NEW ACOUSTIC SYSTEMS FOR AUV TRACKING AND COMMUNICATIONS AT NSWCCD-ARD, LAKE PEND OREILLE, IDAHO

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ABSTRACT

This paper describes a newly developed acoustic system for AUV tracking and communications at the Naval Surface Warfare Center (NSWC), Acoustic Research Detachment (ARD) in Bayview, Idaho. This Acoustic Tracking and Communications System (ATACS) has unique capabilities and is highly versatile to support a variety of AUV tests. The system can be configured to simultaneously track and communicate with a multiple AUVs, each transmitting a unique identifier code.

Software-based ranging receiver algorithms support both coherent and non-coherent ping types. The system can receive frequencies between 10kHz and 120kHz and transmit between 25kHz and 120kHz. Real-time signal detection software runs on a VME-based multi-processor system. Detected waveforms are passed to a single-board host processor for precise timing estimates and telemetry demodulation. Range and telemetry information is then broadcast across ethernet to various client applications such as vehicle tracking and control, beamsteering, etc. Global Positioning System (GPS) clocks are distributed to analog-to-digital (A/D) converters throughout the system to provide global synchronization of sampling.

This system is part of an instrumented test range, which covers over 2 square miles with a lake depth of over 1100 feet. The effective tracking area extends over 10 square miles. Six bottom-mounted transceiver units provide bi-directional communications and ranging with AUVs (fig. 1). Each transceiver unit is buoyed 100 feet off the lake bottom and contains separate broadband source and hydrophone elements.

A state of the art radiated noise measurement system is located in the center of this tracking and communications range. Two vertical arrays of calibrated hydrophones are supported by riser cables. Selected array hydrophones can also be used for tracking and communications. Each riser cable supports eleven omni-directional hydrophones spanning depths from 100 to 800 feet, one vertical directive array, one horizontal directive array, one high frequency source, and an instrumentation pressure vessel (IPV) containing electronics. Data is transmitted to the top-side system using Asynchronous Transfer Mode (ATM) over Synchronous Optical Network (SONET).

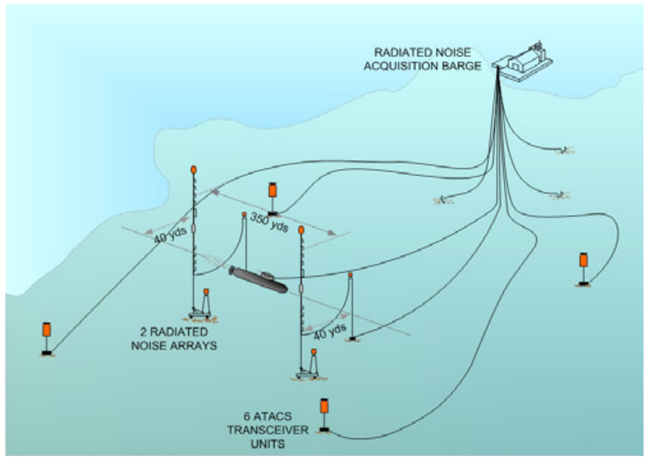

Fig. 1. AUV Range at Lake Pend Oreille.

Low ambient noise and low absorption losses are significant advantages present in this fresh water acoustic environment. Resulting high SNR and efficient receiver design create ranging and tracking capabilities with unprecedented accuracy. The system was designed to be adaptable and can be optimized for individual test requirements. Commercial off-the-shelf hardware was used to minimize total cost of ownership.

I. BACKGROUND

The Carderock Division, Naval Surface Warfare Center's (CDNSWC), Acoustic Research Detachment (ARD) is located on the shore of Lake Pend Oreille in Bayview, Idaho. This facility, established in 1942 as the Farragut Naval Training Station, has been an integral part of the Navy's Research, Development, Test and Evaluation (RDT&E) community under the Naval Sea Systems Command (NAVSEA). With its isolated location, 26 square miles of depths exceeding 1000 feet, and typical ambient noise levels less than ocean Sea State Zero, Lake Pend Oreille is ideal for acoustic testing. The lake's water temperature remains a constant 39.5 degrees Fahrenheit below 300 feet all year, maximizing the repeatability of test results and contributing to measurement accuracy. The lake contains several noise measurement ranges including the Large Scale Vehicle (LSV) range for powered AUV testing, and the Intermediate Scale Measurement System (ISMS) for static signature measurements of submarine models. Also included are the Buoyant Vehicle Test Range for measuring hydrodynamic flow noise on models, and a test range for towed sonar arrays.

