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THE ADVANCED RANGE INSTRUMENTATION AIRCRAFT/SONOBUOY MISSILE IMPACT LOCATING SYSTEM

A Sonobuoy Missile Impact Locating System (SMILS) determines impact location and time in remote ocean target areas. Acoustic signals from ocean-surface sonobuoys are relayed via radio frequency to instrumented aircraft for recording and analysis. Immediate mission assessment (quick-look) is done aboard the aircraft, and detailed analysis is done later by ground-based computer processing of the recorded data. The Applied Physics Laboratory has developed an airborne hardware and software system for providing an immediate best estimate of impact location and has also developed a ground-based computer system and software for postmission analysis of data recorded on the aircraft during a SMILS operation.

INTRODUCTION

Testing the performance of ballistic missile weapons requires determination of the time and location of impact for each test body and telemetry reception from instrumented reentry bodies. Such tests measure impacts targeted to remote ocean areas and are essential both to weapon evaluation for systems under development and to qualification of operational systems.

Sonobuoys deployed on the ocean surface determine impact location by detecting the acoustic disturbances created by impacts. Signals are relayed via radio links to suitably instrumented aircraft, where they are used for initial test result estimates and recorded for later, more detailed analysis.

To provide a geodetic reference, the surface sonobuoy pattern is deployed over an array of deep-ocean transponders (DOT's) located on the ocean floor. Acoustic signals returned from the DOT's in response to interrogating transmissions from one type of surface sonobuoy are used to locate the surface sonobuoy pattern relative to the DOT's. Acoustic signals transmitted by a second type of sonobuoy and received via surface ducting layers are used to locate the surface sonobuoys relative to each other. With the surface sonobuoys located, the detected disturbances created by the impacts of the reentry bodies can then be analyzed to determine impact location and time. This technique and the equipment that implements it is called the Sonobuoy Missile Impact Location System (SMILS). The basic information-gathering process for surface sonobuoy location is sketched in Figure 1, and Figure 2 diagrams the detection of impact acoustic noise by the surface sonobuoys and relay of these signals to instrumented aircraft by radio transmission.

ADVANCED RANGE INSTRUMENTATION AIRCRAFT

Advanced Range Instrumentation Aircraft (ARIA) are large four-engine jets (KC135 or 707 type) instrumented to provide an airborne platform at high altitudes for receiving telemetry from test vehicles. These aircraft can operate over remote ocean areas and establish telemetry communication with instrumented test bodies during reentry.

A key feature of the airborne telemetry capability provided by the ARIA is a seven-foot-diameter dish antenna that can slew and autotrack at high angular rates. This dish provides pointing directivity and signal margin, allowing acquisition and tracking of telemetry signals received from a rapidly descending vehicle.

The ARIA's utility as an effective airborne telemetry platform is long established. The 4950th Test Wing at Wright–Patterson Air Force Base in Ohio, operators of the ARIA fleet, asked APL to develop a SMILS capability for ARIA so that these aircraft could also collect and analyze data to assess impact accuracy. The ARIA/SMILS would then become an effective test-range asset providing airborne telemetry, impact location, and optical coverage for ballistic missile testing. The ARIA/SMILS will supplement the support of the SMILS operation currently provided by Navy P3 turboprop aircraft.[1,2]

Figure 3 is a photograph of an ARIA in flight. The enlarged nose section houses the telemetry antenna. Radio frequency transmissions from the surface sonobuoys are received via redundant blade antennas on the underside of the aircraft. Figure 4 shows the equipment mounted inside the aircraft. The first operational ARIA/SMILS aircraft includes a Global Positioning System (GPS) navigation capability provided by the GPS instrumentation navigator (GIN). The GIN is a prior development carried over to the first aircraft only.

DATA COLLECTION AND PROCESSING

Acoustic Data

The nominal surface-buoy deployment pattern for an ARIA/SMILS operation is shown in Figure 5. As indicated in Figure 1, the three types of surface sonobuoys shown

