NRL/FR/6180--94-9598

Technology Status: Damage Control Hull Communications (DC HULLCOM)

Part 1—Advanced Development Model

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March 22, 1994

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 22, 1994	1985 to 1992

4. TITLE AND SUBTITLE

Technology Status: Damage Control Hull Communications (DC HULLCOM), Part 1—Advanced Development Model

5. FUNDING NUMBERS

PE - 63514
PR - S-1565-SL
TA - DC040COMO

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/FR/6180–94-9598

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Sea Systems Command
Washington, DC 20362-5101

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*SFA Inc., Landover, MD 20785

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A noninterruptible and survivable damage control communications system (DC HULLCOM) has been developed that uses ultrasonic energy to communicate voice and casualty data through the ship's hull and structure. The system consists of a portable, battery-powered transceiver unit capable of voice and/or data communications; an acoustic transducer with clamp attachment; and a headset and VoiceDucer (bone-conduction microphone and earphone) with cable assemblies. The system can be interfaced to the hull-mounted transceiver via a cable or an electromagnetic link from the handheld data entry and display unit. An Advanced Development Model of the system has been built and tested to demonstrate recent improvements in the system and is described in this report.

14. SUBJECT TERMS

Damage control, Ultrasonic, Communications, Acoustic, Survivable

15. NUMBER OF PAGES	16. PRICE CODE
34	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

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EXECUTIVE SUMMARY

A noninterruptible and survivable damage control communications system (DC HULLCOM) has been developed that uses ultrasonic energy to communicate voice and casualty data through a ship hull and structure. The system consists of a portable, battery-powered transceiver unit capable of voice and/or data communications; an acoustic transducer with clamp attachment; and a headset and VoiceDucer (bone-conduction microphone and earphone) with cable assemblies. It can be interfaced to the hull-mounted transceiver via a cable or an electromagnetic link from the handheld data entry and display unit.

An Advanced Development Model of the HULLCOM system has been built and tested to demonstrate recent improvements in the system. These improvements include:

- a 25-watt constant power amplifier with three power-level settings;
- combined AM/FM and FM/AM advanced transmit and receive capabilities;
- two levels of automatic gain control (AGC) for clean reception of signals, both nearby and distant;
- a direct digital synthesizer (DDS) for advanced voice and data transmission capabilities;
- advanced multilayered printed circuit boards;
- capability of operating from field-interchangeable 4-hour battery packs;
- addition of data transmission capabilities;
- capability to operate on multiple channels; and
- capability for using handheld data entry and display terminals.

The voice portion of the voice and data ADM has been tested on the USS *Barry*. These tests show both improved operation of the voice portion, including voice clarity, and improved reliability and extended operating ranges. The data capability is incorporated into the voice and data ADM, but interfacing the data capability to a handheld data terminal has not been completed. A limited development effort could provide data interfacing capability.

TECHNOLOGY STATUS: DAMAGE CONTROL HULL COMMUNICATIONS (DC HULLCOM)

PART 1—ADVANCED DEVELOPMENT MODEL

INTRODUCTION

Shipboard experience during recent damage control (DC) and firefighting (FF) operations has defined a requirement for a communications system to provide reliable, uninterrupted communications between the DC scene and DC/FF organizational units after experiencing shipboard battle damage, operating casualties, and subsequent fire, smoke and flooding damage [1]. Several DC communications systems have been proposed that would greatly reduce these interruptions. One such system, the Damage Control Hull Communications system (DC HULLCOM), has been under development at the Naval Research Laboratory (NRL) since 1985. DC HULLCOM is a self-contained, portable, battery-powered, communications system. It operates independent of ship wiring and power systems and acoustically transfers information through the structure and hull. Signals are introduced into the structure and are present in contiguous portions of ship structure and hull, thereby allowing for communications around damaged areas.

DC HULLCOM is a system design concept in damage control communication that meets the requirements by providing:

- an uninterrupted communication of voice, text messages, and DC symbology between Scene Leaders/Investigators carrying portable devices and repair lockers, DC Central (DCC), Engineering Control (EC), and command personnel equipped with fixed units;
- a transmission medium that cannot be destroyed or degraded by adverse conditions; and
- a dedicated DC communications capability that does not require outlets at fixed locations thereby limiting mobility of personnel using portable units.

Laboratory testing has demonstrated that the ship's hull and structural members can be used to transmit ultrasonic signals and provide an uninterrupted path between portable and fixed communications equipment [2-5].

The DC HULLCOM system consists of portable units that can send and receive voice communications and can also send, receive, and display text messages and DC symbology. Fixed units provide the same capability with the addition of graphics. The fixed units also have a memory system for storage of ship drawings, schematics, compartment geometry, and other data needed to support DC/FF operations. The system is compatible with other communications systems aboard ship, standard Navy DC practices, and firefighting techniques.

Manuscript approved September 16, 1993

The following performance thresholds were established in the Operational Requirement for DC HULLCOM [1]:

1. Operational availability for the total system: $A_o = 0.99$
2. Both the portable and fixed units shall have a mean time between failures (MTBF) of at least 960 hours.
3. All units shall be of modular design where possible, for ease of repair and maintenance and must have a mean time to repair (MTTR) of no more than 15 minutes.
4. Signals reradiated by the ships hull shall not be intelligible at a minimum range of 1 kilometer through seawater.
5. System function shall not be degraded by gross structural damage, electromagnetic radiation (EMR), electromagnetic magnetic interference (EMI), electromagnetic pulse (EMP), or transient radiation electromagnetic effects (TREE).
6. The system shall be capable of two-way communication between a portable unit and a fixed unit, or between two fixed units, with a signal quality suitable for exchange of damage control information.
7. System components shall conform to specific requirements of MIL-S-901C (resistance to grade A, high shock); MIL-E-16400G (sheltered equipment); and MIL-STD-810D (immersion, climatic, vibration and dust).
8. Controls, display, and unit configuration shall conform to Human Engineering Criteria of MIL-STD-1472C:

   Portable Units - A transducer will be attached to the unit with a flexible conductor and will be used to inject and detect the ultrasonic transmissions in the hull or structure. No external power source will be required for operation.

   Fixed Units - A fixed unit will be located in each Repair Locker to communicate with portable units used at the scene. It must also communicate with other fixed units on the ship and will have a minimum of seven selectable channels. The transducer will be attached to the ship structure with a semi-permanent mounting. Each unit will have pertinent ship drawings and schematics in memory such that they can be viewed on an integral screen.

BACKGROUND

Development of the DC HULLCOM system required technology advancements in the following areas:

Transducer Development

Acoustic behavior in steel structures
Attachment methods
Improvement in the efficiency of energy transfer (transducer to ship structure)
Improvements in transducer sensitivity
Optimization of ceramic materials
Improvements in efficiency of power generation and acoustic coupling

Signal Processing
- Operation in multipath environment
- Operation in shipboard noise environment
- Voice enhancement

Computer Science
- Generation and display of casualty reports
- Mass data storage and retrieval
- Graphics for display of DC plates on base computers
- Software development for handheld data entry device
- Communications software development

Human Factors
- Size
- Weight
- Configuration
- Ease of use

The first step in implementing the DC HULLCOM system was to establish an understanding of the problems associated with the transfer of acoustic energy through a ship structure from one point to another. A program was begun to define and address the problems associated with acoustic information transfer through an elastic medium and to determine the current status of these technologies in both industry and government.

Initial work was conducted in 1985 to determine the feasibility of developing a communications system based on the communication of voice and Morse-code-like messages through a steel structure that could be equated to the structure of a Navy ship [2]. Feasibility was demonstrated by using identical ultrasonic transducers as transmitter and receiver with a 100-ft (30.48-m) structural steel communication link. Reference 2 defines transducer design for the demonstration system.

In 1986, ultrasonic communication of voice messages through the steel structure of the USS *Saratoga* was experimentally confirmed at Mayport, Florida, during ship overhaul [3]. Although ship noise was moderate to heavy (because of the overhaul work in progress), intelligibility of messages was not significantly impaired. Reference 3 also provides the power spectra of the transmitted signals. Transducer coupling techniques were modeled to determine energy transfer efficiencies achievable when injecting acoustic energy into the ship structure with a transducer. The use of wedges designed to inject acoustic energy into a steel structure at an optimum angle (critical angle) to reduce energy losses was studied together with the propagation of elastic waves in layered media.

The principal objectives of the 1987 Acoustic Program of the DC HULLCOM Project was to improve the design of ultrasonic transducers used for transmission and reception. The acoustic transmitter was optimized to deliver the maximum power over specified frequency bands and the acoustic receiver for maximum signal-to-noise ratio (SNR) [6]. Computerized models of transmitting and receiving transducers were implemented. The models permitted the effects of varying geometrical and material properties of transducer components to be investigated. An important input to the computerized models is the acoustic loading (driving point impedance) that the ship structure presents to the transducer. Much of the 1987 effort concentrated on developing and testing an experimental system that accurately measures acoustic loading to the transducer by the ship structure.

Laboratory instrumented acoustic communications paths were set up in a building at NRL and on the steel pier at NRL's Underwater Sound Reference Detachment (USRD) in Orlando, Florida, in 1988 and 1989. Acoustic transducers that used both wideband and narrowband design approaches were designed, built, and evaluated at USRD to more efficiently inject and extract acoustic energy into and out of steel structures. Accelerometers in the acoustic path at the NRL building determined the predominate acoustic wave types for the method of injection used, and how the wave type changed as it traveled through the instrumented path.

