The impact of defective ultrasound transducers on the evaluation results of ultrasound imaging of blood flow

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KTH Technology
and Health

Master of Science Thesis in Medical Imaging
Stockholm 2014

This master thesis project was performed in collaboration with
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Advanced level (second cycle), 30 credits
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TRITA-STH. EX 2014:83

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Summary

Following X-Ray, Ultrasound is now the most common of all the medical imaging technologies specifically in obstetrics and cardiology. Plus that the ultrasound hazards perceived to be insignificant compared with X-rays. Considering the fact that the study of cardiovascular diseases, blood flow patterns and the fetal development is essential for human life, the accuracy and proper functioning of ultrasonic systems is of great importance. Hence quality control of ultrasonic transducers is necessary.

In this thesis, a system to standardize the acceptance criteria for quality control of ultrasonic transducers is described. On this ground a study on ultrasound images conducted to compare and evaluate the quality resulted from different types of transducers in different conditions, i.e. defective or functional.

A clinical study was also carried out to evaluate our hypothesis in real cases at department of Cardiology and department of genecology. Results from this study show that the perception of quality is somewhat subjective and clinical studies are time-consuming. But quality factors such as the ability to accurately identify anatomical structure and functional capabilities are of great importance and help.

Acknowledgements

This project could have never been possible without the contribution of several people. First and foremost I would like to thank my advisor at the Biomedical Engineering department of Karolinska University Hospital, Mats Olsson. Tack så mycket for the great support and sharing your experience with me. I'm inspired by your admirable knowledge and commitment to your job. I am also grateful to Heikki Teriö for his support and impressive knowledge. Paljon kiitoksia for your expert guidance.

A very special thank to Aristomenis Manouras, Yacek Nowak, Christine Bruse and Ridvan Furan that without their help I would not be able to finalize this project with clinical results.

I highly appreciate valuable help of Nina Elmstedt, Anna Bjällmark and Matthias Mårtensson. Tusen tack för ert stöd!

My grateful thanks to Dmitry Grishenkov for his constructive comments. Спасибо for your excellent suggestions!

I am so thankful to all the colleagues at the medical engineering department of Karolinska University Hospital. I'm so grateful for your support, trust and patience.

Last but not least, I want to thank my family and friends from the bottom of my heart for their support. My parents for their love and always being there, my sister for her everlasting encouragement. Hartelijk dank to my loving support, Simon who made the start and end of this project more beautiful!

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1 Introduction

It all started in 1880 by employment of the piezoelectric effect (Jacques and Pierre Curie) in transducers to generate and detect ultrasonic waves in air and water [1]. Continued by Paul Langevin in 1917 attempting to detect submarines was the first technological application of ultrasound and as a diagnostic medical tool, has been used for nearly half a century [2]. The initial application of ultrasound for medical purposes was by George Döring Ludwig for detecting gallstones in animal bodies [3]. First medical application on human body, identifying thickness and resiliency of intestine tissue was conducted by John Wild in 1949 made him called "Father of Medical Ultrasound" [4]. The first successful measurements of movements of human heart walls were performed by Inger Edler and Carl Hertz in 1953 [5]. Followed by Ian Doland's work in 1958 on investigation of abdominal masses and later improved to obstetric applications such as assessment of the size and growth of the fetus [6]. The first Doppler ultrasound system for clinical use was introduced by Gene Strandness in 1967 for qualitative evaluation of arterial and venous flow [7]. The role of diagnostic ultrasound has evolved immensely and applied to almost every area of medicine ever since with the advent of minimally invasive techniques.

Use of ultrasound has proved to be a major advance in the noninvasive and non-ionizing diagnosis. The main application area of the ultrasound diagnostic systems are calculation of blood flow and imaging of organs and tissue movements in e.g. heart muscles, movements and developments of embryo, estimation of blood flow in umbilical cord, examination of head and heart in fetus in order to diagnose the deformities, tumor diagnosis, blood circulation in limbs, prostate diseases, rheumatology etc.

Approximately more than 1 in 3 of American adults (83.6 million) have 1 or more types of CVD[1] [8]. Cardiovascular diseases are the leading cause of mortality in Europe with 46% of all deaths [9]. Adjusted to the entire US population, valve disease of any type has 2.5% prevalence [8]. An estimated 1 in 33 infants are affected by congenital anomalies which annually cause about 3.2 million birth defect-related disabilities. Down syndrome, heart defects and neural tube defects are the most common congenital disorders [10]. Congenital CVDs have great significance to healthcare costs and mortality. Reported congenital heart defects are: between 4 and 10 in the United States, 6.9 in Europe and 9.3 in Asia per 1000 live births [8].

All ultrasonic transducers have the same basic components: a piezoelectric plate, a matching layer, a backing layer and a lens, as shown in figure 1.1 and 1.2. The number, size, shape and arrangement of transducer elements vary according to the transducer type and application [11].

[1] CVD: Cardio Vascular Disease/Defect

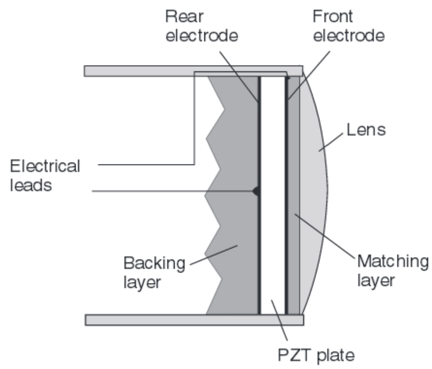

Figure 1.1 Basic components in a transducer [11]

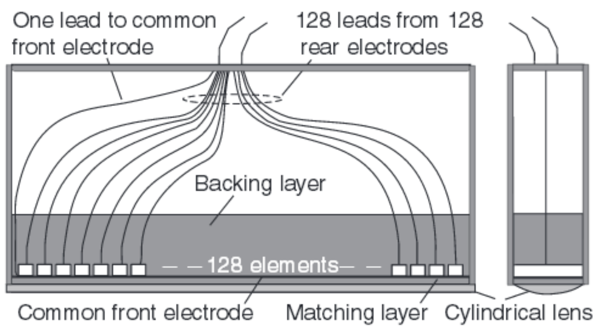

Figure 1.2 Inside of an ultrasound transducer [11]

Owing to this structure, a transducer is vulnerable to different types of damages that result in fault or degradation in quality of image. Considering such a vast application field of diagnostic ultrasound (mentioned above), it is very important to assure the quality of probe and thus quality of image. Our interest in finding yardsticks to label transducers as defective or functional in relation to a required image quality for clinical diagnoses initiated this thesis.

2 Backgrounds

Quality assurance demands for a common standardized protocol that is necessary for ensuring optimal image quality in different exam types and cost-effectively managing the vast amount of equipment.

A reliable diagnosis of any disease is very valuable because outcome in certain cases can be greatly improved by accurate diagnosis and adequate therapy. Echocardiography is recognized as the main diagnostic tool for valve problems [12]. And as previous studies have shown that there is a high error frequency or high rate of defective transducers in clinical routine use [13]. A clinical case at Karolinska hospital in 2006 evidences the problem. A congenital heart disease was missed at the first examination but discovered during a later re-examination. A defective transducer has been the cause that was replaced at the next maintenance test [13].

Statistically, there have been almost 29000 delivery cases in 2012 in Stockholm area [14], therefore at least 29000 ultrasound examinations on fetus. Every year about 9000 ultrasound examinations on heart and vessels are performed at Södersjukhuset [15], thus there are about 30000 cardiovascular ultrasound examinations yearly in Stockholm area.

Considering these statistics and results of previous studies at the Medical Engineering department of Karolinska hospital and KTH-school of technology and health- [13], [16] that show high error frequency and defective transducers at clinics, also other routines than annual testing is required in order to minimize the frequency of defective transducers and risk of incorrect medical decisions. Therefore it is important to identify pending transducer problems before users notice degradation in image quality and while the transducer can still be cost-effectively repaired or replaced. This thesis will be helpful in clarifying repair/replace decision making.

3 Materials and Methods

In this thesis project since the aim is to study the influence of different severity levels of defects on image quality and standardize an acceptance criterion for ultrasonic probes, images had to be taken with a defective probe and with a well functional from the same type.

Moving forward from idea to conclusions, this project has passed through the following plan:

1- Background study about physics of ultrasound,
2- Familiarize with ultrasound machines and making professional images,
3- Technical tests on transducers and categorizing them to functional and defective. Tests were performed on a total of 115 transducers in 14 clinics at 5 hospitals in Stockholm area,
4- Phantom test: Producing images by selected functional and defective transducers on a 2D as well as a moving phantom,
5- Clinical test: Imaging real patients by using same transducers,
6- Evaluation of images by physicians,
7- Assessment of results and conclusion.

First, find a technical test that only studies probe and its attributes but not in relation to the whole ultrasound system in order to find a defective-functional pair of same probe types.

Second, image tests on a phantom with both probes and look at different ultrasonic parameters (such as axial and lateral resolution) so that the quality discrepancies could be examined.

Next, with the view to finalizing the conclusions and criteria, we would like to test the probe pairs on patients and study the clinical images. Then some clinicians help to evaluate image qualities and comparing the visibility of crucial factors for diagnosis. In this way we take a closer step to realistic results and higher standards to match clinical needs.

3.1 Test Equipment

The system used to test transducers is *FirstCall aPerio*[1], which is shown in Figure 3.1. This system provides data from acoustic and electrical parameters necessary for establishing the operational effectiveness of ultrasound transducers.

Figure 3.1 Sonora FirstCall test system [17]

[1] *Unisyn*, a division of GE Healthcare**,** is a provider for ultrasound probe test & repair solutions: www.unisynmedical.com (Former: Sonora Medical Systems, Inc).

Below, the technical tests and interpretation of the status of the probes under test are described.

Technical test begins with placing each probe into the probe holder and align it to face one of the target plates (Figure3.2) that has the same shape as the transducer. Then by using wheel knobs, position the probe's array at the correct distance[1] from the target and the elements of the array perpendicular to and equidistant from the target. The test is performed in water while *FirstCall* pulses and activates each element within an array. The emitted pulse by each element is reflected by the metal target. This returning pulse is analyzed for different elements characteristics such as Capacitance (pF), sensitivity (volts p-p), Pulse Width (ns), Center Frequency (MHz), Fractional Bandwidth (%) and Pulse Shape.

Figure 3.2 Curved and flat target plates [18]

3.1.1 Data Interpretation

This test reveals information about safety and performance problems across the transducer array.

- The number and location of dead elements,
- Elements with reduced sensitivity,
- Delaminations in acoustic lens,
- Broken wires at connector or element side or along the main cable.

3.1.2 Terms

Sensitivity: Element sensitivity is a measure of the relative response of the individual crystals within the transducer array and is shown as a graph of the returning echo intensity. Sensitivity of a well functional probe is shown in Figure 3.3

1 The correct depth for a selected probe is indicated by the testing program automatically after selecting the probe type.

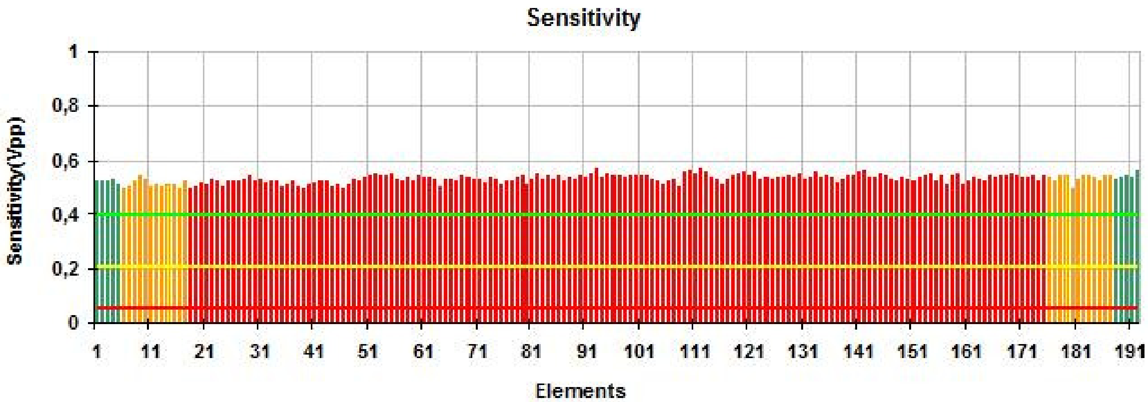

Figure 3.3 Sensitivity of each crystal vs. element number along the probe

There should be only minor variations among the amplitudes of the signals for the individual crystals in an array. Decreased sensitivity of elements can result in degrading image quality as well as lower Doppler sensitivity.

Capacitance: is a measure of the electrical performance of each individual element's circuit. The acoustic array is by nature a capacitor. Each circuit is a complex of the piezoelectric element, cable and connector pin.

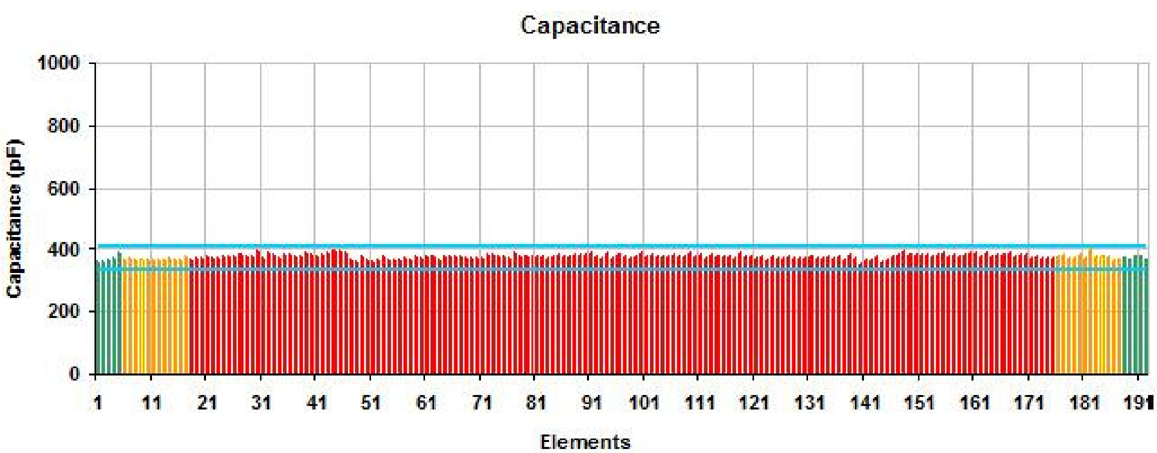

Figure 3.4 Capacitance displayed in pF vs. element number along the probe

The capacitance graph for a probe should be optimally uniform and changes in its value can be used to identify a broken cable, cracked element or connector problem. Figure 3.4 is representing a functional probe.

Pulse width: The length of the returned echo pulse is an indication of the solvency of the acoustic stack bonding. The pulse width is a function of the transducer center frequency and bandwidth. This parameter is shown in Figure3.5 for a well functional probe.

