

ULTRASONIC PHASED-ARRAY CHARACTERIZATION FOR NDE APPLICATIONS

FINAL REPORT
Project 17-9891

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Prepared by

John J. Hanley
Richard F. Tennis
Keith S. Pickens

Prepared for

Advisory Committee for Research
Southwest Research Institute

July 1995



SOUTHWEST RESEARCH INSTITUTE

SAN ANTONIO
DETROIT

HOUSTON
WASHINGTON, DC

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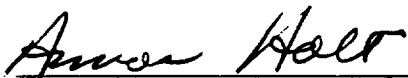
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Arnos E. Holt, Vice President
Nondestructive Evaluation Science
and Technology Division

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1. INTRODUCTION

Southwest Research Institute (SwRI) recently fabricated and delivered the 100-channel Ultrasonic Phased-Array Testbed System (UPATS) for NASA's Langley Research Center. NASA prepared the specifications and provided the funding to develop UPATS in order to provide a tool for the improvement of ultrasonic nondestructive evaluation (NDE) and characterization of materials. UPATS incorporates state-of-the-art phased-array concepts such as beam steering, focusing, apodization, and phase-sensitive detection which make it possible to develop more sophisticated testing methodologies. It also can be used to investigate fundamental ultrasonic propagation and detection phenomena such as refraction, diffraction, scattering, and beam broadening.

Prior to shipping UPATS to NASA, Division 17 personnel were given the opportunity to explore the application of this state-of-the-art technology to some common NDE inspection problems. This Quick-Look IR project provided the support for this effort. The objective of this project was to obtain a body of performance data to be used in making informed decisions about the application of phased arrays to NDE problems in much the same manner as has been done for the application of fixed-focus ultrasonics data to NDE problems which the Division has done for more than a decade.

Conventional focused ultrasonic techniques use a lens or mirror to focus the output of a piezoelectric transducer at a fixed depth and angle within the material to be inspected. The transducer and lens are then physically moved (usually across the part surface) to scan the focal point across the inspection region while observing the received ultrasonic signal. The focusing greatly enhances the sensitivity and signal-to-noise ratio of the received signal while reducing interference from geometrical reflectors located near the inspection region. However, in order to change the focal depth or angle of observation, a new lens must be designed, manufactured, and attached to the transducer.

Phased-array systems consist of a number of small transducers arranged in a pattern. The input and output signals of each transducer are related in time to produce an aggregate signal with characteristics tailored to a specified application. Like conventional focusing transducers, phased arrays also have the ability to focus ultrasound. The focusing, however, is accomplished by assigning a calculated time delay to each array element instead of using lenses or mirrors. By adjusting the delays, the time of arrival of the ultrasonic signals from all the elements is made to coincide at the focus, giving the usual advantages of a focused beam. Unlike the conventional

case, the focal point can be moved through the volume of material by varying the time delays without physically moving the array. Although many investigators have written about the advantages of phased-array systems in theory and have fabricated smaller prototypes in practice, the UPATS system is the only one of its kind in terms of the number of channels and capabilities. NASA will use UPATS as a laboratory tool to develop techniques for inspection of composite materials in aircraft.

Given a specific NDE application requiring focused ultrasonics, the choice of using phased-array versus conventional fixed-focus technology depends on the following technical factors:

- (1) Minimal focal spot size,
- (2) Negligible side lobe effects, and
- (3) Necessity of focusing in different areas.

In general, a smaller focal spot size is desired, since this allows one to resolve smaller geometric features within the material being inspected. Data on focal spot size as a function of various angles and depths provide a working knowledge of the phased-array performance as it applies to specific applications. The focal spot size also provides a measure of performance which allows comparison with fixed-focus technology.

The side lobe effects can degrade the performance of either phased-array or fixed-focus technologies, since they generate signals from objects that are outside the area of interest. These signals can come from extraneous reflectors, which are in the side lobe beam, or from the defect itself at multiple probe positions or angles.

Fixed-focus probes can be used to focus in different locations when multiple probes or changing of probes and lenses can be accommodated. This is only practical if a small number of focal points are all that are needed. However, if many areas need examination, or actual image slices are required, the phased array offers a clear advantage with its ability to acquire image data from the test volume without elaborate physical scanning. This has been done previously with linear arrays to create sector-scan images. However, the NASA array is unique in that it can create a high-resolution focus in three dimensions. This ability provides the opportunity to create 3-D volume images of the material under test.

2. TECHNICAL APPROACH

The information required to characterize the use of the array for typical NDE applications was obtained from two basic types of experiments:

- Focal spot size, side lobe effects, and beam-synthesis artifacts were investigated by setting the array to focus at a fixed point and using a scanner to move the array in a plane parallel to the surface of a calibration target block by a raster scan motion. This motion was used to generate a series of B-scans.
- Beam-steering performance was explored by fixing the position of the array and sweeping the beam focus through a specified volume in the target block which was centered on the target of interest.

Both types of experiments required that the array be focused through a water-steel interface, a capability that the original NASA software did not have, but that was added as part of this investigation.

Along with the target blocks mentioned above, two samples representative of materials found in industrial NDE applications were examined. The data obtained using the phased array can be compared with theoretical characteristics of a fixed-focus probe with equivalent design parameters. The fixed-focus probe is described in Appendix A.

2.1 Focusing in Two Media

The original UPATS single-medium focusing software was modified to focus a beam to a point in one material after traversing another one. The program accepts entry of six basic parameters and calculates the transmit and receive delays needed to produce a focus within the part (i.e., the second medium). The parameters specify the water and metal path (MP) of the central ray as well as the incident and refracted angles and velocities. The calculations are based on Snell's Law, which gives the minimum time path from a given array element to the focal point. For each element, the time will be slightly different, so the program adjusts the transmit delays to make the sound energy meet at the focal point at the same time and with the same phase. The receive delays are then adjusted to make the signals from all the elements line up so that they can be added together in phase to produce a coherent summation signal. Figure 1 illustrates the two media-focusing geometry and defines the coordinate system used. (See Appendix B for details on the focusing calculations and geometry.)

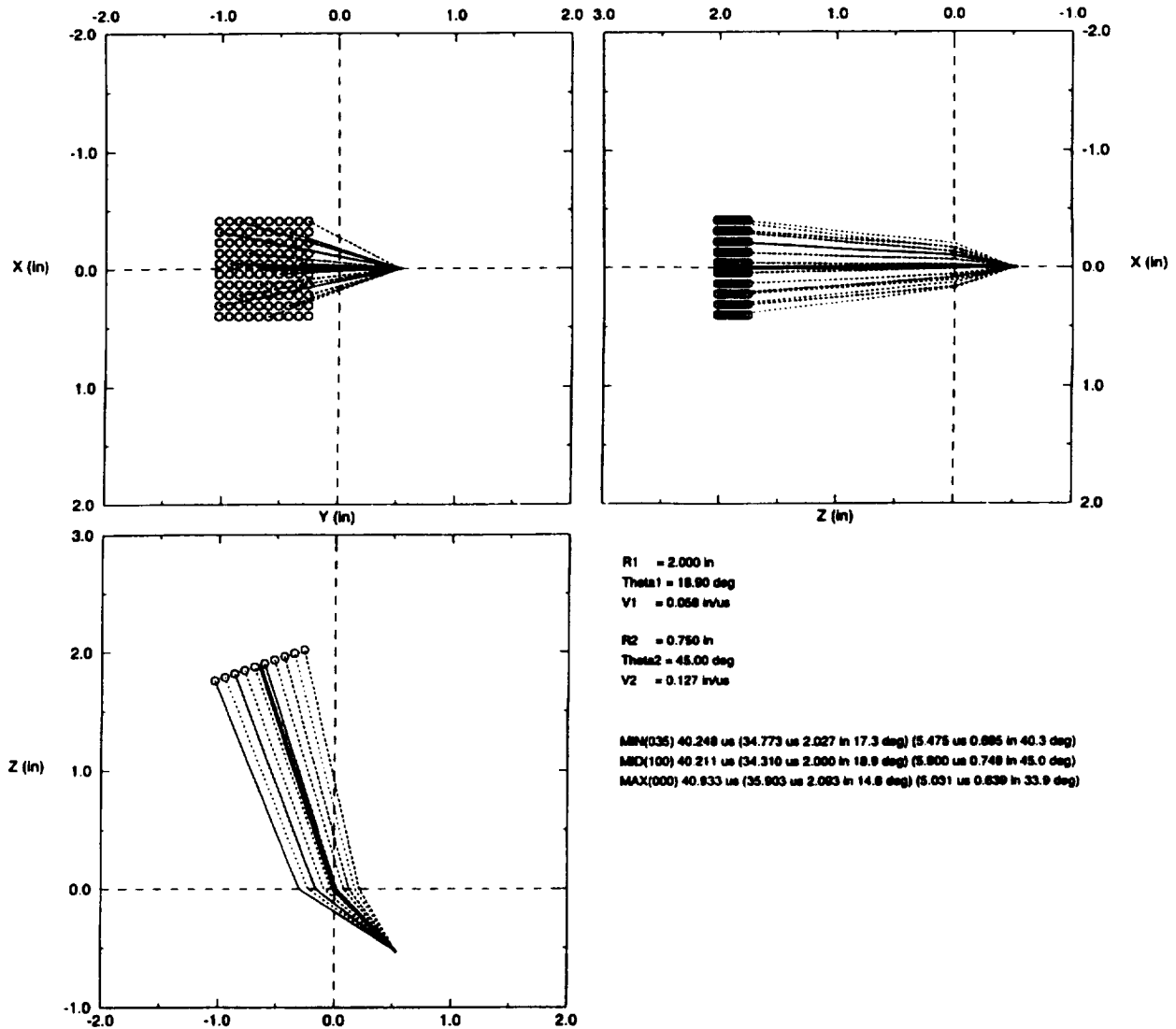


Figure 1. Ray trace of focusing geometry for 45-degree, 0.75-inch MP target

The resolution of the focal point and the steerability of the array depend on the resolution of the delays and the angular range of each element. The program assumes that each element launches a hemispherical wavefront and can receive over a wide range of angles.

2.2 Scanning and Volumetric Acquisition

Scanning the array to obtain B-scan data was accomplished using an IBM-compatible PC-controlled scanner. A set of handshaking lines added to the UPATS hardware allowed the Macintosh™ controlling the phased array to coordinate array operations with the scanner. The B-scan

software allowed the operator to choose a focal point and a 2-D grid of points over which the UPATS would acquire waveforms. The PC would move the array to each point of this grid and wait for UPATS to acquire a waveform. The scanner coordinate system is the same as that given in Figure 1, except that the Y axis is reversed. The waveforms were then stored in binary disk files at the end of each row and later transferred to Sun™ workstations for analysis.

The volumetric data were acquired by a volume scan program which allowed the operator to define a 3-D grid of points within the sample. The program would focus the array at each of these points and acquire a waveform. The waveforms were grouped into sets by depth (Z axis) and stored in binary files for later analysis.

2.3 Samples

The main targets used to measure the basic beam parameters were flat-bottomed holes (FBH) drilled in the steel target blocks at various depths and angles. The hole diameters were 0.064 inch, except for one 45-degree, 0.75-inch-deep hole. The target holes were split between the following two blocks:

- *Multiangle*—fabricated so that the effect of the beam-refracted angle could be investigated for a fixed MP of 0.75 inch. The targets were designed to allow testing at refracted angles of 0, 30, 45, 60, and 70 degrees.
- *Multidepth*—fabricated with holes at 0.375-, 0.75-, and 1.5-inch MP. All were oriented at a 45-degree angle.

Two additional samples were used to study the application of the array to industrial inspection problems:

- (1) A steel block with surface-breaking crack. The crack was approximately 1.5 inches long and 0.1 inch deep and was observed through the block at an MP of 2.65 inches.
- (2) A turbine disk rim was tested to observe the interaction of the turbine-steep geometry with the focused beam generated by the phased array. Data were taken before and after a notch was induced in the steep.

In addition, two B-scan datasets were acquired from a plexiglas block containing side-drilled holes at several depths from 0.25 to 2 inches. This tested the ability to focus in a material with a much lower velocity than steel.

2.4 Analysis

All acquired data were stored as sets of digitized waveforms in a binary file format. For viewing, the B-scan data were plotted as rows of waveforms in waterfall format. The receive delays were always set so that the signal from the focal point occurred at the center of the waveform. Thus, the waterfall plot for the B-scan which was centered on a FBH shows that the amplitude of the signal at the center of the waveforms peaks as the focus passes over the target. This is illustrated in Figure 2.

The B-scan data were used to measure the width of the focused beam. The peak-to-peak amplitude of the target signal was plotted versus position through the target peak for both the X and Y directions. The beamwidth was then defined as the distance between the half-amplitude points on either side of the peak. An example plot is given in Figure 3.

The crack and turbine disk-rim sample data were converted into multidimensional images. These images were displayed as a series of 2-D greyscale or color Z planes. The planes could be "animated" to produce a kind of movie to help the analyst visualize the 3-D volume.