Acoustic receivers of different designs and materials were also evaluated on this path. Reference 6 documents receiving transducer development. Methods of transducer attachment that met HULLCOM requirements and satisfied acoustic limitations were studied. Solutions to the severe discrete frequency attenuation and wide amplitude variations caused by multipath signal arrivals were evaluated. Design modifications to improve the transducer driving point impedances, operation over extended frequency ranges, and positional adaptability were also studied.

It was necessary to design and build customized communications equipment. This equipment had to be capable of modulating, transmitting, receiving, and demodulating signals that represented damage control information being acoustically sent and received. The breadboard was initially tested by using the structural members of a NRL building. Data were transmitted in a byte serial format; eight bits representing a parallel data word were sent at the same time. Each of the eight bits in this parallel data word was represented by a discrete frequency. These discrete frequencies were turned on or off, represented by a 1 if it were ON, or a 0 if it were OFF. The total ASCII character set can be represented by these 8-bit parallel words and can be directly transmitted without further decoding and interpretation.

Late in 1989, the demonstration system was moved to the USS *Barry* to prove the concept of operating the communication system through the ship structure. Additional equipment was produced to set up a demonstration system with three stations: Damage Control Central; Repair Locker; and On-Scene Leader. The purpose of this system was only to prove feasibility and to establish an operable system for demonstration and concept validation. No attempt was made to reduce the component sizes for this demonstration system.

Communications terminals were procured for the three stations to support the *Barry* demonstration. A search was conducted for commercially available fixed and portable computers that could be programmed to generate, transmit, receive, and display casualty reports. These computers had to be compatible with those currently being used for reports in Fleet damage control operations. The base computer terminals were mounted in a fixed position in the repair lockers and DCC. These fixed-base terminals were initially powered by ship power; they would be equipped with an 8-h battery backup for all permanent ship installations. The portable data entry and display terminals were handheld and battery powered. Both the base and handheld units were programmed to generate damage reports that were then acoustically transmitted from the casualty scene [5].

Damage reports were generated and transmitted from the casualty scene by using the portable data entry and display terminals; they were received and displayed in the repair locker and/or DCC on the base units. The casualty reports could also be constructed in the repair locker from voice reports from the casualty scene, and then sent to the casualty scene for verification. Software was developed in a menu-driven format to generate, edit, and display damage reports. This provided ease of use by the scene leader or investigator in a shipboard damage control environment. Repair lockers were equipped with base computer terminals for communicating with and supporting DC personnel at the casualty scene. The terminals were capable of communicating damage reports, displaying damage control plates, overlaying ship systems and damage control symbology on the damage control plates, calling up damage control manuals, and time/date stamping damage reports for future callup, review, and training [7].

Thirty-eight companies responded to a solicitation in the Commerce Business Daily (CBD) to attend a briefing on DC HULLCOM. Industry briefings were held in March 1990. Two briefings each day for 3 days were held on the USS *Barry*. The DC HULLCOM system was demonstrated, the current status of DC HULLCOM research was described, and a request for industry involvement through cooperative R&D agreements was made. The Navy Prospective Contractors Program (NPCP) was used to guide industry internal research and development (IRAD) program involvement. Subsequently, NPCP agreements were negotiated with five companies to advance the state of the art in transducers, displays, human factors, voice recognition, damage control procedures, and signal processing.

The DC HULLCOM system that was set up and demonstrated on the USS *Barry* provided a conceptual outline for an acoustic, shipboard damage control communication system for Navy ships. Operational requirements of a damage control communications system and the hostile shipboard operating environment impose strict limitations on equipment designs. Operation from battery supply sources, in wet and smoky damage control environments, while dressed in DC/FF clothing further limit design options. For the system to operate from battery power, 10-fold improvements in the efficiency of acoustic energy transfer and power amplifiers and in the sensitivity of acoustic receivers were required. In 1990, an intensive R&D effort was conducted in the laboratory and on the *Barry* to reduce the power requirements of the equipment through improved operating efficiencies, optimized acoustic energy transfer, and improved power-generating designs.

Implementing the current system configuration by using a wideband transducer would require efficient operation over the 30 to 100 kHz frequency range. The acoustic load or driving point impedance that the ship structure presents to the transducer was found to change dramatically with frequency, thereby complicating design requirements for the transmitting transducer. Attempts to increase and stabilize the transducer efficiency over the entire 30 to 100 kHz frequency range were not as successful as required. A tradeoff was eventually made to limit the operating bandwidth to 10 kHz and to use a semi-resonant transducer design. The initial 30 to 100 kHz operational frequency band was divided into seven channels of 10 kHz each. By reducing the channel bandwidth, transducer efficiency was improved by more than an order of magnitude. This dramatically improved efficiency and reduced battery power requirements.

To increase data rates and optimize operation in the 10 kHz channel bandwidth, the acoustic channel (the acoustic path between one point on the ship and another) was modeled. Channel modeling is used to determine the most favorable modulation and demodulation scheme for data communication. Modeling was conducted on the USS *Barry* in 1991 [4]. The results of the channel modeling concluded that multipath interference could dramatically decrease acoustic communications reliability. An adaptive equalization technique was found to be highly effective in eliminating multipath interference in this acoustic communication application. A Constant Modulus Algorithm (CMA) adaptive equalization technique has been implemented to compensate for the multipath.

Based on the channel modeling, the optimized modulation scheme was determined to be a noncoherent form of frequency shift key (FSK), called minimum shift key (MSK). With MSK the frequency shift is made in phase. This eliminates self-induced amplitude fluctuations or noise caused by the transmitting transducers active element response to the abrupt frequency shifts found in FSK applications. Reference 5 discusses the use of adaptive equalization in DC HULLCOM, focusing on the use of the constant modulus technique and an analysis of the MSK modulation technique. The technique was tested and demonstrated on both voice and data channels, and the results are presented in the report.

In August 1991, the DC HULLCOM demonstration system that had been installed on the *Barry* was transported to Surface Warfare Officers School (SWOS) in Newport, Rhode Island. A demonstration was conducted by using the structural steel members of a building for the acoustic communications channel. The DC HULLCOM operational configuration was presented. SWOS personnel were solicited for input on customizing the DC HULLCOM system for Fleet use during DC/FF operations. User interface and equipment packaging requirements were emphasized. The two major areas of concern communicated during the demonstration were:

- the size, weight, and power requirements of the demonstration system made DC HULLCOM impractical for portable use by damage control personnel outfitted in firefighting gear, and
- the keyboard interface for the damage scene leader's handheld terminal was too small to be used while wearing firefighting gloves.

A voice-only system was then produced during the last three months of FY 91. This system used the semi-resonant transducer design to minimize system power requirements. The voice-only system was implemented to provide a platform for the optimization of communications components and to evaluate the semi-resonant transducer technology. The voice-only system was packaged into portable, battery-powered enclosures, verifying that DC HULLCOM technology could be downsized to support Fleet operations. This platform supported design improvements in the power amplifier, receiver, transmitter, modulator, demodulator, squelch, battery supply power sources, automatic gain control, and human factor interfaces.

An investigation was also conducted to locate an interactive device for use by the damage scene leader and investigators for reporting casualties and damage back to the repair locker and/or damage control central. It was concluded that a touch-screen-type data input terminal for on-scene reporting would provide a more usable terminal interface during damage control operation because of its ease of information entry. A pen-based portable computer, with touch screen and character-recognition capabilities, was acquired, and user interface software was developed to support damage report construction and storage. This device provided a handheld terminal that allowed construction of damage reports in a format similar to current damage report "chits" used in the Fleet. The pen-based terminal was demonstrated at the Damage Control Firefighting Working Group in November 1991, and was well received by Fleet representatives.

Developmental testing was conducted on the Advanced Development Model (ADM) DC HULLCOM voice-only transceivers on the ex-USS *Shadwell* during March-April 1992 [8]. The test setup used semi-resonant piezoelectric transducers that incorporated an acoustic resonant horn for impedance matching. The transducers are housed in a portable "squeeze grip" clamping device for mounting to the ship structure. The transducers generate and detect ultrasonic frequency-modulated acoustic signals in the 42 to 52 kHz range for voice communications.

The objectives of the *Shadwell* tests were to assess DC HULLCOM voice transmissions for communications capabilities, voice clarity, and quality during normal ship operations, fire tests, and damage control operations. Other tests were conducted to determine communications capabilities (including intelligibility, clarity, and voice quality) during transmissions in, around, and through the fire scene. Fleet personnel operationally assessed the system's capabilities and user interfaces.

The *Shadwell* tests also supported the evaluation of a bone-conduction microphone that permits system operation in high noise environments. The microphone is placed in the ear, much like a hearing aid, and picks up voice signals from the person speaking as the voice propagates through the jaw bone.

Airborne noise in the environment is not picked up and transmitted by the ear microphone. The ear microphone also facilitates the wearing of damage control equipment such as oxygen-breathing apparatus (OBAs) and gas masks. With the use of the ear microphone, high-quality voice transmissions were achieved by personnel wearing OBA masks during the *Shadwell* tests.

