Preliminary Results from a GPS-Based Portable Impact Location System[1]

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Biography

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Abstract

Applied Research Laboratories, The University of Texas at Austin (ARL:UT), has developed a prototype portable impact location system which utilizes air deployed, GPS equipped sonobuoys to localize the acoustic energy released when a projectile impacts the ocean. Meter level impact localization is realized using a low-cost OEM sensor, and DGPS realtime and postprocessing software. This paper reviews the operational concept and development constraints of the portable impact location system, and describes the selection, testing, and integration of a low-cost disposable OEM sensor into an air deployable sonobuoy. In addition, data reduction software developed to optimize DGPS positioning accuracy is discussed, along with preliminary performance results from open ocean demonstration tests.

Introduction

Current methods for scoring the performance of ballistic weapons, such as naval guns, field artillery, or missiles, rely on extensive test range instrumentation (such as ground based radar tracking systems) and/or field spotters. Many of these test systems require periodic re-surveying and calibration to ensure that accurate scoring is achieved, and provide limited flexibility in testing different operational scenarios (in the case of a fixed testing range, the weapon system must be moved to test a shorter or greater operational range). Perhaps one of the most technically challenging weapons systems to support with accurate test instrumentation is the performance of naval guns. Fixed test ranges typically involve long and costly transit times for ships which must periodically test the performance of their guns or missile systems. Use of GPS technology, combined with traditional acoustic based localization methods, provide a means for accurately scoring such weapons at any time, in any ocean, and with minimal cost.

Applied Research Laboratories, The University of Texas at Austin (ARL:UT), has developed a prototype portable impact location system to score the performance of weapons systems which utilize a ballistic projectile. The system utilizes ship or air deployable GPS equipped sonobuoys to localize the acoustic energy released when the projectile impacts the ocean. Meter level impact localization is obtained through the use of a low-cost, disposable OEM sensor, and DGPS realtime and postprocessing software. The portable impact location system was developed with three key design goals:

- Maintain or improve upon the scoring accuracy provided by current methods,

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- Expand upon the scope of traditional testing systems by using a completely portable implementation, and
- Satisfy the first two goals while maintaining operational costs at or below current scoring systems.

The design of the portable impact location system is described graphically in Figure 1. The system utilizes a shipboard reference system, an optional aircraft deployment system, and 10-12 disposable GPS equipped sonobuoys to score the relative impact coordinates of ballistic projectiles. The shipboard reference system includes a geodetic quality GPS receiver, digital recording equipment, computer processing platform, and a VHF data communication system. The optional aircraft deployment system may possess similar components if the baseline between the launch platform is beyond communication range of the sonobuoy array.