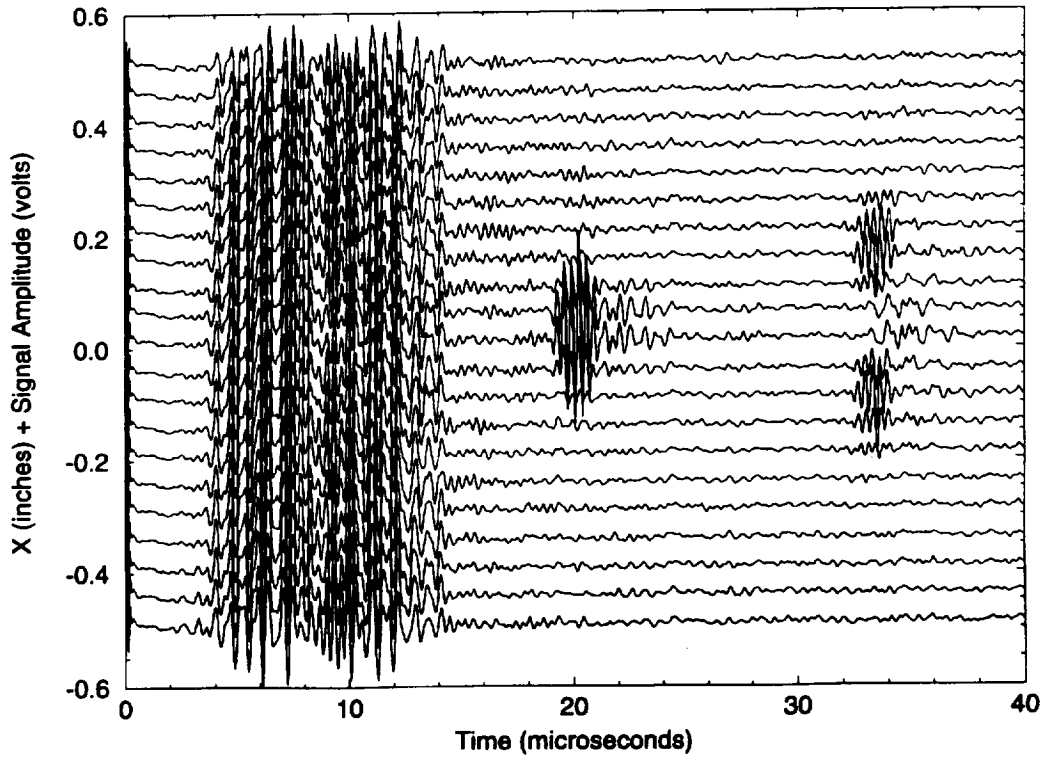


Figure 2. Waterfall plot of 45-degree S-wave B-scan data for 0.75-inch MP x 0.125-inch-diameter FBH. The signal from 4 to 16 μ s is from the water/steel interface; the target is at 20 μ s; and the signal near 35 μ s is from a 0.25-inch counterbore hole.

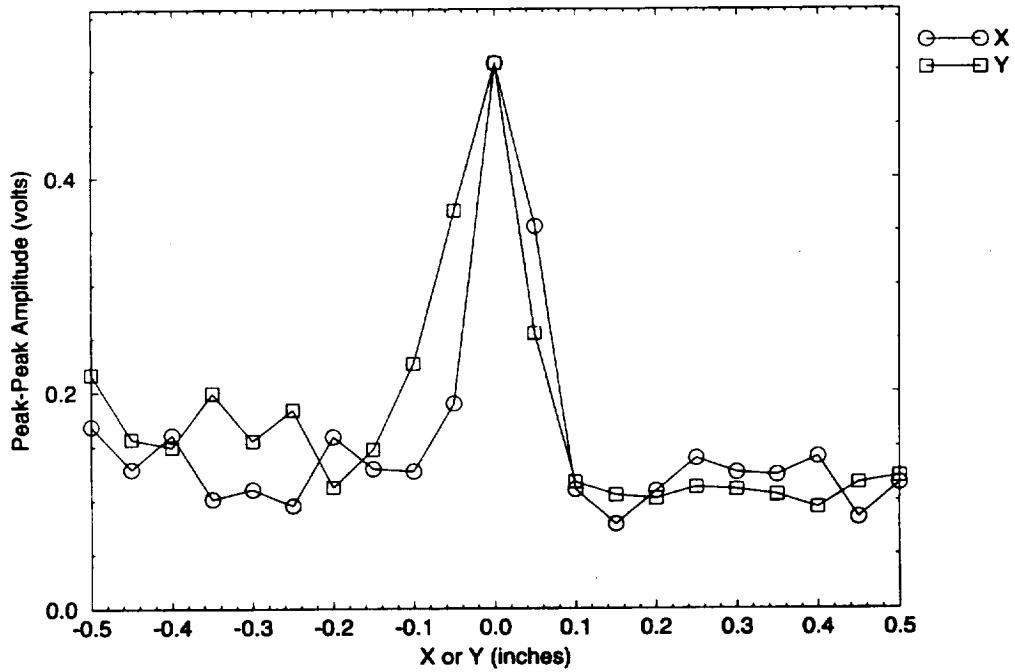


Figure 3. Peak-to-peak amplitude data extracted from B-scan of 45-degree x 0.375-inch MP FBH. The data are from the X and Y rows centered on the maximum target response.

3. RESULTS AND DISCUSSION

Qualitatively, we found UPATS to be very usable. Averaging of the received signal was usually required to produce a visually pleasing display, but the noise floor and sensitivity were satisfactory for all the targets which were observed. The only problem which hampered signal detection was the large water/steel-interface signal produced by the wide angular response of the array elements. This problem was most evident at low angles where the interface signal completely obscured the longitudinal wave (L-wave) response from the FBHs. The slower shear-wave (S-wave) signals were beyond the interference region for all of our calibration targets; therefore, most of our data were acquired with S-wave signals. Even for the S-wave, it was necessary to minimize ringing (standing wave) between the probe and surface by using a 2-inch waterpath from the array center to sample surface. This standoff was maintained for all experiments. It may be possible to mask the array beam in order to reduce this problem; however, time did not permit us to study this possibility.

The following sections discuss the quantitative results for each class of target.

3.1 Calibration Targets

3.1.1 Focused Versus Unfocused

In order to demonstrate the focusing ability of the array, two B-scans were made of the 0.063-inch-diameter, 45-degree FBH in the multiangle block. The first scan was taken with the array focused at infinity (i.e., not focused) and is shown in the waterfall plot of Figure 4. The second scan was focused at the 0.75-inch MP position of the hole. The result is displayed in Figure 5. The focusing increased the signal-to-noise ratio by approximately 7 dB and reduced the beamwidth from 0.2 to 0.1 inch. Although a larger beamwidth was expected for the unfocused array, the full-width half-maximum (FWHM) beamwidth signal from the FBH was only 2 dB above the noise.

3.1.2 Beamwidth Versus Target Angle

Figure 6 shows the beamwidth data measured from the multiangle block. After correction of the Y data for the angle of the target, the X and Y beamwidths are fairly constant with angle. The typical beamwidth of 0.1 inch in the X-direction for all angles agrees well with

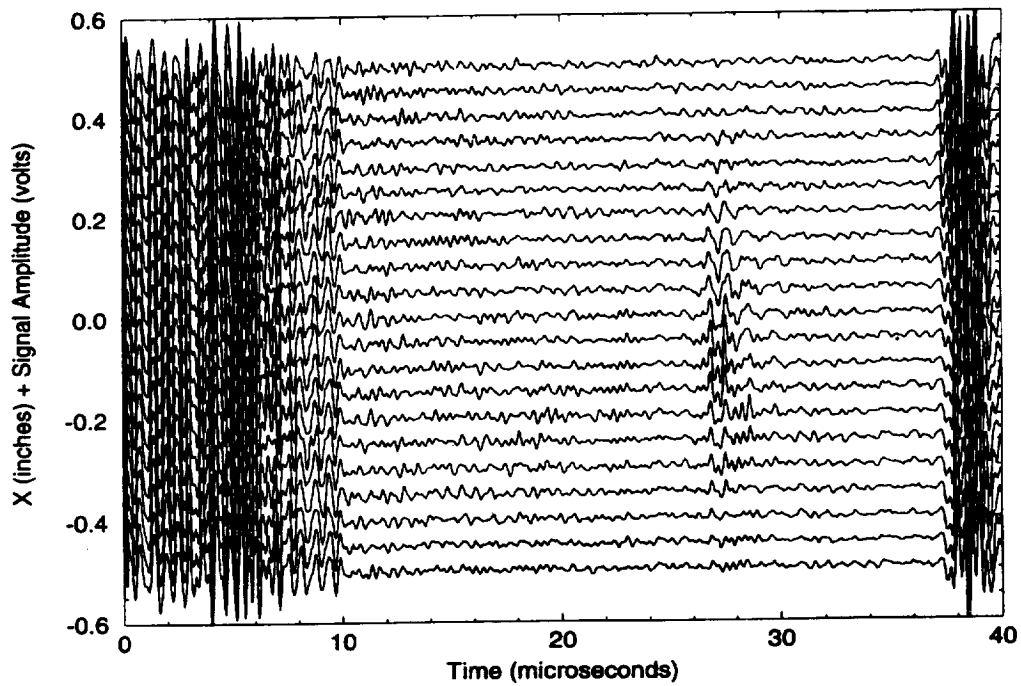


Figure 4. Waterfall plot of peak-to-peak amplitudes of 0.063-inch-diameter FBH with the array unfocused

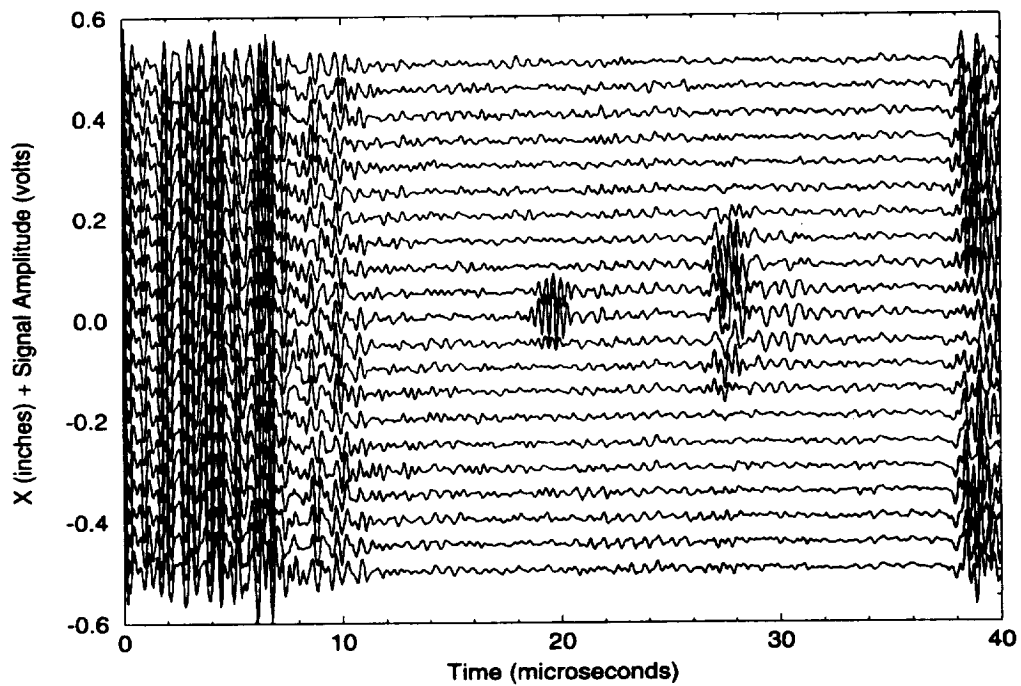


Figure 5. Waterfall plot of peak-to-peak amplitudes of 0.063-inch-diameter FBH with the array focused at the correct MP

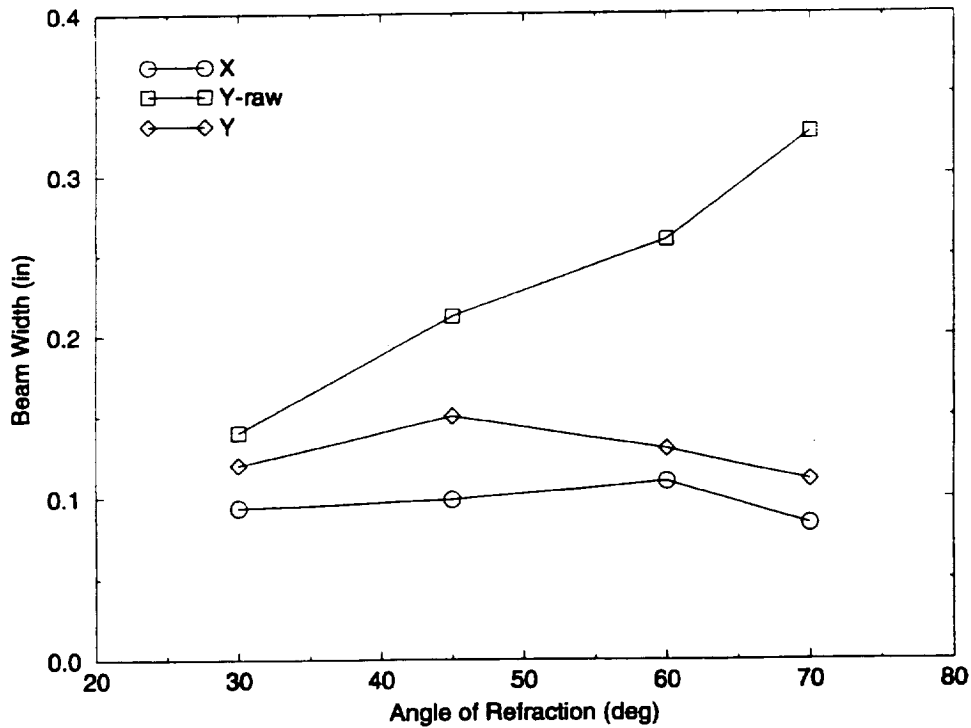


Figure 6. Beamwidths measured from the 0.063-inch-diameter FBHs in the multiangle block. The Y-axis data are shown in both raw (Y-row) and angle-corrected (Y) versions.

the theoretical values found in Figure A-1 in Appendix A. The Y beamwidth is 20 to 30 percent larger than the X beamwidth. This is typically caused by the reduction in aperture in the Y plane and is a common feature of fixed-focus refracted beams as well.

3.1.3 Beamwidth Versus Metal Path

The variation of the beamwidth with depth of focus was measured from the S-wave B-scan data acquired from the multidepth block. Figure 7 displays the results. The angle-corrected Y beamwidth for the 0.375-inch MP appears to be slightly out of line with the other data; however, the general trend is as expected. The beamwidth increases due to diffraction effects as the MP increases. The beamwidths measured compare very favorably with the calculated response of a fixed-focus probe shown in Figure A-2 of Appendix A. For example, at the 45-degree, 0.75-inch MP FBH, a 1-inch-square fixed-focus probe has a theoretical X beamwidth of 0.09 inch at 3 MHz, whereas the array beamwidth was found to be 0.1 inch.