The ARD has been conducting tests with AUVs on the LSV range since 1987. Two unmanned computer controlled submarine models, KOKANEE (LSV-1) and CUTTHROAT (LSV-2), operate on the range. KOKANEE is a quarter-scale model of USS SEAWOLF (SSN-21) and is 90 feet long, 10 feet in diameter, and displaces 155 long tons. CUTTHROAT (Fig. 2) is a 0.294-scale model of the USS VIRGINIA and is 111 feet long, 10 feet in diameter, and displaces 205 long tons.

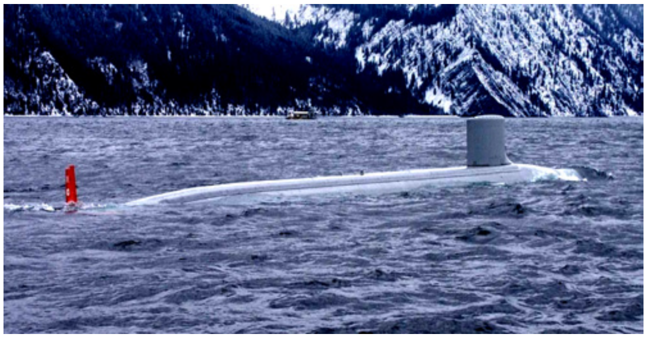

Fig.2. CUTTHROAT AUV preparing to dive.

The Acoustic Tracking and Communication System (ATACS) allows over 10 square miles of operating area. This system was primarily designed and developed by on-site government engineers with support from University of Washington, Applied Physics Lab and Prevco Subsea Housings.

At the center of the range are two vertical arrays of sensors used for measuring acoustic signatures. Cabling from the underwater electronics terminates at a permanent mooring (Fig. 1.). A specially configured Radiated Noise Barge (RNB) contains signal processing, operator control, and data recording equipment. To support testing, the self-propelled RNB is currently required to move on-range where it is moored and connected to the ATACS transceivers and radiated noise arrays. A planned upgrade will extend the ATM network to the ARD and allow operation from shore-based facilities.

II. SYSTEM DESCRIPTION

ATACS was designed to replace three prior acoustic systems, each having unique requirements for ranging, tracking, and communications. The system provides reliable and highly accurate tracking of the LSV AUVs throughout the test range and provides bi-directional acoustic communications. System flexibility was also required to meet needs of future programs and range users.

An important system requirement is that ranging waveforms not interfere with noise measurement and other acoustic systems. Broadband transducers, high sample rate, and flexible software allow tracking frequencies from 10kHz to 120kHz. The system receives acoustic signals from the radiated noise arrays and the ATACS transceiver units. All AUV testing on the LSV range within the past two years has utilized this system.

A. Hardware

Figure 3 shows a block diagram of the ATACS hardware. Two VME chassis, the Acoustic Range and Telemetry Server (ARTS) and the ATACS Hardware Controller (AHC) contain computers and other system electronics.

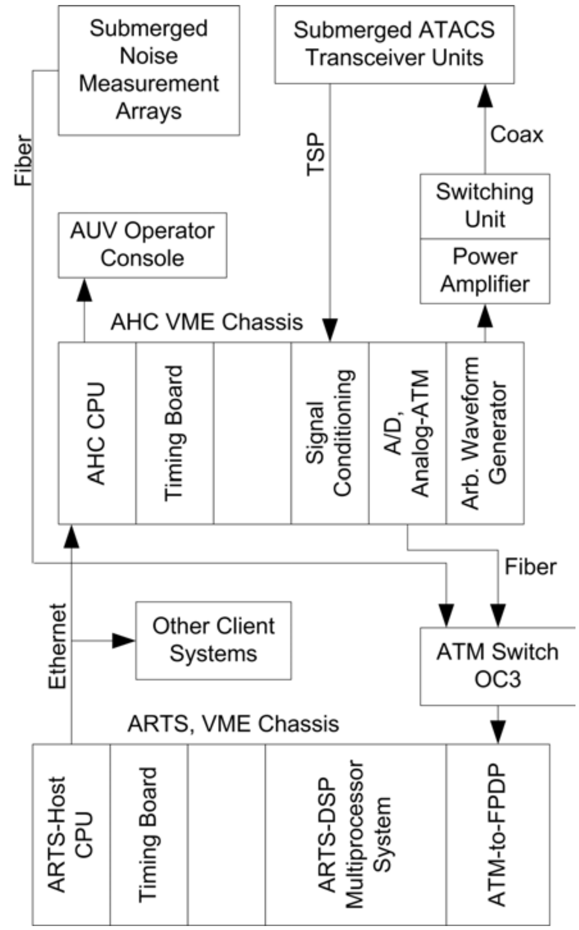

Fig 3. ATACS Block Diagram

The ARTS-DSP is a scalable multiprocessor system, supplied by Mercury Computer Systems, Inc. This system runs Mercury's MC-OS operating system and processes all digitized data channels to detect incoming waveforms. The ARTS-Host is an MVME2604 single-board computer running the VxWorks operating system. This system processes the detected waveforms and broadcasts range and telemetry data to client systems.

