

DEVELOPMENT OF A GLOBAL POSITIONING SYSTEM/SONOBUOY SYSTEM FOR DETERMINING BALLISTIC MISSILE IMPACT POINTS

Testing of ballistic missile systems requires a method for accurately determining the position of at-sea impact points. Historically, this information has been determined by analyzing the acoustic signals received by a number of sonobuoys floating in the target area. The positions of the buoys were determined by using acoustic ping signals emanating from Deep Ocean Transponders located on the ocean bottom. An improved system is being developed by APL to locate the positions of the buoys using signals received from the Global Positioning System. This will eliminate the need for Deep Ocean Transponders along with the associated ship costs for installing, surveying, and maintaining them.

BACKGROUND

The Sonobuoy Missile Impact Location System has been used for a number of years to determine where reentry bodies, released by ballistic missiles, impact in ocean target areas. An Air Force program was initiated over two years ago to develop an improved system to provide the required information at lower cost. The second phase of the three-phase development program is nearing completion.

Figure 1 is an overview of the original Deep Ocean Transponder/Sonobuoy Missile Impact Location System (DOT/SMILS), which makes use of several types of sonobuoys that are dropped by mission support aircraft. A typical sonobuoy is 4.5 inches in diameter and less than 36 inches long. As the buoy falls free from the aircraft, a small drag parachute deploys and stabilizes the descent of the buoy into the water. At the time of impact, the parachute is released and an antenna is erected. In some buoys, the antenna is located in a small balloon (float) assembly that is inflated by gas from a pressure bottle in the sonobuoy. The balloon provides extra flotation for the buoy and protects the antenna from salt spray.

Concurrent with balloon inflation, the buoy releases a hydrophone assembly that descends to a depth of about 30 feet. The hydrophone picks up acoustic signals generated by other buoys and the sound of each reentry vehicle impact and transmits that information by means of a VHF radio link to the mission support aircraft circling overhead. Some buoys within the array deploy a second hydrophone that injects an acoustic transponder command signal into the water.

Various types of buoys are used in the missile impact location system shown in Fig. 1. The velocimeter buoy measures the velocity of sound in water, while the bathythermograph buoy measures the temperature

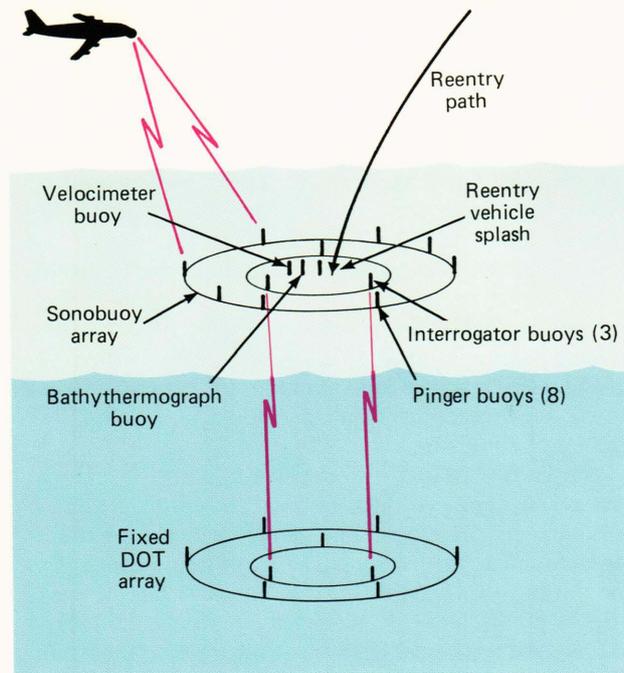


Figure 1 — Overview of the DOT/SMILS system. Up to 12 sonobuoys are dropped in the target area by a range support aircraft. Each sonobuoy is equipped with an acoustic transmitter and a receiver. The acoustic information picked up from the water is transmitted to the aircraft via a VHF radio link. DOTs, previously implanted on the ocean bottom at a known location by a ship, are used to determine the position of the buoys by means of acoustic transmissions. The position of the reentry body impact relative to the buoys is also determined acoustically. When all the information is combined, the geodetic position of the impact can be determined.

