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USING THE ST1000/ST725 SONARS
ON THE NPS AUV II

by

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June, 1994

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Using the ST1000/ST725 Sonars
on the NPS AUV II

by

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) require further technological development in several key areas (including sensor systems) in order to assume a broader role in undersea military and commercial environments. This research was an experimental investigation of the TRITECH ST1000 and ST725 high resolution sonar systems used onboard the NPS AUV II. Tests conducted with the ST1000 Profiler proved that the sonar could successfully be used in AUV positioning maneuvers, but also revealed the requirement for some form of range dependent gain adjustment to ensure vehicle stability. The ST725 sonar was used in progressively complex static environments to clearly image objects. A scanline analysis of the ST725 data was shown to be useful in extracting stationary target information including range, bearing, and approximate size.

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I. INTRODUCTION

A. GENERAL

Autonomous Underwater Vehicles (AUVs) are unmanned, untethered vehicles capable of fulfilling a wide range of military and commercial applications. The heightened interest in autonomous vehicle research and development in the past fifteen years is a natural outgrowth of previous Remotely Operated Vehicle (ROV) experience. The 1990's were predicted as the timeframe for fielding practical, economical vehicles for use in military, industrial, and scientific operations [Ref. 1]. Typical commercial and scientific applications of AUV technology include pipeline and platform inspections, mineral exploration, and oceanographic or pollutant surveys. Envisioned military uses include vehicles for beach reconnaissance prior to amphibious landings and for detection, classification, and disposal of ordnance during mine countermeasures operations [Refs. 2, 3]. The end goal of a highly reliable, fully autonomous vehicle requires further development of technology in several key areas including the power, navigation, communications, and sensing systems [Ref. 4]. The focus of this investigation is on the sensing systems employed by the NPS AUV II testbed vehicle, specifically the capabilities and limitations of the integrated commercial off the shelf (COTS) TRITECH ST1000 and ST725 sonars.

B. BACKGROUND

Sensing technology currently under development for use in the underwater environment includes laser, optical, and acoustical systems. Confining the scope to acoustic systems, previous investigators have generally explored one facet of the use of sonar systems in AUV position control, object avoidance, or target acquisition.

Floyd et al (1991) successfully demonstrated the ability to discern unknown obstacles using a low resolution sonar [Ref. 5]. A least-squares linear regression was applied to data obtained from the Datasonics PSA-900 Sonar Altimeter. Linear segments were extracted and compared to known environmental model features. Segments that did not match the model were classified as contacts and stored in an updated version of the model.

Ingold (1992) further investigated the concepts and application of linear regression analysis and demonstrated results with precision within 2 centimeters using the ST1000 high resolution sonar system [Ref. 6]. Objects were consistently located during the post processing of a series of static tests. The images generated in the analysis consisted of line segments, bounded by key points or discontinuities, which represented contacts.

In 1993, researchers at the MIT Sea Grant Underwater Vehicles Laboratory focused their efforts on a geometric feature extraction algorithm [Ref. 7]. The geometric analysis involved a sensor fusion approach to sonar data interpretation. The key concept is that raw data scans of a target taken at multiple sensing locations can be used to confirm the presence or absence of a contact and allow extraction of distinct patterns. Small circular arcs are isolated from the raw data, tracked during sensor movement, and the series is combined to estimate contact shape. The algorithm successfully extracted two dimensional, horizontal plane outlines of the targets.

C. SCOPE OF THESIS

The primary focus of this thesis was to conduct parallel but independent experimental investigations of the capabilities of the TRITECH sonar systems selected for use in the NPS AUV II. The specific objective of the ST1000 Profiler research was to examine and verify the ability of the sonar to provide the information required for accurate and reliable vehicle positioning. The ST725 sonar test objectives were to ensure that target recognition was possible in progressively complex static environments and, if so, to develop a method to determine the range and bearing of contacts.

Chapter II contains descriptions of the TRITECH ST1000 Profiler and ST725 sonar systems. Hardware, software, and integration into the AUV system are discussed for each sonar. Chapter III delineates the test parameters and describes the experimental procedures completed. Chapter IV presents the experimental results for both sonars and develops the scanline analysis method. Conclusions and recommendations are summarized in Chapter V. All figures are in Appendix A and the MATLAB scanline data conditioning program (THRESH. M) is in Appendix B.

II. TRITECH SONAR SYSTEMS

The NPS AUV II will use both the commercially available off the shelf (COTS) TRITECH ST1000 Profiler and ST725 Scanning Sonars for positioning control and target acquisition. While outwardly similar in appearance, each system has special characteristics and was selected to fulfill specific mission objectives onboard the vehicle. Both sonars are mounted vertically between the nose fairing and the forward vehicle bulkhead as shown in Figure 1, and are mechanically scannable through 360 degrees.

A. ST1000 PROFILER SONAR

The ST1000 is an inexpensive, compact profiling sonar designed for use on all types of underwater systems including Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). The sonar unit is available in either horizontal or vertical configurations for easy installation on platforms regardless of the intended application. In normal use, the sonar system is controlled by a standard personal computer (PC) with all communications between the computer and sonar head conducted over an RS232 communications cable. Multiple sonar heads can be interfaced to communicate over a common cable.

1. ST1000 Hardware

The cylindrical sonar head is 2.91 inches (74 mm) in diameter and 8.86 inches (225 mm) long. The body is constructed of aluminum alloy HE-30 Ni/Al bronze and has a hard, anodized black finish. The unit weighs 2.43 pounds in air and 1.43 pounds submerged. The stepper motor/transducer assembly is encased in a pressure compensated flexible dome filled with castor oil. The head assembly includes a one meter polyurethane-jacketed cable that terminates in a connector. The sonar head pulses a 1.5 degree conical beam operating at a frequency of 1250 KHz., mechanically stepped in either a continuous 360 degree scan or a specified sector scan. Figure 2 illustrates the beam pattern coverage. The stepper motor provides mechanically controlled resolution in either 0.9, 1.8, or 3.6 degree scan step angles; a larger scan step angle corresponds to poorer sonar image resolution but greater rate of area coverage. The system requires an external 24-28 volt DC power supply operating at a maximum of 900 mA. Environmental limitations on the hardware include an operating temperature from 14° F to 95° F and a maximum working depth of nearly 5000 feet.

2. ST1000 Software

As previously stated, the sonar head communicates with the IBM compatible PC through the RS232 serial communications port. The software provides the means to control the sonar head and display the output on a VGA 640X480 monitor. Once the PC has been turned on and the power supplied to the sonar head, a 2-4 second initialization phase is required to properly align the transducer with its internal direction indicator. A red LED in the dome corresponds to the sonar head forward position. After initialization, a sonar display and menu of options is visible on the monitor.

The first option selected by the user should be the type of sonar display desired, either the "profiling" or "scanning" mode. Sector profiling is a "first return" ranging mode which assigns a high intensity value to the first echo return received on the scanline. The results are shown as a dot on a cartesian grid. The scanning (normal analogue) mode includes suboptions for either sector or 360 degree scanning. The sonar display is a full color polar plot with a vertical color bar representing the sixteen different echo intensities. Strong returns are discriminated strictly by clusters of colored dots on a scanline.

The software menus allow variation of many sonar operating and display parameters but principal control functions include selection of range, resolution, gain, threshold, scan direction, and scan width. The actions of the sonar head are controlled directly from inputs on the PC keyboard.

Available operating ranges are 6, 10, 20, 30, 50, 75, 100, and 150 meters. When longer ranges are selected, the response time for alteration of other parameters increases in general. Resolution levels possible are high, medium, and low. High resolution corresponds to 0.9 degree steps, medium to 1.8 degree steps, and low resolution to 3.6 degree steps. The selection of the resolution level involves a tradeoff for the user; high resolution gives greater detail but involves a longer period for one complete transducer rotation while low resolution completes the cycle in a shorter time but will obscure target details and complicate interpretation for the operator.

The gain level of the sonar pulse generation circuit is adjustable between 0 and 100. The operator objective is to manually adjust the gain control to achieve the best display. Too much gain over ensonifies the environment producing false targets and unreliable returns; too little gain will not discriminate actual targets. Threshold values range from 0 to 15. The signal returns to the sonar head are assigned intensity values from 0 (weakest return) to 15 (strongest return). Thresholding effectively masks returns below the operator determined level. The proper combination of threshold and gain will optimize the sonar display to give the cleanest picture while preserving all targets of interest.

Scan direction and scan width are adjusted when operating in the "sector scan" rather than in the "continuous scan" submode. Scan direction is set for the center bearing of the sector desired. Scan width allows variation of the total sector width from a minimum of 3 degrees to a maximum of 360 degrees.

Other useful features of the software include the ability to log sonar scan data and replay the files. One function key on the PC is used to begin logging data and another is used to stop logging after the desired scan coverage is completed. The information is automatically given a sequential log file name and is stored on the hard disk. Data file size depends on the number of 360 degree rotations completed. Approximately 7 kilobytes of space are required per full revolution when operating in low resolution and up to 28 kilobytes per revolution in high resolution. Any logged data file can be replayed or reviewed at any time, with or without the sonar head system attached. If immediate review is desired, a function key will suspend sonar head communication and allow recall of previously recorded files. For post mission analysis, data log files may be viewed on any independent PC using test mode batch program software.

3. ST1000/AUV Integration

The ST1000 manufacturer-supplied software works well with a human operator interface. However, an underwater freeswimming vehicle requires an onboard software "mission package" to act as the "brains" for vehicle and mission control during autonomous operations. The software and hardware selected must be able to direct, coordinate, and integrate the function and operation of all vehicle subsystems including the sensors, thrusters, and navigation equipment. The software design selected for the NPS AUV II is based on the Rational Behavior Model [Refs. 8, 9].

The Rational Behavior Model (RBM) is a three tiered software architecture with strategic, tactical, and execution levels. The strategic level primarily involves mission control aspects. The tactical level (Figure 3) contains the world model, assimilates data, and translates commands to the execution level. The execution level (Figure 4) maintains vehicle stability and carries out the commands at the individual sensor, motor, and actuator level. The RBM architecture is analogous to a military organization. The strategic level (Admiral) makes overall policy, the tactical level (officer corps) sets and monitors intermediate goals, and the execution level (enlisted corps) actually completes the specific tasks. As shown in Figures 3 and 4, sonar control and sensing are involved only in the tactical and execution levels.

Computer system hardware and software currently installed onboard the AUV II include the GESPAC computer and the OS-9 multi-tasking operating system. The GESPAC has a

Motorola 68030 central processing unit (CPU) and card cage connections for analog/digital (A/D) signal interface cards. The execution level control code is written in the "C" computer language. In the current configuration, set points and task descriptors (to be generated by the tactical level) are down-loaded into computer memory prior to the mission. Sonar and sensor data are updated at a 10 Hz rate. The information is processed and control actions are executed in a single continuous process [Ref. 10]. The future version will use two computers with an interface to separate the tactical and execution levels. A GESPAC 80386 processor running a GESPAC DOS operating system and separate card cage will function as the tactical level (including the sonar manager) and the GESPAC/OS-9 system will carry out execution level tasks.

The NPS AUV II uses the ST1000 sonar system operating in the profiling mode to provide dynamic positioning and hover mode motion control. Experiments to date have been conducted to assess the ST1000 performance during wall positioning or "servoing" missions. Commands downloaded prior to test runs (tactical level) instruct the sonar to energize and center or align. The execution level is then responsible for the actual operation of the sonar. The sonar pulse is transmitted, the echo received, and the transducer is stepped to the next scanline. The data, recorded at 10 Hz, is processed and used directly for vehicle motion control. Additionally, processed data is provided to the tactical level for goal assessment and to a data storage file for post-mission analysis.

B. ST725 SONAR

Like the ST1000 system, the ST725 sonar is an inexpensive, compact sonar used in a wide range of underwater applications. The chief advantage of this sonar is that the broader beam provides greater scan area coverage. Figure 5 shows the approximate vertical and horizontal pattern emanating from the sonar head. Comparing Figures 2 and 5, the beam coverage area of the ST725 sonar is nearly 28 times that of the ST1000 sonar. Another inherent advantage of the ST725 is its greater effective operating range.

1. ST725 Hardware

The cylindrical sonar head is similar in outward appearance to the ST1000 Profiler. Overall length is 7.68 inches (195 mm) and maximum diameter is 2.91 inches (74 mm). It weighs 2.2 pounds in air and 1.21 pounds underwater. The body material is an aluminum alloy anodized to a hard black finish. A pressure compensated, oil-filled boot houses the transducer. The primary difference between the two TRITECH sonars is in the beam. The ST725 pulses a 20 degree vertical plane by 2.5 degree horizontal plane beam operating at a frequency of 725 KHz. Scan size is variable from small sectors up to 360 degree continuous scans. Resolution options, power requirements, and environmental operating limitations are identical to those of the ST1000. Mechanical resolution is in 0.9, 1.8, or 3.6 degree step angles. The power needed is 24-28 volts DC operating at 900 mA maximum. Operating temperatures are 14°F-95°F with a maximum working depth near 5000 feet.

2. ST725 Software

The software options, computer interfaces, and control functions for this system are virtually identical to those for the ST1000 system with the following exception. No profiling (first range return) mode is available on the TRITECH-supplied ST725 software. All other important parameters and functions may be selected through system software by PC keyboard. The controllable or selectable menu items include range, resolution, sonar head gain, threshold level, scan direction, and scan width. As in the case of the ST1000 profiler, all data can be automatically logged, filed, and saved for subsequent analysis.

3. ST725/AUV Integration

Although not used to date in actual AUV in-water tests, the ST725 will be integrated and used onboard the vehicle once the sonar manager and DOS computer/card cage are installed. The control and functions of the ST725 will be governed by the tactical and execution levels of the Rational Behavior Model software hierarchy. The intended goal is fusion of the ST1000 and ST725 sonar capabilities to provide better underwater object recognition and enhance obstacle avoidance [Ref. 11].

In order to discover how to properly integrate both sonars into the vehicle motion control problem, new hardware/software interface drivers had to be written and experiments conducted to determine the feasibility of using information gained from the sonars to control motion of the vehicle [Ref. 12].

III. EXPERIMENTAL PROCEDURE

A. GENERAL

The ST1000 and ST725 sonar systems were used in separate test environments to investigate different aspects of the acoustic imaging problems associated with autonomous underwater vehicles. Therefore, the experimental procedures for each system were radically different. The focus of the ST1000 profiler sonar tests was to examine and verify the ability of the sonar to interact with the guidance and control system of the AUV to provide accurate and reliable positioning or "wall servoing". The thrust of the ST725 sonar investigation was twofold: 1) to ensure target or object recognition was possible and, if so, 2) incorporate an algorithm to accurately determine the range and bearing of the targets. The primary common denominator for the experiments was the use of the NPS AUV II Testing Tank Facility.

The testing tank facility, shown in Figure 6, is a 20 foot long by 20 foot wide by 6 foot deep tank. Two 2 foot by 2 foot plexiglass viewports are located on the north and west walls of the tank. The inner surface is covered with a marine grade (but non-anechoic) paint and a pinstripe grid. The grid lines, spaced 30 inches apart, are primarily used for approximate target or vehicle placement and to assist in relative vehicle motion visualization. An aluminum overhead observation platform extends from the east to the west ends of the tank. The AUV II and target items are launched or placed in the tank using a beam-framed electric winch and pulley system parallel to the observation platform. Adjacent to the tank are the computers, power supplies, and ancillary equipment required for experimental testing and post-mission data analysis.

B. ST1000 PROFILER TESTS

The ST1000 profiling sonar was physically onboard and fully integrated with the AUV II during in-water positioning and wall servoing tests. After vehicle launch into the tank, an observer on the platform manually oriented the AUV to the initial attitude desired for the test. Tactical commands including a commanded range, heading angle, depth, and pitch angle were then downloaded from a poolside computer through the vehicle serial port. The onboard GESPAC computer execution level began its continuous control loop at this point including the initialization sequence which involved aligning or stepping the sonar head transducer to the desired bearing. The mission profile was executed and all relevant variables were recorded at a 10 Hz update rate. For each mission, the sonar worked in consonance with the gyroscopes and at least two of the six thrusters to demonstrate vehicle stability, guidance, and control. Longitudinal and lateral wall servoing missions were investigated.

1. Longitudinal Wall Servoing

Fourteen wall servoing test runs were completed. For the first nine tests, the profiler head gain was set at 13, an empirically determined setting. The maximum range level for all tank testing was 6 meters due to tank dimensions. Raw sonar ranges from the ST1000 were processed with a Kalman filter [Ref. 13] to obtain estimated range and range rate (speed). The filtered values were used in conjunction with control law equations to drive the propeller motors, maintain the correct heading, and ultimately achieve the commanded set point position. Real-time and computed data from each run were stored for subsequent analysis. Logged parameters included the time, raw range values, filtered ranges and speeds, vehicle heading, the rate of heading change (yaw rate), and the port and starboard shaft motor voltages. All variables were plotted as functions of time during post-mission analysis.

For the *first seven tests*, the vehicle was manually placed approximately 12 feet from and perpendicular to the east tank wall. Gain and derivative time constant values for the position and heading P/D control laws and set points for the commanded position and heading were downloaded to the onboard computer through the serial port. The commanded position was 7.5 feet from the wall and the commanded heading was 0.0 radians relative to the initial setting. The control law position and heading gain and derivative time constant values were adjusted between the runs in an effort to seek roughly optimized overall vehicle servoing response. Heading gain was either 60 or 80 and position gain was varied from 3-10. It is an important distinction that only the control law gain values were varied; the ST1000 head gain value was fixed. Heading derivative time constant was fixed at 1 and position derivative time adjusted from 1-5.

Similar procedures were used for the *second set of seven longitudinal* servoing tests. Based on the observations from the previous tests, the position gain was fixed at 10 and the heading gain was fixed at 80. The commanded heading was 0.0 radians and the heading derivative time constant was 1 second. The primary variables in this test series were the sonar head gain (5-13) and the commanded position (2.5-7.5 feet). Once again the objective was to determine which values produced the roughly optimum servoing response.

2. Lateral Wall Servoing

Thirteen lateral wall servoing test runs were completed. As in the initial longitudinal tests, profiler sonar head gain was 13 and the maximum range setting was 6 meters. The gain value of 13 was chosen through a study of profile sweeps of the tank as viewed from the PC. Thirteen seemed to be a compromise between over ensonification and enough strength to reach the far tank walls. Commanded positions in the lateral servoing tests required sideways motion of the AUV hence the filtered sonar data was primarily used in the control laws to drive the bow and stern lateral thruster motors rather than the propellers. Variables plotted as a function of time in post-mission analysis included the raw sonar range, filtered range, range derivative (speed), heading, yaw rate, and bow and stern lateral thruster motor voltages.

In the *first series of nine tests*, only the vehicle heading was fixed. Its commanded set point was 0.0 radians. The gains, derivative time constants, and position commanded were independently varied in an effort to achieve the best control combination. Position gain varied from 5-12 and heading gain from 60-100. Position derivative time values of 1-3 were used and heading derivative time varied from 1-2. The initial vehicle position was 4.7-16.1 feet from the target wall with commanded final positions from 3-4 feet.

In the *second series of four tests*, only the threshold was varied. All other input values were fixed from observations of the first series. The initial position was 10 feet from the wall with a commanded final position of 4 feet. Position gain was 10 and heading gain was 60. Position derivative time constant was 3 and heading derivative time constant was 1.

C. ST725 SONAR TESTS

The ST725 was investigated in three different environments: the NPS AUV testing tank, the NPS swimming pool, and in the Monterey Bay. All ST725 sonar data was obtained from static tests, independent of the NPS AUV II. As a precursor to useful integration with the AUV, the sonar system must first be capable of showing a clear picture of objects in the environment (i. e., targets) and then be able to provide accurate range and bearing information to the AUV through the use of an appropriate algorithm.