3.1.4 Longitudinal Versus Shear Beamwidth

Because of the difficulties mentioned above with the interface signal, it was not possible to get many data points for L-wave beam parameters. However, the large incident angle and long metal path for the 0.063-inch diameter FBH at 60 degrees in the multi-angle block allowed a successful L-wave B-scan to be acquired. Since these same conditions prevail in the case of the 70-degree FBH, it was expected that the L-wave signal for the 70-degree FBH in the same block would be observed. Unfortunately, the expected signal was not found.

The beamwidths measured from the 60-degree L-wave data were 0.2 inch in the X direction and 0.2 inch in the Y direction. These dimensions are approximate because the FWHM signals were at the noise level. The corresponding measured beamwidths for the shear wave case were 0.11 and 0.13 inch, respectively.

From theoretical calculations, the beamwidths for 60-degree L-wave are 0.12 and 0.16 inch in the X and Y directions, respectively; for S-wave, the beamwidths are 0.09 and 0.13 inch, respectively. This shows that the calculated beamwidths are slightly greater for L-wave than S-wave, which agrees with the experimental data.

3.1.5 Volume Images

Volume images were acquired by sweeping the beam from point to point within the sample with the array at a fixed position; thus, the angle at which the beam hits the defect will vary over the extent of the target. For FBH targets where the array beam is centered in line with the hole, the angle does not change significantly over the small extent of the target, leading to a point-like response. This is seen in Figure 8, which shows a waterfall plot of a slice through the center of a volume scan of the 0.063-inch-diameter, 45-degree FBH at 0.75 inch MP. The FBH signal is in the center, and the larger signal at a longer MP is the 0.25-inch-diameter counterbore hole. The extent of the FBH signal is determined primarily by the width of the beam.

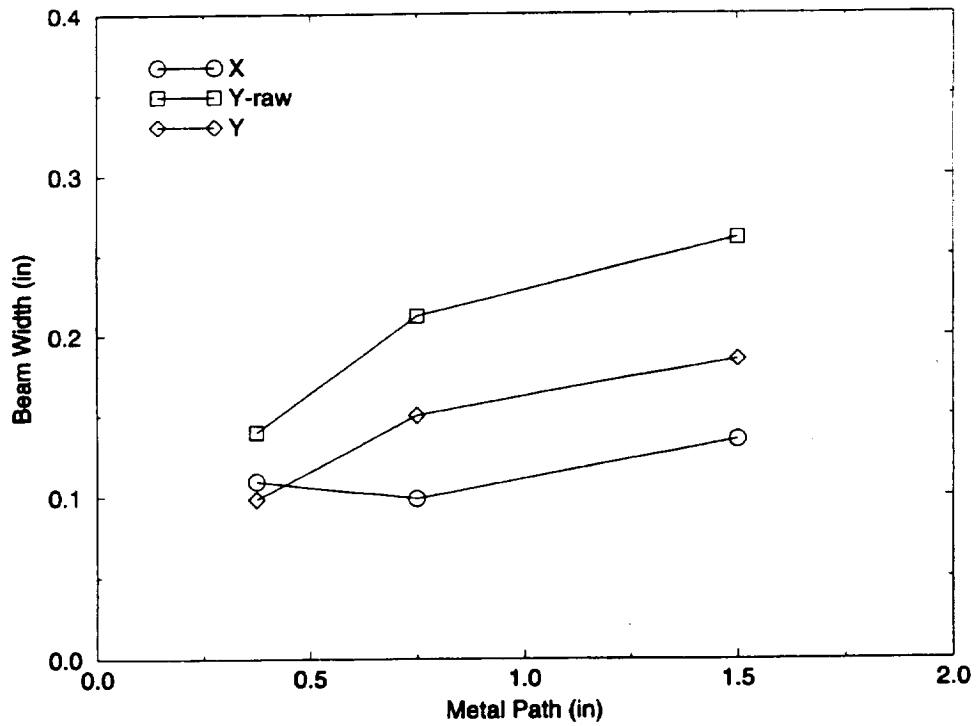


Figure 7. Beamwidths measured from the 0.063-inch-diameter FBHs in the multidepth block. The Y-axis data are shown in both raw (Y-row) and angle-corrected (Y) versions.

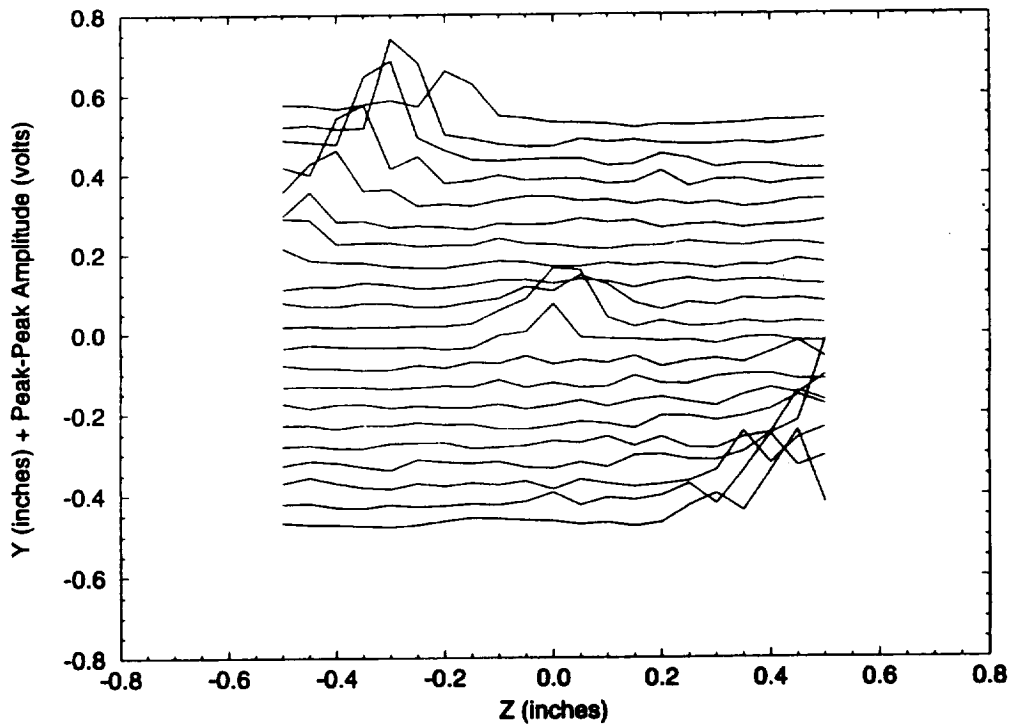


Figure 8. Y-Z plane slice through center of volume scan data for 0.063-inch, 45-degree FBH at 0.75 inch MP. The signal at 0.2 to 0.5 inch Z is from the water/steel interface.

3.1.6 Plexiglas Block

Because the plexiglas S-wave velocity is slightly lower than the L-wave velocity in water, the incident angle required to produce a 45-degree S-wave in the block was 46.8 degrees. This large angle causes the array beam to be spread out over a large area on the sample surface.

The targets in the plexiglas block were seven 0.094-inch-diameter side-drilled holes (SDH) spaced at 0.25-inch intervals in depth so that the metal paths were 0.3, 0.6, 0.9, etc. (for a 45-degree refracted angle). It was found that the signals from the two shallowest SDHs were usable. However, the signal from the 0.9-inch MP SDH was barely detectable. B-scan data from the 0.3- and 0.6-inch MP targets were used to calculate a beamwidth of 0.182 inch for each target.

3.2 NDE Application Samples

Two samples representing typical NDE applications (a steel block with a weld-induced surface-breaking crack and a section of a turbine disk rim) were used to acquire B-scan and volumetric data.

3.2.1 Cracked Block

The crack was approximately 1.5 inches long and 0.1 inch in depth and was observed through the block at an MP of 2.65 inches with a 45-degree S-wave beam. The B-scan data, shown as a waterfall plot in Figure 9, show the echo response of the crack along its length. The waveforms indicate a length of approximately 1.7 inches, not counting the small signals at the lower edge, which are probably due to the edge of the weld. Variations in amplitude along the crack are due to the roughness of the crack surface and the local orientation of the crack face.

It is apparent in the figure that the best signals were obtained from the ends of the crack. Figures 10 through 12 present the volume data acquired from the crack specimen. These figures show several 2-D slices illustrating the length, depth, and angular orientation of the crack. The larger amplitude of the ends of the crack is not affected by the angle difference between the B-scan and volume data (the volume data were acquired from a stationary point centered on the crack). Insensitivity to this angle is further illustrated in Figure 13, where a coarser volume scan was centered on the positive X end of the crack. The signal at the X=1.0 position in this figure may be due to a side-lobe signal.

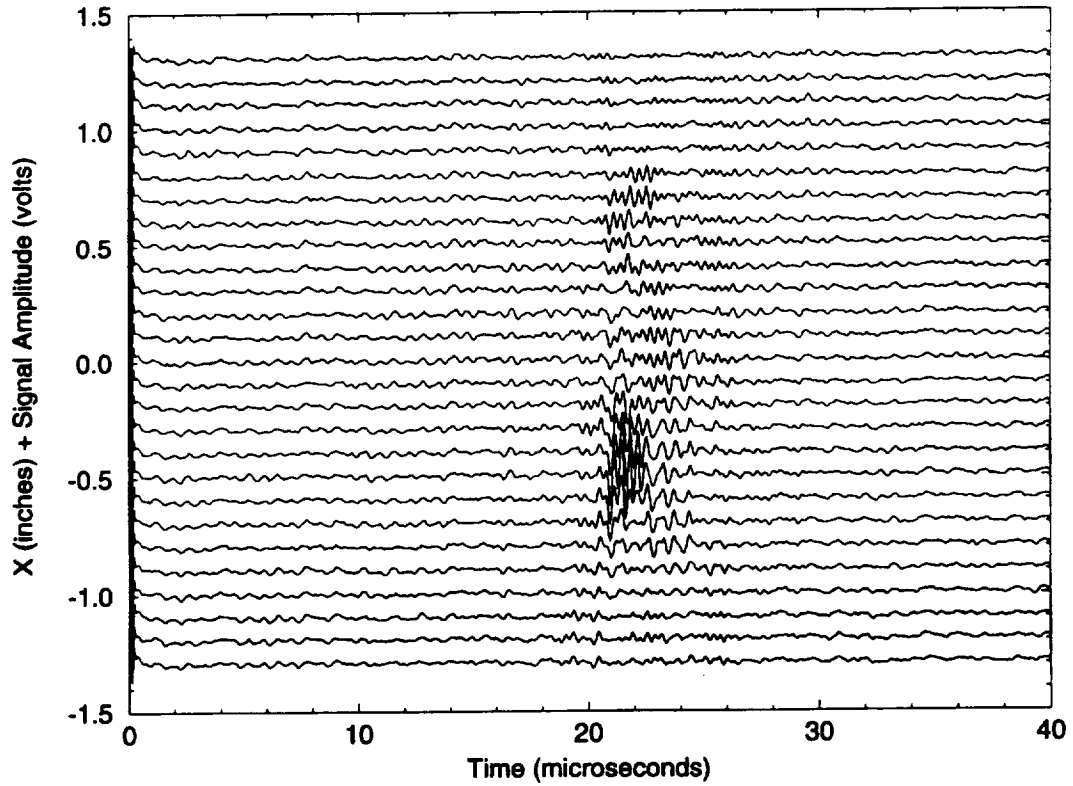


Figure 9. Waterfall plot of crack B-scan data showing the extent of the crack

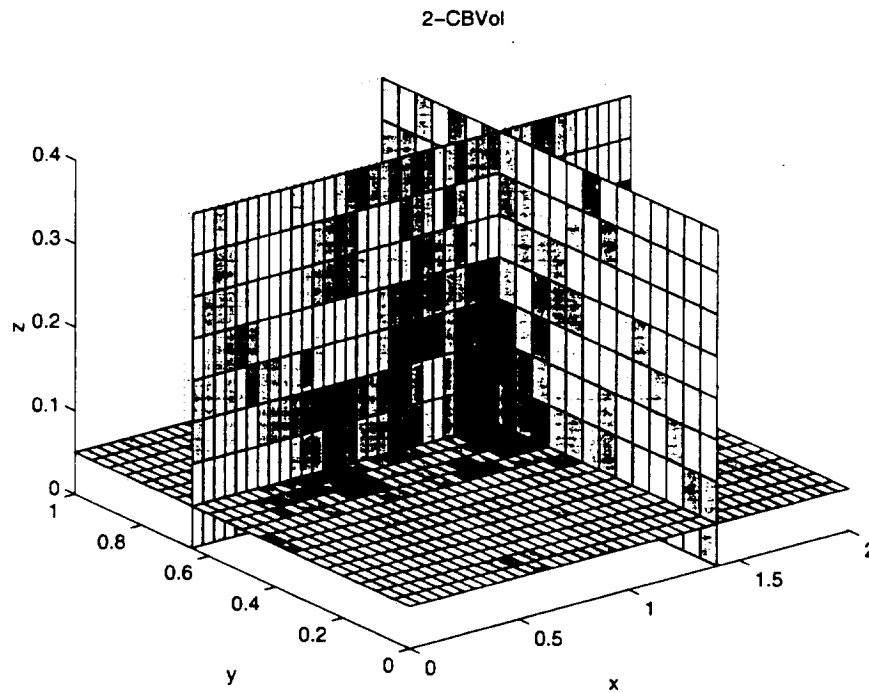


Figure 10. Crack block-volume data presented as 2-D slices. The two dark regions represent the high amplitude crack and signals.

