A Comparison of Resolution Performance Between the Imperium AcoustoCam™ and the Phased Array Ultrasound Testing

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Introduction

A new and innovative ultrasound technique from Imperium, Digital Acoustic Video™ (DAV), embodied in its commercial product, the AcoustoCam™, has demonstrated a unique approach to the use of ultrasound in industrial inspection. Imperium's DAV technology uses a 120 row x 120 column ultrasound detector array to generate real time C-scan images. This is a very different technique than that used by phased array ultrasound testing (PAUT) systems, the currently prevailing ultrasonic inspection technology. The differences in ultrasound physics suggest differences in performance, and one important performance metric is resolution. For a given operating frequency, how well do the opposing techniques resolve features within an inspected material. In this paper the AcoustoCam will be compared to a commercially available PAUT system. It will be asserted that for a given ultrasound frequency, the AcoustoCam™ provides superior resolution. This paper will explain how this improved performance is a result of the AcoustoCam™'s detector array construction, image orientation, lack of geometric distortion, and lack of speckle.

Discussion of PAUT and DAV Operational Principles

The operating principles of a PAUT inspection probe are well understood. A series of piezoelectric elements is assembled into a 1 x N array. Each element is excited by a voltage pulse at a different time delay as shown in **Figure 1a**. The result is an ultrasound beam which can be focused at any arbitrary point in space bounded by the aperture width and depth of focus. **Figure 1b** shows the array focus at depth. The width and depth parameters are determined by the physical construction of the array.

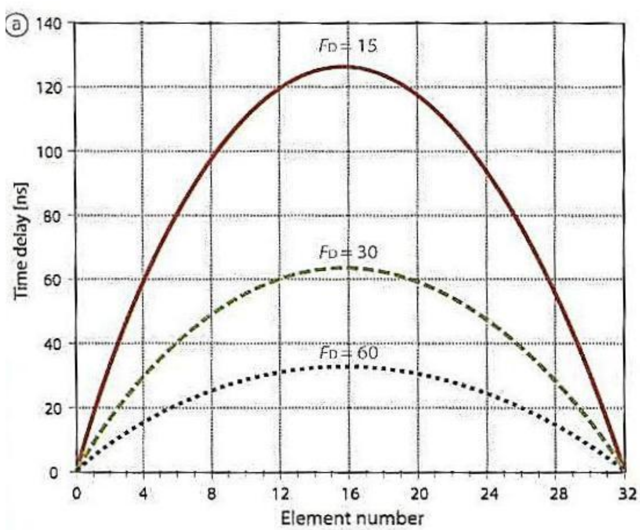


Figure 1a: Array Element Time Delays

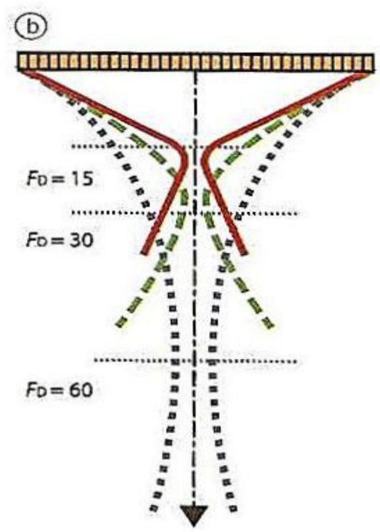


Figure 1b: Array Focus at Depth

The DAV ultrasound imaging technology developed by Imperium operates on a principle similar to that of a digital photo camera, as illustrated in **Figure 2**. A large unfocused source transducer insonifies the target just as a flash bulb would illuminate a target in a photo camera. Ultrasound reflected from the target is focused by the acoustic lens system onto a detector array. These lenses are made from materials which bend the incoming ultrasound waves to focus on an image plane. This is similar to how the lenses in a photo camera serve to bend the reflected light waves from the photographed target.