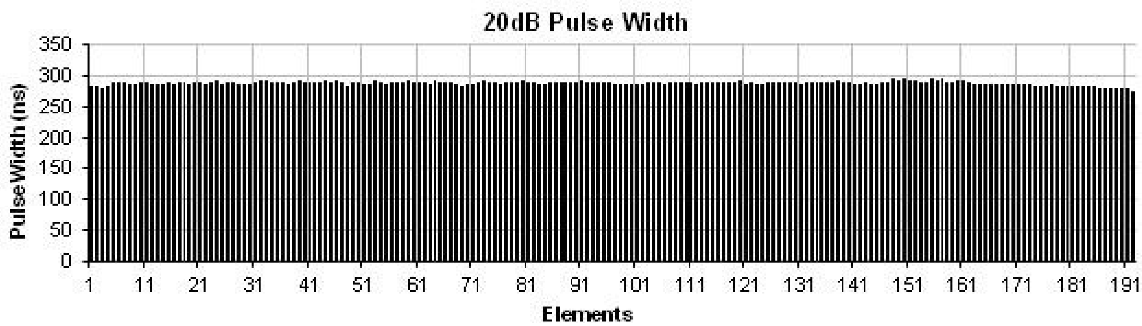

Figure 3.5 Diagram of Pulse Width in mseconds vs. element number along the probe

The pulse width is measured and presented in -20dB, because this important imaging parameter plays a crucial role on the contrast sensitivity of the B-mode image.

Pulse Spectrum: is a graphical image of the magnitude frequency response curve.

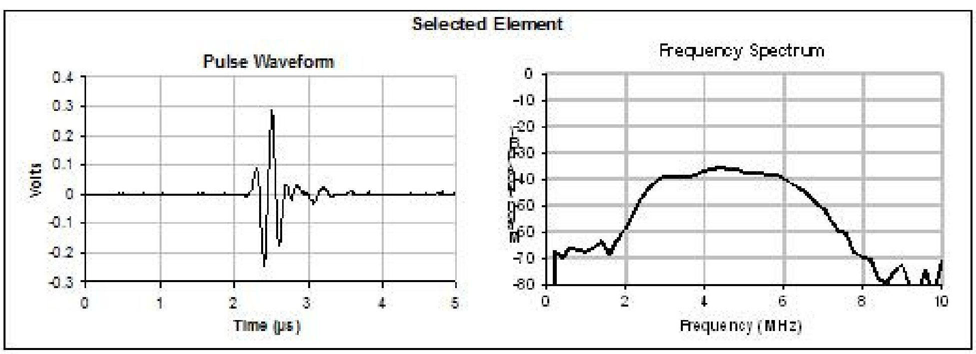

Figure 3.6 Pulse spectrum (right) and Pulse Waveform (left) of a selected single element

Pulse waveform and spectrum (illustrated in Figure 3.6 for a functional probe) are calculated for every single element. In the final FirstCall test report of each transducer, these two parameters are shown for three representative elements.

Center Frequency: is the mid-point of the pulse spectrum. The center frequency is calculated for all the individual elements and is shown for the whole array. Graph should be uniform across the array; as shown in Figure 3.7 for a functional probe.

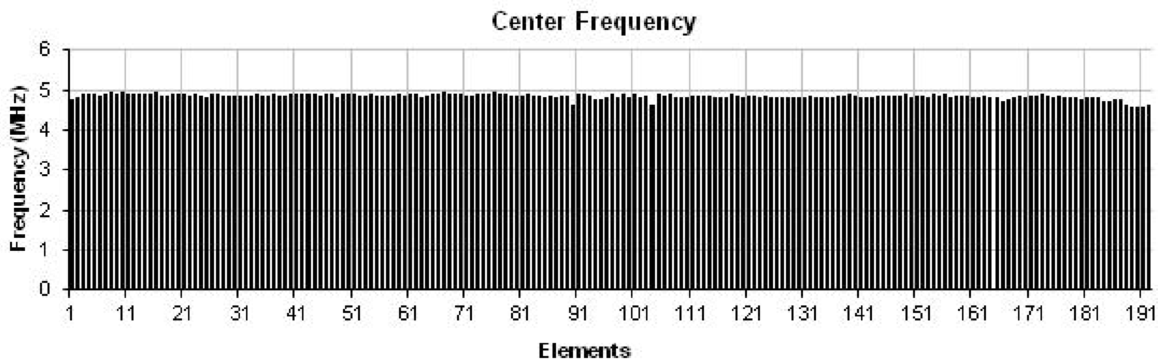

Figure 3.7 Center frequency in MHz vs. element number along the probe

Fractional Bandwidth: is a key parameter for system performance and is related to the overall dynamic range of the ultrasound system. It would not make sense to have an array with a bandwidth that could not be processed by the ultrasound system. This is illustrated in Figure 3.8 and calculated as the ratio of the bandwidth to the center frequency.

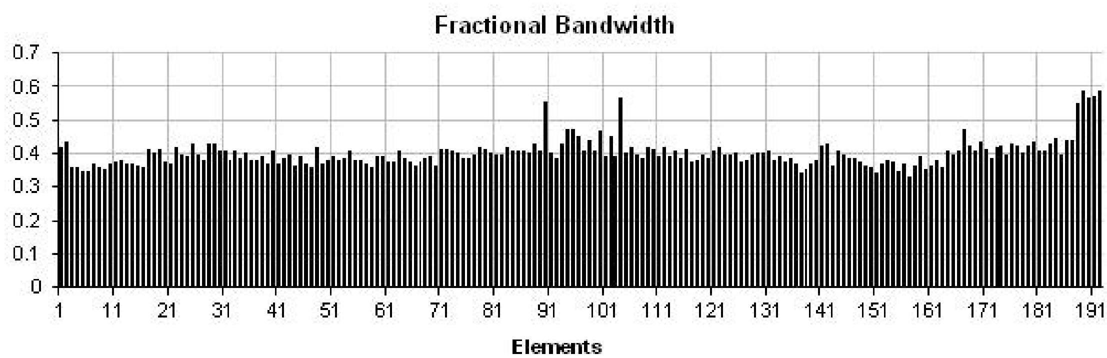

Figure 3.8 Fractional Bandwidth vs. element number along the probe

3.1.3 Definitions of different defect levels

Described below are the definitions and criteria used by the manufacturer[1] of our testing system, in order to estimate a possible required repair.

Functionally Acceptable Element: An element is functionally acceptable if it operates at sensitivities higher than 75% of the mean value of all the sensitivities in the array and there are no successive dead elements and no more than four distant dead elements.

Weak Element: If sensitivity of an element is between 40% and 75% of the mean value of all elements in an array that no successive dead elements and no more than four distant dead elements, this element would be considered as weak.

[1] Sonora Medical Systems, Inc. (www.unisynmedical.com) at the time this thesis was performed.

Dead Element: If an element operates at sensitivities lower than 10% of the highest sensitivity value in the array and there is no delamination of the lens, the element is considered to be dead.

Acceptable Array: An array that has no more than a total of four or two successive weak elements and no more than one dead element.

3.2 Technical Tests

In this thesis we differentiate between problems of transducers and ultrasound systems. Our testing system (Sonora FirstCall) helps us to test only the transducer independent of the whole ultrasound machine. Besides we carried out all the further tests on the same type of transducer either well-functioning or defective on the same ultrasound machine in order to avoid the effect of different systems on the final image quality.

A total of 115 transducers were tested in Radiology, Clinical Physiology, Children Cardiology, Obstetrics and Gynecology clinics at the following hospitals: Karolinska university hospital, Huddinge and Solna, Danderyd, Södersjukhuset, St. Göran. The strategy is to study the effects of different changes in probe arrays on image quality, we should read the probe characteristics mentioned in section 3.1 and find a proper pair of probes. A suitable pair for our test was to find a well-functional probe of a specific model and find a defective one of the exactly same model; in order to compare the results in images. In addition, it is of this projects interest to find criteria to standardize quality assurance tests for ultrasound transducers. Within this project, mostly those probes were searched that are defective, but not destroyed. Those that still can provide an image that seems to be good, but can affect the ability to detect key diagnostic parameters.

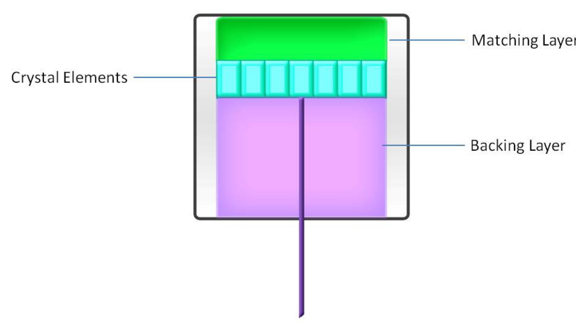

Figure 3.9 Schematic presentation of an ultrasound transducer

3.2.1 Categorizing test transducers

Regarding transducer construction-illustrated in Figure 3.9 dead or weak piezoelectric element, broken cable and short circuit are potential defects that can happen to an ultrasound transducer. Which are going to be described in next part. With reference to the previous studies at the Royal Institute of Technology and Karolinska university hospital, errors originating from the elements are uncommon [13]. Thus the three most frequent error types, considered in this project, are:

Delamination: Occurs when the compound of lens, matching layer, element and backing layer detach from each other; represented in Figure 3.10. This kind of damage leads to a minor reduction to a total die out of the sensitivity signal while the capacitance value is at the correct level. Delamination can result in long term destruction of the array, image drop-out and potential electrical-safety issues.

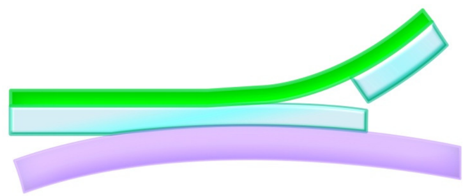

Figure 3.10 Simple presentation of delamination

Break in the cable: The affected element simply represented with the cables to and from the element in Figure 3.11: would have a very low to zero sensitivity and capacitance is lower than normal. If the capacitance is around 50% then the wire is broken around the transducer head. And if connecting wire is broken around the connector pins, capacitance would be around zero.

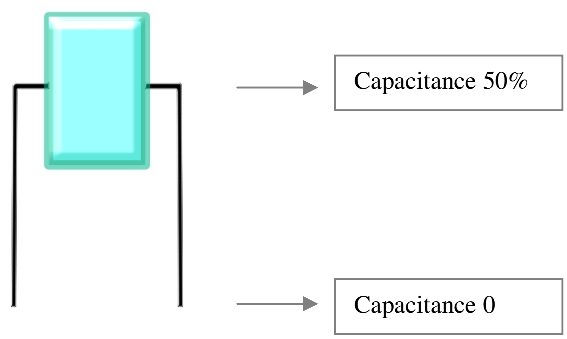

Figure 3.11 Schematic presentation of one single element and its cables

Short circuit: This will result in very low to zero sensitivity signals and a much higher capacitance than others.

In this approach we managed to find four pairs of ultrasound transducers[1] which were helpful for our goal including an acceptable well-functioning probe. Detailed personalities of the defective one is described below.

First pair is a 3V2c that has some delaminated elements in the edges, in the corner to the center and exactly in the center and only one open wire in the center. In this case wire is open at the connector pin. There are 33 delaminated and one open wire of total of 64 elements.

[1] See appendix for complete technical reports for both defective and functional probes.

Second pair is a 4V1c that has its problematic area mostly at the edges and edge-to-center. Broken cable and delamination are major failures. There are 22 elements that have broken cable around the transducer's head (close to elements) and 2 elements that are delaminated out of 112 elements in the array.

Third pair is a L7 which the well-functional one has only one open wire at the connector side and this is in the edge to the center. So we can consider it as an acceptable well-functioning probe. The other one has failures spread over the whole array. At both edges and towards center we notice delamination. In the middle failures are mostly broken cable and short circuit. A number of 72 of a 128-elemnt array are damaged.

And finally the fourth pair is a UST9123 which the acceptable working one has only one broken cable at the connector side and it is located in the edge-to-center area. The other one has been deteriorated because of some broken cables at the probe head which are locating around the middle. Of 128 elements in the array, there are 6 that suffer from damages.

4 Experiments

After testing transducers' quality and finding suitable probe pairs, we continued our project with two experiments which are on phantoms and real patients, in order to find the difference in image quality between the well-functional and defective transducers.

Phantom test includes a two-dimensional phantom and a Doppler one.

4.1 Test with 2D phantom

With this phantom we are able to assess performance of each transducer in 2D imaging mode by estimating spatial properties of the object and comparing the result with the actual properties.

The test phantom[1] used in this project (shown in Figure 4.1) is constructed of Zerdine that accurately simulates the ultrasound characteristics of human soft tissues which is housed in rugged ABS plastic and wire targets are made of nylon monofilaments [19].

Figure 4.1 Test 2D phantom

This phantom is fabricated in a way that some of its properties are controlled and optimal for tissue mimicking aims. Such as:

- The speed of sound is in the range of 1510 to 1700 m/s,
- Attenuation in the 0.05 to 1.5 dB/cm/MHz,

[1] CIRS tissue simulation and phantom technology, model 040GSE

– Scatter or relative contrast between -15 to +15 dB in relation to a scatter baseline equivalent to human liver tissue [19].

Using this phantom we would be able to assess: uniformity, dead zone, depth of penetration, beam profile, vertical and horizontal distances, axial and lateral resolutions and dynamic range. Objects that are built in the phantom helping to measure the above mentioned parameters are shown in Figure 4.2. Each parameter will be imaged and assessed -attain specific information about the phantom properties. By comparing to those specifications stated by the manufacturer, therefore we would get acquainted with how healthy the transducer is.

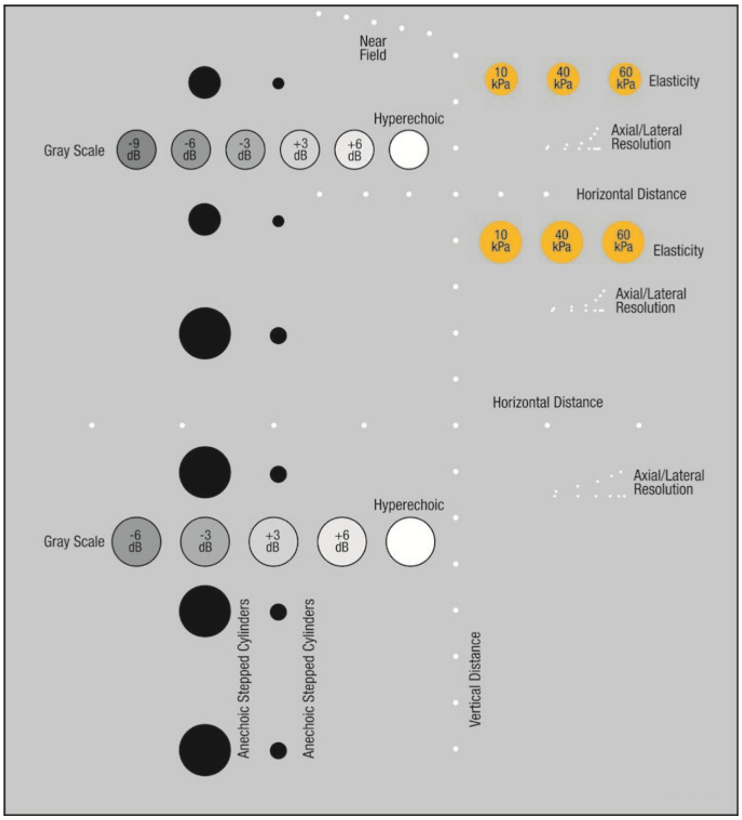

Figure 4.2 Different target groups

Uniformity: is described as machine's ability of displaying echoes of the same depth and magnitude with equal brightness. This is a proper parameter to ensure whether crystals are functioning.

Dead Zone: with this test we assess the distance between transducer's front face and the closest identifiable echo. Dead Zone is the region where no useful information is obtained by the transducer. This can be an indicative of a problem with our transducer.