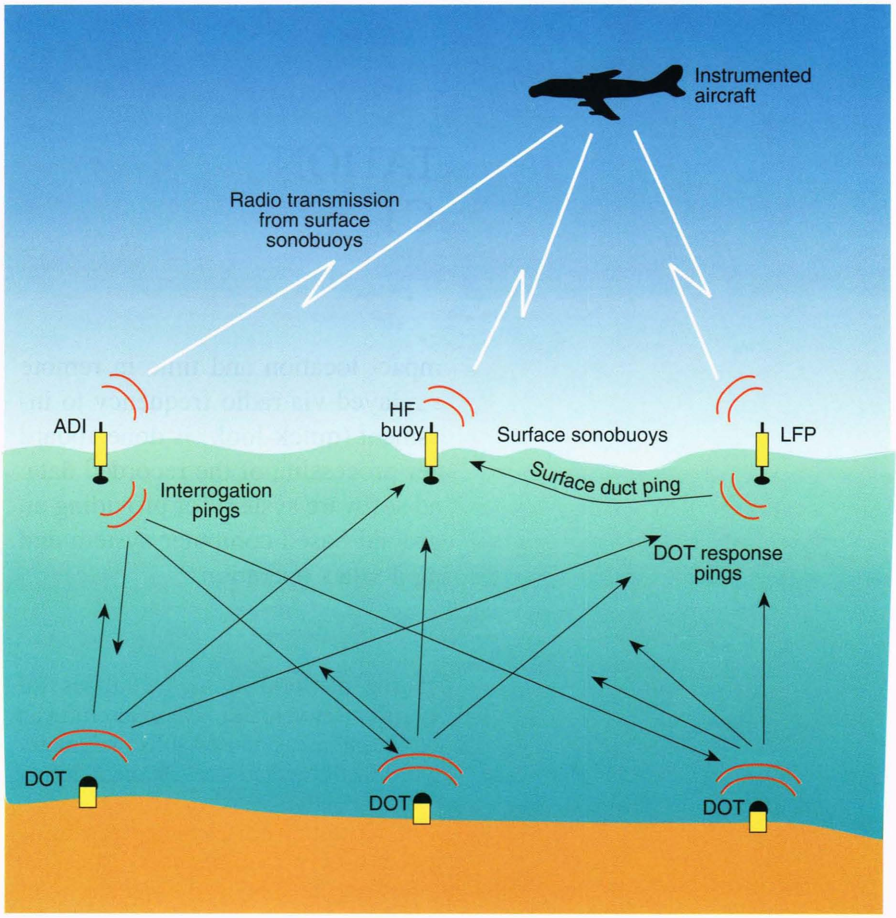

Figure 1. Diagram of the information process used to locate surface sonobuoys in which ADI buoys transmit interrogation pings to DOT's and LFP buoys transmit pings along the surface duct; HF buoys receive both surface pings and DOT responses. In addition to pings, all surface sonobuoys detect impacts, bubble collapse, bottom-bounce reverberations, and other acoustic noise. The DOT's receive interrogation pings from ADI's and respond at different frequencies (DOT = deep-ocean transponder; ADI = air-deployable DOT interrogator; LFP = low-frequency pinger; HF = high-frequency buoy).

are a high-frequency (HF) buoy, a low-frequency pinger (LFP), and an air-deployable DOT interrogator (ADI), which transmits pings to activate the DOT's. Each interrogated DOT returns a signal at a different frequency. (Any DOT's responding at the same frequency are widely separated.) The LFP transmits lower-frequency pings to other surface sonobuoys via surface duct propagation. The HF is a buoy that can detect both DOT responses and LFP pings. In addition to detecting DOT responses and LFP pings (received signals), the ADI and LFP buoys generate marker tones that indicate the initiation of a transmitted ping. Both the transmission and reception of pings can therefore be related to the time of their occurrence by associating acoustic-event detection with a standard time base, that is, the IRIG-B (inter-range instrumentation group B) time code. All buoy receivers can detect impacts, bubble collapse, bottom-bounce reverberation, and other acoustic noise. All detected events are referenced to the same standard time base; valid detections are separated from false alarms during subsequent processing and analysis.

The surface sonobuoys are located (navigated) relative to the DOT's and to each other using two distinct acoustic signal characteristics: frequency and ping rate. Each interrogated DOT responds at a different frequency; each LFP pings at the same frequency but at a different repetition rate. The basic buoy location (navigation) technique is to associate received pings with their source. All marker tones, received pings, and other acoustic events detected by each surface sonobuoy are transmitted to the ARIA/SMILS system on an RF channel selected to receive the RF for that buoy. The standard time base (IRIG-B), to which all detected acoustic events will be referenced, is carried aboard the aircraft.

Sound Velocity Measurement

Inherent in acoustic data analysis for sonobuoy navigation and impact location is the translation of time differences between events into distances, which requires knowledge of acoustic propagation velocity. This velocity is not constant with depth and depends on temperature differences between layers near the surface and, more directly, on salinity and pressure at greater depths. Special buoys are therefore deployed to measure acoustic propagation as a function of depth below the surface as the buoys descend. These data are obtained before deployment of the surface sonobuoys over the DOT array. Using time differences between detected events and knowledge of sound propagation velocity, SMILS analysis determines buoy location and, from buoy position, impact location and time.[3]

Meteorological Data

The ARIA is also equipped to deploy a radiosonde. The radiosonde then descends by parachute. Upon reaching the ocean surface, the instrument package is released to ascend by balloon. Meteorological data and wind veloci-