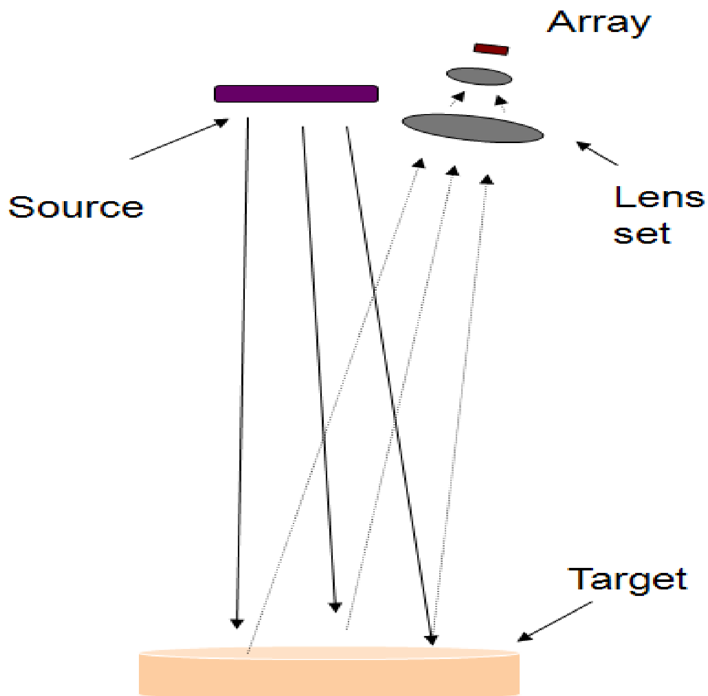


Figure 2: Diagram of AcoustoCam™ Integrated System Components

The ultrasound detector array operates in the same manner as a CCD array in a digital photo camera. Ultrasound incident on the surface of the detector array is converted to pixel voltages by a piezoelectric material bonded with the detector array and the resulting voltages are processed by the array to create an image. **Figure 3** shows the detector array. **Figure 4** shows a 5 MHz source transducer.

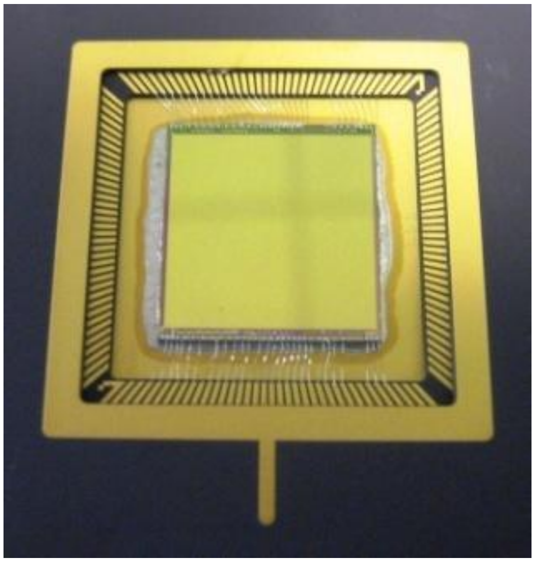


Fig. 3: Detector Array

Fig. 4: Source 5 MHz Transducer

Figure 5 shows the three individual acoustic lenses and their holding bracket, while **Figure 6** shows these parts configured as an integrated acoustic beam focusing system configured for installation inside the camera.

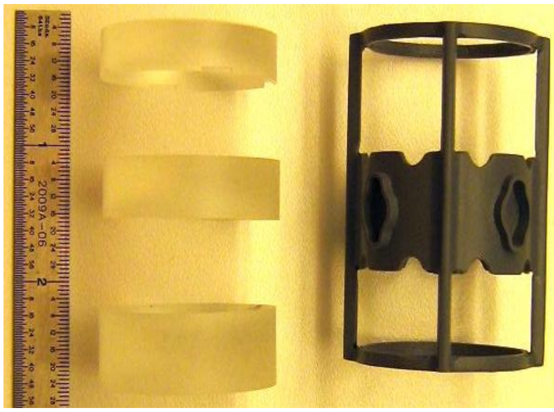


Figure 5: Acoustic Lenses and Bracket

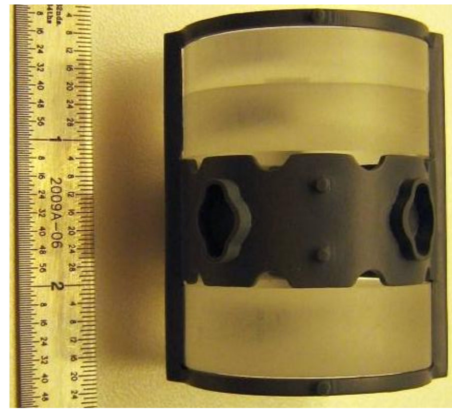


Fig. 6: Integrated Lensing System

Differences in the operating principles of PAUT and the AcoustoCam™ result in differences in the orientation of the image. The image orientations of both a PAUT probe and the AcoustoCam™ are shown in **Figure 7**. In a PAUT probe the shape of the probe elements and time-delayed construction of the phased beam result in a beam formation which is perpendicular to the target as shown in F**igure 7a**. The perpendicular orientation is commonly referred to as B-mode ultrasound, and results in an image of a vertical slice through the target.