In this experiment transducers are moved across the width of the phantom in order to assess the effect of a defective transducer as a whole; as well as its damaged and well-behaved parts. By this means we can obtain an image of the two closest targets to the phantom surface (hence closest to the transducer's face) and most probable to be missed by different areas of the transducer and evaluate whether or not it is possible to capture a target with the well-remained part of the transducer while the same target was missed by the faulty part.

Depth of Penetration is used as a means of evaluating the maximum sensitivity depth or visualization. It is defined as the longest distance in a phantom where echo signals from the scatterers within the tissue-mimicking background are still detectable.

Beam Profile: The beam profile is the shape of the ultrasound beam, illustrated in Figure 4.3.

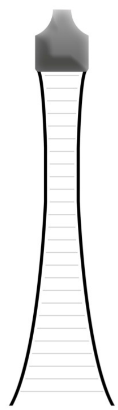

Figure 4.3 A typical beam profile

The narrowest part in the beam profile is indicative of the focal point. Generally, the area around the focal point with about 3dB of maximum intensity is the focal zone.

Horizontal and vertical distance: These measurements are used to determine the accuracy of measurements perpendicular to or along the beam axis.

In this experiment, it is tried to capture different targets at different depths and with different distances to each other. In order to evaluate the effect of each transducer on the horizontal distance with regarding to different parameters: the depth of the studied targets, the length of measured distance, etc.

Axial/Lateral resolutions: With this test group one can measure the distance (in millimeters) between two objects along or perpendicular to the beam axis that are still detected as two distinct objects. Resolution targets pattern is shown in Figure 4.4. By this means it is possible to evaluate the capability of every ultrasound system to resolve objects in close proximity perpendicular or along to the beam axis.

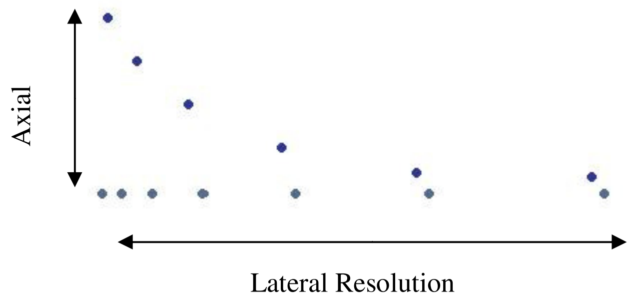

Figure 4.4 Combined Axial/Lateral resolution targets

Dynamic Range: concerns the strongest-to-weakest range of echoes which the ultrasound system is capable of processing and displaying them. Using gray-scale targets having scattering strengths between -9 and +15 dB we can assess the ability of the ultrasound system to distinguish different contrast scales. In other words a degraded dynamic range can be evidence that weaker echoes would be missed by the ultrasound system.

4.2 Doppler test with moving string phantom

With the aim of simulating blood flow we use a moving phantom (Figure 4.5) to be able to evaluate Doppler properties.

Since a moving string phantom can simulate moving blood, choice of the string is important as scattering characteristics of blood need to be matched. The string used in our test phantom is made of synthetic material.

The string is driven in a circuit by a driven wheel. The speed of the drive wheel may be controlled using an external computer and motor to produce waveforms with physiological appearnce. The true velocity of string can be calculated from the rotation velocity of driving wheel.

Figure 4.5 Components of a moving string phantom

Since we use plain tap water to fill the tank, a tissue/water correction factor must always be used. This factor is 1.04 and calculates from a relation between the speed of sound in soft tissues to in water (1540/1480=1.04).

Advantageous features of this used phantom can be mainly mentioned as optional waveforms and flow simulation speeds from 10 to 200cm/sec with 1000points of resolution. These properties enable optimal physiological simulation [20].

This phantom was used at speeds of 0.1, 0.3, 1 and 3 m/sec to evaluate Continuous Wave, Pulsed Wave and Color Doppler properties.

- Continuous wave: By continuously sending and receiving ultrasound waves, shows the changes in pitch of sound waves to provide information about flow (blood flow). The great advantage of CW Doppler is accurate high velocity measurement. Since velocities higher than 1.5m/sec are often seen in heart diseases, this ability of CW Doppler is the key privilege for recognition of the full profile of an abnormal flow and also quantitative evaluation.

Comparing spectra of the functional and defective probe together and their velocities with that of motor will enable us to assess the effect of a defective probe. Using the calipers I measured the velocity out of spectra, converting it to velocity of water, we can follow if there is any difference between measurement errors of both probes.

- Pulsed Wave Doppler: It displays the frequency shifts by alternating between transmission and reception of ultrasound in the same transducer. One of the advantages of PW is that location of the sample volume is under control of users.

Comparing spectra of probes together considering any artifact, delay and sharpness of the profile would allow us to evaluate the impacts of defective and functional probes on the quality of the images.

Generally CW is used when the accurate measurement of flow velocity is required and PW is used to locate the specific area of an abnormal flow.

In every step of this project I have gone through different trials in order to find the most suitable machine adjustments. In other words I have been trying to find adjustments that work best for a specific velocity and starting with defective probe. Finding a set of adjustments that gives the best possible image for the defective one, I have tried the same on functional probe and evaluated how these affect the image of functional probe. Having the same adjustments for both probes makes it easier to compare the results of two probes. If the mentioned adjustment was the most proper for the functional one as well then it is sufficient to evaluate comparisons. Otherwise, I have continued trying different settings on the machine until I found the best image of functional one. Finally there are adequate arguments for evaluation of image quality being affected by the probe itself.

- Color Doppler: By adjusting an specific velocity on the motor of our phantom V, and since the moving phantom is running at an angle θ (in this experiment 60°) relative to the transducer then the velocity that transducer actually is watching is $V_1 = \mathrm{V} \times \cos\theta$. The scale limit on the ultrasound machine display is showing the velocity of flow if it was blood but we are using a water tank therefore we calculate the velocity that the ultrasound could show if it was water V_2 = Scale value / 1.04. Comparing V_1 and V_2 will reveal the defect of a probe.

4.3 Clinical Tests

Our goal is to achieve the most realistic result and evaluate the effect of a defective transducer in real clinical tests. Testing on phantoms guide us on which parameters would be affected of a defective transducer and these are predefined characteristics that we actually compare the measured parameter with the one that is known. But while examining patients in a clinic physicians do not have any sharply defined parameters to compare. A physician can look after abnormalities in function and anatomy of the examined area. The image that they look at might seem normal but is missing crucial information due to a poor transducer or in reverse can be normal but displayed as a malfunction or abnormality. Testing transducers in real cases will establish our theory about having standard criteria for quality test.

In order to know how quality of images and diagnoses would change we continued our experiments by clinical tests on real patients. This part of our tests included twelve patients for 3V2c, twelve other patients for 4V1c and four with the UST9123; while the same examiner using same machine performed the experiments for us. For each probe type the same Medical Laboratory Technologist has examined every patient with both probes by the same machine, once examining with the well functional probe and once with the defective one. By this means we could eliminate the effect of subjectivity of both examiner and image processing properties of ultrasound machines. At last, we performed a blind test on two experienced cardiologists and two gynecologists. For every patient they got a series of images which was a mix of results from defective and functional one. They had to judge quality of those random images for their diagnostic and explain why.

In case of those two probes 3V2c and 4V1c that are mostly used in cardiac examinations, clinical tests include three parts: (1) a continuous wave on Aorta in order to find out the velocity of blood flow, (2) a pulsed wave on Mitral valve to look at function of Mitral and how it closes/opens, (3) color Doppler to check if blood retrogrades.

5 Results

5.1 Two-Dimensional results, 2D phantom

5.1.1 2D results of 4V1c

Dead zone: the defective probe gives a larger dead-zone meaning we miss one of the point targets. Besides it shows more blurry dots while in the functional one we are able to see more bright and sharp dots.

Resolution:

For 3cm deep: The axial and lateral resolutions are quantitatively the same but with functional probe one can get a better general perception of the images. Two objects that are resolved of each other have the same distance as the objects in the defective case. But because of better perception of general quality of the image (such as sharpness of targets), it is much easier to distinguish them and define the resolution in the functional probe. Furthermore one of the point objects is not shown in the original form, by defective probe.

6.5cm deep: With the same adjustments, axial and lateral resolutions are two times better in case of functional probe. It means the distance between two distinguishable targets by functional probe was 2 times shorter than those were distinguishable by defective one. In the image made by the defective probe some shades were present between resolution targets. Although it was possible to imagine resolution targets separately and assess the lateral resolution but those shades or doubling in the image made it more difficult to determine.

In addition, we were able to get a better lateral resolution for the functional probe by changing the imaging adjustments on the machine which was not possible for the defective one.

10.5cm deep: Axial resolution is the same in both cases.

Lateral resolution is better about 1.5 to 2 times better in case of functional probe. In other words, those two targets that are clearly distinguishable by functional probe are two times closer to each other than those by the defective one.

In some cases we have numerically the same resolutions for both defective and functional probe. But thanks to better image characteristics such as sharper borders, less shade, brighter targets, etc; it has been much easier to find targets and distinguish between two. Either we could get an even better quality by adjusting the imaging parameters. This is of crucial importance for a clinician to be able to attain better quality or an easier experience.

Depth of Penetration:

Although in case if functional probe we have shorter depth-of-penetration but it is more even spread and through the whole width of phantom we have quite the same depth.

But in defective images we have a deeper penetration exactly in the middle of the phantom but corners and center differ a lot. There is a shorter penetration in the edges which means loss of information comparing to the other one.

Beam Profile, Focal Zone, Lateral Response Widths:

With the functional probe we are able to get more sharp images and by changing the adjustments and repeating the experiment procedure for different focal zones it's possible to discern a deeper focal zone.

Vertical and Horizontal Distance:

Considering Vertical distance, the functional probe shows perfect results for smaller distances when measuring adjacent targets with the error between 0 to 0.5%. But the defective probe has larger error showing the closer targets while seems to have a trend to show a better result for larger distances.

In Horizontal cases, for targets at 4cm functional probe gives 3 times smaller errors in showing close targets but defective one gives better result measuring the largest distance (distance between first and last target) and it probably is because of gain loss that makes it easier to locate the caliper at a more precise location.

For targets at 9cm depth, the functional probe is perfect at showing distances between targets. A variety of distances between targets is measured with an error rate between 0% and 1%, while the defective one has approximately triple the errors. Besides it is not possible to detect the first and last target. One can only guess if there could be such targets at those two places knowing the phantom and its properties. Otherwise if you were experimenting on an unknown phantom you were not able to recognize these two targets, this makes a mistake in the measurements.

Dynamic Range:

For both categories of grays scale targets at different depths, the performance of the defective probe is inferior to that of functional one. If measuring the height and width of every target, it shows larger errors than the functional one. Specifically in the case of 11cm-deep targets, those with higher contrasts are seriously affected by the defective probe which shows them as a crescent like target and with shadows.

5.1.2 2D results of 3V2c

Dead Zone:

Dead zone for the defective probe is much bigger which results in missing information in our images. The functional probe can easily and clearly show all five near-filed targets while the defective one fails to show two of them. In some steps of the experiment when the transducer was moved and the second uppermost target happened to locate in the well-remained part of the transducer then it was detectable. But it was drawn into a white shadow that if the examiner did not know the properties of the phantom, you would not be able to recognize this target.

Resolution:

At 3cm deep: Lateral resolution is two to three times better than the defective one but axial resolution does not differ so much. Quantitatively are the same but in functional case it is more convenient to detect it.

At 6,5cm deep: Lateral resolution is quantitatively the same for both but defective probe displays another type of weakness. It results in images that the distance between A_1 - A_2 (4mm) seems to be shorter than A_3 - A_4 (2mm) that proves a faulty transducer which can be harmful if used to measure and diagnose critical parameters such as cardiac ones!

Axial resolution is much (about two times) better than that of the defective one.

At the 10,5cm deep: Both lateral and axial resolutions in this case are obviously –approximately two times- better than what we get from the defective transducer.

Besides, the image from the defective one is very difficult to assess for the resolution since the targets in this case are either merged together or look really like the background noise that makes it very difficult to distinguish them and evaluate the resolution.

Depth of Penetration:

Functional probe presents a greater depth of visualization or sensitivity. Depending on which point in on the phantom we are looking at, functional probe detects the backscatter echoes 1- to 4% deeper in the phantom.

Beam Profile, Focal Zone, Lateral Response Width:

The images resulted by the defective probe are blurred in a way that makes it difficult to discern the targets (and their horizontal length to be measured) leading to an unclear beam profile.

Vertical and Horizontal distances:

Functional probe is much better at showing correct results when measuring smaller distances (e.g. adjacent targets).

For both categories of horizontal distance targets at different depths, functional probe have a distinct advantage over the defective one because of a much higher quality of results. In other words it shows and measures with much less error than defective one does.

5.2 Doppler results, moving string phantom

As we described before, these experiments were performed at different speeds of the moving phantom in order to be able to study the consequences of using a defective probe on different possible blood velocities.

5.2.1 Doppler results of 4V1c

Color Doppler

In lower velocities, the defective probe is not able to thoroughly show velocities in both directions. Artifacts are a part of all results from a defective probe. Artifacts, noise and missing velocity information in one direction are obvious outcomes of defective probe. In some cases these differences are so distinct that even non-professional eyes can distinguish between the sharper images displaying more information and the images destroyed by the artifacts. However all these faulty information in the image are detectable because we can predict how a normal good image should look like if we test our phantom with a functional system. Otherwise these noises or artifacts in the outcome could mislead any tester to recognize a flow that does not exist or ignore flows that really exist.

CW – 4V1c

By comparing and evaluating spectrum characteristics of the images, some differences are perceptible between results of functional and defective probes. Wider, sharper and brighter spectra belong to the functional probe while the defective probe gives thinner spectrum that are blurred and hence very difficult to distinguish the main spectrum out of background noise. In some cases defective probe results in less background noise which I will discuss about it in the conclusion part.

Furthermore, the quantitative comparison of the measured velocities demonstrates an approximately 3 times larger error in case of defective probe.

PW – 4V1c

A defect that appears to be often at any tested velocity by the defective probe is an uneven spectrum with peaks at different heights and different brightness.

In some cases the result has more noise and artifacts for the defective probe with the same adjustments.

5.2.2 Doppler results of 3V2c

Color Doppler

Using the defective probe shows obvious deterioration in the image quality, suffering from extra faulty colored pixels of a noisy character will deceive the tester that there are some flows that they are not in fact existing. In these cases results of two probes are quite distinct in quality because images by functional probe have no noise and clearly can be interpreted. Or in few cases it is not able to display a flow that in fact exists and therefore loosing information.

In some other cases we see another type of difference that the signal-to-noise ratio is higher with the functional probe, where images by the defective probe show larger areas of disturbed information or no separate blue and red area, e.g. blue and red are so mixed together that one is not able to distinguish between where red and blue information. There are so much of blue in red and vice versa.

Another difference between results is quantifiably larger error in displaying velocity by defective probe. Using the method described below and the same adjustments in machine will lead to less calculated error for outcome of the functional probe.

Difference between a bad and good probe is more obvious at very low or very high velocities.

CW – 3V2c

Using the calipers we measured the velocity out of spectra, converting it to velocity of water, we can follow a great difference between measurement errors of both probes. Defective probe shows three to four times greater errors in velocity measurement. Beside the quantitative comparison, one can only compare the profiles which prove these contrasts: sharpness, noise and thickness of spectra are affected by the probe. The functional probe display a thicker spectrum which means that another spectrum is missing some information of velocities or frequencies. The better spectra are sharper and have less noise which makes it easier to assess any profile. Furthermore it is possible to change some adjustments and get even better results for the functional probe but all the comparisons were done for machine adjustments that could show a relatively good image of the defective probe.