GPS clocks are distributed throughout the system to provide synchronization. Onboard GPS rubidium holdover clocks maintain synchronization when AUVs are submerged.

ATACS submerged hardware includes six bottom-mounted acoustic transceiver units (Fig. 4) positioned throughout the tracking range area with a unit-to-unit spacing of approximately 5000 feet. Each unit is buoyed

100 feet above the lake bottom to delay the arrival of bottom-bounce multi-path interference.

Each transceiver unit has separate hydrophone and projector elements mounted above an anechoic plate made of Syntactic Acoustic Damping Material (SADM) produced by Syntech Materials, Inc. Approximately one inch thick and 16 inches in diameter, this plate absorbs acoustic reflections from the floatation buoy and from the lake bottom.

Reflections off the SADM plate become significant at very low grazing angles (near horizontal). These acoustic reflections are found to be phase inverted and create a frequency-dependent null in the vertical directivity pattern just below the horizontal angle. By adjusting transducer height during installation, the null could be steered up or down to enhance directivity roll-off below horizontal angles.

To maintain flexibility to alter transmitted and received waveforms, and to minimize maintenance costs, submerged ATACS transceiver units were designed to contain minimal electronics. The underwater pressure vessels contain voltage regulators, a tuning transformer to match the cable impedance to the source, and a line driver for boosting the hydrophone signal. Each unit is individually connected to top-side systems with multi-conductor cable containing a coax for amplified projector signals, a twisted-shielded pair (TSP) for received hydrophone signals, and a triad for power.

Fig 4. Submerged transceiver unit being deployed.

Noise measurement hydrophones on the two vertical arrays are also utilized as ranging hydrophones. Array hydrophone signals are digitized within submerged pressure vessels and transmitted topside on a high-speed ATM over SONET network [5].

All analog hydrophone signals, in the AHC chassis and array pressure vessels, are sampled on 16-bit, multi-channel, sigma-delta, A/D converter boards with integrated ATM over SONET telemetry. Receiver signals are in a star network topology and are routed to the ARTS chassis via an ATM switch. Data streams are input to the processors via ATM-to-FPDP interface cards.

B. Software Design

Due to the complexities present in acoustic environments (i.e. multipath), and the possibility of new requirements from future range users, the acoustic receiver software was designed to be highly configurable and easily modified. Numerous configuration parameters can be specified at program startup. These parameters include ping frequencies, repetition rates, filter coefficients, decimation factors, correlation replica coefficients, FFT sizes, DSP processor assignments, detection thresholds, sample rates, etc. Supported modulation types include Quadrature Phase Shift Keyed (QPSK) and Multiple Frequency Shift Keyed (MFSK).

To achieve accurate time synchronization, digital clock pulses generated by GPS receivers are sampled simultaneously with hydrophone signals on multi-channel A/D boards. Sampled data channels are routed to the ARTS-DSP multiprocessor system which detects incoming waveforms and writes detection data blocks to VME shared memory. The ARTS-Host processes these detection data blocks to determine timing and range, and to demodulate telemetry. Range and telemetry data is then broadcast to multiple client systems over a secure LAN. Detection data is also logged to disk for later analysis and post-processing. A suite of utility programs have been developed which process log file data.

Four primary tasks were developed for the ARTS-DSP multiprocessor system:

1. Demux task - Demultiplex input data streams and distribute to receiver tasks.
2. PSK receiver task - Detect broad-band acoustic waveform and generate detection data block.
3. FSK receiver task - Detect leading tone of FSK waveform and generate detection data block.
4. Clock receiver task - Detect digital clock pulse and generate detection data block.

Configuration parameters control which tasks are assigned to each DSP processor and the distribution for each input signal.

C. Processing Efficiency

CPU loading is a major concern in many real-time processing systems. PSK and FSK tasks first translate signals to base-band and decimate, which reduces loading during subsequent detection processing. A system of circular queues (buffers) was developed to hold time-domain data between processing steps. A set of queue utility functions handles over-run, under-run, and end-of-queue conditions.