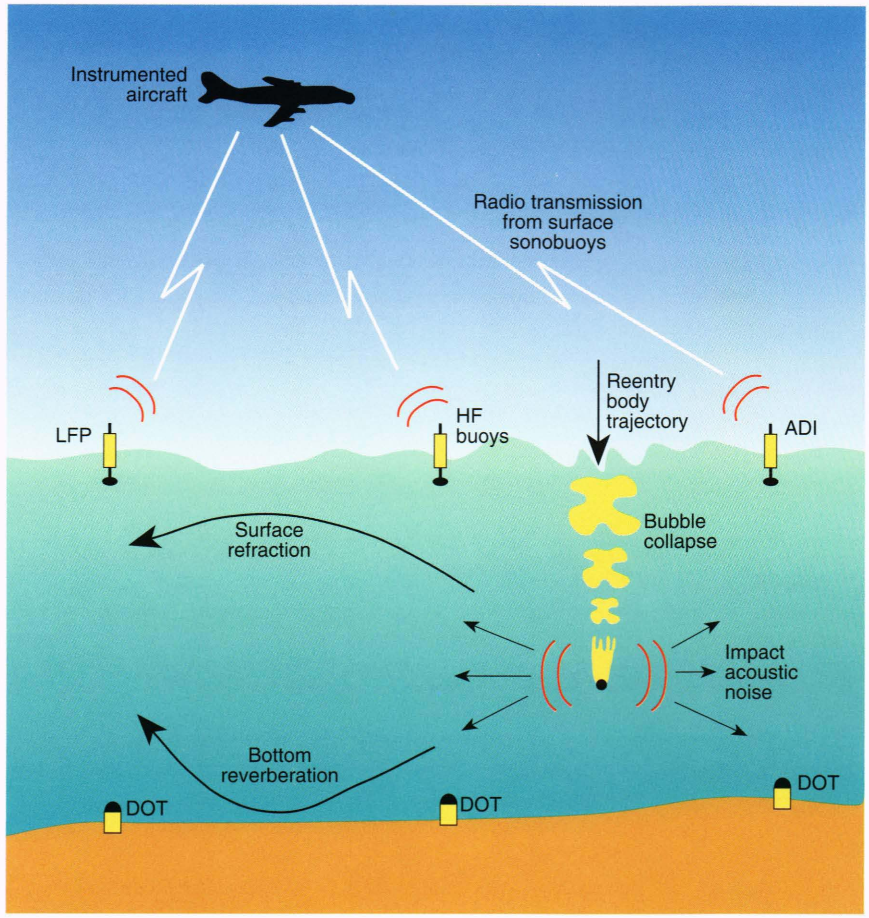

Figure 2. Diagram of the impact detection process. The deep-ocean transponders (DOT's) have no active role in impact detection (ADI = air-deployable DOT interrogator, LFP = low-frequency pinger, HF = high-frequency buoy).

Figure 3. The Advanced Range Instrumentation Aircraft (ARIA).

ty are obtained as functions of altitude during the ascent, transmitted back to the aircraft, and processed by a special-purpose receiver/computer for later use in mission analysis.

Data Processing

As discussed, SMILS data processing requires that acoustic events be detected, the time of detection marked, and the source of pings identified. Typically, the number of acoustic signals to be identified and processed is quite large, because many surface-buoy pings and DOT responses are generated and used for navigation of the surface sonobuoys. (In principle, all DOT's can respond to interrogation pings from all ADI's, and all buoys can detect all surface duct pings. The large number of signals requires significant sorting of received pings and their sources on the basis of frequency or the ping repetition interval. In fact, separation distance and acoustic propagation effects reduce the number of DOT responses and surface ping detections.) Multiple and almost simultaneous impacts are accompanied by "bubble collapse" and bottom- and surface-bounce reverberations (Fig. 2). Pings and impacts are valid signal detections, whereas bubble collapse, surface and bottom reverberations, or other acoustic noise are false alarms and must be rejected if practical. Frequency content is the principal means by which surface and bottom reverberations are rejected. Because the bubble-collapse signal is strongly time-correlated to actual impacts, it can be rejected on that basis. Some false alarms are expected, however, as generally more than a minimum number of buoys will detect pings and impacts. Ambiguous solutions (impacts, for example) can be rejected by using least-squares analysis and threshold settings that reject extreme points.

THE AIRBORNE FLIGHT SYSTEM AND THE POSTMISSION ANALYSIS SYSTEM

The ARIA/SMILS installation consists of two basic elements: the airborne flight system and the ground-based postmission analysis system (PMAS). The essential re-

