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DEVELOPMENT OF THE SENSOR FOR ENVIRONMENTAL ASSESSMENT (SEA Buoy)

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This paper presents background on the research and development that has led to the concept of the Sensor for Environmental Assessment (SEA Buoy). It begins with references to initial data gathering missions under the Harsh Environment Program (HEP) and then proceeds to describe the Air-Expendable Multi-Parameter Environmental Probe (AEMEP), the Tactical Acoustic Measurement (TAM) sonobuoy, and the TAM Decision Aid (TAMDA) programs. It outlines the achievements of those efforts and then describes the progress made and status of the SEA buoy. The characteristics, features, and capabilities of the first article test units delivered in June 2009 are discussed. This includes a summary of the in-buoy signal processing features, a discussion of the acoustic dynamic range, and a review of the present and potential future capabilities of the stores module. A brief summary of the testing to date (April 2011) is also included. A recommendation is provided to continue the development of the SEA buoy as a crucial tool in the effective use of active and passive acoustics in Air ASW.

I. INTRODUCTION

Early in 1993, the Naval Air Warfare Center Aircraft Division, in Warminster, Pennsylvania, (NAWCADWAR) initiated an effort to obtain environmental information that affects the execution of an anti-submarine warfare (ASW) exercise using a P-3 aircraft. A dedicated flight was conducted during which a series of air expendable bathythermographs (AXBTs) as well as passive sonobuoys and active acoustic sources were launched to obtain measurements of acoustic ambient noise, transmission loss, monostatic and bistatic reverberation, and temperature versus depth profiles of a predefined ocean area to better predict acoustic detection performance. These measurements, conducted at a number of sites, became known as the Harsh Environment Program (HEP), primarily because they were conducted in shallow water regions with dynamic acoustic characteristics.

The measurements, providing data that were used as inputs to acoustic prediction models, were often made days before the exercise but still provided relatively timely information to assist in planning sonobuoy loads for the aircraft as well as sonobuoy deployment spacing and settings and estimate sonobuoy field detection performance. The HEP program evolved into the Bear-Trap Environmental Characterization Program (BTEC) and was later renamed the Battlespace Tactical Environment Characterization Program, maintaining the same acronym. Over 123 reports compiling processed information from these data acquisition missions were eventually produced and are archived at Naval Air Warfare Aircraft Division Patuxent River, Maryland (NAWCADPAX).

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14. ABSTRACT

This paper presents background on the research and development that has led to the concept of the Sensor for Environmental Assessment (SEA Buoy). It begins with references to initial data gathering missions under the Harsh Environment Program (HEP) and then proceeds to describe the Air-Expendable Multi-Parameter Environmental Probe (AEMEP), the Tactical Acoustic Measurement (TAM) sonobuoy, and the TAM Decision Aid (TAMDA) programs. It outlines the achievements of those efforts and then describes the progress made and status of the SEA buoy. The characteristics, features, and capabilities of the first article test units delivered in June 2009 are discussed. This includes a summary of the in-buoy signal processing features, a discussion of the acoustic dynamic range, and a review of the present and potential future capabilities of the stores module. A brief summary of the testing to date (April 2011) is also included. A recommendation is provided to continue the development of the SEA buoy as a crucial tool in the effective use of active and passive acoustics in Air ASW.

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In generating these reports, data from individual sonobuoys, each having different sensitivities and very limited acoustic dynamic range, were combined to synthetically produce an extended acoustic dynamic range, enabling the presentation of plots of transmission loss and mono-static and hi-static reverberation over the entire area of interest. This synthesis was labor intensive and time-consuming and was also subject to variations due to sonobuoy relative positions. It became apparent that the data acquisition techniques would benefit by a more versatile and comprehensive measurement tool.

Air-deployable Expendable Multi-parameter Environmental Probe (AEMEP) Program

As a result, and not long after the initial HEP measurements, another program was initiated at NAWCADWAR, the Air-deployable Expendable Multi-parameter Environmental Probe (AEMEP) Program.

Under a Small Business Independent Research (SBIR) announcement issued by the Naval Air Systems Command (NAVAIR), the Navmar Applied Sciences Corporation (Navmar) began a technology development in 1995. Phase I of that SBIR defined the details of various sensors for an environmental probe called AEMEP. Successful completion of Phase I[1] led to a Phase II technology demonstration effort begun in December 1996. This technology demonstration focused on four of the twelve AEMEP environmental measurement parameters: bottom sediment type, ocean water optical properties, ocean current profile, and surface current (this latter as measured by sonobuoy-compatible GPS technology). An at-sea demonstration was conducted during the Littoral Warfare Advanced Development (LWAD) 98-2 exercise and was successfully completed in September 1998.

The final report for Phase II is contained in Reference 2. Successful demonstrations of prototype sensors were achieved but not in an A-size configuration; furthermore, these sensors were each separate units—the objective being the validation of the sensor measurement technique. However, indications were that A-size constraints could be accommodated for three of the techniques but not necessarily for the phased array current profiler. The phased array current profiler was an Edo Corporation development program intended to provide an ocean current profiler with a significant size and weight savings. It utilized a transducer array of several disks to form a beam to measure the Doppler shift of a return signal and thus determine the sound speed at the measurement point (depth).

Tactical Acoustic Measurement (TAM) sonobuoy Program

This led to the initiation of a Phase III program in June 2000 to develop the Tactical Acoustic Measurement (TAM) sonobuoy under the TAM Decision Aid (TAMDA) Program. The TAMDA program was driven by a Mission Need Statement (MNS); the objective of which was "to understand and exploit the environment in the conduct of tactical ASW operations through the on-scene collection and processing of environmental data pertinent to the ASW problem at hand." This program was intended to meet the requirement for improving ASW acoustic environmental data collection and *in situ* updating of tactical mission planning. It was to replace the existing AN/SSQ-36 sonobuoy, but in addition to temperature profiles, the requirements for active acoustic measurements for TAMDA were also investigated.

A buoy design was recommended (configuration TAM-I), and an Advanced Development Model (ADM) prototype was planned for FY-02. This ADM prototype featured an in-buoy signal processor (IBSP) to process all measured data and format it for transmission to ASW aircraft or a Tactical Support Center (TSC). It also included omni-directional and directional acoustic sensors, a sound velocity profiler, four Mini-SUS (small impulsive acoustic source 60 grams) sources, and VHF/UHF (very high frequency/ultra high frequency radio links), and IRIDIUM (satellite phone system) transceivers. The goal of A-size was almost, but not quite, achieved.

Acoustic signal source alternatives were explored for the purpose of obtaining measures of transmission loss (TL) and reverberation because at that time only impulsive sources could achieve the required source levels. Finally, IBSP was also recommended as a technique to improve dynamic range.

A signal processing functional description, incorporating some of the notes from Reference 3, was prepared by Undersea Sensor Systems Incorporated (USSI). Plans called for completing the software and delivering a functioning TAM buoy with IBSP, and at-sea data collection was planned for FY-03.

Two tests were then conducted in the Gulf of Mexico; they successfully demonstrated the use of a mini-SUS acoustic source, the UHFNHF RF data link, an over-the-horizon (Iridium Satellite) link, and the deployment of a sound velocity profiler (SVP).

The Navy/Industry team then prepared a plan requesting $25 million to launch a full scale engineering development model (EDM) program. A contract would be issued to a sonobuoy manufacturer, and the program was to be directed by the Navy with the Yorktown Naval Weapons Station, as well as Navmar, involved in support. However, the funding was not authorized, and no further tasking was issued.

But an initiative by Navmar, requesting $4.5 million to keep the program going, resulted in an authorization of $2M through Naval Air Systems Command (NAVAIR). This effort was designated the Sensor for Environmental Assessment (SEA) Program. The deliverables included over-the-side reusable hardware to collect data in conjunction with other Navy data acquisition exercises to validate acoustic inversion algorithms (an algorithm that utilizes acoustic reverberation data to predict acoustic transmission loss). The intent was to develop a sonobuoy which can provide the desired environmental information as well as provide a long life (3 to 5 days) data gathering buoy for meteorological and oceanographic (METOC) missions and still retain the goal of making the hardware as close as possible to A-size.

Shallow Water Directional Noise Measurement Sensors

In response to another SBIR entitled “Shallow Water Directional Noise Measurement Sensors (SWDA),” a study was proposed to determine the requirements for the active acoustic environmental measurement portion of the TAM buoy. (The motivation for this work lies in the inability of historical data to enable an accurate estimate of the probability of detection for a tactical mission, such as for Air Deployed Active Receiver (AN/SSQ-101) (ADAR). TAM buoy measurements of reverberation, transmission loss, ambient noise, and sound speed profiles, combined with tactical decision aids, should reduce the error in achieving the desired detection probability.) SWAD added directional measurements of ambient noise, reverberation, and transmission loss to TAM.

