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Investigation of the Use of Surface Electrical Currents for Short-Range Shipboard Data Communications

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ABSTRACT

In January 1991 the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) Code 252 undertook to investigate for NAVSEA PMS 400D52 the possibility of communicating data through a ship's bulkhead without penetrating the bulkhead physically. Four possible methods of transmission were identified; ultrasonic, electric current injection, magnetic coupling, and current carrier. Of these, the electric current injection method was selected as the most promising, and a device using this technique was developed.

This device injects a 1.0 MHz current into the steel plating adjacent to a watertight door, hatch, or other gasketed bulkhead penetration aboard ship. The current is injected using two copper plated threaded electrodes, which are attached using a stud welding gun. The injected current flows as a surface, or "skin effect" current not only directly between the injection electrodes but also in an indirect, spread pattern, which wraps around the edge of the penetration, producing a pattern of surface currents on the other side of the bulkhead. The injection current is modulated and data is received on the opposite side of the bulkhead using either voltage sensing electrodes or a coupling loop, which senses the field generated by the surface currents. By this means data can be transmitted through the bulkhead at rates up to 1.0 Mbps without the need to open watertight doors or hatches or install special penetrations for cable.

This technique for wireless transmission of data through ship bulkheads and submarine pressure hulls is immune to most noise sources that could interfere with the desired signals. It is simple in concept and requires a minimal amount of electronics. It is highly adaptable to typical shipboard compartment arrangement, and can be quickly installed and removed with minimal refurbishment required after removal. No other method considered or known to exist provides all of the desirable features of this technique.

This technical note describes the development activities leading to the development of the wireless shipboard data coupler, a technical description of its operation, and ongoing work to better characterize the surface current flow patterns and to increase data transmission rates.

ACKNOWLEDGMENTS

This work was sponsored by the Naval Sea Systems Command, Code PMS400D52, Program Elements SCN and O&M,N. Special thanks are extended to Mr. Jesse Terres of PMS400D52 for his support and encouragement, and to Dr. Fredrick Williams and Mr. Arthur Durkin of the Naval Research Laboratory (NRL), Code 6180, for their support during testing conducted aboard the NRL Fire Research and Test Ship ex-USS Shadwell.

CONTENTS

LIST OF FIGURES

INVESTIGATION OF THE USE OF SURFACE ELECTRICAL CURRENTS FOR SHORT RANGE SHIPBOARD DATA COMMUNICATIONS

1.0 INTRODUCTION

Navy ships and submarines require extensive testing following their construction and over their lifetime. Such testing includes Hull, Machinery and Electrical performance tests, acoustic noise trials and shock trials. This usually involves temporary installation and later removal of hundreds of sensors in dozens of ship compartments. Traditionally, electrical wiring that connects the sensors to data collection/instrumentation equipment has been routed through special penetrations temporarily cut in the bulkheads separating compartments. These penetrations are fitted with "stuffing tubes" that are capped off before and after testing to maintain water tight integrity of the ship. During testing, open stuffing tubes may present the potential for leakage should flooding occur. Furthermore, installing and removing special stuffing tubes is so costly that consideration is sometimes given to routing wiring through open watertight doors in the bulkheads. This approach avoids the high cost of providing special bulkhead penetrations, but severely jeopardizes the water tight integrity of the ship. In the case of potentially dangerous tests such as explosive shock trials, open watertight doors are totally unacceptable.

In the case of submarine tests, there is often the need to transmit data from special sensors or equipment located outside the pressure hull to collection equipment inside the pressure hull. Because of the extreme pressures of submergence, any connection between the outside and the inside of the pressure hull requires special types of hull penetrations. It is expensive, difficult and extremely time consuming to install new SUBSAFE hull penetrations, so much so that special testing must normally be restricted to the use of existing fittings. There are usually very few existing fittings that are available for use.

A method is needed for transmitting sensor data through ship bulkheads and submarine pressure hulls without leaving watertight doors or hatches open and without the need for costly installation and removal of special penetrations. Such a technique must accommodate a wide variety of sensor signals and provide sufficient bandwidth/data rate to transmit a large amount of data quickly and reliably. Installation and removal must be simple and quick, with minimal refurbishment of bulkheads required after removal.

The authors recognized this need and, sponsored by NAVSEA PMS400D52, in 1991 undertook to develop a device that would meet all of the requirements outlined above. The result of these efforts is the wireless shipboard data coupler device described herein.

2.0 DEVELOPMENT AND TESTING

Initial development efforts were driven by the following premise: two electrodes would be attached some distance apart on the transmitting side of the bulkhead, and two receiving electrodes would be placed directly opposite them on the other side. An electric current would be circulated through the transmitting electrodes, and it was felt that a small but measurable potential would be developed across the electrodes on the other side of the bulkhead by virtue of the current penetrating the steel plate.

A section of 3/8 inch high-strength steel 18 inches square, of the type used to fabricate the thickest bulkheads on the DDG-51 class ships, was procured from Ingalls Shipbuilding. On each side of the sheet, two 1/4 inch studs spaced 12 inches apart were attached using a stud welder; the studs on opposite sides were directly opposite one another.

As predicted, passing a direct current through the studs on one side of the bulkhead produced a detectable potential difference between the studs on the other side. Although slightly smaller than predicted, it was felt that this potential could easily be detected, and work was begun on a transmitter and receiver to inject and detect a signal at the selected carrier frequency of 1 MHz. The transmitter operates into very nearly a short circuit while generating several amperes of current, while the receiver has to be capable of detecting a signal level of several tens of microvolts. Figures 1 and 2 show the initial test arrangement and block diagram of the transmitter and receiver electronics.

Upon completing the transmitter/receiver pair, tests were undertaken to determine whether or not the signal could be coupled from one side of the plate to the other. These tests appeared successful, in that an easily detectable signal was received from the transmitter. There were some anomalous results that were unexplained at the time, but did not seem to interfere with the correct operation of the system. Chief among these was a sensitivity of the receiver to a magnetic field found on the side of the plate opposite the transmitter.

In order to investigate the transmission of data, modem cards were designed and built that could be plugged into AT class computers and used to transmit and receive data in the system. These cards generated the necessary 1.0 MHz carrier, and modulated this carrier using Frequency Shift Keying at a data rate of 100 kbps. They were also capable of accepting the 1 MHz carrier from the receiver, demodulating it, and presenting the data stream to the receiving computer. Concurrently, software was developed that was capable of exercising control of the modem cards (baud rate selection, etc.) and allowing for the transmission and reception of several data types, including messages from the keyboard, data files from disk, and pseudorandom binary sequences in order to determine error rates.