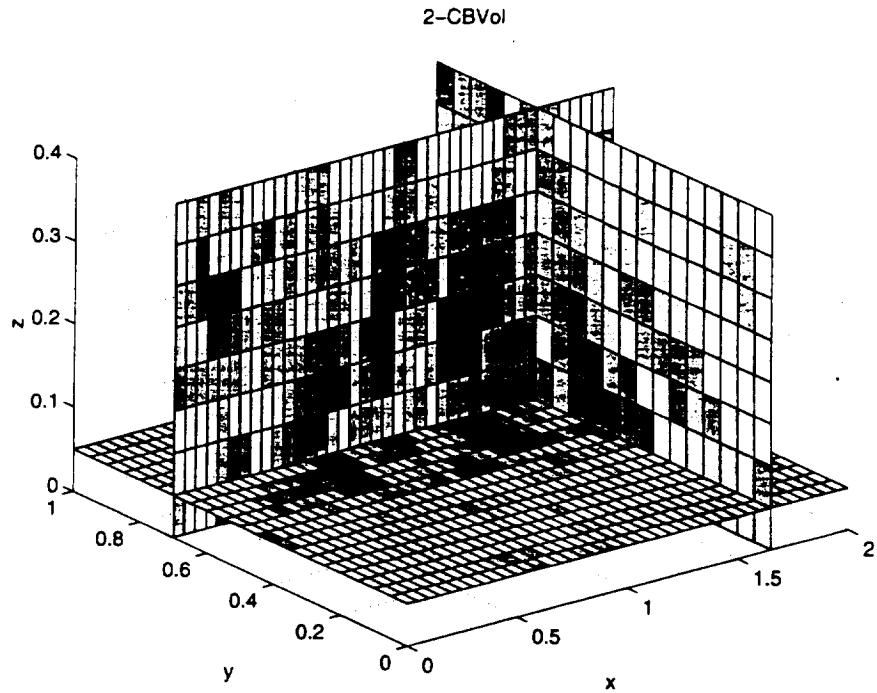


Figure 11. Crack block-volume data. Comparison with the last figure and following figure shows the angular response of the crack.

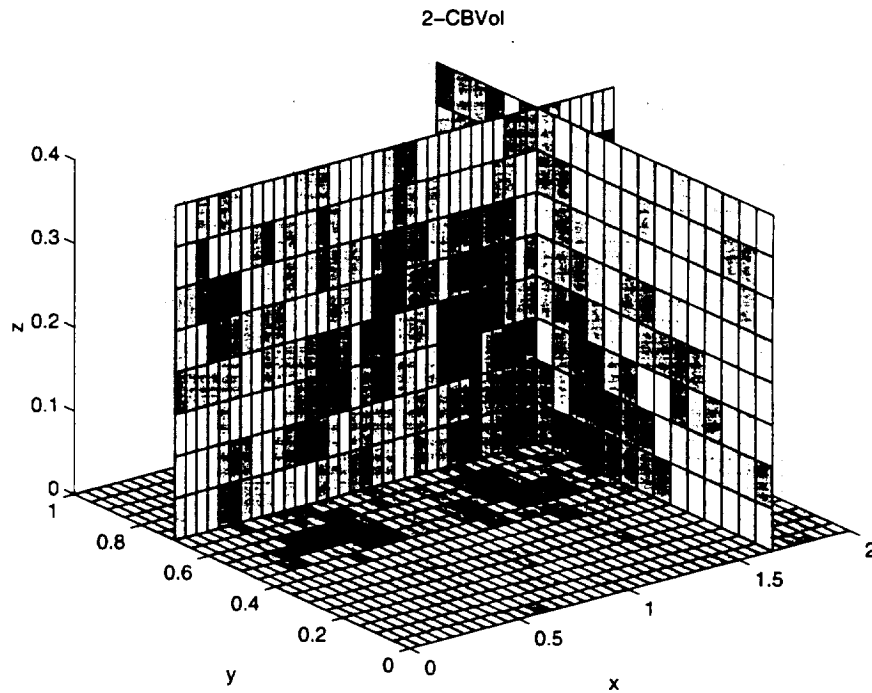


Figure 12. Crack block-volume data. The Y-Z plane shown is the last in which the crack signal is prominent, and shows that the crack reaches a depth of approximately 0.15 inch at one end.

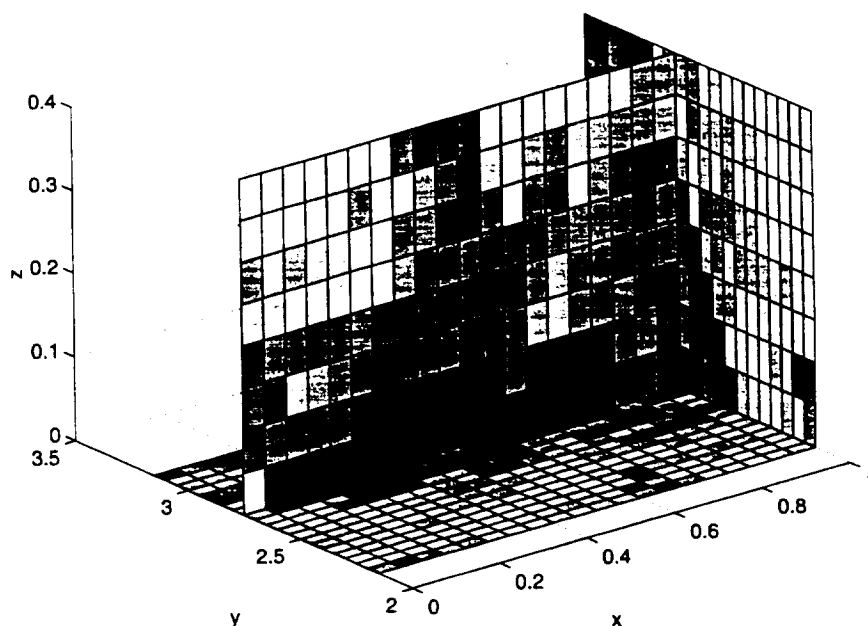
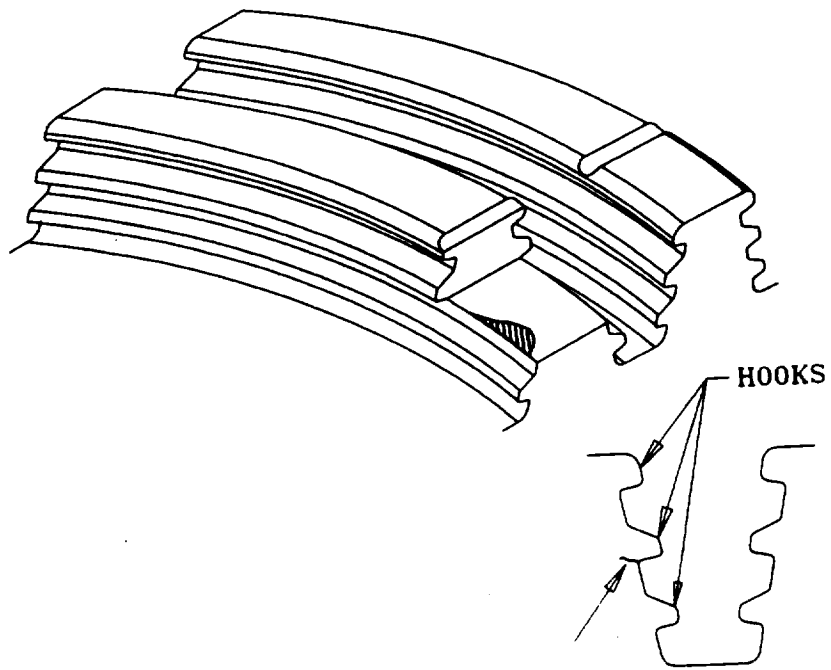


Figure 13. Volume data acquired with the array centered on the +X end of the crack. The signal at the far right ($X=1$) may be due to a side-lobe of the array.

3.2.2 Turbine Disk Rim

UT inspection of turbine disk rims can be complicated due to the geometric reflectors present in typical specimens. Figure 14 illustrates the shape of the area of interest. Also shown is the typical location of stress corrosion cracking within the rim. Focused probes have been successfully applied to inspection of these areas, because they avoid the problems with geometric reflections. However, several fixed-focus probes are required to cover the inspection region. The phased array could eliminate the need for multiple probes, thus reducing inspection time.

Figures 15 and 16 show volume data for the disk rim before and after a notch was made under the second hook. The volume shown is a 0.5 x 0.5 x 0.5-inch cube roughly centered on the second hook. The images without the notch show very little clutter from the hook geometry, but the signal from the notch is very clear. The notch simulation and depth (approximately 0.12 inch) can be inferred by observing the signal amplitude and position on each X-Y plane.



Typical SCC Crack

Figure 14. Illustration showing the geometry of a typical turbine disk rim

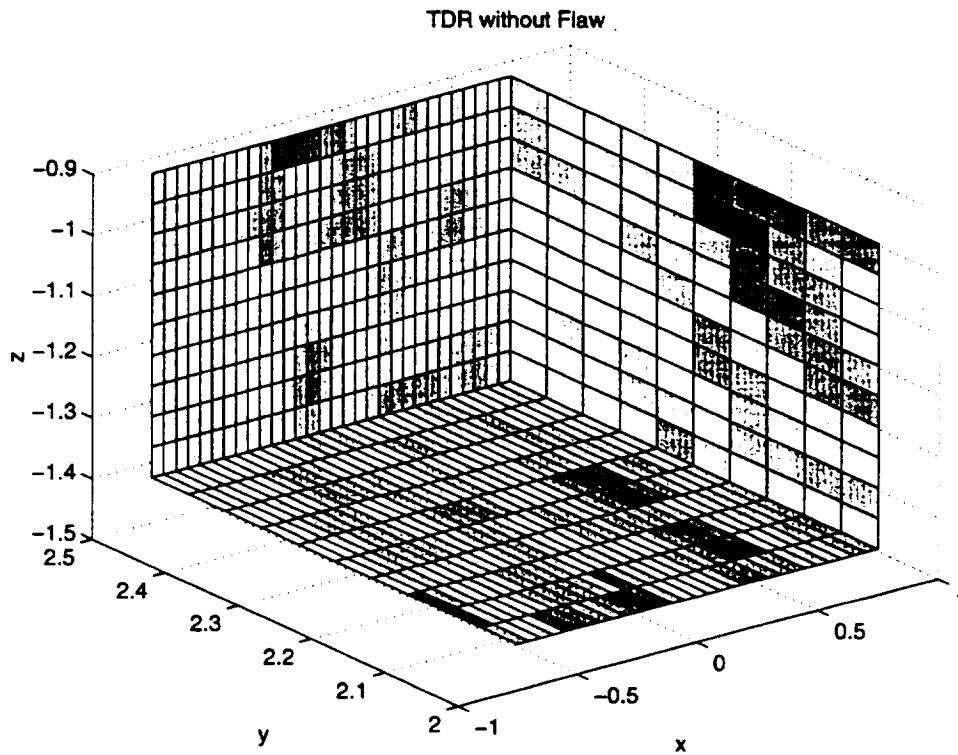
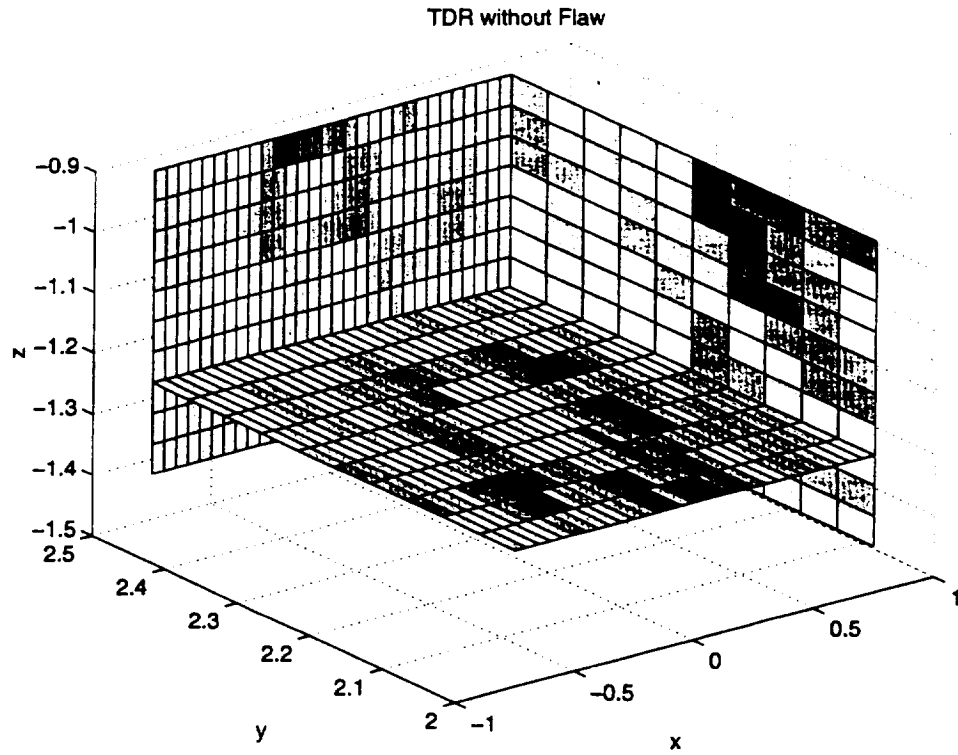


Figure 15. Two slices of the turbine disk-rim volume data before introduction of a notch into the sample