The current process of collecting the desired data (as done in HEP and BTEC) is cumbersome (requiring at least 5 buoys to achieve the required dynamic range) and is costly. The study indicated that the use of a TAM buoy could cut this cost in half, would reduce the overall buoy load for the measurements (1 buoy instead of 5), and would eliminate the need for an AN/SSQ-36. TAM would also increase the area surveyed per flight, decrease the time to provide performance prediction, and improve buoy placement.

The report[4] included a table showing a variety of TAM buoy hardware configurations, dependent upon the mission, as well as a method of obtaining transmission loss information.

It also concluded that an energy source level of approximately 200 dB re 1 μPa2 in a one octave band should be sufficient to measure transmission loss and that an energy source level of about 230 dB re 1 μPa2 in a one octave band may be required to measure reverberation level to tactically significant ranges.

To compute transmission loss from reverberation measurements, several competing inversion techniques were considered. Those, and other details concerning the SWDA efforts, may be found in Reference 5.

An acoustic data acquisition sea test, SPIRAL 1, was conducted in April 2003 in water approximately 420 feet deep. Over 15 hours of data were collected on the TAMDA Acoustic Data Collection (ADC) version of the buoy. This data validated the dynamic range design, the IBSP concept, the data storage, and the selection of a 60 gram mini-SUS as the source. HEP transmission loss data along 2 directions, as well as reverberation data, was collected on the ADC buoy from 54 SUS in an effort to validate the inversion algorithm.

Alternate sound sources were demonstrated, including pressurized sound tubes, imploding glass spheres, and a sparker source, but the high sea states pre-empted the collection of acoustic data. The project also successfully exercised an IRIDIUM satellite link to transmit data, even in the relatively high sea states; collected GPS data; used the Modular Ocean Data Assimilation System (MODAS) data base to aid performance predictions; and collected over 20 hours of reverberation, ambient noise, and transmission loss data with the TAMDA Test Bed buoy. Details of this field exercise may be found in Reference 6.

In August 2003, the SPIRAL 2 sea test7 was conducted and achieved the following objectives:

1. It demonstrated the ability to perform a tactical calculation (computed first with historical data prior to the test) in less than one hour with on-site TAM-collected data.
2. It demonstrated an RF commanded deployment of a sound speed probe as well as a dummy mini-SUS.
3. It successfully exercised a tactical decision aid using the on-site collected data.
4. It successfully deployed a near-bottom source string and data was collected from 13 small (1. 3 gram) sources.
5. It collected additional ambient noise and reverberation data (from 60 gram sources) for SWDA to validate the acoustic subsystem design.

Shallow Water Bottom Characteristics Measurement Sensor

In response to another SBIR (NO1-017), an independent study was conducted to investigate the feasibility of making high resolution measurements of bottom characteristics in shallow water to improve the performance prediction for active sonar in shallow water. Conceptual designs for a Shallow Water Bottom Characteristics Measurement Sensor (SWBCMS) were explored with a view towards supporting several systems of concern, including ADAR (AN/SSQ-101), ALFS (AN/AQS-22), and DICASS (AN/SSQ-62).

The results of the Phase I SWBCMS were reported on in Reference 8. It was concluded that the SWBCMS measurement system, whereby two closely spaced buoys with sources and receivers placed close to the bottom, could measure bottom back-scatter versus grazing angle and bottom loss versus grazing angle in shallow water at very low angles needed for performance prediction at long range. Other successful tasks included: the determination of source level requirements, the determination of source and receiver geometry with a recommended design, a packaging study which indicated that the system could be built within an A-size weight and volume, and an in-buoy signal processing study which also indicated that requirements could be met.

A Phase II study was authorized since this effort was in direct support of the TAM development program. However, funding constraints limited the amount of effort that could be devoted to the implementation of source measurements to be obtained during field testing. The program eventually was suspended due to its integral dependence upon the successful continuation of the TAMDA program.

II. SENSOR FOR ENVIRONMENTAL ASSESSMENT PROGRAM

Funding was received in April 2006, and the SEA sonobuoy project (a follow-on from TAMDA) proceeded to build upon the experience gained in the programs described in the background above. Several decisions were made concerning design changes and goals.

The desired frequency band was expanded to include 62. 5 Hz through 8 kHz, and additionally, it was further segmented into 1/3 octave bands rather than full octave bands.

The sound speed information would be extracted from a temperature probe which was to consist of a string of about 25 point sensors deployed from the surface float and able to provide continuous measurements of sea water temperature at specific depths. In addition, a conventional descending temperature probe such as those employed in AXBT's would be deployable from a stores module.

The stores module was also to be capable of deploying four mini-SUS in one of its design configurations to measure TL and reverberation.

The IBSP would be redesigned to handle the 113 octave bands but would be programmed in conventional C++ Code so that design variation flexibility, driven by different mission requirements, could be easily implemented.

One of the most important goals was to achieve a large dynamic range. This would provide the ability to measure transmission loss as a function of range from data obtained from the initial high energy level of a nearby source to the low level signals arriving from long distances; it would also allow the recording of acoustic reverberation as it decayed from a high energy level nearby source to that arriving many seconds or even minutes later. A goal of 120 to 130 dB was deemed extremely desirable. This goal was achieved and demonstrated in SWAD utilizing two staggered analog channels which were each converted to 16 bit digital data (98 dB) each and combined into one 130 dB data stream.

Design

In the three years that elapsed from receipt of funding until first article delivery, the design described below evolved. A preliminary space allocation was developed early and remained the baseline design, since the volume layout (Fig. 1) indicated that the planned components would eventually be accommodated in the classic "A-size" sonobuoy form factor.

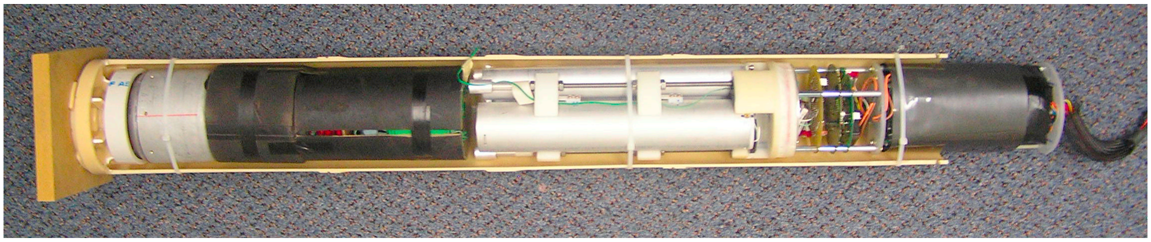

Fig. 1 – SEA Buoy Preliminary Layout

During configuration deliberations, a variety of stores module concepts were explored. Eventually, the most appropriate design (designated Mod 0, shown in Fig. 2), was fabricated and tested. This included the development of a reliable stores release concept.

In the final configuration, three hardened surface floats were to be used to house all the antennas for the SEA buoy during Over-The-Side testing.

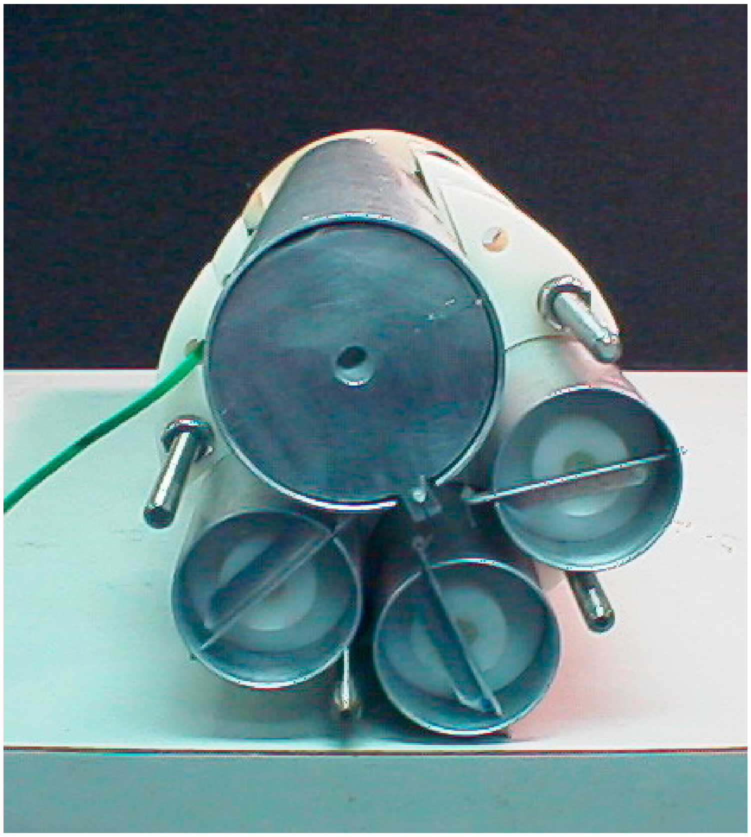

Fig. 2 – Stores Module Configuration of one AXBT Tube and three Mini-SUS Tubes

Non-explosive Alternative Sources

Previous studies had indicated that a relatively high acoustic source level would be required to capture the transmission loss and reverberation data needed to determine the bottom characteristics needed for performance predictions. Although such sources, as Navy standard SUS, exist, the SEA application would require physically smaller sources in order to fit several of them within the planned "A"-size design. During the TAMDA program "mini-SUS" (60 gram) were developed and could be used for SEA. However, there was a desire to explore the possibility of unconventional and non-explosive sources. Several concepts were investigated. Testing of a technique and device for rapid gas generation to produce an acoustic pulse was conducted. Results indicated that source levels would still fall slightly short of the desired strength for the low angle transmission loss measurements. For the present, a version of the mini-SUS still remains the most promising in terms of source level.