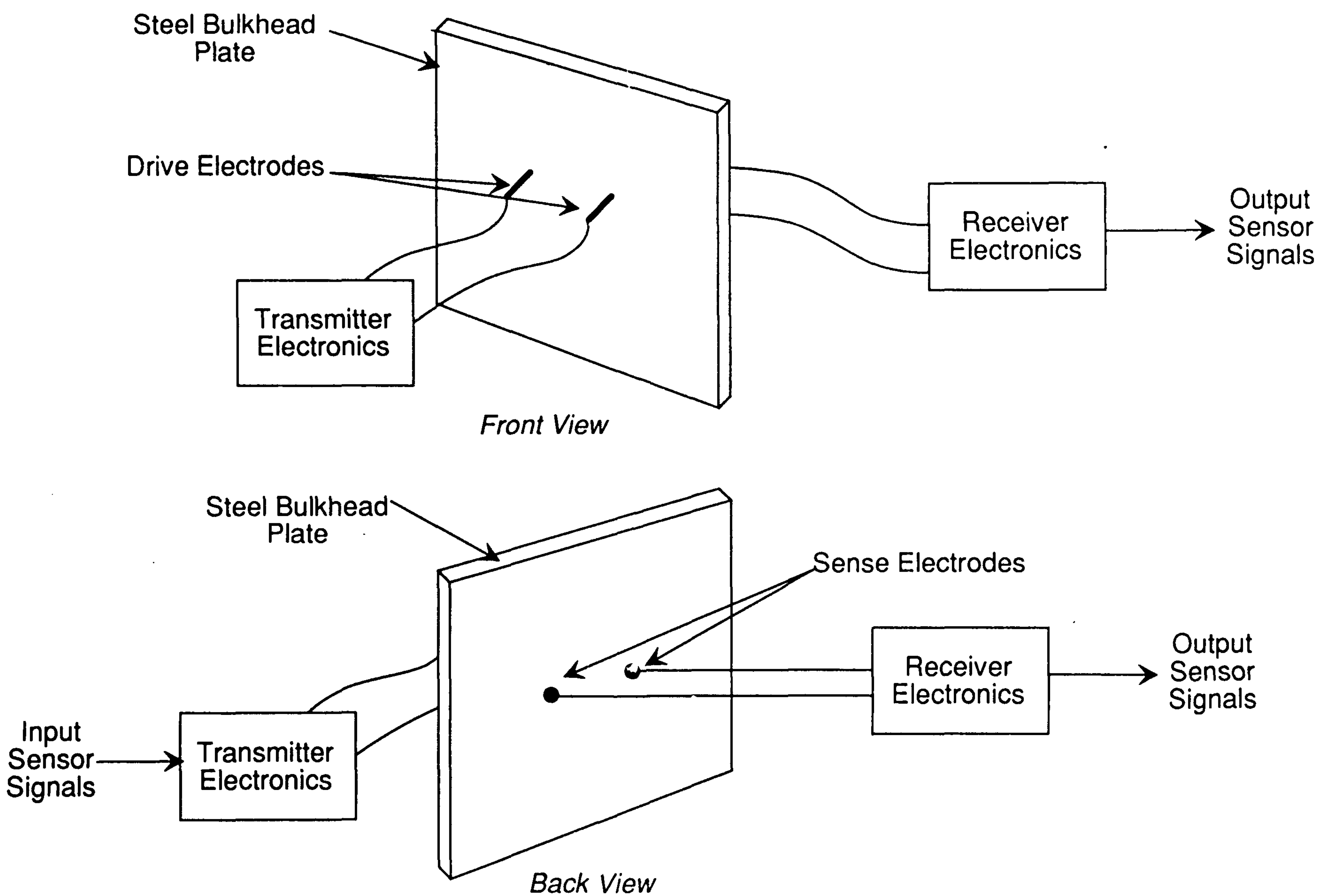


Figure 1. Wireless Shipboard Data Coupler Initial Test Arrangement.

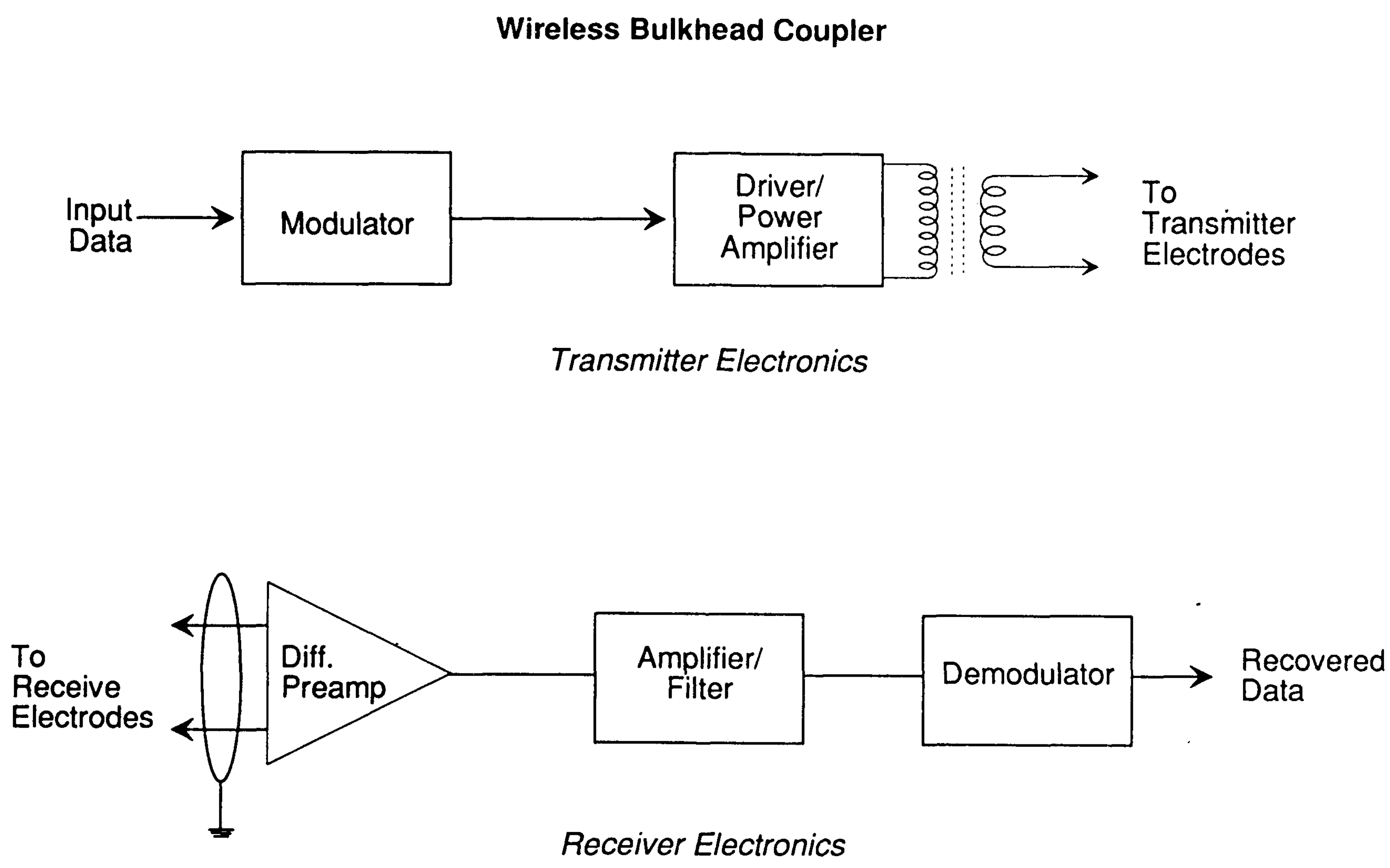


Figure 2. Transmitter/Receiver Electronics.

Upon completion of the modem cards and software, a system test was run, in which data from a transmitting computer was sent via a transmitter through the bulkhead section, picked up by the receiver, and detected and decoded by the receiving computer. This test was successful, but there were still some anomalies in the results, and investigation continued into the cause of these.

The probable cause of these anomalous results was determined to be "skin effect". That is, rather than a current from the transmitting electrodes penetrating the plate and being distributed throughout the cross section, diminishing with depth, a surface current was flowing that penetrated the bulkhead only to a depth of a few thousandths of an inch. This current not only ran between the electrodes on the transmitting side, but also in the opposite direction as well, flowing around the edges and across the receiving side of the plate.

In order to confirm this, a series of experiments was run to measure the extent of these effects. These involved several metal containers and ultimately a welded box made of 3/8 inch steel plate, into which a battery powered transmitter was placed, while the receiver was used to attempt to receive a signal on the outside. These experiments confirmed that skin effect was the source of the signal that had been detected. However, they also indicated that this effect was very difficult to contain, leading to the conclusion that perhaps the skin effect current could be used as the coupling mechanism, if there were suitable locations usually available on the ships.

At this point, it was decided to conduct a series of experiments run under realistic shipboard conditions, to be sure that this mechanism would work as predicted. Arrangements were made to use the ex-USS Shadwell, the Naval Research Laboratory Fire Research and Test ship anchored in Mobile Bay, Alabama. A survey of the ex-USS Shadwell was conducted on October 9, 1991 and a test plan developed in order to structure a logical series of tests and make certain that nothing was overlooked. The test plan is attached as Appendix A.

On October 16-17, 1991 experiments were conducted aboard the ex-USS Shadwell. These experiments included both signal strength measurements and use of computers to transmit and receive data. Although there are a few unanswered theoretical questions, it seems clear that the skin effect can be used as a data transmission medium through and around hatch openings normally encountered, and possibly near existing penetrations of opportunity as well. An important finding was that the receiver was much less sensitive to the potential generated in the steel between sense electrodes than to the magnetic field generated by the flowing surface current. Use of a coupling loop to sense this magnetic field may increase susceptibility to noise, but proper filtering should avoid this problem. A copy of the trip report detailing the experiments conducted and the results of the measurements made appears in Appendix B.