of the water as a function of depth. The interrogator buoys are equipped with sonic transmitters that trans-

mit acoustic command signals to DOTs located at known positions on the ocean floor. Ten transponders typically are used in a target area to provide the necessary coverage. The DOTs respond to interrogations by generating an acoustic signal, each DOT responding on a different acoustic frequency. The pinger buoys on the surface are key system components, both receiving and generating acoustic signals. They receive acoustic transmissions from all buoys equipped with acoustic transmitters and also detect the loud acoustic signals generated by the reentry bodies as they strike the water.

Electronic equipment aboard the aircraft is used to monitor the RF signals transmitted by all of the buoys in the water. After being processed, these transmissions allow us to determine the time of arrival of each acoustic signal received by each buoy, as well as the time of acoustic pulse transmission by each buoy. This information can be processed mathematically to yield the position of each buoy relative to the others. In addition, whenever an interrogator buoy generates a command transmission, all transponders within range respond with a high-frequency reply. The responses as received at the interrogator buoy enable an accurate estimation to be made of the slant range from the buoy to each DOT. When the transponders were originally implanted on the ocean floor, their geodetic positions were determined accurately, typically by means of the Navy Navigation Satellite System. By combining that position information with the slant range measurements, the geodetic position of each interrogator buoy can be determined accurately. When the positions of two or more interrogator buoys have been derived, the geodetic positions of all the buoys in the system can be determined because their relative positions are already known.

When a reentry body impact occurs, the resulting acoustic signal is picked up by all buoys. If the relative times of arrival of the signals at the buoys are compared, the impact position can be determined to a high degree of precision.

The DOT/SMILS system described above requires that relatively large ships be used to plant the DOTs, survey their positions, and perform essential maintenance in the target areas far from land. Currently, the transponder position survey requires nearly a week, principally because the Navy Navigation Satellite System is used as the primary position source. To obtain the required accuracy, data from a minimum of 20 satellite passes should be taken and averaged; this requires a number of days because of the system's orbital configuration. In the future, by using the Global Positioning System (GPS) (see the boxed insert) to perform the survey function, the on-station time should be reduced significantly. Relatively large ships will continue to be required for survey and implant, however, because of the remote locations. It is possible to replace inactive DOTs in the array by means of aircraft. Such a system is the Air Launch Deep Ocean Transponder system under development for the Navy. It will reduce maintenance costs for the DOT/SMILS array.

DEVELOPMENT OF THE GPS/SMILS SYSTEM

Several years ago, the Air Force Western Space and Missile Center at Vandenberg AFB investigated alternative approaches to the current system with the aim of reducing or eliminating the cost of implanting the DOTs. A concept called the Global Positioning System/Sonobuoy Missile Impact Location System (GPS/SMILS) (Fig. 2) was found to be very promising, and the Air Force selected APL to develop it.

In that system, the interrogator buoys and the DOTs are replaced by buoys known as GPS transdigitizer buoys (Fig. 3). The buoys not only perform the functions of the pinger buoys, but also receive signals from the GPS satellites and amplify, filter, and down-convert the signals to a low frequency of 20 kilohertz. The signals are then fed via a voltage comparator into