Temperature Sensor String

To determine the feasibility of using COTS sensors for the SEA Buoy, the basic ADAR cable pack was initially considered as a host for the string itself, and a design was formulated (see conceptual design in Fig. 3). Thermistors, along with solid state digital sensors, were assembled into a set of nodes, spliced into the cable, and potted. In testing, the adhesion of the potting compound surrounding the temperature nodes to the surlyn jacket material of the standard sonobuoy cable was suspect. Eventually, that was corrected using another potting, "Scotchgard", and was further improved by designing slightly smaller nodes. The selection of the appropriate potting compound, as well as the development of the potting technique, required several iterations.

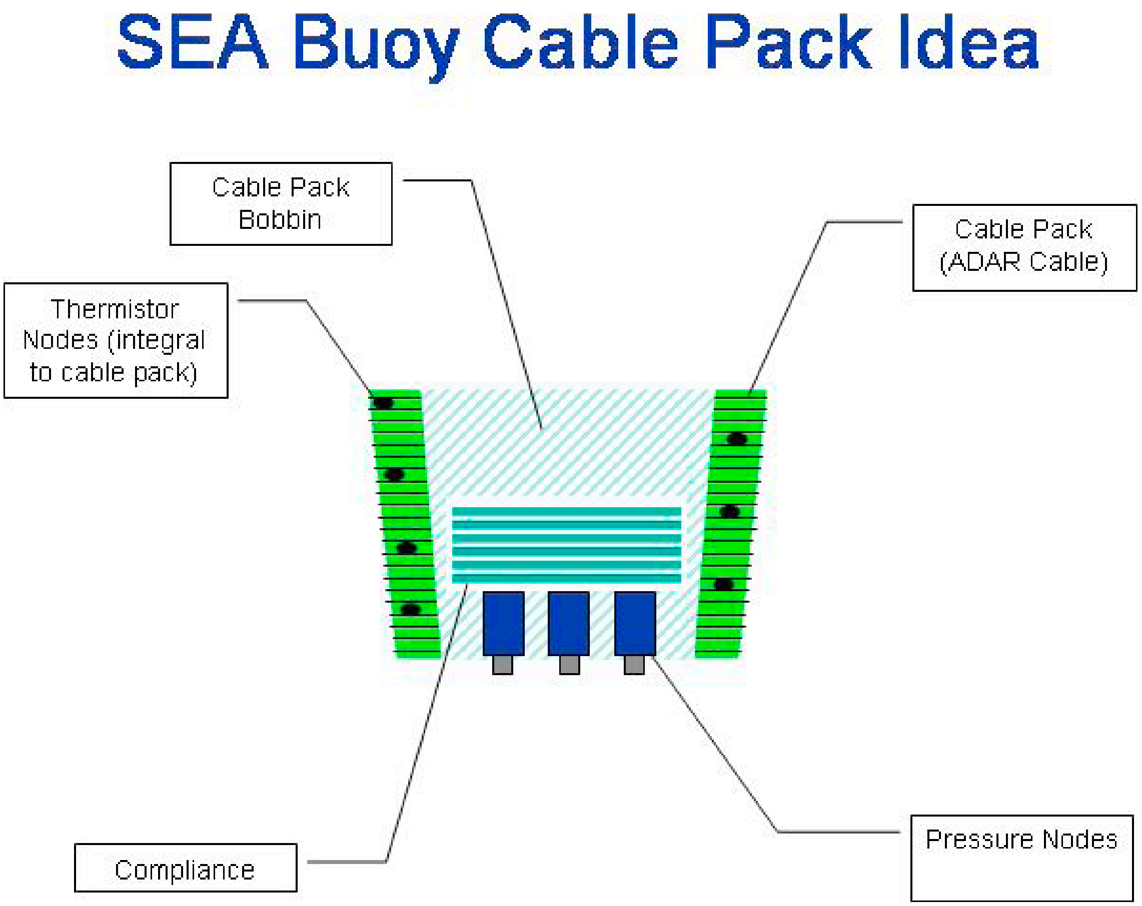

Fig. 3 – Concept for the Temperature String hosted in an ADAR Cable Pack

At the Naval Sea Systems Command Sonar Test Facility, Seneca Lake, New York, in December 2006, a 10-element temperature sensor line was deployed into the water to demonstrate the node design. This included the physical layout, power and signal operation, integrity of potting, and signal sampling technique. (The final temperature sensor string design included 25 nodes and 500 feet of integrated cable. Additional cable nodes could be added and cable length could be adjusted as the design evolved and as packaging constraints permitted.) Readings from the thermistors were recorded and compared to those obtained with the reference bathythermograph (B/T} used at the lake. Multiple deployments were made, and the system withstood the associated handling; no leaks were encountered, and the data showed excellent correlation with the reference B/T data.

By using parasitic power and a water ground, only one conductor on the sub-surface cable would be required; however, the water ground needed to be tested, as well as the effect of voltage drop over long cable runs. Tests were then conducted using the water path as a signal ground, but results indicated difficulties with noise. An additional test was then performed in salt water off the coast of New Jersey. A short length of cable, approximately 10 feet long, successfully conducted data with no problem, but lengthening the cable to 50 feet introduced significant noise, and when the cable was lengthened to 100 feet, usable data was not transmitted through the cable. The cable was replaced with another containing four conductors. This places the temperature data on two separate conductors and isolates them from other system components and their attendant noise. Using the new cable and circuitry, a full 500-foot long temperature string and cable was built for subsequent testing.

The SEA buoy cable response was evaluated with the Free Floating 2D Extensible Cable (FF2E) computer model using the RESOC* current profiles. The FF2E is a two-dimensional steady state computer model of a free-floating cable with various body masses included in the system. The model predicts buoy drift speed, surface float draft, cable shape, stretch, and tension. It includes ocean current effects and wind effects on free floating systems. One of the inputs is from RESOC (a series of studies related to Research on Sonobuoy Configurations) current profiles. It was concluded that adequate depth estimation was achieved with no sensor depth input for the 90% RESOC Profile (worst case 2-D deep water shear profile), and that there was little reduction of depth error when multiple tilt sensor inputs were included. However, it was recommended that a depth sensor be mounted near the DIFAR element to verify proper deployment and to aid in the estimate of the cable scope, cable angle and element locations in the event of unusual current profiles.

Winding, packaging, and deployment techniques, compatible with the buoy requirements, were developed. Constraints include the requirement that none of the nodes become entangled with each other during deployment and that there is sufficient cable pack integrity and tension to maintain an intact spool prior to deployment yet not be too tight to inhibit smooth release. The cable strings were wound with an adhesive between layers to provide holding force. All sensors were arranged to be packed at one end, allowing a smooth deployment. In-laboratory payout testing was performed on six spool designs, and for the final design, a maximum of 3 pounds of load spikes were recorded (matching the nominal AXBT probe descent rate of about 5 feet per second), providing confidence in a smooth payout. Subsequent successful testing was conducted at the quarry.

In summary, temperature string designs have gone through a number of iterations, but the design has been firmed. Hardware selection and electrical signal issues (noise, due to grounding, as well as the ability to drive the full cable length) have been discovered and treated. Embedding and potting the sensors into the cable required several design changes. Implementation and design of a mechanical deployment concept also evolved through several iterations and a successful in-laboratory test has been performed.

Battery / Power Supply

An initial assessment of the power budget for the SEA buoy was compiled by combining estimates for the various subsystems, which included that needed for the surface float (radio receivers and transmitters), the acoustic source requirements and data collection, the sound speed data collection (temperature string), and the IBSP. These requirements can be met with a variety of batteries or battery chemistry (alkaline or nickel metal hydride) in AA, C, or D size.

The advantages of alkaline batteries are their low cost, safety, availability, and relatively high capacity, while their disadvantages include the decaying voltage during discharge and their non-rechargeability. Nickel metal hydride batteries are rechargeable; they are also relatively safe and available and have a much steadier voltage versus time curve, but they have less power capacity and require a higher initial cost. Another issue concerns the packing density of the various battery sizes—the ultimate goal is a buoy within an "A"-size configuration. Without that constraint, the Nickel Metal Hydride D-size battery should be chosen; otherwise, the C-size alkaline batteries should be used.

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* Research on Sonobuoy Configurations (RESOC) was a program to explore a variety of sonobuoy-related technology. One of the tasks was to develop a standard set of water current profiles using sets of data from deep water sites obtained from around the world. These profiles were then combined statistically to produce a set which represented a percentage of some average current profile to be expected under normal operating conditions. These RESOC Current Profiles were then used as environmental inputs to computer models evaluating the mechanical behavior of devices suspended in the water.