1. Testing Tank Experiments

Forty-one sonar scan tests were conducted in the NPS testing tank facility with varying conditions to examine the ability of the ST725 system to discern targets. The targets selected were large and small open-ended cylinders and a sphere. The largest target was a 40 inch long by 11 inch diameter aluminum cylinder with a 3/8 inch wall thickness. The smaller cylinder was also aluminum but was 19 inches long and 12 inches in diameter with a 1/4 inch wall thickness. The spherical target was an 8 inch diameter rubber ball. The sonar head was suspended at mid-depth level in the tank. Targets were placed in the tank with the geometric center at sonar head depth and were observed singly and in combination. Horizontal plane distance from the sonar head and target aspect (end view vs. side view, horizontal suspension vs.

vertical suspension, etc.) were varied. Communicating with the sonar through the PC keyboard, the operator varied the gain, threshold, and resolution for each test condition to obtain the optimum display. Sonar gains from 9-25 were used with threshold values from 11-15. High and medium resolution settings were compared. The sonar head maximum range selected for all tests was 6 meters due to physical tank dimensions. Test run results were logged on data files for further analysis.

2. Swimming Pool Tests

One series of seven tests was completed in the NPS swimming pool. The ST725 was suspended from a styrofoam float at mid-depth in the shallow end of the pool (approximately two feet deep). A 1.5 inch diameter metal rod and the 19 inch cylinder from the tank tests were placed in the water column at varying horizontal distances from the sonar head. The range scale, sonar gain, and threshold were adjusted to obtain the clearest discernable display. Results were logged to data files.

3. Monterey Bay Tests

The final series of eight in-water tests was completed on the piers of Fisherman's Wharf Harbor in the Monterey Bay. The sonar head was lowered 4.5 feet into the harbor at three locations. The environment included wooden pier support pilings and metal boat keels. In each case the objective was to optimize the sonar display and log the results. The range scale, sonar gain, and threshold were adjusted to achieve this goal.

IV. RESULTS

A. ST1000 PROFILER

The longitudinal and lateral wall servoing tests were conducted to investigate the ability of the ST1000 to interact with AUV guidance and control systems and to provide reliable and accurate positioning. To assess the sonar system performance, output parameters from each test run were plotted as a function of time. Key to this analysis were graphs of the filtered range versus time. During wall servoing data analysis, the most common recurrent problem area observed involved the sonar head gain setting and target wall distance.

1. Longitudinal Analysis

In the most informative tests of this series, the sonar head gain and commanded distance from the target were varied while the control law parameters were held constant. The primary findings of these tests was that the sonar head gain must be decreased as the AUV approached the object otherwise over ensonification caused vehicle instability. Figures 7 and 8 show the range as a function of time with a sonar head gain setting of 13. Figure 7 is the stable vehicle response to a commanded position of 7.5 feet from the wall. The commanded position was decreased to 5 feet (Figure 8) and the vehicle response went unstable. When the commanded position remained at 5 feet but the sonar head gain was reduced to 9, vehicle response stabilized once again, as shown in Figure 9. Figure 10 shows the effects of further decreasing the gain. At a sonar head gain setting of 5, not only was the vehicle response stable but less time was required to reach the steady state condition. This anomaly is best explained by the fact that, with over ensonification, the sonar raw range is noisy, so the Kalman filter is unable to track accurately. This, in turn, causes an apparent slowdown in vehicle settling response.

The crux of the issue is that a range dependent gain must be variable to ensure vehicle stability when positioning. A formula must be incorporated into the sonar manager (tactical level) to reinitialize the sonar head gain setting as the range decreases. The proposed formula should use empirically determined values for gain triggered at specific estimated range points since the gain/range relationship is nonlinear and very dependent on target characteristics. From experimental observation in a metal tank, the sonar head gain should be reduced from 13 to 5 (nearly a factor of three) when the vehicle range to the target becomes less than 3 meters.

2. Lateral Analysis

The sonar head gain for all lateral testing was fixed at 13 since the primary test objective was to ensure the AUV would achieve the commanded position set point, as well laterally as it did longitudinally. While only indirectly related to ST1000 sonar performance, some interesting observations were noted. The variation of control equation gains on vehicle response is shown in Figures 11 and 12. When the commanded position was closer to the wall or target, either the control law heading gain had to be increased (Figure 11) or the position gain had to be decreased (Figure 12) to ensure stable vehicle response. The variation of control law parameters apparently compensated for the over ensonification at short ranges.

Figures 13 and 14 demonstrate the effects of different thresholds on the Kalman filter. The filter processes raw sonar data for use in the control laws and the threshold determines the range of signal variation outside of which the filter will propagate without update. The threshold value in Figure 13 was 0.5 feet and the AUV control was unstable. Figure 14 shows a stable response with the threshold at 1.0 feet, all other parameters held constant. These figures again show that manipulation of the control laws can mitigate the effects of incorrect sonar head gain, although an adaptive head gain would be a preferred solution.

B. ST725 SONAR

The ST725 sonar system proved to be quite capable of providing clean images in each testing environment, as will be shown in sample sonar displays. Plots of the raw scanline data on specific bearings illustrated what the sonar head actually "saw". Thresholding the scanline data smoothed the output to reject false targets and provide a method of range determination for actual targets.

1. Testing Tank

Figures 15 and 16 are examples of sonar imaging on a single target, the small cylinder. In each case, the ST725 was operating in the high resolution mode with a maximum range of 6 meters. Figure 15 shows the target with the gain at 19. The target with the same aspect, but in a different quadrant, is shown at a gain of 21 in Figure 16. Note the tank wall outline in each figure; corners and wall points directly perpendicular to the sonar beam are particularly good reflectors hence consistently have a higher intensity return than the oblique wall sections. Another commonly observed characteristic in the tests was that high intensity areas produced mirror image reflections beyond the tank boundaries.

The high resolution/high gain display in Figure 16 closely approximated the target's horizontal orientation and size. Actual target length was 19 inches and the interpolated length from the sonar display was 22.7 inches, about a 16 percent overestimation. The high resolution but lower gain image in Figure 15 clearly shows a valid target but orientation and size are less discernible.

Figures 17 and 18 are images of three targets in the testing tank. The small cylinder, orientated vertically with respect to the sonar head, is the target in the upper center of each figure. The large cylinder, also vertically oriented, is in the lower center of the images. Finally, the rubber ball is located nearest the upper left corner in each display. The gain of 21 in Figure 17 was increased to 27 in Figure 18. As in single target tests, a rough estimate of size was possible. However, target orientation was less readily apparent. Figure 18 illustrates that a gain level of 27 was the highest possible value in this environment. False targets with a magnitude greater than that of the ball return appear beyond this setting.

In summary, all forty-one tank tests confirmed that the ST725 sonar could "see" the targets, but that operator adjustment of gain values was required to obtain the best visual display. At the close ranges inherent in tank tests, high resolution was clearly preferable to medium resolution. The ST725 sonar data could be used to approximate target size but was less capable of providing useful target orientation information.

2. Swimming Pool

In general, the ST725 pool tests demonstrated the ability of the sonar to provide good target imagery in an environment larger than the testing tank. The pool primarily provided the opportunity to study the effect of different maximum range settings on sonar performance. To a lesser extent, the effects of adjusting the gain and resolution were also explored.

Figures 19-21 all clearly show the rectangular outline of the pool walls and the small cylinder target near the wall. The tests were conducted at maximum ranges of 20, 25, and 30 meters respectively with a medium resolution setting. Although the desired target was clearly visible in each figure, a more prominent but disturbing feature was also present. A high intensity ring or shadow zone surrounded the sonar head at a range of about 1.5 meters.

The most probable explanation is that a combination of high gain, extended range settings, and close wall proximity contributed to the shadowing phenomenon. Comparison of the figures shows progressive deterioration of sonar performance in the immediate (1-2 meter) head vicinity as the maximum range setting is increased. A second, but far less probable, explanation for the shadow zone is that the return is a result of direct surface reflection. Surface and bottom reflection problems are unlikely due to the sonar head test depth and the beam pattern of the ST725. The sonar head was over 2 feet deep for all tests and the beam pattern in the vertical plane is 20 degrees high hence the first direct surface reflection possible would be nearly 3.5 meters horizontally from the head. The shadow zones in each figure occur at distances less than 3.5 meters. A solution to the shadowing problem is to disregard or gate out any contacts within 2 meters of the sonar head, since the sonar manager (tactical level) will pass control to the ST1000 sonar when contacts are within 5 meters.

Figures 22 and 23 compare the effects of the resolution setting. Each has a gain of 15, maximum range of 50 meters, and a threshold of 12. The medium resolution display in Figure 22 clearly shows the target and the pool outline. The high resolution scan in Figure 23 not only shows the same features in greater detail but also identifies a second target. The second target is the pool ladder at the bottom right corner of the rectangular pool outline. Note in both figures that the shadowing problem previously evident still exists but has been suppressed by selection of a greater maximum range setting.

Figure 24 shows a small sector scan over the known target area. The test was completed at high resolution, a gain of 21, and a maximum range setting of 25 meters. Both the target adjacent to the near wall segment and the pool ladder near the far wall segment are clearly evident. The noise band or shadowing within 2 meters of the sonar head also appears as a viable target but could again be rejected by scanline data processing or gating. Figure 25 also plainly illustrates the need for raw data conditioning prior to use by the AUV. If the shadow area near the sonar head is not gated, the target near the wall segment would be imperceptible from the noise.

The series of pool tests provided several important results. The ST725 sonar clearly images targets and outlines pool boundary walls in a shallow water environment more complex than a small testing tank. Bottom and surface reflections do not interfere with the sonar images at any of the range settings examined. For maximum range settings less than 50 meters, the medium resolution mode is sufficient to accurately identify targets and requires less time for a complete head rotation than the high resolution mode. Finally, raw scanline data within 2-3 meters of the sonar head must be gated to eliminate shadow zones.

3. Monterey Bay

The tests run at Fisherman's Wharf in the Monterey Bay were conducted primarily to investigate the ability of the ST725 to operate in a real-world environment. The test series confirmed that objects could be successfully imaged. Two figures were particularly noteworthy. Figure 26 illustrates two pier segments perpendicular to the sonar head, one in the upper left quadrant, and the other in the lower left quadrant. Note the shadow zone around the head, as previously observed in pool tests. Figure 27 shows a short range display of a second pier. The regularly spaced contacts in the two lower quadrants are pier pilings.

4. Scanline Analysis

Whether displayed by audio or visual means, sonar return interpretation by the human operator is comparatively easy. Human advantages include a general knowledge of the working environment and a cognitive ability to recognize patterns and anomalies. These capabilities must be translated by algorithm and incorporated in the AUV software to accurately and reliably detect true targets. The ability to systematically analyze sonar scanline data is implicit in these efforts.

On each stepper motor controlled bearing, a pulse is sent out by the ST725 sonar head. For each pulse, the returned sonar scanline data is collected as a string of 64 bins. Bin width is determined by the maximum range setting. For example, if the maximum range setting is 6 meters, then each bin is 6/64 or 0.09375 meters long. Each bin is assigned an intensity value from 0 (weak) to 15 (strong) based on return strength. High intensity values indicate the presence of a target or object at that bin number or range.

The first key issue in analysis is to determine what useful information the individual scanline contains. The second key issue revolves around processing the data and comparing the intensity/bin values from the current, previous, and subsequent bearings. If pulses on at least three adjacent bearings show high intensity values in the same general range, the presence of a true target is highly probable. Comparison of values over a series of bearing lines allows extraction of the initial and final bearing angles of the contact. Thus from scanline analysis, the median bearing and range to the target may be directly determined and contact size may be estimated.

The raw data from the testing tank run shown in Figure 17 (three targets) was selected to investigate the scanline analysis methodology. Scanlines in the vicinity of the small cylinder were the specific focus. The sonar data file in binary form was run through a translation program to convert the raw data into a 632X65 ASCII matrix. Column 1 contained the bearing lines and columns 2 through 65 contained the intensity values for each of 64 successive range bins. Raw ASCII data in matrix form was amenable to post processing in MATLAB.

The first step required determination of bearing lines of possible interest. Plotting the intensity values in successive columns of range bins resulted in high intensity peaks around the scanline number when a target was present. Figure 28 illustrates the presence of a possible target around scanline 200 at a range bin of 12 (1.125 meters from the sonar head). Note that the peak observed around 600 is actually on the same bearing, but is just a subsequent 360 degree head rotation.

Once the general bearing line is identified, the second step is to analyze that specific scanline and all others in close proximity. Figure 29 shows the raw intensity values as a function of the range bin for a scanline near the middle of the contact. Figures 30 and 31 demonstrate scanline raw intensity versus range values in the target boundary area. Note the marked increase in intensity around range bin 12 from Figure 30 to Figure 31. The step-by-step investigation of scanlines in this manner determines both target boundaries. Combining the angular extent (number of scanlines) with the range data (number of range bins) reduces the estimation of target breadth to a simple geometric problem.

Reducing the raw data into a simplified and useable form requires gating and thresholding, the third step in scanline analysis. The MATLAB program THRESH.M in Appendix B accomplished this task. Gating eliminated all intensity values under 0.5 meters and over 4 meters. Thresholding allowed all range bin intensities over the selected threshold value to be set to unity. Range bin values below the threshold were set to zero. Gating and thresholding provided a clearer understanding of the critical information on each scanline without extraneous and irrelevant clutter. Figures 32, 33, and 34 are gated/thresholded versions of Figures 29, 30, and 31 respectively.

The final step in scanline analysis was to determine the first range return for a target. An algorithm to achieve this objective is included in the program THRESH.M. The ability to extract the range of the first returns allows the ST725 sonar to be used as a profiler similar to the ST1000 sonar. An example of the profiler behavior is shown in Figure 35.

In summary, scanline analysis proved to be a feasible and useful method for determining target range, bearing, and approximate size. Raw scanline data must be processed (through gating and thresholding) to simplify extraction of salient range and bearing information. An automated version of the scanline analysis methodology could be written into computer code and integrated into the sonar manager (tactical level) of the AUV.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. ST1000 Profiler Sonar

It has been clearly demonstrated that the ST1000 sonar can be integrated with the AUV guidance and control system software for accurate longitudinal and lateral positioning (wall servoing). Raw sonar data processed through a Kalman filter was used by the control laws to drive the vehicle and to successfully achieve the set points commanded. The Kalman filter is necessary to eliminate false returns and to provide estimates of range rate. Tests revealed that some form of range dependent gain adjustment was crucial to vehicle stability. As the target or object was approached, sonar head gain had to be reduced or over ensonification caused vehicle instability. Finally, manipulation of control law parameters to some extent moderate the ill effects of incorrect sonar head gain. However, for the slightly higher margin of stability there was a drastic decrease in vehicle response. It is believed that an adaptive sonar head gain is the best solution to noisy sonar induced AUV stability problems during execution of positioning maneuvers.

2. ST725 Sonar

The ST725 sonar was consistently capable of providing clear target imagery in progressively complex static environments. Bottom and surface reflection and interference problems in shallow water were not observed in any of the fifty-six tests. However, a shadow zone in the near-head vicinity was noted in the larger pool and bay environments. The shadow zone problem was not prohibitive. The ST725 is primarily intended for long range object/target location hence range returns under 3 meters should be gated or suppressed and the sonar manager could pass contact tracking responsibility to the ST1000 Profiler at target ranges below 5 meters.

Sonar resolution and maximum range settings involved a tradeoff. At the shorter ranges, high resolution was preferable due to its ability to better estimate target size. Medium resolution was desirable for longer ranges to decrease the time required for one complete head revolution although contact detail was sacrificed.

The feasibility of scanline analysis was demonstrated. Scanline-by-scanline processing of the ST725 sonar return proved to be a particularly useful and accurate method of determining target range, bearing, and approximate size. Using a simple algorithm to extract the range of the first return, the ST725 emulated the ability of the ST1000 Profiler.

B. RECOMMENDATIONS

It is recommended that an ST1000 range dependent gain formula be developed and triggered at discrete estimated range points to ensure AUV stability during positioning. Further testing is required to empirically determine proper range/gain combinations for different target types (i. e., metal, wood, rock, etc.). The range/gain relationship is nonlinear and target construction is environmentally dependent. The results from these tests could be correlated to determine the optimum range/gain set points. The set points could be incorporated into the tactical level sonar manager to automatically reinitialize and reduce the sonar head gain as the range to the target decreased.

The scanline analysis method tested on raw ST725 sonar data should be written into computer code and integrated into the tactical level of the AUV software. The code should include provisions to gate scanline intensity values in range bins under 3 meters to avoid sonar head shadowing problems and the appearance of false targets.

During the NPS AUV II upgrade currently in progress, every effort should be made to integrate the tactical level sonar manager system which will link operations of the two sonars. Initial experiments after rebuild should include a series of runs in the dynamic environment to confirm and validate the ST725 sonar performance observed in static tests.

