introduction

A. Background

This document presents the results of investigations into the performance of the model ATM850 underwater acoustic telemetry link. These investigations were made by the Marine Systems Engineering Laboratory (MSEL) under Defense Advanced Research Project Agency (DARPA) contract #MDA972-90-K-0003.The link is produced by Datasonics, Inc., Cataumet, Ma., under license from the Woods Hole Oceanographic Institute, Woods Hole, Ma.

The objective of MSEL's research and evaluation program, supported primarily by the DARPA contract, was to evaluate the units on the basis of their suitability for use in an autonomous underwater vehicle (AUV) communications system. The specific type of data presented in this report is the measured bit error rates (BERs) for the ATM850 link at various ranges and in various operating scenarios.

Evaluations were performed using a pair of prototype units provided to MSEL by Datasonics. The transmitter was a Datasonics model ATM840 unit modified to behave as an ATM850. The receiver was an ATM850. Both units had omnidirectional transducer configurations with a source level of 178 dB referenced to 1 μPa at 1 meter. Datasonics is reportedly able to achieve a source level increase of 12 dB by using a directional transducer configuration.

The model ATM850 advances the state-of-the-art in underwater acoustic telemetry through the use of imbedded digital signal processing hardware and software. At the present time, the unit is capable of a transfer rate of 1200 bits per second.

B. Organization of the document

This report has been divided into four sections.

1. **Section 1** -This is a brief introduction to the rest of the document.
2. **Section 2** - The second section describes the experimental procedures and events used to collect and analyze ATM850 error performance data. It is more detailed than is necessary for a report of this kind and is not intended to be read unless background information is desired.
3. **Section 3** - The third section is the focal section of the document and presents the experimental results of the ATM850 evaluation tests. The third section also includes observations and conclusions regarding the experimental data.
4. **Section 4** - The fourth section presents further derivations of point-to-point protocol performance when using the ATM850 links. Previous interim status reports to DARPA concerning this project have covered this subject using typical, but not experimentally based, performance values.
5. **Section 5** - This section summarizes the findings of the program.

2. Evaluation Procedures

This section summarizes the process of field experimentation and data collection for this program. It is expected that this section will not be of primary interest to the intended readers of this report. However, it was felt that this section may provide valuable background information and it was included for that reason.

A. General Procedures

The units supplied to MSEL by Datasonics were packaged in a pressure cannister. The package housed the telemetry electronics, interface electronics, and battery stacks. Communication with the host was accomplished via three-wire serial (RS-232) communications over a four-conductor, Kevlar™-sheathed cable. See Figures 1 and 2.

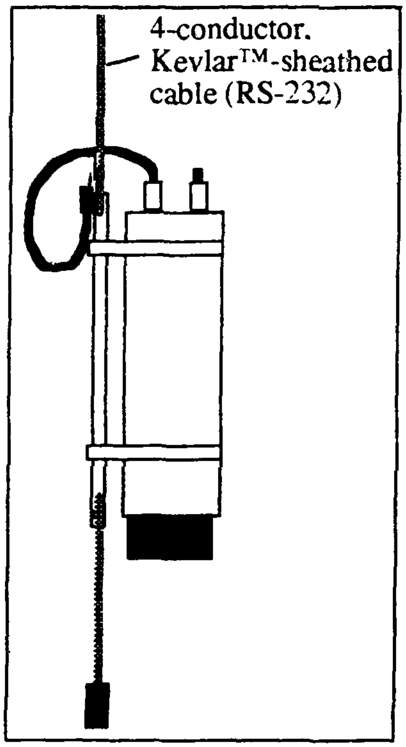


Figure 1 ATM850 Deployment Package

Determination of error rates was accomplished by two means. The primary method was through use of the system self-test, described below. The secondary means was through the host to host transfer of data and the comparison of the transmitted data to the received data. Both types of transfer were performed at several ranges and in two operating situations.

The two operating situations were in bodies of water that offered horizontal path length to vertical water depth ratios of approximately 20:1. The first operating situation was in a shallow body of water (12-13 meter depth), where multipath interference is pronounced. The second operating situation was in a deep (> 150m) body of water, where multipath is reduced and a more accurate estimate of maximum communications range could be made.

The units were powered by stacks of D sized alkaline batteries that had been specially constructed and supplied to MSEL by Datasonics. Datasonics initially estimated that each set of batteries supplied power sufficient to transfer 225 kilobytes of data between units. After observing the operation of the test packages for a time we realized that this figure was conservative. We revised the figure and now estimate that a set of batteries will transfer at least 500 kilobytes when using the ATM850 with an omnidirectional transducer configuration.

The ATM850 Self Test

WHOI and Datasonics have imbedded a point-to-point error analysis function within the ATM850 operating system that provides immediate error results to the user. The test is initiated by the receiving host, which "awakens" the receiving modem and issues a command via the host-to-modem serial connection. The command is then transmitted by the modem playing the role

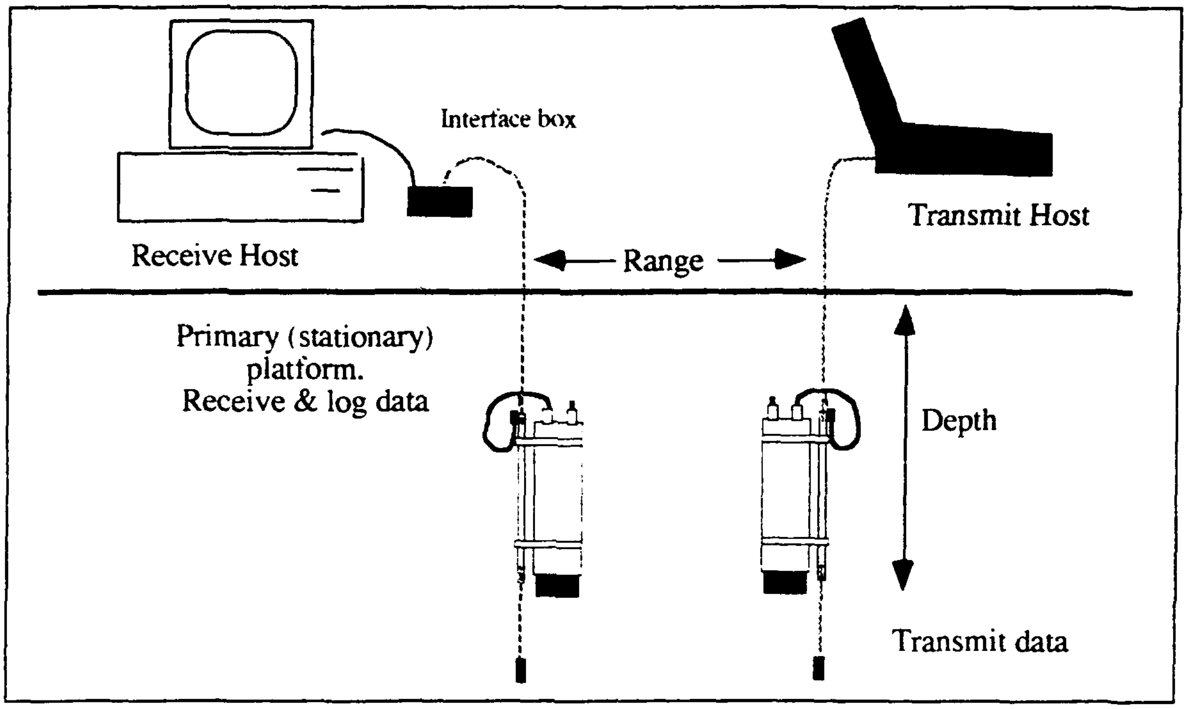


Figure 2 - General ATM850 Evaluation Test Setup

of receiver to the modem playing the role of transmitter. Upon receipt of the command, the transmitter transmits a 18,432 bit data stream that is permanently stored in modem memory. The receiver, which is awaiting this specific data sequence, compares the received data to the original stream and reports the number of errors to the receiver host.

Other information is reported to the receiving host as well. Changes made in the adaptive functions of the receiver are reported. The signal-to-noise ratio (SNR) of the acoustic signals measured by the ATM850 during transmission is reported.

```
00FF02030001010001000200020202010202020202020218EA0202020101020202020300000
10002010202010101FF030101FF030001000202020300BB000E0707007F0677M
```

The example above (excerpted from actual data logs) shows a report from the receiving ATM850 after an iteration of a self-test. The section of the report prior to the BB in the second line gives numbers which indicate the changes made in the ATM850 adaptive receiver functions. The four characters (underlined) immediately following the BB give the count of errors as a hex number. The four characters following the error count (dashed underline) give numbers related to the signal-to-noise ratio. These numbers are converted from hex to decimal and divided by 100 to give the SNR in decibels (dB). The numbers from the excerpt above show 14 errors (out of 18,432 possible) and a SNR of 17.99 dB.

Host to host data transfer

The self-test transfer described above is quick and convenient, but provides only the results of a diagnostic analysis. It provides no raw data that can be used for further analysis, e.g., error time history analysis. As an alternative, MSEL wrote a program that generates a size-variable, unique-sequence ASCII data stream and downloads the stream to an ATM850.