FFT-based frequency-domain processing is employed for filtering and correlation. The queue system allows FFT routines to transfer data directly to and from circular queues. The overlap-save method [1] is utilized where successive inverse FFT (IFFT) results contain a discard portion. Filter and replica coefficients are pre-shifted so that this discard portion appears at end (right side) of each IFFT output. This allows subsequent IFFT results to over-write the prior discard portion eliminating unnecessary vector move operations.

D. Client Systems

Multiple client systems, both newly developed and legacy, utilize the range and telemetry data supplied by ARTS. These systems include general tracking and communication with vehicle, and precision tracking needed for real-time beamsteering of acoustic sensor arrays.

III. ACOUSTIC RECEIVER ALGORITHMS AND RANGING WAVEFORMS

A PSK receiver algorithm, illustrated in Fig. 5, was developed for high ranging accuracy. It incorporates a correlation (matched filter) detector and supports QPSK telemetry modulation. For applications requiring no telemetry, alternate forms of broadband ranging waveforms can be used such as linear frequency modulation (LFM).

PSK encoded waveforms are well suited for ranging and telemetry and allow tracking of multiple on-range vehicles. Each pinged waveform contains a unique ID code (pseudo-noise sequence) followed by a short telemetry payload. Data is encoded to control bit error rates. To prevent interference with other acoustic systems (i.e. radiated noise measurement), band-limited pulse shapes are used. Shown in (1), where T represents the signaling interval, these base-band pulse shapes have raised cosine spectrum [2]. The tails of each pulse are allowed to extend several intervals and are smoothed to zero with a hanning window.

$$x(t) = \frac{\sin(\pi \cdot t/T)}{\pi \cdot t/T} \bullet \frac{\cos(\pi \cdot t/T)}{1-4t^2/T^2} \qquad (1)$$

High-speed multiprocessor system and efficient FFT-based algorithms allow numerous correlations to be simultaneously performed on each hydrophone signal. Using the ambiguity function method, which incorporates multiple Doppler-shifted replicas, simultaneous estimation of range and Doppler is achieved [3]. The required number of Doppler-shifted replicas depends on waveform duration and frequency, and maximum vehicle velocity. Fig. 6 shows correlation output for detected PSK waveform having zero Doppler.

Acoustic signals are first base-band translated (BBT), filtered, and decimated. These three steps are performed efficiently in one elegant frequency-domain operation. The decimation greatly reduces CPU loading for subsequent correlations, with no loss of signal content.