Shadwell testing of the voice-only units exercised and evaluated design changes in the power amplifier, receiver, transmitter, modulator, demodulator, squelch, and battery-power source. The testing also indicated a need for automatic gain control (AGC) in the receiver and supporting amplifiers and the redesign of human factors interfaces. The tests were instrumental in evaluating system components from a reliability standpoint.

Portable voice and data transceivers were designed and built during the remainder of 1992. They incorporated the improvements in acoustics, electronics, communications, and human factors identified through the voice-only component improvement platform and the tests conducted on the USS *Barry* and the ex-USS *Shadwell*. Software can easily be developed for a portable data entry and display terminal to interface with the HULLCOM voice and data units for transferring information to fixed base units. The data transmission portion of the voice and data system uses the new MSK data modulation technique, and the receiver portion can be enhanced by the use of adaptive equalization filtering techniques to eliminate the multipath interference. A handheld terminal is currently being integrated with the portable voice and data units for demonstration and evaluation. The remainder of this report describes the design and operation of this equipment.

ADVANCED DEVELOPMENT MODEL

A research and development program was initiated to advance the state of the art in technologies required to support a portable DC HULLCOM acoustic communications system. This system must be capable of meeting the Operational Requirement (OR) [1] for a system operating in shipboard damage control environments. The R&D program produced significant advances that enabled the production of an Advanced Development Model (ADM) DC HULLCOM system (Figs. 1-3). Reference 9 provides detailed descriptions of individual components, including drawings and schematics.) This ADM DC HULLCOM model was built with two objectives:

- to provide equipment to support active shipboard testing of the technology for transmitting acoustic information through a ship structure (hull); and
- to provide shipboard demonstrations of a communications system that supports damage control operations.

Testing conducted with DC HULLCOM components was instrumental in the development of acoustic transducers and signal processing techniques to improve system performance. However, additional testing is required to provide an accurate assessment of DC HULLCOM shipboard communications coverage, data reliability, error correction requirements, and voice intelligibility in an active shipboard environment. An active ship implementation of DC HULLCOM is desirable for providing a realistic model to evaluate the usefulness of an acoustic communication system to support damage control operations.

Testing accomplished to date on the DC HULLCOM system has been focused on characterizing and modeling the communications channel and on acquiring data to aid in the development of demonstration hardware. Channel characterization testing was essential in specifying the transducer (Fig. 4) and in optimizing the signal processing designs. Channel modeling facilitated the selection and development of an adaptive equalization filtering technique, which enhances the received signal before demodulation by

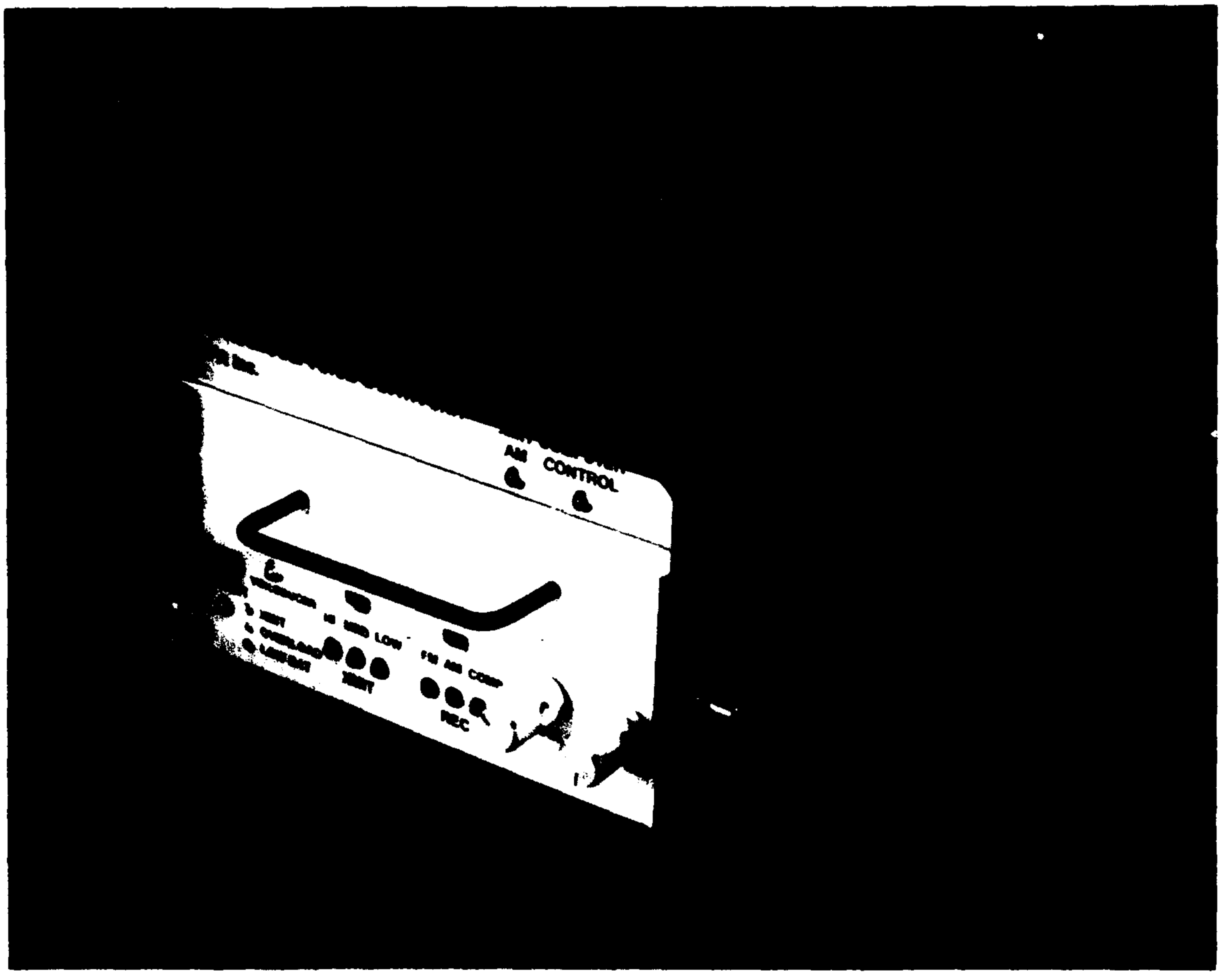

Fig. 1 — DC HULLCOM Portable Voice and Data Unit (PVDU)

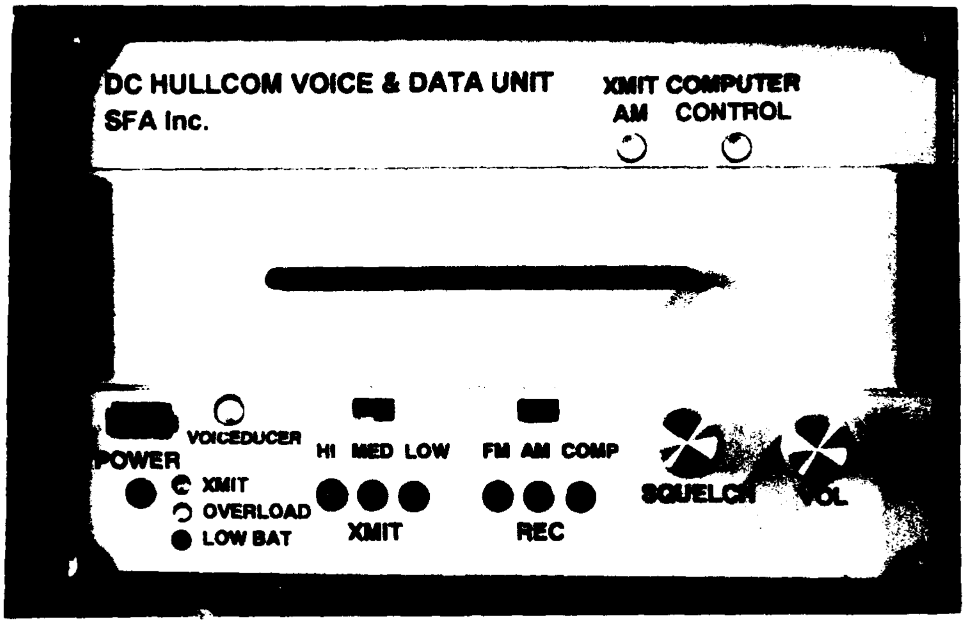

Fig. 2 — DC HULLCOM PVDU front panel view

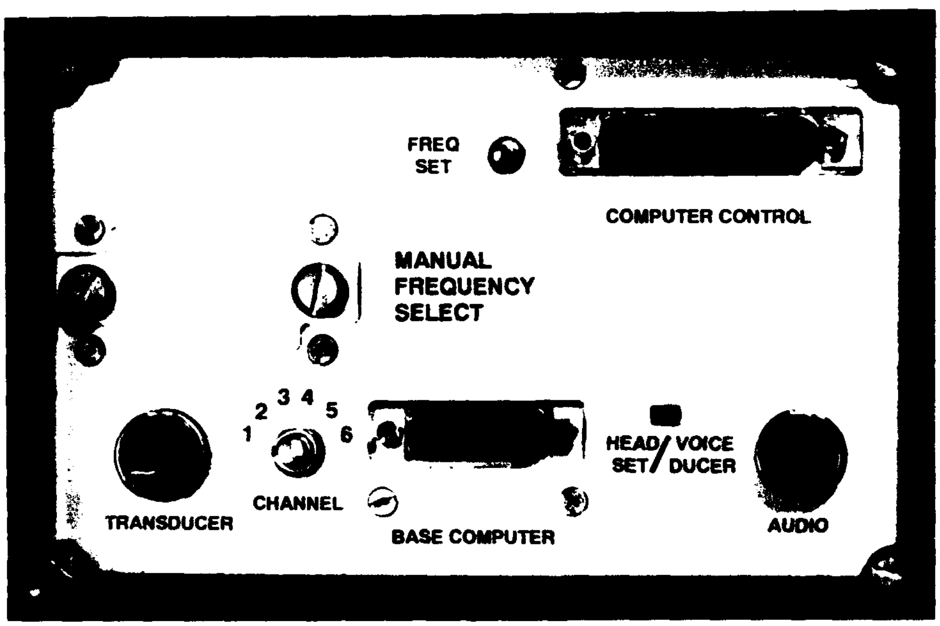

Fig. 3 — DC HULLCOM DVDU rear panel view

removing the channel effects caused by multipath interference. The ADM equipment was produced to provide a rugged, portable, battery-powered system that would facilitate active shipboard testing of acoustic information transfer through a ship structure and to demonstrate the capability to meet operational and functional requirements.