Lower Electronics and Acoustic Sensors

The SEA Buoy lower electronics package consists of acoustic sensors, a magnetic compass and signal conditioning, and analog-to-digital conversion circuitry. It utilizes the hydrophones and the lower unit enclosure from an AN/SSQ-53E sonobuoy for its acoustic sensors. All the original electronics were removed and replaced with custom preamps, sonic amplifiers, digitization electronics, digital compass, and line driver. A block diagram is included as Fig. 4.

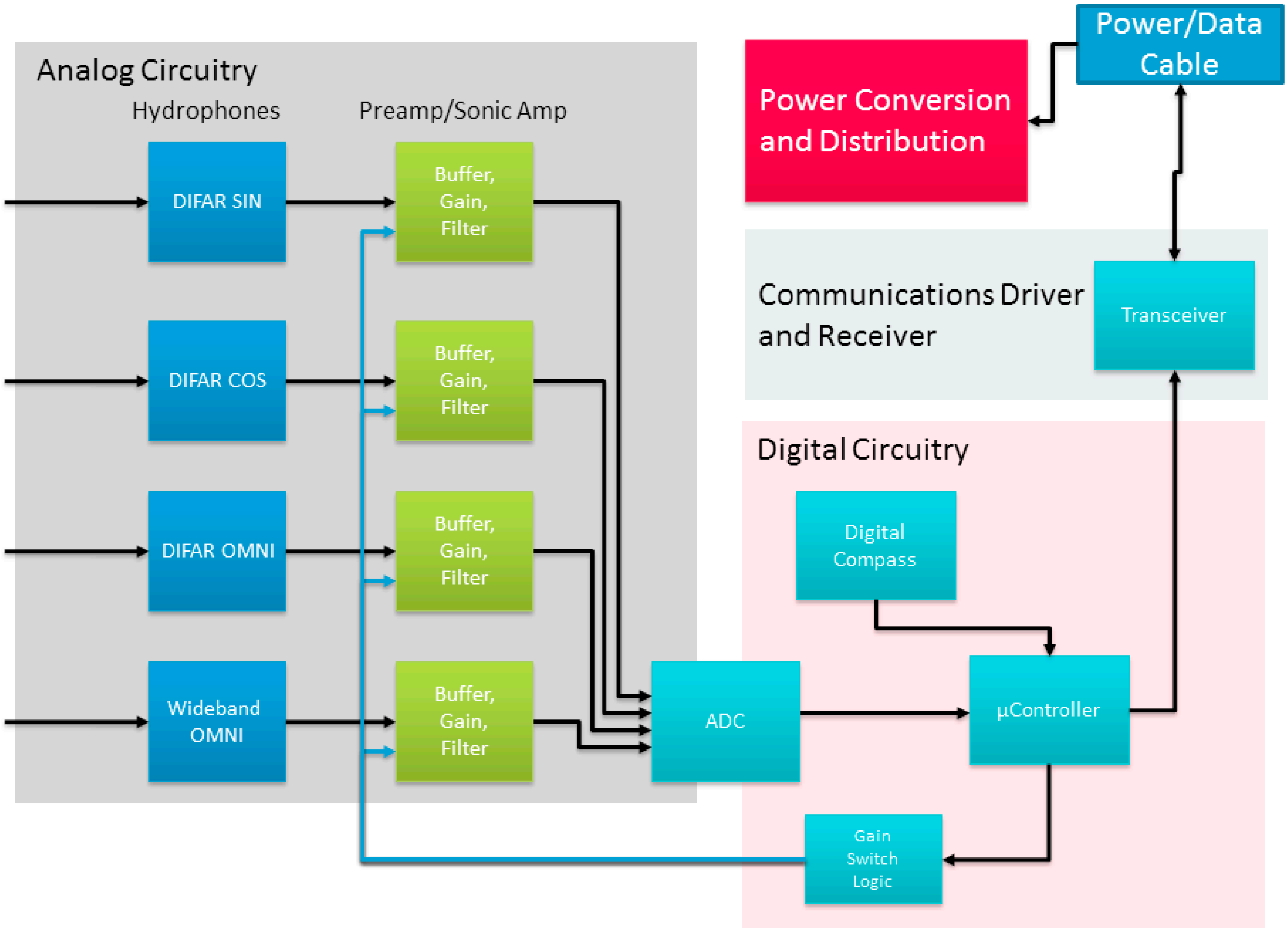

Fig. 4 – Functional Block Diagram of SEA Buoy Lower Unit Electronics

The system will provide directional acoustic data in the frequency range from 62. 5 Hz to 2. 0 kHz and omni-directional acoustic measurements from 62. 5 Hz to 8 kHz. (The DIFAR omni has had its pre-amp replaced with two amplifiers to accommodate the full SEA band, one for 2. 0 Hz to 2. 0 kHz and the other for 2. 0 kHz to 8. 0 kHz). Data is processed in 1/3 octave bands.

The requirement for a wide dynamic range is achieved with a dual gain amplifier circuit. After exploring a number of designs, the final implementation incorporates a Navmar designed variable gain amplifier for hydrophone outputs to the signal conditioning and digitization unit.

Communications between the lower and the upper units is via the hard wire, which also contains the embedded temperature sensors. Thus, isolation must be preserved between the power to the sensors, the digital sensor output data, the power down to the lower electronics, and the returned digital acoustic data. When the lower electronics is turned off, the T-string can be interrogated successfully. This requires disconnecting, or grounding, the upper connection.

The lower unit electronics is supplied with a nominal 60 volts (it is capable of handling from 18 to 72 volt inputs) from the upper electronics and converts this voltage to the levels required by the various circuits.

The Power/Data Cable which provides communications from the upper unit also provides acoustic data from the lower unit. The Transceiver uses the RS485 protocol to provide a noise-resistant and high bandwidth differential digital link between the upper and lower units. The power board (Fig. 5) then provides regulated DC outputs of 1. 8, 3. 3, and 5 volts as well as+/- 12 volts.

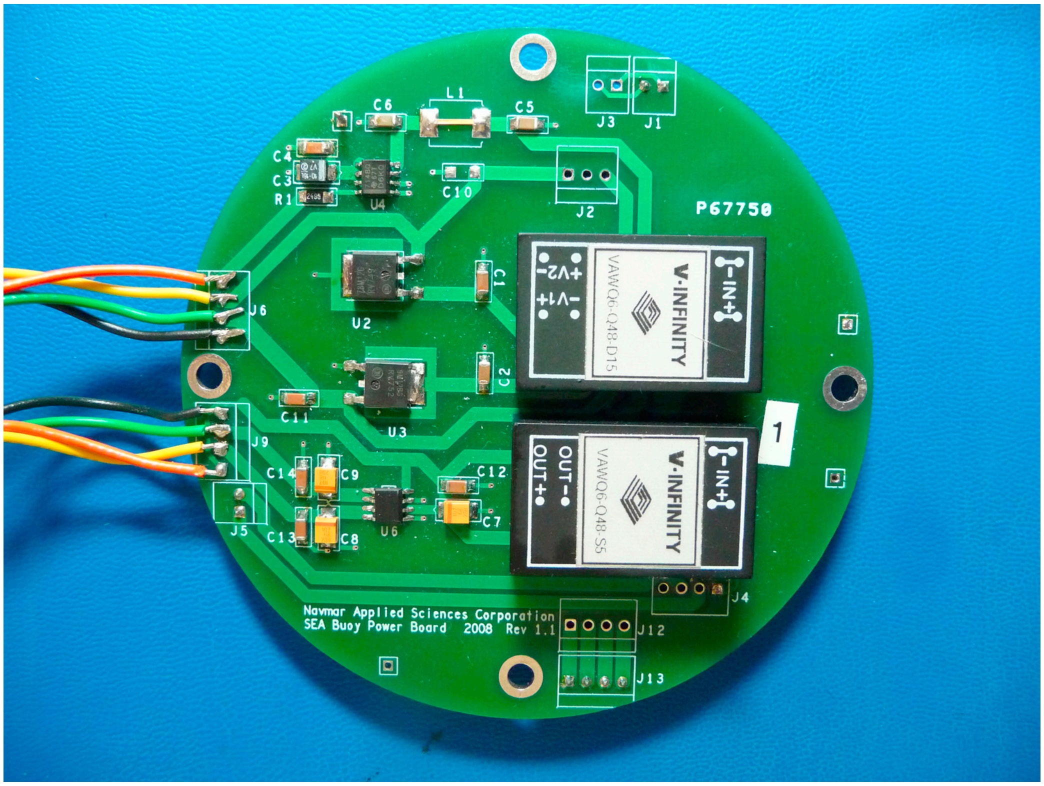

Figure 5 – Photo of Top View of Power Board

A microcontroller (µC) manages the operations of the lower electronics. It handles commands from the upper unit to change dynamic range modes—a high sensitivity mode for collecting ambient noise readings or a low sensitivity mode for capturing reverberation signals and measuring transmission loss. Upon receiving the mode command, the µC outputs a logic signal to the Gain Switch Logic to set the amplifiers to the correct gain levels. The µC reads the 24-bit Analog to Digital Converter (ADC), which digitizes the analog hydrophone signals, compresses them from a 24-bit value to a 16-bit value, reads the compass bearing from the Digital Compass, generates data frames that encapsulate the hydrophone data samples and compass value, and transmits the frames up the Power/Data Cable to the IBSP for processing. Analysis of the averaging process indicated that down-sampling to 5kHz is adequate.