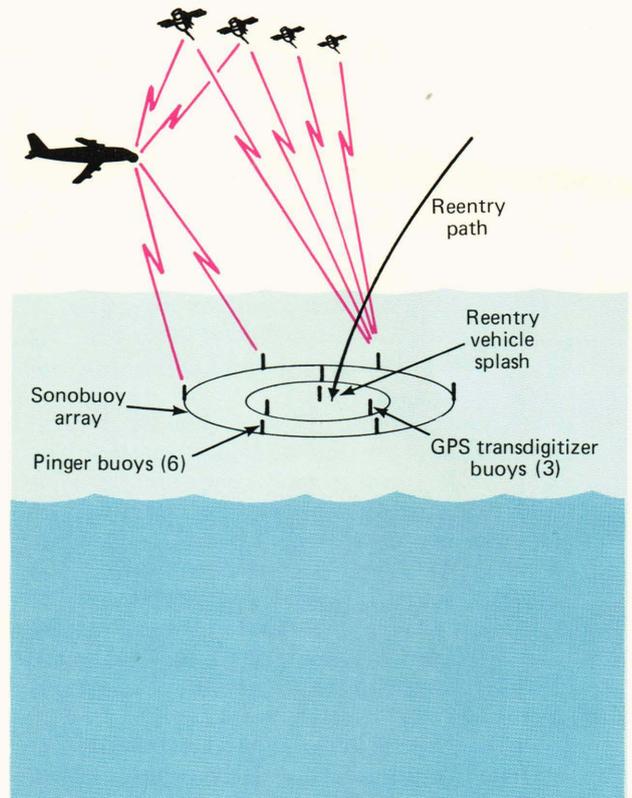


Figure 2 — Overview of the GPS/SMILS system. Buoys are dropped in the target area by a range support aircraft. Three buoys are equipped with transdigitizer assemblies that receive transmissions from GPS satellites, convert the signals to digital format, and retransmit them to the support aircraft. Hardware in the aircraft processes the signals and determines the geodetic position of the three buoys. The other buoys (known as pinger buoys), as well as the GPS transdigitizer buoys, are equipped to transmit and receive acoustic signals. The received acoustic signals are retransmitted to the aircraft for processing. The position of the pinger buoys relative to the GPS transdigitizer buoys is determined by acoustics. When a reentry body impact occurs, its position relative to the buoys is also determined by acoustics. When all the information is combined, the precise position of the impact can be determined.

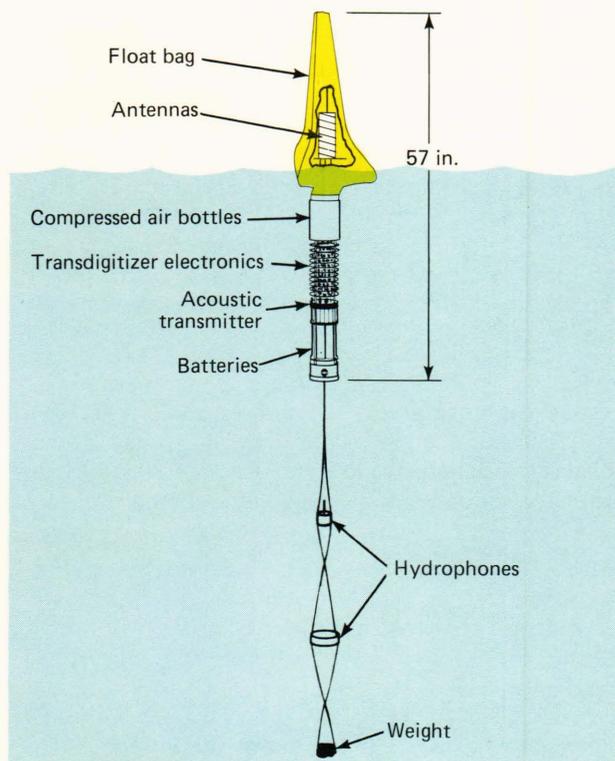


Figure 3 — The GPS/SMILS transdigitizer buoy. The transdigitizer buoy is supported in the water by a float assembly that also contains the GPS antenna and the antenna used to receive commands and transmit data to the aircraft. The middle portion of the assembly houses the buoy electronics, including the transdigitizer, command receiver, data transmitter, acoustic transmitter, and processor. The batteries are located below this assembly. Receiving and transmitting hydrophones are deployed below the buoy.

a 1-bit latch circuit to generate a digital data stream. These data, along with digitized acoustic data, are used to modulate a carrier for transmission of the signals to the system aircraft over a VHF link.