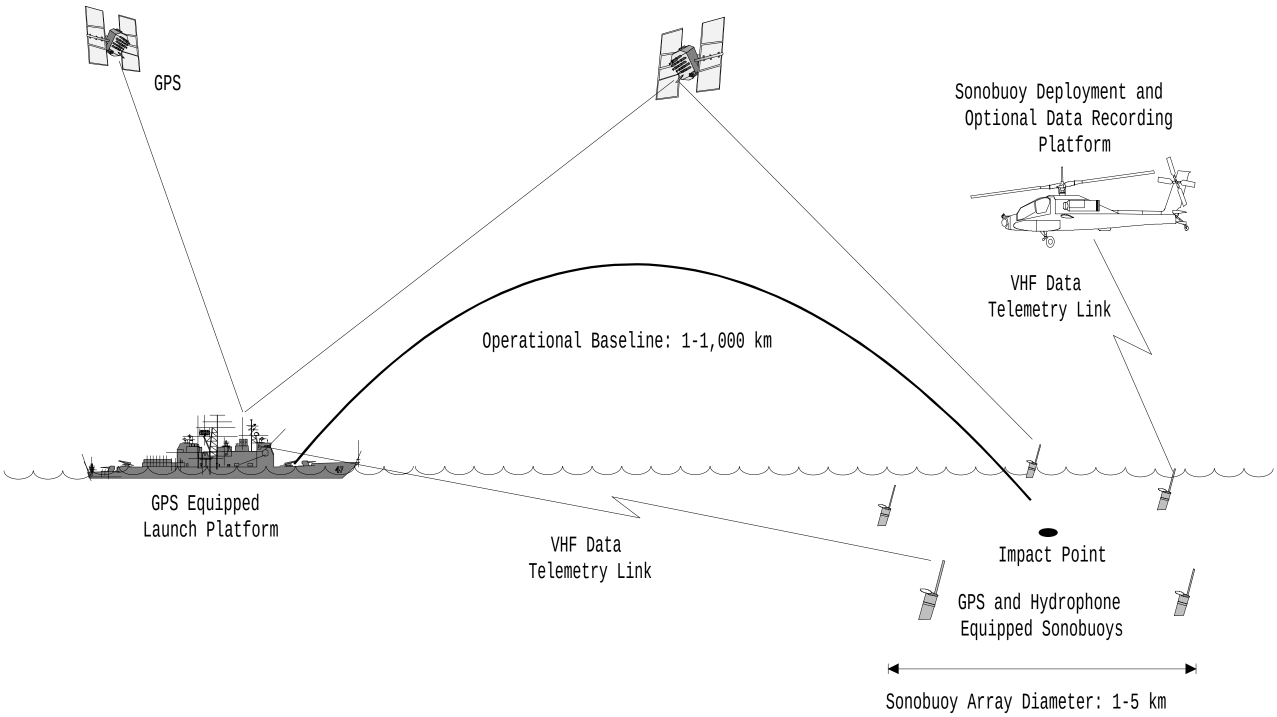

Figure 1. The portable impact location system operational concept.

In operation, the free-floating sonobuoys may be deployed by ship or aircraft in a pattern which encompasses the targeted impact area. During weapons firing, GPS and acoustic data telemetered by the sonobuoys are recorded onto digital tape and onto a personal computer (PC). In addition, the realtime autonomous positions and satellite tracking information from each sonobuoy is displayed to assess the operational performance of the sonobuoys.

Following data collection, data from the dual frequency all-in-view GPS receiver onboard ship, along with similar GPS data collected onboard the deployment vehicle (if available), and L1-only GPS data collected onboard the sonobuoys are transferred to the processing PC and converted to receiver independent exchange (RINEX) format. Following this conversion process, the sonobuoy GPS data is edited, smoothed, and processed through a DGPS solution algorithm to provide a meter-level relative position for each of the sonobuoys. The GPS data smoothing and differential GPS processing is described in greater detail later in the paper. To obtain impact positions, the relative positions of the sonobuoys are used, in conjunction with the received time of each acoustic signal, to estimate a range from each sonobuoy to the impact point. These ranges are then combined in a least squares solution to determine the position of the impact point(s) relative to the ship.

System Design

The portable impact location system is best described as a system comprised of four subsystems; the shipboard reference subsystem, the deployment vehicle recording/display subsystem, the sonobuoy subsystem, and the geolocation subsystem. Each of the subsystems are described in the following sections, with emphasis on issues affecting the use of GPS technology to meet the operational system goals.

Reference Subsystem

The reference subsystem is responsible for tying the DGPS positioning results to a known WGS84 benchmark or to the launch platform (in the case of relative positioning). The system, depicted in Figure 2 below, includes a dual frequency all-in-view GPS receiver, a 486/50 MHz ruggedized PC for data logging, a Davis digital weather station for collection of temperature, pressure and relative humidity data, and an UPS and gasoline powered generator for power. All of these components, with the exception of the generator, are rack mounted in a transportable case. The geodetic quality GPS receiver was selected for use in the reference subsystem due its excellent codeless L2 pseudorange performance (critical for ionospheric correction), its all-in-view tracking capability (important over long baselines), the availability of extensive command and control software, and the option to upgrade to Precise Positioning Service (PPS) capability at a later time. In operation, the PC collects 5 second GPS and 15 minutes weather data continuously throughout the test period. The data is archived to diskette (along with a log file containing benchmark and antenna height information) for geolocation data reduction.