The image in **Figure 7b** is representative of the AcoustoCam™'s operation where the orientation of the ultrasound wave is parallel to the surface of the target. This planar orientation produced by the AcoustoCam™ is commonly referred to as C-mode ultrasound, and the resulting images are horizontal slices of the target. The thickness of the slice is determined by a time gate which selects the range of time-delayed ultrasound returns which are incorporated into the image. Note that there is no axial resolution within the time gate.

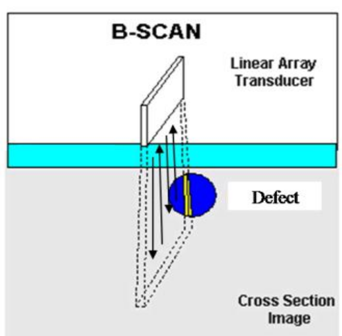


Figure 7a: PAUT Beam

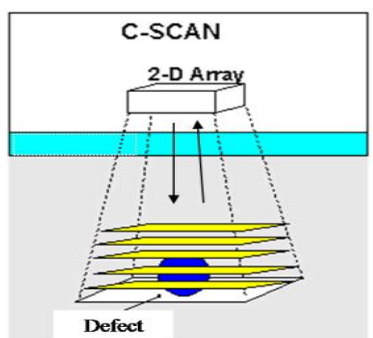


Figure 7b: AcoustoCam™ Beam

The differences in image orientation result in dramatically different image presentations as shown in **Figures 8a and 8b**. Figure 8a depicts a typical B-mode PAUT image enhanced with false color. As stated, this is a vertical slice through the inspected target. Note that the flaws are shown in red, and that they appear stretched and distorted. This distortion is a result of the nature of the beamforming and is inherent in PAUT technology. Note also the blue speckles which appear throughout the image in Figure 8a. This speckle is a result of the coherent detection process employed in phased array beamforming and is also inherent in PAUT.

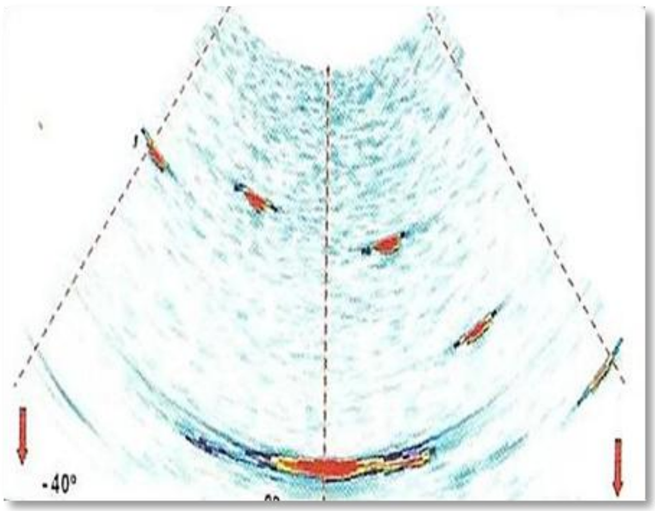


Figure 8a: B-mode PAUT Image

Fig. 8b: C-mode AcoustoCam™ Image

Figure 8b is an ultrasound image of a U.S. quarter taken by the AcoustoCam™ at 7.5 MHz. Note the difference in image orientation. The quarter looks like a quarter because of the planar orientation of the image. Note that there is no geometric distortion or speckle. The AcoustoCam™ employs a non-coherent detection scheme which does not produce the speckle. The lack of geometric distortion is a result of the camera lens focusing technique which, like a photo camera, does not distort the image.

Discussion of Axial, Elevation, and Lateral Resolution in PAUT & DAV

Axial resolution is defined as resolution in the axis perpendicular to the surface of the ultrasound probe commonly referred to as the Z-axis. The minimum practical time gate for the AcoustoCam™ is 0.5 µs. With an ultrasound speed of 2.97mm/µs in a graphite epoxy composite material the axial resolution would be 1.5 mm. The AcoustoCam™ has no axial resolution within the depth of a time gate. The AcoustoCam™™ employs an A-scan sensor which can be used to measure axial position with greater resolution.

In a PAUT system, axial resolution, in millimeters, is defined as**:

$$\Delta Z = V \times T/2$$

where:

V = ultrasound velocity for the material, mm/µs;

T = ultrasound pulse width, µs.

For graphite/epoxy composite materials:

V = 2.97 mm/µs;

T = 0.2 µs (at a frequency of 5 MHz).

Substituting these values into the PAUT axial resolution equation gives:

$\Delta Z = (2.97) \times (0.2/2) = 0.297$ mm.