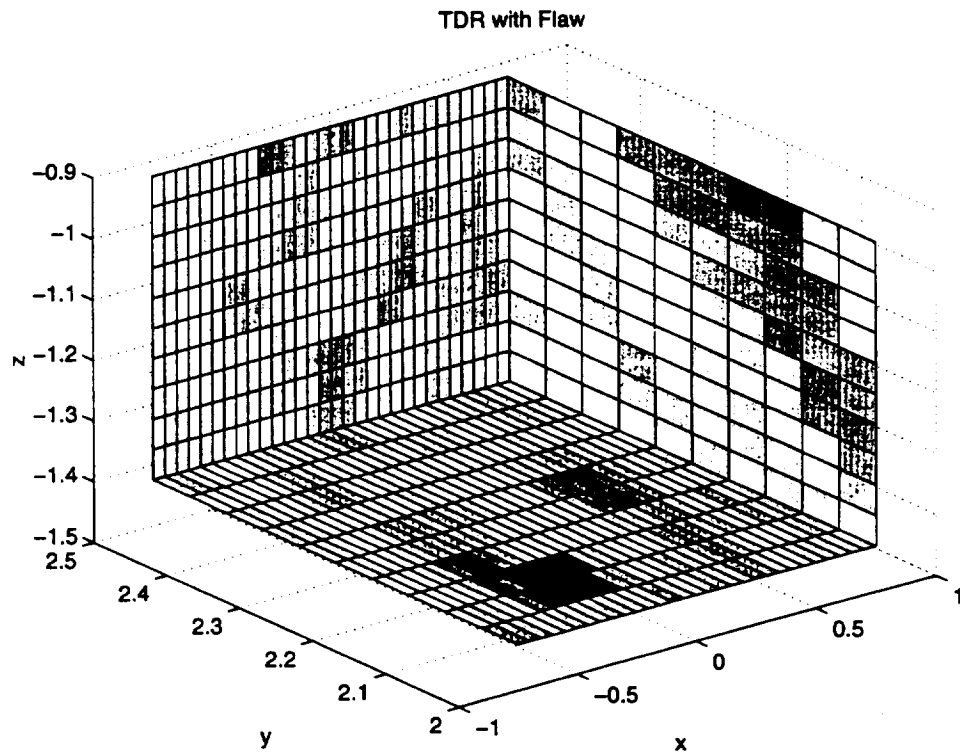
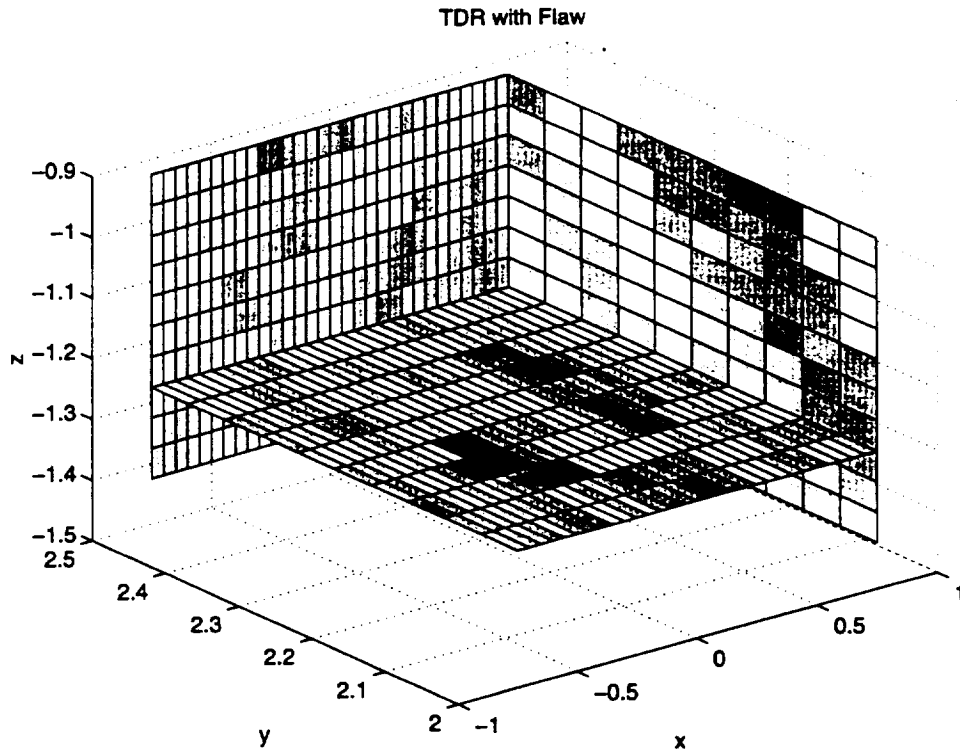


Figure 16. Two slices of the turbine disk-rim volume data showing the notch cut in the underside of the second hook

4. CONCLUSIONS

The UPATS hardware has proven to be an excellent platform for the study of phased-array applicability to problems in NDE. In the course of this study, it has been shown that the array can be successfully focused in two media, achieving beamwidths comparable with those of fixed-focus lenses of the same aperture. It has also been found that the array can be used to obtain volume image data that can be used to reveal defects in NDE samples with complex geometries.

Information about the system performance capabilities, as well as data on array limitations, such as interface signal problems and sensitivity limitations, is valuable input for business and technical decision making. It allows the application engineer to make informed estimates of the costs, benefits, and risks involved in applying phased arrays to actual industry problems. This knowledge also gives SwRI an advantage in pursuing the phased-array market.

Appendix A

**THEORETICAL PERFORMANCE CALCULATIONS
FOR A FIXED-FOCUS PROBE**

Appendix A

THEORETICAL PERFORMANCE CALCULATIONS FOR A FIXED-FOCUS PROBE

The following theoretical characteristics of a fixed focus probe are shown in this appendix to provide a basis for comparison with the phased array:

- (1) Point spread function
- (2) F number
- (3) Side lobe level

Lenstop v2.0.2, a program developed at SwRI for analyzing and designing ultrasonic lenses, was used to generate the theoretical data. The location of focus, material parameters, and probe parameters can be input to the program to match those of the phased array. The nominal frequency of the probe is 3 MHz, the bandwidth is 50 percent, and the element is a 1-inch square.

The point spread functions are actually printed out on graphs such as the one in Figure 3 in the main body of the report. These plots have been summarized in Figures A-1 and A-2.

The F numbers are graphed in Figures A-3 and A-4. The side lobe level, which was measured from the point spread functions, was typically 13 dB below the peak signal level.

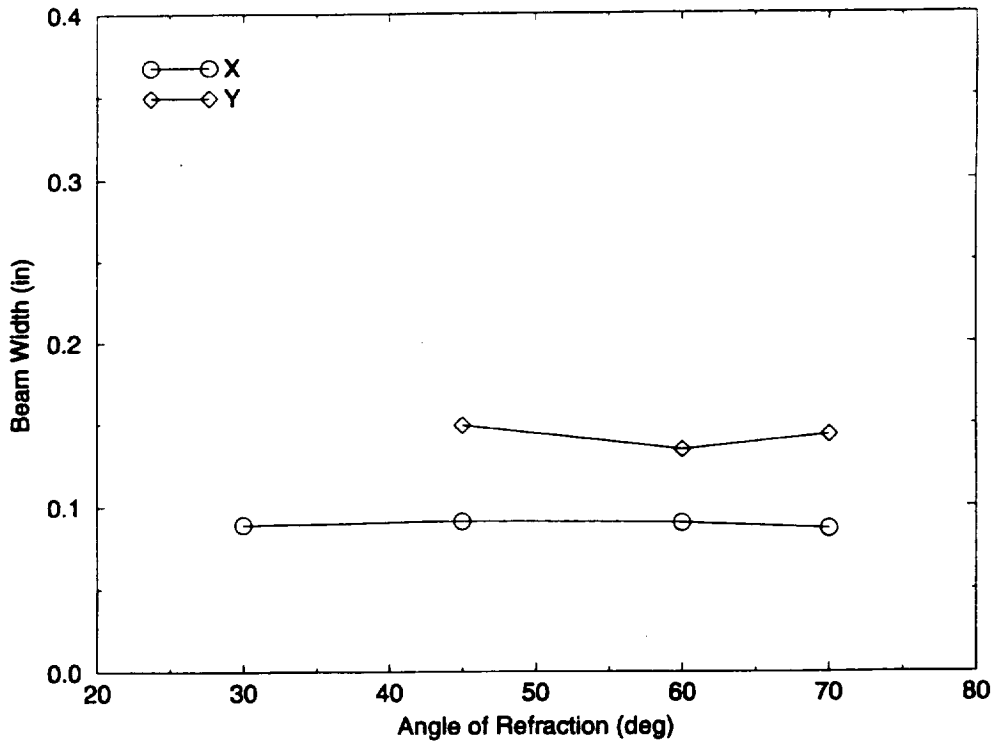


Figure A-1. Beamwidths as a function of refracted angle calculated using the Lenstop program for a fixed metal path of 0.75 inch

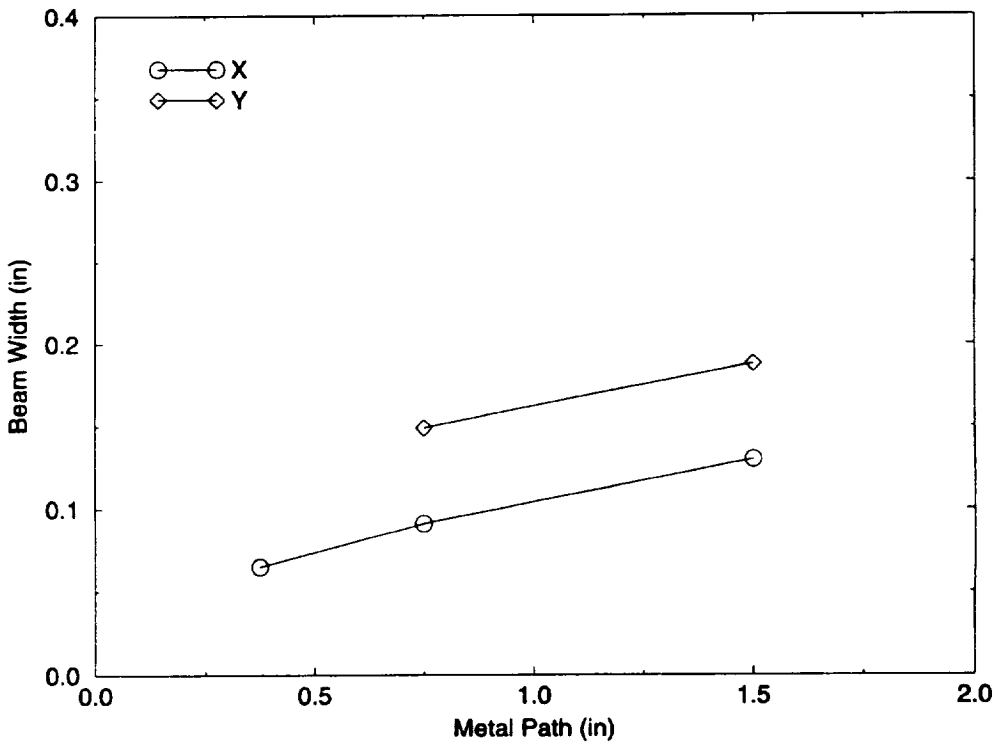


Figure A-2. Beamwidths as a function of metal path calculated using the Lenstop program for a fixed refracted angle of 45 degrees

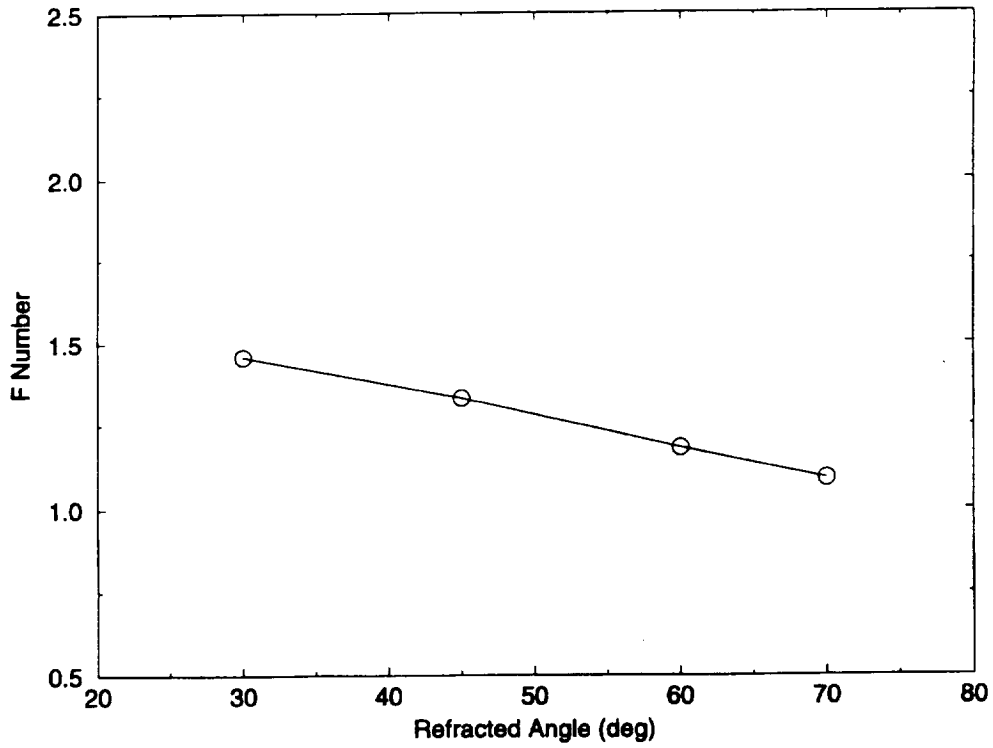


Figure A-3. F number as a function of refracted angle calculated using the Lenstop program for a fixed metal path of 0.75 inch

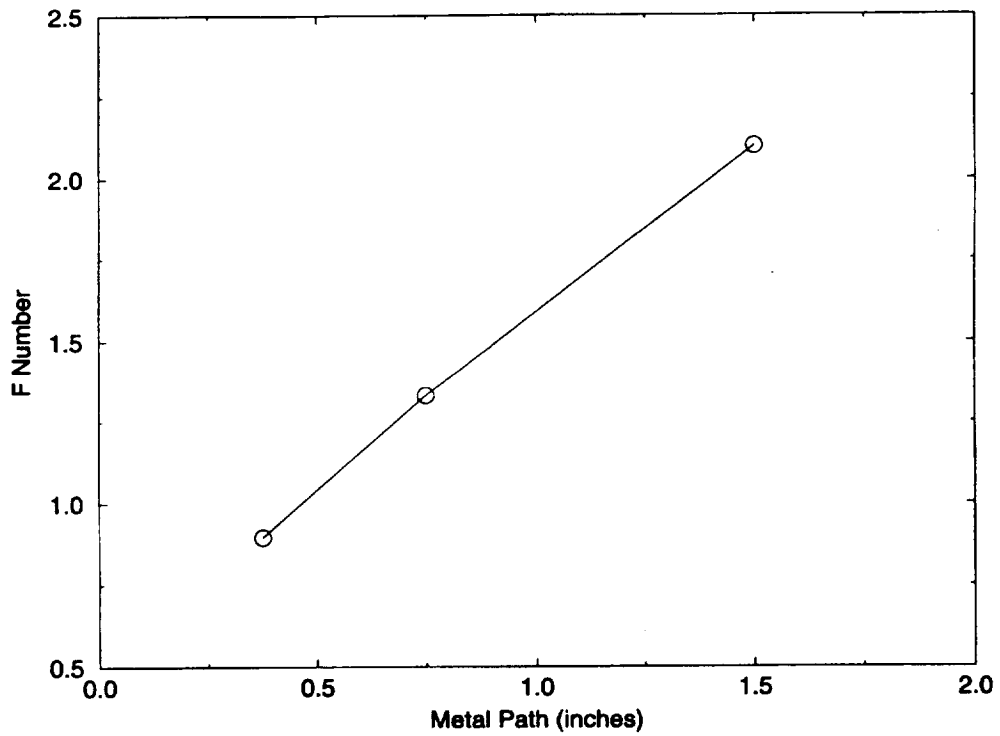


Figure A-4. F number as a function of metal path calculated using the Lenstop program for a fixed refracted angle of 45 degrees

Appendix B

**DOCUMENTATION FOR SOFTWARE DEVELOPED
DURING THE QUICK-LOOK IR PROJECT**

Appendix B

DOCUMENTATION FOR SOFTWARE DEVELOPED DURING THE QUICK-LOOK IR PROJECT

During the course of the Quick-Look project, programs were written for (1) performing focusing calculations, (2) controlling the acquisition of data from the phased array, and (3) converting the data to usable format. Two different types of data were acquired: BSCAN and VOLUME.