3.0 DESCRIPTION AND OPERATION

The following is a description of the Wireless Shipboard Data Coupler in its present configuration. Stated data rate capabilities assume the use of a more advanced modulation scheme, but design and operation of all other system elements are the same as described in Section 2.

The data coupler injects a 1.0 MHz current into the steel plating adjacent to a watertight door, hatch, or other gasketed bulkhead or pressure hull penetration aboard ship. The current is injected using two copper plated threaded electrodes, attached using a stud welding gun. The injected current flows as a surface, or "skin effect" current not only directly between the injection electrodes but also in an indirect, spread pattern, which wraps around the edge of the penetration, producing a pattern of surface currents on the other side of the bulkhead (see Figure 3). The injection current is modulated and data is received on the opposite side of the bulkhead using either voltage sensing electrodes or a coupling loop, which senses the field generated by the surface currents.

Stud welding was selected as the preferred electrode attachment method because installation requires only minutes. Furthermore, electrodes are removed with a single blow to a cold chisel at the base of the electrode. Refurbishment consists of priming and painting four bare spots about the size of a quarter.

The transmitter electronics accepts an encoded data stream at a data rate of up to 1.0 Mbps , and amplifies and couples it to the low-impedance load represented by the bulkhead and its attachments. Figure 4 shows the transmitter electronics schematic diagram.

The input signal arrives via the input jack and is amplified if necessary by stage U1A; the level may be controlled by adjustment of potentiometer R2. In addition, a direct-current offset voltage is developed by adjustment of potentiometer R11.

Thus, the output of stage U1A is a carrier superimposed on a DC level. Stage U1B has an AC gain of -1 and a DC gain of +1, and therefore has a DC level equal to that of U1A, but an AC component equal in amplitude but 180° out of phase with U1A.

The outputs of the U1 stages drive the gates of VMOS FET transistors Q1 and Q2. The DC level is used to provide a bias level appropriate to the threshold voltage of the transistors used, biasing them for class AB operation. Because the AC components are 180° out of phase, they operate in a push-pull mode combining to produce the output signal in center-tapped transformer T1.

T1 is a center-tapped transformer wound on a toroid core and having a 25:1 turns ratio. C6 and C7 are used to provide filtering for the power supply. D1, C8, C9, R8, and R9 form snubber circuits to reduce transient voltages appearing at the drain terminals of Q1 and Q2.

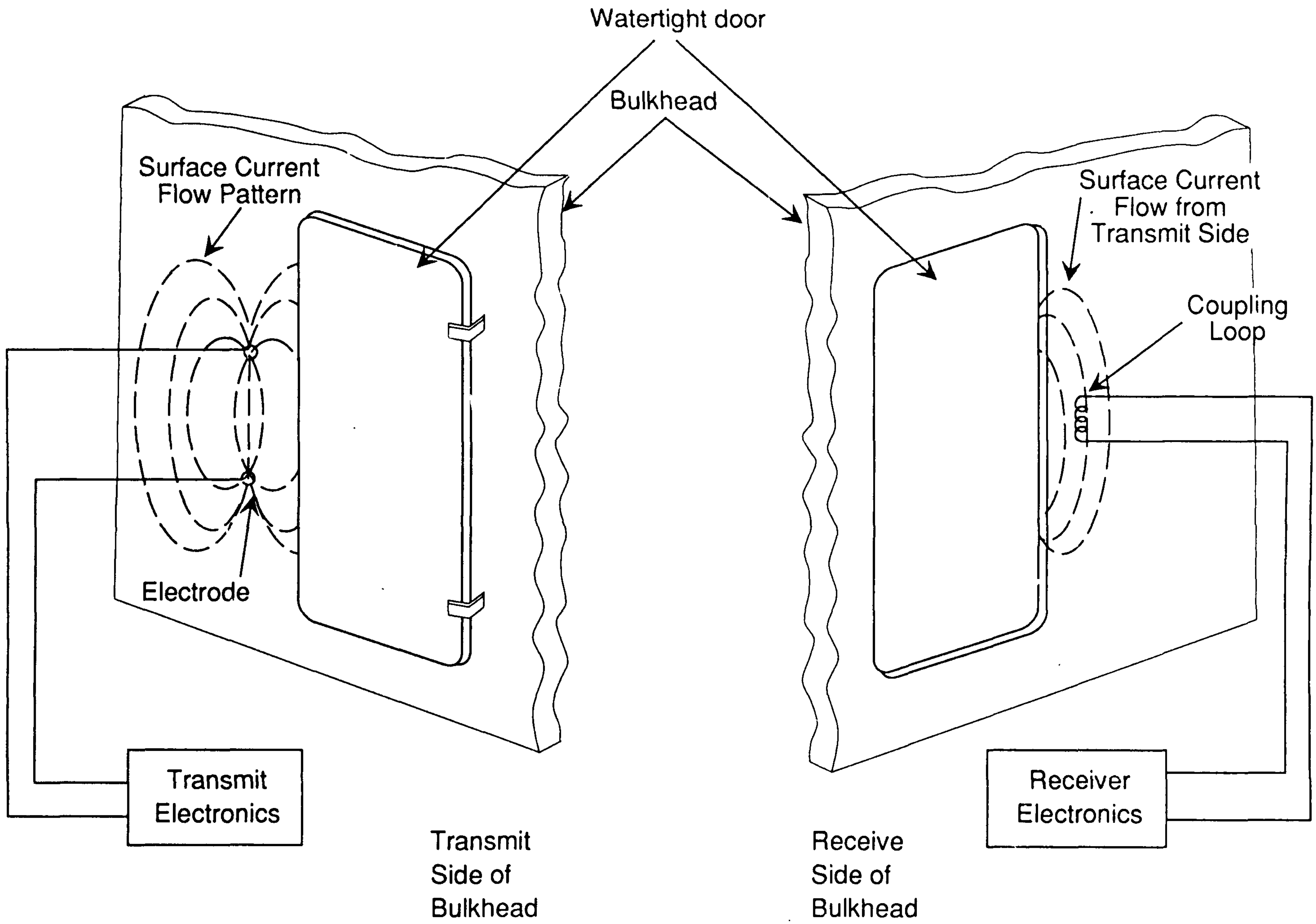


Figure 3. Surface Current Data Coupler Concept.