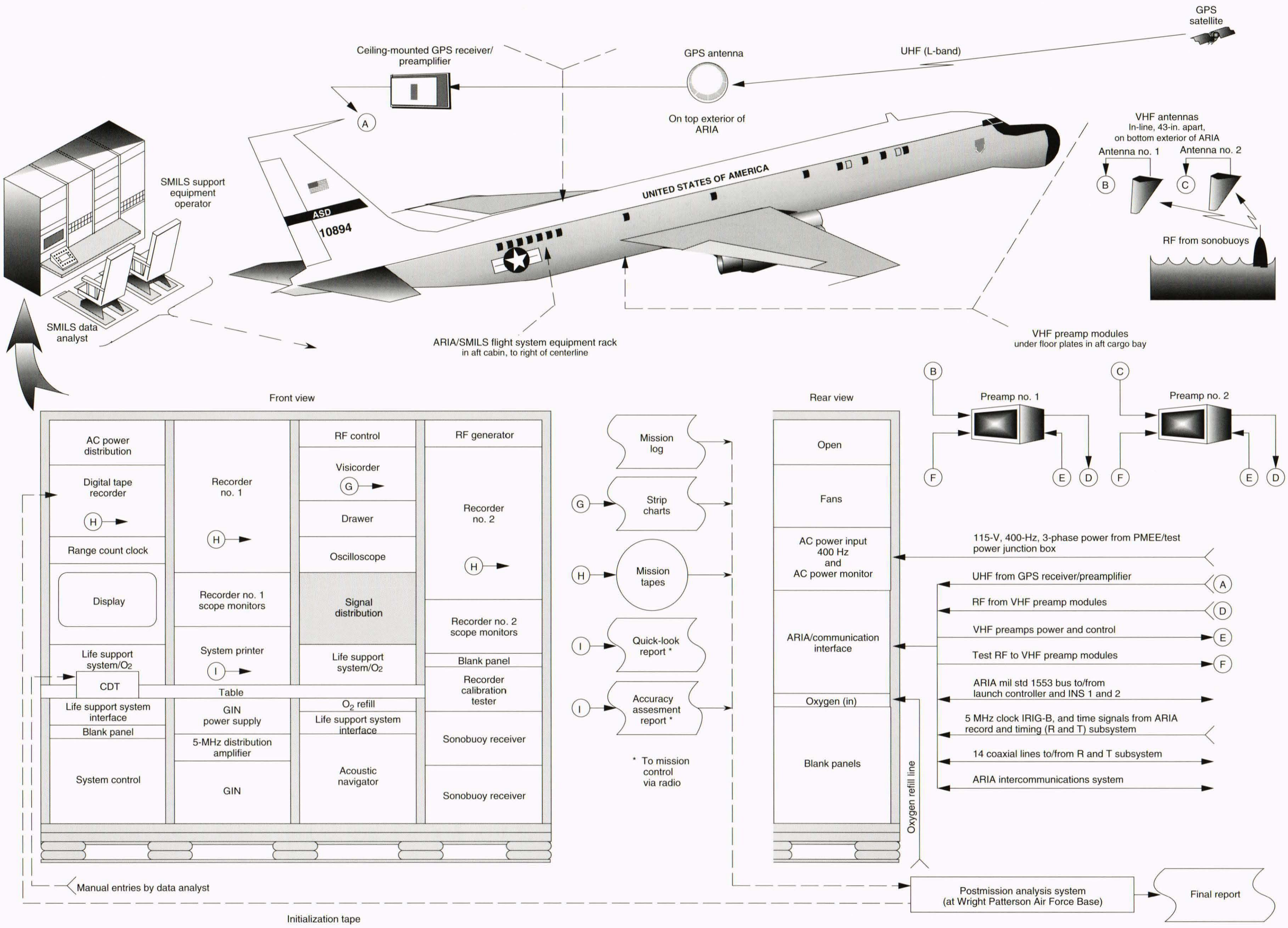

Figure 4. Illustration of the Sonobuoy Missile Impact Locating System (SMILS) equipment mounted inside the Advanced Range Instrumentation Aircraft (ARIA) (GPS = Global Positioning System, GIN = the GPS instrumentation navigator, CDT = the command and display terminal, IRIG-B = inter-range instrumentation group B, INS = inertial navigation system).

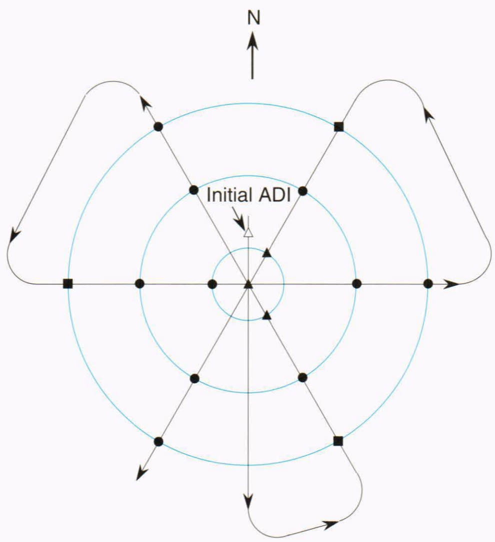

Figure 5. Nominal Advanced Range Instrumentation Aircraft/Sonobuoy Missile Impact Locating System (ARIA/SMILS) sonobuoy deployment pattern. Triangles indicate air-deployable interrogator (ADI); circles, low-frequency pingers; and squares, high-frequency buoys.

quirement for the flight system (prime mission requirement) is to obtain a tape recording of the acoustic signals received from the surface sonobuoys. As described, these acoustic signals are relayed to the aircraft via RF transmission from the sonobuoys. The standard time code is also recorded to allow detected acoustic events to be marked by the time of their occurrence.

Other requirements for the flight system include obtaining the sound velocity profile, accurately deploying the air-launched surface sonobuoys over the DOT array, and obtaining an immediate best estimate of impact location and time. The acoustic navigator subsystem of the flight system locates (navigates) the surface sonobuoys, detects impacts, and provides an in-flight quick-look estimate of impact location and time. These functions are performed with limited sampled data memory and essentially fixed-detection algorithm parameters.

The PMAS is a computer installation with analog-to-digital interface hardware and analysis software for processing the tape-recorded acoustic signals obtained by the flight system. It is located at the 4950th Test Wing, Wright–Patterson Air Force Base, Ohio. The tape playback control and analysis software selects active data intervals, locates (navigates) the surface sonobuoys relative to the DOT's, locates impacts in both position and time, and generates hard-copy test results in both tabular and pictorial formats. The PMAS processes the database in considerably more detail and with more precision than can be done by the acoustic navigator subsystem. The PMAS employs adjustable parameters and stored data and is not constrained to analyzing events as they occur. The APL-developed flight system and PMAS constitute the SMILS instrumentation segment of ARIA/SMILS.

A block diagram of the SMILS flight system is shown in Figure 6. This flight system uses two high-quality tape recorders to provide a total of twenty-eight recording channels for storing the acoustic signals received via RF relay from the surface sonobuoys. The interval required to record the data is normally about half an hour. Typically, sixteen or more sonobuoys are deployed, and signals from selected buoys and the time code standard are recorded. The time reference is redundantly stored on one channel of each recorder, leaving twenty-six channels available for data. One channel on each recorder is reserved for a servo reference to maintain accurate playback speed control, which allows eight buoy signals to be recorded redundantly.

The RF receiving system is fully redundant, including two separate antennas, two preamplifier links, and four receivers, each with multiple channels. These elements help to ensure that the ARIA/SMILS flight system will achieve its primary mission objective of recording all data necessary for analysis of reentry vehicle impact location and time by the PMAS. The system control subsystem provides displays. The operator interface establishes waypoints for aircraft maneuvers and buoy deployment and transmits buoy release signals to the launch equipment.