System Configuration

The ADM was also developed to support a demonstration DC HULLCOM system. Operational requirements identify the need for both portable and fixed communication stations. Fixed communication stations will be established in Damage Control Central, Engineering, the Bridge, and in each Repair Locker; portable stations will be established in close proximity to all damage areas. The ADM was developed to support both portable and fixed communication stations. Equipment for the portable stations is rugged, lightweight, transportable, and battery powered. The following equipment was developed to support a portable communication station:

- portable voice and data unit (PVDU)
- handheld data entry unit
- transducer
- headset/microphone with push-to-talk cable
- VoiceDucer with interface cable.

Figure 5 is a block diagram of the equipment configuration for a portable communications station. On-scene damage control personnel complete damage reports by using a pen-type stylus to enter information on the touch screen of a handheld data entry unit. The damage reports use Standard Navy Symbology and are configured similar to the DC "chit" currently used by Fleet damage control personnel. The handheld data entry unit translates the damage report into data words that control the PVDU for transmitting data. Voice transmission is initiated by pressing a push-to-talk (PTT) button. Two options exist for interfacing audio signals (transmit and receive) with the PVDU: the headset/microphone and the VoiceDucer. The VoiceDucer, which uses a combination bone-conduction microphone and audio earpiece, has a reduced sensitivity to airborne noise and is recommended for use in an environment with a high ambient noise level. The VoiceDucer also provides a usable audio interface for personnel in firefighting gear and emergency breathing apparatus, and provides the option of being used in a PTT or voice-operated transmit (VOX) mode. The transducer, which is housed in a mounting mechanism, is easily clamped onto the ship structure, providing an acoustic antenna for signal transmission and reception.

The fixed communications station is configured with advanced digital signal processing capability and is supported by a standard IBM PC-compatible computer terminal. The following equipment is required for a fixed communications station:

- portable voice and data unit (PVDU)
- IBM PC-compatible computer with digital signal processing (DSP) cards
- transducer
- headset/microphone with push-to-talk cable
- VoiceDucer with interface cable.

Figure 6 is a block diagram of the equipment configuration for a fixed communications station. Received AM and FM audio signals are demodulated in the PVDU, and the audio is sent to the headset or VoiceDucer. Received data signals are conditioned and sent from the PVDU to the computer for digital

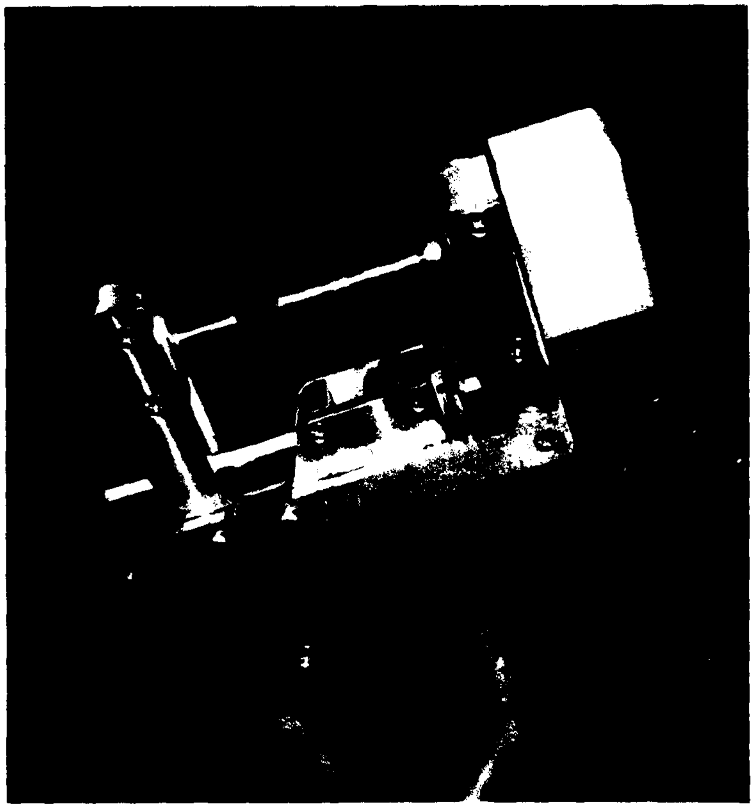

Fig. 4 — DC HULLCOM transducer prototype

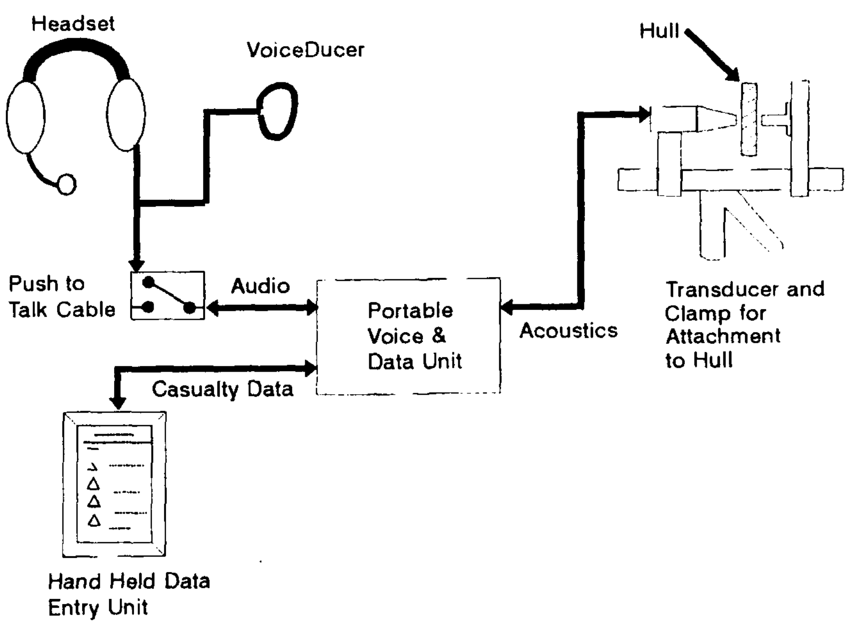

Fig. 5 — Portable communications station

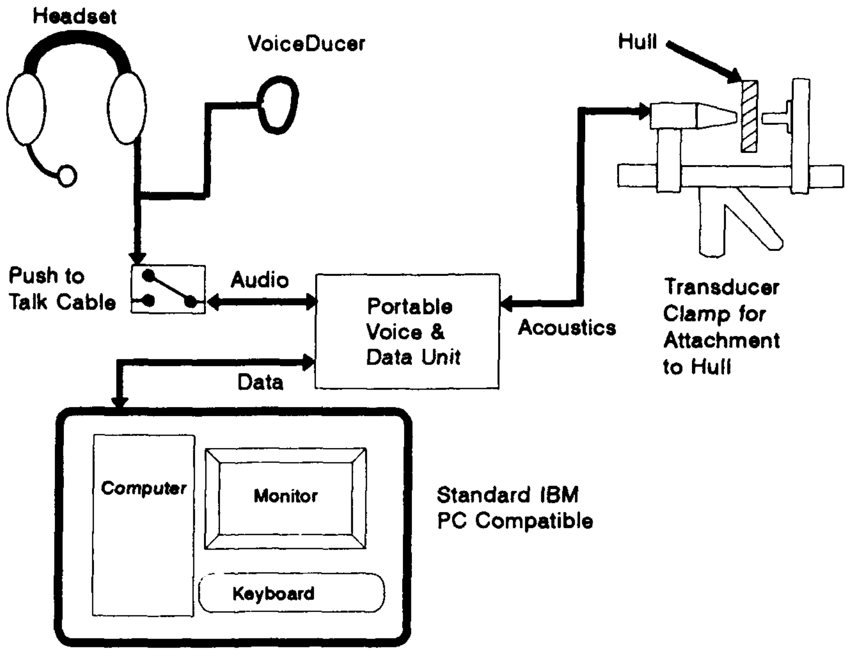

Fig. 6 — Fixed communications station

signal processing and demodulation. The computer provides support for constant modulus algorithm (CMA) filtering, digital signal processing, and retrieval and display of the damage reports and information.