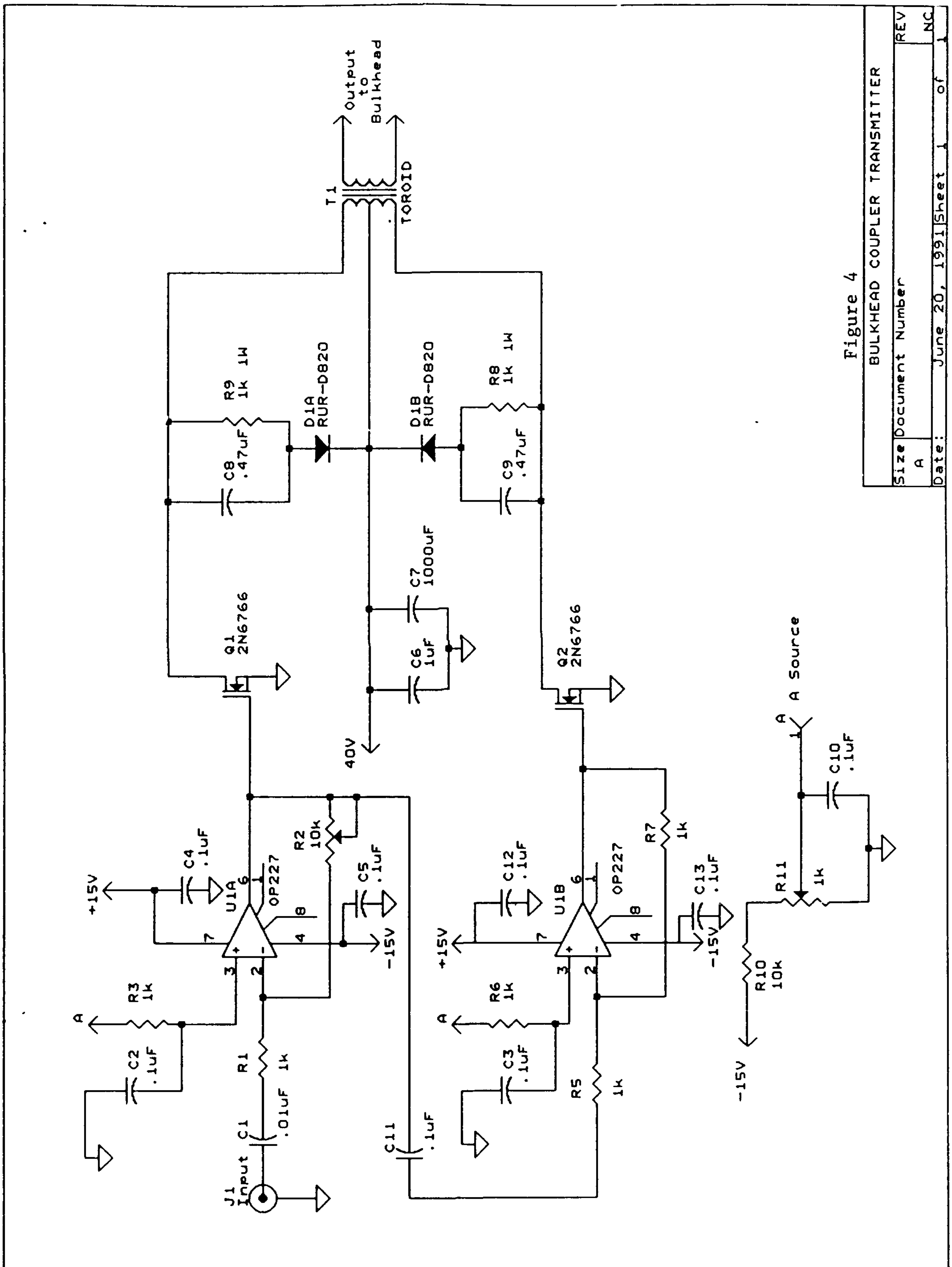

BULKHEAD COUPLER TRANSMITTER
Size
A
Document Number
REV
NC
Date: June 20, 1991 Sheet 1 of 1
Output to Bulkhead
T1
TOROID
R9 1k 1W
D1A RUR-D820
D1B RUR-D820
R8 1k 1W
C8 .47uF
C9 .47uF
C7 1000uF
C6 1uF
Q1 2N6766
Q2 2N6766
40V
A Source
A
C10 .1uF
R11 1k
R10 10k
-15V
+15V
C4 .1uF
U1A
OP227
R2 10k
C5 .1uF
-15V
R3 1k
A
C2 .1uF
R1 1k
C1 .01uF
J1 Input
C11 .1uF
+15V
C12 .1uF
U1B
OP227
R7 1k
C13 .1uF
-15V
R6 1k
A
C3 .1uF
R5 1k

Figure 4

The output of transformer T1 is coupled directly to the bulkhead injection electrodes, providing the necessary low-voltage, high-current signal.

The receiver electronics uses a low-noise amplifier designed to accept the signal from the input coupling loop or voltage sensing electrodes and produce an output at an appropriate level such that the data may be recovered. In addition, bandpass filtering for out-of-band signals is provided. Figure 5 shows a schematic diagram of the receiver electronics.

The signal from the input loop is coupled via C1 and C2 to the U1 input stage, arranged as a low-noise balanced differential amplifier. This minimizes amplification of common-mode signals such as many noise sources. A very low noise level operational amplifier is used here.

The output of the first stage is coupled to the second stage by the high-pass filter consisting of C5, L1, and C6. Because of the large bandwidth required, bandpass filtering is accomplished by successive high-pass and low-pass filters.

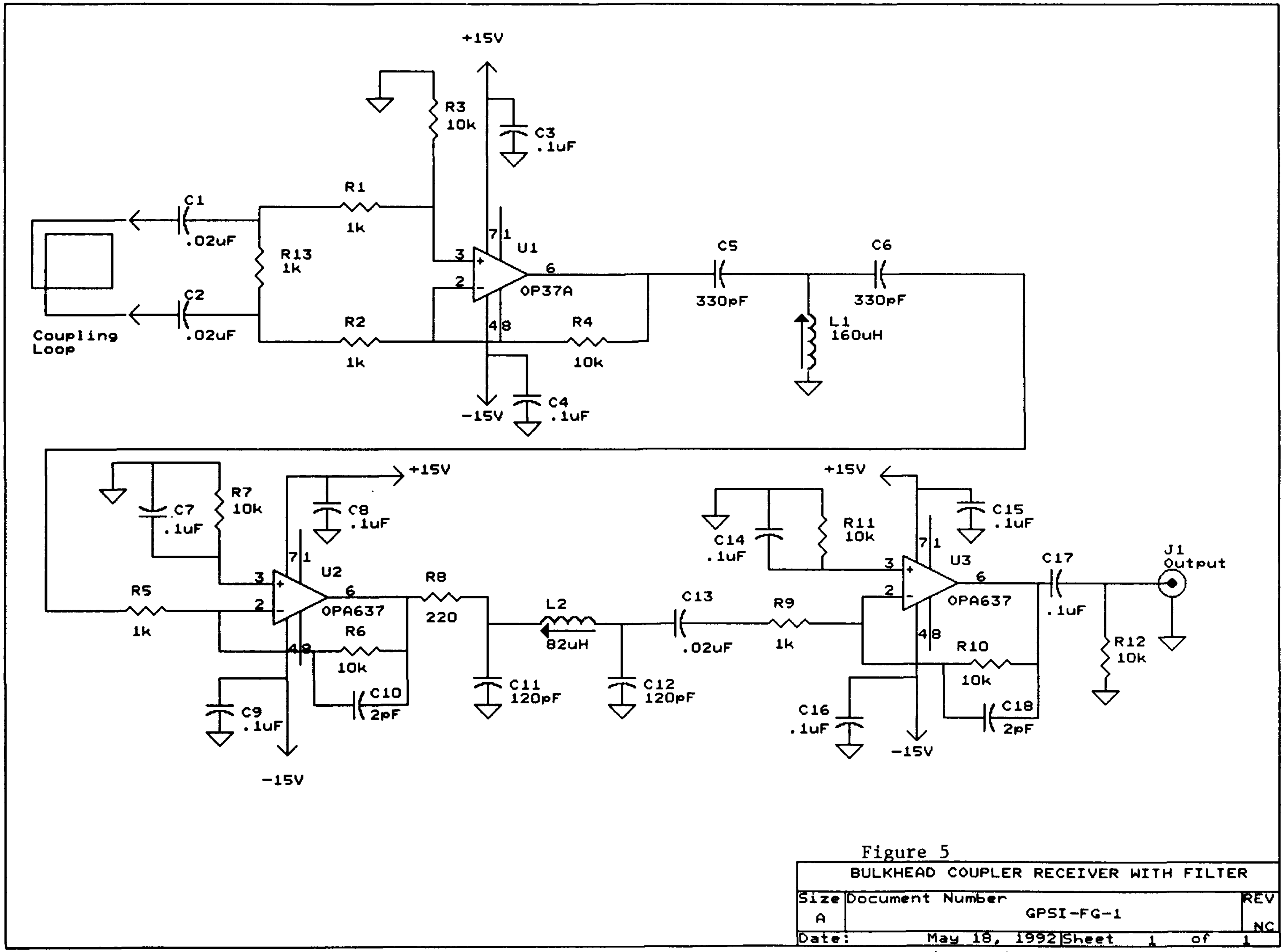
Stage U2 is a second stage of low-noise amplification, which in turn drives the low-pass filter composed of C11, L2, and C12. The output of the low-pass filter drives a third amplification stage that also has sufficient output capability to drive the decoding circuitry. The output signal is AC coupled to the output jack via C17. Output is in the form of a serial data stream that can be accepted by standard computer serial communications interface devices.

4.0 CONCLUSIONS

Results of the tests conducted on the present system clearly show that it is possible to communicate between compartments utilizing the currents passing between compartments at hatches or other openings. Signal to noise ratios are easily sufficient to allow for reliable communication. With an improved modulation method such as Manchester encoding, it will be possible to reach data rates of 1.0 Mbps.