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APPENDIX A: FIGURES

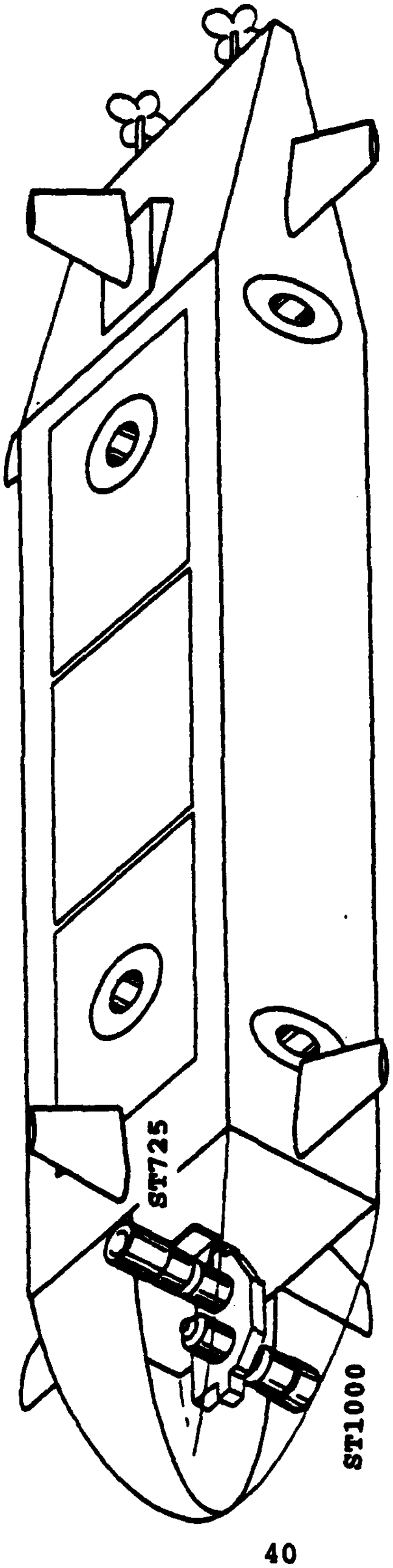

Figure 1. Location of Sonars in AUV

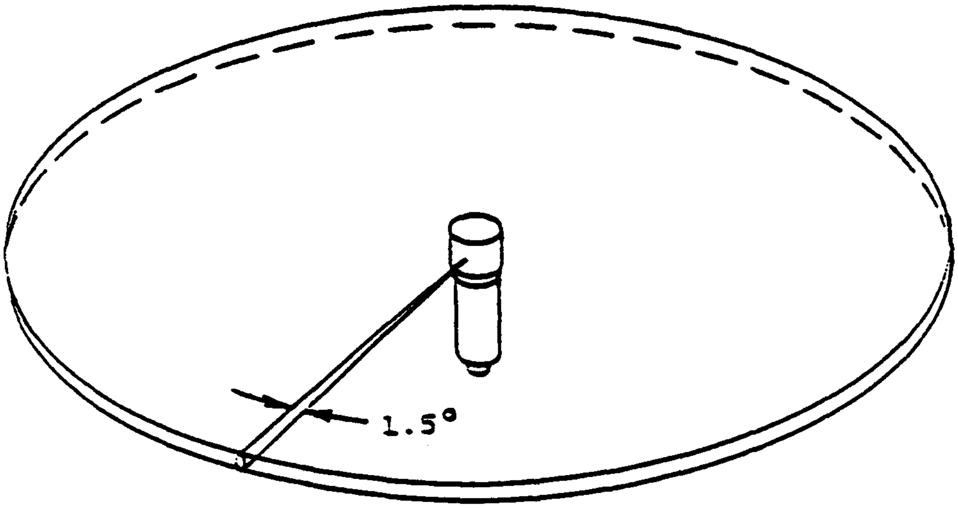

Figure 2. ST1000 Profiler Beam

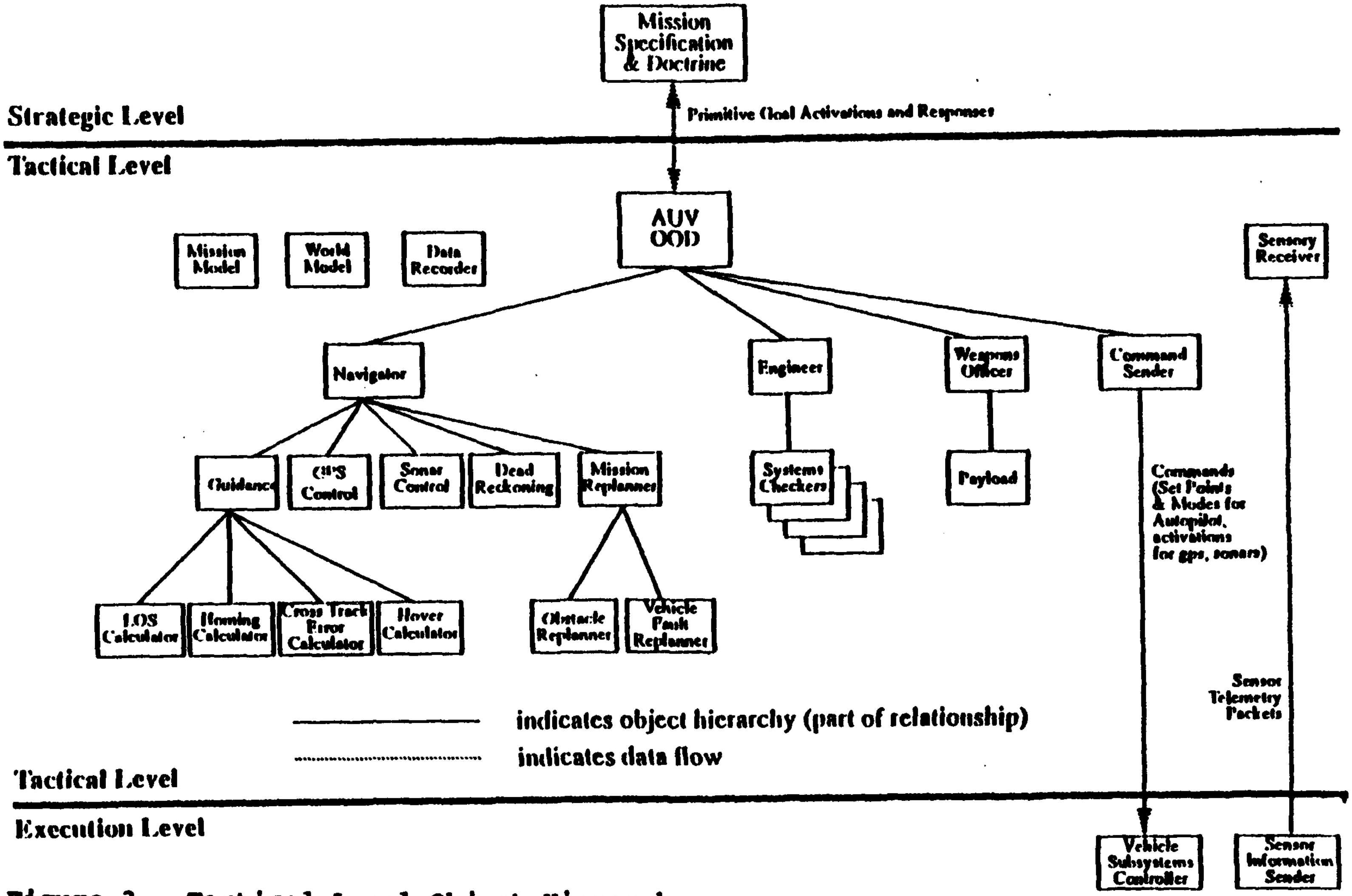

Figure 3. Tactical Level Object Hierarchy

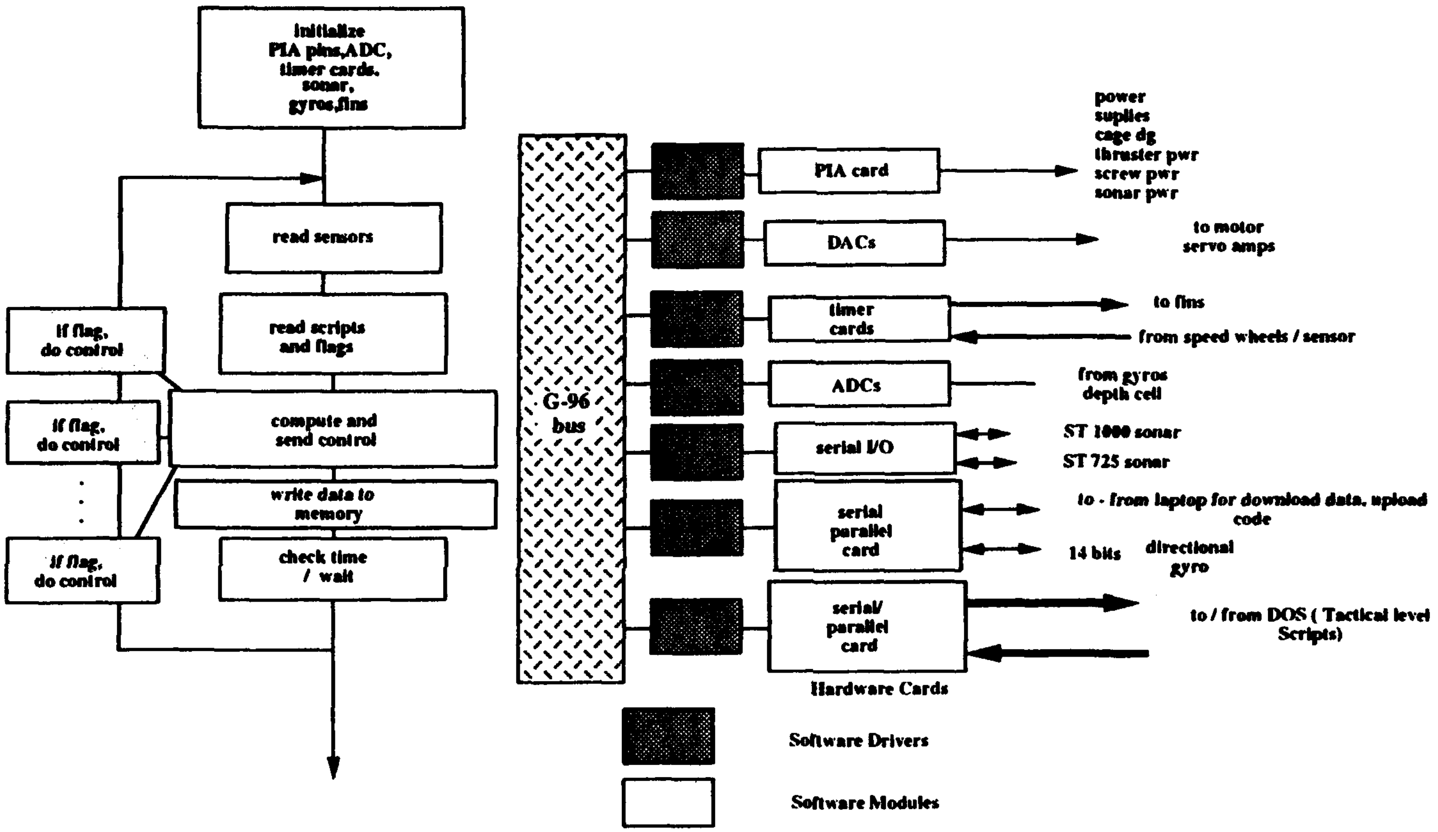

Diagram of the Software / Hardware Interface of the Execution Level of the NPS AUV II

Figure 4 Execution Level

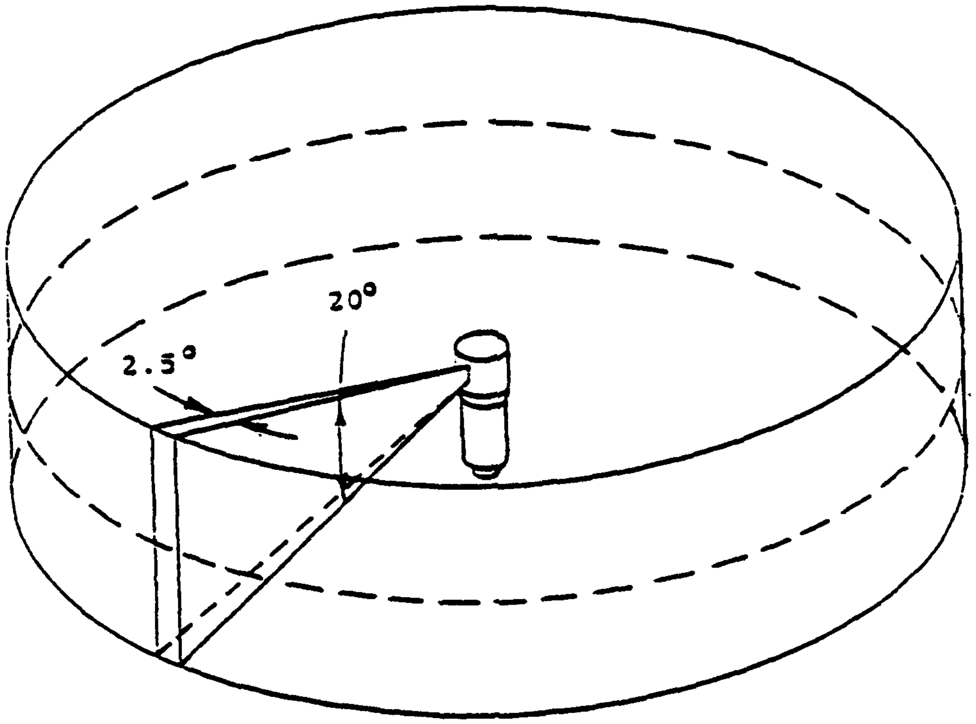

Figure 5. ST725 Beam

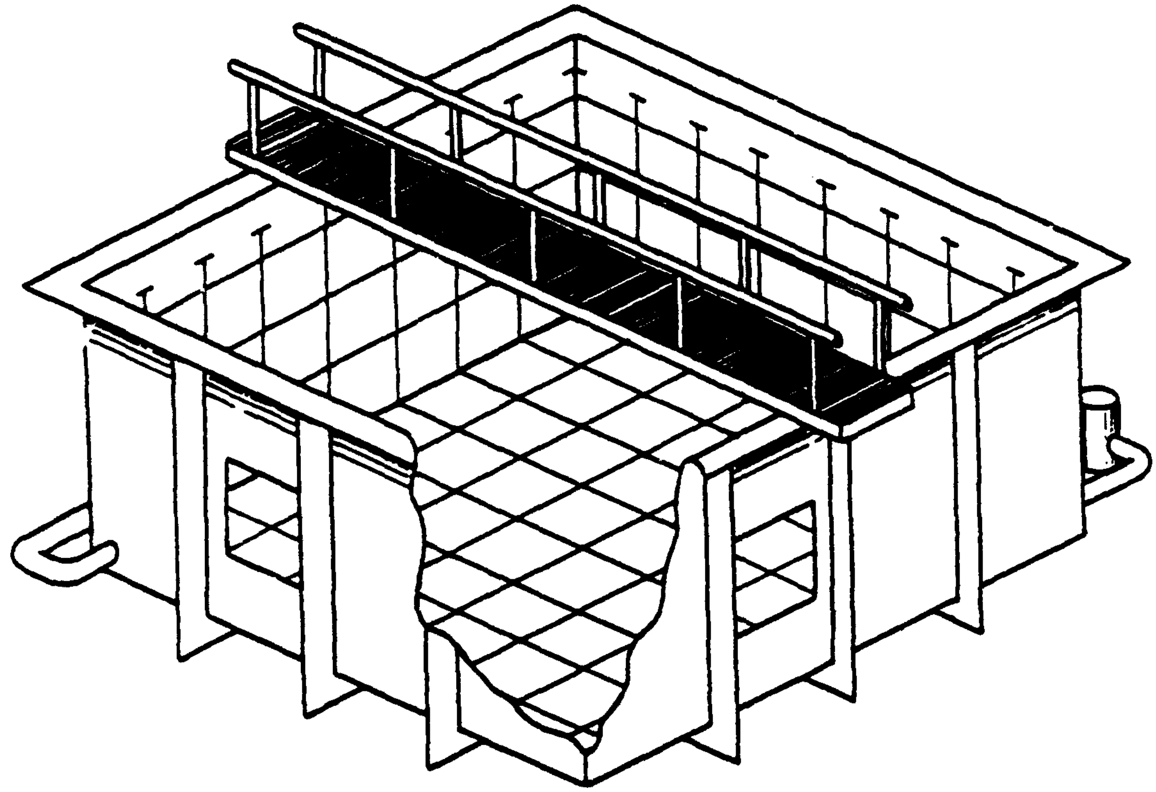

Figure 6. NPS AUV II Testing Tank Facility

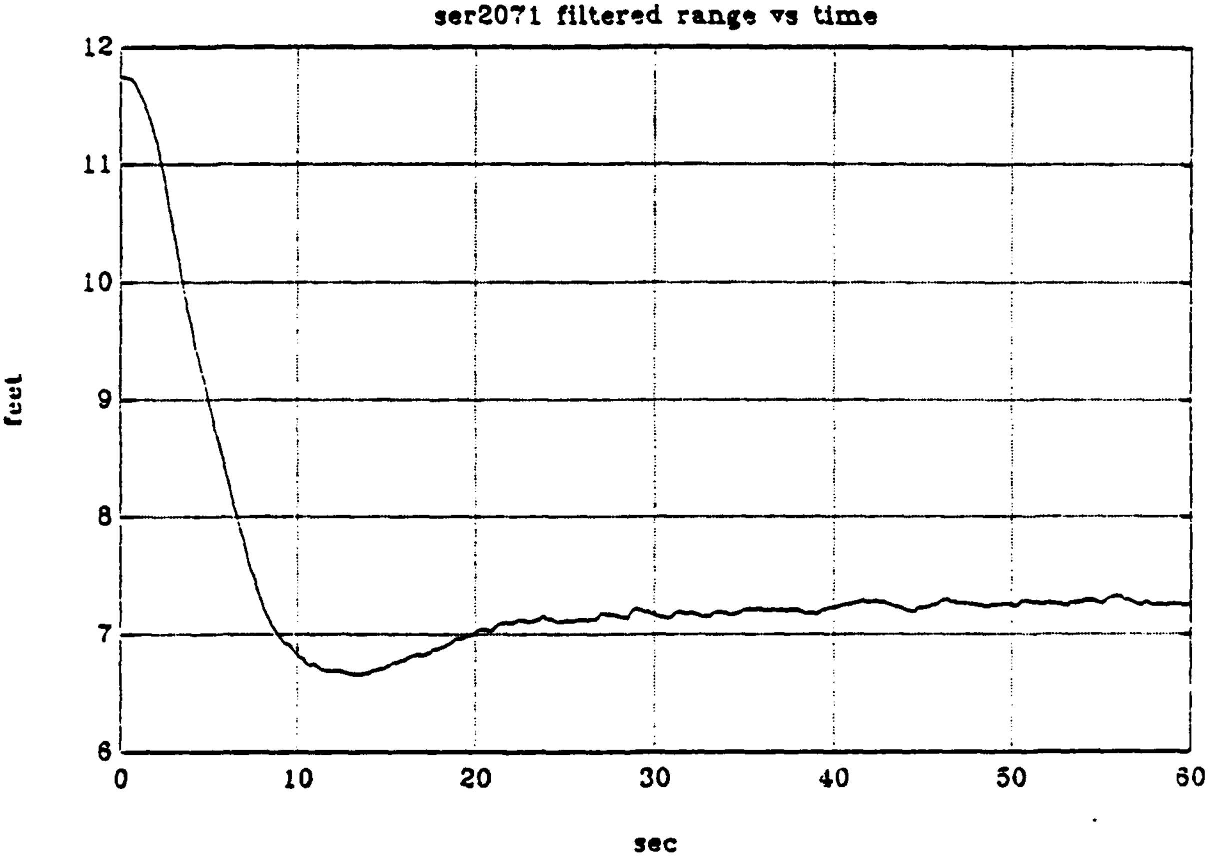

Figure 7. Longitudinal Wall Servoing (Gain 13)

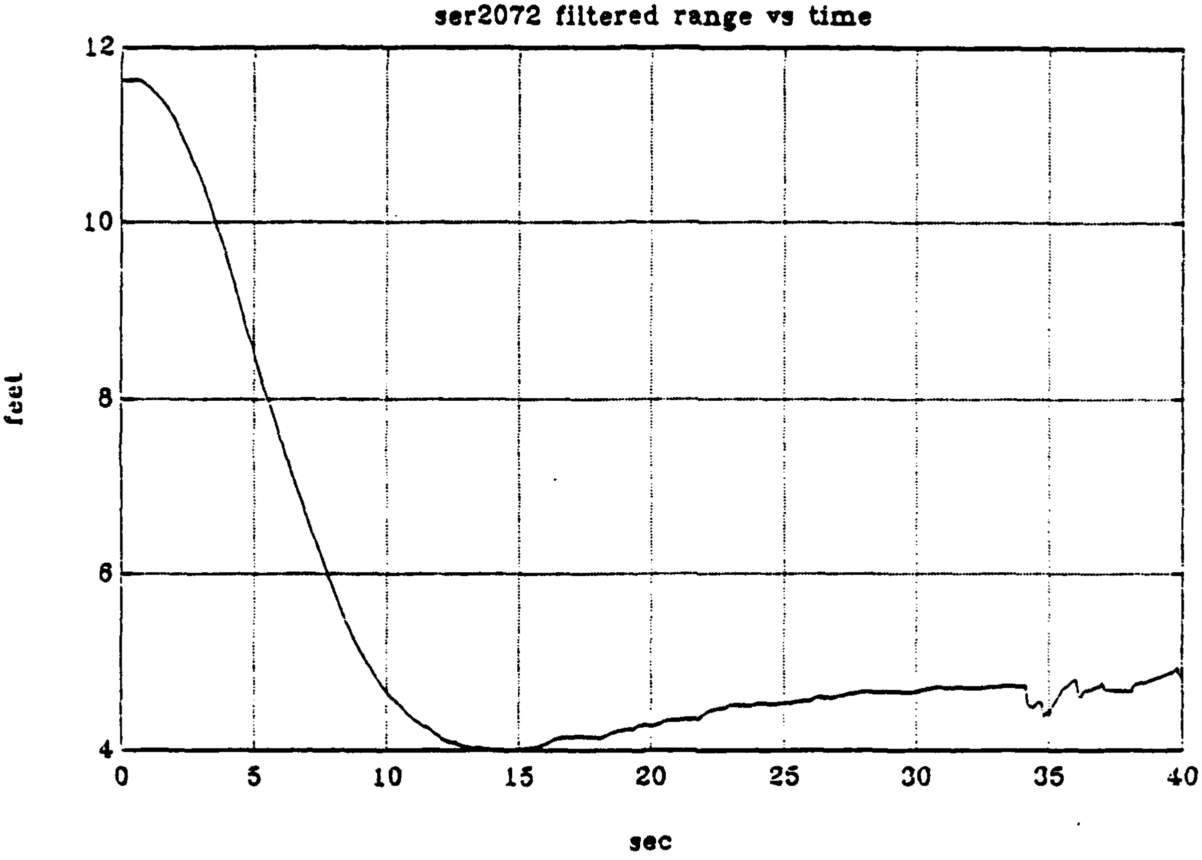

Figure 8. Unstable Longitudinal Wall Servoing (Gain 13)