The ADC has 24-bits of resolution, which means that it can reasonably provide about 120 dB of dynamic range if it is assumed that the low end of the ADC's range encompasses about 20 dB of noise. The SEA Buoy lower unit was designed for two overlapping ranges of operation, Ambient Mode, and Reverberation or TL Mode. When a measurement Command Function Select (CFS) command is issued, the upper unit controller will set the lower unit to the corresponding mode. In a reverberation measurement, the lower unit will first be set to low gain mode (hereafter, simply TL Mode), to capture the high level pings, and after a pre-set time, will revert to high gain mode to record the decaying signal.

In the final version of the SEA buoy lower electronics (see Fig. 6), the omnidirectional (omni) hydrophone that is embedded in the DIFAR housing serves as both a wide band (8 kHz) reference and a DIFAR reference (2 kHz). Provisions have been made to allow the replacement of the wide band omni with a dual output (padded and unpadded) external calibrated omni to achieve wider acoustic dynamic range.

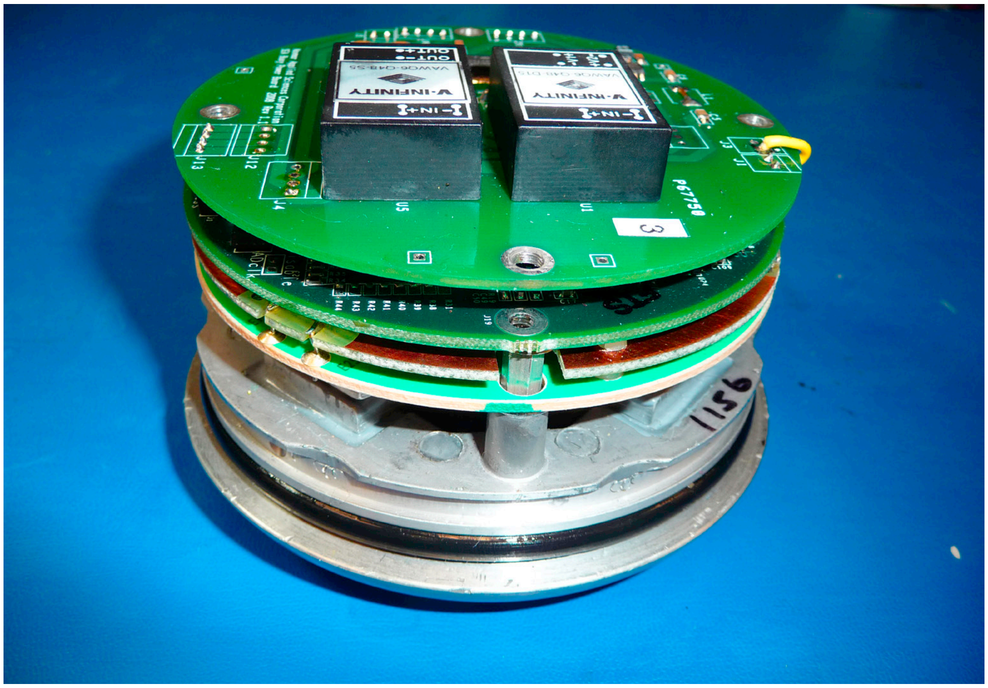

Fig. 6 – Lower Electronics Circuit Boards Mounted in Canister

The lower unit electronics underwent three iterations, with each revision improving upon an aspect of the baseline design:

The initial version provided a working platform to prove the functionality of the custom electronics. Form and function were verified with this build. All of the circuitry fit as designed into the AN/SSQ-53E canister and a process was developed for feeding through and attaching the Power/Data Cable. The housings were pressure tested, and all functional elements worked including communications, hydrophone preamp/sonic amplifier, digitization, and compass. The communications was thoroughly tested electrically to ensure that the relatively high bandwidth of the acoustic data (-1 Mbps) could be supported. The algorithms for framing and compressing the acoustic data were verified with end-to-end tests from lower unit to the upper unit receiver to the IBSP. The amplifiers (Fig. 7) were designed using initial sensitivity assumptions of the hydrophones and tested for gain and bandwidth and for electrical interface compatibility to the ADC. The firmware for the μC was programmed, including the framing and compression algorithms, digital compass interface, analog-to-digital converter (ADC) interface, and transceiver interface.

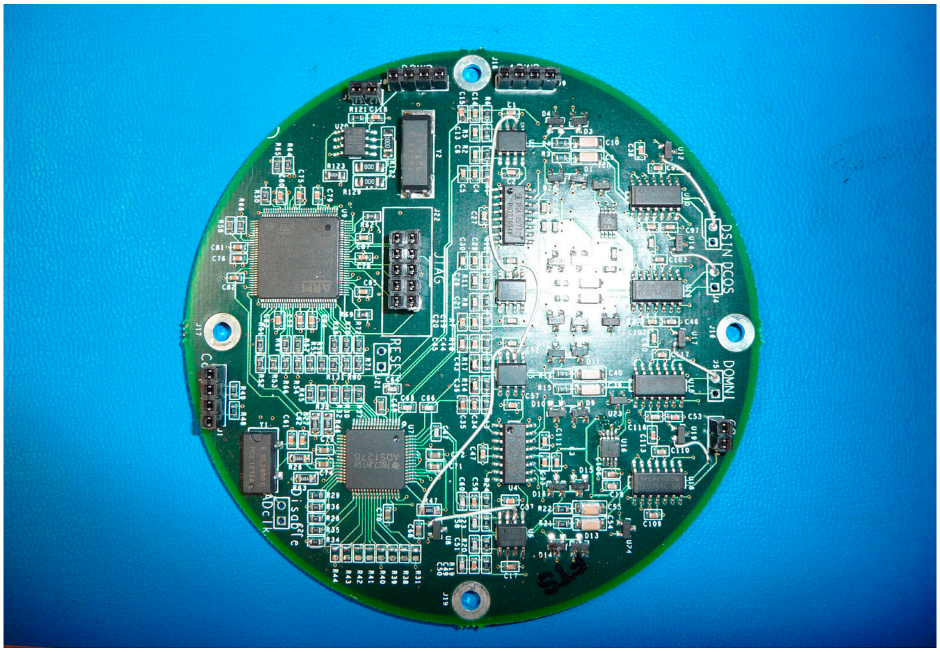

Fig. 7 – Lower Electronics Amplifiers Circuit Board

The initial design of the lower unit electronics featured an automatic switchover from high gain (ambient) mode to low gain (TL and reverb) mode that did not need a command from the upper unit. The intention was that the lower unit would be an independent module that simply streamed raw acoustic data up to the IBSP with no other interaction from the upper unit. Previous designs used two channels per hydrophone, with each channel being set to a different gain, but by using a single amplifier channel with a switchable gain mechanism, the noise was reduced on each hydrophone (by reducing the number of components directly attached to the hydrophone), and the number of components on the amplifier board were minimized. The automatic switchover function was accomplished using a power measurement circuit that determined the gain mode of the amplifier channel.

Although the initial version was fully functional, it was decided to increase the gain for each channel to reduce noise. No changes were needed to the circuitry layout, but new filter and gain values were employed, and corresponding coefficient changes in the microcontroller were made. Tests were performed in a laboratory calibrator demonstrating the increased gain and better sensitivity.

Additional analysis indicated that the dynamic range should be adjusted. Since a 215 dB (re1μPa) signal at the hydrophones would generate a voltage sufficient to damage the circuit electronics, more attenuation would be needed prior to the amplifier chain. The existing amplifier boards would be reused, but an additional board would be required to provide the needed attenuation.

During this design effort, it was also decided to address a deficiency with the automatic switchover circuit. The peak detector circuit could not be designed with both a very fast rising edge to detect the first impulse of a blast and a slow enough decay to limit switching back and forth between low and high gain modes. This resulted in a high frequency glitch when switching between modes that could be interpreted by the processing routine as a false echo. To prevent the circuit from rapidly switching gain settings during a large, rapid oscillation of input signals, some components were added to hold the switching level at the lower gain setting (for the higher level signals) for a longer period of time. This required a change to the board layout.