Equipment in the aircraft receives the signals from the transdigitizer buoys, separates out the acoustic data from the GPS data, and processes all the data. The GPS data are fed into a number of tracking channels, each of which tracks the signal from one satellite. The output of the channels is pseudorange and pseudo-range-rate for the satellite-buoy-aircraft path and GPS message data that describe the satellite orbits. The data can be processed mathematically to provide accurate position data for the transdigitizer buoys. The positions of the pinger buoys in relation to the transdigitizer buoys are then obtained using acoustics, in a fashion similar to that used for the original system. The GPS/SMILS system will function more automatically than the earlier system. The advantages are that no ship is required and there is target flexibility, thereby reducing costs.

DESCRIPTION OF THE TRANSDIGITIZER BUOY

Figure 3 is an exploded view of the transdigitizer buoy following inflation of the float bag and release

DESCRIPTION OF THE GLOBAL POSITIONING SATELLITE SYSTEM

The Navstar Global Positioning System is a space-based radio positioning navigation and time transfer system. Its development is being managed by a Joint Program Office at the Space Division of the Air Force Systems Command in Los Angeles. The management team is comprised of Department of Defense, Department of Transportation, and NATO personnel. When fully implemented, the system will consist of a minimum of 18 satellites orbiting at an altitude of 10,900 miles. At that height, the satellites have a period of 12 hours. The satellites will be arranged in six orbital rings of three satellites each. The rings are at an inclination of 55° relative to the earth's equator.

All the satellites continuously transmit at frequencies of 1575.42 megahertz (MHz) (L1) and 1227.6 MHz (L2). The 1575.42 MHz frequency is modulated in quadrature by two pseudorandom-noise coded signals, while the 1227.6 MHz signal is modulated by a single pseudorandom-noise code. To allow the user to determine the position of the spacecraft as a function of time, each satellite transmits a message data stream that contains the orbital elements plus data to allow compensation for spacecraft clock errors. The message data are added to both of the pseudorandom codes.

of the hydrophones (acoustic transducers). The antenna system, located in the float bag, must provide for receipt of signals from the GPS satellites, receipt of VHF command signals from the aircraft, and transmission of the data back to the aircraft at VHF. The antenna system consists of a backfire helix antenna for reception of the 1575.42 megahertz (MHz) transmission from the satellites. A monopole antenna located at the center of the helix is used both for reception of VHF command signals and transmission of data to the aircraft. The tops of both the helix and the monopole antennas are tied to the top of the float assembly. At the time the buoy is dropped from the aircraft, the float bag and antenna are folded into a compartment at the top of the buoy. When the buoy strikes the water, the float is inflated by the release of air from bottles of compressed air located underneath the float storage area, and the antennas are erected automatically.

Underneath the float storage area is a group of boards containing the electronics for the transdigitizer, including the transmitter and the command receiver. There is also a board containing circuitry for processing the acoustic data received from the hydrophone. The board at the bottom of the stack houses the acoustic transmitter. Below the electronics is a compartment housing the batteries.

At the bottom of the buoy is a chamber that houses the acoustic transducer, a damper, and the cable prior to deployment. One transducer serves as a damper. Part of the cable connecting the buoy to the damper

is elastic and can readily be stretched. The function of the damper and the cable is to keep the hydrophones stationary while the buoy rides up and down on the ocean swells, in order to reduce the water noise that would occur if the hydrophones were riding up and down in the water following the vertical motion of the buoy.

Figure 4 is a block diagram of the electronics within the transdigitizer. The 1575.42 MHz signals received by the antenna are filtered, amplified, and heterodyned to a first IF frequency of 75.42 MHz. This signal is further amplified and heterodyned down to a frequency of 20 kilohertz. It is then passed through a 1 MHz low-pass filter/amplifier and thence to a zero crossing detector that provides a digital output. This signal is sampled by means of a flip-flop that is clocked by a 2 MHz signal. The digital signal is then fed into one input of a quadrature modulator where it modulates one phase of the uplink carrier.