The exact mechanism involved, however, is still not fully understood. It appears that a surface current passes through the opening, and this is the mechanism for coupling. However, the specific pattern of surface current flow through various types of openings has not been characterized. A satisfactory model to account for all of our observations is needed.

At present, work is continuing on an improved modulation scheme in order to achieve desired data rates. A finite element analysis program will be used to model the flow of current across and through the bulkhead in an attempt to gain a better theoretical understanding of the mechanisms involved. Additional testing aboard the ex-USS Shadwell will be conducted in July 1992.



+15V
R3
10k
C3
.1uF
C1
.02uF
R1
1k
R13
1k
C2
.02uF
R2
1k
Coupling
Loop
U1
OP37A
R4
10k
-15V
C4
.1uF
C5
330pF
C6
330pF
L1
160uH
+15V
R7
10k
C7
.1uF
C8
.1uF
U2
OPA637
R5
1k
R6
10k
C10
2pF
C9
.1uF
-15V
R8
220
C11
120pF
L2
82uH
C12
120pF
C13
.02uF
R9
1k
+15V
C14
.1uF
R11
10k
C15
.1uF
U3
OPA637
R10
10k
C18
2pF
C16
.1uF
-15V
C17
.1uF
R12
10k
J1
Output
BULKHEAD COUPLER RECEIVER WITH FILTER
Size
A
Document Number
GPSI-FG-1
REV
NC
Date: May 18, 1992
Sheet 1 of 1

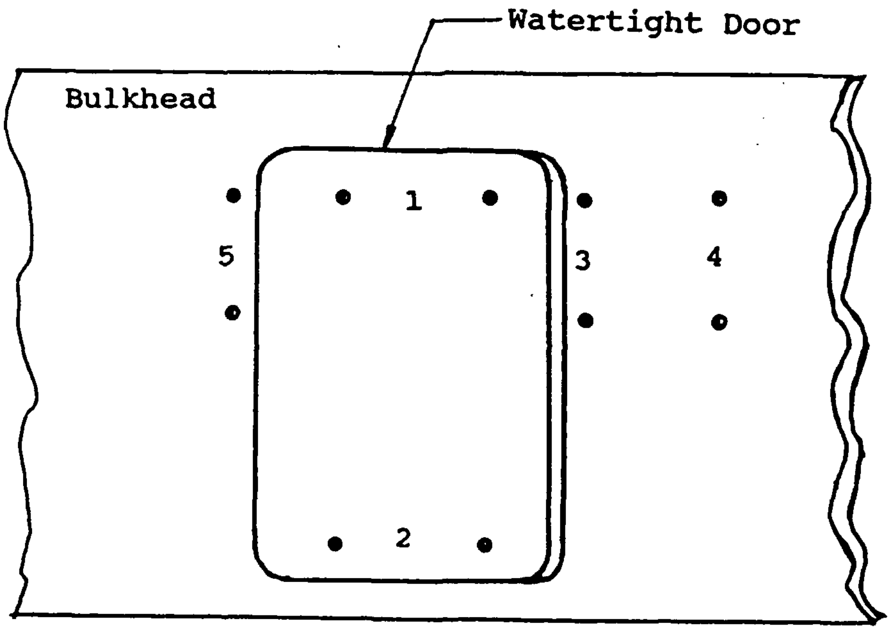
Figure 5

APPENDIX A

BULKHEAD COUPLER TEST PLAN
October 16-17, 1991 aboard ex-USS Shadwell

Current plans are to install 6 quads of studs on or near a hatch in an interior compartment of the Shadwell, the machine shop. The hatch chosen is located in a wingwall bulkhead, which is the thickest available. Each quad will consist of two pairs of studs, located approximately one foot apart. In each pair, one stud will be located on each side of the bulkhead, the studs being as nearly opposite one another as possible. Studs will be 10-24 and installed with a stud welder.

The first stud quad will be located approximately 6" below the top of the hatch, or as close as practical to the top, parallel with the floor. The second quad will be located in a similar fashion approximately 6" above the bottom of the hatch, or as close as possible. The third quad will be located to one side of the doorway, approximately 6 inches from the hatch edge, or as closely as possible, and approximately 1′ below the top edge of the hatch. The fourth will be at the same height and parallel with the third, but at a distance of 18" from the hatch edge. The fifth will be located in line with the third, but 1′ above the bottom edge of the hatch. The sixth and final quad will be located at the same height and distance as the third, but relative to the opposite edge of the hatch. The position of each quad is shown on the diagram below.



Test Frequencies will be 1.024 MHz, PAM modulated with a 128 kHz square wave; 8 kHz, PAM modulated with a 500 Hz square wave; and 1.024 MHz modulated with a data stream at a rate to be chosen during the tests.

Transmitter connections will be made using direct connection to the studs on the bulkhead. Signal pickup will be made by connecting the receiver directly to the studs on the bulkhead and by inductive coupling using both tuned and untuned loops. In all cases the signal will be amplified by the receiver. Reception will be confirmed by use of an oscilloscope, a spectrum analyzer, or a computer with receiver board, as appropriate.

In each case, the transmitter will be directly connected to a pair of studs on one side of the bulkhead. On the other side, signal level and signal plus noise to noise ratio will be measured using direct connection, an untuned loop and the tuned loop. Measurements will be made utilizing the following pairs of studs:

Transmitter	Receiver
1	1
1	2
2	2
3	3
3	4
3	5
3	6
4	3
4	4
5	5
6	6

The reason for pairing these measurements in this way is to also investigate the feasibility of providing bidirectional communications through a single hatch. These measurements will be made using the oscilloscope and/or spectrum analyzer. At each point, appropriate data will be recorded to document the results.

Once the most promising signal paths have been identified, along with the most promising coupling methods for the receiver, the computers will be connected to provide for the transmission and reception of data. If data can be transmitted through the hatch in this fashion, the ship's crew will be asked to turn on and off various available machineries in an attempt to assess the sensitivity of the system to the ambient electrical noise environment.

It is anticipated that all of the above measurements will be made at 1 MHz. Only in the event that no suitable signal paths can be identified will the process be repeated at 8 kHz with the corresponding lower data rate.

APPENDIX B

TRIP REPORT
October 15-17, 1991 aboard ex-*USS Shadwell*

On Tuesday, October 15, 1991 personnel from NOARL Code 252 traveled to Mobile, AL for the purpose of making measurements of the Bulkhead Coupler aboard ex-*USS SHADWELL*. Personnel making the trip were R. Miles, S. Griffin, F. Grosz, and R. Smith.

The van departed SSC at 1145 hours. Upon arriving in Mobile, we went to Welding Engineering Supply Co. (WESCO) and picked up the stud welder that had been rented. We then drove to the Coast Guard Base, Mobile and met the boat from the ex-*SHADWELL* at 1515 hours. Equipment was loaded aboard the boat and we accompanied the boat out to the ship on the last trip of the day. The equipment was offloaded onto the ex-*SHADWELL* and, with the assistance of the ship's force, transported to a secure location for the night. We returned with the boat to the dock and drove to the motel.

On Wednesday, October 16, we met the boat at the dock for the first trip of the day at 0615 hours. Upon arrival at the ship, equipment was transported to the ship's sheet metal shop, which had been selected as the most likely location for the tests on the previous visit. This location was chosen because the bulkhead involved was a part of the wing-wall and therefore 3/8″ thick, and it was out of the way and would not interfere with the ship's personnel during preparation for their fire tests. In addition, it had suitable hatches and a clear section of bulkhead approximately 12′ from the hatch.

The first order of business was to obtain the use of a grinder and small table from the ship's force and to ascertain the location of the necessary power outlets. Suitable locations for the attachment of the studs were chosen, and the sites prepared for the studs by grinding the paint off down to bare metal. At each location, a copper-coated 10-24 stud was welded to the metal. The locations were approximately in accordance with the test plan, and located as shown in Figure 1 (view from inside the shop).