The sequence of bytes is made unique by creating a series of character triplets- the header character of the triplet is always the same character, the second character of the triplet is the result of being the outer counter in a loop, and the third character is the inner counter in a loop. To illustrate, we first define the header character to be ':'. We make the lower and upper bounds on the second character to be 'A' and 'E', respectively. We then make the lower and upper bounds on the third character to be 'A' and 'C', respectively. The resulting stream would be:

```
:AA:AB:AC:BA:BB:BC:CA:CB:CC:DA:DB:DC:EA:EB:EC
```

The program gives the user the ability to change the pattern and size of the data stream by changing the bounding characters. In general, we used the entire range of the printable ASCII character set to get a stream size of 27,075 bytes.

Data Capture

The receiving host used a communication program called Kermit to connect to the receiving ATM850. When it was required that the user send commands to initiate the self-test portion of the measurements, the user typed the appropriate keystrokes at the keyboard. The keystrokes were relayed by Kermit to the ATM850, which then started the transfer procedure.

Data uploaded to the host by the receiving modem was logged to a text file by the SESSION LOG feature of Kermit. This included all results of the self-test diagnostics as well as the received ASCII data stream when a host-to-host transfer took place. Log files were closed and new files were opened according to significant events during the experiment; generally, this corresponded to a change in the range separating the modems.

Data Analysis

Data analysis for this report varies according to the type of data used as a source. The desired result in both cases is a table or graph that gives measured bit error rate versus range and test situation, i.e., water depth.

For the self-test measurements, where several iterations of the self-test transfer were made, analysis consisted simply of adding the errors found for all the iterations and dividing by the total number of bits transferred in all the iterations. For the hypothetical case where six transfers were made with error counts of 22, 10, 18, 45, 67, and 39, respectively, the bit error rate computation yields the ratio $(22+10+18+45+67+39)/(6 \bullet 18{,}432) = 201/110{,}592 = 1.8 \times 10^{-3}$.

Analysis of the host-to-host data stream is a more complex and involved procedure. The logged data is a series of characters which contains errors due to the transfer process. The general procedure is to compare byte by byte the transmitted and received sequence. When a byte is discovered to be wrong, the event of an error is logged. In addition, the byte is rendered and the number of bits in error within the byte is logged. This procedure works smoothly for those cases where the bit error rate is low. When the bit error rate is high, however, there are instances where entire bytes are lost or characters that are outside the printable range are produced. This requires time-consuming character searches and substitutions and leads to a highly inefficient analysis process. Because of these inefficiencies, this type of analysis was generally not performed on data files resulting from high error rate tests. Data files resulting from low error rate tests were analyzed and the results were used to augment the bit error rate data set.

B. Mendums Pond Evaluation Procedures

This set of measurements was made at MSEL's facility at Mendums Pond, Barrington, N.H., on June 14, 1991. The primary testing area at Mendum's Pond is an oval-shaped area that is approximately 1000 meters long and 300 meters wide. The water depth in this area is 13 meters.

Prior to the actual test, MSEL personnel placed moorings and markers in the test area at the ranges scheduled for testing. A temperature profile of the water column (see Figure 3) was taken in the area the day before the test date and was used to locate the thermocline. It was also used to calculate the sound velocity profile for use in post analysis. Surface conditions were calm with no swells or chop. The vessels used as test platforms were anchored at the mooring indicators during testing.

Measurements consisting of six self-tests and a 27 kilobyte data stream were made at 50, 100, and 300 meters. Measurements consisting of six self-tests and an 11.5 kilobyte data stream were performed at 400 and 500 meters. Measurements were attempted at 600 meters but were unsuccessful. Bit error rate versus range results were generally consistent with results implied by ray trace analysis (see Figures 4, 5, and 6). Measurement results are summarized in Table 2.

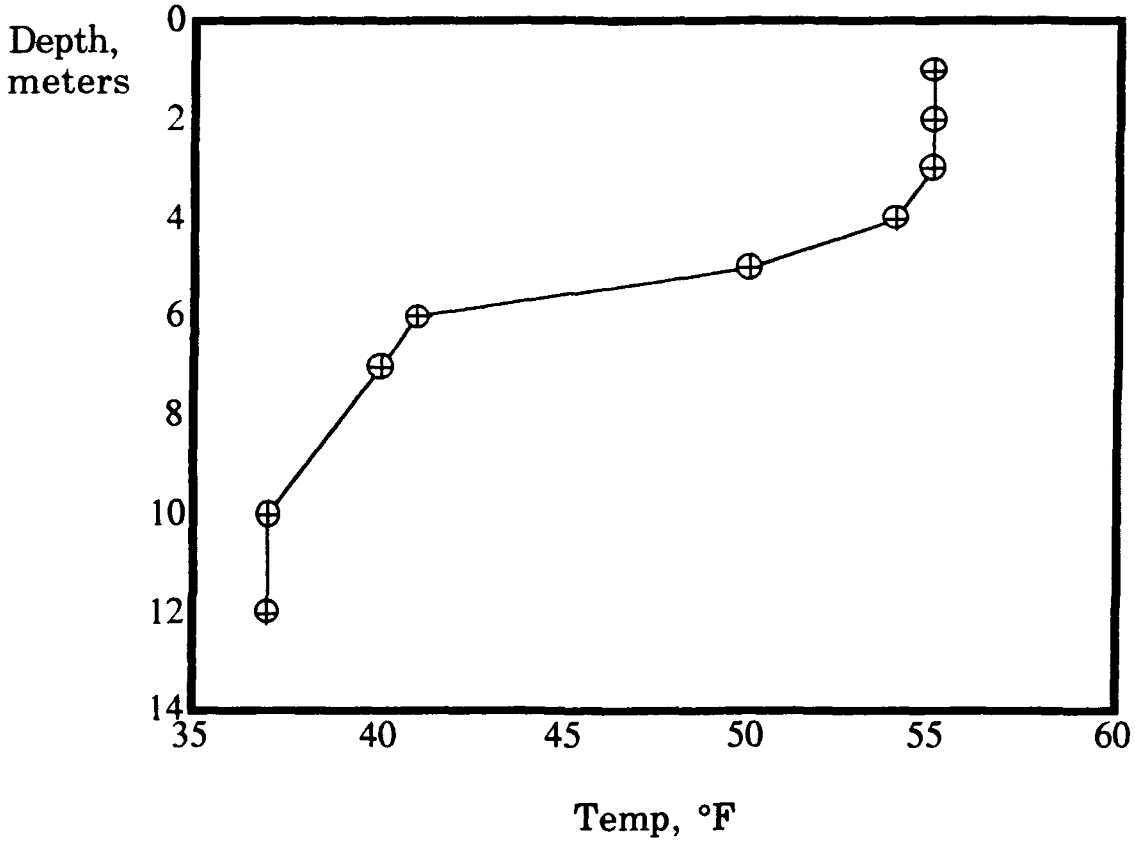
Communications performance at a separation of 100 meters was initially poor. It was realized that the transmitting modem was incorrectly suspended above the thermocline while the receiver was below the thermocline. This was rectified and communications performance improved dramatically. No other problems were encountered.

C. Open Ocean Evaluation Procedures

There were two objectives to deep water evaluations. The first was to obtain a data set which complemented the shallow water results and showed the performance of the modems in a non-multipath environment. The second was to obtain the maximum operating range of the units.

The scheduled experiments were intended to evaluate the ability of the ATM850 links to communicate in a variety of situations. Three configurations were scheduled. The first configuration had both units placed at a depth of 61 meters. The second configuration had the transmitter placed at some depth above the thermocline while the receiver remained at the 61 meter depth. The third configuration had both units placed at depths above the thermocline. For each configuration, several ranges of separation were scheduled to occur.