PW – 3V2c

An obvious difference between the results is that the functional probe gives a sharper spectrum while the defective one has a spectrum with more noise and artifacts which make it difficult to determine the main spectrum. Furthermore in some cases, spectrum peaks are not in the same height as each other.

5.3 Clinical Results

Tables below show the evaluation results of two physicians on patients for every probe type. Both physicians were asked to choose the images that they think has the best and worst quality for their diagnostic purposes. Then I have counted number of cases that the images evaluated to be best were actually from the functional probe, accounting for *Best Image* column. Then percentage of *Best Image* to the total number of cases was calculated. In the same way, column *Worst Image* is the percentage of cases were the image evaluated to be most improper one is actually from the defective probe. Every column bar represents the average for two physicians and percentage of evaluated matching the

5.3.1 Clinical results of 4V1c

The following chart in Figure 5.1 demonstrates the evaluation results of two physicians on twelve patients whom were studied by 4V1c probe.

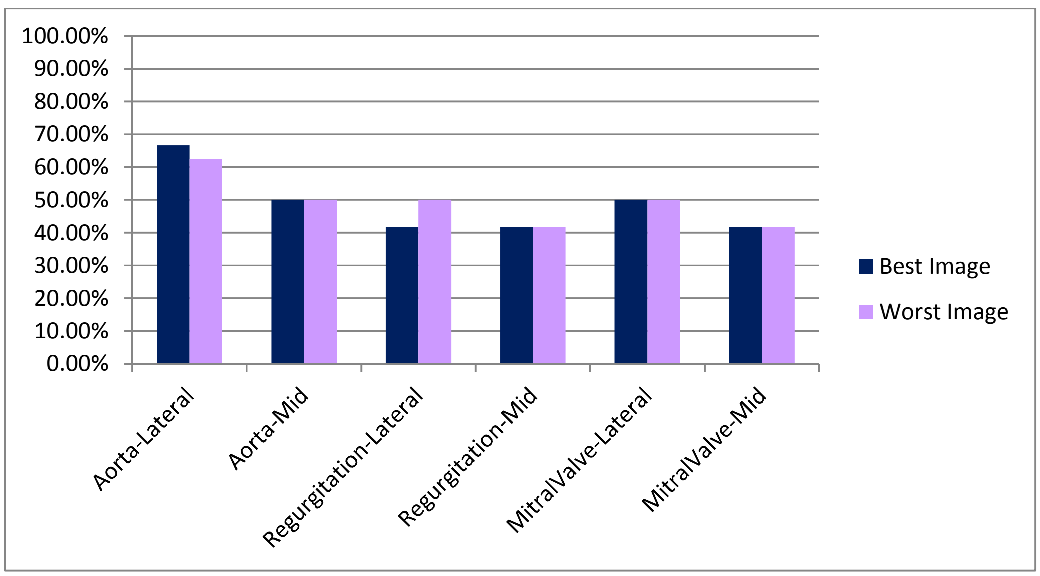

Figure 5.1 Evaluation results of clinical test, 4V1c

In at least 40% of the cases the evaluated image to be most suitable for diagnostic purposes have been taken by functional probe and the evaluated poor images are results of a defective probe.

In every part of experiment there have been some patients that in their specific case, the images that are evaluated to be of good or bad quality are not actually from the correlated probe.

5.3.2 Clinical results of 3V2c

Evaluation results of two physicians on twelve patients whom were studied by 3V2c probe is charted in Figure 5.2.

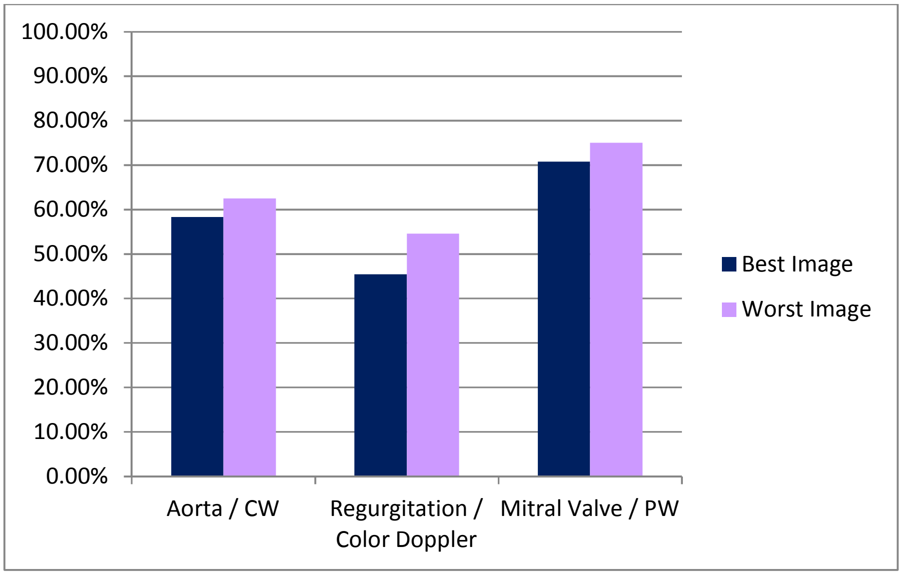

Figure 5.2 Evaluation results of clinical test, 3V2c

In first test that was examining blood velocity in Aorta by CW, there are same three patients who in their case both physicians have not evaluated the best and worst images as they were from the relative probe. Similarly it was one patient in PW test and four patients for color Doppler test.

5.3.3 Clinical results of L7

This chart represents assessment results of two physicians on only one patient. Although it is a single test; it is important in this study to show how different probe types get affected by common defects.

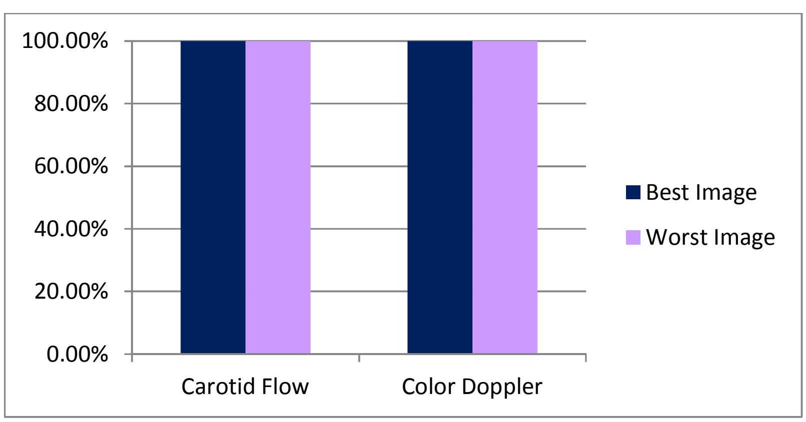

Figure 5.3 Evaluation results of clinical test, L7

5.3.4 Clinical results of UST9123

This chart shows average percentage of evaluation results of two gynecologists on 4 patient cases, examining the fetus.

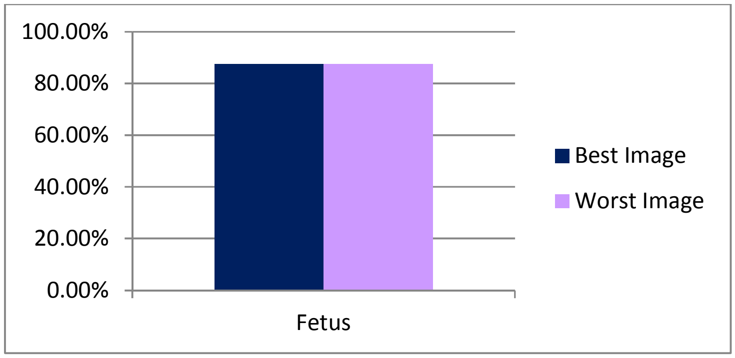

Figure 5.4 Evaluation results of clinical test, UST9123

6 Discussion

6.1 Limitations of this work

During experiments and thereafter collecting the results, this project got in to some difficulties such as:

- Defective-functional pairs of the same transducer type: Since most of the clinics have high quality awareness and had used the test system for routine maintenance, it was difficult to find both functional and defective of the same probe type. In some cases the discovered defective one was destroyed and thus not in this project's interest.
- Available ultrasound machines and probes: Since experiments and testing probes were performed on the machines that they were actually used of clinics in everyday examinations, the project had to adjust the time to clinics. There were many days that was not possible to get hold of machines to do the tests. Therefore it took longer time to gather all the test information, both for technical tests on probes and then phantom tests.
- Converting image format: In some cases there were no recording possibilities and I had to photograph the display. Also, working with the Aloka machine needed some special programs to convert image format which were either very expensive to buy or had left watermarks on the images[1].
- Biomedical Analyst dependant: Clinical tests had been done by one biomedical analyst, have pros and cons. It limits the test quality to one examiner and his/her experience and carefulness. On the other hand it is a great advantage having the same BMA[2] do the tests, because this project was only studying effect of transducer quality. It makes it less objective to not involve more people in the image gathering steps
- Not finding evaluators at first: After gathering images for clinical tests, assessment of real clinical tests required some physicians to evaluate the results and give their opinion but it took a long time to find one willing to collaborate, which caused a major delay to project schedule.
- Few evaluators: Having only two physicians eager to collaborate can be a liability to the clinical results; due to tiredness, different levels of carefulness and other subjective parameters.

6.2 Discussion of results

Considering phantom tests we usually see a pattern:

In case of quantitatively measured parameters e.g. resolution, the quality of images from the functional probe is between two to four times better than that of defective one. In some cases quantitative results are the same for both defective and functional probe. But thanks to the higher entire quality of the image (e.g. sharper borders, less shade, brighter targets, etc) it has been much easier to find targets and distinguish between two.

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[1] Power Dicom, Show Case, ADViewEZ, Image Converter Plus
[2] BMA : Biomedical Analysist

Even better quality could have achieved for the functional one by adjusting the imaging parameters. As it is described earlier, different adjustments are tested until have found the one that produces the optimal result for defective one. In some cases functional probe images are already better than defective one and by adjusting machine settings we can get even higher quality.

I would like to focus on the great advantage of phantom tests. Since results can be predicted in advance and we can compare the actual results of a defective probe with what was expected. But a physician examining physiological parameters of different patients that they are suspected for having a disease can miss some information or can be deceived to interpret something that actually does not exist.

Clinical tests are done in a way that the BMA working with defective probe have changed the probe position, gain, other settings, pressing probe toward the body, until he get the optimal result for just that probe. For tests with functional probe, one might have other adjustments like hand force towards the body. In contrary to phantom tests, where we have kept the adjustments the same and compared how good or bad is the result.

Out of clinical tests and evaluations:

The functional probe is linked to superior quality of spectra, better signals, able to show higher velocities (in case of CW), better color signal and showing well insufficiencies or deteriorations (in case of Color Doppler).

The defective probe is related to less noise which can be a result of gain loss.

Images that are labeled by the evaluators to be good are in at least 45% from the functional 3V2c probe. And those that were assessed as worst are in lowest 55% from the defective probe which had deficiencies at the edges and center. Different tests show respectively PW, CW and color Doppler to have higher percentage of evaluated images to be from the relative probe. An explanation can be phased array type of this probe that in some degrees compensates for the small local defects. The other reason might be because of the defect spread in both the middle and edges of the probe, the difference between defective and functional images are more distinct.

And for 4V1c, in at least 40% of the cases the evaluated image to be good was actually from the functional probe and the same for the evaluated results to be bad. Here CW, PW and Color Doppler have got respectively higher evaluation results, while in every test type the lateral view has higher percentage of evaluated images to be from the relative probe.

Again the phased array type of the probe can have effects on the results and since in this case the edges of the probe were defect, less difference is detectable between images resulted of defective and functional probes. Furthermore, a direct impact of defects location on the results is noticed. Because in every repeated test for 4V1c, the difference between a good and bad quality is 10% more recognizable in lateral views than that of middle views.

Considering clinical results of both phased-array probes (4V1c and 3V2c), the change in evaluation results of CW and PW is discussable. In a case like our defective 3V2c that has defects over the whole array, PW (result of a user selected sample volume) might have been selected in an area including more number of better elements than the defective ones. On the other hand CW is result of everything along the ultrasound beam and most cases the probe is located in a way that the flow to be measured is located in the middle and since the middle of our 3V2c probe was defective the CW in this case has lower results than PW of the same probe and CW of 4V1c. Besides, the CW has got better results than PW for the same probe (4V1c) because it is the result of everything along the ultrasound beam and has gathered more information to show to the evaluators. Thus the difference can be differentiated more easily.

In all test cases, probe L7 have been related to defective probe for having low quality images and vice versa for the functional one.

L7 is a linear probe and in this project the defect was spread along the array. Which the 100% good image to functional probe and bad image to defective probe is a clear result of it.

In UST9123 probe tests, evaluators have assessed the good images for having better resolution. In 87% of the cases the good image and functional probe are correlated to each other and the same percentage for defective one.

Here a multi-frequency Convex probe that has some defects in the middle has resulted in 87% of correct relating of good image to functional probe and vice versa.

In some cases, defective transducer can still generate images where the main structures of the heart are visible. This makes the evaluation of clinical experiments tricky. Physicians can be deceived that there is an abnormality (where in reality is not) or will not be able to suspect an abnormality (where it really exist but missed of transducer).

In 2D phantom, where the resolution of images by defective probe is better at smaller or deeper targets, is due to loss of gain, Which in its turn because in that area of the transducer there is an open wire, or lower sensitivity, etc.

The difference between the good and bad probe in the pulsed-phantom is some artifacts and the sharpness of the spectra.

If there is not a significant difference in image quality of a functional and defective transducer it would be visible with the change of depth and angle.

7 Conclusion and Future Works

Higher quality and easier interpretation of information in ultrasound images are of crucial importance for a clinician to be able to make an accurate diagnosis.

Drawing this conclusion that evaluation of physicians is strongly dependant on transducer type, location and extent of defects; also considering that if a physician uncertainly examining a patient (e.g. looking whether there is any malfunction or abnormality in physiological parameters) then s/he might have missed a target, the following improvements are recommended in the potential future works:

* More different transducer types to be tested,
* Transducers with variable degree of faults that even a tiny defect in a key location along the array can be studied,
* Using an advanced adapter in order to make different types and grades of deficiencies in transducer elements,
* The Biomedical Analyst who performs clinical test and gather information would be well-experienced,
* More number of evaluators and with different degrees of experience so that we get more reliable statistical evidence.