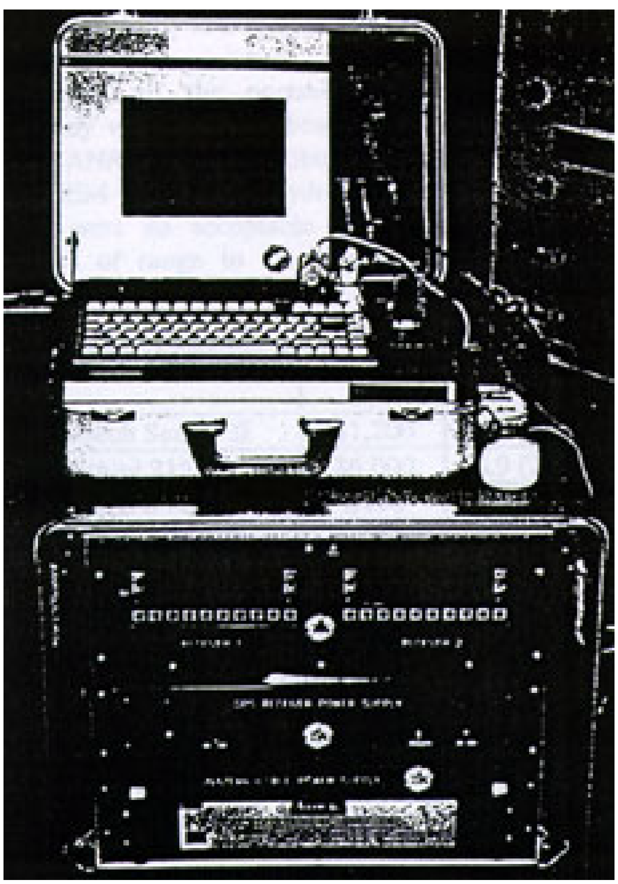

Figure 2. Photograph of the reference subsystem.

Deployment Vehicle Recording/Display Subsystem

The role of the vehicle recording/display subsystem is to provide a "portable" short baseline reference site to the sonobuoy array, and to link the array to the reference subsystem site which may be over a thousand km away. In this capacity, the recording/display subsystem deploys the sonobuoys, records telemetered GPS and acoustic data from the sonobuoys, and records GPS and weather data collected onboard the aircraft. The system hardware, depicted in Figure 3 below, includes 2 dual frequency Ashtech Z-12 all-in-view GPS receivers, 2 Metrum RS512 40 KHz digital tape recorders, an Industrial Computers Pentium 90 MHz PC, and assorted peripherals such as 16 bit A/D converters, multi-port digiboards, time code reader cards, etc. (some of which is located within the PC).

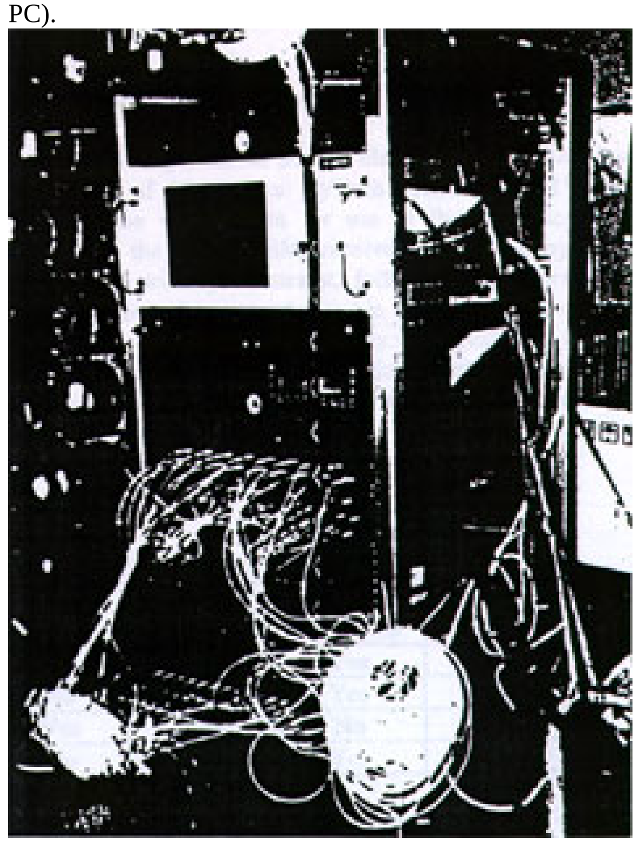

Figure 3. Photograph of the realtime display and recording subsystem.