For the first set of quantitative measurements, an interrupted CW signal at 1.024 MHz was used. The receiver was powered from batteries and a plot was made of the noise of the receiver circuitry using the spectrum analyzer (Figure 2). Next, the receiver was connected directly to the studs on the outside of the hatch (designated 1 in Figure 1) while the transmitter was off, and a measurement made of the combined ambient and system noise was made (Fig. 3).

Next, the transmitter was powered up, using a Lambda dual power supply set to ±12 Volts as the power source. The output of the transmitter was connected to the corresponding pair of studs on the inside of the hatch cover using a shielded, twisted pair wire. The level of the carrier at 1.024 MHz was measured with the door open to be -13.4 dBm at the output of the receiver (Figure 4). The door was then closed tightly, but not dogged. The level increased approximately 24 dB, to +11.9 dBm. Next, the hatch cover was dogged down fully, and the level decreased considerably, to -33.4 dBm.

Because this level was still significant, and the S+N/N ratio exceeded 20 dB, it was decided to power the transmitter from batteries as well, to eliminate any possibility of signal propagation via the power lines. This was done, and the signal level through the dogged door increased approximately +3 dB, to -30.5 dBm. It is felt that this small increase is likely due to the slightly higher battery voltage compared to the AC supply.

Next, the transmitter was left connected to the lower inside studs, but switched off. The tuned loop was connected to the receiver inputs and the ambient noise measured; this was determined to be approximately -55 dBm (Figure 5). The transmitter was powered up and the loop location and orientation adjusted to provide the maximum signal. This proved to be with the long side of the loop colinear to the line passing through the two studs on the receiver side of the door, and approximately midway between them. The resulting signal was measured to be -19.1 dBm, resulting in approximately a 35 dB S+N/N ratio (Figure 6). In order to remove any effect due to the hand holding the loop, it was then taped in position and the measurement made again; this was found to be -14.4 dBm. Finally, an untuned ferrite-core loop was made using 100 turns of wire on 1/2 of a T-400-2 core, and the signal level determined to be -42.5 dBm; therefore, no further measurements were made with this loop.

In order to measure crosstalk, the tuned receiver loop was moved to the corresponding position between the upper pair of studs (location 2 in Figure 1), while the transmitter remained connected to the lower pair. This measured the separation in order to establish the feasibility of multi-channel operation on the same carrier frequency. The signal drop was approximately 16 dB, to -31 dBm. It is felt that this difference is not sufficient to allow multiple channels to operate on the same channel.

Next, the transmitter and receiver were directly connected to the terminals on the hatch coaming (location 3 in Figure 1). With power removed from the transmitter, a measurement of ambient noise was made and found to be approximately -55 dBm. Then the transmitter was powered up and the signal on the receive side measured to be approximately -19 dBm. However, there was a strong dependence of the signal level on the exact position of the receiver leads, a phenomenon that had earlier been noticed in the lab, and is assumed to be due to magnetic coupling. With careful placement of the leads, it was possible to raise the received signal level to +2.5 dBm.

Next, the tuned loop was connected to the receiver input and placed on the outside of the hatch cover with the long side of the loop vertical and the plane of the loop perpendicular to the hatch. Whether or not the hatch was open or closed and dogged down made no significant difference in the signal level; it remained at about +11.5 dBm. This is a very large signal level, and, the S+N/N ratio was about 66 dB, which should be sufficient for reliable high-speed data communications.

To investigate crosstalk, the transmitter was left connected to the studs inside the hatch at location 3, and direct connections made to other locations previously identified. With the receiver connected to location 4, the signal level was -7.5 dBm and the noise level varied erratically without any changes in the setup. With the receiver connected at location 5, the signal level was only -2.3 dBm, and with the receiver connected to the hatch at location 1, the level was -16.7 dBm. It was felt that the 25 dB difference found here might be marginally acceptable for dual-channel operation.

Finally, an open section of bulkhead located approximately 11 feet from the hatch opening was chosen, and a quad of studs,separated by 15″ in the vertical direction, was attached (location 6 in Figure 1). These studs were approximately 30″ below a large penetration of the bulkhead by the exhaust for the emergency diesel generator, and several smaller penetrations. Initially, the transmitter was left connected to the inside studs next to the door (location 3). With the receiver connected directly to the bulkhead, a signal level of -35.6 dBm was detected. In order to confirm that this was not a purely magnetic phenomena, the transmitter was disconnected from the studs at location 3 and a 1 turn wire loop placed immediately adjacent to and parallel with the transmit studs at location 3; no detectable signal was found.

When the transmitter was attached to the studs inside the bulkhead at location 6, the received signal level outside the bulkhead was -40 dBm; however, this value was very sensitive to the location and orientation of the receiver leads. However, when the direct connection was replaced with the tuned loop, oriented with the long side vertical and the plane of the loop perpendicular to the bulkhead, the received signal level was -25 dBm, with a S+N/N ratio of 30 dB. This signal fell off rapidly as the loop was moved away from the location 6; at a distance of 5′ form the studs, there was no discernible signal.

This concluded testing for the first day.

On 17 October 1991, a pair of studs were located to the level of the lower stud, 15″ to the left (away from the hatch), forming the horizontal quad labeled 7 in Figure 1. The transmitter was left unpowered and a receiver plot of ambient noise made; as before, the noise level was approximately -55 dBm. The transmitter was then connected to the vertical pair of studs, and an attempt was made to follow the apparent path of the current using the tuned loop. The signal was strongest just below the diesel exhaust pipe penetration, at a level of -16.5 dBm. The current appeared oriented in the vertical direction, and the signal level dropped rapidly below the pipe. For example, below the studs the signal level was 10-20 dB below that just below the pipe. The signal level continued to drop as the loop approached the deck.

The transmitter was then connected to the horizontal pair of studs inside the bulkhead, and the tuned loop used to follow the current path outside. Again, the strongest current was found to be just below the exhaust pipe and oriented vertically at a level of -26.6 dBm. The current orientation appeared primarily vertical at all times, and there was no detectable current found in the horizontal direction between the studs at location 7. This seems to indicate that perhaps a skin current was flowing out of the exhaust penetration; however, no return path could be located.

At this time, it was decided to attempt data communications over the most favorable path found, namely using the studs at location 3 with the tuned loop. Two Z-248 computers were set upon the opposite sides of the bulkhead, one connected to the transmitter and the other to the receiver. The transmitter was connected to the inside studs, while the receiving loop was located between the studs outside the hatch, which was shut and dogged.

Various baud rates and message types were tried. For example, at 2400 baud we sent 468 packets of a pseudo-random binary sequence and a 31 kB text file with no errors, as well as several short text messages. Short messages were successfully sent at rates up to 19.2 kbaud, but longer messages failed at these higher data rates.

It was felt that the limitation on data rate was caused by the modulation scheme employed. The system at the time used a PAM modulation scheme with a diode detector on the receiver. The diode detector placed severe limitations on the minimum detectable signal level. It is considered highly likely that an FSK or Manchester II coding system will provide much higher data rates without any problem, especially given the signal-to-noise ratios encountered in the system.

In order to be able to transmit data reliably at a higher data rate, the transmitter final amplifier was removed from battery power and connected to an AC power supply set to 24 Volts. This increased the signal level from the receiver by approximately 10 dB. With this increased power, 243 packets of data were transmitted at 30 kbaud with 0 errors. Successful transmission was also made at 19.2 kbaud, again using 243 packet messages.

An attempt was made to send data using a direct receiver connection to the bulkhead, but the signal level at the output of the preamp was -10 dBm, not sufficient to operate the diode detector in use for this test. There was some discussion as to whether this potential was actually developed by IR drop or was induced by a magnetic field, so a simple 1-turn loop was made and placed next to the bulkhead between the studs. The signal level dropped 20 dB, probably indicating that there was a voltage drop due to current flow, rather that a magnetic field.

At this time, it was necessary to end the experiments in order to pack the equipment for the trip back to the dock. The stud welder was returned to the rental agency and all returned to SSC at 1900 hours on 17 October 1991.

CONCLUSION

It is clear from the results of the tests conducted aboard the *ex-SHADWELL* that it is possible to communicate between compartments utilizing the currents passing between compartments at hatches or other openings. Signal to noise ratios were easily sufficient to allow for reliable communication, and with a more advanced modulation method it should be possible to reach data rates of 100 kbaud.