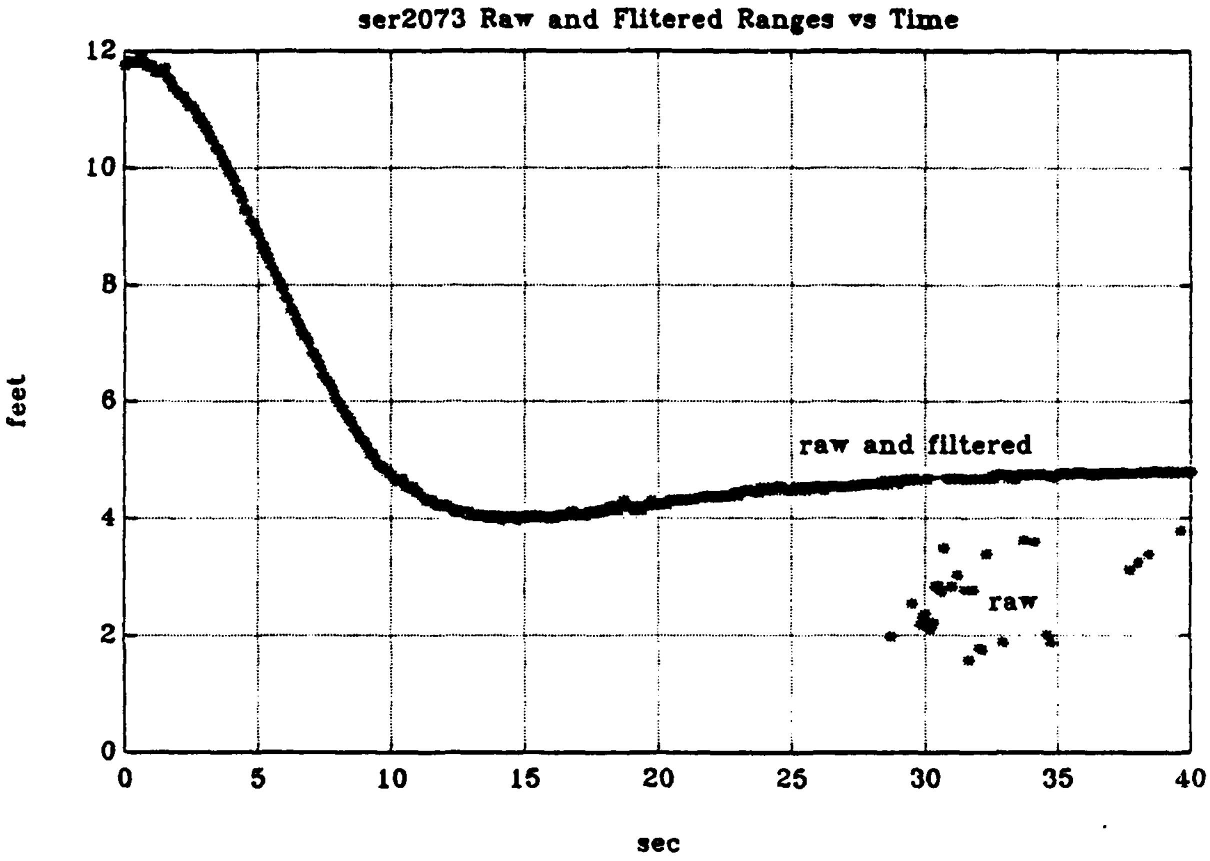

Figure 9. Longitudinal Wall Servoing (Gain 9)

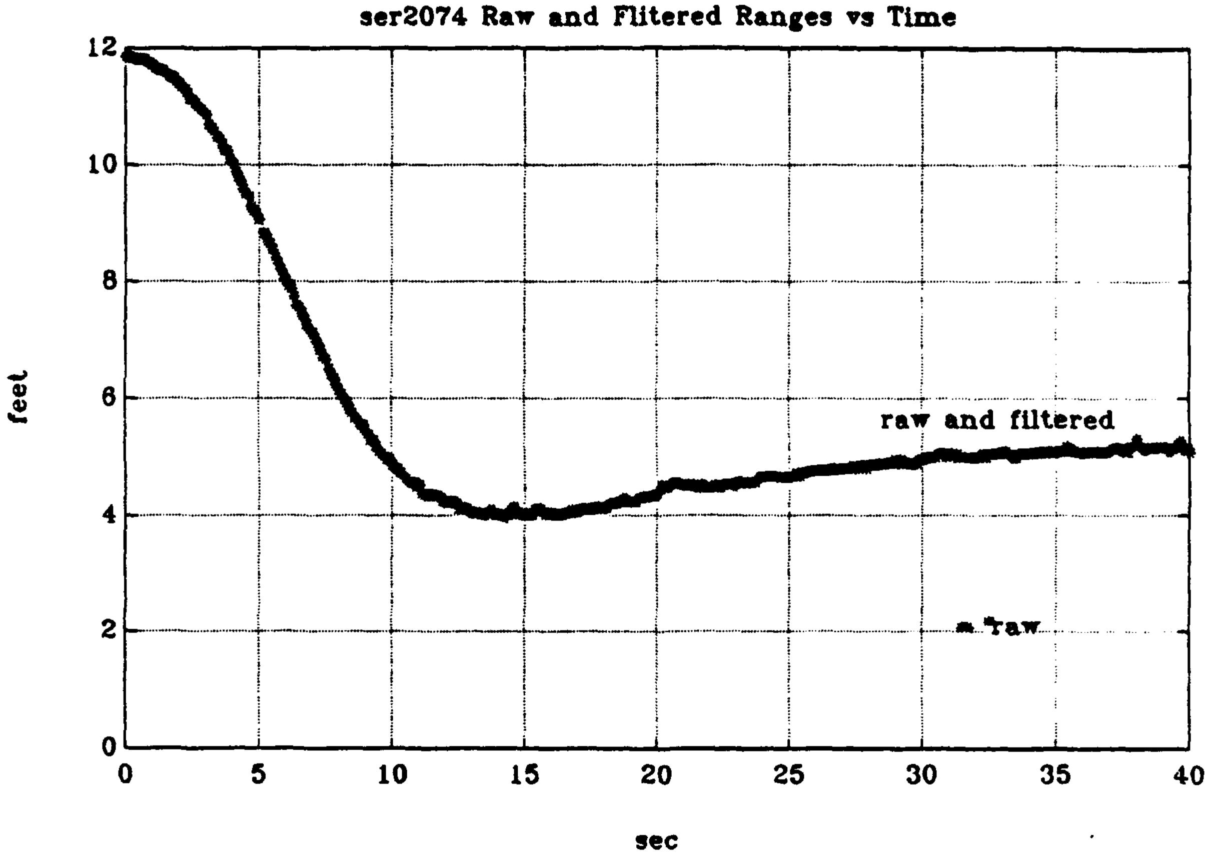

Figure 10. Longitudinal Wall Servoing (Gain 5)

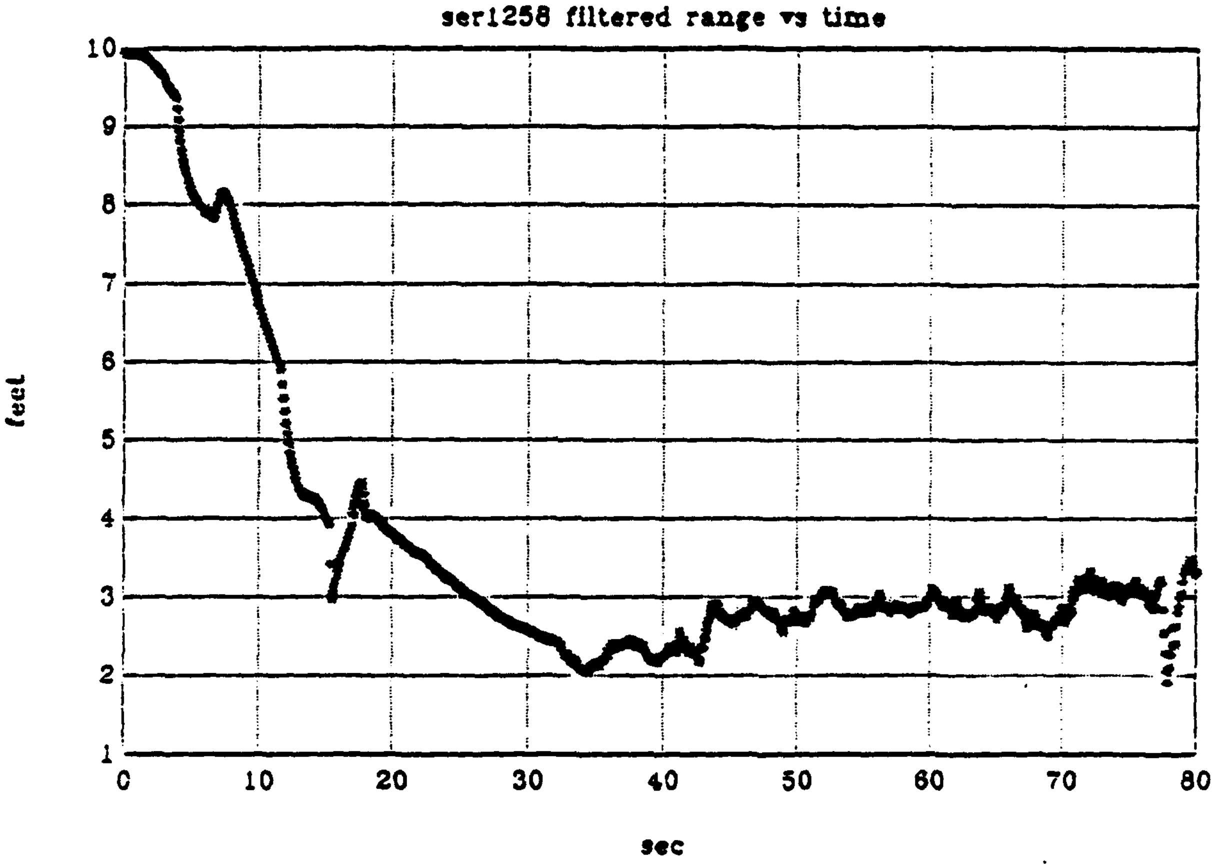

Figure 11. Lateral Wall Servoing (High Heading Control Gain)

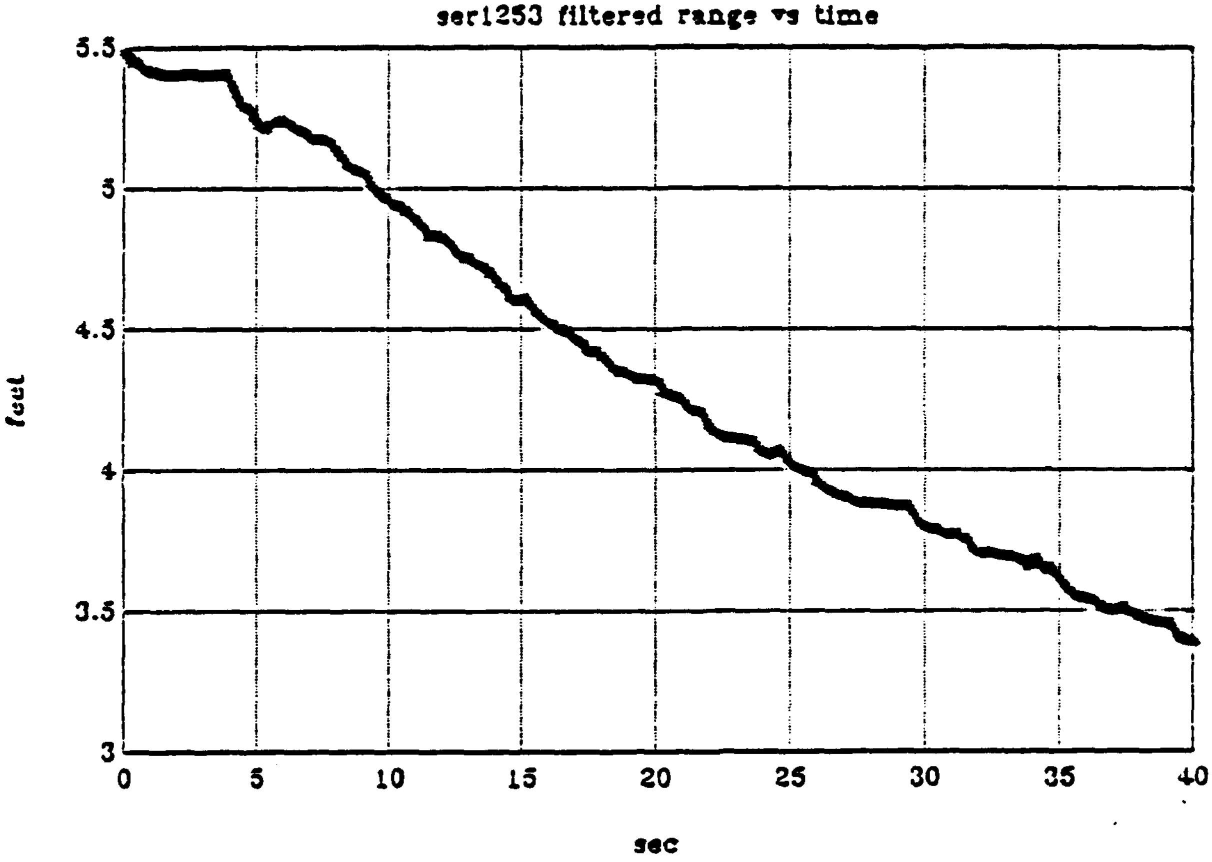

Figure 12. Lateral Wall Servoing (Low Position Control Gain)