BSCAN data were acquired by using a scanner controlled by a PC. The focal point relative to the position of the array was held constant, thus emulating a fixed-focus probe while the array was moved from position to position on a rectangular grid.

VOLUME data were acquired with the array at a fixed position, with the focal point being moved about a rectangular volume within the material. These programs are documented here for NASA's purposes. A description of known problems is also given.

1.0 Focus-Array Program

1.1 Description

The focus-array program was written to test the calculations for focusing the array in two media, since the official deliverable software to NASA addressed single-medium focusing only. The same calculations are later applied in the BSCAN and VOLUME programs, which run on the Macintosh™ and are used to acquire the phased-array data for two media. Part of the focused-array program also tests file header creation that is also applied in the BSCAN and VOLUME programs. The software was written in the C programming language and developed and run on a Sun™ SPARCstation 10 computer.

1.2 Coordinate System

The coordinate system in relation to the array is shown in Figure B-1. The array lies on the positive side of the $Z=0$ plane, while the material is on the negative side. For both BSCAN and VOLUME acquisitions, the location and orientation of the array with respect to the surface of the material is described as follows:

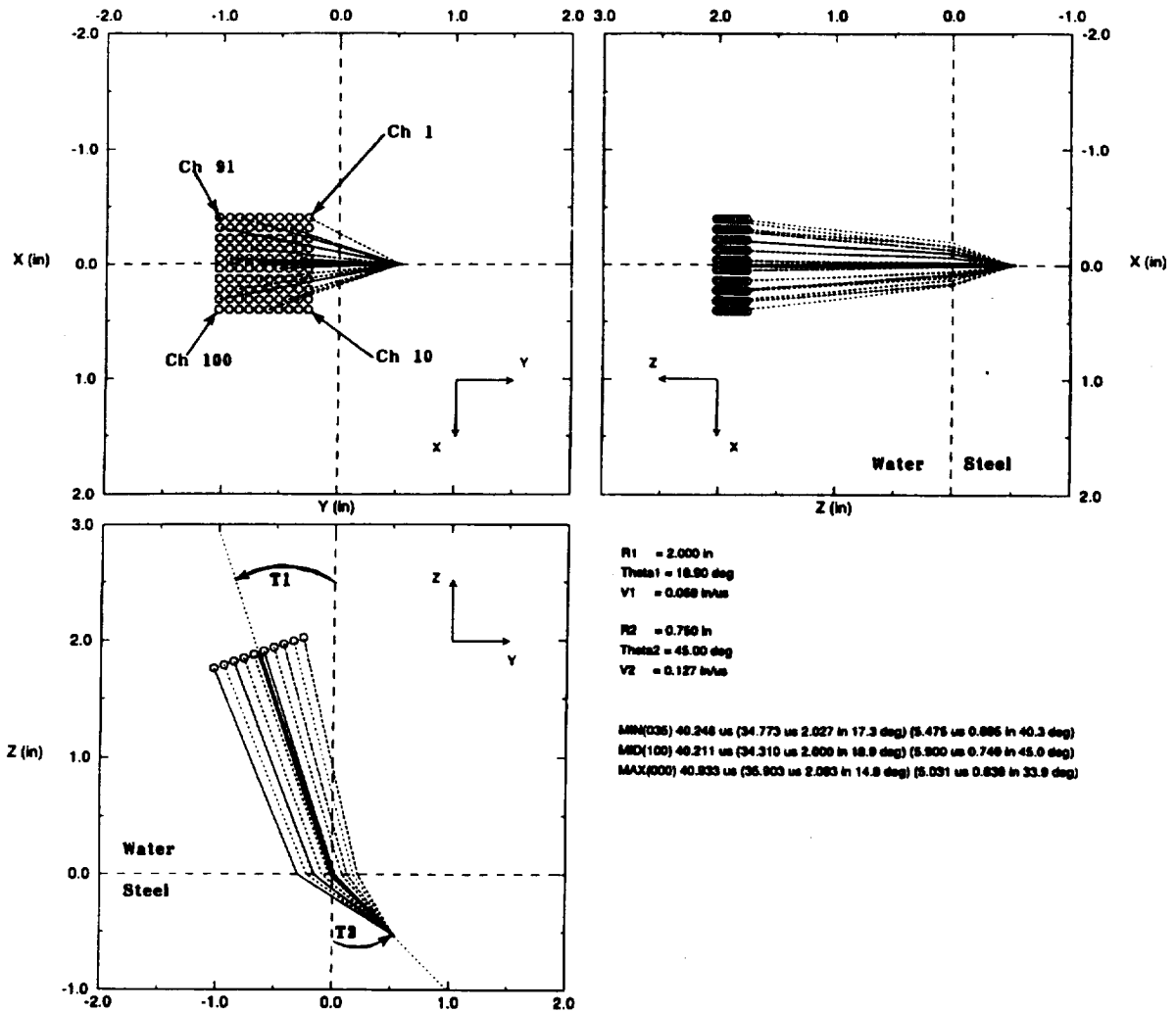


Figure B-1. Three views of phased array using the VOLUME definition to describe focal point position. T1=Theta1, T2=Theta2.

- (1) The array is originally in the Z=0 plane, as described in Section 3.5 of the UPATS User's Manual.
- (2) The array is translated by R1 inches along the positive Z axis while maintaining its orientation.
- (3) The array is then rotated by Theta1 degrees about the X axis away from the positive Z axis into the -Y, +Z plane.

The Y-X view of the array in Figure B-1 shows where the elements are as viewed from behind the array after translation and rotation have taken place.

For BSCAN acquisition, focal-point location is locatable by the following method:

- The focal point is originally at $(X,Y,Z) = (0,0,0)$
- The focal point is translated by R2 inches along the negative Z axis
- The focal point is then rotated by Theta2 degrees about the X axis away from the negative Z axis into the +Y,-Z plane.

A more general method using cartesian coordinates $(X2,Y2, Z2)$, as shown in Figure B-2, was employed for VOLUME acquisition.

For general problem-solving purposes, the focal point positions $(R2,Theta2)$ were converted to the $(X2,Y2,Z2)$ format.

1.3 Focusing Calculations

A flat entry surface was assumed for the material, since these were the only geometries encountered during the project. This assumption also simplified the calculations.

The minimum time path for each element to the focal point must be calculated in order to program the individual delays. To simplify the calculation for a given element at location $(X1, Y1,Z1)$, the element is translated to $(0,0,Z1)$. The focal point then must be translated by $(-X1, -Y1,0)$. The focal point is then rotated about the Z axis so that it lies entirely within the +Y,-Z plane, thus resulting in Figure B-3.

Snell's Law is then used to calculate the minimum time path which passes through the material surface at the unknown Y-Z coordinate $(y,0)$.

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{V_1}{V_2} \quad (1)$$

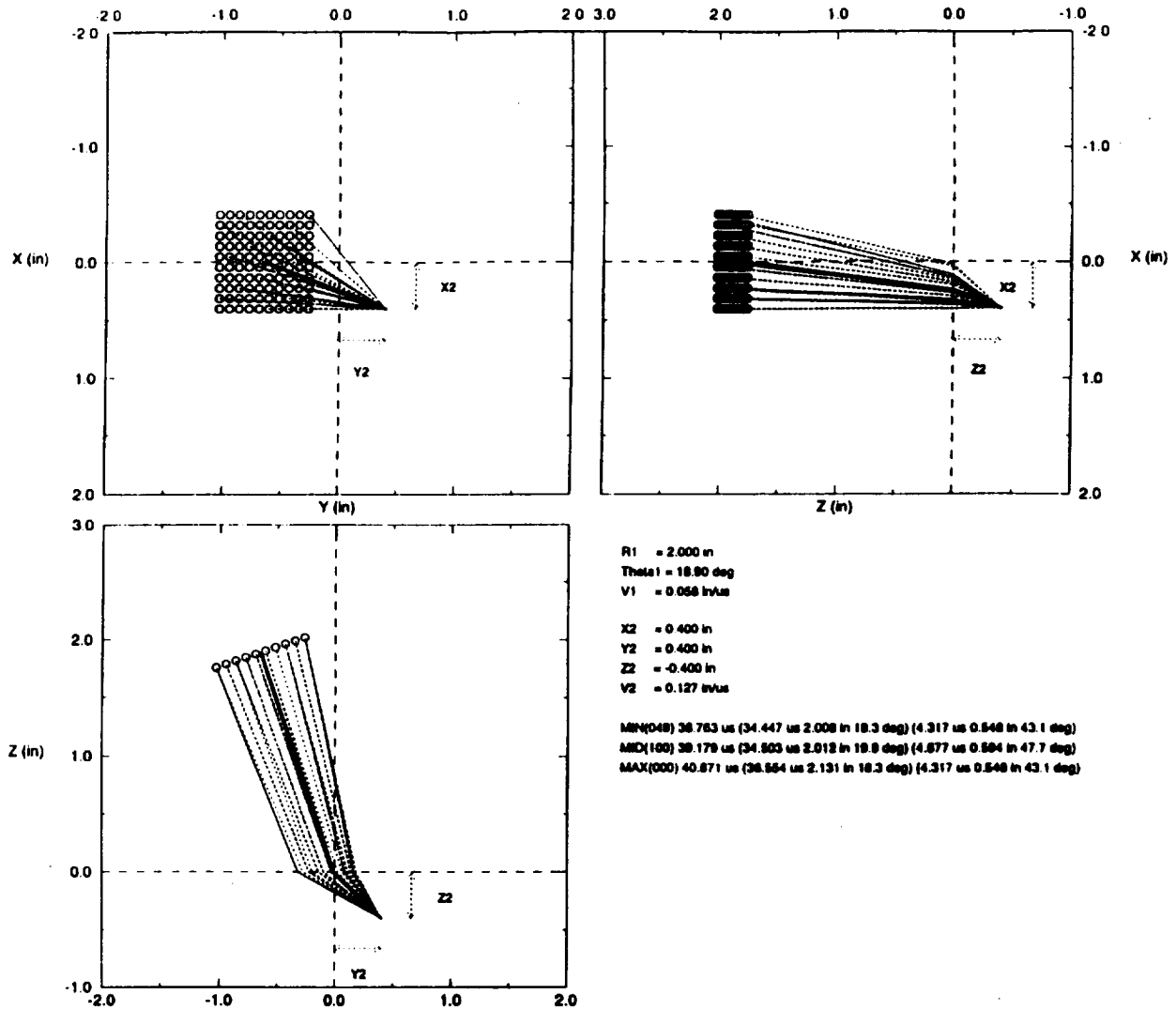


Figure B-2. Three views of phased array in relation to the coordinate system. The location of the phased array in relation to the metal surface is shown, and the BSCAN definition is used to describe the focal point position.

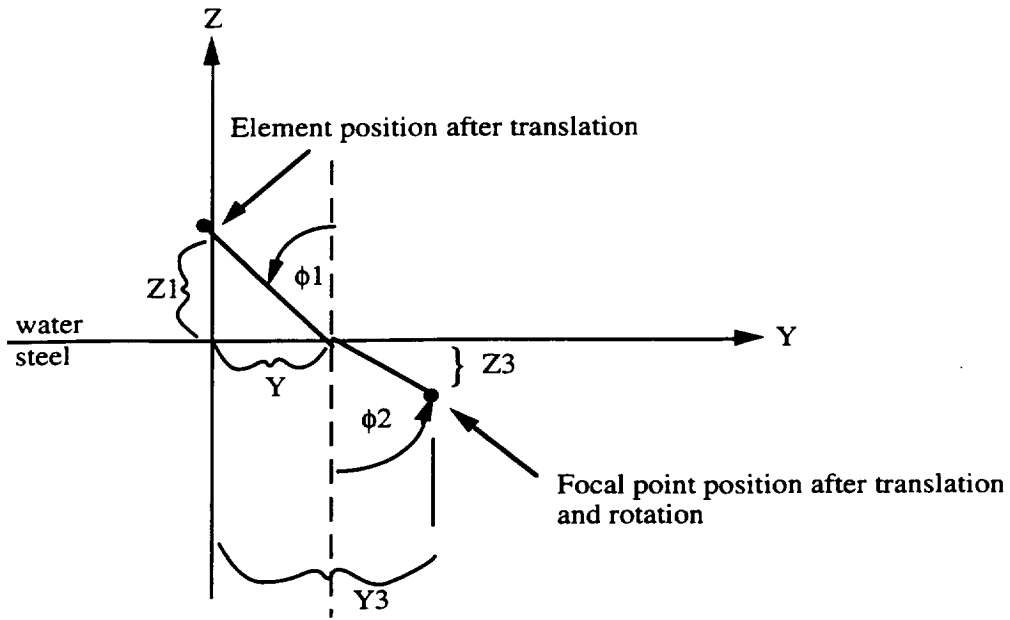


Figure B-3. Element and focal position after translation and rotation. The solution of Y , the point of surface entry, is facilitated by transforming the positions into one plane.

which can be rewritten as

$$\frac{\frac{Y}{\sqrt{Y^2 + Z_1^2}}}{\frac{Y_2 - Y}{\sqrt{(Y_3 - Y)^2 + Z_2^2}}} = \frac{V_1}{V_2} \quad (2)$$

where V_1 and V_2 are the acoustic velocities in water and the material, respectively, and Y_3 is the distance from the element to the focal point in the X-Y plane only. This is expressed as

$$Y_3 = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \quad (3)$$

An expansion of (2) to solve for Y results in a fourth-order equation, which is solved by using the Newton-Raphson method. When Y is solved, the transit time for the given element to the focal point and back can be calculated. When the transit times for all the elements are calculated, delays for each element can be assigned.