The second input to the quadrature modulator is an asynchronous digital data stream generated by processing the acoustic data received by the hydrophone. The signal from the modulator is amplified to provide an RF output power of 2 watts to the antenna.

AIRCRAFT EQUIPMENT

Figure 5 is a block diagram of the equipment required in the aircraft to support the operation of the

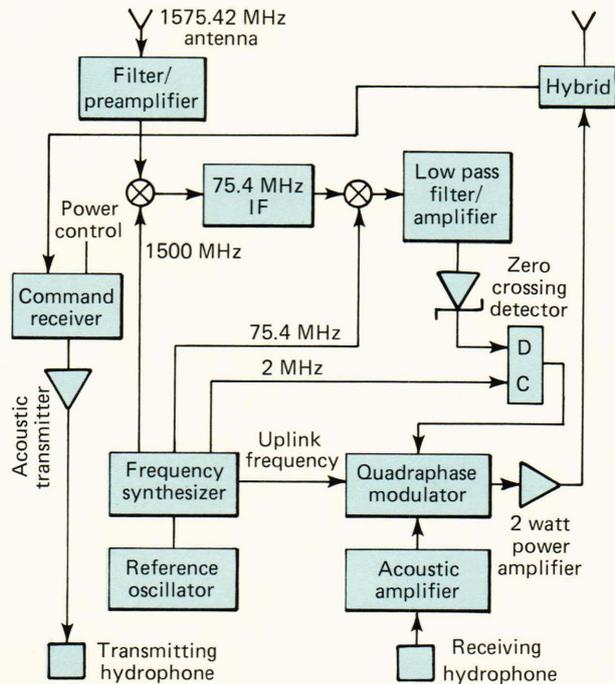


Figure 4 — Block diagram of the buoy electronics. The signal received from the GPS satellite at 1575.42 MHz is filtered, amplified, and converted to low frequency by mixing with signals generated in the frequency synthesizer. The signal is then sampled and converted to two-level digital format. The acoustic data picked up from the water are amplified, filtered, and converted to digital format. These and the GPS data are transmitted to the aircraft via an RF link. The buoy is also equipped with a command receiver and an acoustic transmitter.

system. The equipment will be housed in a modified Boeing 707 aircraft along with other range equipment. The aircraft will be equipped with the electronics shown in the diagram and also with the facilities to carry and launch sonobuoys. It will also have special antennas to receive the signals from the buoys and an antenna to receive signals directly from the GPS satellites. The former antennas will be mounted under the fuselage, while the latter will be top mounted.

The signals received from the buoys are fed to two receiver groups. The first is a standard antisubmarine warfare receiver used for receiving the signals from all buoys except the transdigitizers. The transmissions from the transdigitizer buoys are processed by a specially designed 6-channel uplink receiver that filters and amplifies the signals and separates the acoustic data from the GPS data. The GPS and acoustic data are recorded by a standard 14-track analog recorder.

The GPS data are also fed to a 12-channel digital tracking system. Twelve channels are required in order to allow the simultaneous processing of four satellite signals received from three transdigitizer buoys. The system also computes the position of each transdigitizer buoy.

A second bank of digital trackers is used to process the signals received directly from the satellites. The principal function of this subsystem is to determine the effect that ionospheric refraction has on the