Figure 3 Mendums Pond Temperature Profile, June 13, 1991



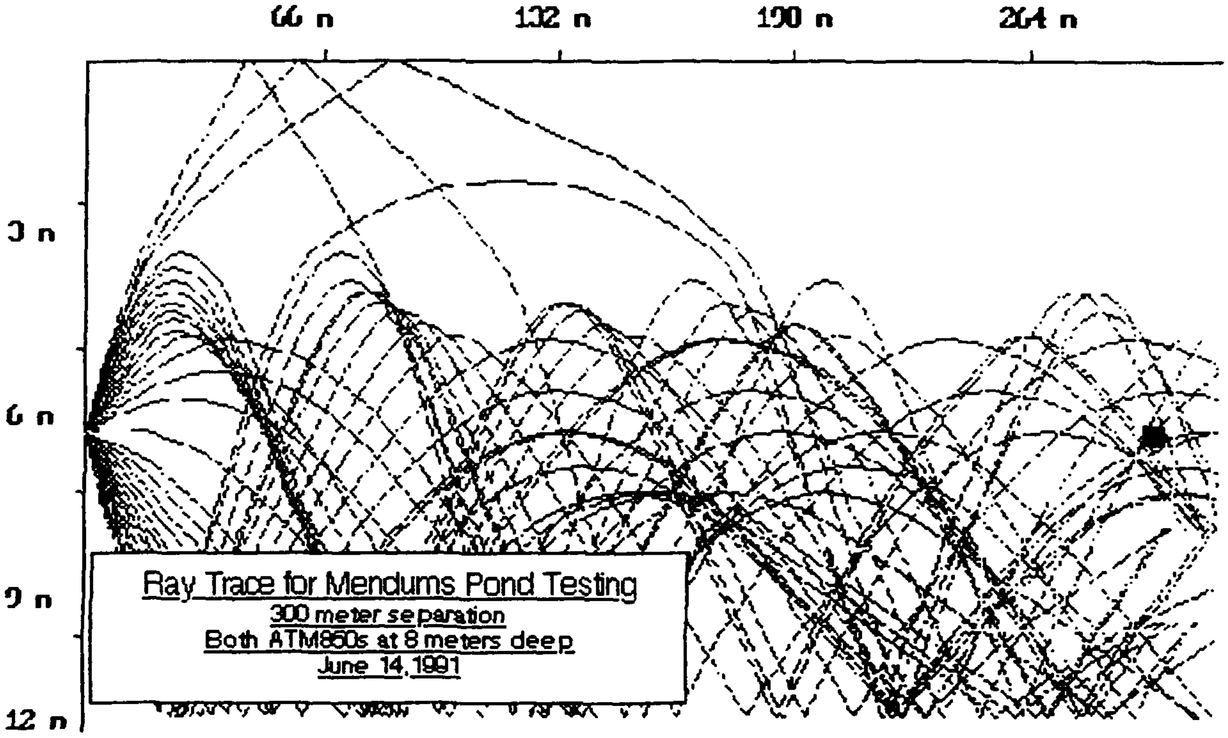


Figure 4 - Ray Trace for ATM850 Error Testing at Mendums Pond, 300 Meter Separation, June 14, 1991

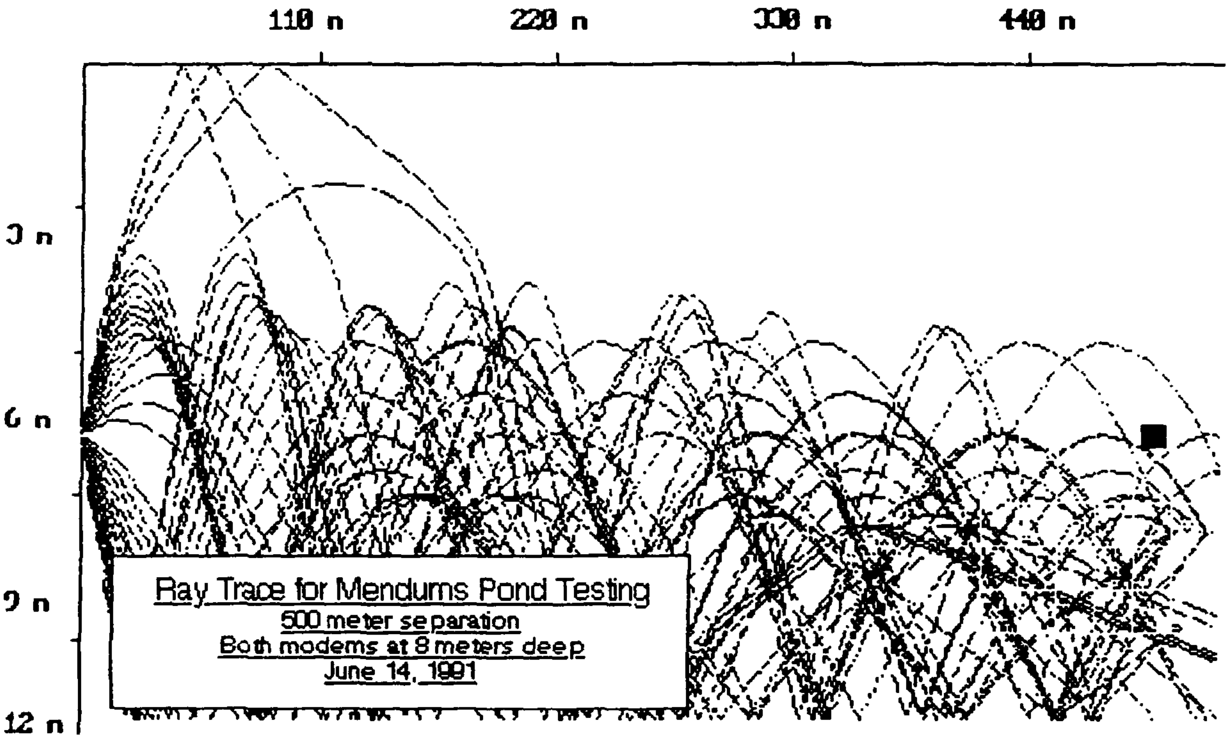


Figure 5 - Ray Trace for ATM850 Error Testing at Mendums Pond, 500 Meter Separation, June 14, 1991

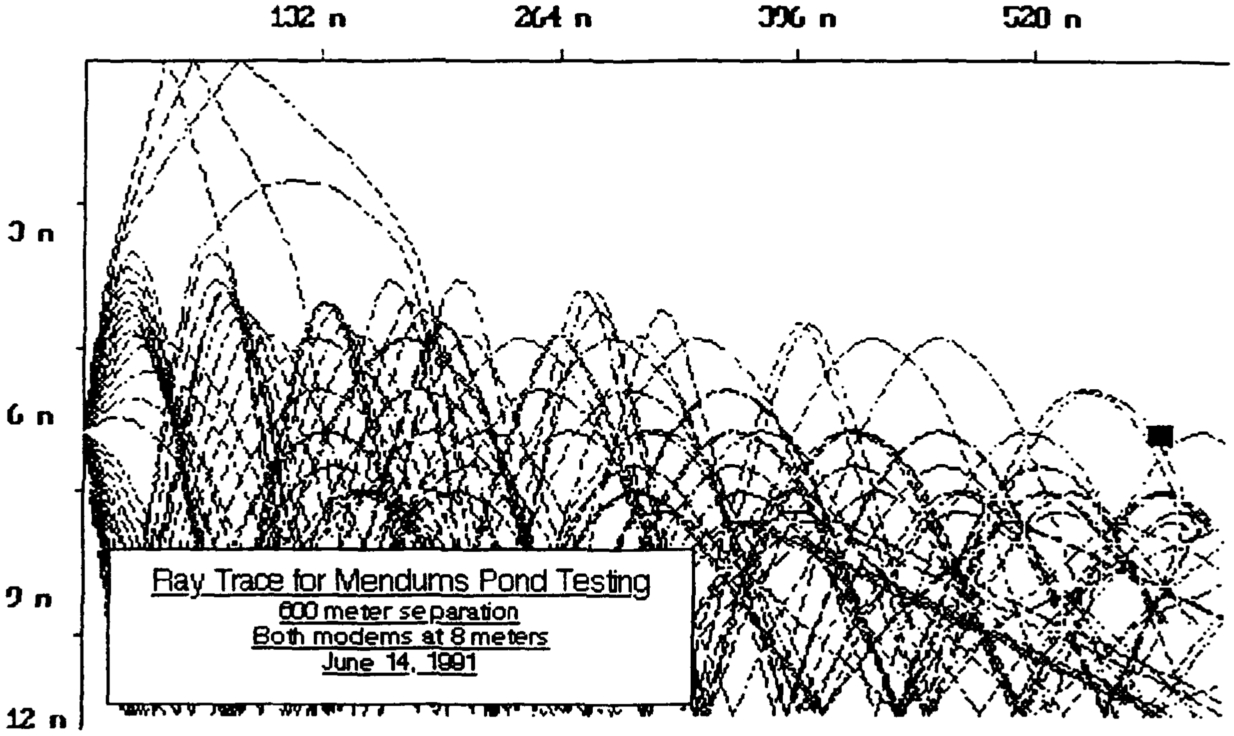


Figure 6 - Ray Trace for ATM850 Error Testing at Mendums Pond, 600 Meter Separation, June 20, 1991

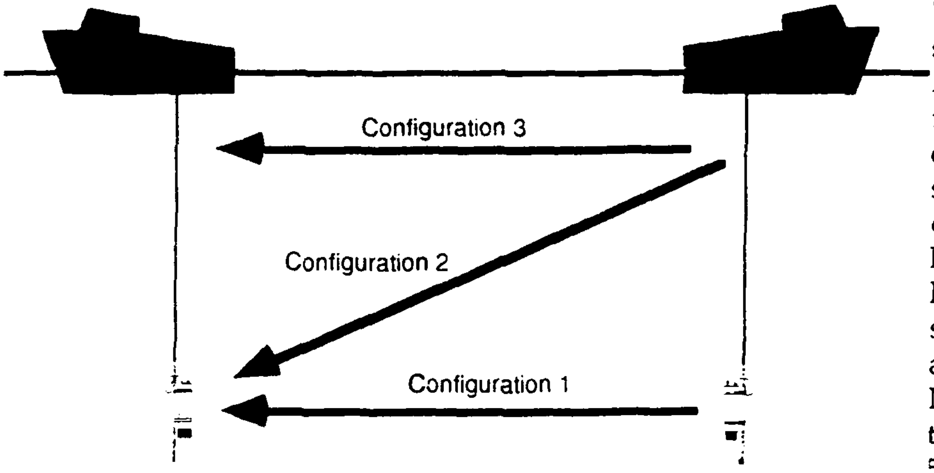


Figure 7 - Modem Configurations for Open Ocean Testing

The test site was fifteen miles east-southeast of the New Hampshire coast at 70°26' N longitude, 42° 53' W latitude. This was one of the sites closest to MSEL that had nearly 500 feet of water. The primary test vessel was the University of New Hampshire research vessel *R.V. Jere Chase*. A second motorboat was taken to act as the mobile platform.