Theory of Operation

DC HULLCOM is a portable, half duplex, point-to-point communication system that provides both voice and data links by means of acoustical signal propagation through the ship hull. This system is designed to provide reliable communications between two points within the ship during damage control operations, even when the ship is severely damaged. Channel modeling conducted on the USS *Barry* identified significant interference caused by multipath signal arrivals in the DC HULLCOM channel. This multipath interference causes frequency-selective attenuation of the signals that are transmitted through the communications channel and adversely affects the reliability of a point-to-point acoustical communication system. It has been found that adaptive equalization before demodulation can greatly enhance the signal, removing most of the channel effects (Fig. 7). The constant modulus algorithm (CMA) equalization technique was chosen for system implementation because initial testing conducted on the USS *Barry* had provided advantageous results.

The constant modulus algorithm is a blind equalization technique that replaces the requirement for a reference signal by the mathematical requirement that the modulus of the signal be constant. The adaptive filter architecture is an N-tap transversal FIR filter using stochastic gradient descent for convergence, similar to the least mean squares (LMS) adaptive algorithm. However, instead of determining the error signal magnitude by comparison with a reference signal, the modulus of the output signal is compared to an ideal constant modulus, typically set at one. Deviation from this criterion generates a new set of filter weights that drive the error towards zero. For this technique to be successful, the original (transmitted) signal must have a constant modulus. Any angle modulation technique (phase or frequency modulation) has this property. The CMA method is applicable to DC HULLCOM because the MSK modulation technique can be considered to be:

- a *frequency* modulation technique when transmitted *noncoherently* (a subcase of FSK); and
- a *phase* modulation technique when transmitted *coherently* (equivalent to offset quadrature phase shift keying (OQPSK)).

Figure 7, which summarizes system testing conducted on the USS *Barry*, shows the results of implementation of the CMA equalization technique, . A FSK signal was transmitted through the ship structure on the DC HULLCOM channel. Figure 7(a) shows the received signal; Fig. 7(b) shows the signal after passing through the CMA equalization filter. The frequency-selective attenuation effects have been removed, restoring the signal to a constant amplitude. The modulus and phase of both the transmitted and received signal were calculated and plotted in a circular format in Figs. 8 and 9, respectively. The transmitted signal has a uniform amplitude of one. The received signal no longer shows this property after passing through the channel. The resulting demodulated waveform, while transformable into a non-zero bit stream, is sufficiently jagged to induce significant bit errors during signal restoration. The received signal was then processed using the CMA adaptive filter algorithm. Figure 10 shows the modulus and phase of the filter after it was processed by the CMA adaptive filter algorithm. The CMA adaptive filter algorithm successfully restored the received signal to an ideal modulus of one.