Test Program Results

As of mid-1991, both the flight system and PMAS have been exercised in controlled tests and in subsidiary support of actual reentry body tests. The PMAS, operated by 4950th Test Wing personnel, has demonstrated the accuracy, timeliness, and flexibility expected in processing recorded data; it is now considered operational. The flight system has successfully performed the routine tasks of aircraft control, buoy deployment, and data recording. During these tests, the acoustic navigator of the flight system has located surface buoys in real time and determined impact locations for quick-look mission assessment, but not as yet with consistency or acceptable accuracy. Certain software changes have been implemented that await further testing before the acoustic navigator is declared operational.

System Control

Aircraft control during buoy deployment is guided by the system control subsystem of the flight system. The system control subsystem is linked to the inertial navigation system (INS) of the aircraft to provide the waypoint sequence that will be followed in laying the sonobuoy pattern. Waypoints are designated navigation points that the aircraft will fly from and to as it maneuvers to drop the air-deployable sonobuoys. Certain waypoints are actual buoy drop points where system control sends a buoy release signal to the buoy launch equipment located at the rear of the aircraft.

The system control subsystem provides much of the operator interface for the ARIA/SMILS flight system. Menu selection and data entry are via a pressure-sensitive two-dimensional display that allows the operator simply to press a designated option to call up certain data or to give a command. A second, separate two-dimensional display presents graphic patterns in addition to tables and lists to indicate status. For example, the aircraft track buoy deployment pattern in Figure 5 is generated and dis-

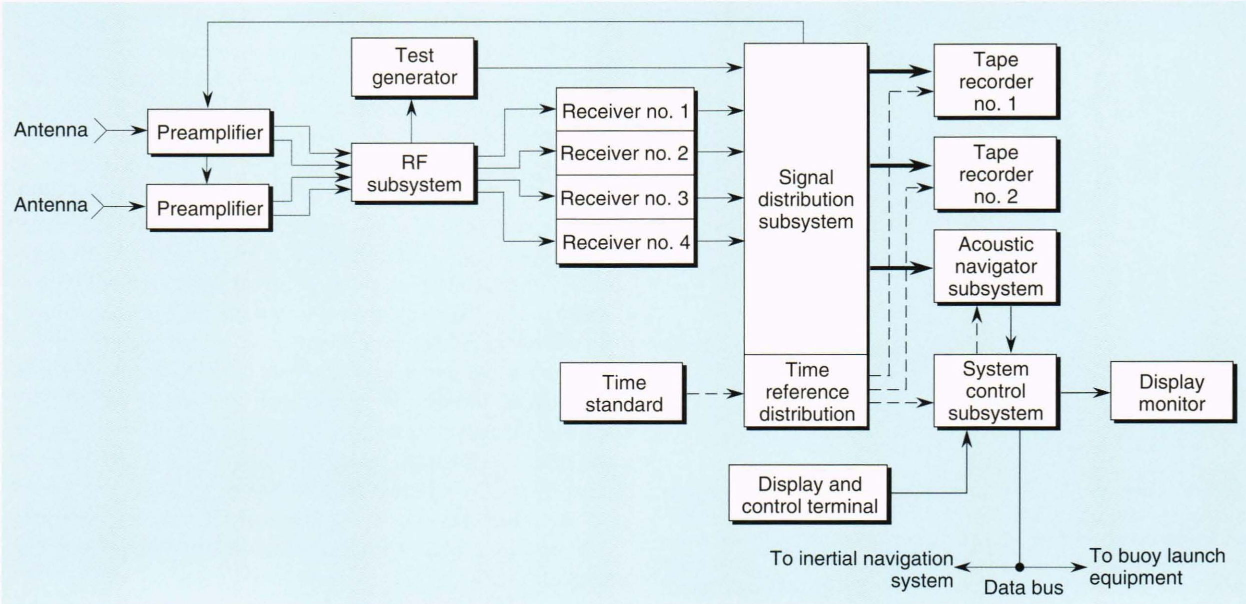

Figure 6. Block diagram of the Advanced Range Instrumentation Aircraft/Sonobuoy Missile Impact Locating System (ARIA/SMILS) Airborne Flight System.

played during the buoy launch process. Figure 7 is a photograph of the system control display showing a plot of a simulated aircraft track and buoy launch sequence. Figure 8 shows a sound velocity profile as displayed by system control. This display combines computed and historic data. An example of menu selection for operator entry is shown in Figure 9. Figure 10 is a display of buoy locations required for a "reseed" operation, in which failed sonobuoys must be replaced. These displays were generated as part of development testing, not during an actual flight test.