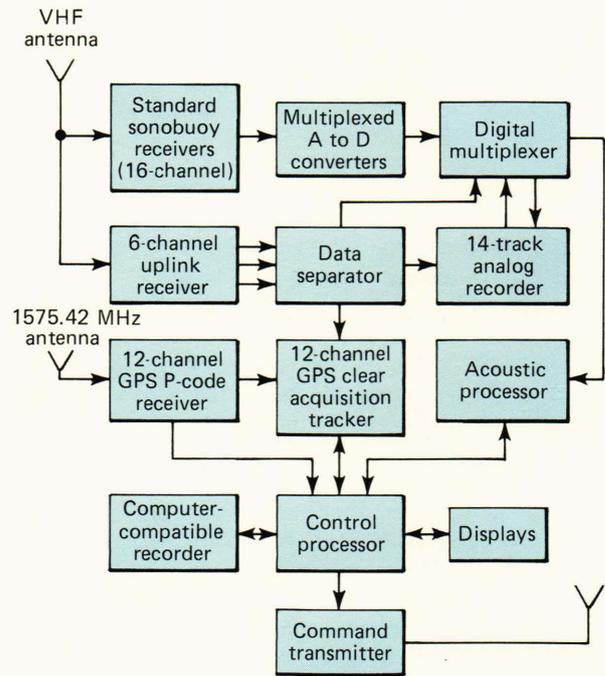


Figure 5 — Block diagram of the aircraft SMILS system. Equipment aboard the aircraft controls the buoys in the water by means of a command transmitter, and receives both acoustic and digitized GPS satellite data from the buoys. The relayed GPS signals are tracked in the GPS tracker and the positions of the three buoys equipped with transdigitizers are determined. The acoustic data are processed in the acoustic processor to provide the relative position of each buoy to all the other buoys. The system is equipped with necessary recorders and operator displays.

1575.42 MHz transmission from each satellite. This is accomplished by processing the 1575.42 and 1227.6 MHz pseudorange and range-rate signals from each spacecraft to estimate the refraction effect. The refraction data are used to correct the 1575.42 MHz signals received at the transdigitizer buoys. Studies have indicated that at the maximum range of the aircraft from the buoy, the refraction effects at the aircraft and at the buoy will be essentially identical, allowing the technique to be used. In addition to providing the refraction data, the receiver will also provide the aircraft's position; these data will be used to ensure accurate dropping of the sonobuoys in the intended reentry area.

The acoustic processor determines the acoustic transmission time between the various buoys in the array. The information is used to compute the relative position of the buoys. The position data and the transdigitizer position data are fed to the control processor, which combines the information to provide the geodetic position of the buoy. The acoustic processor also processes the splash data from the reentry bodies and computes the geodetic coordinates of the reentry body splash points. The computed results are recorded on a computer-compatible magnetic tape recorder. Displays of buoy status are provided for the operator. There is also a command transmitter that is used to control the transdigitizer buoys.

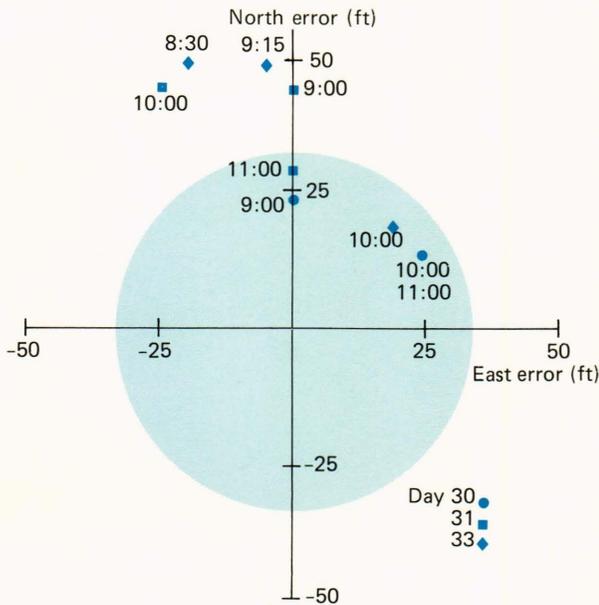


Figure 6 — Results of the navigational test at St. Croix. During a system test there, a transdigitizer assembly located at a surveyed point was used to collect signals from the GPS satellites in view. The data were processed to determine the location of the point. Shown is the difference between the computed position and the position as determined by a local survey, for a number of data samples collected over a 3-day period. The cause of the bias, which can readily be seen, has yet to be determined but may be in the local survey.

POSTMISSION PROCESSOR

A postmission processing system will also be developed. The processing facility will use many of the same hardware and software modules as the aircraft systems and will be equipped with a large minicomputer for performing the various acoustic and position computations. A larger computer will allow more sophisticated software to be used in the calculations, resulting in improved accuracy.