Lateral resolution is defined as resolution in the axis parallel to the active aperture of the probe commonly referred to as the X-axis. The lateral resolution of the AcoustoCam™ is defined by the size of the detector array pixel cell which is 100 µm x 100 µm and the frequency of ultrasound transmission. At ultrasound frequencies of 1 MHz to 5 MHz, which is the typical operating range of most industrial ultrasonic inspection, the detector elements are smaller than the wavelength which results in spatial oversampling. This is beneficial in that the returning ultrasound wave reflected from a point in the target material is detected by multiple detector elements which has a smoothing effect in the resulting image.

A picture of the detector array taken by a microscope camera is shown in **Figure 9**. This image was taken before the piezoelectric material was applied so the individual pixel cells can be seen.

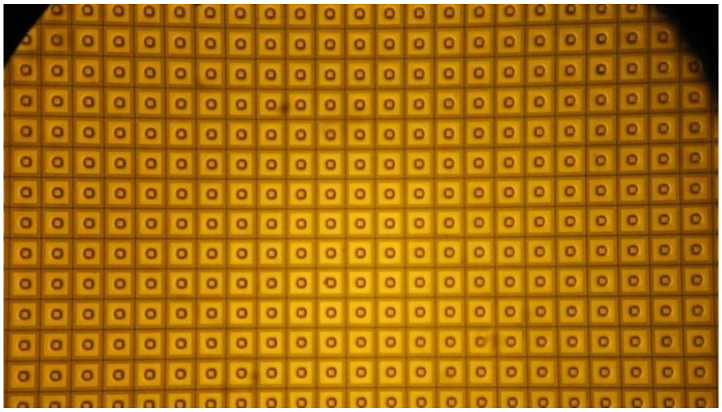


Figure 9: Detector Array Pixel Cells

In a phased array ultrasound system lateral resolution, in millimeters, is defined as**:

$\Delta D = (0.44 \times V) / (F \times \sin(\theta/2))$

where:

V = ultrasound velocity for the material, mm/µs;

F = ultrasound frequency, MHz;

θ = active area angle as seen from the focal point.

In graphite epoxy composites at a depth of 10 mm, using a 64 element probe with an active aperture of 24 mm:

$V = 2.97$ mm/µs;

$F = 5$ MHz;

$\theta = 100^0$.

Substituting these values into the PAUT lateral resolution equation gives:

$$\Delta D = (0.44) \times (2.97) / (5 \times \sin(100^0/2) = 0.341 \text{ mm}.$$

Elevation resolution in a PAUT system is defined by the length of the array elements, and will be on the order of several millimeters in the 1 MHz to 5 MHz frequency band. In the AcoustoCam™ the resolution in the elevation axis is the same as in the lateral axis which is 100 µm.

Table 1 below shows the numerical comparison of the three resolution axes between the AcoustoCam™ and the PAUT in graphite/epoxy composites using the systems at an ultrasound frequency of 5 MHz. This is a rough comparison based on theoretical data and will vary based on ultrasound frequency and target material. It can be seen for instance that in aluminum with a higher velocity both lateral and axial resolution would be worse for the PAUT and axial resolution would be worse for the AcoustoCam™. Important aspects of resolution comparison not included in the table are image orientation, and lack of distracting artifacts such as geometric distortion and speckle. Add these factors to the superior performance in lateral and elevation resolution and the assertion is made that the AcoustoCam™ is superior in resolution performance to a typical PAUT system.

INSPECTION SYSTEM	AXIAL RESOLUTION	LATERAL RESOLUTION	ELEVATION RESOLUTION
AcoustoCam™	1.5 mm	0.1 mm	0.1 mm
PAUT	0.3 mm	0.34 mm	> 1.0 mm

Table 1: Numerical Resolution Comparison of DAV to PAUT at 5 MHz

** *Advances in Phased Array Ultrasonic Technology*, Olympus NDT, 2007

Imperium
Advanced Ultrasonic Imaging

Image Resolution Comparison of PAUT and DAV

A comparison of the image resolution between the PAUT and the AcoustoCam™ was conducted using a custom made graphite/epoxy composite standard that Imperium uses for calibration. **Figure 10** shows the standard's back wall with several milled flat-bottom holes (FBHs). The sample is 0.250" thick, with the section shown at the top of **Figure 10** milled to a thickness of 0.130", and the section shown in the bottom of Figure 7 milled to a thickness of 0.210". The images shown herein were all taken in pulse echo mode for both the PAUT System and AcoustoCam™.

For the resolution comparison tests described in this report, three sets of the FBH's were selected, labeled "Set A", "Set B", and "Set C". The Set A holes are 0.100" in diameter, spaced 0.140" apart, and 0.070" in depth from the front surface. The Set B holes are 0.040" in diameter, spaced 0.050" apart, and 0.125" in depth from the front surface. The Set C holes shown are 0.023" in diameter, 0.023" apart, and are 0.100" in depth from the top surface.