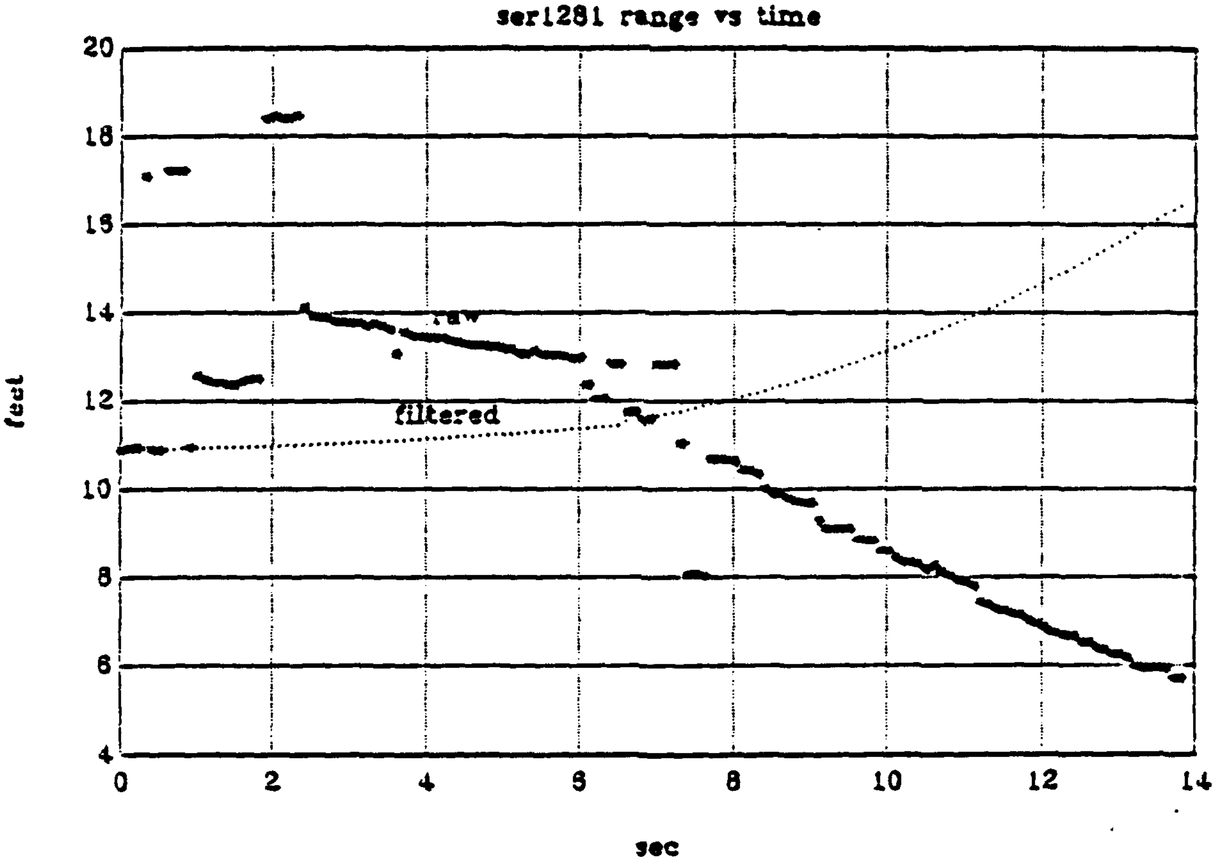

Figure 13. Unstable Lateral Wall Servoing Response

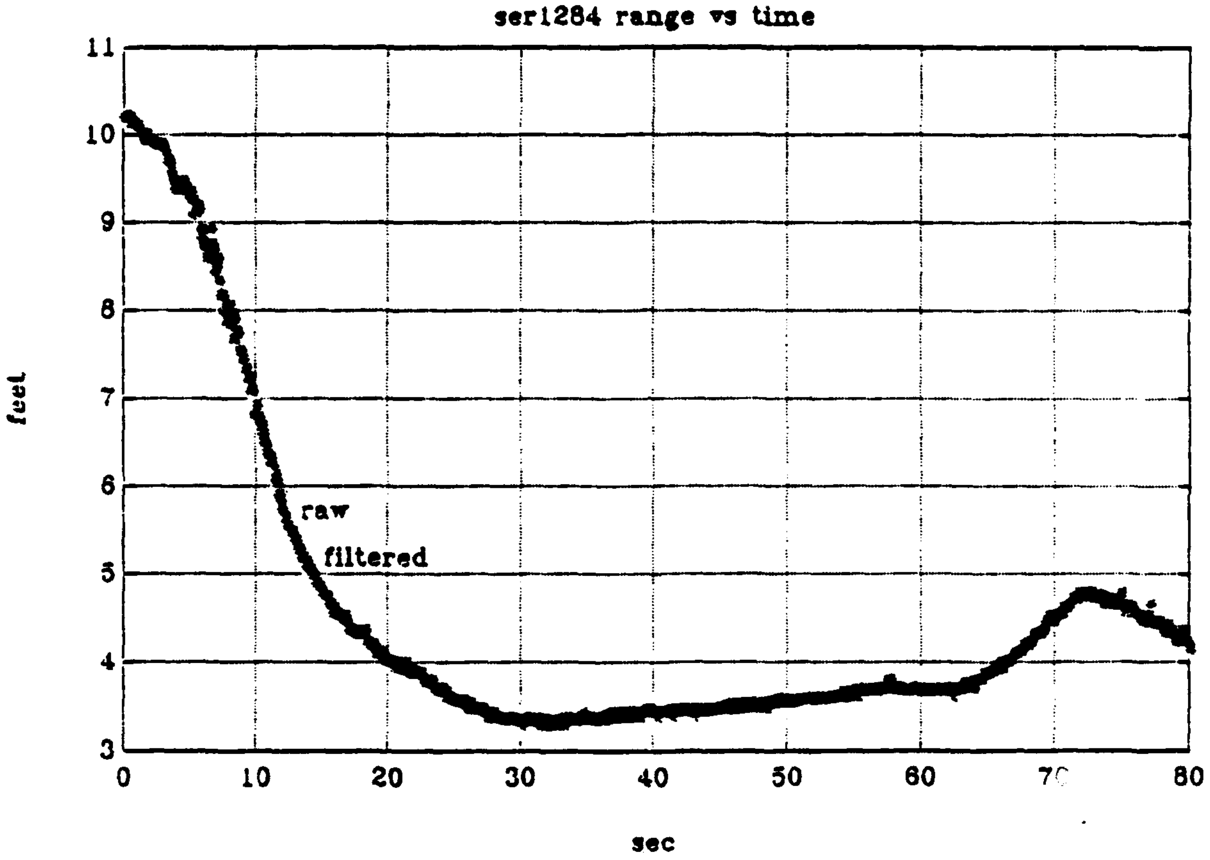

Figure 14. Stable Lateral Wall Servoing Response

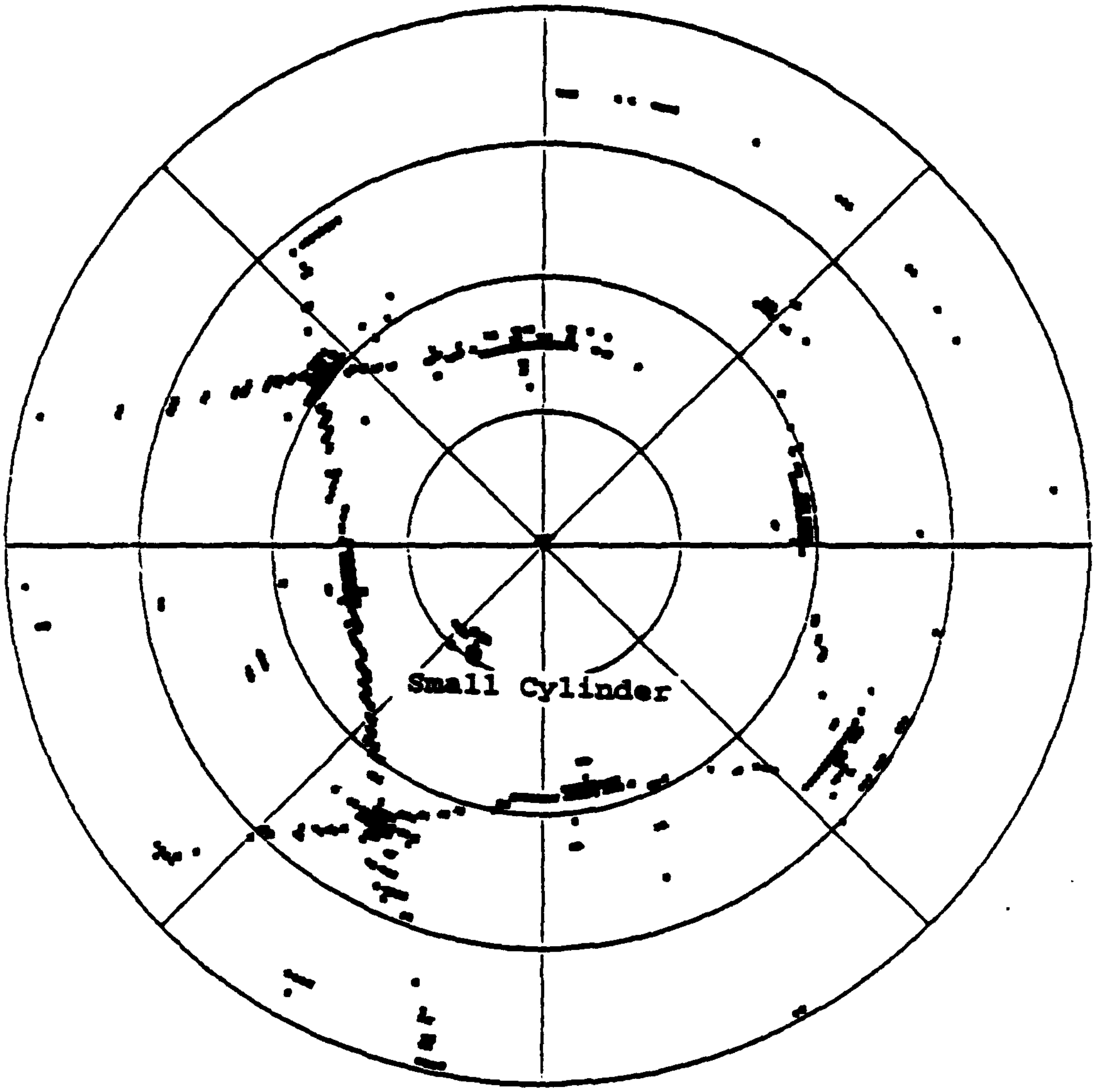

Figure 15. ST725 Sonar Display (One Target, Gain 19)

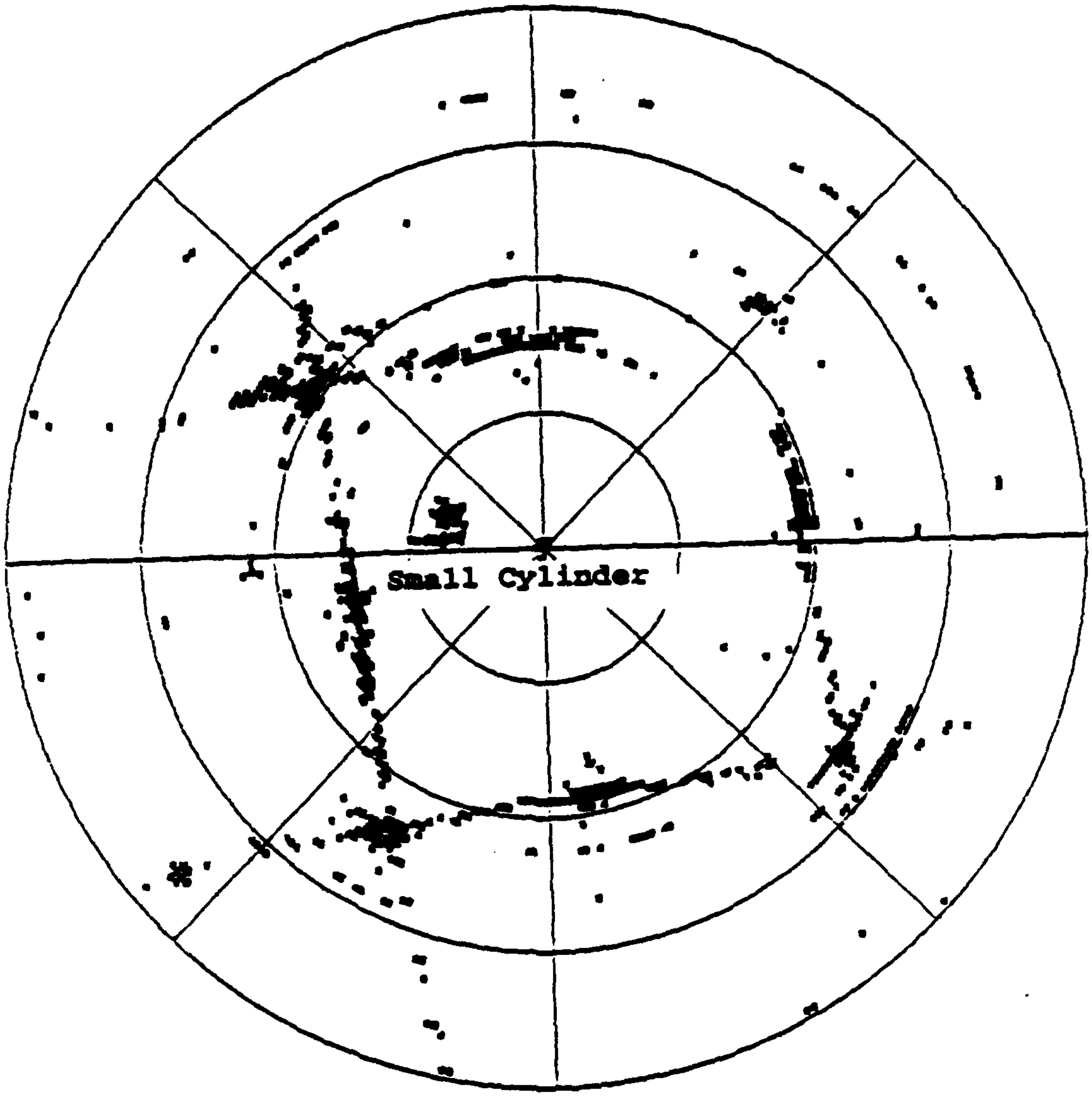

Figure 16. ST725 Sonar Display (One Target, Gain 21)

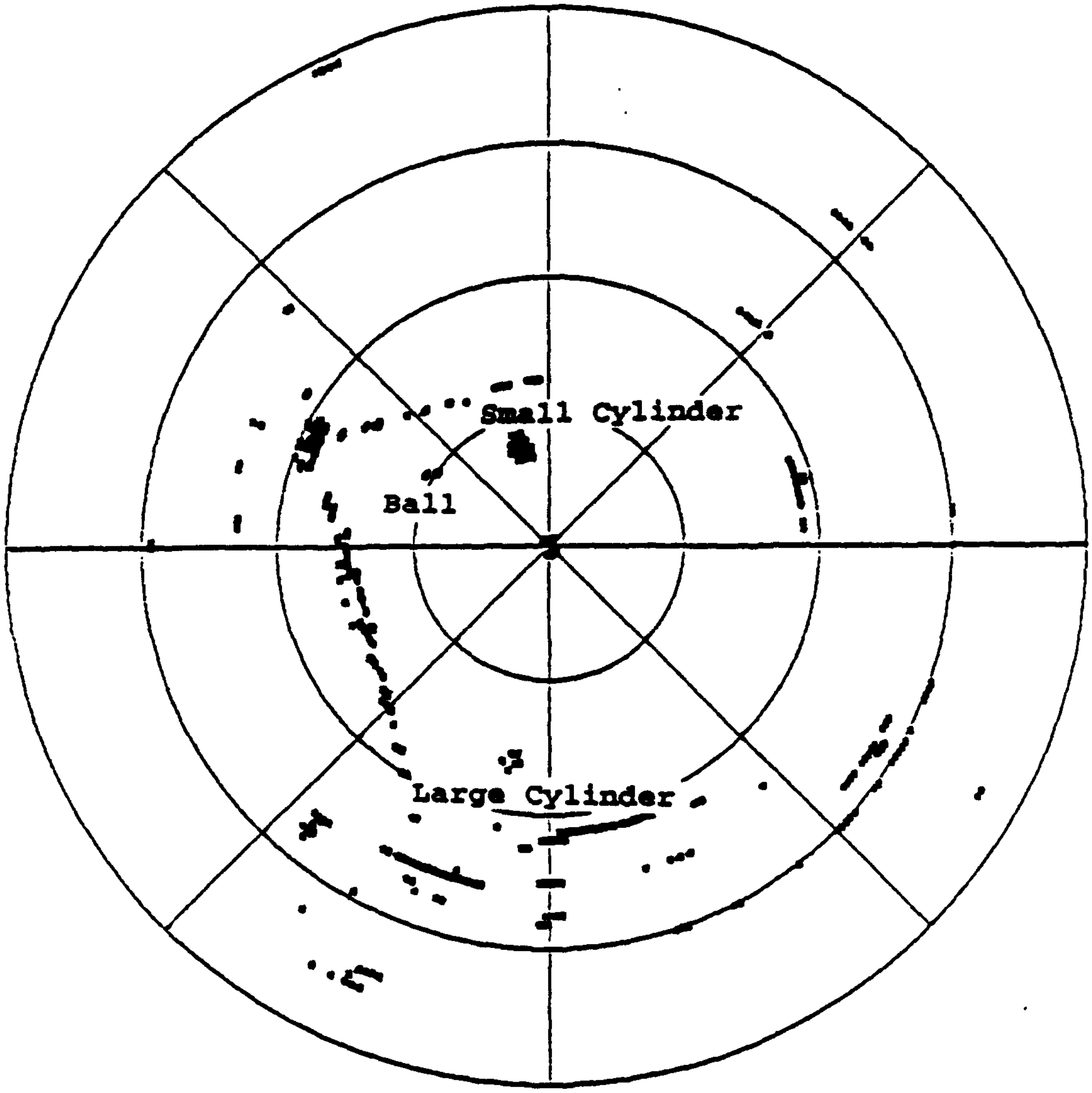

Figure 17. ST725 Sonar Display (Three Targets, Gain 21)

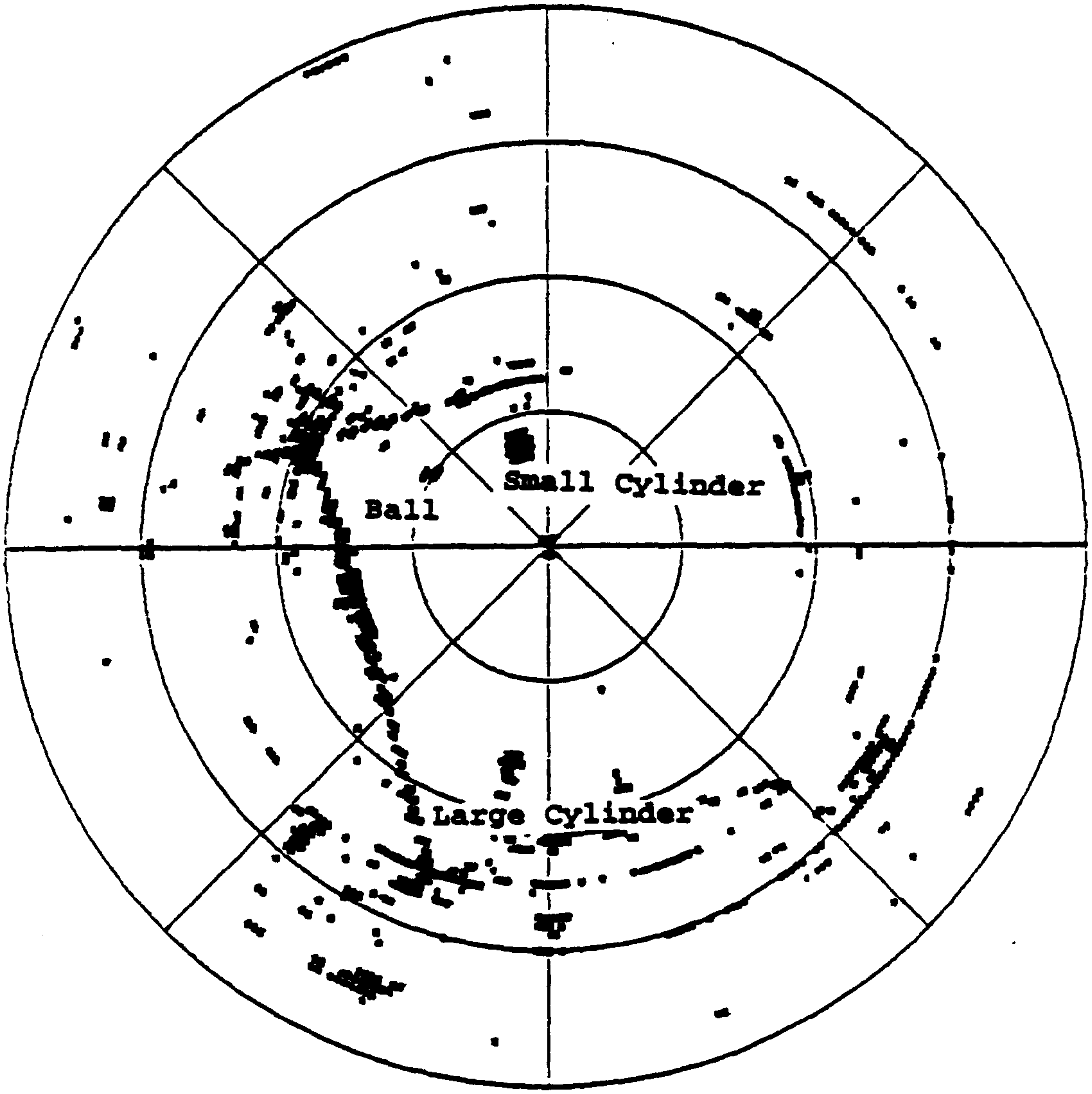

Figure 18. ST725 Sonar Display (Three Targets, Gain 27)

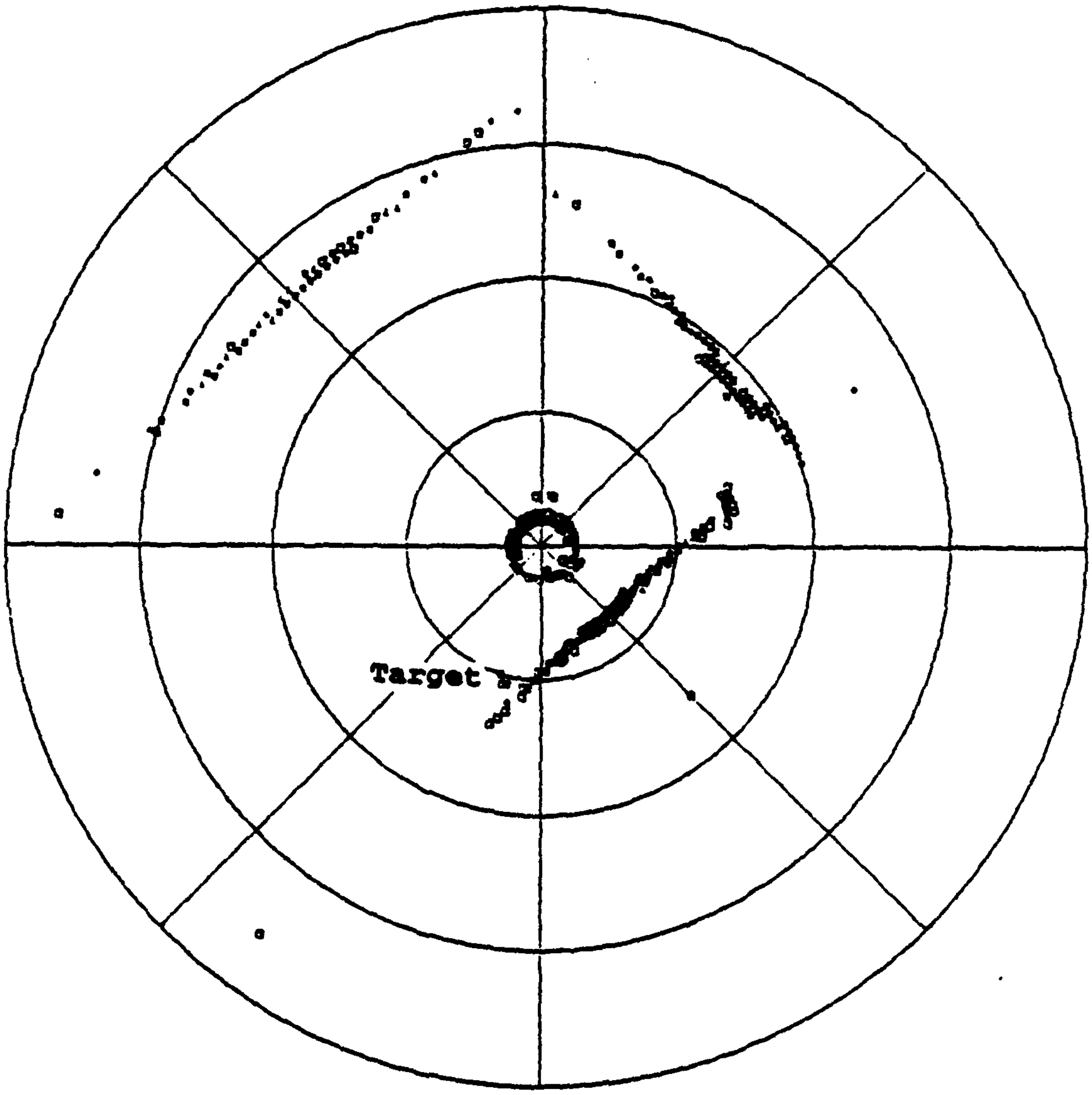

Figure 19. ST725 Pool Display (Gain 15, Range 20 Meters)