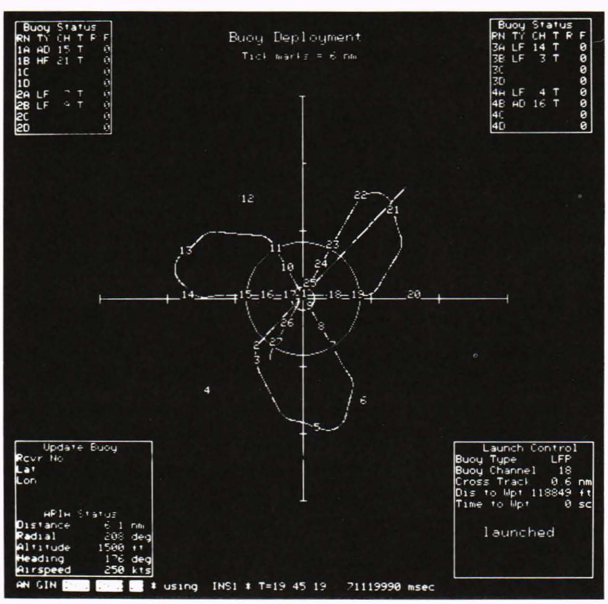

Figure 7. Aircraft track and buoy launch sequence as displayed by system control (LFP = low-frequency pinger, AN = acoustic navigator, GIN = Global Positioning System instrumentation navigator, INS = inertial navigator system, T = time, Wpt = waypoint).

Acoustic Navigator

The acoustic navigator subsystem is the flight system counterpart of the ground-based PMAS. The acoustic navigator detects and processes acoustic events as they occur, that is, in real time, to locate (navigate) the surface sonobuoys and give an immediate best estimate of impact location and time. Input to the acoustic navigator comes directly from the surface-buoy channel receivers.

Because the acoustic navigator must process acoustic events as they occur, frequency-scanning windows and integration times for acoustic-event detection are constrained. This subsystem has therefore been developed as

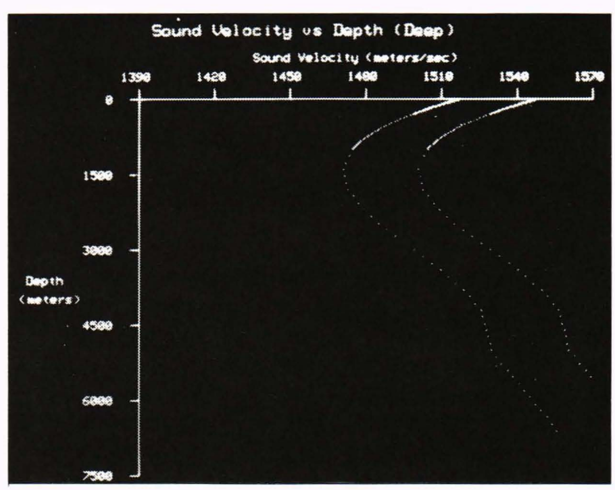

Figure 8. Sound velocity (SV) profile computed by the acoustic navigator and displayed by system control.

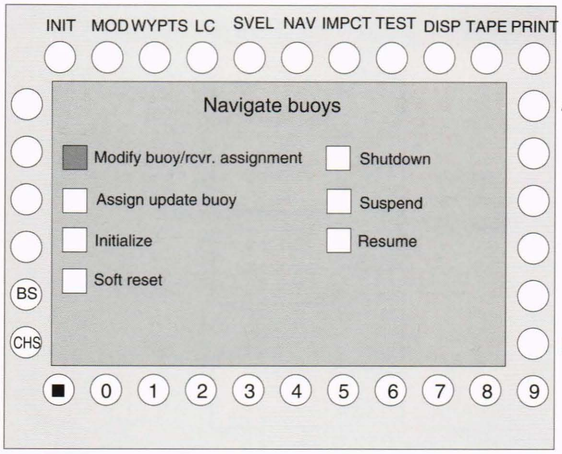

Figure 9. Example of menu and selection made by the operator during buoy navigation. The operator makes a selection by pressing the control next to the appropriate choice (INIT = initialize the menu; MOD = modify parameters menu; WYPTS = waypoints menu; SVEL = sound velocity menu; NAV = navigate buoys menu; IMPCT = impact location menu; DISP = display menu; TAPE = magnetic tape recorder menu; PRINT = printer menu; ACK = acknowledge message; ENT = enter; CHS = change sign; BS = backspace).

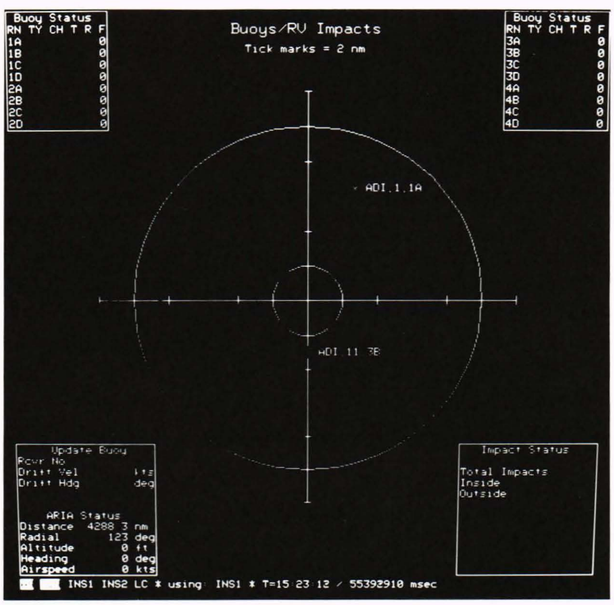

Figure 10. Display generated during "reseed" development tests where failed sonobuoys must be replaced (RV = reentry vehicle; ADI = air-deployable DOT interrogator).

a high-speed, special-purpose digital computer that converts analog input to digital samples and performs all required computations during limited time intervals. As noted, the analog input is received directly from the buoy receiver channels during the SMILS mission operation. The acoustic navigator can play back tapes of mission data later for verification checks or failure recovery.