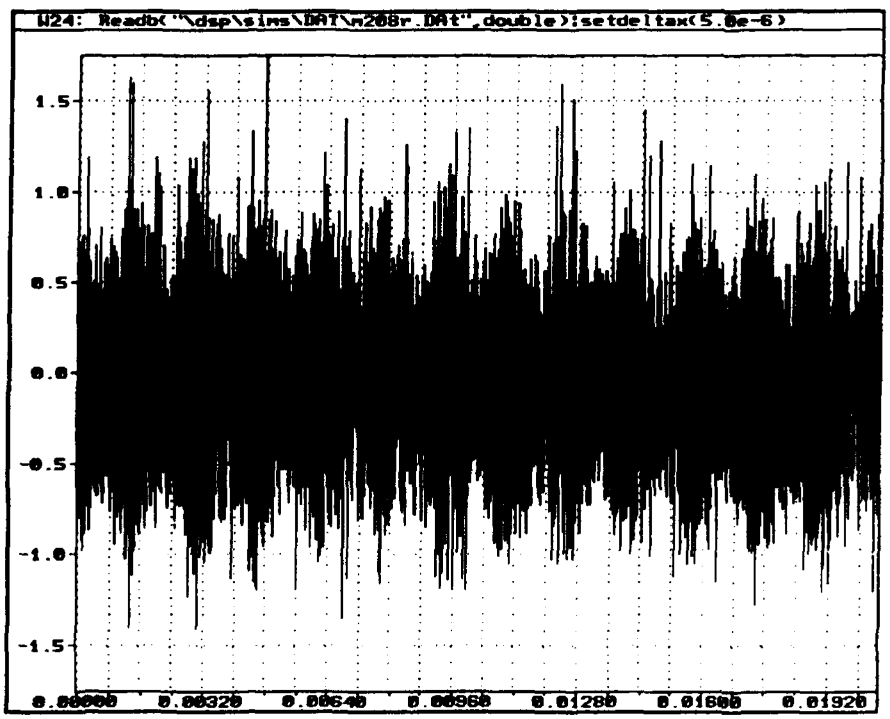

Fig. 7(a) — Received HULLCOM signal before CMA conditioning

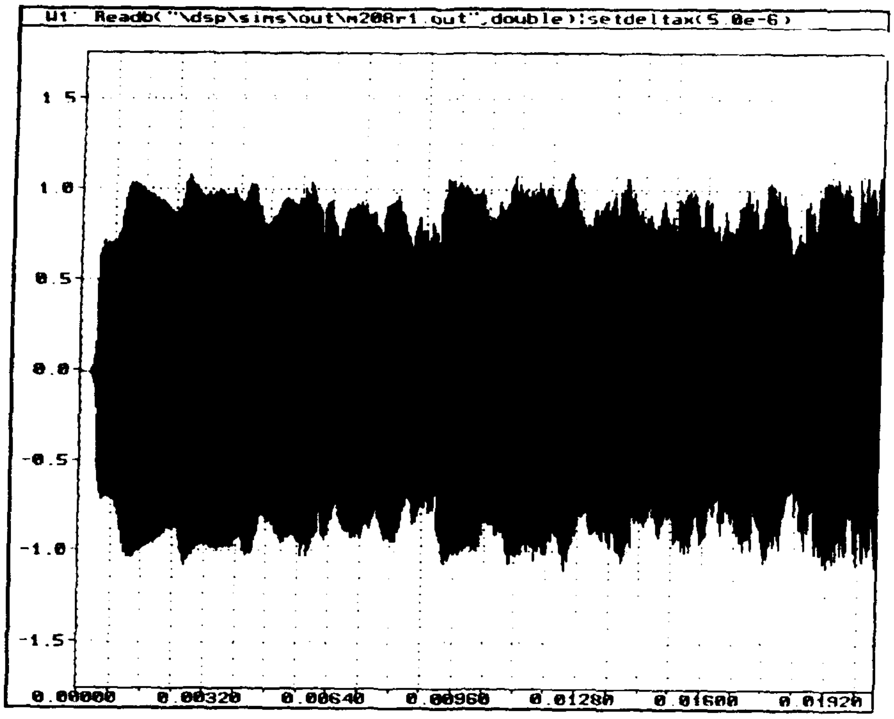

Fig. 7(b) — Signal after being processed with CMA equalization routine

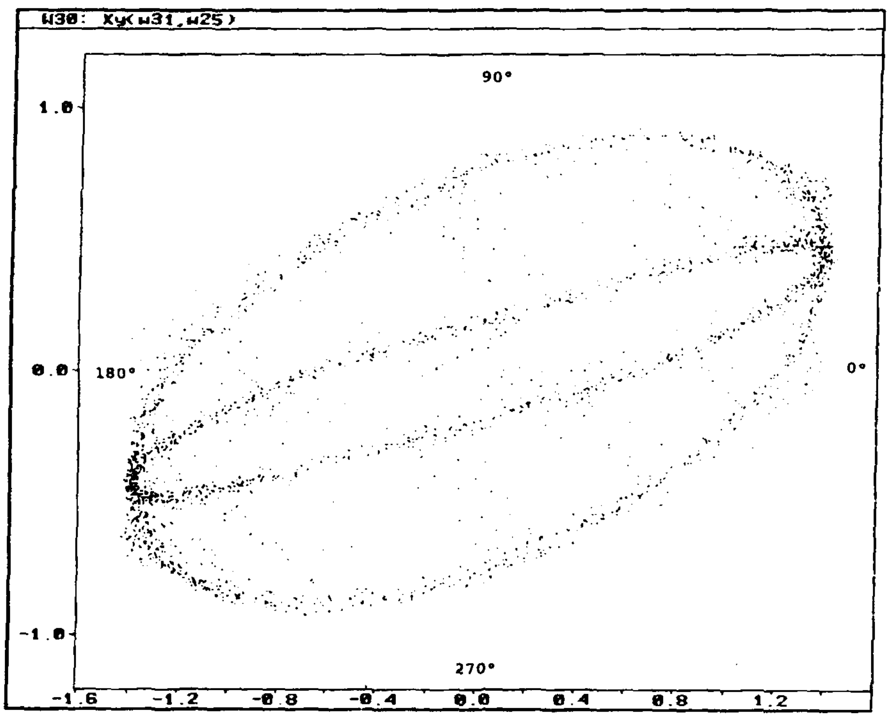

Fig. 8 — Modulus plot for HULLCOM transmitted signal

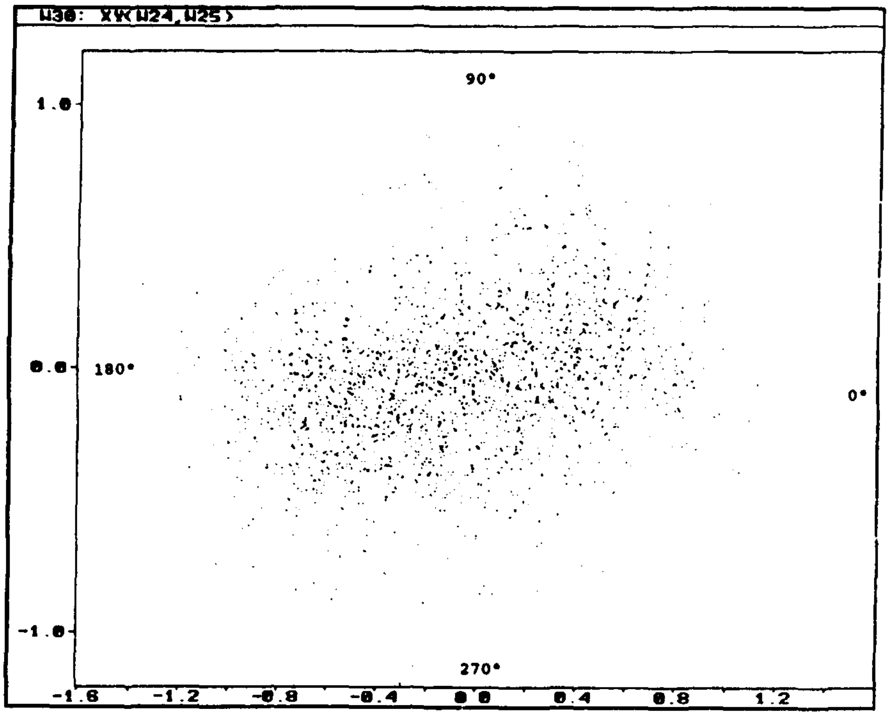

Fig. 9 — Modulus plot for HULLCOM received signal

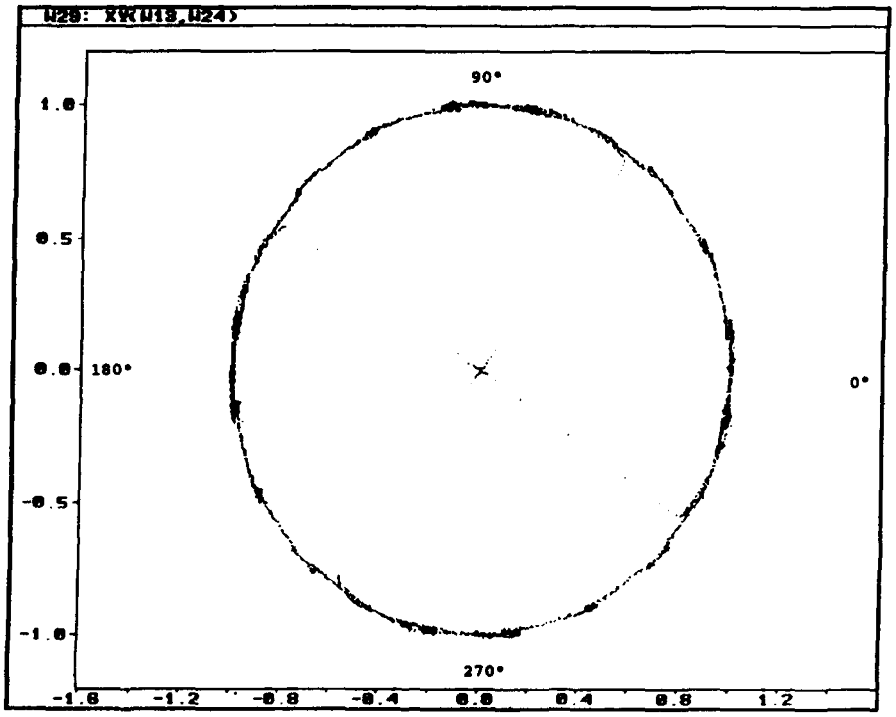

Fig. 10 — Modulus plot for HULLCOM received signal using constant modulus algorithm (CMA)

SUMMARY

The objective of this summary is to discuss the current developmental status of DC HULLCOM, assessing its ability to provide the reliable communication of damage control information (voice, casualty management information, and text messages) during damage control operations. Recommendations for system implementation are provided in the next section to aid in assessing the system's ability to meet the operational requirements. Design options that could be used to enhance or improve these operations are discussed. These assessments are based on an in-depth R&D effort, ship testing and demonstrations, cooperative R&D efforts with industry, and knowledge of damage control practices and procedures.

System Configuration

The recommended DC HULLCOM system configuration provides a permanent, noninterruptible acoustic communications network for data and voice between fixed terminal nodes in the manned Repair Lockers (RLs), Damage Control Central (DCC), Engineering, and Bridge stations (Fig. 11). This permanent configuration of fixed terminals will operate as a stand-alone system. Each terminal node consists of a portable acoustic communications transceiver interfaced to a standard IBM-compatible computer terminal with off-the-shelf data acquisition and signal processing cards installed (Fig. 12). The terminals use state-of-the-art signal processing hardware and software that maintains an noninterruptible and highly reliable communications capability for the dynamically changing shipboard acoustic environment. The fixed station network will provide total ship coverage, allowing access from portable stations attached to any major ship structural member (Fig. 13). Because nodes of the network are connected by acoustic links through the ship structure, redundant channels of operation exist. This redundancy and the noninterruptible nature of HULLCOM acoustic signals will allow the system to continue to function in the event that one or more of the nodes are removed from operation, through damage or equipment malfunction.