STATUS OF THE PROGRAM

The program has been under way for over two years and is in phase two of a three-phase development program. During phase one, two sonobuoys were designed and fabricated, along with a rudimentary version of the aircraft equipment. For the phase one test, only GPS-related equipment was provided. During that phase, it was felt that there was no need to test the acoustic portion of the system because similar techniques have been used in the past.

Testing of the phase one system was performed at the St. Croix, V. I., test range in February 1983. Although two buoys were available, only one was deployed in the ocean at a time. However, a second transdigitizer was operated at the land-based collection site to provide reference data. The recording subsystem was capable of recording signals simultaneously

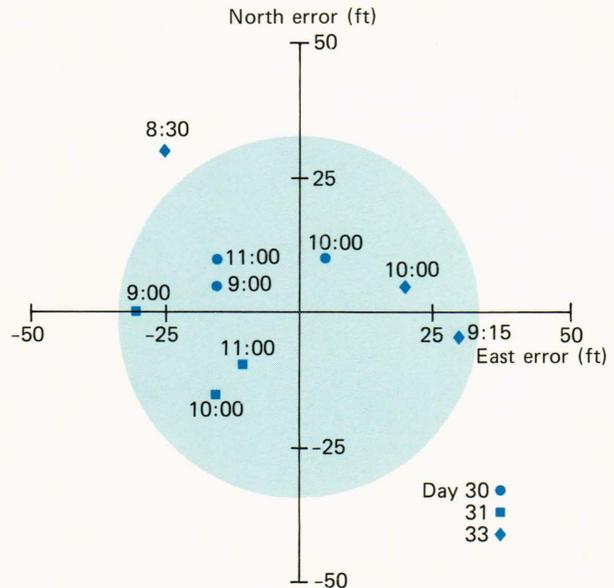


Figure 7 — Relative position results. During the test at St. Croix, a reference transdigitizer located at the tracking site was operated concurrently with a buoy in the water. Tied to the GPS transdigitizer buoy by a 10 foot cable was a reference buoy provided by the test range. Its position was determined by an acoustic system operated by the test range. The relative positions of the two transdigitizers were determined by the GPS signals and by the range acoustic system, which was tied to the local survey. Plotted on the figure is the difference between the two differences. Part of the error results from the cable between the reference buoy and the GPS transdigitizer buoy.

from both transdigitizers. Only a single-channel tracker was available at the field site; it provided for system checkout, but detailed processing had to be performed after the test.

The results of the phase one test were very satisfactory. Figure 6 is a bullseye pattern showing a number of typical fixes. The difference between the position determined by GPS and a survey is shown. The slight bias in the data can readily be seen; the source of the bias has yet to be determined. Figure 7 is a bullseye plot showing the error in the translocated buoy positions. To generate the plot, the positions of the reference transdigitizer and the buoy were first determined by tracking the recorded signals from three or more GPS satellites as received by each transdigitizer. The data were processed, and the error in the computed position of the land-based antenna was subtracted from the computed position of the floating transdigitizer buoy. These positions were compared with the acoustic position data provided by the St. Croix range through the use of pinger buoys attached to the trans-

digitizer buoys via a 10 foot tether. The resulting differences are plotted in Fig. 7. A significant part of the error shown is due to the fact that the range buoy could be as much as 10 feet from the transdigitizer buoy. Note, however, that there is essentially no bias in these data.

The second phase of the program consists of developing an improved buoy that has full capability (including the reception and generation of acoustic signals) and prototype aircraft equipment. Testing of the complete system, including developmental buoys and aircraft equipment, will be carried out at St. Croix.

During the third phase of the program, operational hardware will be fabricated. APL will generate a full set of specifications that the Air Force will use to procure commercial production quantities of transdigitizer and pinger buoys. APL personnel will serve as technical advisors to the Air Force for that procurement. APL personnel will also oversee the fabrication of six sets of aircraft equipment and will generate the operational software.