In operation, the deployment vehicle begins by deploying a sound velocity profile (SVP) buoy to record the sound velocity in the impact area from 10 to 100 meters, and deploys 10 to 12 sonobuoys in an elliptical pattern about the intended impact area. During sonobuoy deployment, realtime display of sonobuoy position and satellite tracking data is used to determine if the pattern provides sufficient geometry to support scoring. If not, additional buoys are deployed. Throughout the buoy deployment, and for several minutes following the test, GPS data is recorded on the deployment vehicle at a 5 second rate, and weather measurements are logged every 15 minutes. Following the test, post-test engineering diagnostics are generated to provide a quick assessment of system performance, and to ensure that sufficient data are available for postprocessing.

Sonobuoy Subsystem

The portable impact location system sonobuoy, graphically depicted in Figure 4, is designed to transmit, via its 2,400 bps VHF communication link, raw GPS measurement data and acoustic data, at a 1 Hz rate. The cost of recovering the sonobuoys, coupled with the need for a flexible system that could be deployed in severe sea state conditions, led to the design of a disposable sonobuoy. The targeted sonobuoy design goals were:

- Maximum cost <$1,000.00 per unit
- GPS OEM form factor <4x4 inches
- GPS OEM power draw of <5 watts
- GPS pseudorange measurement noise <1 m (1 σ)
- Survivability rate of 85% (when aircraft dropped)

Design of the portable impact location system sonobuoy was therefore based upon a standard Spartan model AN/QQS-53D sonobuoy, coupled with a low-cost GPS OEM receiver and hydrophone. The primary design issues were an acceptable hydrophone response as a function of range to the impact point, and use of a calibrated hydrophone to provide some insight into cross-correlation signal processing techniques to improve accuracy.

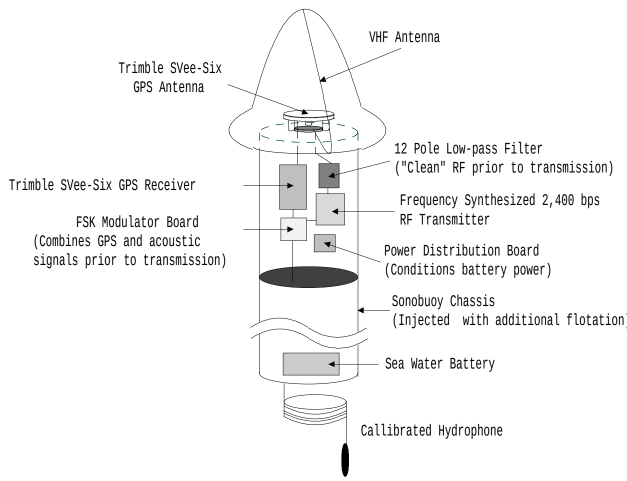

Figure 4. Graphical sketch of the sonobuoy components.

Following a test of several classes of hydrophones in the Gulf of Mexico, a HyTech -168 dB re 1V/mPa hydrophone was chosen for use in the sonobuoy. In selecting the GPS OEM receiver for the buoy, cost became a primary constraint, followed by performance, suitable form factor, and flexible command and control functions. Several OEM receivers were evaluated for use in the portable impact location system sonobuoy. Laboratory test results, displayed in Table 1, were used to identify two primary candidate receivers which were tested in actual aircraft drops in the Gulf of Mexico.

Table 1. Laboratory Test Results GPS OEM Receivers

Receiver Type	Receiver Cost	Measurement Error 1 Sigma (m)	Size (<4x4 in)	Power (<5 watts)	Variable Data Rate	Error Checksums
Ashtech Sensor II	$1,200	3.5 (22,069 epochs)	Yes	Yes	Yes	Yes
NovAtel 2151R	$6,000	0.9 (25,928 epochs)	No	Yes	Yes	Yes
Trimble SVee-Six	$450	4.6 (21,322 epochs)	Yes	Yes	No	No
Navstar XR5	$3,000	3.0 (18,569 epochs)	No	Yes	Yes	Yes

Of the receivers tested, the Trimble SVee-Six GPS OEM receiver was selected for use in the sonobuoy. The SVee-Six receiver did not represent the best available GPS receiver technology with regards to performance. However, given future trends in receiver form factor and capability, the Trimble receiver was identified as the best choice for the current sonobuoy. Use of the SVee-Six OEM receiver did, however, require unplanned development in the postprocessing software to address limitations in receiver command and control and measurement quality.