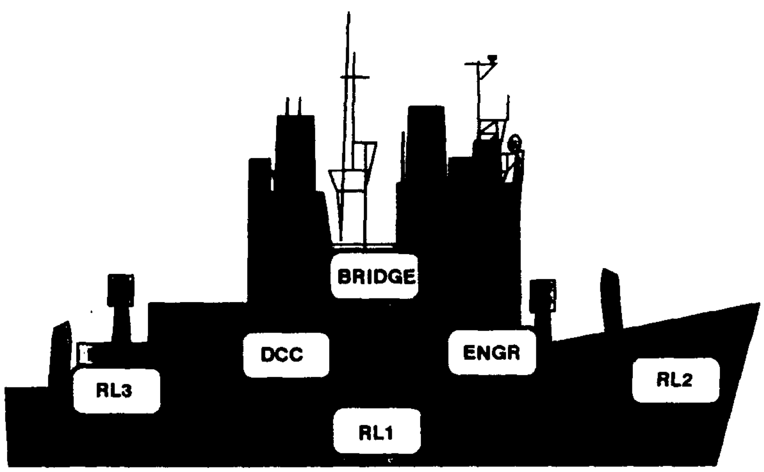

Fig. 11 — DC HULLCOM communications network

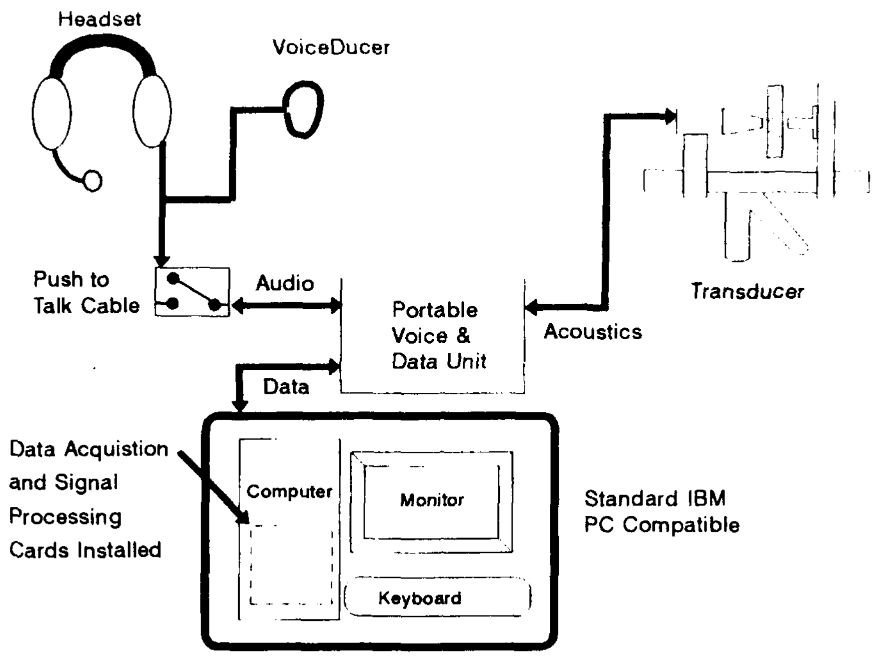

Fig. 12 — Fixed communications station

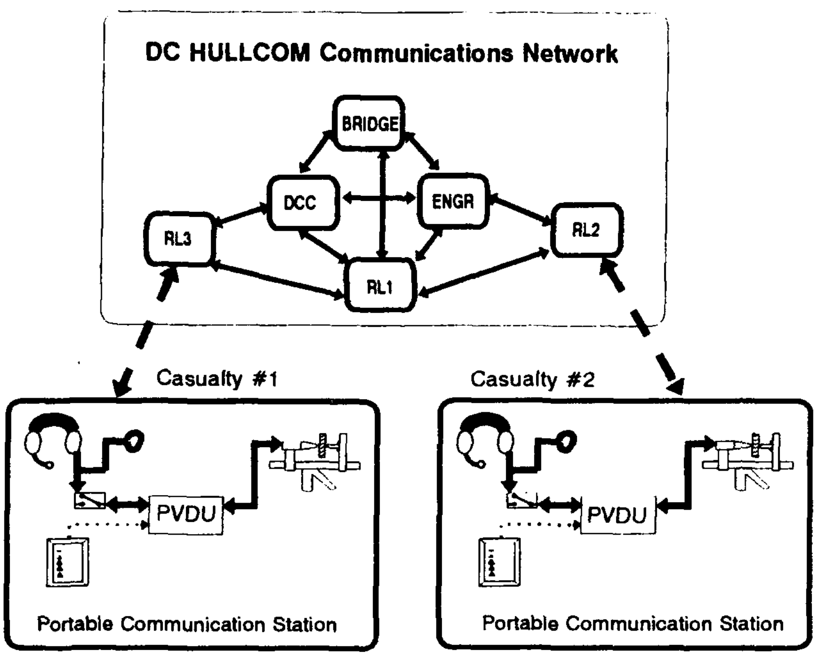

Fig. 13 — Portable communications station interface

An identical portable HULLCOM transceiver interfaced to a handheld data entry and display terminal will operate from the casualty scene, independent of the fixed system (Fig. 14). Casualty reports and voice will be transferred from the casualty scene, on temporary communications links, to the nearest fixed terminal node. All nodes of the communications network will be automatically updated. The portable station will have the ability to be easily relocated and attached to any major structural member of the ship. On-scene leaders and investigators will move freely within and around the damage area, investigating and reporting damage and casualties on untethered, portable, handheld terminals. The reports and communications are relayed to the portable HULLCOM transceivers by means of an RF channel link from the portable terminals (Fig. 14). The damage reports are then sent acoustically to the nearest terminal node in the communications network. The system is capable of automatically accepting, disseminating, and updating casualty information at all fixed and portable stations. The system configuration establishes an upward flow of information from the scene of a casualty to Repair Lockers, Damage Control Central, and engineering and bridge stations. The system also facilitates the downward flow of commands to the casualty scene and accommodates command relocations when necessary without the movement of communications equipment.

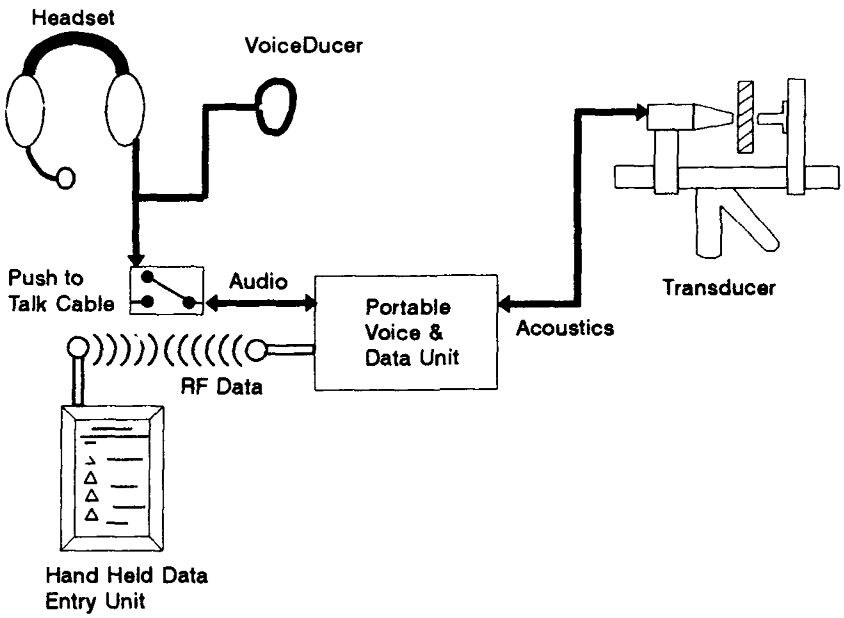

Fig. 14 — Portable communications station

Each fixed terminal node will have the capacity to provide additional capabilities to improve on-scene support to the casualty scene (i.e., ship system and compartment drawings, damage control manuals and procedures, and built-in training scenarios). The layout and complexity of a DC HULLCOM system deployed on individual Navy ships is dependent on ship size, the number of manned repair lockers, and the interface requirements to existing and future damage control systems (i.e., Integrated Ship Management System (ISMS)).

Systems Status

Communications Equipment

An optimized portable DC HULLCOM system has been implemented that takes advantage of improvements in component operation and demonstrates the ability to downsize DC HULLCOM components. The portable system provides state-of-the-art communications, implemented on multiple-layer printed circuit cards. Improvements include an optimized power amplifier design, improved receiver designs, improved squelch operation, and the implementation of an advanced form of automatic acoustic gain control (AAGC) to handle the widely varying signal input expected from acoustic propagation. This system also incorporates a digital data synthesizer (DDS) to generate the modulated HULLCOM information. The DDS uses a continuously variable sinewave generator that smoothly changes the frequency of operation to eliminate sudden level changes that produce wideband noise in the transmission of acoustic signals.

The DDS, which is integrated into the printed circuit card design, is controlled by the on-scene leader's portable handheld terminal. Casualty reports are generated on the handheld terminal at the casualty scene. When a report is ready for transmission to command locations, the handheld terminal translates the damage report into a computer file that is used to control the DDS.

A power amplifier optimizes the electro-mechanical interface to the acoustic load while providing a constant power output for changes in frequency. This amplifier is capable of delivering a maximum of 25 watts to the transducer. Three power-level settings (high, medium, and low power) are available for conserving battery life. These power levels are controlled from the front panel of the HULLCOM transceiver. A lower power output level can be used over acoustic paths that have lower path attenuations; higher power output levels are available for paths with increased attenuation. With the use of the multiple power level settings and the automatic acoustic gain control, a high-quality communications channel can easily be established.

Under certain conditions, voice communications quality can be improved by using different AM and FM transmit and receive modulation setups. The ability to manually select combinations of AM and FM transmission and reception modulation setups for voice communications has been incorporated into the new DC HULLCOM transceivers. These setups are:

- transmit AM and receive AM,
- transmit FM and receive FM,
- transmit AM and receive FM, and
- transmit FM and receive AM.

Modulation setups should be checked initially, if possible, to determine which setup delivers the highest voice quality over a particular communications path.

Acoustics

Acoustic noise emission testing on active (USS *Saratoga*) and non-active (USS *Barry* and ex-USS *Shadwell*) Navy ships indicate that large transient and continuous noise levels exist below 30 kHz in the ship structure. Acoustic wave propagation testing was conducted on the ships, on a pier at NRL facilities in Orlando, Florida, and through building structural members at NRL, Washington, DC. Wave propagation testing indicated that the attenuation in steel structures is excessively high for frequencies above 100 kHz; this agrees with acoustic theory for elastic members. The increased attenuation above 100 kHz makes these frequencies impractical for shipboard communications, because of the increased power required to achieve a reasonable system range. Therefore, the frequencies of operation were chosen to be 30 to 100 kHz.

Experiments using different technologies (piezoelectrics, lasers, fiber optics, electromagnetics) determined the feasibility of developing transducers using those technologies. Piezoelectric ceramic technology was found to provide optimum performance and increased versatility for DC HULLCOM applications. Piezoelectric transducer performance was found to be related to:

- the contact surface area of the piezoelectric element;
- the thickness of the piezoelectric element;
- the active piezoelectric ceramic composition;
- the presence of air or other impurities between the internal coupled surfaces of the transducer; and
- the hardness and stiffness of the tailmass.

The following transducer mounting characteristics were also shown to affect transducer performance:

- impedance matching of dissimilar materials that are coupled during transducer mounting;
- transducer coupling pressure;
- mounting-surface flatness; and
- mounting-surface roughness.

Initially, a broadband piezoelectric transmitting transducer was developed to operate across the entire frequency range. A smaller, lower power broadband piezoelectric transducer was used for signal reception. This system effectively established both voice and data communications at distances greater than 150 ft on the USS *Barry*. However, power requirements for the broadband transmitting transducer made it unrealistic for a portable, battery-powered system. The acoustic load that the ship structure presents to the transmitting transducer was measured and was found to vary erratically across the 30 to 100 kHz bandwidth. Attempts to improve transducer efficiency were hampered by the erratic acoustic load.

Eventually, a semi-resonant transducer approach was adopted. Six 12 kHz wide channels were established in the 30 to 100 kHz frequency range. Specifications for six semi-resonant transducer designs with integral mounts were developed, and transducers to support two of these frequencies were acquired. The transducer designs used a resonant acoustic horn to couple to the ship structure. The transducer was housed in a squeeze-grip mounting mechanism to greatly simplify installation. The semi-resonant design increased the acoustic efficiency significantly and reduced the transmitting power requirements by more than an order of magnitude. This design also increased the receiving sensitivity by more than 15 dB. To further increase the sensitivity of the receiver, an amplifier was added to the transducer, immediately after the piezoelectrics. Compared to a system that amplified the signal at some distance (cable length) away from the piezoelectric ceramic element, this amplifier reduced noise levels and RF interference and increased sensitivity.