The exact mechanism involved, however, is still not fully understood. It appears that a skin current passes through the opening, and this is the mechanism for coupling. However, the results obtained using the studs located far from the hatch opening (locations 6, 7) do not fully support this view. It was initially supposed that the skin current passed through the bulkhead at the opening for the emergency diesel generator exhaust, but no return path for the current could be found. In addition, it was determined that in all cases the current appeared to flow vertically. We do not yet have a satisfactory model to account for all of these observations.

At present, we will continue to develop the coupler itself by adding an improved modulation scheme in order to achieve the desired data rates. We are also attempting to obtain use of a finite element analysis program to model the flow of the current across and through the bulkhead in an attempt to gain a better theoretical understanding of the mechanisms involved.

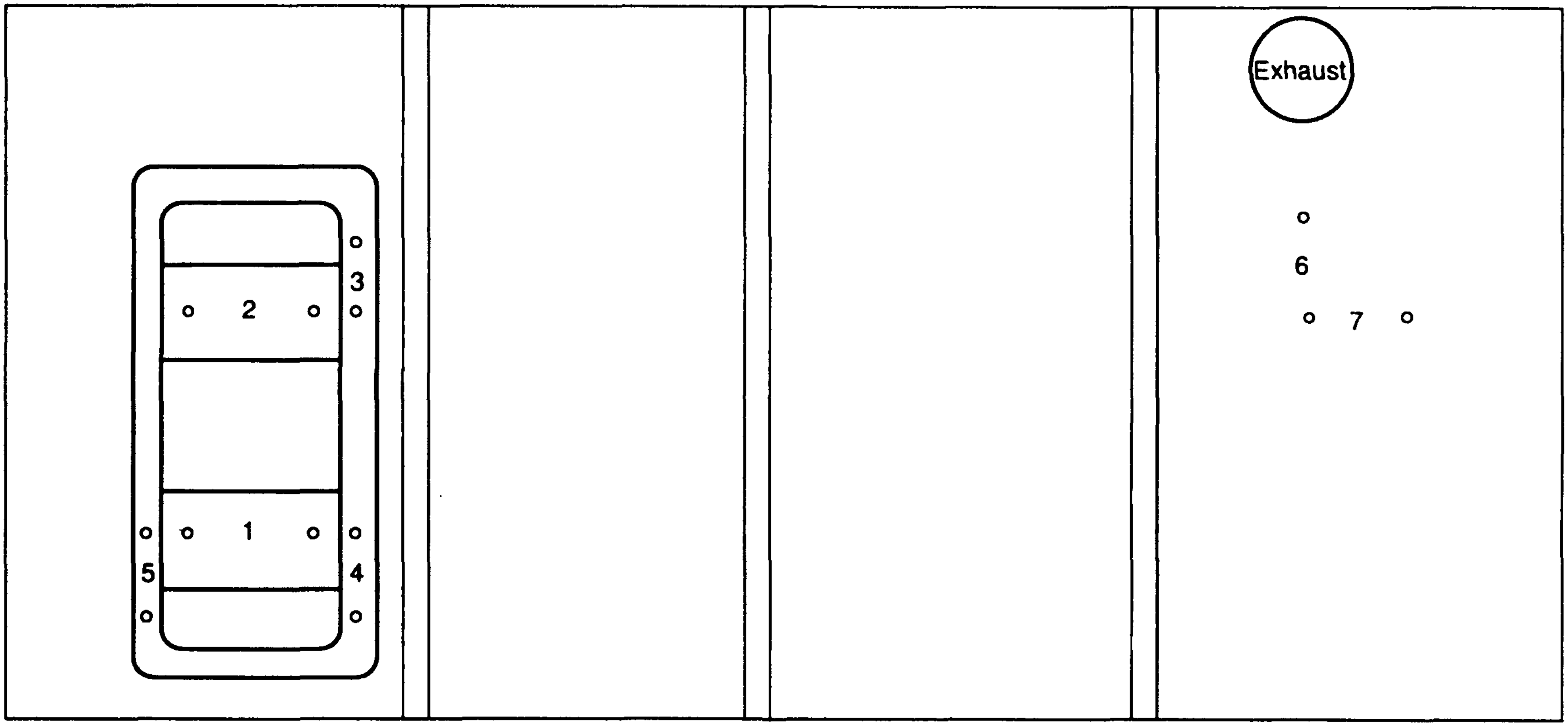


Figure 1.

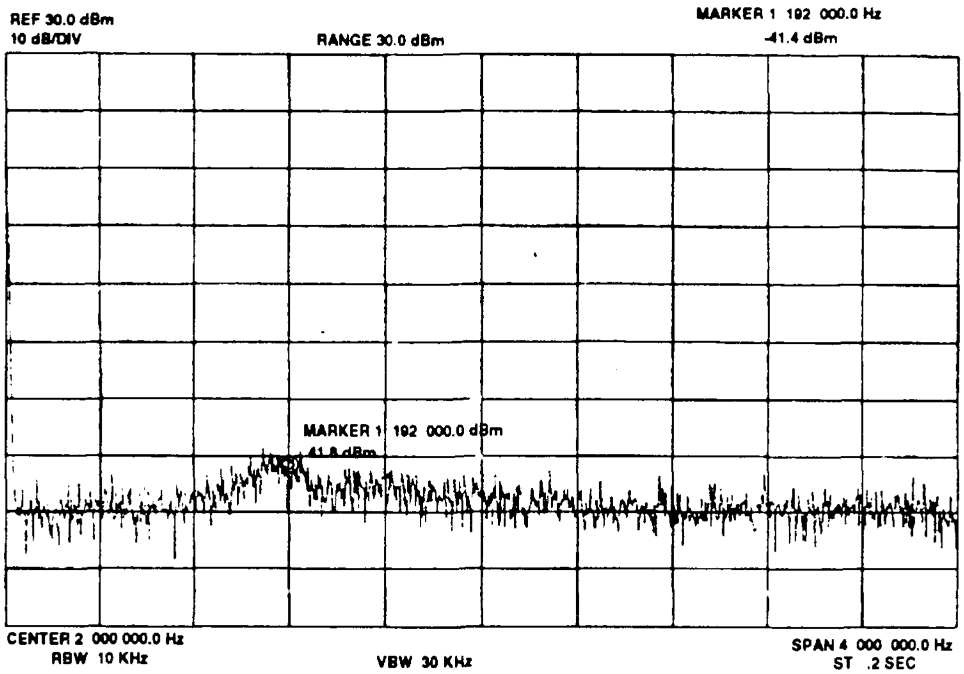


Figure 2.

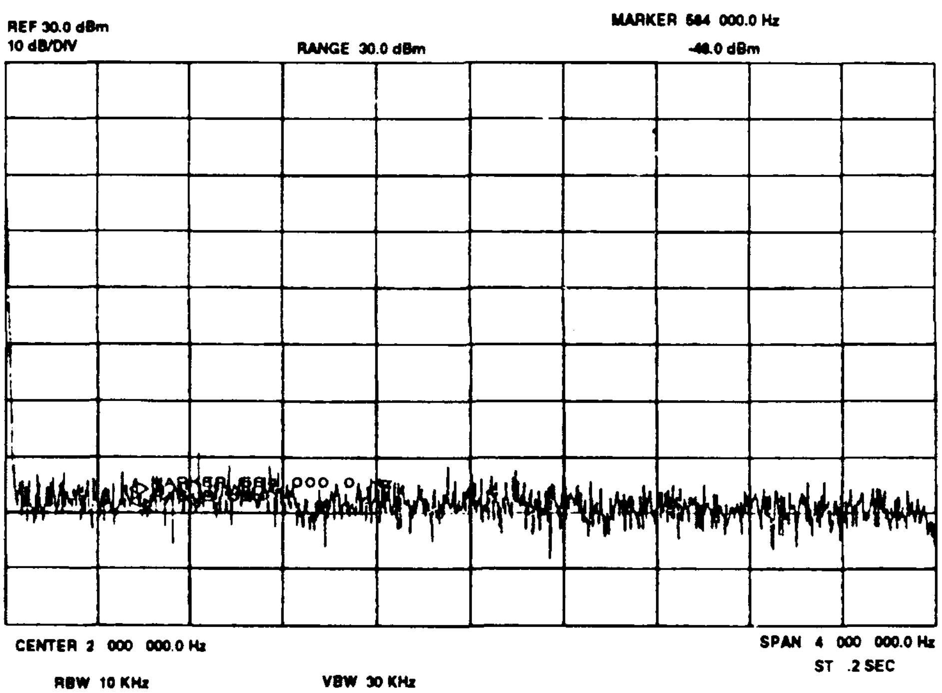


Figure 3.