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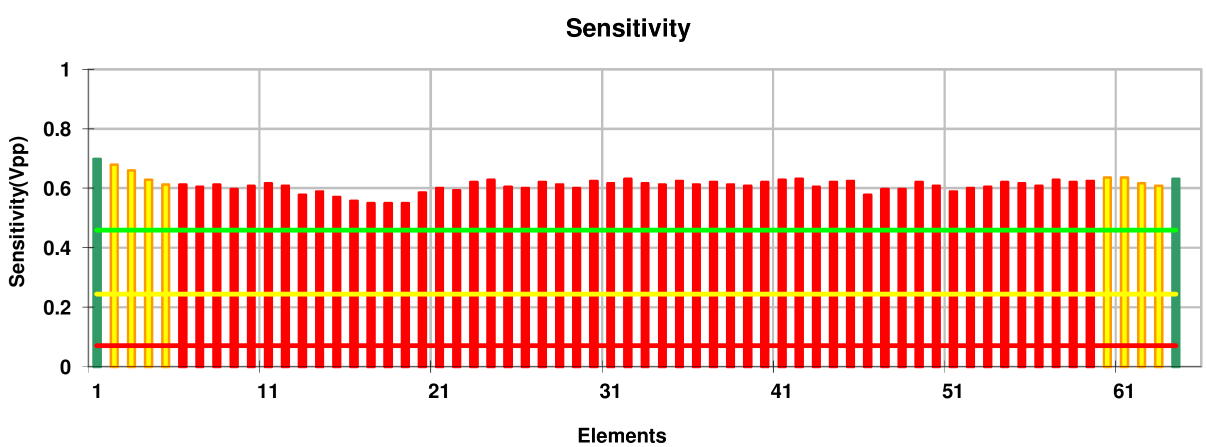
Appendices

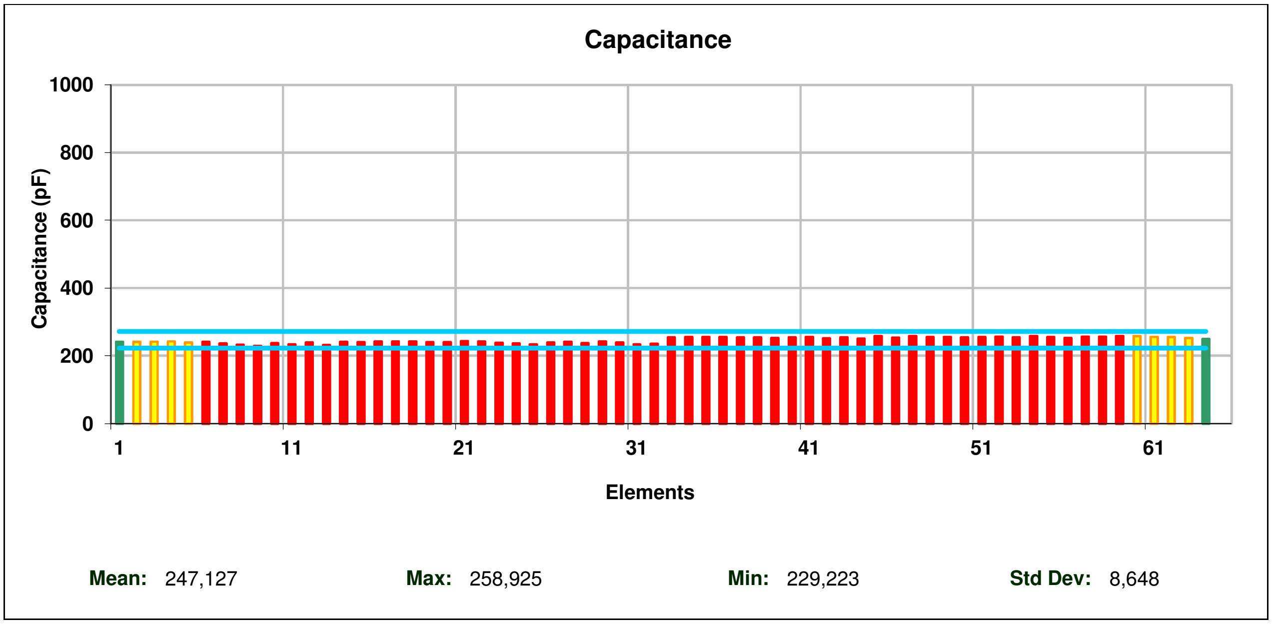
Appendix A – Test report – 3V2C - Functional

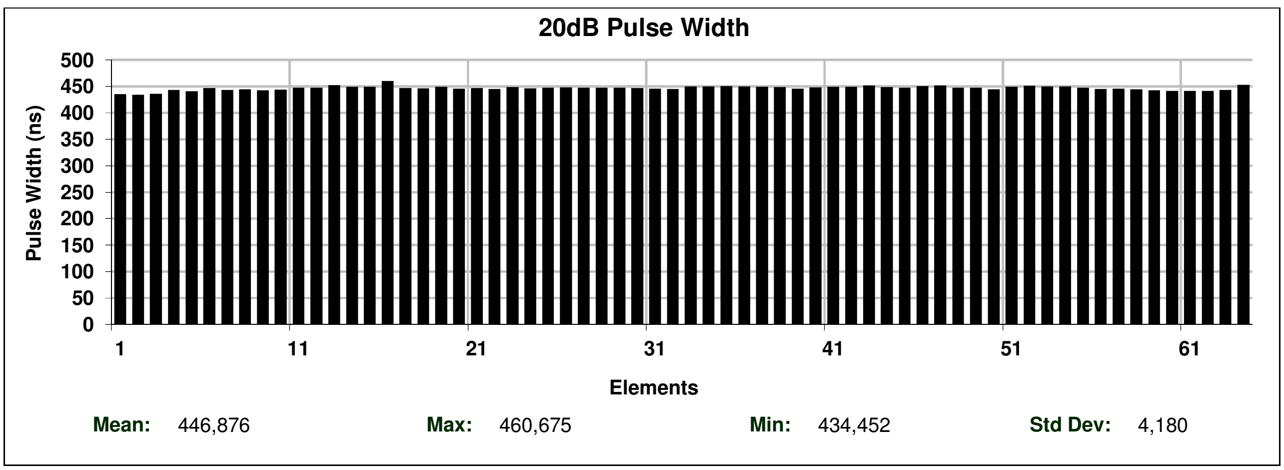
Transducer Evaluation Report

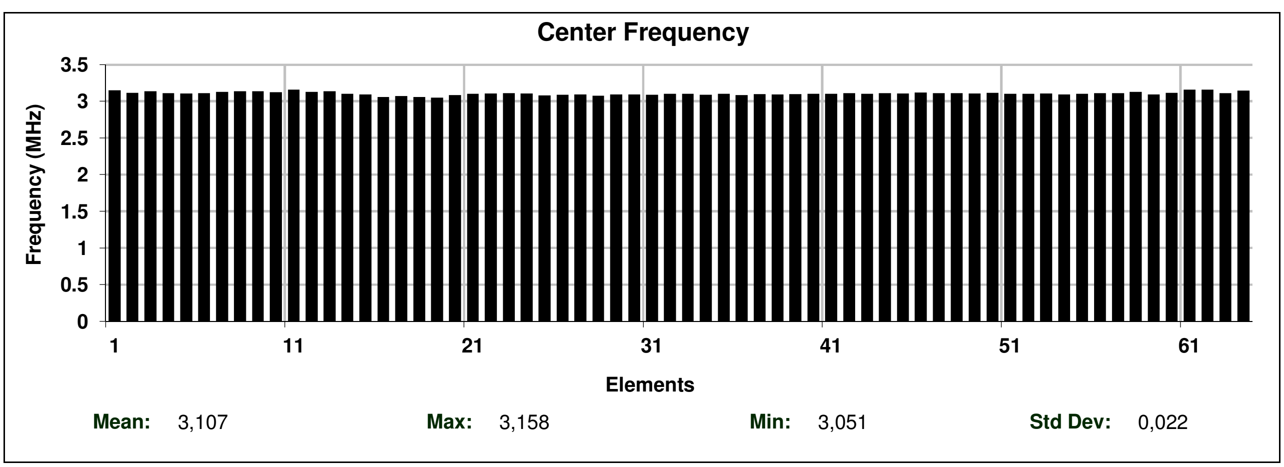
Manufacturer:	Acuson	**Customer:**	Customer			**Contact:**	Contact
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**		**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					

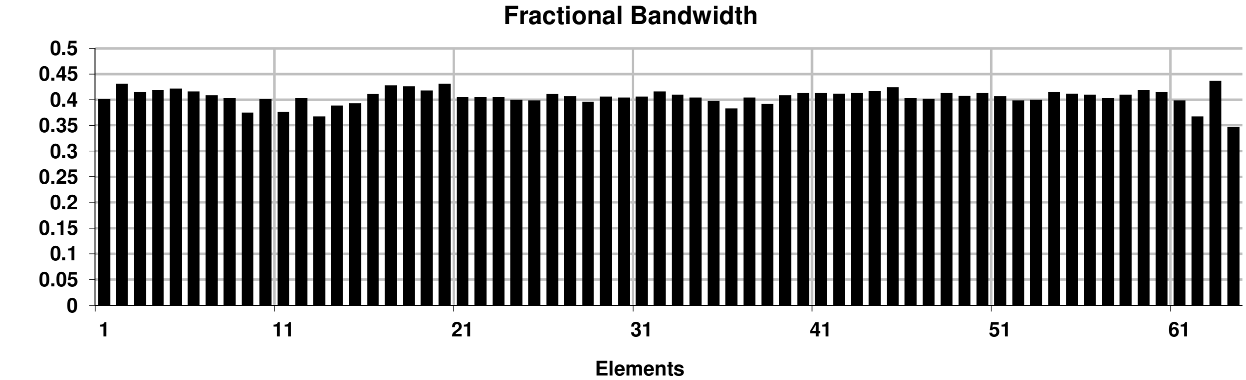


Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB


Capacitance
Capacitance (pF)
1000
800
600
400
200
0
1
11
21
31
41
51
61
Elements
Mean: 247,127
Max: 258,925
Min: 229,223
Std Dev: 8,648

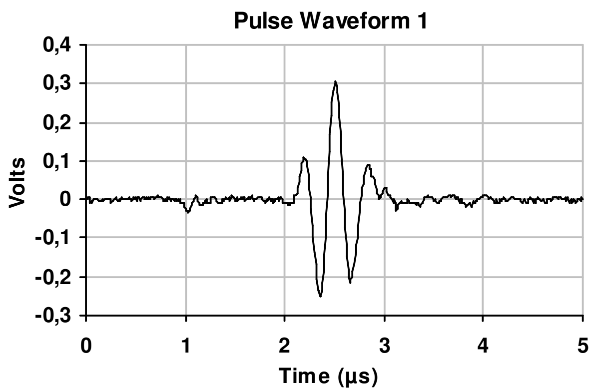

20dB Pulse Width
Pulse Width (ns)
500
450
400
350
300
250
200
150
100
50
0
1
11
21
31
41
51
61
Elements
Mean: 446,876
Max: 460,675
Min: 434,452
Std Dev: 4,180

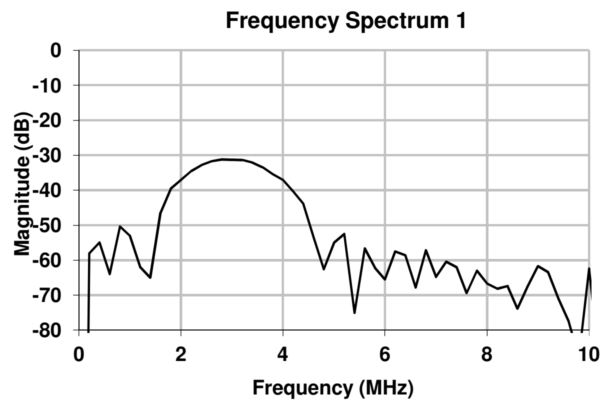

Center Frequency
Frequency (MHz)
3.5
3
2.5
2
1.5
1
0.5
0
1
11
21
31
41
51
61
Elements
Mean: 3,107
Max: 3,158
Min: 3,051
Std Dev: 0,022



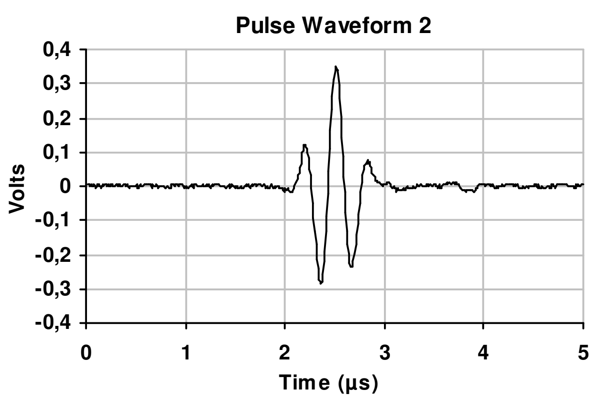
Mean: 0,406 **Max:** 0,437 **Min:** 0,347 **Std Dev:** 0,015

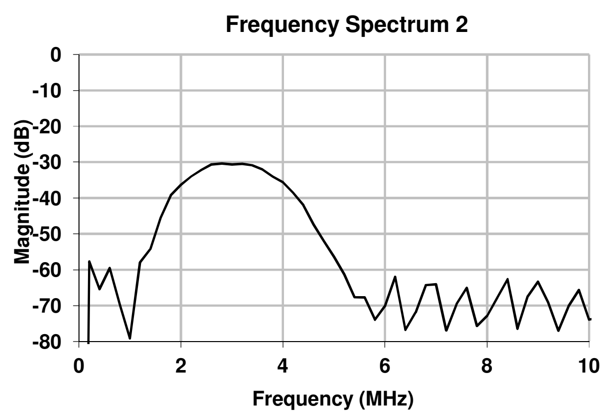
First Selected Element: 16



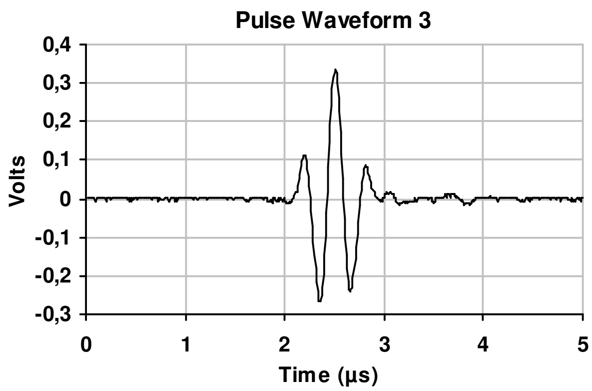


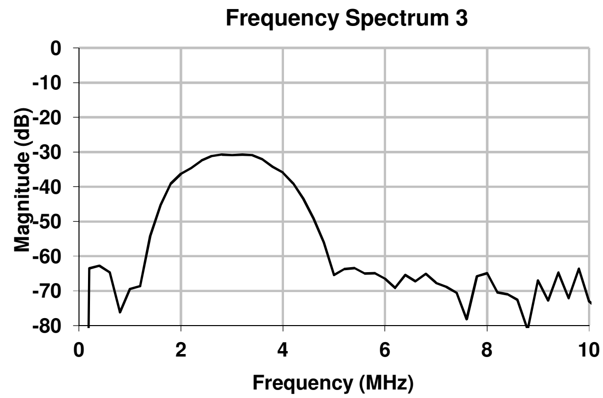
Middle Selected Element: 32





Last Selected Element: 48

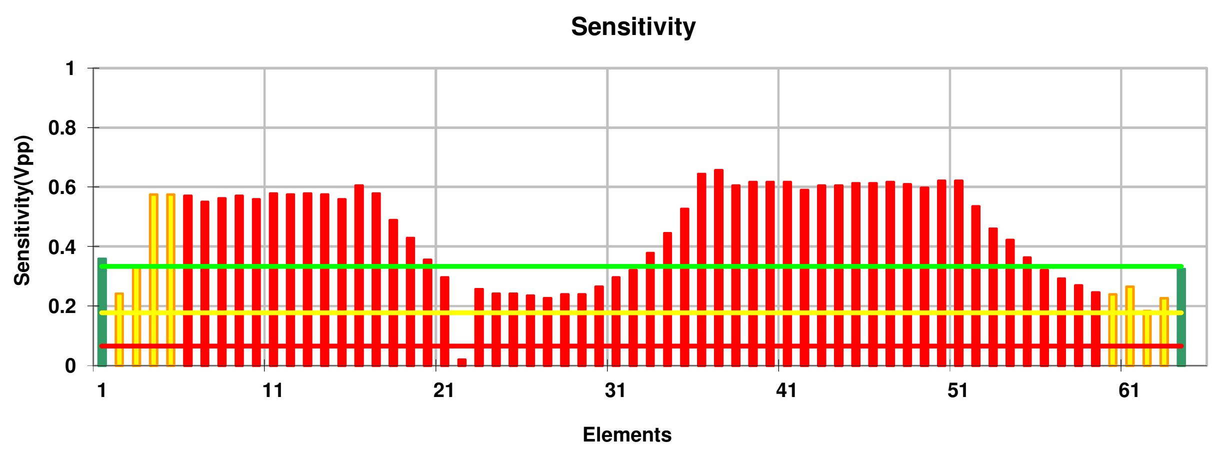

Pulse Waveform 3
Volts
Time (µs)
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
0
1
2
3
4
5