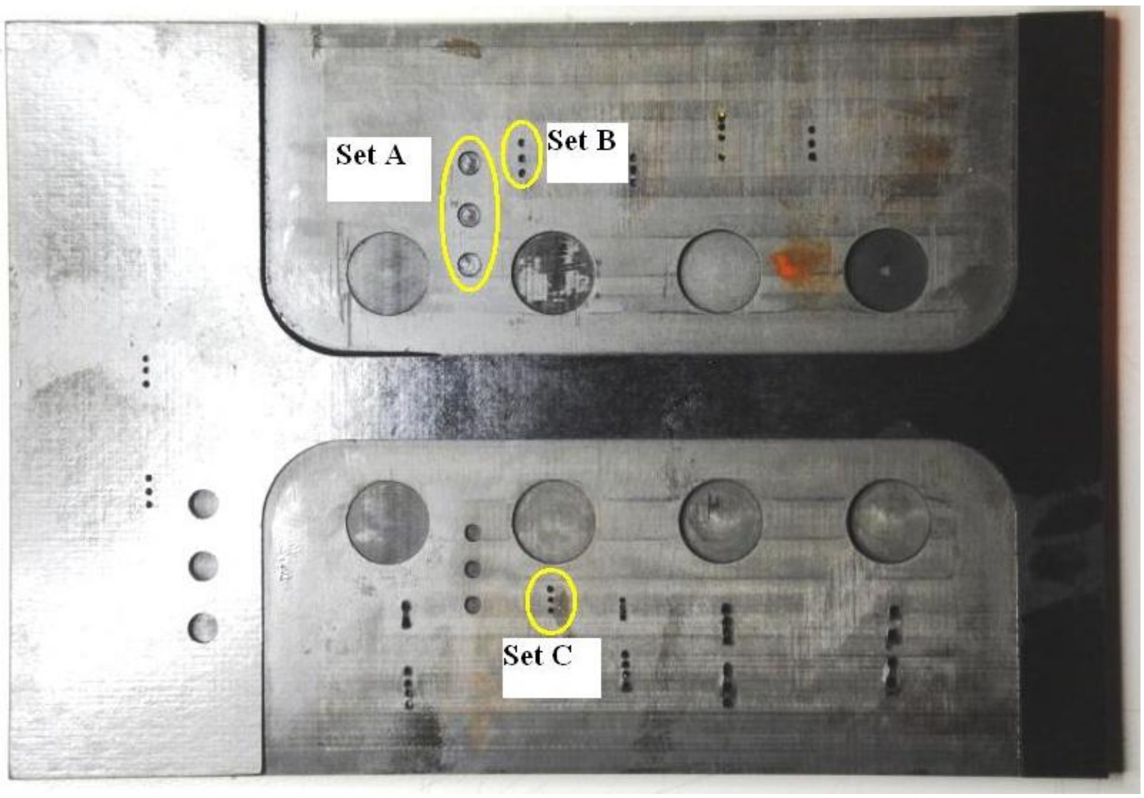


Figure 10: Imperium's Graphite/Epoxy Composite Resolution Standard

The PAUT System used in the test is shown in **Figure 11a**. A manually operated encoder system used to scan the standard is shown in **Figure 11b**. The AcoustoCam™ used in this test is shown in **Figure 12**.

Figure 11a: PAUT System

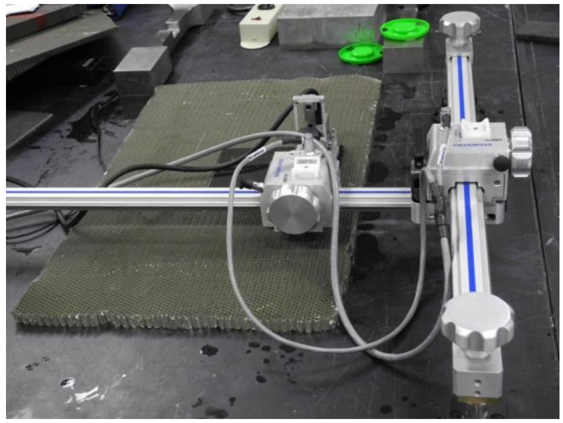


Figure 11b: Manual Encoder System

Figure 12: AcoustoCam™

PAUT System Test Settings:

Probe:	5L64-NW1 (5 MHz)
Wedge:	SN1-0L5L64
Mode:	Phased array
Focal Depth:	0.1”
Focal Law:	Linear sector with overlap
Skew Direction:	90^0 (straight down look mode)
Scan Offset:	0
Index Offset:	0

Element Quantity:	8
First Element:	1
Last Element:	64
Thickness:	0.25"
Material:	Composite
Surface:	Flat plate
Display Mode:	Amplitude display

AcoustoCam™ Test Settings:

Frequency:	5 MHz
Number of Pulses:	1

An image taken by the PAUT System of the Set A holes is shown in figure 13a. The images in figures 13b and 13c were taken by the AcoustoCam™. The thick red line in figure 13a and the bright background return in figure 13b display the back wall of the composite standard. The deeper back wall on the right side of the image in figure 13a is the rib down the center of the standard.