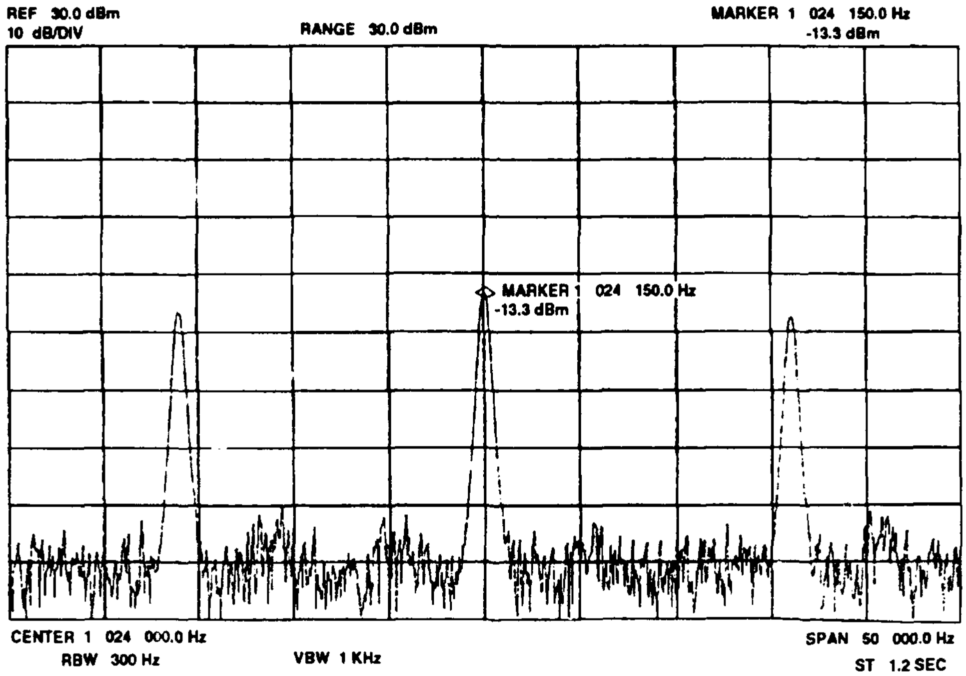


Figure 4

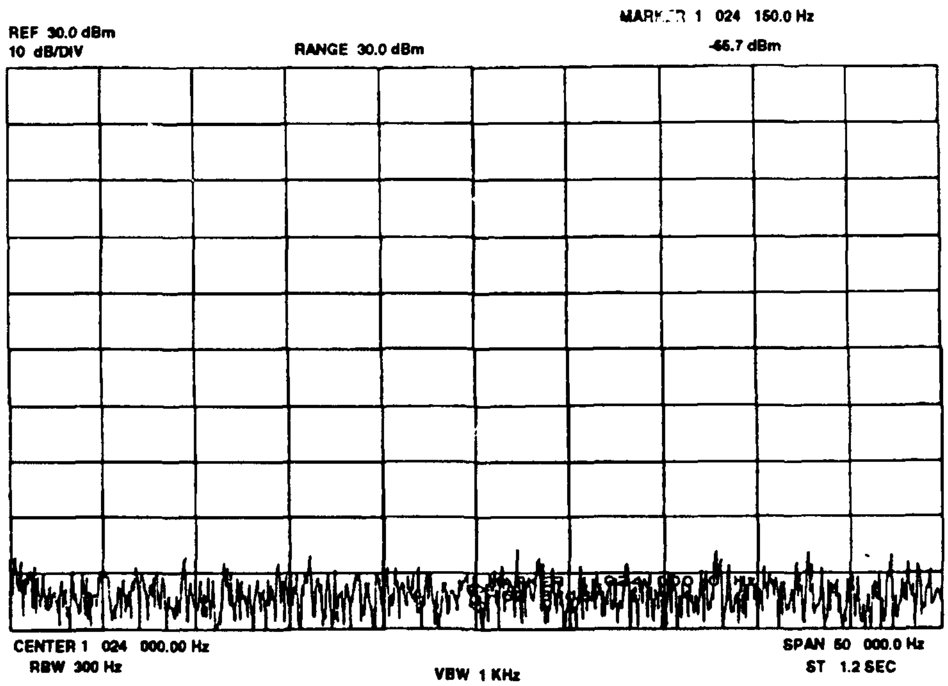
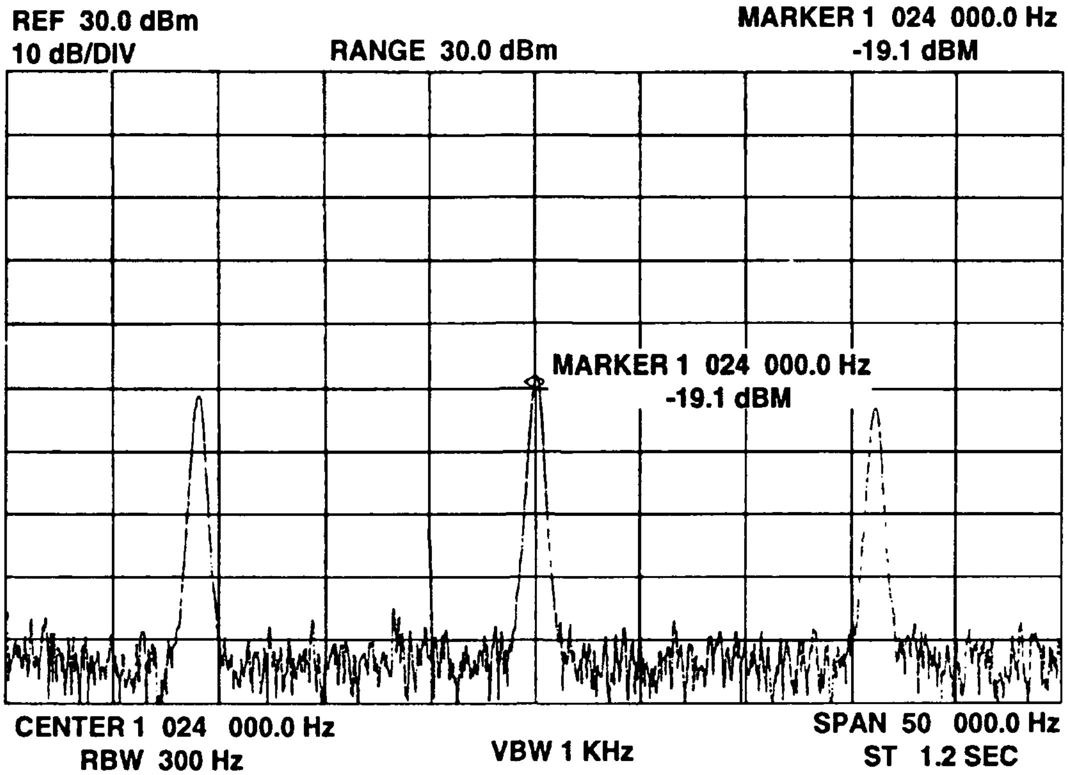


Figure 5.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10 dB/DIV
RANGE 30.0 dBm
MARKER 1 024 000.0 Hz
-19.1 dBM
MARKER 1 024 000.0 Hz
-19.1 dBM
CENTER 1 024 000.0 Hz
RBW 300 Hz
VBW 1 KHz
SPAN 50 000.0 Hz
ST 1.2 SEC

Figure 6.

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In January 1991 the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) Code 252 undertook to investigate for NAVSEA PMS 400D52 the possibility of communicating data through a ship's bulkhead without penetrating the bulkhead physically. Four possible methods of transmission were identified; ultrasonic, electric current injection, magnetic coupling, and current carrier. Of these, the electric current injection method was selected as the most promising, and a device using this technique was developed.

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