Frequency Spectrum 3
Magnitude (dB)
Frequency (MHz)
0
-10
-20
-30
-40
-50
-60
-70
-80
0
2
4
6
8
10

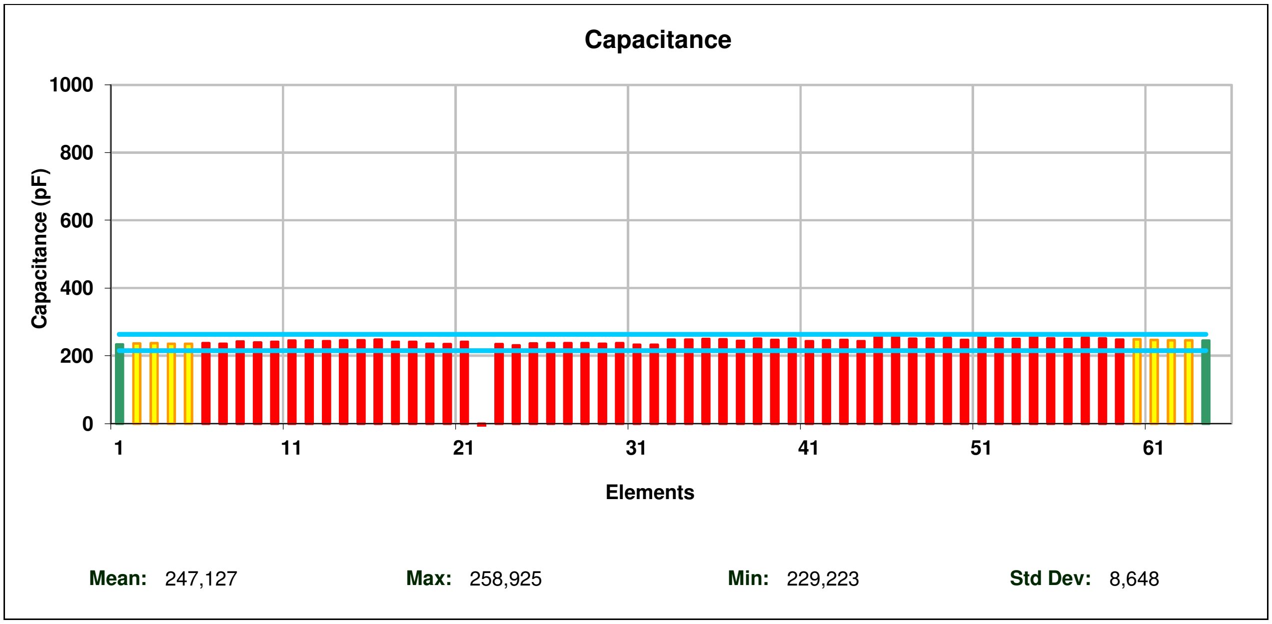
Appendix B – Test report – 3V2C – Defective

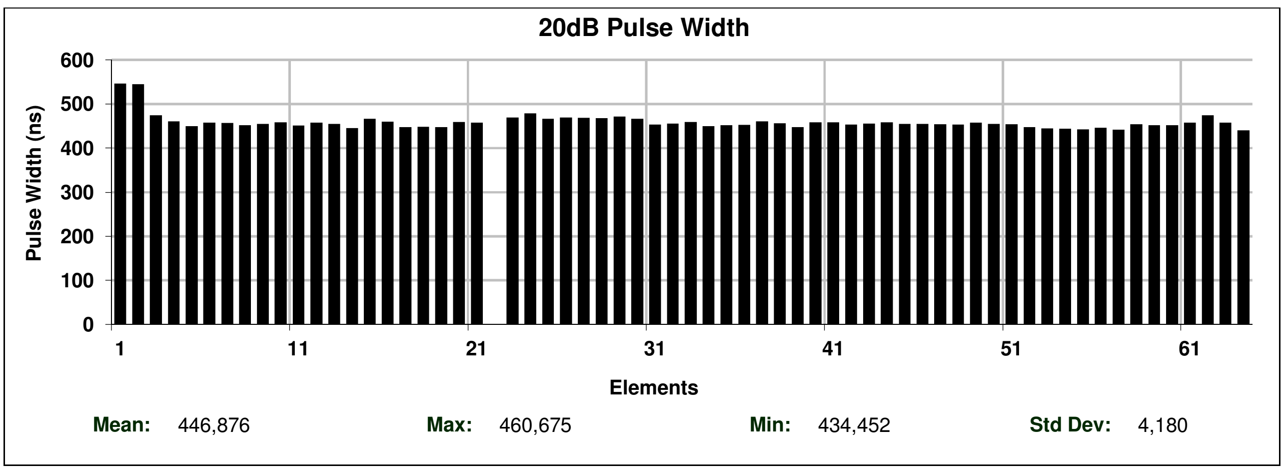
Transducer Evaluation Report

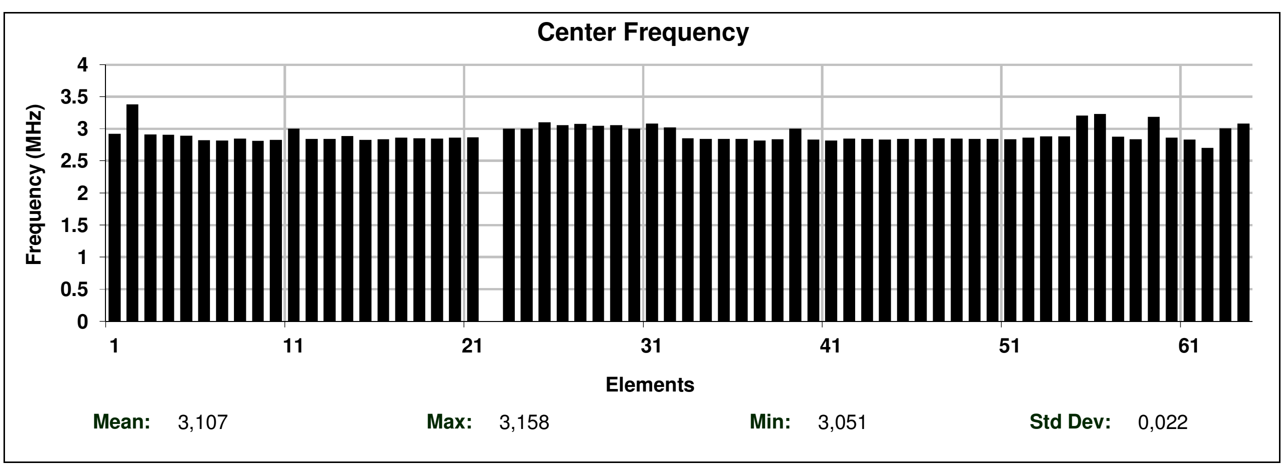
Manufacturer:	Acuson	**Customer:**	Customer			**Contact:**	Contact
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**		**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					

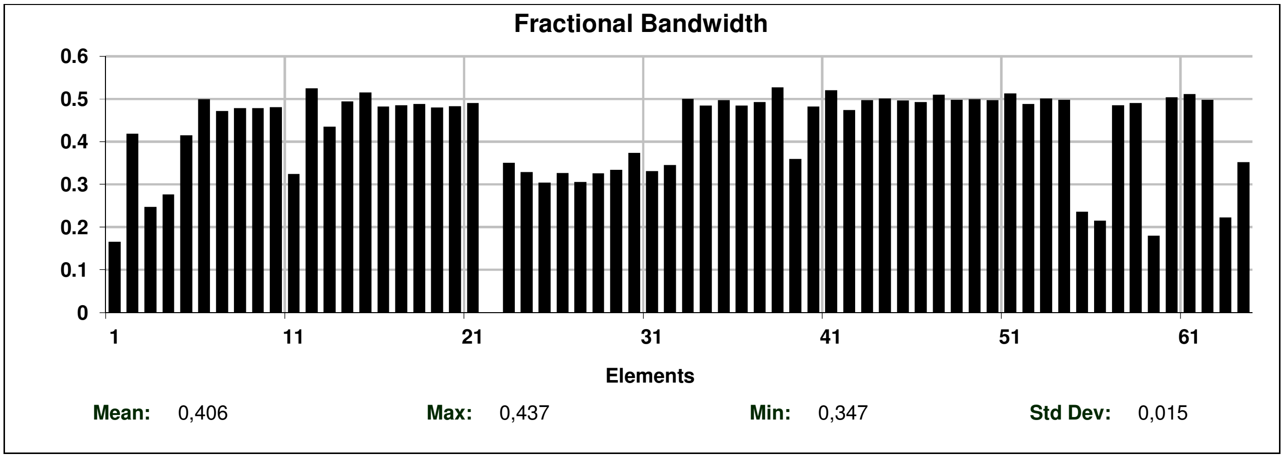


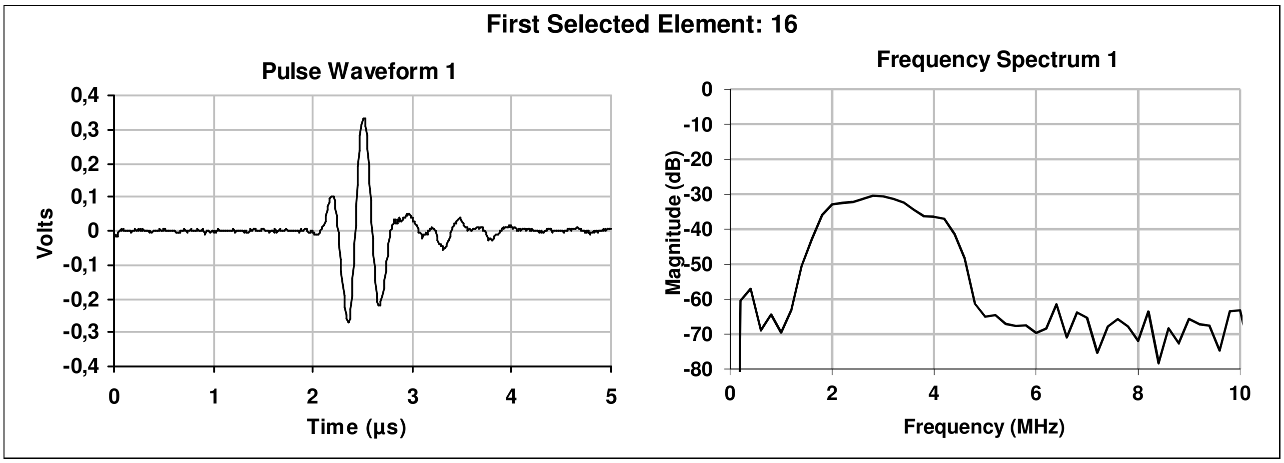
Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB

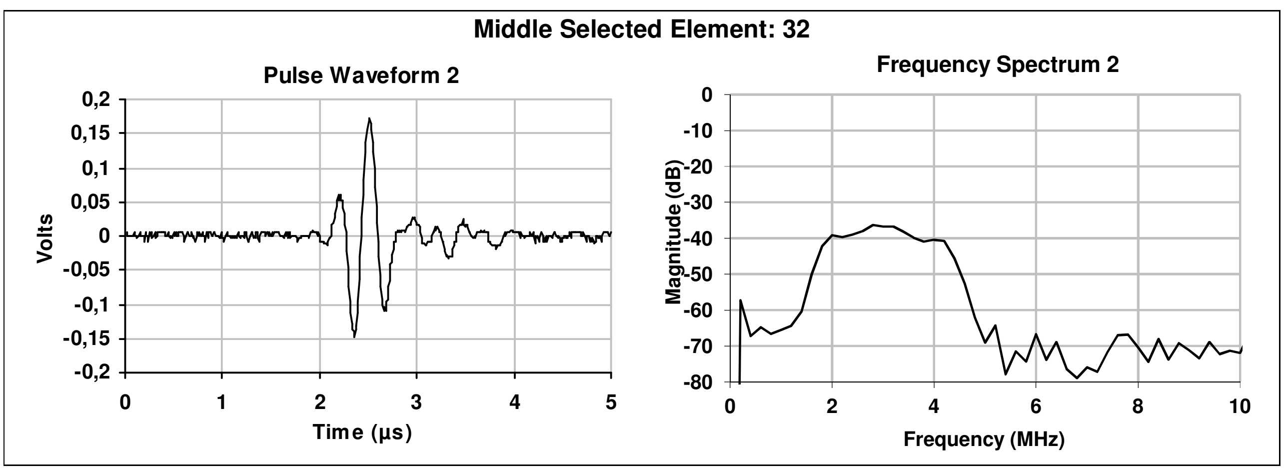

Capacitance
Capacitance (pF)
1000
800
600
400
200
0
1
11
21
31
41
51
61
Elements
Mean: 247,127
Max: 258,925
Min: 229,223
Std Dev: 8,648


20dB Pulse Width
Pulse Width (ns)
600
500
400
300
200
100
0
1
11
21
31
41
51
61
Elements
Mean: 446,876
Max: 460,675
Min: 434,452
Std Dev: 4,180

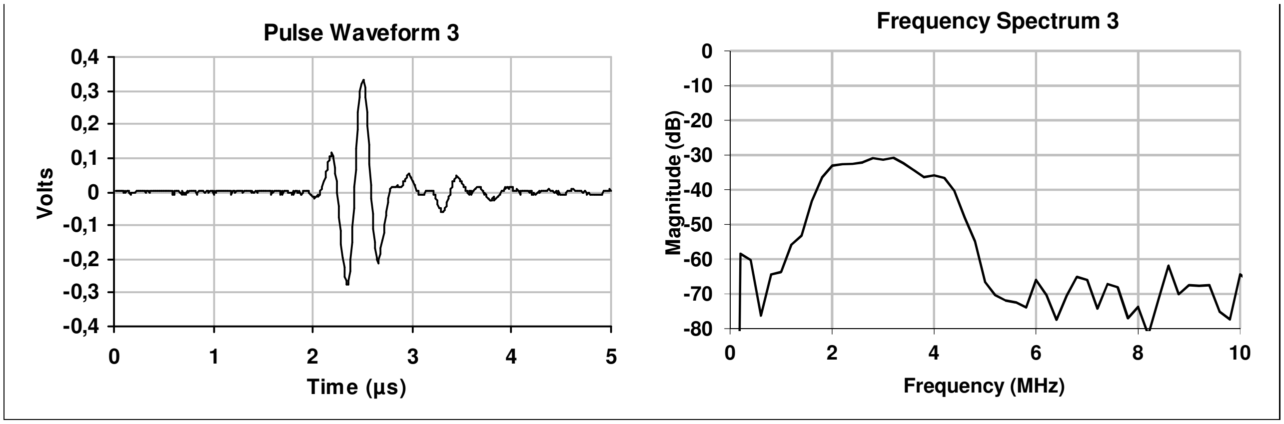

Center Frequency
Frequency (MHz)
4
3.5
3
2.5
2
1.5
1
0.5
0
1
11
21
31
41
51
61
Elements
Mean: 3,107
Max: 3,158
Min: 3,051
Std Dev: 0,022