An issue related to gain switching was that no provision had been made to identify the mode in the digital data frame of the acoustic signal. This was important because the compression and decompression schemes were limited to 24 bits. These schemes worked well with no loss of precision for values less than 11 bits (< 2048) and less than 0. 05% error for all other values. But, the problem with this was that the maximum value was limited to 24 bits, whereas to fully provide an un-sealed dynamic range, 30 bits of resolution are required. Thus, in the auto switching mode, all samples were rescaled to a final 24-bit value, resulting in a significant loss of precision and a high noise floor. In the implemented switching mode, no scaling is performed on the data, so each range maintains a full 24-bit resolution, but there is an assumption as to the sound pressure level (SPL) of the maximum 24-bit value. That is, in auto mode, every sample was rescaled, so that a digital value of 224 represented 215 dB (re1µPa) SPL, whereas in the present implementation, 224 represents 142 dB (re1µPa) in ambient mode, but 215 dB (re1µPa) in TL mode.

The decision to proceed with a manual mode reduced the number of components on the amplifier board, since the peak detection circuitry was no longer needed for each channel. It also simplified the µC firmware, since no gain-dependent scaling was needed in the algorithm.

Gain

Analysis was conducted to select the appropriate gain. Then, some design research was conducted to select components to achieve that gain. One possibility was to increase the gain of the directional hydrophones by about 40 dB, but that also meant increasing the gain of the omni by about 70 dB (a factor of about 3000). Testing of directional versus omni hydrophones without gain revealed an average difference of 30 dB, from 100 Hz through 1700 Hz. This gain change was possible on the differential amplifier circuits but not on the level detect circuit without component changes. Another option was to change the omni gain to 50 dB.

Reference Omni

The reference omni used with the DIFAR directional hydrophones is being used for the omni sensor. This eliminates the need for another external hydrophone and subsequent canister penetration wires. However, there is a risk that this omni hydrophone may not be as sensitive as the directionals, further exacerbated by incorporating it into the electronics canister with which it may be baffled and/or interfered. Using a gain set at 40 dB addresses the sensitivity problem, but this does not permit achieving the low end dynamic range.

To solve that, one option is to use two calibrated hydrophones, one with high gain and the other attenuated. This provides the wider dynamic range; however, two hydrophones would then be needed, and they would not provide automatic change-over without significant circuit redesign and additional components. Change-over prior to data collection could be accomplished with an electronic switch and a command sent by the upper electronics. The addition of another command word to choose which hydrophone to use for a specific mode was discussed; however, this would be useful only if the full dynamic range is not needed in any specific collection mode. Eventually, the gain of the embedded omnis was adjusted and calibrated for use in data collection.

Code Changes

The above considerations required adjusting some of the parameters in the lower electronics microcontroller software code, especially to update the gain settings. This was not extensive but had to await the selection of the final component values.

Since the lower unit was initially designed to continuously stream acoustic data to the upper unit, the firmware needed to be modified to accept an additional command from the upper unit. But the acoustic data stream is continuous, with no time between frames during which the upper unit can transmit down to the lower unit. The only reasonable time to communicate to the lower unit is during the power up initialization sequence. The lower unit pauses briefly when power is applied and listens for a command from the upper unit. After a pre-set time, if no command has been received, the lower unit goes into ambient mode and streams data. Therefore, in order to change measurement modes, the upper unit cycles the power and sends the mode command during the initialization period.

Amplifier Channels

For each channel, a single amplifier is used. An acoustic signal causes the hydrophone to generate an electric potential that is amplified according to the gain setting determined by the measurement mode, filtered, and then converted into a digitized version. All channels are sampled simultaneously at a rate of 20kHz, though the DIFAR channels are decimated in the μC at a sampling rate of 5 kHz. A scaling coefficient is applied to the digital data to factor out the analog gain and produce a full scale output regardless of mode. The preamp/sonic amplifiers were designed using assumptions about the sensitivity of the hydrophones which were calculated from measurements made in the laboratory calibrator, but using calibrated omni hydrophones instead of the original reference hydrophones allowed a more controlled measurement.

Overall Sensitivity Measurements

The completed lower units were then measured for sensitivity at four different locations: at AAI in the laboratory calibrator; at the AAI Oreland, Pennsylvania, quarry; at the Lapel Acoustic Test Facility in USSI Lapel, Indiana; and at the Naval Sea Systems Command Acoustic Test Facility at Seneca Lake, New York. The test results indicated that the hydrophones were more sensitive than initially estimated, resulting in better noise figures than originally estimated.

Design Notes

The lower electronics underwent some circuitry changes to achieve the wide dynamic range. As mentioned, the design separates the measurements into two modes, each of which can accommodate a span of signal levels, limited by the dynamic range of the 24-bit digital circuitry. These two modes overlap, so that switching from one to the other maintained a relatively common resolution. In addition, the design was intended to minimize the gain to be applied in the ambient noise mode and to minimize the attenuation applied in the transmission loss mode.

A large gain had to be applied to each signal output in order to bracket the signal levels within the dynamic range values needed to be seen by the IBSP. As a result, the noise sensitivity was greatly increased, and another acoustic test, with higher signal levels and higher frequencies on both the omnidirectional and directional hydrophones, was conducted.

A calibration check on the hydrophones was also performed, during which it was discovered that the attenuator acted as a low pass filter, an effect that had not been seen in the breadboard version. One solution was to add a capacitive divider in the circuit, and another was to calibrate this out of measured data when in this mode.

It was also discovered that mode switching affected the compass. Latching relays (which had been designed into the acoustic signals circuit as a protective measure) contained magnets which interfered with the compass.

Compass

The initial intent was to adapt the DIFAR compass resident in the AN/SSQ-53E sonobuoy for use in the SEA buoy because it is proven technology, but in order to leverage off work from another project in which a digital interface had been explored, it was decided to design for that device. Thus, the Honeywell HMC6352 compass has been incorporated into the SEA buoy. It runs at a continuous rate of 20 Hz with an accuracy of +I- 2. 5 degrees and a resolution of 0.5 degrees. A 9-bit data resolution results in 0.703 degrees per bit, which this device meets. The interface to the IBSP asks for compass information to be sent up with every block of data. This implies a 5 kHz sample rate, which can handle the lower update rate of the sensor.

Measurements were conducted to assess the compass accuracy, and during testing, it was observed that the compass exhibited errors due to internal magnetic deviations. The digital compass has an internal calibration routine that maps these internal deviations and saves calibration coefficients that cancel out the errors. But, even though the lower unit firmware has been modified to access that calibration routine, the units had already been sealed, and the microcontrollers had not been flashed with the latest firmware. Therefore, an external calibration file was generated. With that, the compass bearing was corrected to within 10 degrees; without external calibration, error values were as high as 45°.

Although the hardware implementation of the compass exhibited some instability in the form of a lock-up after the units had been running for a while, this problem was eliminated by adjusting some circuit values. A verification of proper compass operation was conducted during a test at the USSI Acoustic Test Facility in Lapel, Indiana, in April 2009.

In-Buoy Signal Processor

The In-Buoy Signal Processor effort was performed by RDA, Incorporated, who selected the commercial Texas Instruments (TI) TMS320DM as the DSP processor. Top level software was designed for the data flow and interrupt schemes, and software was written. Using the TI Code Composer, various stand-alone signal processing library functions were tested and timed. Internal TI device and interface programming was initiated. The DSP filters and the Wide Band Omni scheduler were implemented in the C programming language. Compress/Uncompress and Uplink Frame File Lists and record formats were coded. Signal processing design for the core algorithms, including post-processing for the Ambient Noise and Reverberation modes, was completed in MATLAB. A prototype board is shown in Fig. 8.

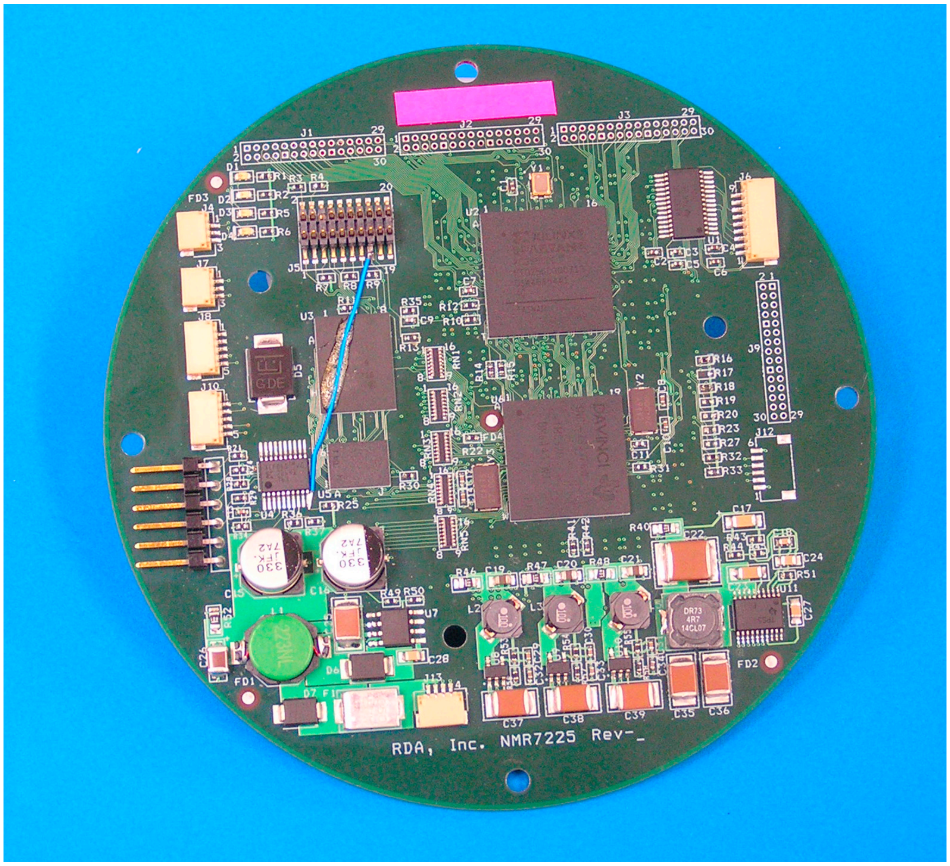

Fig. 8 – Prototype SEA Buoy Processor Board

The processor was exercised using simulated data and messages, and further testing occurred during the integration period after completion of the lower electronics circuitry and the telemetry modules. Integration testing revealed certain incompatibilities and/or suggested desirable features which have been delineated for a subsequent modification to the design.