The transmitting unit was deployed from the motorboat. The receiver was deployed from the *R.V. Jere Chase* , which housed the MS-DOS personal computer used to log data. Separation between vessels was monitored with the *R.V. Jere Chase* radar system. The *R.V. Jere Chase* radar system is calibrated in yards.

Two iterations of this experiment were performed. The second test was performed because results from the first test were inconsistent with expected results and because there was an unexplained series of events leading to a failure to communicate during the first test. We summarize each test separately.

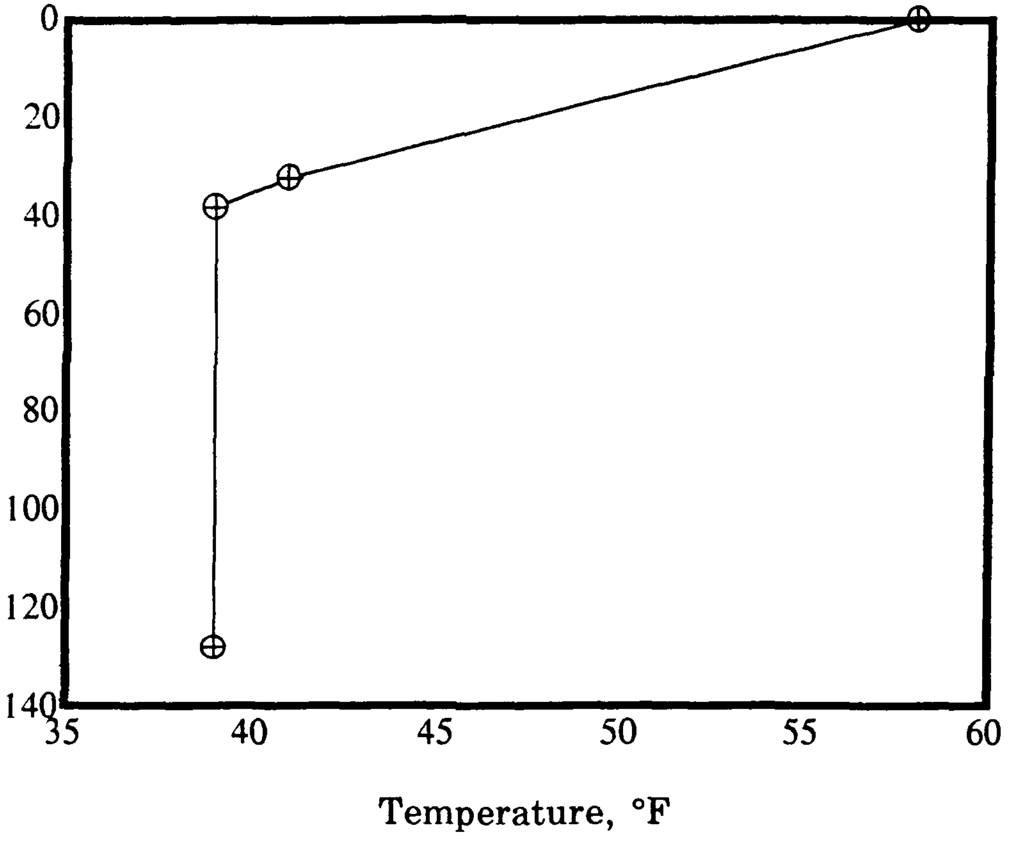
Open Ocean Experiment Number 1- June 20, 1991.

Three self-test transfers and a 11K data stream were scheduled at each combination of configuration and separation. This number of individual tests was reduced from the number performed during shallow water testing because only one set of fresh batteries was available and it was believed that the total data transferred was required to be less than 225 kilobytes. Section 2A explains the battery supply situation more fully.

We arrived at the test site in the late morning and began with the first configuration (both units at 61 m). Surface conditions at this time were calm with maximum swells of roughly 2 feet. One team member made a temperature profile measurement (see Figure 8) of the water column while error measurements carried on. Measurements (three self-tests and an 11K transfer) were taken at 500 yards and at progressively larger separations of 1000, 1500, and 2000 yards. Measurements were attempted at 2500 yards but were unsuccessful- no connections between units occurred despite repeated attempts.

We placed the transmitter at a depth of 25 feet (configuration 2) and reduced separation to 2000 yards. No connections were achieved in this situation. We then lowered the transmitter to a depth of 50 feet. No connections occurred yet again. We then decreased vessel separation and repeated attempts at connection at 1500, 1000, 750, and 500 yards. All attempts were unsuccessful. We reduced separation to 300 yards, where we were able to make several

Figure 8 Open Ocean Temperature Profile, June 20, 1991



transfers of only poor quality.

At this point, believing that the batteries may be depleted of power reserves, we brought the units up and changed the batteries. We then continued with testing, but continued to get poor results- at a separation of 80 yards, we recorded error rates of higher than 10^{-2}. With such poor results, we terminated the test.

Mendums Pond Motion Experiment- June 25, 1991

The loss of communications in the June 20 experiment was unexpected and an explanation was sought. More obvious explanations such as lost electronic connections were eliminated while at sea. Depletion of battery power was eliminated upon return to the laboratory. Two explanations which remained to be explored were ray bending and modem motion.

Using a ray tracing program created by Mr. Jeffery McCalla [1] and the sound velocity profile measured at the site on June 20, we correlated poor data transfer performance to the test geometry. We learned that, in some cases, shadow zones arising from acoustic ray bending did explain the occurrence of poor communication. However, ray bending did not provide a general explanation for the events during that experiment.

Over the course of the June 20 experiment, we observed increased surface wave action over the course of the day. Swells approached a maximum of roughly 1.5 meters. Both the *R.V. Jere Chase* and the motorboat moved with a pronounced roll, and the modems were subjected to pronounced random accelerations. Data transfer performance appeared to decline as surface wave action increased.

On June 25, we went to MSEL's Mendums Pond facility to grossly duplicate the conditions of the June 20 experiment. We stationed two vessels with a separation of roughly 300 meters and deployed the modems to 8 meters deep, a duplication of one June 14 test configuration . We used the same equipment, including batteries, as was used during deep water testing on June 20. We first verified that the units were functioning properly and then manually forced the modems to move in a manner similar to that when mounted to a rolling vessel. One experiment had each modem moving with excursions of between 0.5 and 1.0 meters in a regular oscillatory motion. Another experiment had the modems moving with excursions of between 0.75 and 1.5 meters in a violent, irregular motion. The results of this experiment are given in Table 1.

	Both ATM850s motionless	Both ATM850s with 0.5 to 1.0 meters excursion in a regular motion	Both ATM850s with 0.75 to 1.5 meters excursion in an irregular motion
Average Bit Error	0	1.66 e -3	No connection
Average Signal to Noise Ratio	23.23 dB	19.96 dB	No connection

Table 1 - Results of the June 25 Mendums Pond Experiment on the Effect of Motion on ATM850 Performance

We concluded from observing results from the June 25 experiment and from modeled ray bending that the poor performance on June 20 may have been due to sharp, random motion of the modems. Acceleration of the modems resulted in a Doppler shift in acoustical frequencies. The ATM850s have adaptive equalization and can partially compensate for steady relative motion-but apparently not the random and pronounced motion to which they were subjected. In addition, the ATM850 transducer head is not truly *omnidirectional*, but has a toroidal pattern. It was likely that the beams of the transmitter and receiver modems were sometimes pointed away from the other, resulting in lost data. Table 1 shows that communication performance deteriorated from the motionless case (no errors) to the case with minor motion (one error in one thousand bits). Communications were eliminated in the case with violent motion.

Open Ocean Experiment Number 2- July 16, 1991.

Based on the results summarized in the previous section, we repeated parts of the June 20 test. In order to somewhat uncouple the modems from wave action, we suspended the units from elastic cord attached to a mooring buoy that was floating on the surface (Figure 9).

It was decided that, in the interest of acquiring a more complete data set for the determination of ATM850 maximum transfer ranges, higher priority would be put on the configuration that placed both modems at a depth of 61 meters. Lower priority was placed on the other two configurations. More data was to be taken at each range, and so the scheduled tests were increased to six self-tests and a 27 kilobyte data transfer. It was also decided that measurements would be made at the longer ranges initially to take advantage of the calmer water surface found in the morning.

The first set of measurements was made at a separation of 1500 yards. This was followed by a separation of 2000 yards. Separation was increased to 2500 yards, where we were again unable to achieve communications of any kind. This was followed by measurements at 1000 and 500 yards. A set of measurements for configuration 2 was made at a separation of 500 yards.