The digital sampling rate for the analog inputs to the acoustic navigator is 64,000 samples per second, with each sample comprising 12 bits. The processing span is 256 samples; all computations are done for the 256 samples in 4 ms. Fast Fourier transform techniques are used wherein the acoustic energy level in selected bandwidths is determined in rapid sequence by discarding previous samples and examining the next set. A detection is declared when, during this scanning process, the energy level exceeds previous values by a controlled ratio. Whereas ping detection uses narrow bandwidth scanning, impact detection uses somewhat broader bandwidths. The time resolution obtained for marking acoustic events is ± 2 ms or a distance of about ± 3 m.

The acoustic navigator locates (navigates) a subset of the surface sonobuoys to allow an immediate estimate of impact locations and time. The general buoy navigation sequence is first to detect the signals returned from at least three DOT's in response to interrogations by a selected ADI buoy (prime ADI), after which other sonobuoys can be navigated from DOT returns in response to the selected ADI.

So-called lost LFP's are found by using LFP's propagated near the surface. This process must use the difference in ping repetition interval for each LFP as the unique signal characteristic for source identification, because the pings are all at the same frequency. A similar process locates the lost HF buoys, which are acoustic event receivers only.

Another function of the acoustic navigator is to generate the acoustic propagation velocity profile from the signal received from the sound velocity buoy (Fig. 8). The velocity profile can influence surface sonobuoy deployment and can be applied to the solutions for surface-buoy navigation and impact location.

Signal Distribution

The RF channel for each sonobuoy is selected at the appropriate sonobuoy receiver and routed to both the acoustic navigator input and the tape recorders by the signal distribution subsystem. This subsystem allows a number of combinations of receiver channels (buoys) to be prefiltered and routed to the acoustic navigator. Tape-recorder tracks are also selected and routed directly through signal distribution. The receiver-channel connections to tape tracks and to acoustic navigator channels are made through signal distribution via an external patch panel that is preconfigured for the mission.

Radio Frequency Subsystem

The RF subsystem provides two independent (redundant) antenna and preamplifier paths to the sonobuoy receivers. The antennas use a blade-type aerodynamic radome and are attached to the underside of the aircraft. The preamplifiers are mounted internally, near the antennas, and a test-signal injection port is included in each preamplifier. The preamplifier outputs are routed to the RF subsystem, where one or the other is selected and distributed to the sonobuoy receivers. Each sonobuoy receiver channel can be tuned to a selected buoy; these receivers are commercial units developed for sonobuoy signal reception.

POSTMISSION DATA ANALYSIS

The ground-based PMAS, like the acoustic navigator subsystem, converts analog acoustic input data into digital format for processing and analysis. In contrast to the airborne acoustic navigator, however, the PMAS is not limited to acoustic event detection as events occur (real time) or during a single tape-playback pass. The PMAS uses only recorded data as input, specifically those data obtained by the flight system during the mission. These recorded data are stored in digital format and can be retrieved for detailed processing. An entire sequence of acoustic event signals over active time intervals can be examined, allowing much better noise smoothing, selection of detection parameters, and rejection of ambiguous solutions. The time resolution of acoustic events with PMAS processing is 0.125 ms for pings and 1 ms for impacts, which corresponds to distance resolution of about 0.2 m for pings and 1.5 m for impacts. Figure 11 presents a block diagram of the PMAS.

The first step in postmission data analysis as performed by the PMAS is to detect and time-mark pings. Marker tones, DOT responses, and LFP pings (received) are all detected during playback of the mission tape. First-pass detections are reexamined using stored data. For pings, a narrow-bandwidth correlation process using fast Fourier transform techniques is used to define the time of occurrence. For impacts, the acoustic-event data over a selected time interval are scanned for power-level changes in selected frequency regions, thus providing discrimination between impacts, bubble collapse, and reverberations.

Figure 12 shows a recording of an acoustic ping, and Figure 13 shows an expanded scale plot of a ping leading edge. This expanded scale plot was obtained from digitized data held in PMAS memory. Figure 14 shows an example of an expanded-scale DOT response, and Figure 15 shows the acoustic noise burst of an impact.

After the times for all ping detections have been established, all received pings from all buoys are sorted to associate received ping times with their sources. The unique frequency (DOT's) and different ping repetition intervals (LFP's) are keys to this process. These steps are part of the first phase of PMAS operation, called preprocessing. Other preprocessing activities include tabulating the impact detection times for all buoys and calculating the sound velocity profile.

The preprocessing tabulations are stored on disk files to be used during the second phase of PMAS operation, postmission processing. This processing uses the tabulation of sorted pings to determine surface-buoy locations relative to the DOT's and the tabulation of impact detection times to locate impacts. Impacts are located by a grid-search process that rejects invalid solutions. The PMAS also calculates the best estimate of sound velocity. Two basic velocities are important: (1) the effective vertical propagation velocity to and from the DOT's, calculated as harmonic velocity, and (2) the horizontal velocity associated with surface ducts. A least-squares fit is applied to determine a "best fit" of buoy location, sound velocity, impact position, and time. Error estimates, or residuals, are calculated to provide a quality measure of results. The formats for data presentation and summary are specified and selected in advance so that final answers are in the form required by the user. Documented results of PMAS analysis are available about three days after the mission tapes are delivered. Because the results of PMAS analysis for actual reentry tests are classified, they cannot be presented here. Any references to test data, test dates, or the tape recorded during the mission, including non-numerical results, are also classified.