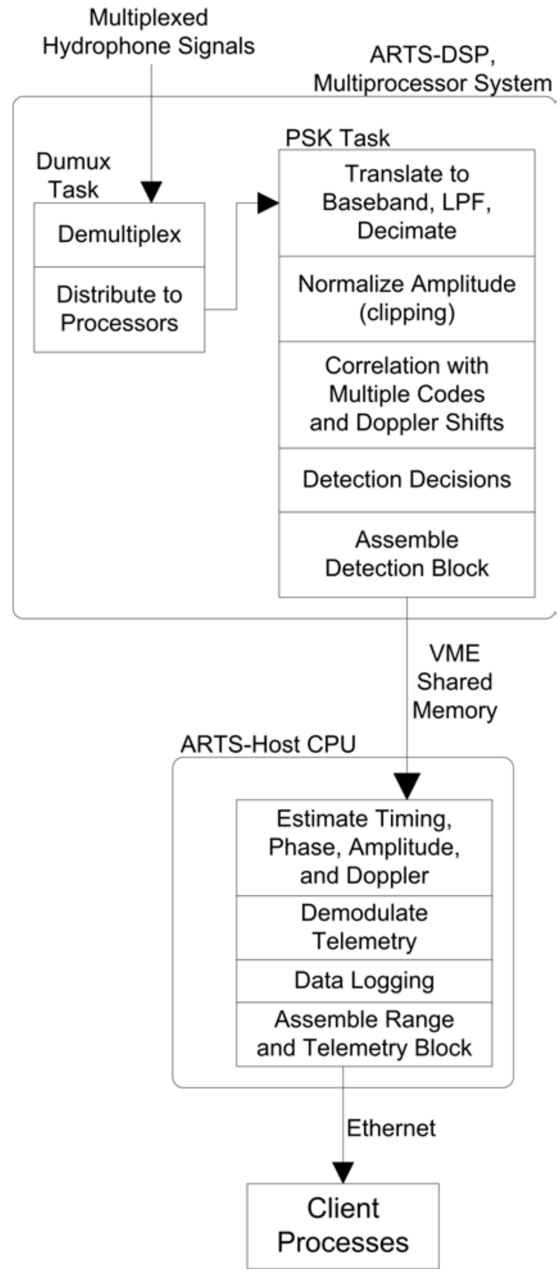

Fig 5. PSK Receiver, Data Flow

Dynamic range of acoustic signals vary widely as the vehicle moves throughout the test range. Normalization of the complex base-band signals removes amplitude variations while preserving phase information. This limits the correlation amplitude which simplifies signal detection by allowing for a fixed threshold.

For each detected signal, a data block containing corresponding linear (non-normalized) base-band data is assembled and passed from the ARTS-DSP system to the ARTS-Host processor using VME shared memory. Host software uses the linear signal and a much larger set of Doppler-shifted replicas for obtaining the best time and Doppler estimates. Doppler is searched linearly, starting with the rough estimate obtained during signal detection.

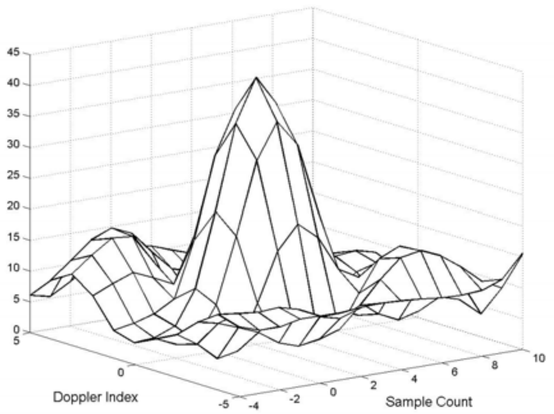

Fig. 6. 2-D correlation for PSK signal, zero Doppler.

To evaluate each Doppler-shifted replica, several correlation points are computed and a simple interpolation algorithm is used to accurately locate the peak. Using the magnitude of the complex correlation function, a three-point parabolic fit is used to first estimate the peak location. A reconstruction filter is then used to accurately interpolate three up-sampled correlation points, uniformly spaced about this estimated peak. A second parabolic fit then provides an improved and final estimate of the peak location. Lastly, the reconstruction filter is applied to determine peak amplitude and phase. This iterative process can be repeated for increased accuracy but a point of diminishing returns is quickly reached. For reconstruction of complex analytic signals, the real and imaginary parts are interpolated separately.

The reconstruction filter is shown in (2). In this expression the sample period is assumed to be 1. For best accuracy τ is limited to $-1 \leq \tau \leq 1$. Interpolation accuracy is dependent on the value a, which also effects host processor loading since $2a+1$ correlation points must be computed for each replica evaluated. For the ATACS system, a value of $a = 7$ is generally used.

$$x'(\tau) = \sum_{n=-a}^{a} \left[x(n) \bullet \frac{\sin[\pi(n-\tau)]}{\pi(n-\tau)} \bullet \frac{\cos[\pi(n-\tau)/a]}{2} \right] \quad (2)$$

The time, phase, and Doppler of the correlation peak provide synchronization for extracting PSK telemetry. This method of Doppler tracking works well for short telemetry payloads, but phase errors grow as telemetry payloads lengthen.

A 3-tone FSK receiver was developed to support existing LSV on-board acoustic systems. The structure of the FSK receiver is similar to the PSK receiver, differing mainly in the detection processing. Frequency-domain base-band translation algorithms work especially well for multi-tone FSK where a separate base-band signal is generated for each frequency band. Narrow-band FSK tones allow large decimation factors, reducing the IFFT block sizes correspondingly.

IV. TIMING AND RANGING ACCURACY

Acoustic ranging is performed by measuring signal propagation time and multiplying by the average sound-speed. ATACS allows for different ranging waveforms to meet different test requirements. In general, timing accuracy increases with increased signal bandwidth, amplitude, and duration. A linear frequency modulated (LFM) waveform having 40kHz bandwidth and 5ms duration is used for surveying stationary transducers. A shorter PSK signal with 20kHz bandwidth is used for ranging to high-speed vehicles. Before ATACS deployment, a thorough timing calibration was performed on all signal path components.