It is anticipated that the highest level sinusoidal input to be processed linearly from the lower unit (24 bit AID) is 215 dB µPa2 (in reverberation or in transmission loss mode). The mode dependent gain in the IBSP software modifies this for the ambient noise mode, resulting in the l42 dB//µPa. The scaled data from the lower electronics is used to position the input to the IBSP data fields for processing. The “operating point” for each of the modes (Ambient, RVB/TL) was set so that the 24-bit A/D range covers from the peak input level expected for the mode to about 138 dB below the peak. (The IBSP reports values in dB (integer) as output data.)

Stores Module

Two stores module designs were developed and built, one which can accommodate three mini-SUS plus a conventional expendable bathythermograph (AXBT) probe or a sound speed profile probe and one which can accommodate four mini-SUS only. (The AXBT’s were ordered from Sippican, Inc., requiring modifications to the wiring of the cable pack in the stores module.)

The deployment tubes have also undergone a water-integrity test (3 feet below water surface for 2. 5 hours with no leaks) and successfully passed bum resistor tests and a bench-top SUS ejection test, in which a SUS deployment tube was loaded with ejection spring, SUS, 0-ring disk, deployment door, and retaining string. The retaining string was cut, and all contents ejected from the tube successfully.

The Stores Module Controller (SMC) PC board, the source controller chip, and twelve stores module ordnance housings were built. The feed-throughs for the stores module were designed; the wiring harness was built and pressure tested, and then the stores module mini-SUS separation mechanism was designed and tested. AAI also completed the electronic circuit design interfaces between the stores module and the IBSP and the lower electronics.

A view of the stores module is shown in Fig. 9. On the left is a cylinder which contains an expendable bathythermograph probe. Two slots are shown—each can accommodate a miniature SUS source; a third SUS slot is shown in the back, loaded with a dummy mini-SUS.

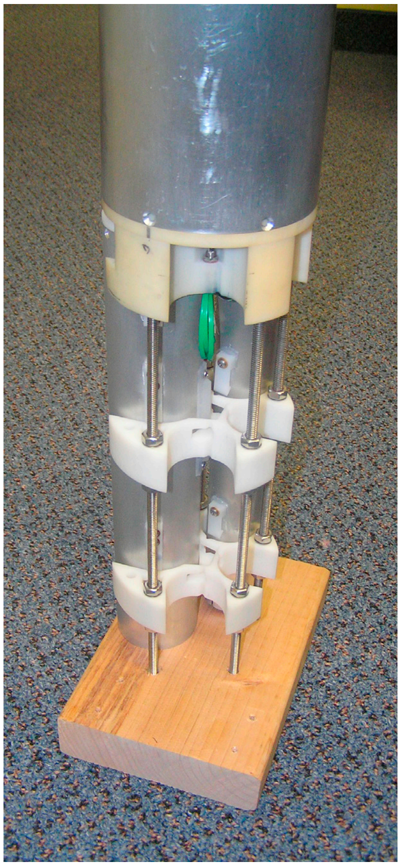

Fig. 9 – Stores Module Assembly

Telemetry Module

The telemetry encompasses one system to receive GPS information for subsequent routing to the IBSP, and another system (UHFNHF) for both command reception from an aircraft as well as transmission of data to an aircraft, and an Iridium link to provide data to other platforms or installations. An existing unmodified stand-alone combination GPS/Iridium system had been previously selected, but it is not compatible with the IBSP concept in SEA. An alternative modem model (one of the A3LA series of NAL Research, Inc.) was then selected in order to access the data required by the SEA buoy, and a combination GPS/Iridium antenna was installed on the surface float.

AAI selected the ADAR transmitter/receiver for the UHF and VHF links of the telemetry module. A prototype interface unit was built to develop the circuitry needed to convert the interrogative UHF command signals into digital format for use by the IBSP and to convert the IBSP output data into a format usable for the VHF receiver aboard the aircraft. This prototype was then compressed and fit into the upper portion of the SEA buoy in the final integration phase. This design was then successfully demonstrated. Finally, laboratory tests of the 96 kilobits per second transmission data rate with the Advanced Sonobuoy Communication Link (ASCL) receiver were successfully conducted.

Interface Notes

The IBSP needs to switch its expected sensitivity based upon the CFS command.

The stores module controller does not know what the CFS command is; it is told by the IBSP what store to deploy—such as a mini-SUS. In addition, the stores controller will not know if the SUS was a dud; only the IBSP knows when has seen the impulse and selects the 30 seconds of reverberation data.

When a store is dropped (mini SUS for reverberation or transmission loss), the IBSP assumes the lower electronics is in the less sensitive gain mode and waits before returning to the ambient noise mode. There is no synchronization between the IBSP and the lower electronics. The IBSP does not tell the stores controller (or the lower unit) to change modes. (The lower unit defaults to ambient noise mode.)

The GPS data is input to the IBSP, so that position information is imported into the data stream that is eventually transmitted.

The stores module controller shuts down power to the lower electronics in order to change the mode. That puts the lower electronics into a listen mode (at the lower gain setting). If it hears nothing, the lower electronics returns to ambient noise mode (higher gain setting).

At this point in the project, the aircraft interface has not been finalized. The formats for data from the IBSP have been defined and are available when interfacing design is initiated.

Testing and Calibration

Laboratory, quarry, and open water facility tests have been conducted. In preparation for an anticipated sea test of opportunity during September 2009, some checkouts were performed at Patuxent River, but because these were not done in a water environment, the lack of an RF ground plane caused problems. However, several modifications ultimately proved successful. Using ferrite beads on exposed wires, placing a shield of aluminum foil around the transceiver's non-metallic housing, and using an RF grounding disk allowed successful reception of the CFS commands. During the at-sea excursion, the Electronic Function Select (EFS) functioned properly, RF energy was transmitted when the system was powered, and the RF channel could be changed remotely.

III. RESULTS

An environmental sensor buoy, designed around the A-size format, has been developed.

An in-buoy signal processor has been developed which can provide statistical acoustic data in full and in 1/3 octave bands in seven frequency bands.

GPS, Iridium, UHF, and VHF RF links have been established and interfaced with the upper electronics. The ADAR system has been modified to perform the data relays. All RF antennas have been incorporated into the surface float.

A stores module controller has been built and has demonstrated its ability to send and receive control signals between the IBSP and the lower electronics. The module itself can accommodate the latest design mini-SUS acoustic sources. The electrical and mechanical interface has been developed to accommodate a conventional AXBT probe, and a probe deployment has been demonstrated in an over-the-side test at sea.

A temperature string deployment was demonstrated in Seneca Lake. An efficient and successful cable winding technique for the temperature string has been developed.

A wide dynamic range of about 120 dB has been designed into the lower electronics. During Seneca Lake testing (May 2009), acoustic signals from a projector were received and recorded.

A rechargeable battery pack and power supply controller capable of powering the tactical version of the SEA buoy has been built.

Deployment of the sonobuoy itself was demonstrated at sea.

In addition, an alternative non-explosive source was demonstrated at the quarry and in controlled laboratory conditions. It is capable of providing an approximately 185 dB source level, which may satisfy most, if not all source level requirements.

A detailed listing of the status of each of the subsystems is provided in Table 1.