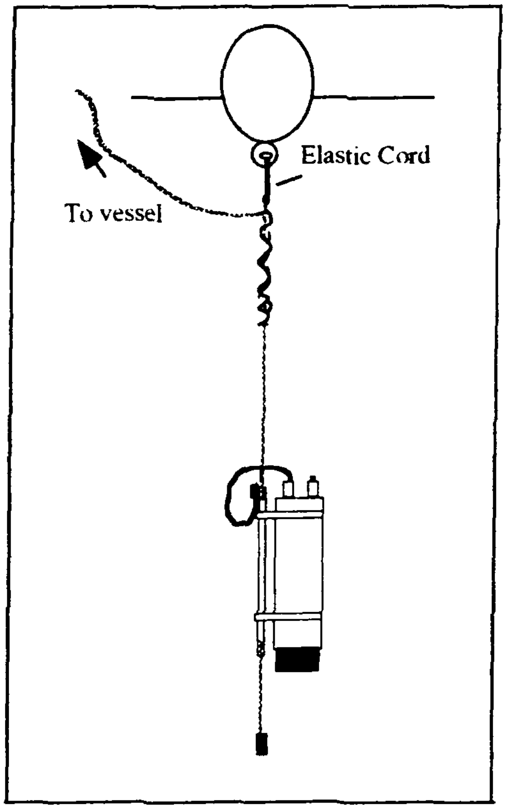


Figure 9 - Depiction of the Decoupling Buoy Deployment for the July 16 Experiment

The addition of the uncoupling buoy was apparently the reason for improved communications. Comparison of measurements from June 20 and July 16 (*Tables 3 and 4, respectively*) shows that at 1000 and 1500 yards the error rate dropped by approximately an order of magnitude. Similar improvements in error rate did not occur at 500 and 2000 yards.

The lack of an improvement at 500 yards was unexpected and the measurements were repeated. The repeat of the experiment showed no significantly different results. The presence of strong multipath components (see Figure 10) is a possible explanation for the anomalous performance.

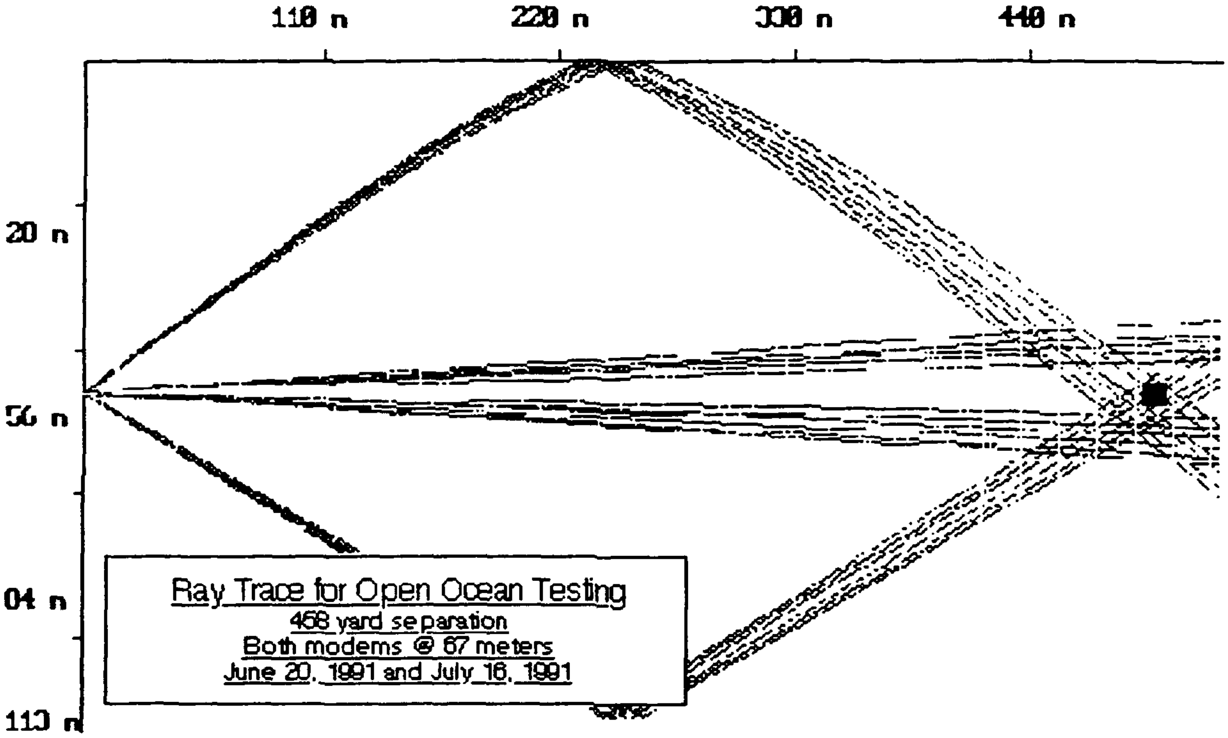


Figure 10 - Selected Rays of Ray Trace for ATM850 Error Testing in the Open Ocean, 460 meter (500 yard) Separation, June 20 and July 16, 1991

Moving Platform Experiment- August 2, 1991

In order to further explore the performance of the ATM850 when subjected to relative motion, we performed an experiment where one modem was stationary and one moved with a velocity of between 0.5 and 3.0 knots. The receiving modem was attached to a pole and the pole was extended straight down from the barge so that the modem was at a depth of 6 meters. Using the hints given by a ray tracing program (Figure 11), we suspended the transmitting modem from an anchored boat to a depth of 4 meters. The pole supporting the receiving modem was supported at several points along its length, including the wet end. Despite the multitude of anchoring points long the pole, the modem still vibrated with high frequency (0.5 to 10 Hz) swings of up to 2 to 15 centimeters.

Data was recorded as before and consisted entirely of self-test transfers. Each test run concatenated several self-test transfers while the barge moved toward and away from the stationary platform. Runs had a minimum modem to modem range of 50 meters and a maximum range of 300 meters.

Table 2 gives the results from the motion sensitivity experiments of August 2. The data shows unexpectedly high error rates and does not display the logical tendency of increasing error rate with increasing velocity. In our judgement, the vibration of the receiving modem during the experimental runs exceeded tolerable levels and led to corrupted data. We therefore discount this experiment and its results.

Velocity* (knots)	+3.0	0	-0.8	-1.8	-3.0
Average Bit Error Rate	No connection	100m -> 1.3 e-2 150m -> 1.8 e-2 250m -> 1.7 e-2 300m -> 2.1 e-2	16.0 e -2	5.4 e-2	24.0 e-2

Table 2 Measured ATM850 Error Rates for Moving Platform Tests- August 2

* Velocity has a direction component- a positive velocity indicates that the dynamic platform moved away from the stationary platform, a negative movement indicates that the dynamic platform moved toward the stationary platform.

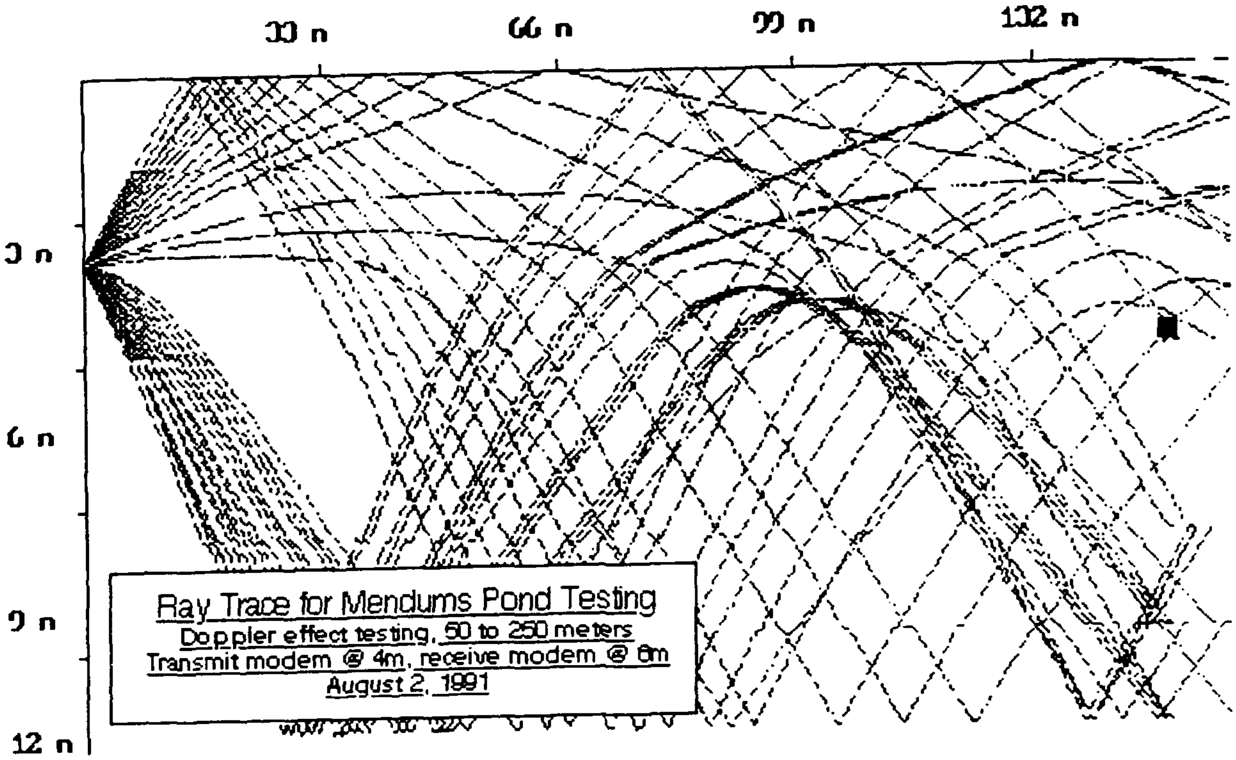


Figure 11 - Ray Trace for ATM850 Mendums Pond Error Testing, Moving Platform (Doppler effect) Tests, August 2, 1991

3. Experimental Results and Analysis

A. Presentation of data

We present in this section the bit error rates found using the experimental procedures summarized in section 2. Since measurements were performed at discrete ranges and in dissimilar situations, the data is presented in tabular form. Figures that present the data graphically are included at the end of the section.