The holes in Figure 13a are well formed with a significant drop in the back wall amplitude. The amplitude return from the holes isn't as strong as the return from the back wall but these holes are detected with no problem. Note that the image in figure 13a displays the lateral axis horizontally and the axial axis vertically, this presents a display of a vertical slice through the target.

The image in Figure 13b was taken with a wide 10 µs time gate and a time delay set to remove the front surface return from the image. In Figure 13c a narrow 0.5 µs gate was used to remove the front and back walls from the image leaving only the returns from the holes. In Figure 13c the effects of varying ultrasound speed across the curvature of the lens can be seen as concentric rings. As with the PAUT System the images of the holes taken by the AcoustoCam™ are well formed and the holes are detected with no problem.

Note the difference in perspective of the images. The AcoustoCam™ presents a planar image as if you were looking through the top surface of the standard. In contrast, the PAUT System presents a vertical slice as if you were looking through the edge of the standard.

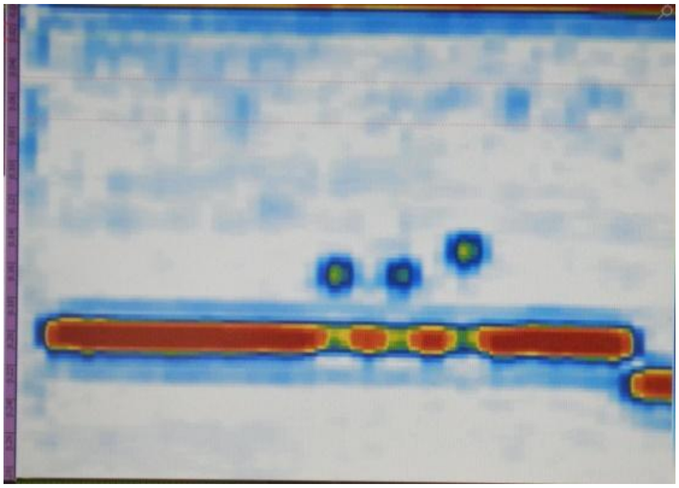


Fig. 13a: PAUT System Image of Set A FBH's

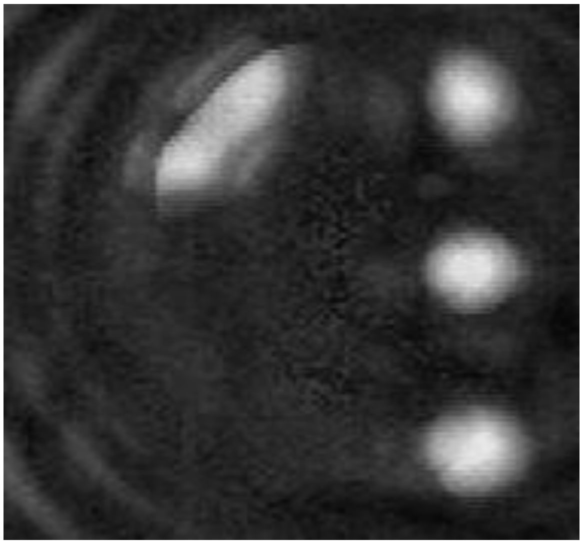
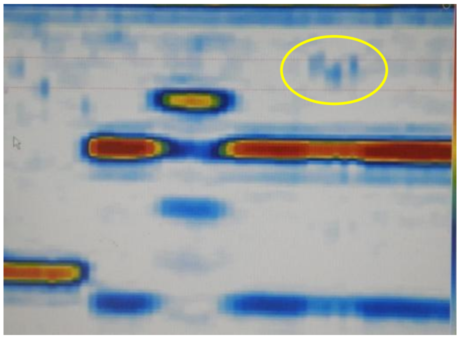


Fig. 13b: AcoustoCam™ Set A & Back Wall Wall **Fig 13c: AcoustoCam™ Set A & No Back**

An image taken by the PAUT System of the FBHs in Set B is shown in **Figure 14a** and the image in **Figure 14b** was taken by the AcoustoCam™. The Set B holes in Figure 14a are not well formed, and the drop in the back wall amplitude is the most prominent indication that the holes exist. The amplitude return from the holes themselves is weak, and blends in with the image speckle. Detection of these holes is problematic. The large return to the left of the Set B holes in figure 14a is from one of the 0.500" holes shown in Figure 10, while further to the left is a return from the rib in the center of the standard.