CONCLUSION

The ARIA/SMILS has now provided supplemental support for several reentry missions. As noted, postmission analysis is now operational. Future missions will be supported to verify that acoustic navigation software upgrades are effective in producing consistent quick-look assessments.

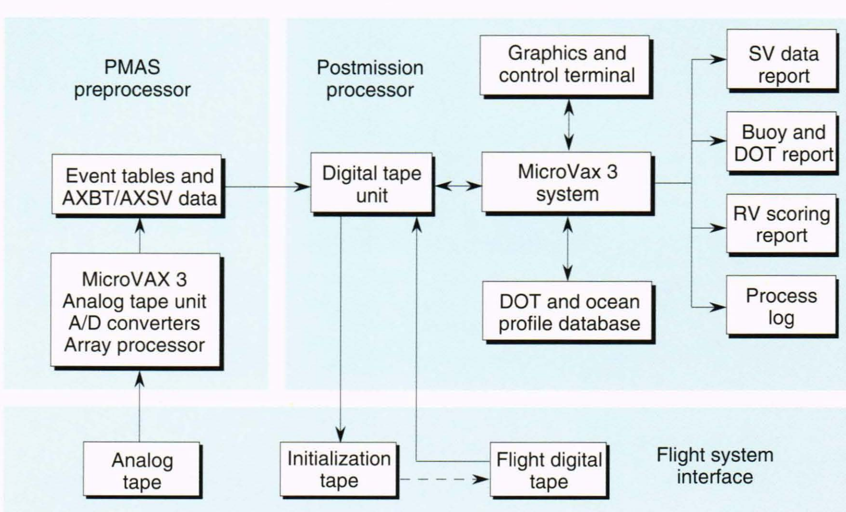

Figure 11. Postmission analysis system (PMAS) block diagram (RV = reentry vehicle, DOT = deep ocean transponder, A/D = analog-to-digital, AXBT/AXSV = aircraft-launched expendable bathythermograph/aircraft-launched sound velocimeter, SV = sound velocity).

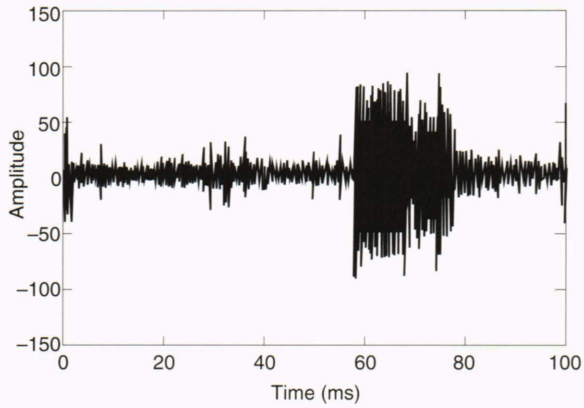

Figure 12. Recording of an acoustic ping.

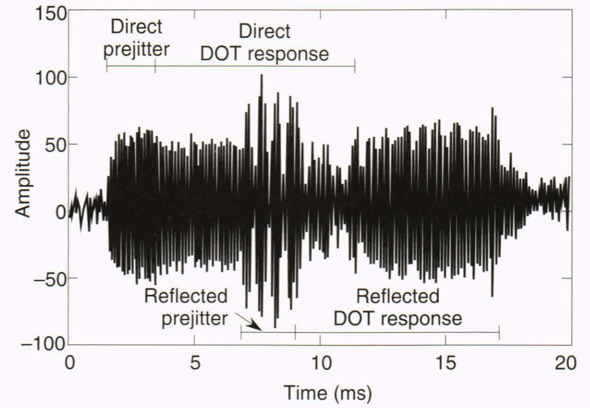

Figure 14. Deep-ocean transponder (DOT) response.

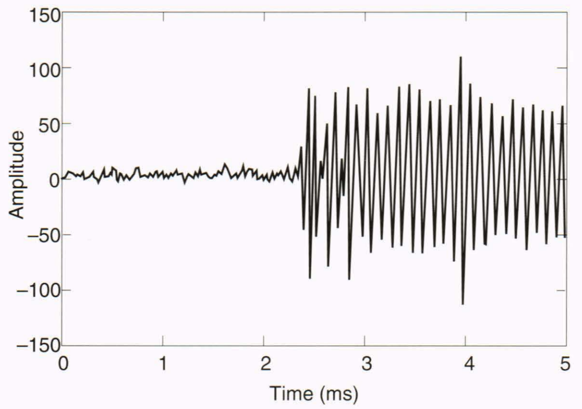

Figure 13. Expanded scale plot of a ping leading edge.

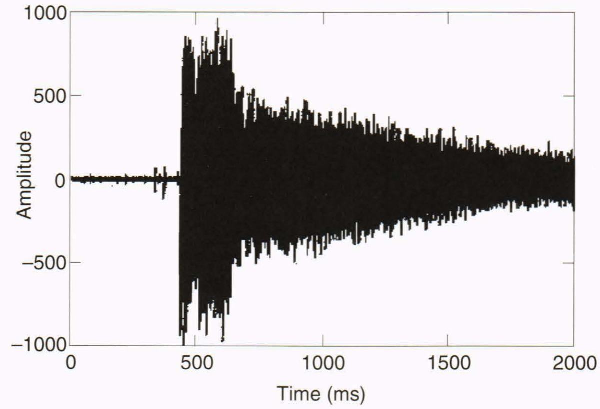

Figure 15. Acoustic noise burst of an impact.

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