The OEM command and control interface did not support variable data rates, and therefore the realtime recording system had to be stripped of any processes not critical to data recording in order to keep up with a 1 second data rate. In addition, an error message checksum was not provided on the output messages. This required a modification to the realtime read routines to include a time consuming bit-by-bit read whenever the message was corrupted during transmission. These modifications limited the amount of realtime monitoring and sonobuoy tracking planned, but were mitigated by converting much of the realtime processing software to OS/2 to take advantage of parallel processing, and by upgrading the PC used in the recording/display subsystem from a 486/50 MHz to a Pentium class 90 MHz PC.

The portable impact location system relies upon meter level relative positioning between sonobuoys to achieve meter level acoustic positioning of the impact points. To achieve this level of positioning, not only must the buoy-to-buoy separation distance be short enough to cancel common mode errors (such as selective availability (SA), satellite orbit, and atmospheric errors), but the measurement quality from the sonobuoys ideally should be at the 1 meter level as well (1 sigma). Statistics from OEM measurement data collected in the laboratory and at sea indicated a 1 sigma pseudorange measurement error of 4.6 to 5.5 meters, as shown in Table 2. Although this was a recognized limitation in the low-cost OEM receiver chosen for the sonobuoy, it was expected that some form of smoothing technique would reduce the random component of the measurement error.

To this end, several measurement enhancement procedures were implemented in the postprocessing software. First, the doppler data reported by the receiver was integrated to form low-noise doppler range. The intent behind this modification was to provide an observable for directly smoothing the pseudorange measurements [Hatch, 1982]. However, doppler integration outside the code tracking loops produced doppler range measurements with repeated cycle discontinuities, which made direct pseudorange smoothing ineffective. However, this observable did provide a reliable model of SA, satellite orbit, and other GPS system trends. Therefore, differencing the pseudorange from the doppler range provided an observable which represented pseudorange measurement noise, signal multipath, and twice the ionospheric drift. A Fast Fourier Transform (FFT) smoothing technique was then applied to this observable to reduce the measurement noise component [Press, W., 1992]. This was performed by using an FFT conversion over a 400 second window of data, and removing the high frequency (10+ KHz) signals which represented measurement noise. The resulting "smoothed" measurements were then re-applied to the doppler range measurement to produce pseudoranges with a 1 sigma measurement error of 1.9 to 2.3 meters; a factor of about 2 improvement over unsmoothed pseudorange measurements. The results of this smoothing approach are summarized in Table 2 below.

Table 2. Results of FFT Smoothing on Trimble SVee-Six Pseudorange Measurement Data

Data Type	Laboratory Environment 1 Sigma Error (m)	Ocean Environment 1 Sigma Error (m)
Not Smoothed	4.6 (21,322 epochs)	5.5 (111,284 epochs)
Smoothed	1.9 (20,945 epochs)	2.3 (109,318 epochs)

Finally, several hardware modifications were required to successfully adapt the low-cost OEM receiver to the AN/QQS-53D sonobuoy. For example, laboratory testing indicated that the 9th and 10th harmonic of the sonobuoy transmitter significantly interfered with the GPS L-band signal. The original transmitter used a crystal frequency multiplier to obtain the transmit frequency, and while this was suitable for its original use, we found it to be unusable even with a 12 pole low pass filter on the transmitter output. Transitioning to a frequency synthesized transmitter and reducing the output power to 0.8 watts (from 1.25-1.50 watts) provided a much cleaner signal and eliminated L-band interference. In addition, it was discovered that the sea water battery induced a power spike into the OEM receiver which erased its pre-loaded command instructions. A power distribution board was therefore added to the system to prevent power spikes from effecting the GPS receiver. Several other electronic and mechanical modifications were required to integrate the GPS receiver into the stock sonobuoy, including development of a Frequency Shift Keying (FSK) modulator board to combine the acoustic and GPS measurement data into a 16 KHz signal for transmission, and injecting additional floatation into the sonobuoy chassis to offset the added weight of the GPS electronics.