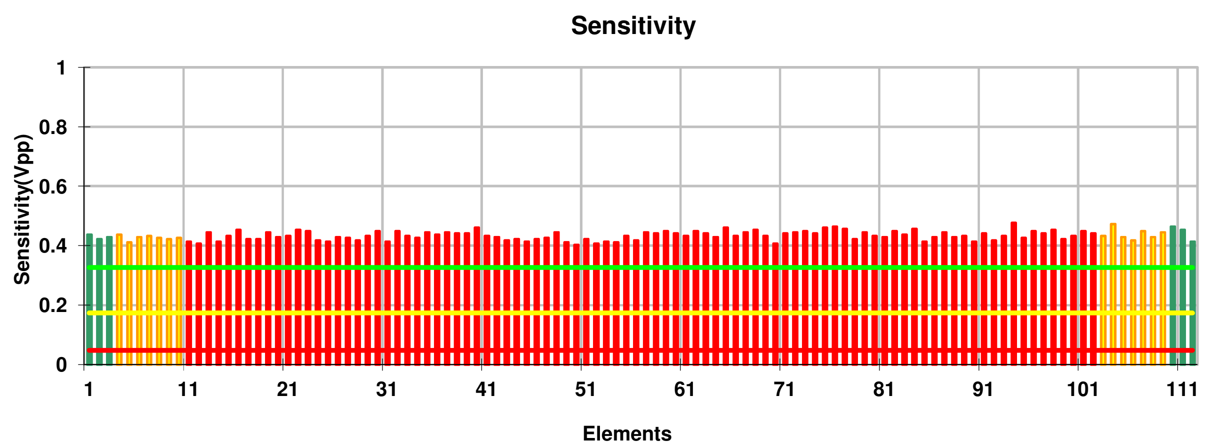
Last Selected Element: 48


Pulse Waveform 3
Volts
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
0
1
2
3
4
5
Time (µs)
Frequency Spectrum 3
Magnitude (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
0
2
4
6
8
10
Frequency (MHz)

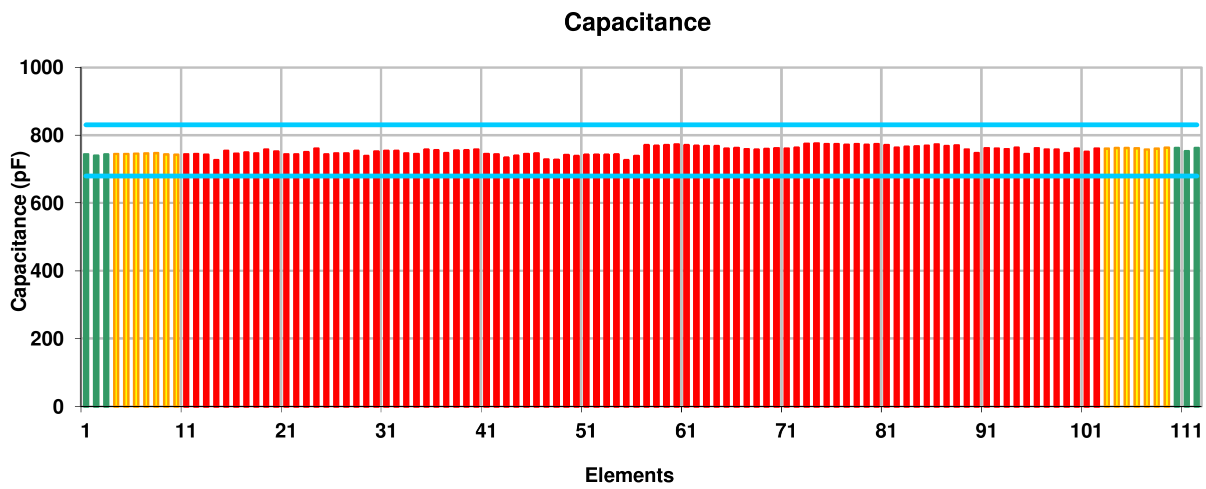
Appendix C – Test report – 4V1C – Functional

Transducer Evaluation Report

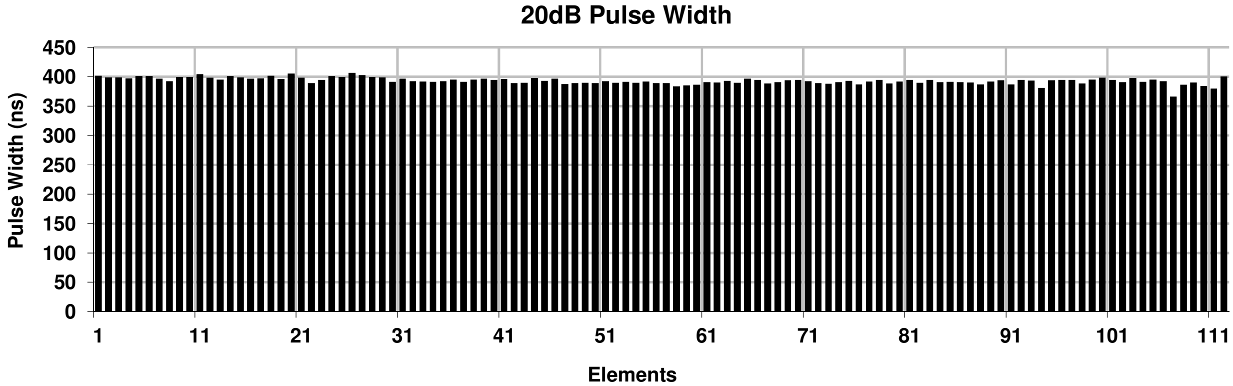
Manufacturer:	Acuson	**Customer:**	Customer			**Contact:**	Contact
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**		**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					



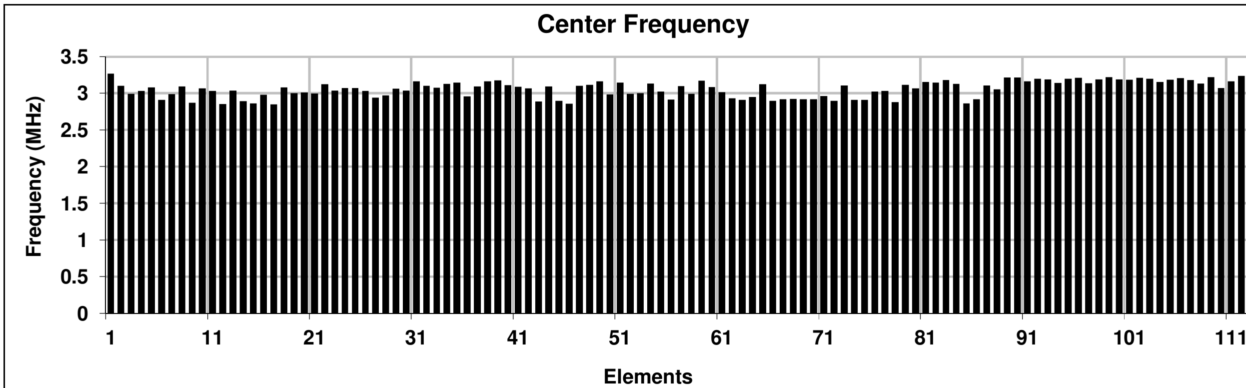
Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB



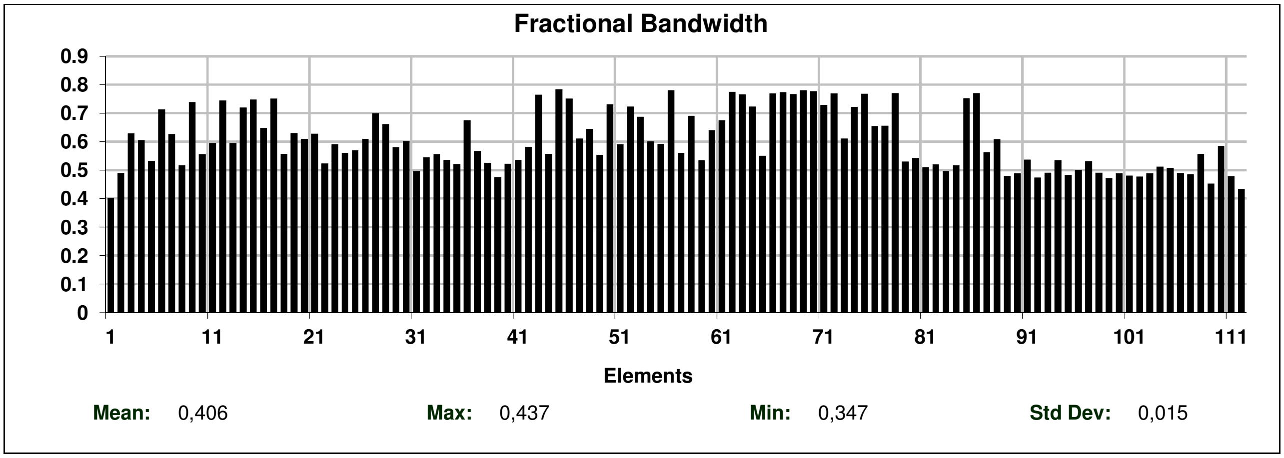
Mean: 247,127 **Max:** 258,925 **Min:** 229,223 **Std Dev:** 8,648



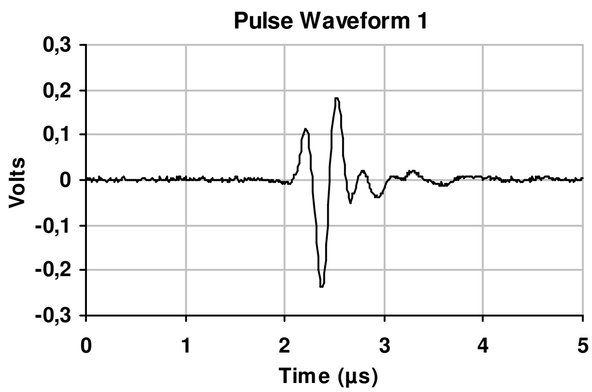
Mean: 446,876 **Max:** 460,675 **Min:** 434,452 **Std Dev:** 4,180

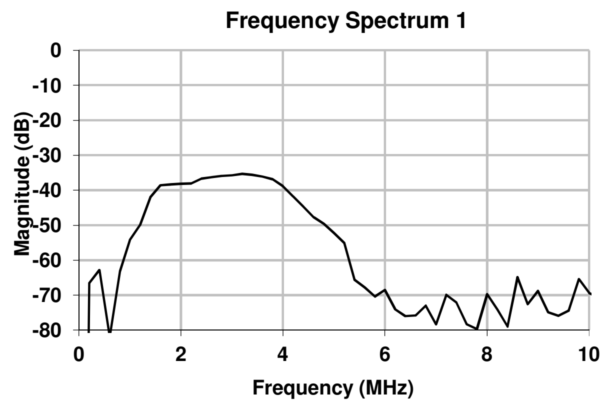


Mean: 3,107 **Max:** 3,158 **Min:** 3,051 **Std Dev:** 0,022

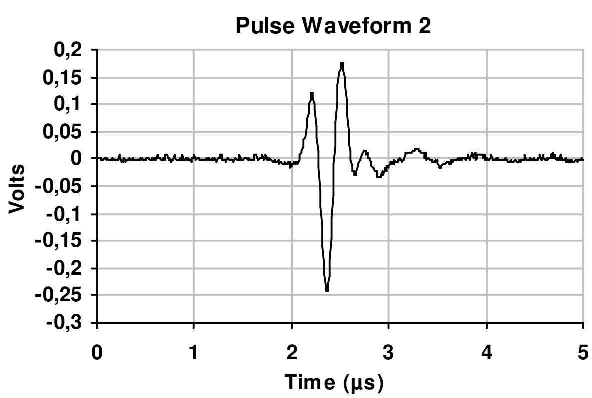


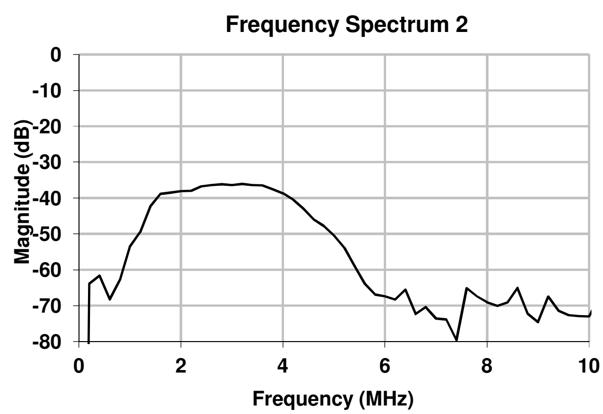
First Selected Element: 16



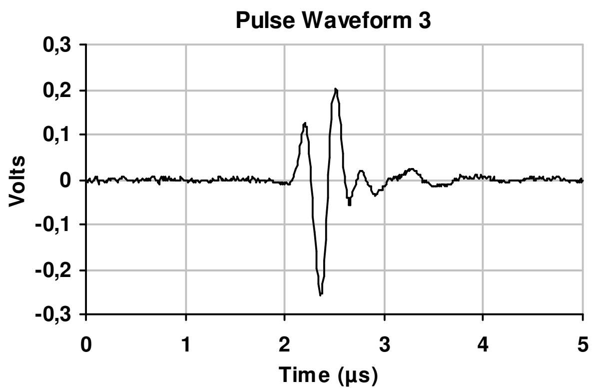


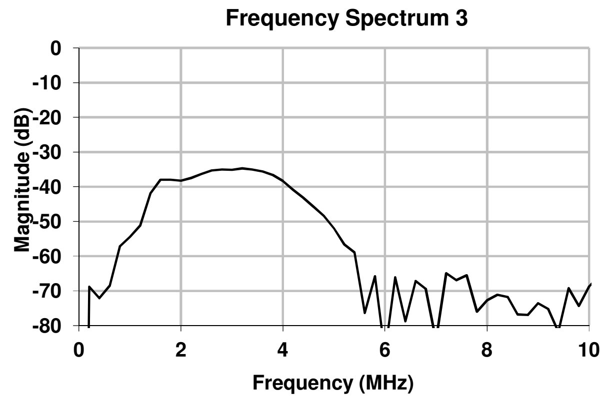
Middle Selected Element: 32





Last Selected Element: 48

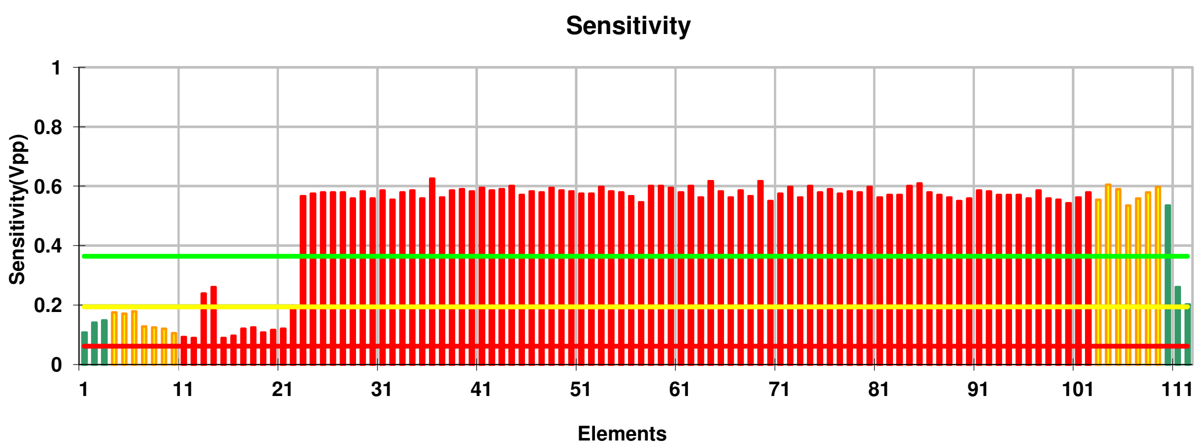

Pulse Waveform 3
Volts
Time (µs)
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
0
1
2
3
4
5