In **Figure 14b**, the AcoustoCam™'s C-scan clearly shows the Set B holes, with each hole distinctly resolved from the adjacent ones. An advantage of the AcoustoCam™'s imaging technology is the lack of speckle. In contrast, PAUT System's speckle in Figure 14a masks the return from the holes.



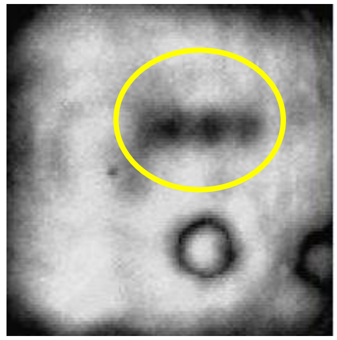
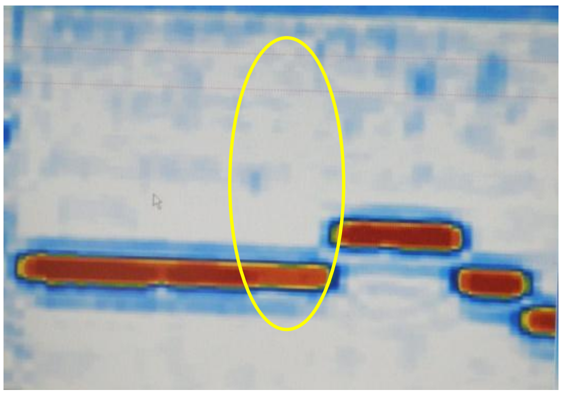


Figure 14a
PAUT System Image of Set B holes

Figure 14b
AcoustoCam™ C-scan of Set B

An image taken by the PAUT System of the Set C holes is shown in **Figure 15a,** while **Figure 15b** is the AcoustoCam™'s corresponding C-scan.



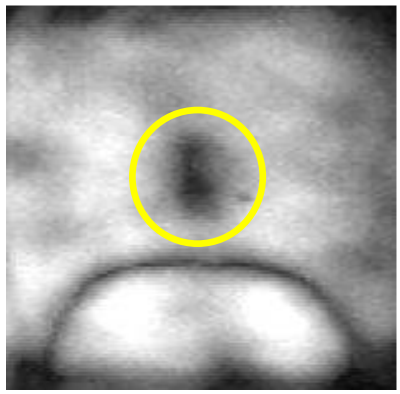


Figure 15a: PAUT System Image of Set C

Fig. 15b: AcoustoCam™'s Set C

The return from the Set C holes in **Figure 15a** is missing, and the drop in back wall return is barely visible. The Set C holes are not detectable in this image. The image in **Figure 15b** shows the holes, but they are not distinct from each other, with their returns combined to show them as a single hole. These holes are detectable, but not resolved as distinct from one another.

C-Scan images of the composite standard shown in **Figures 16a, 16b, and 17** are used to present a comparison of resolution performance between the PAUT System and the AcoustoCam™ that would be useful to an NDT inspector. In most inspections native mode B-Scan phased array displays are not used. The B-Scan images are processed to produce C-Scan images which are easier to understand. **Figure 16a** uses time of flight (TOF) from the phased array return to construct the C-Scan image and **Figure 16b** uses amplitude returns. In **Figure 17** the large C-Scan image is constructed from a series of 1"x1" native mode AcoustoCam™ C-Scan images which are pieced together using position information. As seen in these figures, the large 0.500" holes and Set A 0.100" holes are visible in all three images. The smaller Set B 0.040" and Set C 0.023" are only visible in **Figure 17**, the AcoustoCam™ image. In **Figures 16a and 16b** the Set B and Set C holes are not visible at all. It is thus asserted that the AcoustoCam™ has superior resolution performance.

Several aspects of the image in **Figure 17** unrelated to the resolution comparison deserve discussion. One of the large ½" holes is dark, not bright. This is because the time-gated detection window was set past the top surface of the hole, thus ultrasound reflected from the top surface is not included in the image. The second notable aspect of the image in Figure 17 is the clear presentation of porosity in the composite standard. Porosity is detected in the 0.250" thick sections of the image on the lower left side and upper right hand side.