Geolocation Subsystem

The geolocation subsystem consists of a Pentium 90 MHz PC with embedded multiport Digiboard, a National Instruments multifunction I/O A/D board, and a Datum PC05XT time code reader board. Sonobuoy GPS and acoustic data recorded to the Metrum digital recorders onboard the aircraft, along with aircraft and reference site GPS and weather data, are all downloaded to the geolocation PC for processing. Several programs written in C and FORTRAN are used to process the GPS and acoustic data. All software is activated through Windows icons, utilizes graphical user interfaces (GUIs), and is designed to run in batch mode. The geolocation postprocessing methodology is described graphically in Figure 5.

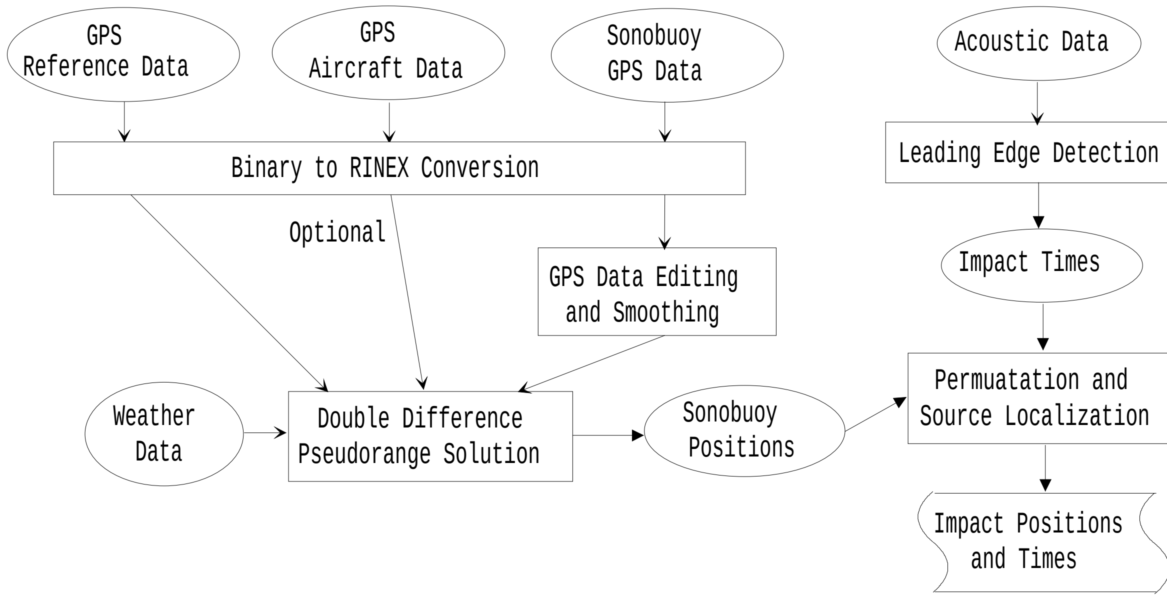

Figure 5. Graphical representation of the geolocation subsystem software.

As shown in Figure 5, the geolocation postprocessing software begins with several batch driven programs for converting the GPS data into RINEX format. Following the conversion process, GPS data from the sonobuoys are edited for spurious pseudorange measurements utilizing the fact that they are constrained to the geoid. In addition, the sonobuoy GPS data is smoothed (discussed earlier), and combined with GPS and weather data from the reference site and aircraft (if used). The weather data is used in a Modified Hopfield model to account for most of the tropospheric error, and dual frequency pseudorange measurements are used to correct for the ionospheric error between the reference site and the aircraft (if necessary). Other errors, such as SA, satellite and receiver clock, satellite orbit, and residual tropospheric errors, effectively cancel in the least squares double difference pseudorange solution algorithm. The relative differential GPS (DGPS) positions for the sonobuoys are then used in the acoustic processing software to determine the positions of the impact points.

Processing of the acoustic data is performed in two steps, 1) the acoustic data is digitized at a 10 KHz rate, and the leading edge of the received signal is time stamped with 1 millisecond timing accuracy, and 2) the impact time tags and corresponding sonobuoy positions are processed through a permutation program to determine a specific impact point which agrees with a set of sonobuoy positions and impact times.