The delays are set for focusing during transmission and reception of the signal.

1.4 Input

The name of the program is 'ir.' By typing 'ir' alone on the command line, the following will be printed to the screen:

```
usage: ir filename flag shape r1 theta1 <parameters>
      if flag = 0 : <parameters> -> r2 theta2 v2
      if flag = 1 : <parameters> -> x2 y2 z2 v2
```

Shapes:

- 0 - big_square
- 1 - small_square
- 2 - linear_horz
- 3 - linear_vert
- 4 - circle
- 5 - sparse

To plot data use: `xvgr -p 3view.x filename.yz, filename.yx filename.zx`

The velocity, v_1 , in the first medium is assumed to be that of water, 0.0583 inches per microsecond. Distances are expressed in inches, angles in degrees, and velocities in inches per microsecond. The 'shapes' refer to which elements are turned on:

big_square: (10 X 10) all 100 elements
small_square: (6 X 6) centered about the middle of the array
linear_horz: (10 X 4) centered vertically about the middle of the array
linear_vert: (4 X 10) centered horizontally about the middle of the array
circle: roughly circular with radius=5 elements
sparse: every seventh element

1.5 Output

The files, filename.yx, filename.zx, and filename.yz will contain ASCII data that can be used to create three view images of the array, coordinate system, and ray traces from selected elements defined by the 'shapes' parameter. The result can be plotted with the public domain program, xvgr or xmgr, along with a parameter file, 3view.x, which is provided.

An output file, base_0.000_bscan or base_0.000_volume, is also created to test the writing of the output header to be created for BSCAN or VOLUME acquisitions.

2.0 BSCAN Program

2.1 Description

BSCAN is found in the Mac_HD:jjh:QLIR_BSCAN directory under the executable name 'upats.' The focal-point location is fixed in relation to the array while the array is moved with an X-Y scanner controlled by a PC. The PC and Macintosh™ monitor common handshaking lines so that position and data acquisition can be coordinated. A summed waveform is stored at each location by the Macintosh™.

2.2 Input

The Mac_HD:jjh:QLIR_BSCAN:upats icon is clicked in order to start the BSCAN program. The following steps are recommended after the start:

- (1) Load the UAU file,
- (2) Open the Mode Control Window and turn on Transmit Enable, Receive Enable, and Sum Enable bits,
- (3) Open the Timing Control Panel to set Averages desired,
- (4) Open the Transmitter Focus Control Panel to set Gain desired,
- (5) Open the Receiver Focus Control Panel to set Rate, Gain, and Filter desired, and
- (6) Open the BSCAN Control Panel which should appear as in Figure B-4.

Each field in the BSCAN Control Panel must be filled in by selecting a field by clicking, filling in the field with text, then typing <ENTER>. The information at the top is the geometric data concerning water and metal path (R1 and R2 in inches), incident and refracted

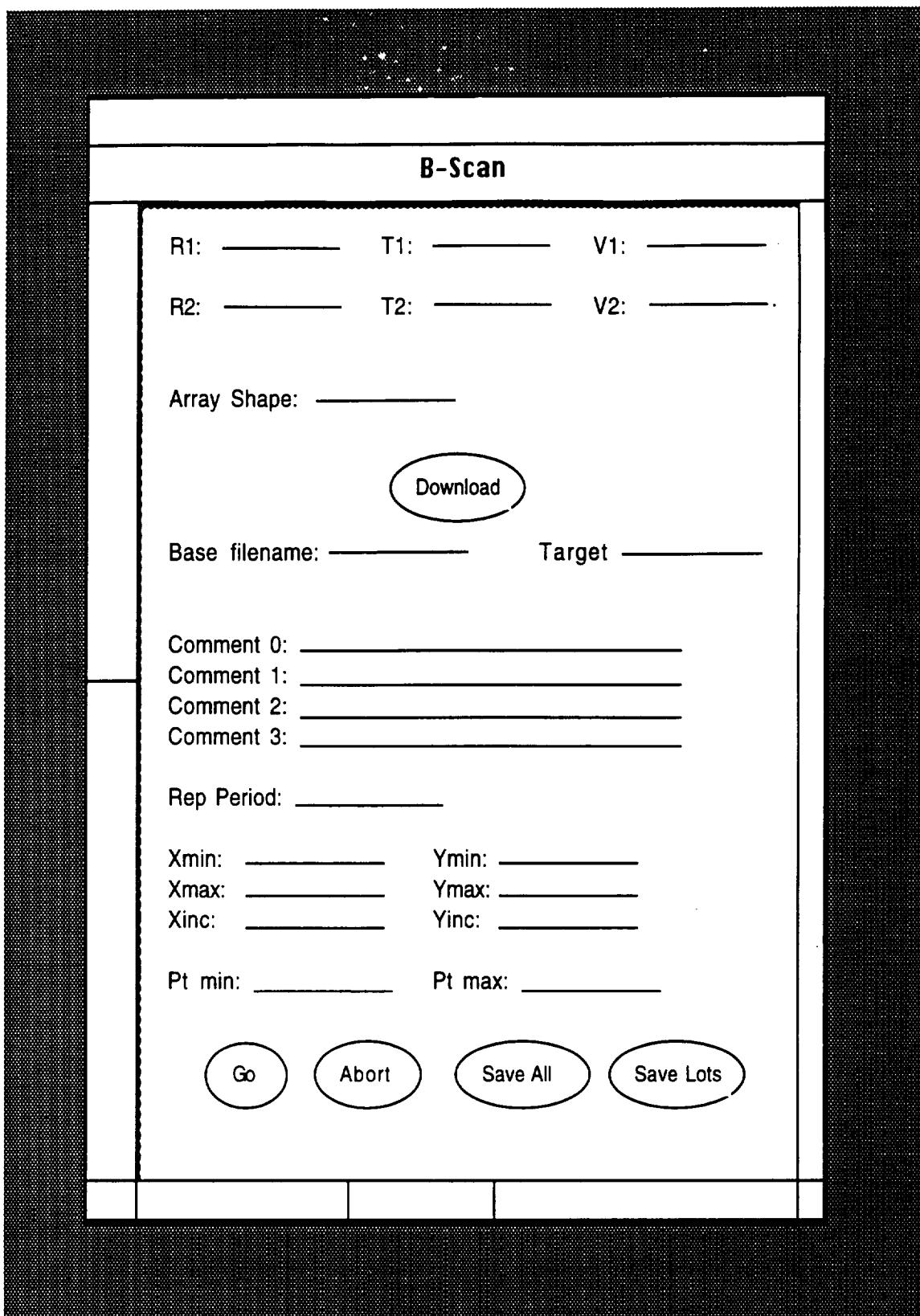


Figure B-4. BSCAN Control Panel

angles (T1 and T2 in degrees), and acoustic velocity in the first and second media (V1 and V2 in inches per microseconds). The 'Array Shape' is a number to an index of shapes as described in Section 1.2 above. By pressing the 'Download' button at this time, all delays are sent to the UPATS instrument. The 'RWS Delay' field of the Timing Control Panel is adjusted automatically. If 'Start Acquisition' is pressed in the Mode Control Panel, the result of the downloading can be observed on an oscilloscope from the summed output.

Typically, a family of files is created, one file for every Y row starting with extension '.000,' with the beginning of the file name being the entry of the 'Base filename' field. The 'Target' field is a number which indexes into a list of targets studied in the project:

- 0 - 45-degree block with 3/8-inch metal path
- 1 - 45-degree block with 3/4-inch metal path
- 2 - 45-degree block with 1-1/2-inch metal path
- 3 - 3/4-inch metal-path block with 0-degree orientation
- 4 - 3/4-inch metal-path block with 30-degree orientation
- 5 - 3/4-inch metal-path block with 45-degree orientation
- 6 - 3/4-inch metal-path block with 60-degree orientation
- 7 - 3/4-inch metal-path block with 70-degree orientation
- 8 - other

Four lines of comments can be typed in. The 'Rep period:' field is a number expressed in seconds which should be equivalent to the repetition period of the UPATS system measured on an oscilloscope. Since there is not a direct way to gauge when the system has finished averaging after the array has been moved to a new position, a delay of repetition period times the number of averages times two is used in the program. 'Xmin:,' 'Xmax:,' and 'Xinc:' are the minimum, maximum, and increment values, respectively, of X for position. Similarly, 'Ymin:,' 'Ymax:,' and 'Yinc:' are the minimum, maximum, and increment values, respectively, for Y. 'Ptmin:' and 'Ptmax:' are the minimum and maximum samples for the waveform to be stored. Values of '0' and '1023' for 'Ptmin:' and 'Ptmax:,' respectively, would store the entire waveform.

The 'Xmin:,' 'Xmax:,' 'Xinc:,' 'Ymin:,' 'Ymax:,' and 'Yinc:' information must be typed into the PC scanner parameter file 'XYSCAN.CFG,' since this information is not directly communicated by the Macintosh™ to the PC.

UPATS must be in the 'Stop Acquisition' mode as controlled from the Mode Control Panel in order for data acquisition to commence. The 'Go' button can then be pressed. On the PC side, the program MAC_SCAN.EXE must be started. Section 2.7, PC Program and Interface, should be consulted for further details on this program.

The 'Abort' button can be pressed at any time to abort an acquisition.

2.3 Output and File Format

Starting at Ymin, the scanner traverses all the X positions from Xmin to Xmax at increment Xinc, and the summed waveform at each of the X positions is acquired and stored. The scanner then moves to Ymin +Yinc to gather the next set of data for Xmin to Xmax. All of the waveforms for a given Y value are stored in one file. Each file consists of:

- An ASCII header and
- Binary data which are composed of $(X_{max}-X_{min})/X_{inc}+1$ number of records of time delay in microseconds, $(P_{tmax}-P_{tmin}+1)$ number of samples per waveform.

The ASCII header contains name of the file, time of acquisition, instrument parameters, geometric parameters, and comments. The end of the header is delimited by the string 'END_HEADER:<formfeed><linefeed>'. The fields 'FILE:,' 'DATE:,' 'TIME:,' 'YINDEX:,' and 'YPOS:' will change as each new set of Y data are acquired.

Following the header are the binary data. At every location, the RWS delay in microseconds and the waveform are stored. The delay is stored as a 64-bit IEEE double. The waveform is then stored as a series of 16-bit signed shorts.

Each short is the sum of the received signal at a given time sample: for a big_square arrangement, each short is the sum of 100 channels; for a small_square arrangement, each short is the sum of 36 channels.

2.4 Save All

The 'SaveAll' button is used to store each individual pulse-echo response of the element given the current downloaded instrumentation parameters. The data are stored without ASCII header or time-delay values. Each waveform is stored as a binary image of 1024 16-bit signed shorts. All 100 waveforms are stored in a file with the base filename and extension '.100_channels.'

2.5 Save Lots

The 'SaveLots' button is used to store the waveform received at each receiver when each element is transmitting alone. A total of 100 files are created with the base filename and extension '.channel_XXX,' where XXX is the channel number that is transmitting. Each file contains 100 waveforms from each of the 100 receivers. The file format is the same as that of the 'SaveAll' data described in Section 2.4.

2.6 PC Program and Interface

The PC program, MAC_SCAN.EXE, is used to control the scanner and communicate with the Macintosh™ via handshaking lines. The scanner is moved from Xmin to Xmax at increment Xinc for every Y value. Y values range from Ymin to Ymax at increment Yinc. These values are stored in an ASCII file XYSCAN.CFG in the following format:

```
Xmin Xmax Xinc  
Ymin Ymax Yinc
```

where all values are expressed in inches.

Two handshaking lines, ACQMAC and RDYMAC, are controlled by the Macintosh™. These two lines emanate from two unused bits of the State/AVE register. ACQMAC indicates that the Macintosh™ is in the acquisition loop. RDYMAC signifies that the Macintosh™ has finished acquiring a waveform, and the scanner can move the array.

Three handshaking lines, ACQPC, RDYPC, and ROWEND are controlled by the PC. These three lines are UAU-ID inputs of the Status register. ACQPC indicates that the PC is in the scanning loop. RDYPC signifies that the scanner is at the next acquisition position and is

waiting for the Macintosh™ to acquire data there. ROWEND indicates that the end of the row has been reached. The ROWEND signal initiates activity in the Macintosh™ to close the present file and open a new file if necessary.

The overall timing diagram for handshaking is shown in Figure B-5. A signal cross-reference table is shown in Figure B-6. The pin numbers and signal designations are from the Metrabyte™ PIO-12 card, which was used as the digital I/O interface for the PC.