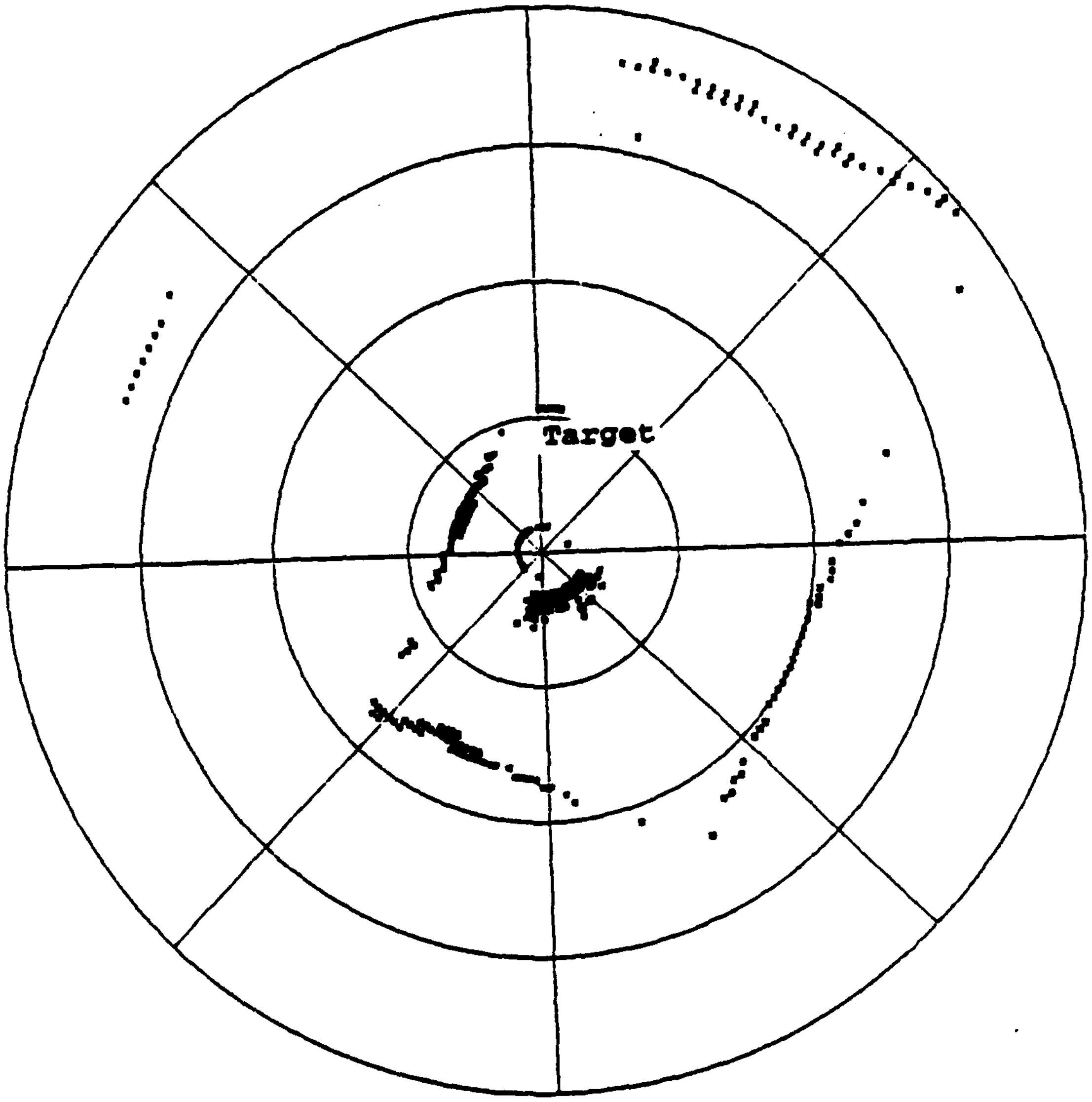

Figure 20. ST725 Pool Display (Gain 15, Range 25 Meters)

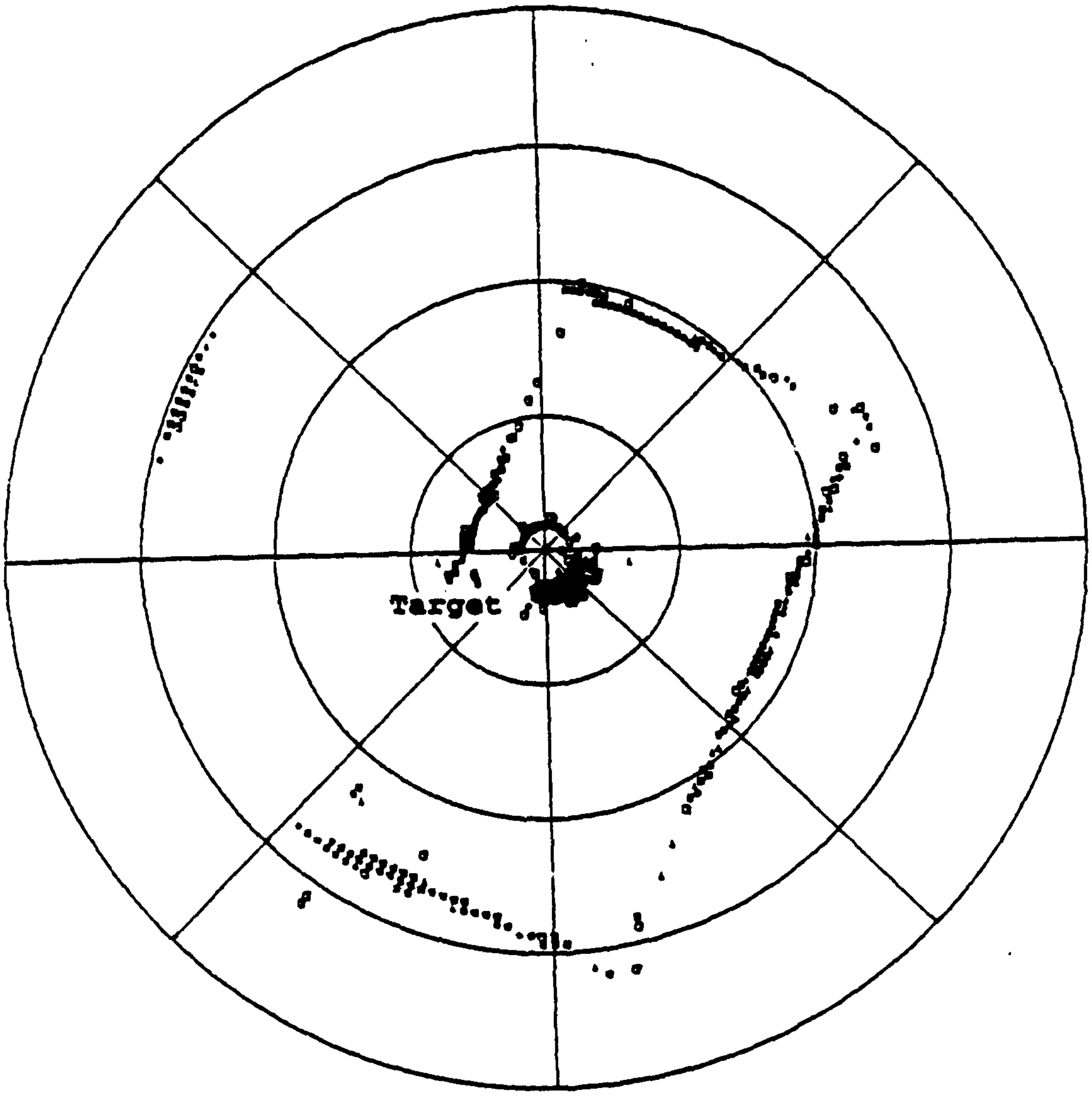

Figure 21. ST725 Pool Display (Gain 13, Range 30 Meters)

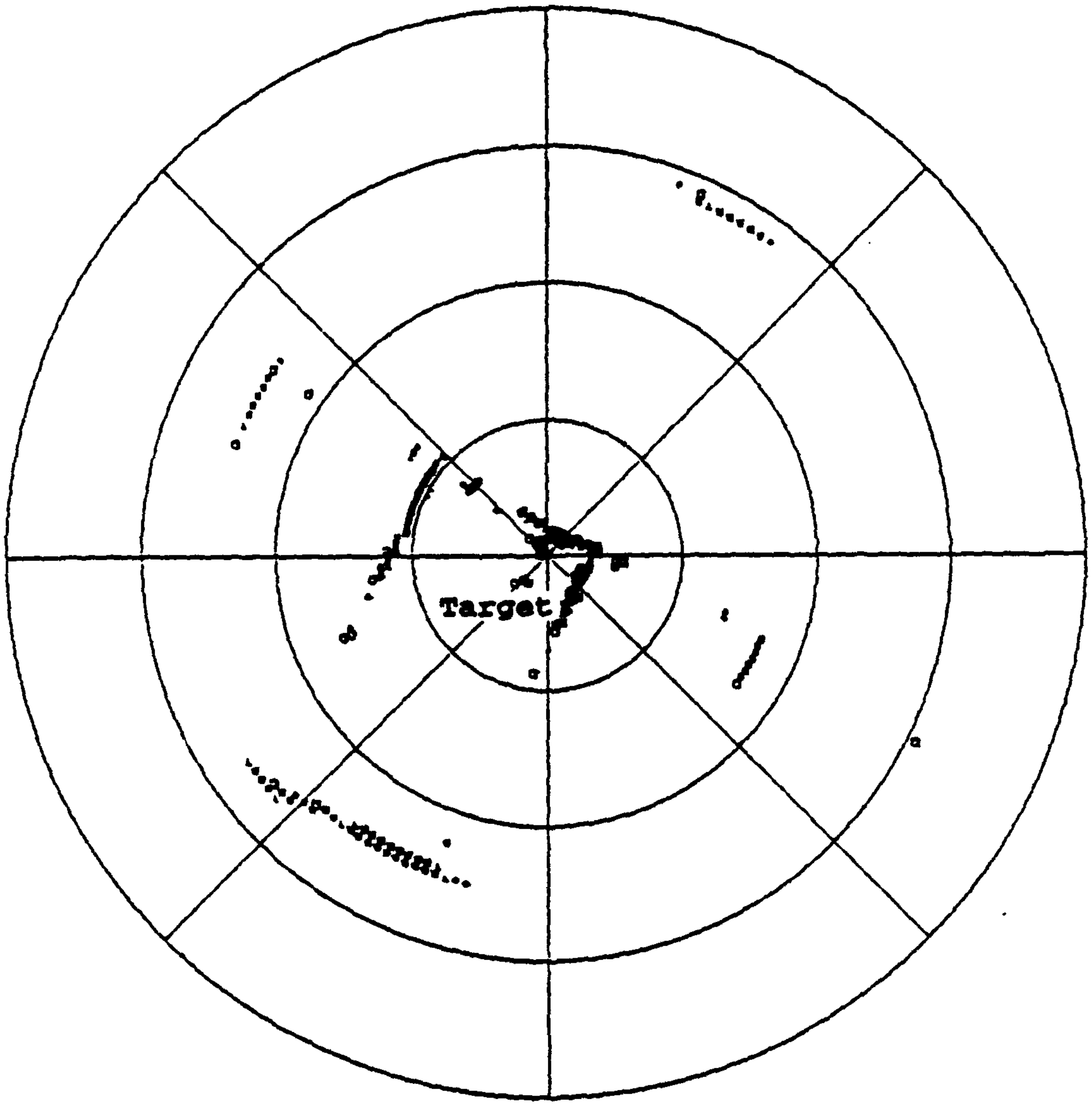

Figure 22. ST725 Pool Display (Gain 15, Range 50 Meters)

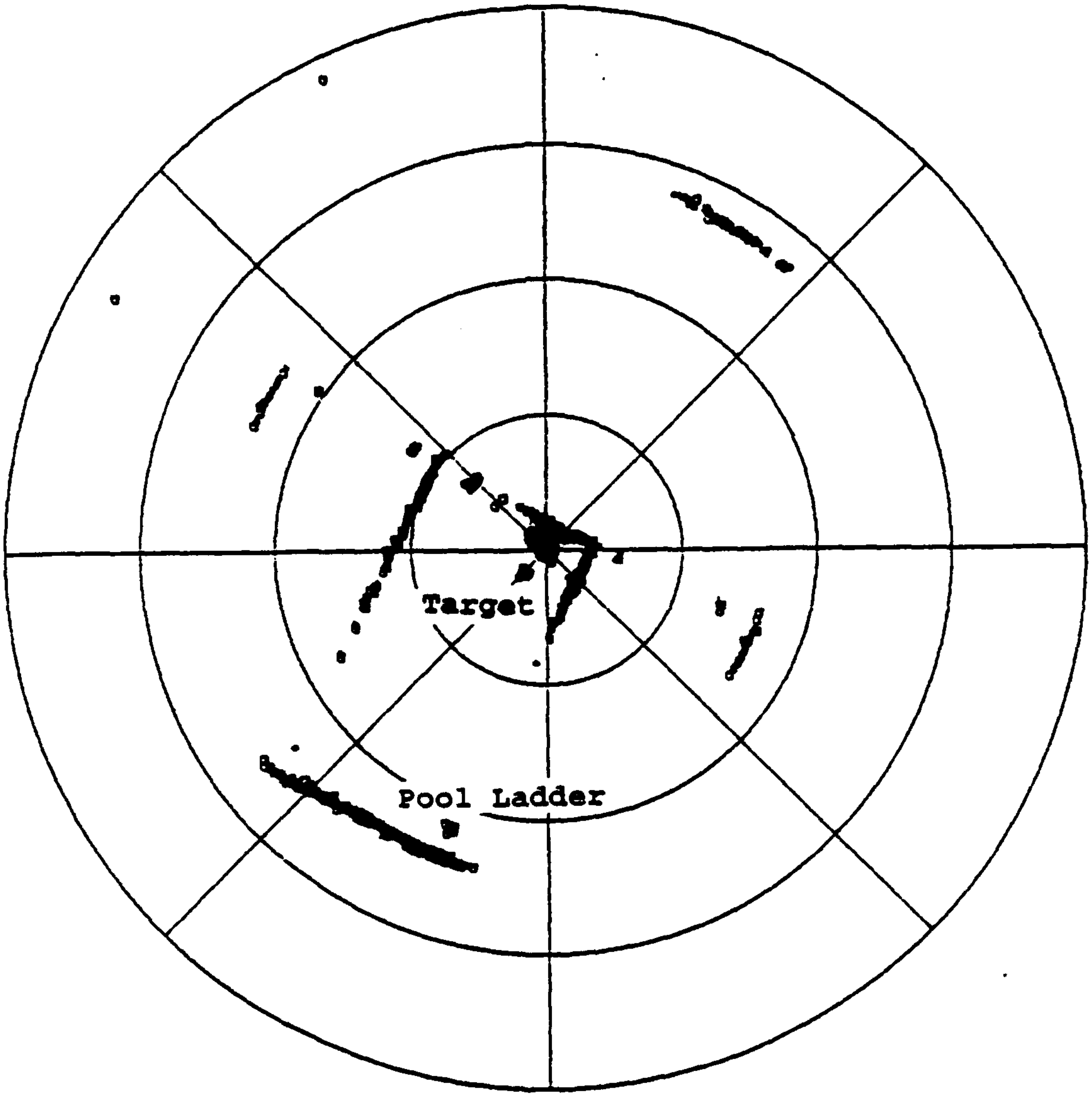

Figure 23. ST725 Pool Display (Gain 15, Range 50 Meters)

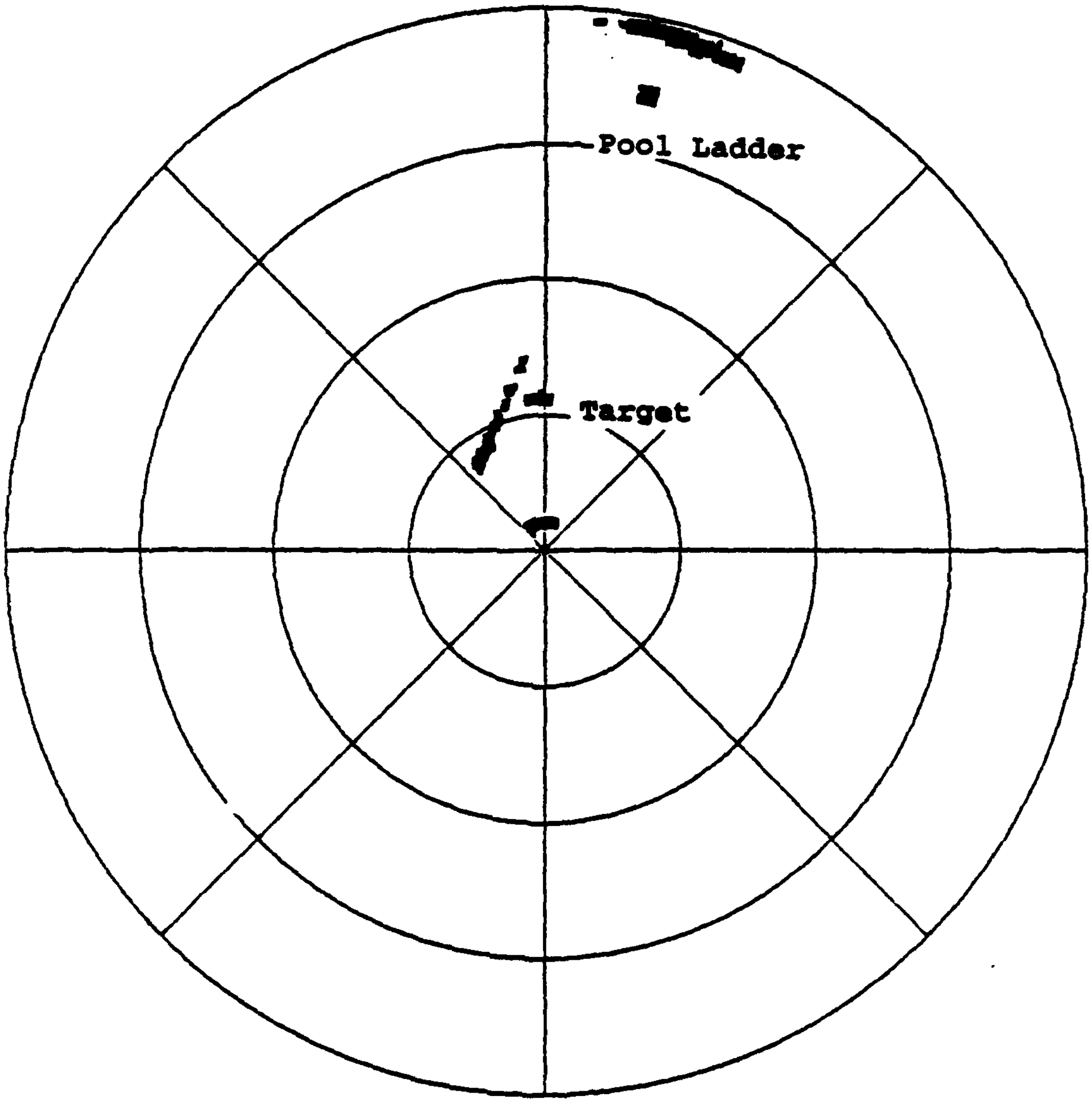

Figure 24. ST725 Pool Display (Gain 21, Range 25 Meters)