Table 1 – Status of SEA Buoy Sub-systems

UHF Command Receiver	Operational
VHF Transmitter	Operational
GPS Receiver	Accommodated - Command Signal interface must be completed in a testing environment
Iridium Data Link	Installed and Tested - Requires contract for link services obtained when arranging for sea test. The Iridium units and Lithium battery packs /charging circuits are ready.
Stores Module Release Mechanism	Operational - All mini SUS tubes are functional and ready. Bathythermograph launch canisters are loaded and ready.
Stores Module Controller	Operational- Successfully operated stores release and temperature sensor string, provided power to lower unit and sent lower unit mode command
Temperature Sensor Pack	Operational
Lower Electronics	Operational - Interface Integration Testing Complete; Need to verify latest signal updates and study noise floor
In Buoy Signal Processor	Operational - Interface Integration Needs Full Validation; Processing Needs Full Validation
Upper Unit Floats and RF Modules	Assembled and ready
Surface Floats	Assembled and ready. For testing, a magnetic turn-on switch mounting stud has been attached.
Battery Packs	Installed, charged, and ready

IV. PROGRAM STATUS

The SEA Buoy program was launched in April 2006 by the signing of a contract for follow-on work to the original efforts of AEMEP and TAMDA.

Development progressed and the SEA buoy was scheduled for sea trials in July 2008. However, due to unresolved technical issues with the buoy at that time, the test was not conducted. These issues involved aspects of the digital circuit design and the intricacies of multiple interface boundaries. Work continued until June of 2009, when the project office directed that efforts on the program be completed and all existing hardware be delivered to NAWCPAX (photographs of the delivered units are included in Appendix A). At this time, Navmar believes that the technical issues have been resolved, and that some modest over-the-side testing could provide the information needed for the Navy to proceed with the generation of an engineering development model specification for issuance to sonobuoy manufacturers.

The project has been briefed at a number of conferences and meetings. They include presentations to:

- NAWCPAX in September 2006 on the background (including a report[9] describing the relevant historical and on-going projects) and progress of the SEA program; The National Defense Industrial Association (NDIA) at the Joint Undersea Warfare.
- Technology Spring Conference at San Diego, California, in March 2006 concerning plans to proceed with an environmental sonobuoy development.
- The NDIA at the Undersea Distributed Networked Systems Conference at Newport, Rhode Island, in February 2007.
- The International Sonobuoy Interoperability Conference ISIC 2008 in September of that year on the status of the SEA buoy.

Operational Concepts and Systems Notes

At present, there is no officially authorized or recognized concept of operations document delineating requirements for the SEA buoy; however, information exchanges over the course of the project have taken place, and a collection of notes relevant to these discussions have been accumulated. They are referenced in the final report.[10]

V. GENERAL RECOMMENDATIONS

A comprehensive concept of operations (CONOPS) should be developed to provide the needed guidance for the next logical phase of this program. An analysis of alternatives would then follow, and a path forward should be defined. (Funding priorities may suggest that an interim solution be accommodated using the engineering change proposal (ECP) concept to an existing model of an AN/SSQ-36.)

An Engineering Development Model (EDM) specification should be written. It should incorporate what has been learned and accomplished during this development phase and then be issued for proposal solicitations by sonobuoy manufacturers.

In the EDM, Navrnar recommends that the design of the in-buoy signal processor (IBSP) include sending and receiving more commands. The IBSP should be the system executive controller for all functions. The commands to each subsystem should be acknowledged and that there should be a more comprehensive exchange of signals between the IBSP and all subsystems.

Alternative acoustic sources should receive further consideration. They should not be dismissed due to the source levels that are presently achievable. As sea testing progresses and the ability to extract environmental information from the acoustic signals matures, a revised estimate of the required source level may suggest that non-explosive sources will be adequate.

Specific technical recommendations have been included in the SEA buoy final report. These include hardware and feature updates, as well as recommendations for testing and calibration (in the quarry and in a lake, prior to going to sea).

VI. ACKNOWLEDGEMENT

This work evolved from the AEMEP and TAMDA programs and was supported by the Naval Air Warfare Center at Patuxent River Maryland, and the PMA-264 Project Office.

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Arthur W. Horbach has over 45 years working for the Navy Laboratory community in the research and development of undersea systems, primarily in the field of underwater acoustics. His work encompasses a broad spectrum of acoustic systems: passive and active sonobuoys (and arrays), geobuoys, acoustic communications, transponders, ocean bottom penetrating systems, side-looking sonars, obstacle avoidance sonars and imaging systems. He has extensive experience in maritime patrol aircraft, accumulating over 1200 hours in flight as a project specialist, contributing to the development of a number of air deployable sensors. His field experience also includes helicopters, surface ships, submarines and deep diving submersibles. In the airborne Arctic sensors program, he has participated in over a dozen field expeditions to the Arctic. Dr. Horbach has the Bachelor and Master degrees in Electrical Engineering and the Doctorate degree in Acoustics from The Pennsylvania State University. He has taught physics at the College of New Jersey, and oceanography short courses at George Washington University, The Pennsylvania State University and the United States Naval Academy. He is a member of the Acoustical Society of America, the Institute of Noise Control Engineers, and the Sigma Xi Scientific Research Society. He is currently a senior systems engineer at Navmar Applied Sciences Corporation.

Appendix A

SEA BUOY DELIVERED UNITS

Fig. A-1 – SEA Buoy in Clear Canister with Test Surface Float

Fig. A-2 – Two Complete SEA Buoys

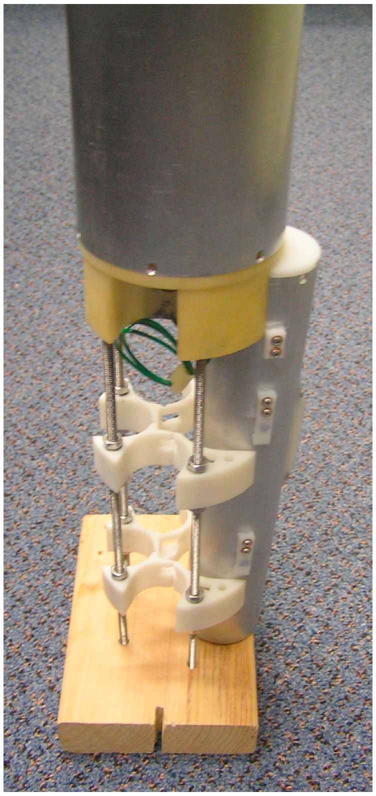

Fig. A-3 – Stores Module

Fig. A-4 – Three SEA Buoy Lower Electronics and Cable Packs

Fig. A-5 – Three SEA Buoys

Appendix B

GLOSSARY OF ACRONYMS

AAI	Advanced Acoustic Incorporated
Acronyms	Definition
ADAR	Air Deployable Active Receiver - AN//SSQ-101 Sonobuoy
ADC	Analog to Digital Converter
ADM	Advanced Development Model
AEMEP	Air Expendable Multi-Parameter Probe
ALFS	Airborne Low Frequency Sonar - AN/AQS - 22 (helicopter dipping sonar in the MH-60 R)
AN//SSQ-36	Air Expendable Bathythermal Buoy
AN//SSQ-53E	DIFAR Sonobuoy (directional frequency analysis and recording sonobuoy)
ASCL	Advanced Sonobuoy Communication Link
ASW	Anti-Submarine Warfare
AXBT	Air Expendable Bathythermograph
B/T	Bathythermograph
BTEC	Bear-Trap Environmental Characterization Program – also Battlespace Tactical Environmental Characterization Program
CFS	Command Functional Select
CONOPS	Comprehensive Concept of Operation
COTS	Commercial Of-The-Shelf
DICASS	Directional Command Active Sonobuoy System - AN//SSQ-62
DSP	Digital Signal Processor
ECP	Engineering Change Proposal
EDM	Engineering Development Model
EFS	Electronic Function Select
GPS	Global Position System
HEP	Harsh Environment Program
IBSP	In-Buoy Signal Processor
IRIDIUM	Satellite Phone System
LWAD	Littoral Warfare Advanced Development
METOC	Meteorological and Oceanographic
Mini-SUS	Smaller than Standard Size Sound Undersea Signal - impulsive source - 60 grams
MNS	Mission Need Statement
MODAS	Modular Ocean Data Assimilation System
NAVAIR	Naval Air Systems Command
Navmar	Navmar Applied Sciences Corporation
NAWCADPAX	Naval Air Warfare Center Aircraft Division Patuxent River, MD
NAWCADWAR	Naval Air Warfare Center Aircraft Division Warminster, PA
NAWCPAX	Naval Air Warfare Center Patuxent River, MD
NDIA	National Defense Industrial Association
PC	Printed Circuit
RESOC	Research on Sonobuoy Configurations

RVB	Reverberation
SBIR	Small Business Independent Research
SEA	Sensor for Environmental Assessment
SMC	Stores Module Controller
SPL	Sound Pressure Level
SUS	Sound Undersea Signal - Impulsive Acoustic Source
SVP	Sound Velocity Probe
SWAD	Shallow Water Directional Active
SWBCMS	Shallow Water Bottom Characteristics Measurement System
TAM	Tactical Acoustic Measurement
TAMDA	Tactical Acoustic Measurement and Decision Aid
TL	Acoustic Transmission Loss
TSC	Tactical Support Center
UHF	Ultra High Frequency Radio
USSI	Undersea Sensor Systems Incorporated
VHF	Very High Frequency Radio
XBT	Expendable Bathythermograph
µ C	Micro-Controller

Table of Contents