3.0 VOLUME Program

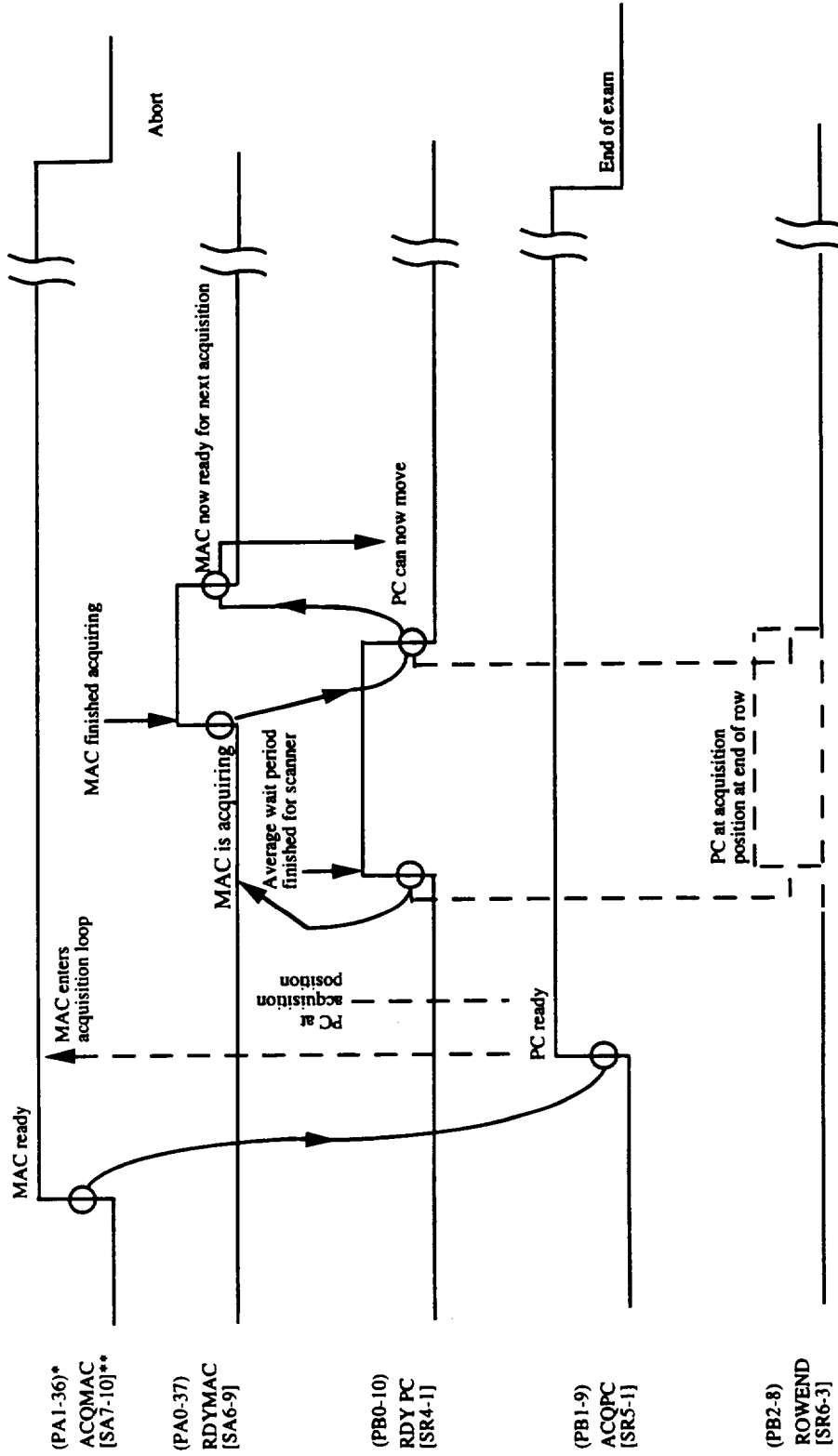
3.1 Description

VOLUME is found in the Mac_HD:jjh:QLIR_VOLUME directory under the executable name 'upats.' The focal-point location is varied in relation to the array while the array position is fixed. No handshaking takes place with the PC. A summed waveform is stored at each location by the Macintosh™.

3.2 Input

The Mac_HD:jjh:QLIR_VOLUME:upats icon is clicked in order to start the VOLUME program. The following steps are recommended after the start:

- (1) Load the UAU file.
- (2) Open the Mode Control Window and turn on Transmit Enable, Receive Enable, and Sum Enable bits.
- (3) Open the Timing Control Panel to set Averages desired.
- (4) Open the Transmitter Focus Control Panel to set Gain desired.
- (5) Open the Receiver Focus Control Panel to set Rate, Gain, and Filter desired.
- (6) Open the VOLUME Control Panel which should appear as in Figure B-7.



*PC card designation - pin number
 **MAC/VME designation - pin number

Figure B-5. Timing diagram for handshaking lines between PC and Macintosh™. These signals are used to coordinate the movement of the scanner by the PC with the data acquisition of the Macintosh™.

Signal Name	PC PIO-12 Card			VME UAU-ID Interface		
	Port	Bit	Pin #	Register	Bit	Pin # (Cable)
ACQMAC	PA	1	36	State/Ave	7 (MSB)	10
RDYMAC	PA	0	37	State/Ave	6	9
ACQPC	PB	1	9	Status	5	2
RDYPC	PB	0	10	Status	4	1
ROWEND	PB	2	8	Status	6	3
GND	-	-	11	-	-	5
Connected but not used	PB	3	7	Status	7	4

Figure B-6. Cross-reference table for handshaking lines

Each field in the VOLUME Control Panel must be filled in by selecting a field by clicking, filling in the field with text, then typing <ENTER>. The information at the top is the geometric data concerning phased array and focal-point position (R1, X2, Y2, Z2 in inches), incident angle (T1 in degrees), and acoustic velocity in the first and second media (V1 and V2 in inches per microseconds). The 'Array Shape' is a number to an index of shapes as described in Section 1.2 above. By pressing the 'Download' button at this time, all the delays are sent to the UPATS instrument. The 'RWS Delay' field of the Timing Control Panel is adjusted automatically. If 'Start Acquisition' is pressed in the Mode Control Panel, the result of the downloading can be observed on an oscilloscope from the summed output. Note that the setting of X2, Y2, and Z2 does not affect acquisition. It merely provides a tool to focus in different locations in the volume and observe the effect of the focusing.

Typically, a family of files is created, one file for every Z slice starting with extension '.000,' with the beginning of the file name being the entry of the 'Base filename' field. The 'Target' field is a number which indexes into a list of targets studied in the project:

- 0 - 45-degree block with 3/8-inch metal path
- 1 - 45-degree block with 3/4-inch metal path
- 2 - 45-degree block with 1-1/2-inch metal path
- 3 - 3/4-inch metal-path block with 0-degree orientation
- 4 - 3/4-inch metal-path block with 30-degree orientation
- 5 - 3/4-inch metal-path block with 45-degree orientation
- 6 - 3/4-inch metal-path block with 60-degree orientation
- 7 - 3/4-inch metal-path block with 70-degree orientation
- 8 - other

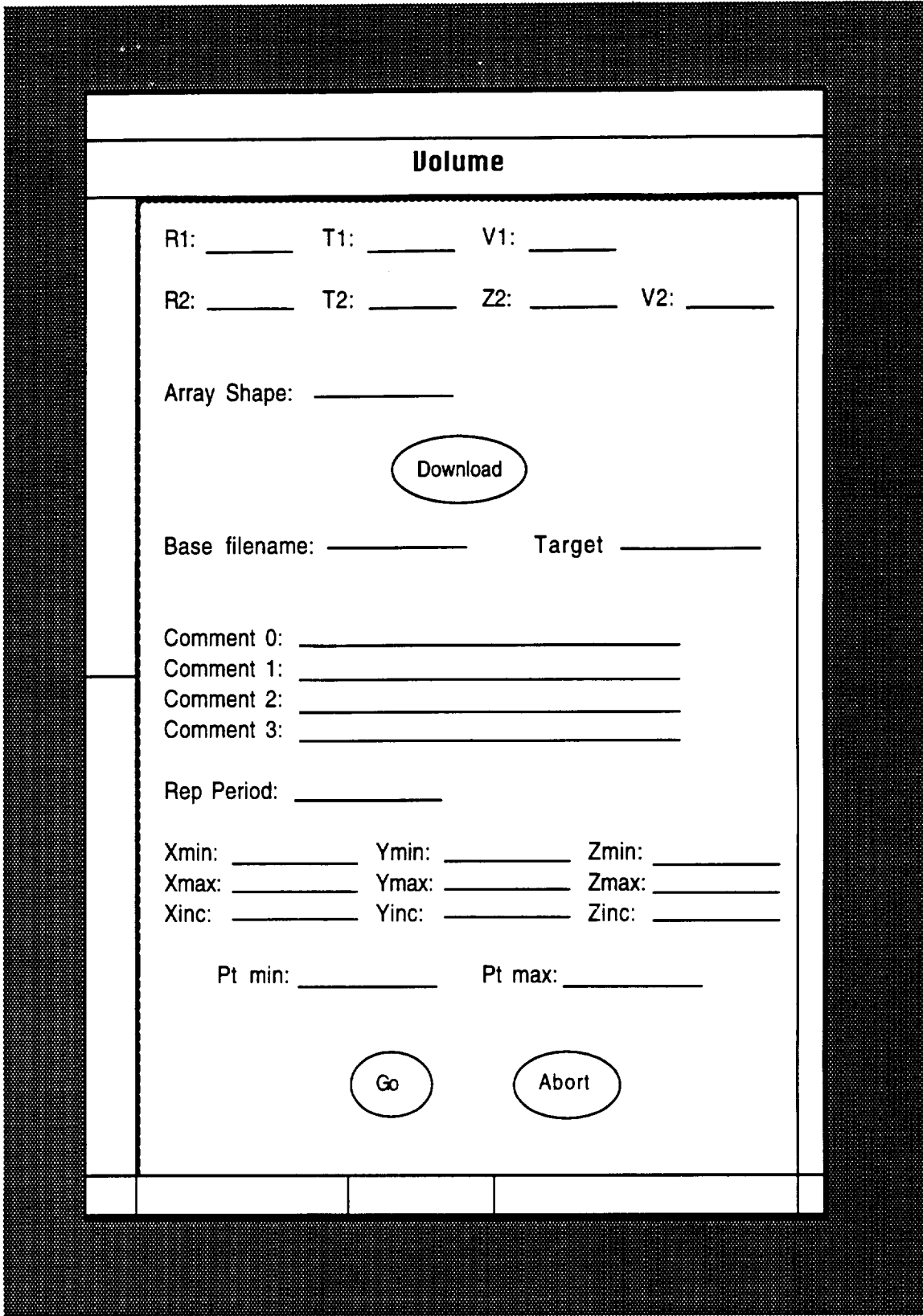


Figure B-7. VOLUME Control Panel

Four lines of comments can be typed in. The 'Rep period:' field is a number expressed in seconds which should be equivalent to the repetition period of the UPATS system measured on an oscilloscope. Since there is not a direct way to gauge when the system has finished averaging after the array has been moved to a new position, a delay of repetition period times the number of averages times two is used in the program. The volume through which the focal point is moved is defined by the values set for:

- 1) 'Xmin:', 'Xmax:', and increment 'Xinc:' for X
- 2) 'Ymin:', 'Ymax:', and increment 'Yinc:' for Y
- 3) 'Zmin:', 'Zmax:', and increment 'Zinc:' for Z

'Ptmin:' and 'Ptmax:' are the minimum and maximum samples for the waveform to be stored. Values of '0' and '1023' for 'Ptmin:' and 'Ptmax:', respectively, would store the entire waveform.

UPATS must be in the 'Start Acquisition' mode as controlled from the Mode Control Panel in order for data acquisition to commence. The 'Go' button can then be pressed.

3.3 Output and File Format

Starting at Zmin, Ymin, the program moves the focal point through all the X positions from Xmin to Xmax at increment Xinc, and the summed waveform at each of the X positions is acquired and stored. The program then moves the focal point to Ymin + Yinc to gather the next set of data for Xmin to Xmax. This process is repeated until all of the data for Zmin are stored in one file. The Z value is incremented by Zinc, and a new file is opened for the next Z slice.

Each file consists of:

- An ASCII header and
- Binary data which are composed of $(Y_{max}-Y_{min})/Y_{inc}+1$ number of $(X_{max}-X_{min})/X_{inc}+1$ records of time delay in microseconds, $(Pt_{max}-Pt_{min}+1)$ number of samples per waveform.

The ASCII header contains the name of the file, time of acquisition, instrument parameters, geometric parameters, and comments. The end of the header is delimited by the string 'END_HEADER:<formfeed><linefeed>.' The fields 'FILE:,' 'DATE:,' 'TIME:,' 'ZINDEX:,' and 'ZPOS:' will change as each new set of Y data is acquired.

Following the header are the binary data. At every location, the RWS delay in microseconds and the waveform are stored. The delay is stored as a 64-bit IEEE double. The waveform is then stored as a series of 16-bit signed shorts.

Each short is the sum of the received signal at a given time sample; therefore, for a big_square arrangement, each short is the sum of 100 channels; for a small_square arrangement, each short is the sum of 36 channels.

4.0 Convert Program Template

A conversion program is provided as a template to read BSCAN- or VOLUME-type data. The three primary reading blocks are:

- (1) The 'while(!finished_header)' loop reads each line of the header and extracts some information from it;
- (2) The 'while((read(handle,&d,8)!=0))' loop first reads the RWS delay into the double variable 'd;' and
- (3) The 'read(handle,i_array, n*sizeof(short));' statement reads n points of a waveform into the short array 'i_array'.

5.0 Known Problems

5.1 UAULib

In the UAUFocus procedure in the UAULib.c source file, the following changes must be made so that polar and azimuthal angles are interpreted correctly in relation to the coordinate system used within the program:

theta = (azimuth + 90.0) * DEG2RAD; should become
theta = (-azimuth + 90.0) * DEG2RAD;

phi = polar * DEG2RAD; should become
phi = (180.0 - polar) * DEG2RAD;

zf = focal * (-cos(phi)); should become
zf = focal * cos(phi);

5.2 Save PICT

The Save PICT option in the UPATS program was written according to the guidelines specified in the Inside Macintosh™ manuals. However, upon further investigation, it was discovered that the files created by the UPATS Save PICT option could not be read by either Adobe Photoshop or a public-domain program capable of saving and reading PICT files.

These programs may only be capable of reading PICT bitmap images while the UPATS Save PICT option writes graphical commands such as moves and draws into the file. The files were not tested with any other programs, so it is not known whether the format is correct.

The public-domain program left on the Macintosh™ can be used to save images which are readable by Adobe Photoshop.

5.3 QLIR_VOLUME Abort Button

The QLIR_VOLUME 'Abort' button does not work during acquisition.