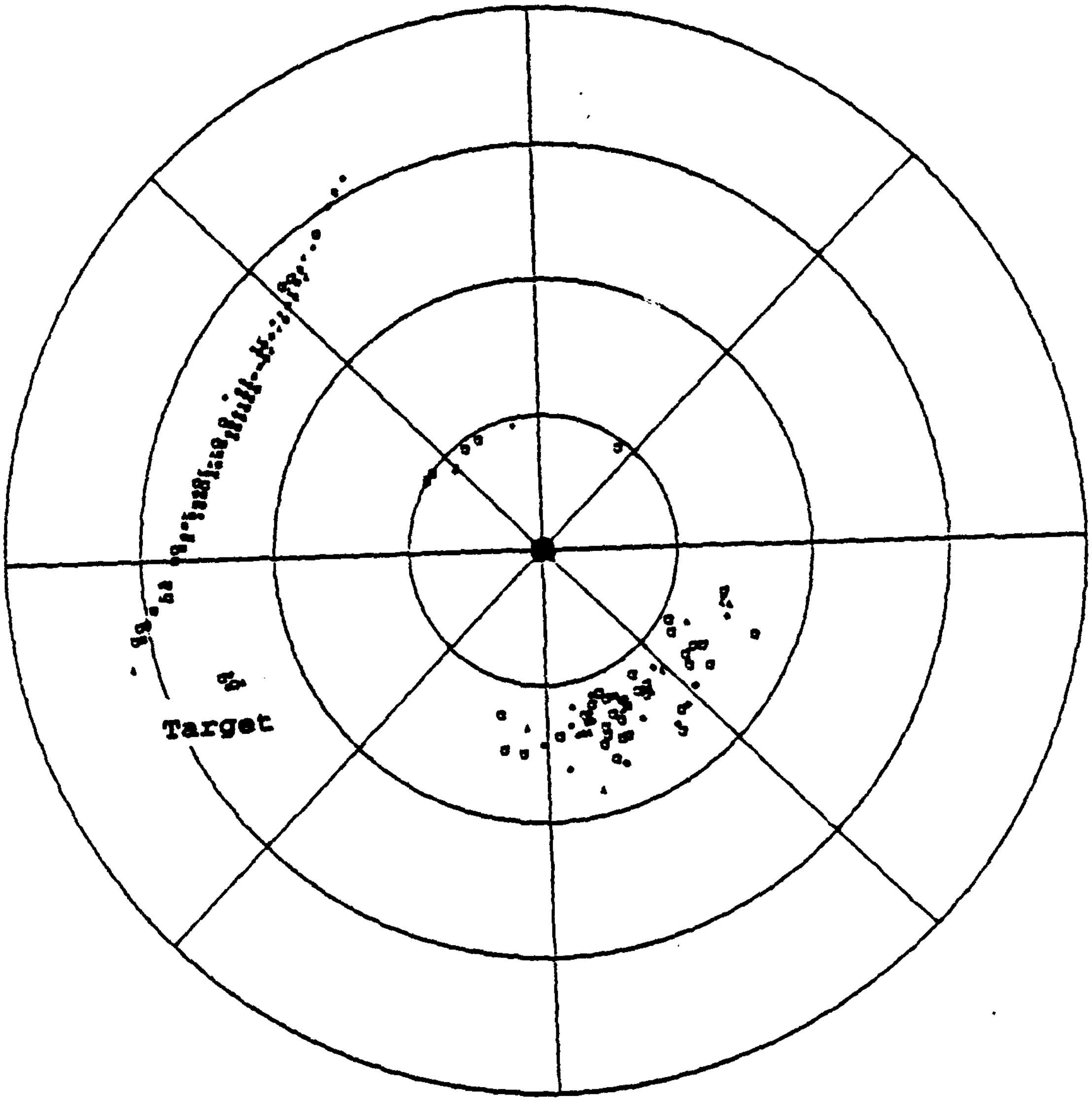

Figure 25. ST725 Pool Display (Gain 15, Range 6 Meters)

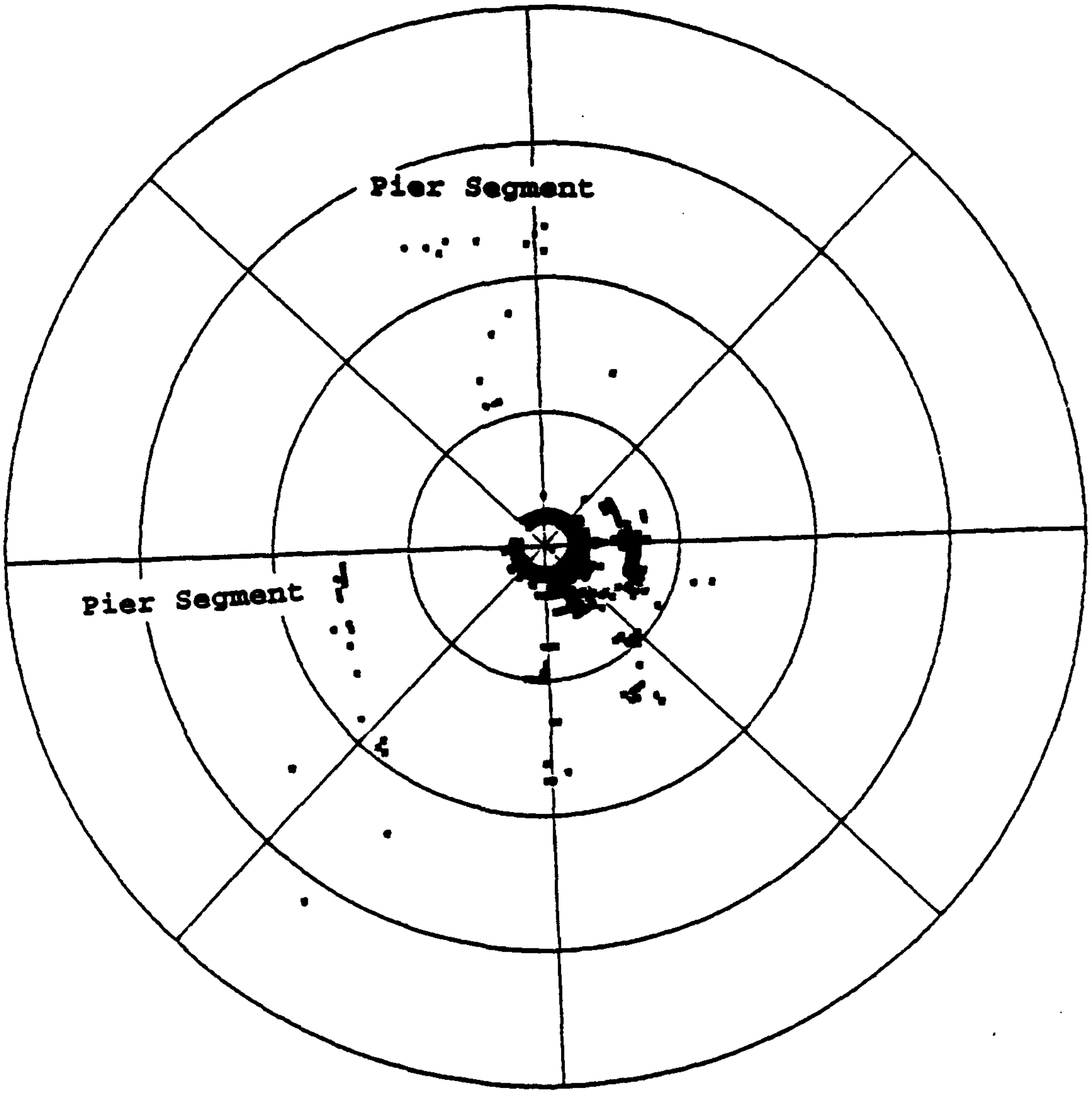

Figure 26. ST725 Wharf Display (Gain 33, Range 50 Meters)

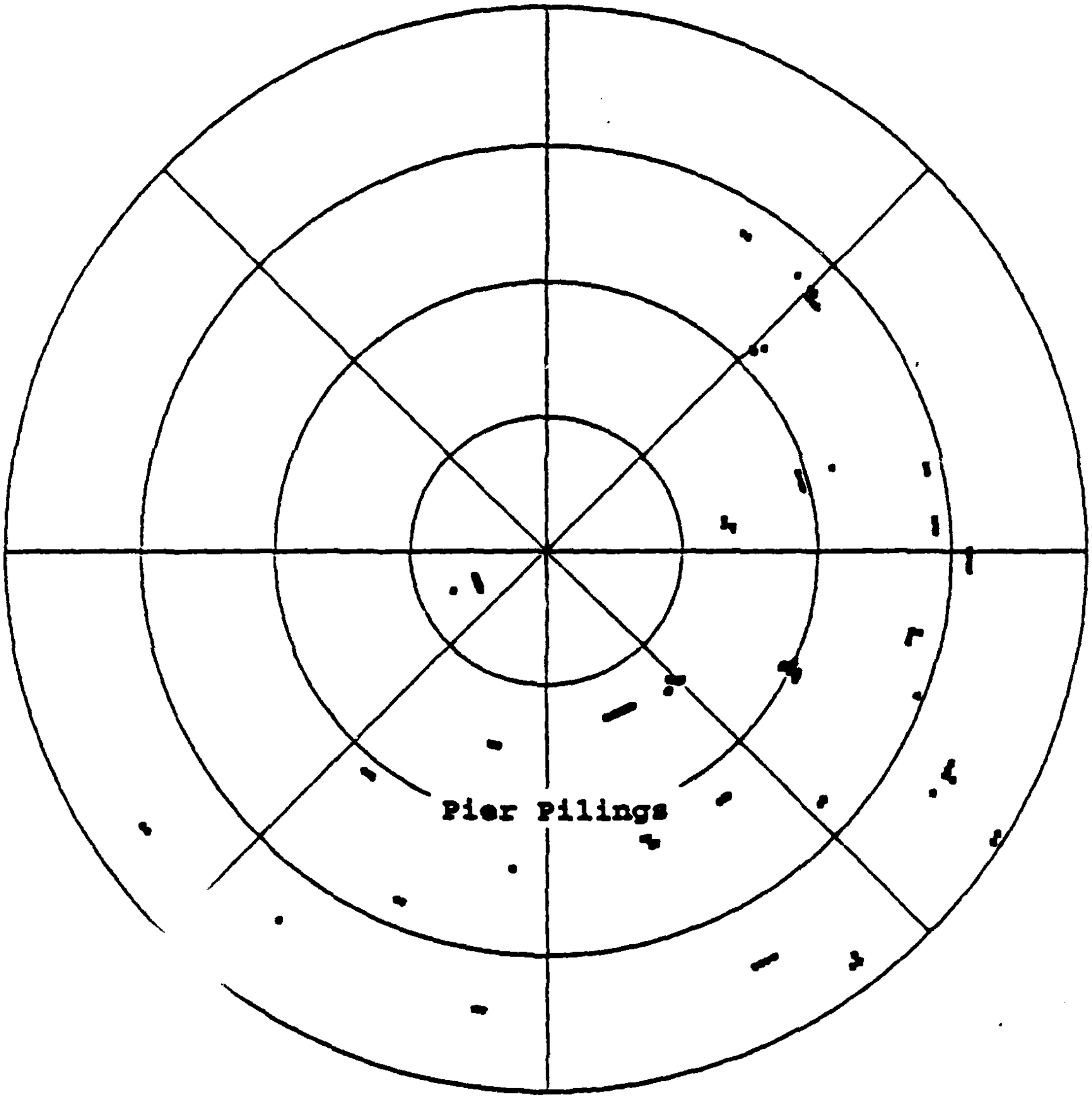

Figure 27. ST725 Wharf Display (Gain 21, Range 10 Meters)

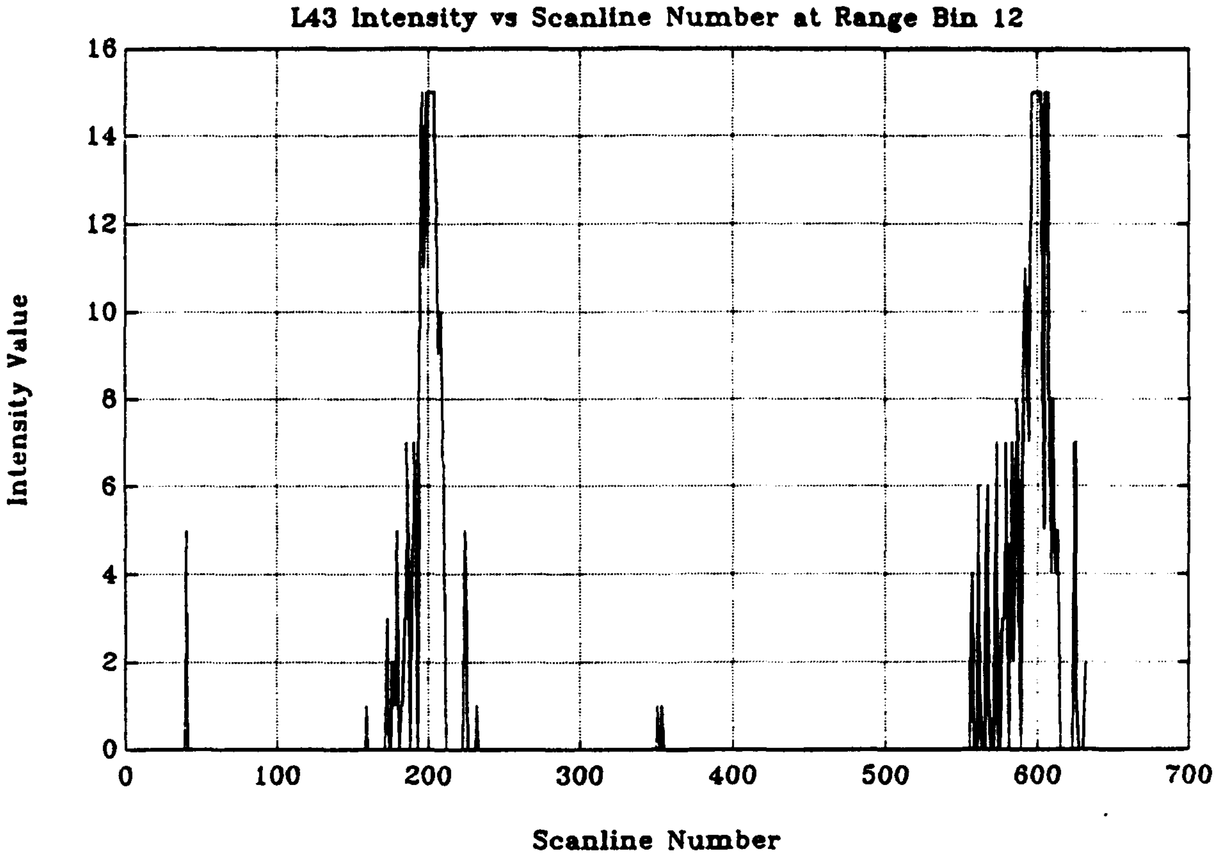

Figure 28. Range Bin 12 (Intensity vs. Scanline)