Human Engineering

DC HULLCOM implementations are required to interface effectively with the damage control personnel, clothing, and equipment currently used for shipboard damage control. This includes operation by gloved, OBA-masked damage control scene leaders, and investigators operating at or near the damage scene. On-scene personnel using HULLCOM equipment must be able to generate, update, and manage casualty reports, and maintain voice communications with command locations, while remaining mobile in and around the casualty area. The equipment must not hinder performance of their duties. The physical size, shape, and weight of the equipment are important factors. More importantly, the equipment must interface with the damage control personnel and their protective clothing, and must perform intended functions in the intended environment.

Technology currently exists to equip the damage control scene leaders and investigators with handheld communications and display terminals which are lightweight, compact, and easy to use. Figure 15(a-d), are artist conceptions of portable handheld communications terminals, developed through discussions with industry, active Fleet personnel, and students and instructors of the Surface Warfare Officers School (SWOS) in Newport Rhode Island, and through technology assessments conducted by NRL.

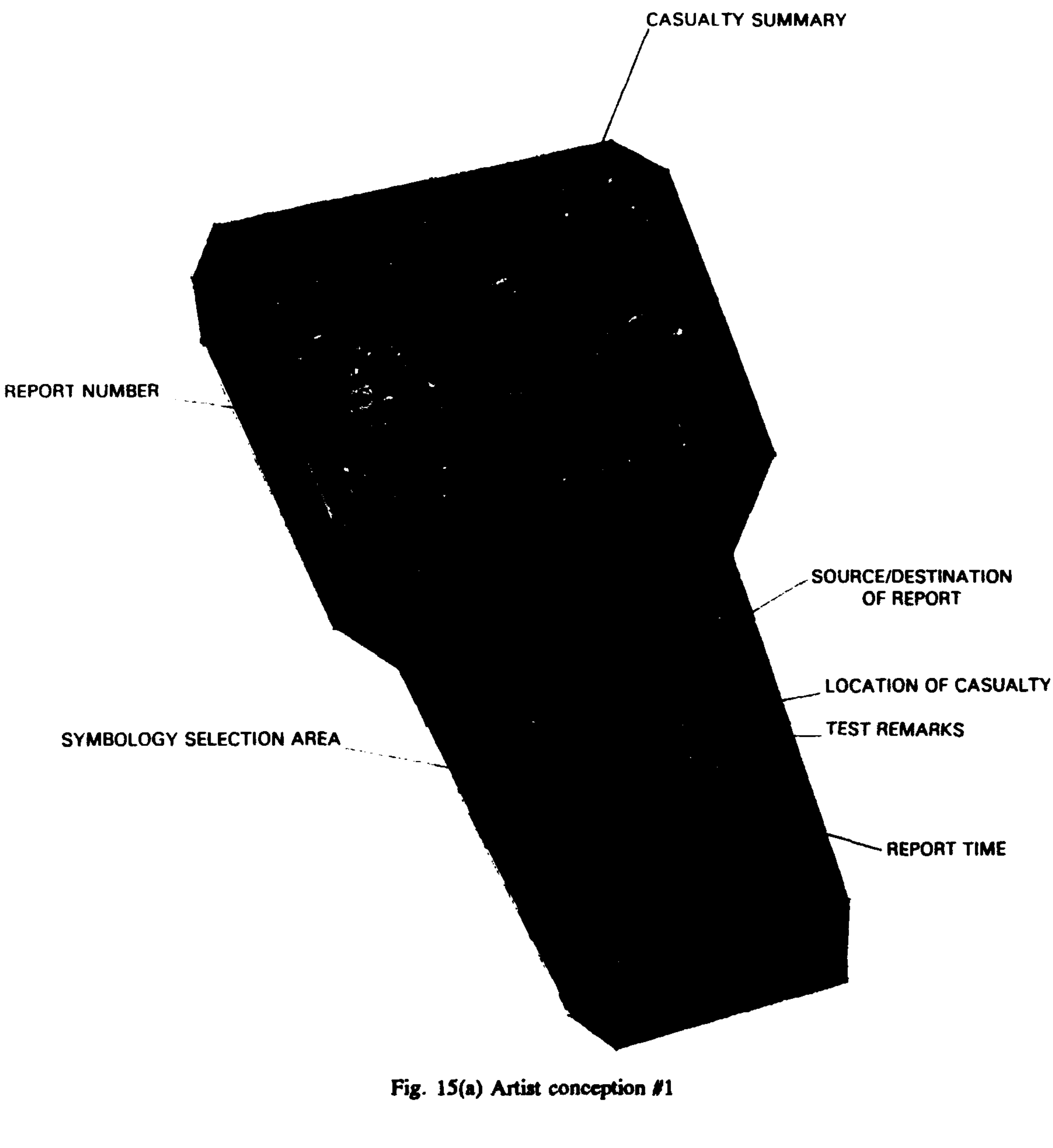

Fig. 15(a) Artist conception #1

Fig. 15(b) — Artist conception #2

Fig. 15(c) — Artist conception #3

Fig. 15(d) — Artist conception #4

RECOMMENDATIONS

1. It is recommended that the new, and as-yet-untested, ADM DC HULLCOM system be supported for shipboard testing on an active Fleet ship to determine the ship communication coverage, data and error rates, signal processing effectiveness, voice intelligibility, and system reliability.

2. It is recommended that development of the voice and data system be completed and that it be thoroughly evaluated on an active Navy ship. Navy research and development has yielded significant advances in the technologies necessary to support the implementation of a highly survivable communications system for shipboard use. The current state of the HULLCOM equipment demonstrates that a survivable communications system implementation is possible, and that implementation costs could be much lower than previous estimates. A properly configured and permanently installed acoustic system, integrated with current ship communications, has the potential to significantly improve ship survivability.

3. It is recommended that continued development of this technique be funded, and that advances be used to improve HULLCOM and WIFCOM shipboard communications. Many Navy systems, such as sonar and communications (HULLCOM and WIFCOM [wire-free communications on electromagnetic systems, currently being deployed on Navy ships]) are adversely affected by multipath interference. Multipath causes "dead zones" in communications coverage. One of the technology areas advanced by DC HULLCOM R&D was the use of adaptive equalization filtering using a constant modulus algorithm (CMA) to remove the effects of multipath on HULLCOM signals transferred through the steel framework of Navy ships.

4. It is recommended that DC HULLCOM use an RF channel link for on-scene personnel between the handheld data entry and display terminals and the portable HULLCOM acoustic communications equipment. This RF link will allow the on-scene leaders and investigators to remain mobile, to operate untethered to any equipment.

5. It is recommended that DC HULLCOM implementations include the use of bone-conduction microphones in high-noise environments and with DC/FF protective clothing. This option offers the ability to operate hands free. Because HULLCOM equipment must be operated in high-airborne-noise environments and must interface with personnel dressed out in DC/FF protective clothing, the bone-conduction microphone was incorporated into the voice and data HULLCOM communications equipment. The bone-conduction microphone picks up speech through the bone in the operator's ear canal, using a device much like a hearing aid. This device is inserted in the operators ear and allows voice communication system without the use of a handheld microphone. The ear pickup device does not pick up and transmit ambient noise. This provides reliable operation in high-noise environments. A voice-operated transmit (VOX) mode can be used to key the transmit button automatically when the operator speaks, allowing hands-free operation.

6. It is recommended that a custom-built, handheld, data entry and display terminal dedicated to damage control operations be designed, specified, and acquired to support communications from the damage scene to command locations. An available off-the-shelf touch screen terminal should be acquired to demonstrate and evaluate the on-scene casualty reporting capability. The terminal could be programmed (inexpensively) to interface with damage control personnel through a menu-driven software program. This would permit the operator to complete a damage or casualty report (Fig. 16) by touching the screen with a stylus to select from options displayed on the screen. Most pen-based terminals recognize alphanumeric characters written on the screen by the operator. Once recognized, the terminal replaces the handwritten characters with computer-generated characters, indicating that the terminal had recognized the proper handwritten character. Damage reports can be generated on the touch screen terminals and then transmitted acoustically to the command centers by the portable HULLCOM communications equipment.

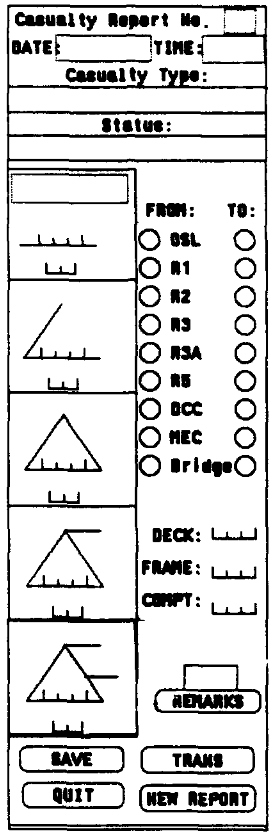

Fig. 16 — Recommended custom-built terminal

7. It is recommended that permanently mounted acoustic transducers be developed for use in all command locations to substantially increase existing power-handling capabilities and improve acoustic receiver sensitivities. It is further recommended that increased power output generating capabilities of up to 100 watts be implemented and permanently installed in all command locations for improved communication capabilities in damage control situations.

8. It is recommended that the communications technology used in HULLCOM be tested and evaluated to determine additional Navy applications.

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