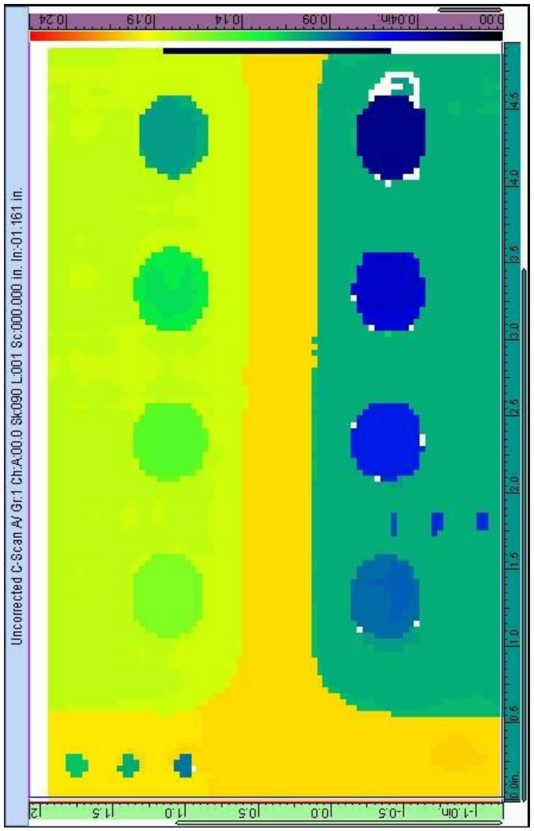


Figure 16a PAUT System TOF Image

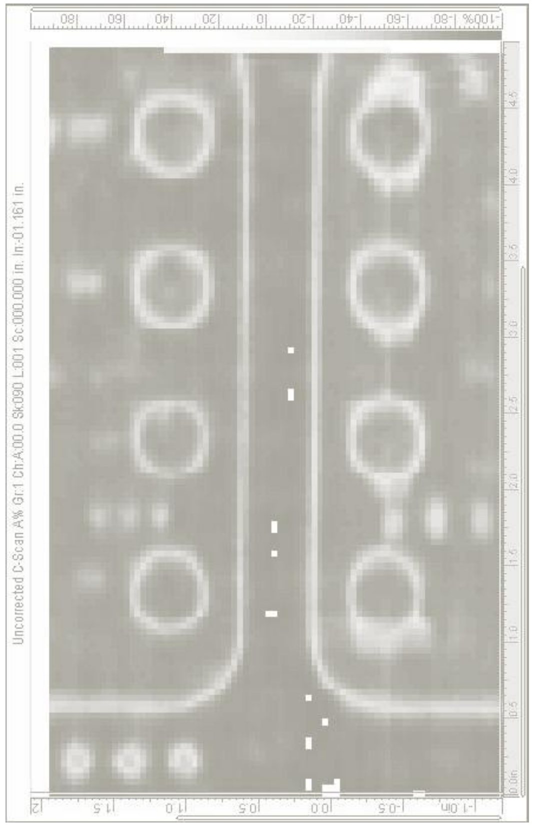


Figure 16b PAUT Amplitude Image

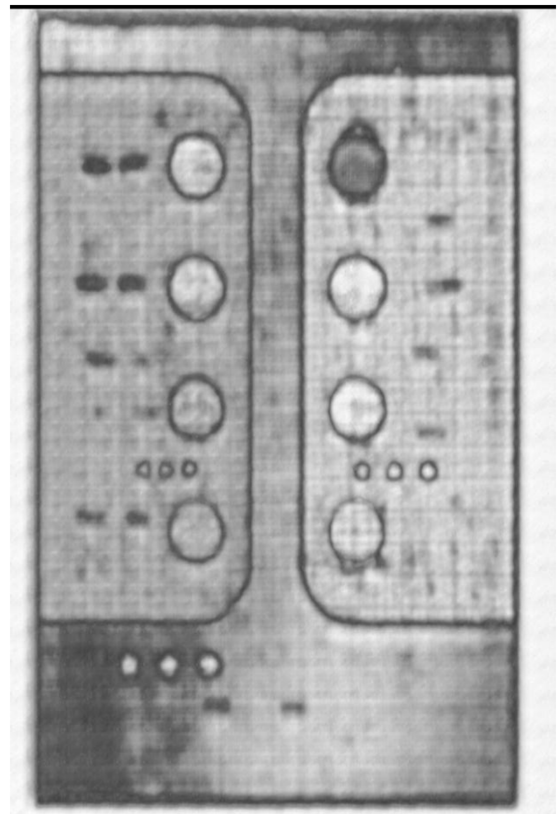


Figure 17 AcoustoCam™ Image