Table 2 gives the results of the measurements made at Mendums Pond, where the channel was a maximum of 13 meters deep. Both modems were below the thermocline. The data set is made up of six self-tests and a host-to-host data stream. The data stream was 27 kilobytes for 50, 100, and 300 meters. The data stream was 11.5 kilobytes at 400 and 500 meters.

Range	50 meters	100 m	300 m	400 m	500 m
Errors : Total	373:331776	0 : 313344	8 : 313344	1546:208880	496:208880
Bit Error Rate	1.12 e -3	0	2.55 e -5	7.4 e -3	2.3 e -3

Table 3 Measured ATM850 Error Rates at Mendums Pond - June 14

Table 3 gives the results of the first open ocean experiment on June 20. Both modems were deployed to 61 meters of depth at an open ocean site with a water depth of 150 meters. Because of limited battery power, a reduced set of measurements was scheduled. The data set for this day of experiments run consists of 3 self-tests at the ranges of 500, 1000, 1500, and 2000 yards. Communication was attempted at 2500 yards, but was unsuccessful. Attempts at communication with the transmitter at 16 meters of depth and the receiver at 61 meters of depth were made, with no resulting data.

Range	500 yards	1000 yds	1500 yds	2000 yds
Errors : Total	220 : 55296	106 : 55296	305 : 55296	3272 : 55296
Bit Error Rate	3.9 e -3	1.9 e -3	5.5 e -3	5.9 e -2

Table 4 Measured ATM850 Error Rates in the Open Ocean - June 20

Range	500 yards	1000 yds	1500 yds	2000 yds
Errors : Total	1685 : 110592	22 : 110592	151 : 165888	2316:110592
Bit Error Rate	1.5 e -2	2.0 e -4	9.1 e -4	2.1 e -2

Table 5 Measured ATM850 Error Rates in the Open Ocean - July 16

Table 4 gives the results of the second deep water experiment on July 16. This is the experiment performed using the wave uncoupling system depicted in Figure 3. Because we had better information concerning battery power reserves, we made six self-tests at ranges of 500, 1000, 1500, and 2000 yards. Attempts were again made at 2500 yards without success. A data set of 11 self-tests (202,752 bits) for configuration 2, where the transmitter was at 10 meters while the receiver was at 61 meters, was made a range of 500 yards. The measured bit error rate for that experiment was 1.4 x 10^{-2}.

Tables 3 through 5 give the absolute ratio of errors and the number of bytes transmitted. This indicates the quantity of data used in arriving at the results for bit error rate, and can be used to judge the statistical value of the data set. However, the tabular format does not show the bit error rate data in a convenient manner, and so we include Figures 12 and 13, which graphically displays the entire data set.

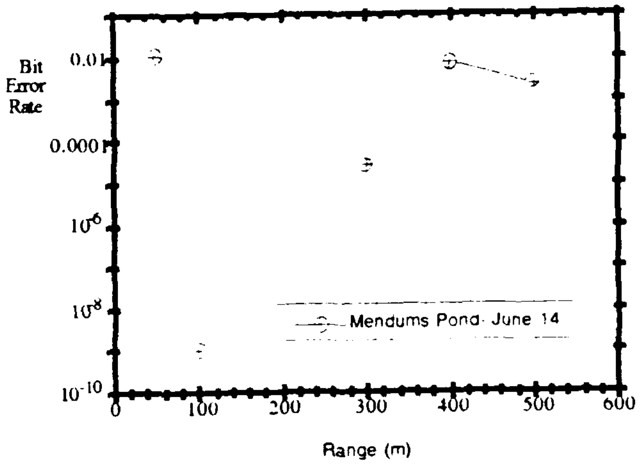


Figure 12 - Graph of ATM850 Bit Error Rates Measured in Mendums Pond, June 14, 1991

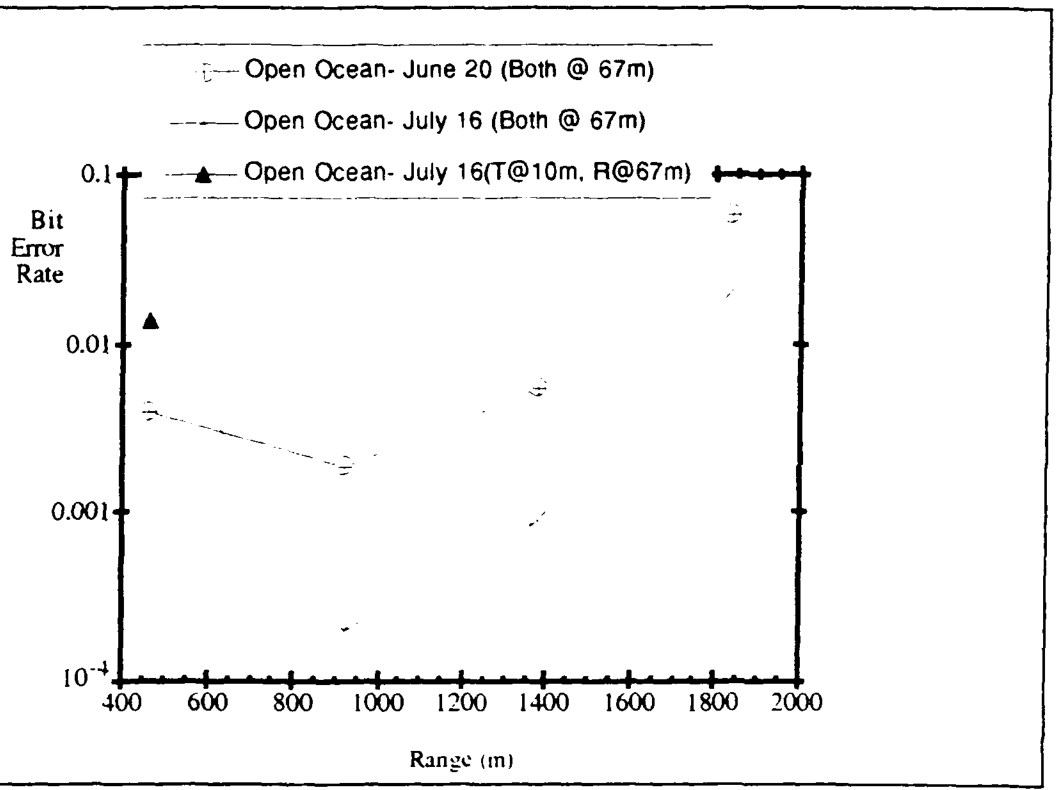


Figure 13 - ATM850 Bit Error Rates Measured in the Open Ocean

ATM850 bit error rate versus received signal bit error rate

A useful set of data related to ATM850 is the relationship between the signal to noise ratio at the receiver and the bit error rate of the transfer. This information is provided by the ATM850 self-test. The resulting relationships for the Mendums Pond experiments and the open ocean experiments are shown in Figures 14 and 15, respectively.

B. Corroboration of Measured Data

Among the information generated by the aforementioned ray trace program [1] is the acoustic level loss from transmitter to receiver. We summed the loss figure with the signal to noise ratios measured by the ATM850 at the receiver to get the information presented in Figures 16.

The object of the procedure was to verify that system losses were consistent; the sums of the predicted loss and SNRs were between 180 and 184 dB re 1 µPa for all ranges except for the 500 yard range, where multipath interference appears to have reduced the signal to noise ratio.

The consistency of the results in Figure 16 heighten the credibility of the measured bit error rate results. Anomalies also show a consistent pattern and can be accounted for by multipath interference.

4. Point-to-point Protocol Performance using the ATM850

Point-to-point flow control protocols are those protocols that control the rate of data block transfers and prevent the receiver from being overwhelmed by the transmitter. These protocols can also include mechanisms that increase reliability, as in the case of the Automatic Repeat Request (ARQ) protocols. A previous interim status report [2] for this project discussed at length the performance of the ATM850 with classic flow control protocols.

Because MSEL had not yet acquired working versions of the ATM850 and had been unable to make measurements of ATM850 performance, the derivations and calculations of that report were based on preliminary measurements made by Datasonics and WHOI. In general, the range of values that could be expected for ATM850 bit error rate was extrapolated from the preliminary data and ATM850 performance was explored for that range.