Acoustic data recorded in realtime to tape is played back through a 10 KHz high pass filter, and digitized at a 10 KHz rate. Through the digitization process IRIG-B time code (recorded on one channel of the tape from a GPS timing receiver) is used to assign a UTC time stamp every 1 millisecond to the digitized samples. Up to 8 sonobuoy channels can be digitized simultaneously using the LabView-based program. In addition, the audio track is monitored during digitization to distinguish actual acoustic events from reverberation, and to limit the amount of data digitized to only the data of interest about the impact period. Once digitized, a high resolution graph of a subset of the captured data is displayed, and the leading edge of the acoustic events for each sonobuoy are tagged. The digitization process concludes with a file of event times for each sonobuoy stored for permutation processing.

The permutation process begins by recording the sound velocity profile of the impact region using a disposable sound velocity buoy. This information, along with precise GPS positions for the sonobuoys and the impact times file created earlier, are used to compute a position for the impact points relative to the sonobuoy positions. This processing is performed using the permutation program GAMARAY [Stotts, 1994], developed at ARL:UT. Source localization begins with a two dimensional grid overlying the entire sonobuoy array. At each grid point a direct path is calculated to each receiver location. A reference receiver (sonobuoy) is chosen arbitrarily to compare the model time structure arrivals with the data. All travel times are then calculated relative to this reference receiver. The horizontal range, R, from grid point (x_i,y_i) to the j^{th} receiver , is given by,

$$R = \left((x_i - x_j)^2 + (y_i - y_j)^2 \right)^{1/2} \qquad [1]$$

The direct path travel time from grid point (x_i,y_i), assuming constant sound speed, to the j^{th} receiver is given by

$$T_{ij} = \frac{\left((x_i - x_j)^2 + (y_i - y_j)^2 \right)^{1/2}}{C_{rec}} \quad [2]$$

where C_{rec} is the sound speed taken at the receiver depth (10 meters). The relative travel time of the grid point from the reference receiver, r, for the i^{th} receiver is therefore given by

$$T_{ij} = T_{ir} - T_{ij} \quad [3]$$

Based upon these relative travel times, a least squares error term is calculated for each grid point. This error is calculated through the following expression

$$L_i = \sum_{i=1}^{N} (T_{ij} - T_{dj})^2 \quad [4]$$

where N corresponds to the number of receivers, and the d subscript in the second T term in equation [4] corresponds to the reference receiver data. Next, the minimum value of L_i is found, and the grid location corresponding to this value is saved. This corresponds to

$$E_{min} = \min (L_i) \quad [5]$$

A new grid is constructed centered about the minimum point, E_{min}, with a smaller grid spacing, i.e., 100 meters. This procedure is repeated for 10 meters and finally 1 meter grid spacing. This final spacing approaches the limit of the GPS buoy location accuracy.

System Performance Results

The prototype portable impact location system has been demonstrated in two sea tests. The first test occurred in mild sea conditions (estimated sea state 2), while the second occurred during fairly rough seas (estimated sea state 4). For both tests the baseline distance between the reference site and the impact region was approximately 2,500 km, and therefore an aircraft deployment/recording platform was used. In both tests the recording/display subsystem performed well, with GPS and acoustic data successfully recorded onto the digital tape recorders, and with realtime displays of the sonobuoy reported PVTs used for deployment of the buoy pattern. Performance of the sonobuoys and the geolocation subsystems are described in greater detail in the following sections.

Sonobuoy Subsystem Performance

Initial aircraft drop tests in a controlled ocean environment were used to assess sonobuoy performance, finalize the baseline sonobuoy configuration, and identify any necessary enhancements prior to the planned at sea tests. Based upon these drop tests, the expected survivability rate for the sonobuoy was approximately 80% (80% of the sonobuoys fully operational following deployment), and the root mean square (RMS) of the smoothed pseudorange measurement error was 2.3 meters (as shown in Table 2).

Sonobuoy performance based upon drop test A, however, was not as successful. Only 4 of the 8 sonobuoys dropped provided realtime PVT information. Further analysis of the recorded data, however, revealed that the aircraft RF receiver control interface introduced errors into the data received from buoys 5, 6, and possibly 7, as shown in Table 3. When taken into account, this indicates a sonobuoy survivability rate of 75% (6 of 8); consistent with the results of the initial drop tests. Another interesting result from test A was the observed GPS measurement noise. The RMS value of the 1 sigma measurement error was approximately 3.1 meters, about 0.75 meters above what was anticipated based upon the initial drop test analysis.