Although sound-speed errors limit absolute ranging accuracy, the high SNR of the lake acoustics combined with efficient and unbiased receiver algorithms allow extremely sensitive range measurements. During range survey measurements, motion of less than 1/16 inch can be resolved between ATACS transceiver units buoyed 100 feet off the lake floor. This accuracy is consistent with simulation results, and with the calculated Cramer-Rao bound [3].

Fig. 7 shows the independently surveyed X-Y positions (overhead view) of eleven omni-directional hydrophones attached to a noise-measurement array riser cable. The depths of these hydrophones span from 100 to 800 feet and are spaced at 50 and 100 foot intervals. Each hydrophone is mounted to a stand-off arm which holds it 20 inches from the riser cable. The large circle in Fig. 7 has a radius equal to this 20-inch stand-off distance and was added to provide a measure of survey accuracy.

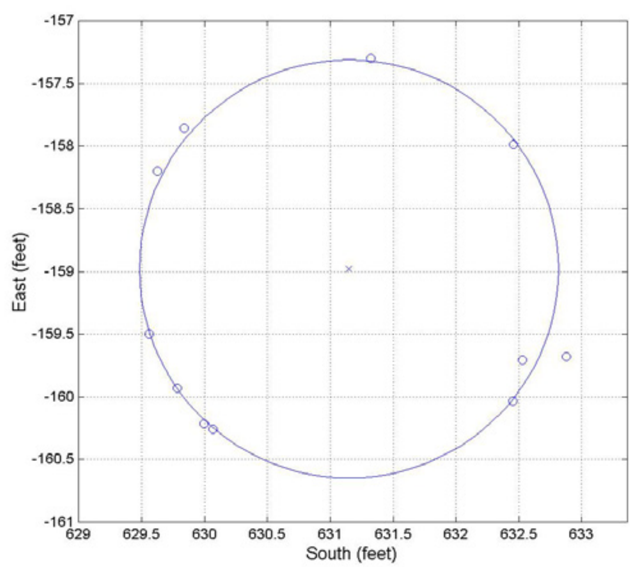

Fig. 7. Surveyed X-Y locations of omni-directional hydrophones, shown with a 20 inch radius circle.

Acoustic ranging accuracy from AUV to omni-directional noise measurement hydrophones is addressed in [6]. In these tests a pinger was tracked at short range with a largely over-determined set of range measurements and the residual least-squares error was analyzed and compared to simulation. Results predict the standard deviation of ranging errors to be about 1/8 inch.

V. TRANSDUCER POSITION SURVEYS

Accurate tracking of on-range vehicles requires accurate locations of stationary transducers. As discussed earlier, six transceiver units are buoyed 100 feet off the lake floor to a depth of approximately 1000 feet, and positioned uniformly across the range area. Each unit contains separate hydrophone and projector elements which are spaced 6.5 inches apart (Fig. 4). Once surveyed, these units form a stable base from which all other range transducers are surveyed.

Self-survey techniques and algorithms were developed to accurately determine the position and angular orientation of each transceiver unit. The vertical depth of each unit was independently measured using echoes off the lake surface. Accuracy was increased by calm surface conditions and by averaging hundreds of measurements. Using methods described in [4], least-squares optimization routines were developed to solve for the relative X-Y position and angular orientation of each unit. The horizontal range between each pair of transceivers was measured in both directions (i.e. from projector of unit 1 to hydrophone of unit 2, and projector of unit 2 to hydrophone of unit 1). The average of these two ranges was used in solving X-Y positions, and the difference was used in solving angular orientations. Correction factors were then needed to translate and rotate this self-consistent survey into real-world coordinates. To obtain these corrections, ranging pingers were suspended at two distant locations within the tracking range area, and the acoustically measured positions were compared with GPS measured positions.

VI. FUTURE APPLICATIONS

With funding from Office of Naval Research, software and hardware are being revised for compatibility with the frequency-hopped FSK protocols developed by Woods Hole Oceanographic Institute (W.H.O.I) [7]. This will allow AUVs equipped with W.H.O.I. acoustic modem hardware to operate within the ATACS range without deployment of transponders or other navigation aids.

ATACS software and hardware create a turnkey system to be replicated and deployed in a wide variety of ocean or fresh-water environments. Both hardware and software are scalable to accommodate virtually any number of sensors. Software can be configured for different waveform and modulation types. The ethernet broadcast technique for range and telemetry data provides a simple interface to existing and future client systems.

Conceptual designs have been developed which adapt ATACS software and hardware to create an accurate portable tracking range. Transducers suspended from drifting surface floats would be dynamically self-surveyed where transducer separation is periodically measured using acoustic ranging signals at alternate frequencies or ID codes.

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