We now present further calculations for point-to-point performance. These calculations are based on the bit error rates measured by MSEL and presented in section 3. They are also based on the true, not assumed, operating characteristics of the ATM850.

One operating characteristic that affects performance is the ATM850 active equalization/synchronization mechanism. Transfers are accomplished after a somewhat involved, though transparent to the host, process of connection and synchronization. The synchronization procedure, a mechanism for allowing the ATM850 to dynamically adapt processing functions to a changing channel, occurs periodically during a transfer through interruption of the data stream. Presently, this occurs every *one kilobyte*. Data fragments of less than one kilobyte are held in a buffer until it is filled. Each iteration of the synchronization mechanism causes a two second delay. Connection and wake up are controlled by the initial synchronization transmission; modems have individual, group, and "world-wide" identifiers and will respond only to the correct address.

While active equalization is part of the reason for the ATM850's ability to provide relatively low error communications at high data rates, it also wastes bandwidth. There is an efficiency conflict between the synchronization mechanism and the sending buffer size. A large buffer wastes less bandwidth because synchronization occurs less frequently. However, a large buffer is more likely to have an error occur during transfer, and, if packet size is equal to buffer size, the packet is more likely to be in error and must be discarded. It also holds data fragments until the buffer is filled. This leads to more wasted bandwidth as the buffer must be padded with informationless data in order to force transmission of the fragment.

The existence of the synchronization mechanism was not known at the time that [2] was written. Its effect is therefore not reflected in those calculations. However, its effect is reflected in the calculations of parts B and C of this section.

We once again examine the send and wait flow control protocol and the continuous transmission family of flow control protocols. For each of the protocols, we calculate the channel utilization ratio. Channel utilization ratio is a primary indicator of the protocol efficiency. It is the effective data transfer rate to the raw data rate of the channel when it is under no constraints. A flow control protocol generally inserts control information and time delays into the data stream. This causes effective data rate to be less than the raw rate, and the utilization ratio is therefore less than one.

Performance of the Send and Wait Protocol using the ATM850

The send and wait protocol behaves as follows: the sender transmits a block of information (data and control bits) and waits for an acknowledgement from the receiver. The receiving station examines the block for errors; if the block is correct, the receiving station will acknowledge receipt. Upon acknowledgement, the sending station transmits the next block. If the packet is incorrect, the receiver doesn't reply. The sender will time-out and retransmit the block in error.

	50 meters	100 m	300 m	400 m	500 m
Bit Error Rate	1.12 e -3	0	2.55 e -5	7.4 e -3	2.3 e -3
Utilization	8.3 e -05	0.26	0.24	2.1 e -27	2.7 e -9

Table 6 Send and Wait Utilization Using Mendums Pond Error Rates

	500 yards	1000 yds	1500 yds	2000 yds
Bit Error Rate	3.9 e -3	1.9 e -3	5.5 e -3	5.9 e -2
Utilization	4.6 e -15	1.2 e -7	0.02	1.7e-76

Table 7 Send and Wait Utilization Using Open Ocean Error Rates

Tables 6 and 7 give the results of calculations for ATM850 send and wait performance when the field measured error rates were used. The calculations used the frame size as the ATM850 buffer size of 1024 characters, or 8192 bits. Parity and other overhead is assumed to be 64 bits out of the 8192. A service delay of 50 milliseconds per node and synchronization overhead of 2 seconds was used. The data sets used for Tables 6 and 7 were from June 14 and June 20, respectively.

Send and wait analysis and conclusions

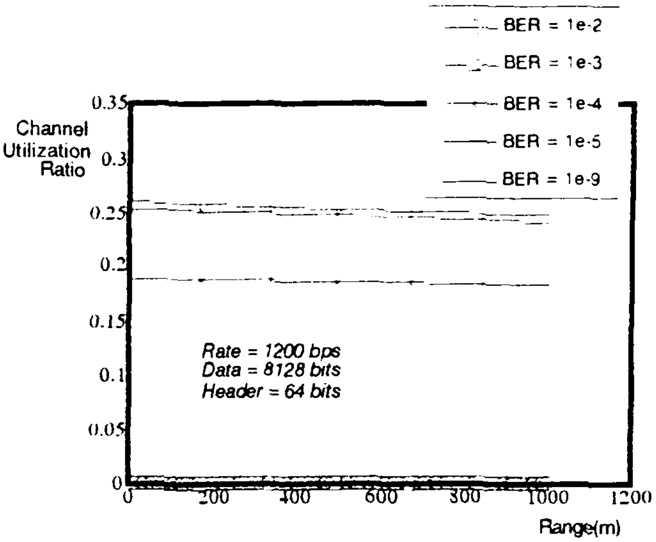


Figure 17 - Utilization for Send and Wait @ 1200 bps & 8128 Data Bits

Examination of the results in Tables 6 and 7 are perhaps surprising. From Table 6, at 50 meters, despite minimal propagation delay and a seemingly acceptable[1] error rate of 1.1 x 10^{-3}, the send and wait utilization ratio is less than one in ten thousand. At a greater propagation delay, but with a bit error rate measured as zero, utilization approaches 0.26.

This wide range of utilization values demonstrates the effects of losing bandwidth to error-forced retransmissions. In addition, achieving a utilization of only 0.26 demonstrates the bandwidth lost to the re-synchronization mechanism.

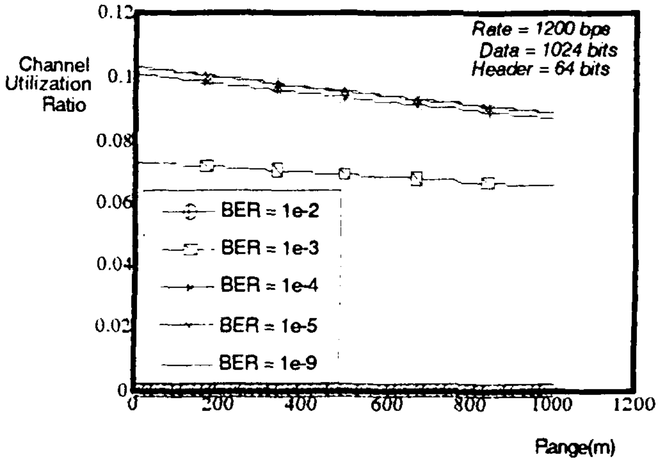


Figure 18 Utilization for Send and Wait @ 1200 bps & 1024 Data Bits

Figure 17 shows the theoretical channel utilization versus station separation for various assumed error rates. The synchronization overhead of the ATM850 is included in the utilization calculation. At error rates of 10^{-2} and 10^{-3}, utilization is essentially zero regardless of propagation delay. Errors force so many retransmissions that no real transfer of information occurs. At lower error rates, both synchronization and propagation delays tend to dominate performance results and limit utilization to less than 0.30 even at error rates of 10^{-9}. Because propagation delay is small relative to the synchronization overhead, utilization is only mildly sensitive to changes in station separation.

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[1] for underwater acoustic communications, that is.

Comparison of Figures 17 and 18 show a relationship between utilization and block size. A reduction in block size decreases the chances of an error in the block and reduces retransmissions. Efficiency at lower error rates is reduced in exchange for a much improved utilization at the higher error rates. In the example, changing block size from 8128 bits to 1024 bits improves utilization at the 10^{-3} error rate from 0.002 to 0.07 (a factor of 35). The cost is a loss of efficiency at the lower error rates from 0.26 to 0.10.

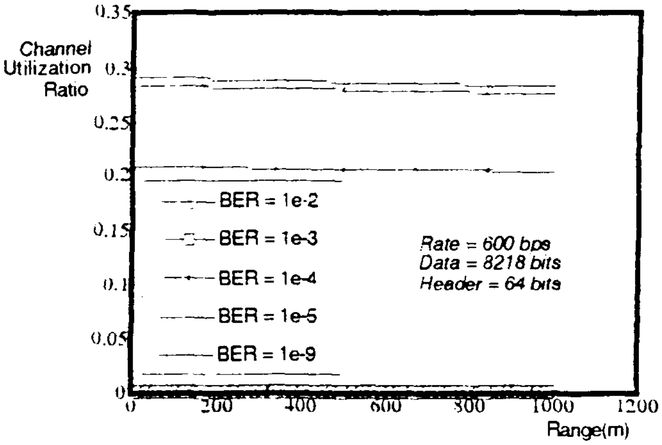

Figure 19 - Utilization for Send and Wait @ 600 bps and 8128 Data Bits

One might wonder about the effect that forward error correction (FEC) would have on performance. Figure 19 gives curves for utilization at 600 bps, the effective transfer rate of a modem using a one-half convolutional FEC scheme. If we assume that FEC leads to a 10x improvement in error rate, then comparison of the numbers in figures 17 and 19 shows the following: for 1200 bps uncoded at a bit error rate of 10^{-3} *utilization* is 0.002. For the 600 bps coded transfer at 10^{-4} the utilization is 0.21. The improvement in bit transfer rate is a factor of 52.