Table 3. Sonobuoy Performance : Drop Test A

Buoy	GPS Data	No. of Epochs	% >3 SVs	GPS SNR	1 σ(m) Error
1	Yes	973	95.6	11.3	3.6
2	Yes	652	93.6	9.0	4.8
3	Yes	1047	92.4	10.7	0.9
4	Yes	1036	92.7	11.8	1.3
5	Yes	467	54.6	12.5	34.4
6	Yes	45	N/A	N/A	N/A
7	Yes	38	N/A	N/A	N/A
8	No				

The results of test B were noticeably better; which is particularly promising given the severe sea state condition (sea state 4). Of the 10 sonobuoys deployed, 9 provided GPS and acoustic data suitable for processing; indicating a 90% sonobuoy survivability rate, as shown in Table 4. It is also interesting to note that the RMS value of the 1 sigma measurement error improved to about 2.8 meters. Although this is still about 0.5 meters above the initial estimates, it suggests that the OEM receiver is performing well in this type of ocean environment.

Table 4. Sonobuoy Performance : Drop Test B

Buoy	GPS Data	No. of Epochs	% >3 SVs	GPS SNR	1 σ(m) Error
1	Yes	1480	86.4	9.5	4.5
2	Yes	1316	86.2	14.1	1.3
3	Yes	1764	77.9	13.8	0.6
4	Yes	1331	86.6	N/A	3.1
5	Yes	1472	72.2	9.5	4.6
6	Yes	1426	82.5	13.3	3.7
7	Yes	1608	86.1	16.1	1.6
8	Yes	1451	85.9	12.5	0.8
9	Yes	1662	85.7	N/A	0.8
10	Yes	46	N/A	N/A	N/A

Geolocation Subsystem

The portable impact location system postprocessing time goal is 48 hours from receipt of the raw data, to generation of the final scoring information. During test A, previously discussed aircraft communications problems created several fragmented GPS and acoustic measurement files. Although half of the data were processed in 2-3 hours, a great deal of effort in manual processing and analysis were required to extract any useful information from the remaining sonobuoy data. Test A was therefore not considered a valid estimate of expected geolocation processing time. With the aircraft problem resolved, however, measurement data from the 9 sonobuoys deployed in test B were processed in approximately 6 hours; well within the 48 hour postprocessing goal.

Future System Development Efforts

There are two planned enhancements for the prototype portable impact location system; improvements to the sonobuoy design, and implementation of cross-correlation processing techniques.

Customized MCM GPS Technology

A review of current and future GPS receiver technology developments suggest that a Multi-Chip Module (MCM) GPS receiver design may be well suited for this application. Such a receiver could be customized to improve pseudorange measurement quality, provide a flexibility in customizing measurement data output and output rates to minimize communication bandwidth requirements, and possibly provide phase data to evaluate ambiguity resolution processing between sonobuoys. In addition, use of MCM technology allows for development of a single electronics board assembly, which would reduce the cost of future sonobuoy fabrication.

Cross-Correlation of Acoustic Signals

Presently the portable impact location system utilizes a leading edge detection technique to identify the arrival time of the acoustic signal. If, however, a complete spectrum of data from a calibrated hydrophone were available, a cross-correlation technique could be used to more accurately identify and tag arrival times between sonobuoys, as well as eliminate the need for a permutation program to identify specific impact events. In addition, cross-correlation techniques may provide a means for automated leading edge detection. Currently the process of identifying the impact leading edges is labor intensive, accounting for about 50% (3-4 hours) of the total geolocation postprocessing time.

Summary

ARL:UT has developed and field tested a prototype impact location system. To support this effort, ARL:UT has successfully integrated a low-cost OEM GPS receiver into an air deployable sonobuoy. This disposable sensor provides GPS and acoustic information in realtime, over the existing VHF communication link. Although limited in performance, techniques applied in postprocessing to edit and smooth the sonobuoy GPS data were successful, and allow the portable impact location system to provide scoring of ballistic projectiles with meter level accuracy.

Acknowledgments

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