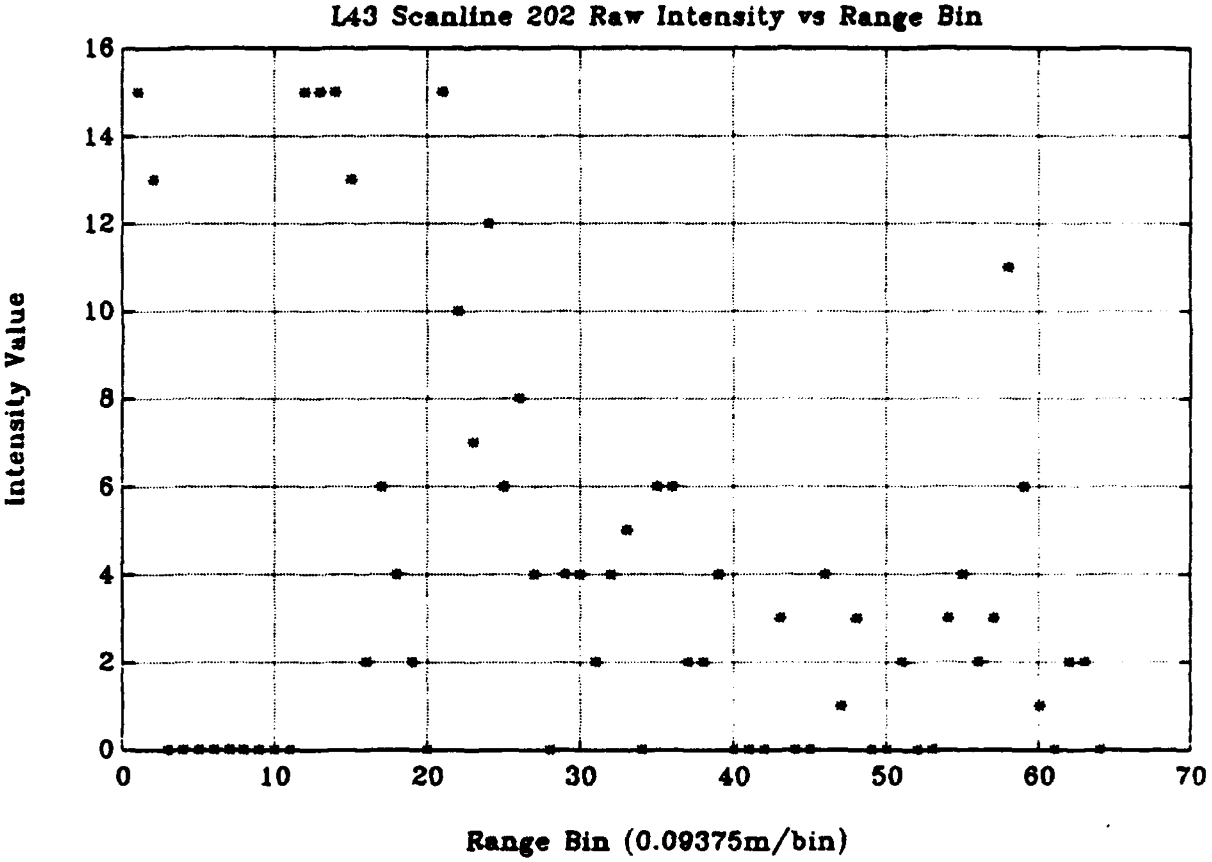

Figure 29. Raw Scanline 202 Data

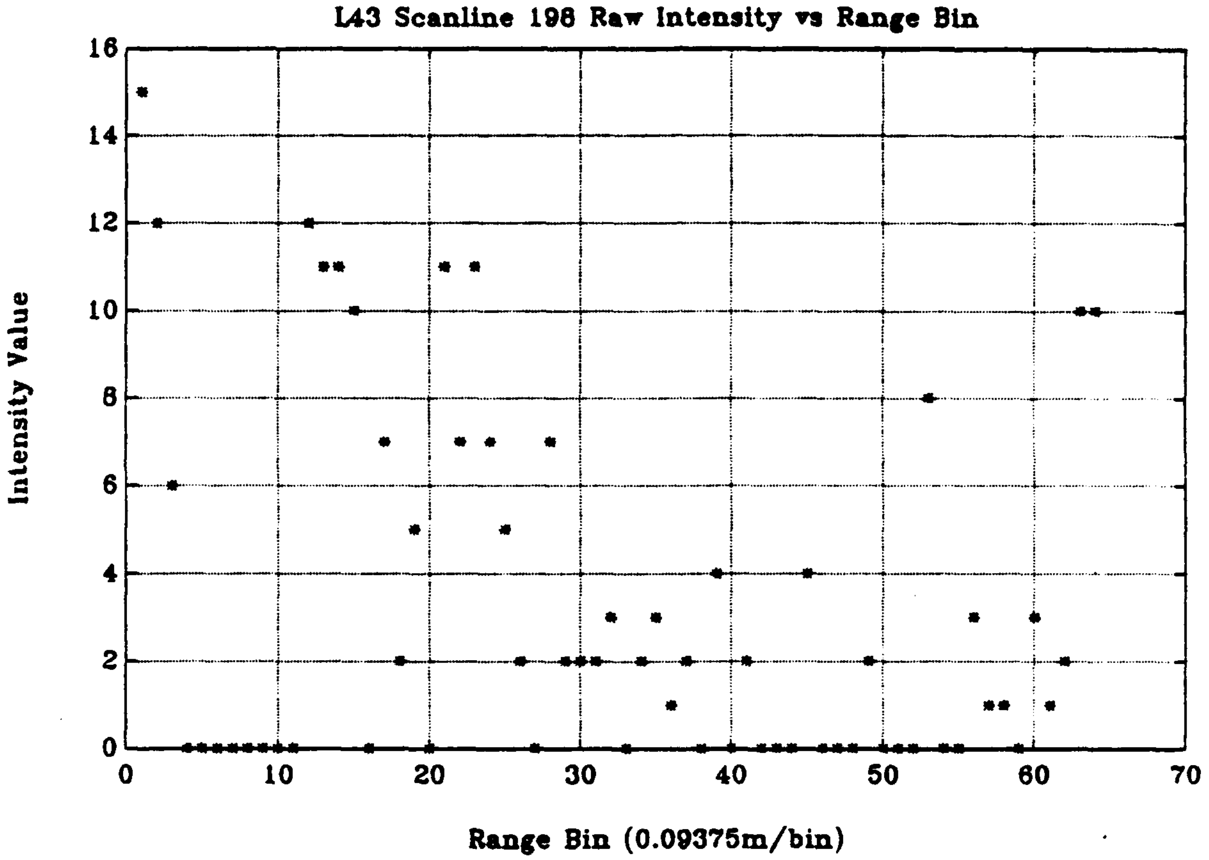

Figure 30. Raw Scanline 198 Data

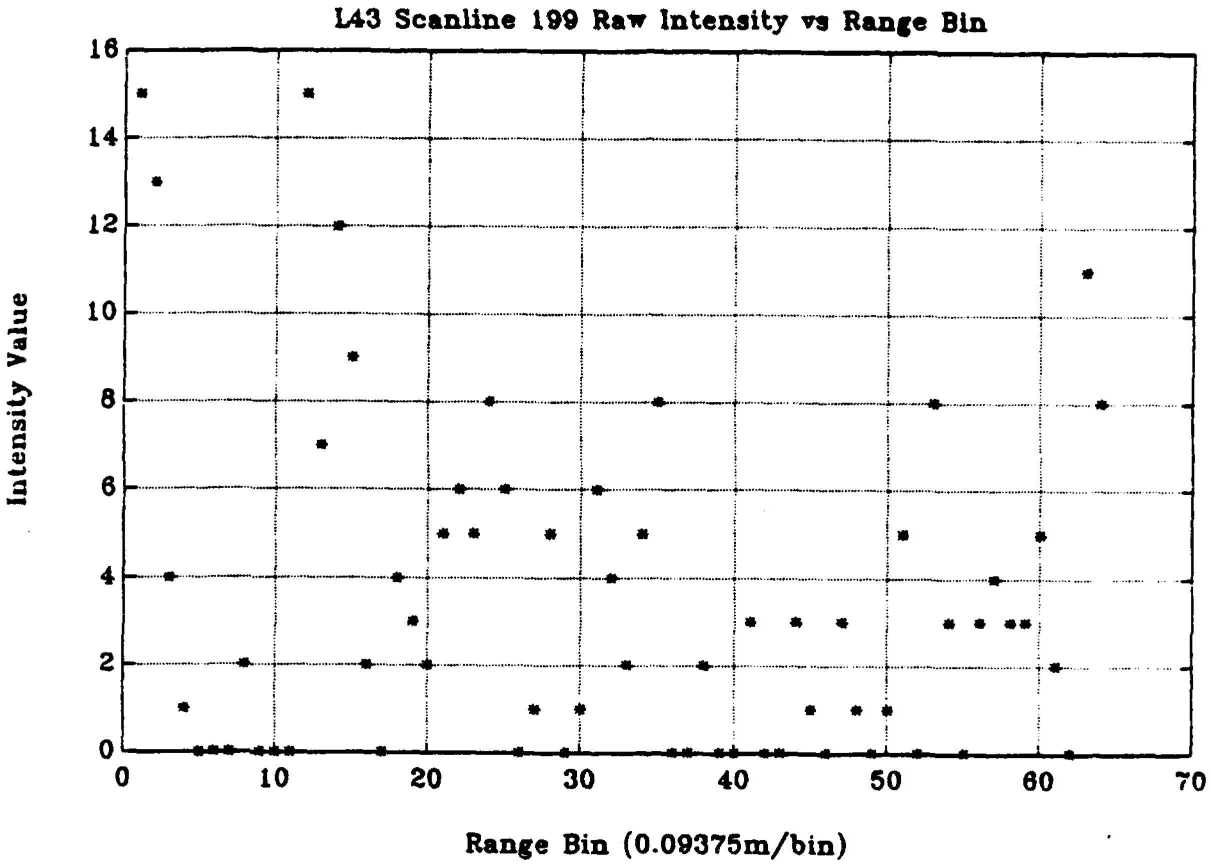

Figure 31. Raw Scanline 199 Data

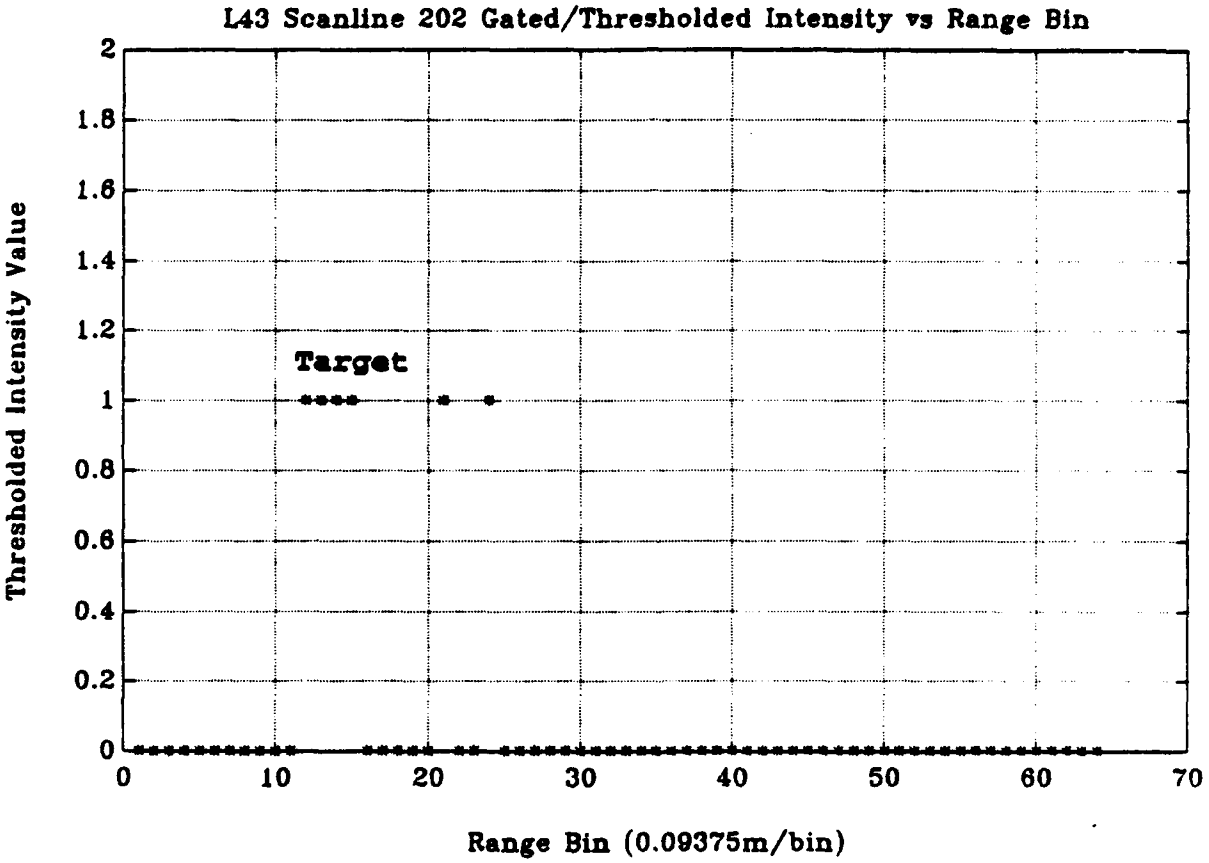

Figure 32. Processed Scanline 202 Data

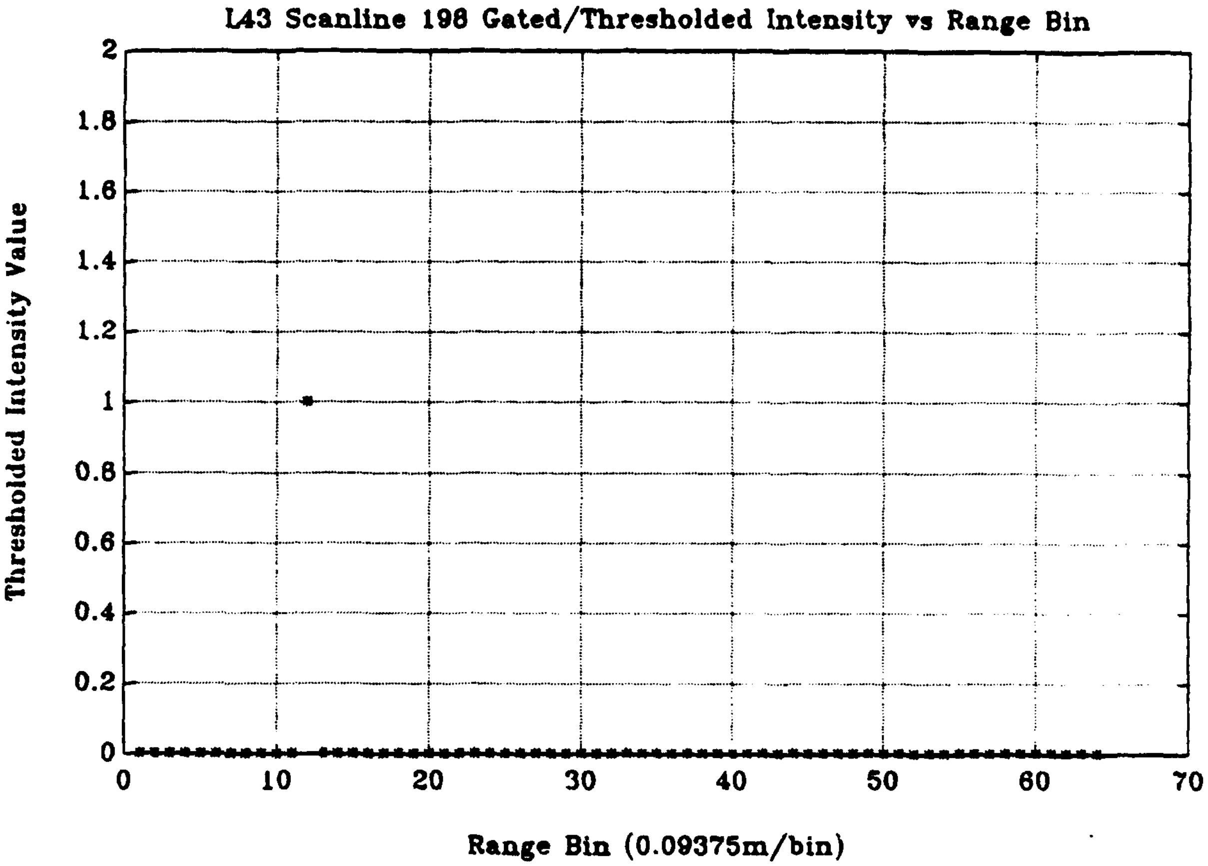

Figure 33. Processed Scanline 198 Data

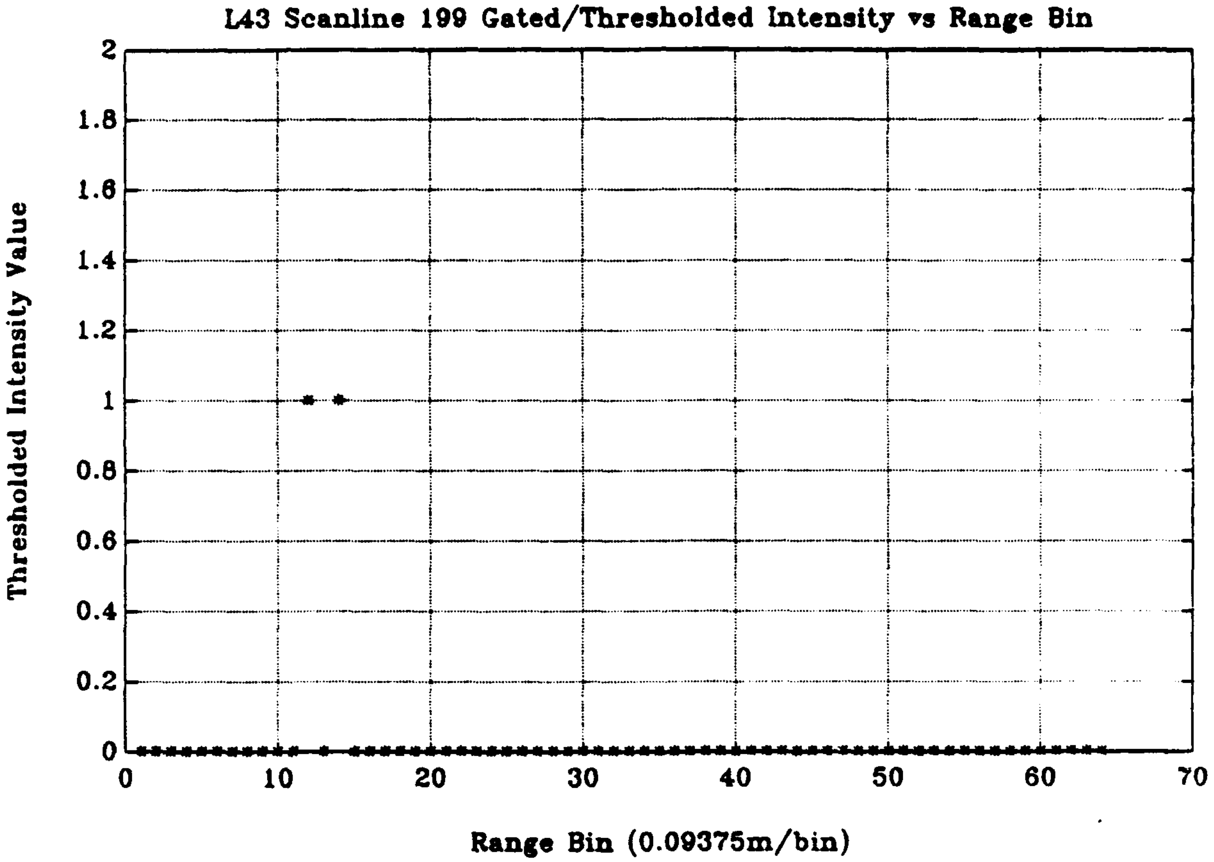

Figure 34. Processed Scanline 199 Data

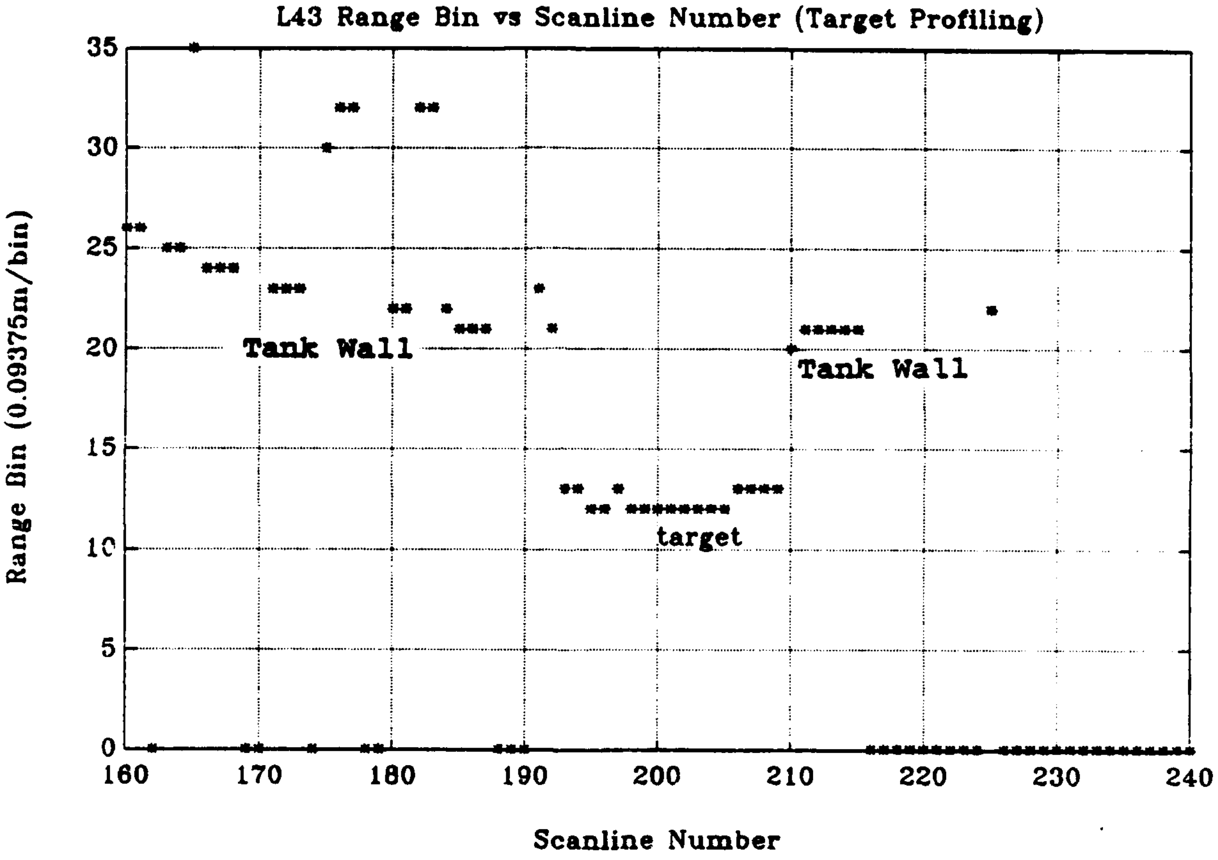

Figure 35. ST725 Profiler Behavior

APPENDIX B: THRESH.M

```
% THRESH.M is a program designed to post process (gate and threshold)
% raw scanline data from ST725 sonar runs.  The data must first be
% translated from raw binary form to raw ASCII form by the program
% read_scan_matrix.  The output, scan_matrix.d, is renamed d.d.
% The matrix d.d can be manipulated in MATLAB to investigate scanline
% bearings, range bins, and sonar return intensities.

% Load the ASCII data file
load d.d;

% Determine matrix file size
[l,m]=size(d);

% Designate bearing/scanline (b) as column 1 of matrix d.d
b=d(:,1);

% Designate the I matrix.  It is 64 range bins wide and each range bin
% contains an intensity value from 0 (weak) to 15 (strong).
I=d(:,2:65);

% Set user determined threshold value (T1).
T1=12;

% Gate values under about 0.5 meters from the sonar head and beyond
% about 4 meters.
I(:,1:6)=zeros(1,6);
I(:,40:64)=zeros(1,25);

% Threshold intensities below selected value to zero.  Make all
% other intensities equal to unity.
for i=1:l
for j=64:-1:1
        if I(i,j)<T1 ,I(i,j)=0;
        end;
        if I(i,j)>=T1, I(i,j) = 1;
        end;

% Find first range return on each scanline (R).
        if I(i,j)==1, R(i)=j;
        end;
end;
end;
```

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