Optimization of Block Size for the Send and Wait protocol

For a given round trip delay, efficiency is improved by increasing packet size. On the other hand, increasing the size also increases the probability that the packet will contain errors. If this happens, the entire packet is discarded and the time spent transferring it was wasted. Chu [3] and Field [4], among others, have shown that a block size which balances these factors and maximizes performance can be found. Tanenbaum [5], in a derivation similar to ours for send and wait performance, gives an equation which we use to approximate optimal block size. The optimization process is summarized in [2].

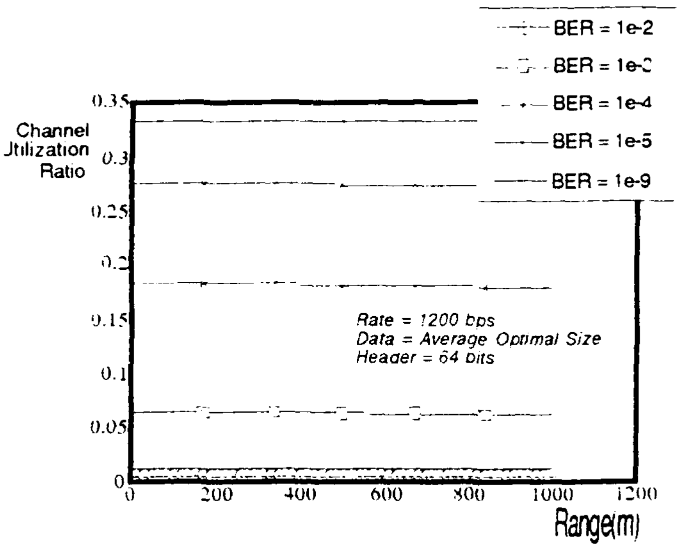

Figure 21 - Utilization for Send and Wait @ 1200 bps and with Optimal Block Lengths

The values for optimal block length as a function of error rate and range were calculated using Tanenbaum's example and averaged over range for a single error rate. The average optimal block sizes (221 bits @ 10^{-2}, 1768 bits @ 10^{-3}, 9055 bits @ 10^{-4}, 33953 bits @ 10^{-5}, 3674788 bits @ 10^{-9}) were then used to calculate new values for send and wait utilization, where each error rate used the corresponding block length in the calculation. Figure 21 shows the results. Compared to a block size of 8128 bits, the average optimal block size improved send and wait performance by factors of 6.0 x 10^{33} at a BER of 10^{-2}, 270.8 at a BER of 10^{-3}, 0.98 at a BER of 10^{-4}, 1.11 at a BER of 10^{-5}, and 1.31 at a BER of 10^{-9}. The observant reader will notice a drop in utilization at the 10^{-4} error rate. This is probably due *to the fact that* Tanenbaum's equation is but an approximation for this case.

Optimization of block size for the experimental measurements

Optimum Block Size Range, meters	Mendums Pond Test, June 14	Open Ocean Tests, June 20	Open Ocean Tests, July 16
50	1568		
100	106990		
300	19761		
400	295		
458		529	149
500	1573		
916		1036	6010
1374		396	1989
1832		37	107

Table 8 Optimal Block Sizes for the Measured Bit Error Rates

The above technique is applied to the bit error rate results of the field evaluation measurements to yield the results for optimal block size as given in Table 8. Figures for channel utilization were then computed using the values for optimal block length, and are given in Table 9.

Comparison of the utilization values from Tables 6,7 and 9 show that performance improves by factors that are often measured in orders of magnitude. For instance, for the Mendums Pond measurements (Tables 6 and 9), utilization at 50 meters is improved by a factor of 735. For the 400 meter Mendums Pond measurement, utilization is improved by a factor of nearly 4 x 10^{24}. For the June 20 open ocean measurements (Tables 7 and 9), utilization is improved by greater than 4 x 10^{12} at a range of 500 yards and a factor of 1 x 10^{70} at a range of 2000 yards.

Channel Utilization Ratio Range, meters	Mendums Pond Test, June 14	Open Ocean Tests, June 20	Open Ocean Tests, July 16
50	0.061		
100	0.31		
300	0.25		
400	0.008		
458		0.02	0.02
500	0.01		
916		0.04	0.14
1374		0.01	0.06
1832		1.7e-6	0.0007

Table 9 Channel Utilization Ratio Using the Optimal Block Sizes for the Measured Bit Error Rates

Performance of Continuous Protocols

Error Rates Baud	Channel Utilization Ratio			Data Block Size = 8128 bits	
	1e-2	1e-3	1e-4	1e-5	1e-9
1200	1.3 e -36	0.002	0.33	0.71	0.77
600	1.5 e -36	0.002	0.38	0.80	0.87

Table 10 Upper Bounds on Sliding Window Performance with a Block Size of 8128 Bits

Continuous, or sliding window, protocols improve channel utilization by reducing the time wasted on transferring acknowledgement packets. Rather than sending a single packet or block and halting until an acknowledgement or time-out occurs, continuous protocols send many packets consecutively. This arrangement is reasonable only if a significant number of blocks await transfer.

A true implementation of a sliding window protocol requires a full duplex channel. Acknowledgements are returned via a different channel and do not interrupt the transferring data stream. However, the ATM850s presently provide only a half duplex channel. We assume that a clever implementation can approach sliding window performance and present these results as an upper bound.

The performance of the Selective Repeat sliding window [12] protocol is well known as the upper bound on utilization performance for all ARQ protocols. Table 3 gives selective repeat performance as a function of chosen error rates for a single block size. We have accounted for the bandwidth wasted by the ATM850 synchronization mechanism in the selective repeat utilization calculations.

Continuous strategies analysis

The results of Table 3 demonstrate the effectiveness of limiting the effects of propagation and re-synchronization delay to one direction of transfer. Utilization is approximately twice the maximum achievable using the send and wait protocol. Theoretically, selective repeat utilization will approach one (100%) at low error rates, e.g., 10^{-9}. However, the delay of the re-synchronization mechanism limits performance to 0.77.

The dominating effect of bit errors on performance is still seen at the higher error rates. At bit error rates of 10^{-2} and 10^{-3}, where a packet of 8128 bits is very likely to have an imbedded error, utilization is virtually nonexistent. Once error rates improve to the point of little likelihood of an error in a packet, performance improves dramatically.

Error Rates / Baud	Channel Utilization Ratio		Data Block Size = 1024 bits		
	1e-2	1e-3	1e-4	1e-5	1e-9
1200	5.2e-6	0.10	0.26	0.29	0.29
600	8.0e-6	0.15	0.40	0.44	0.44

Table 11 Upper Bounds of Sliding Window Performance with *a Block Size of 1024 Bits*

Reducing packet or block size (as shown in Table 4) again shows that one can improve performance in the instances of higher error rates as long as one is willing to sacrifice performance at low error rates. Utilization at a BER of 10^{-2} is still nonexistent, but utilization at a BER of 10^{-3} has improved from 0.0002 to 0.10, a factor of improvement of 500.

In both Tables 3 and 4 we have included results for performance at 600 baud. If we again assume that forward error correction yields an order of magnitude improvement in bit error rate, we observe dramatic improvements in utilization ratio as follows: for a block size of 8128 bits, utilization at 1200 bps and a BER of 10^{-3} is 0.0002 whereas utilization of at 600 bps and a BER of 10^{-4} is 0.38. Using FEC at a slower transfer rate improves effective transfer rate by a factor of 950. For a block size of 1024 bits, similar analysis at error rates of 10^{-2} (1200 bps) and 10^{-3} (600 bps) shows a factor of improvement of over 14 x 10^{3}.

Summary

In conclusion, we emphasize several key points regarding ATM850 performance.

- At short ranges of 100 to 300 meters, the ATM850 is capable of communications with an exceptionally low error rate, i.e., 10^{-5} to 10^{-9}. This was measured in a high multipath environment, i.e., Mendums Pond.
- The range for measured bit error rates over all operating scenarios was 10^{-1} to better than 10^{-9}. The majority of measured error rates was in the range 10^{-2} to 10^{-4}.
- ATM850 error rate performance is generally acceptable, i.e., error rates of 10^{-3} or less, only when signal to noise ratio exceeds 16 dB at the receiver. Marginal performance, i.e. error rates of 10^{-2} or less, is achieved when the signal to noise ratio exceeds 12 dB at the receiver.
- ATM850 send and wait protocol channel utilization is generally nonexistent for the combination of error rates of 10^{-2} and 10^{-3} and ATM850 data buffer size. In order to improve send and wait performance at these error rates, the ATM850 buffer size should be reduced from 1024 bytes to approximately 100 bytes.
- The inclusion of forward error correction may improve send and wait protocol performance. In section 4A, an assumed improvement in bit error rate of one order of magnitude led to improvement of send and wait performance by many orders of magnitude.

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[3] Chu, W.W., "Optimal Message Block Size for Computer Communications with Error Detection and Retransmission Strategies", *IEEE Transactions on Communications,* V. COM-22, No. 10, Oct 74.

[4] Field, J.A., "Efficient Computer-Computer Communication", *Proc. IEE,* V. 123, No. 8, Aug 76.

[5] Tanenbaum, A.S., *Computer Networks,* Second Edition. New Jersey: Prentice-Hall, 1988.