Frequency Spectrum 3
Magnitude (dB)
Frequency (MHz)
0
-10
-20
-30
-40
-50
-60
-70
-80
0
2
4
6
8
10

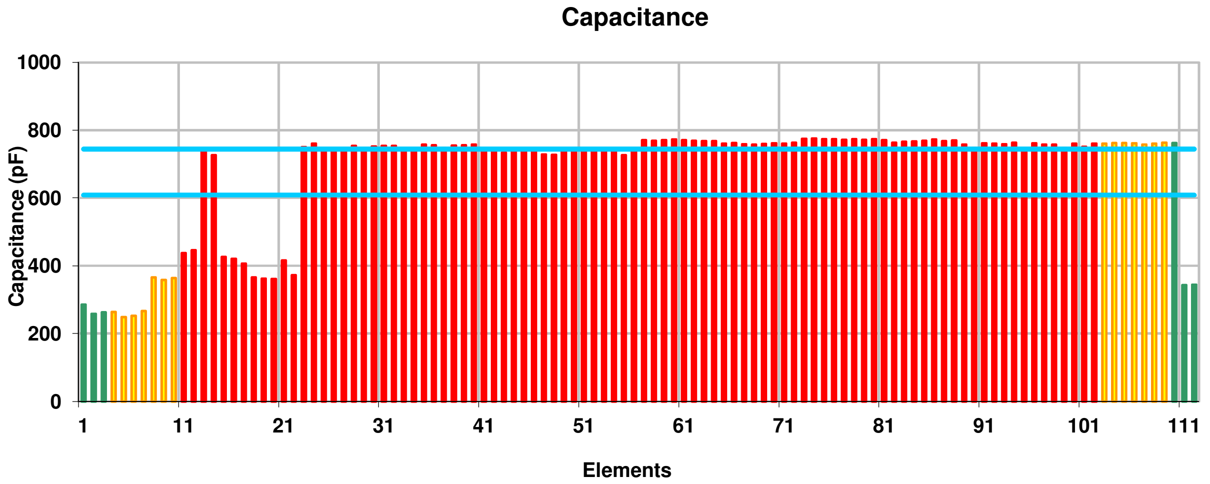
Appendix D – Test report – 4V1C – Defective

Transducer Evaluation Report

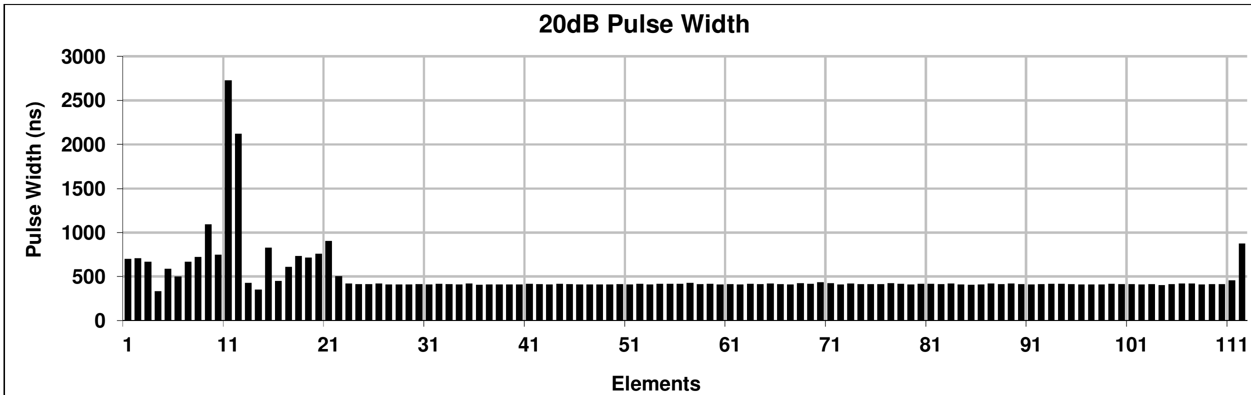
Manufacturer:	Acuson	**Customer:**	Customer			**Contact:**	Contact
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**	Johan Mårlid	**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					



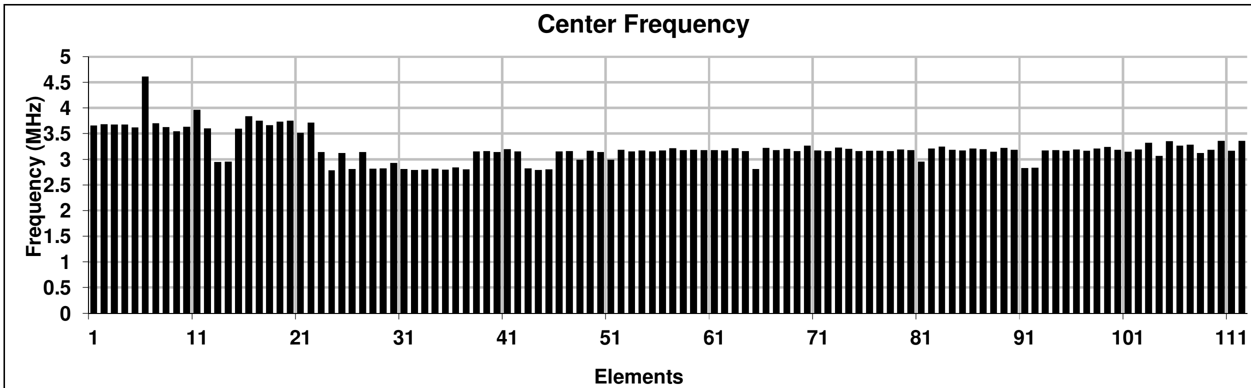
Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB



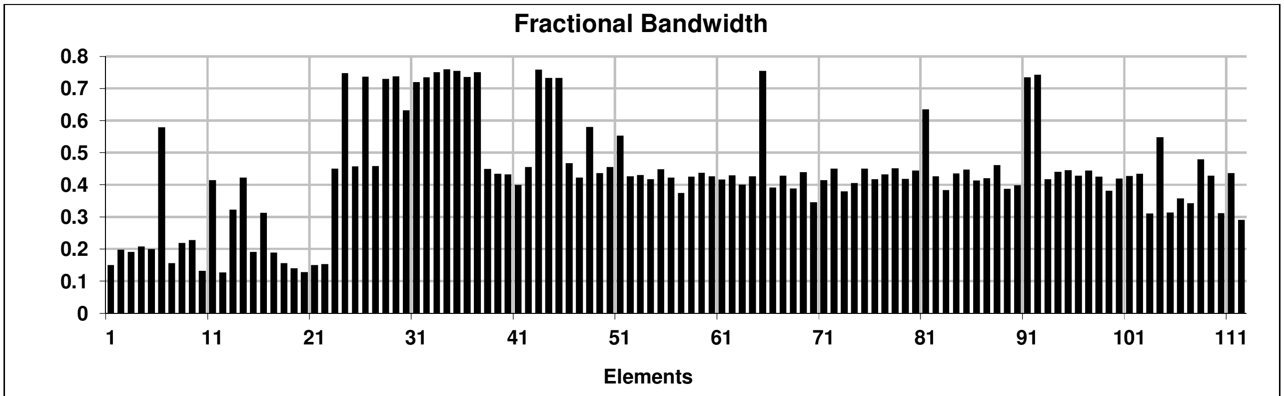
Mean: 247,127 **Max:** 258,925 **Min:** 229,223 **Std Dev:** 8,648



Mean: 446,876 **Max:** 460,675 **Min:** 434,452 **Std Dev:** 4,180

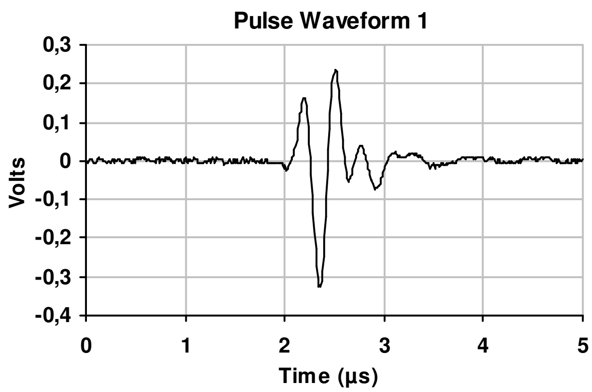


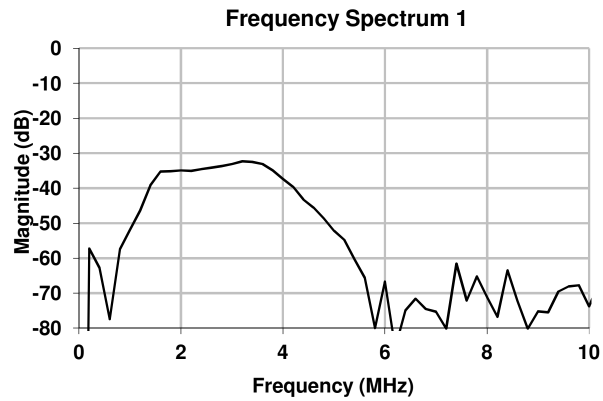
Mean: 3,107 **Max:** 3,158 **Min:** 3,051 **Std Dev:** 0,022



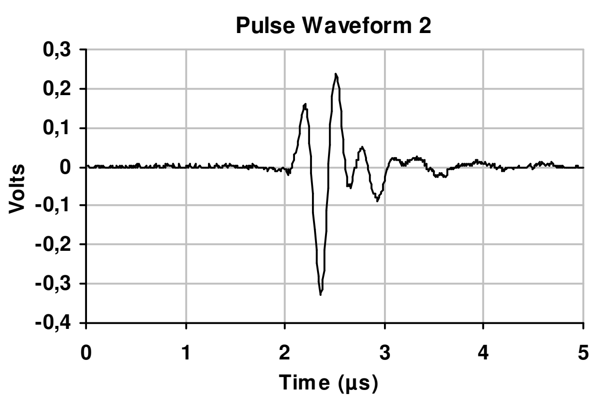
Mean: 0,406 **Max:** 0,437 **Min:** 0,347 **Std Dev:** 0,015

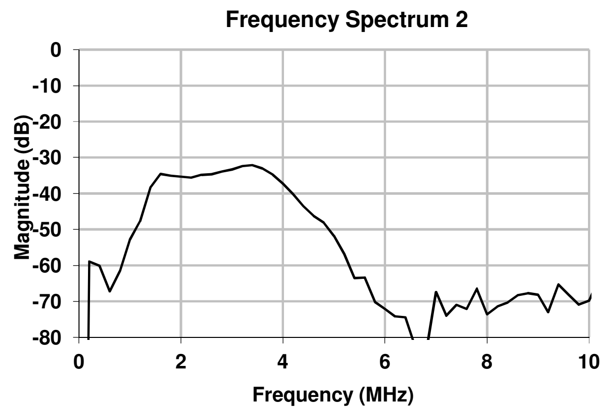
First Selected Element: 16



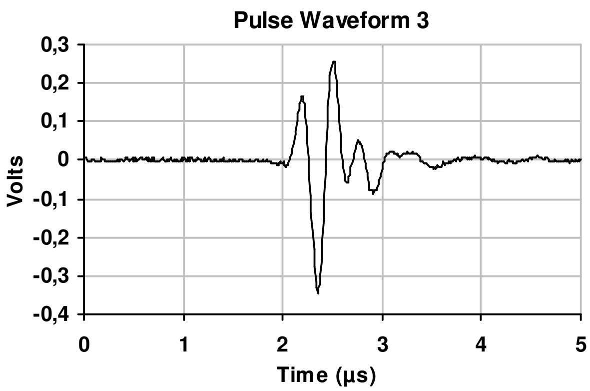


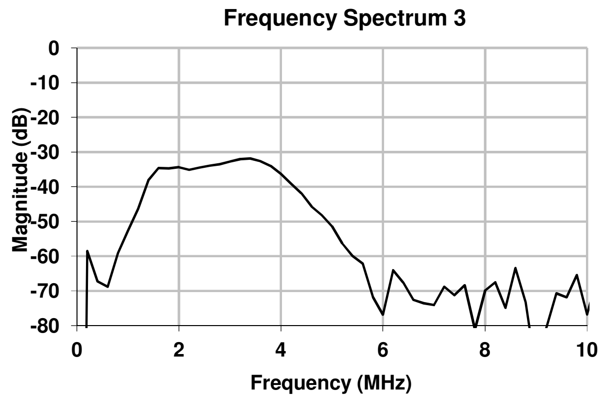
Middle Selected Element: 32





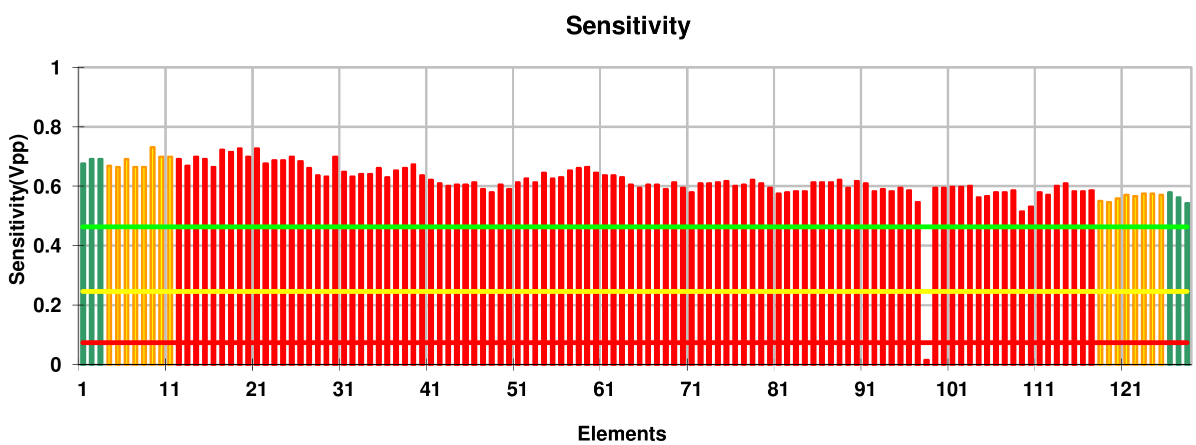
Last Selected Element: 48


Pulse Waveform 3
Volts
Time (µs)
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
0
1
2
3
4
5

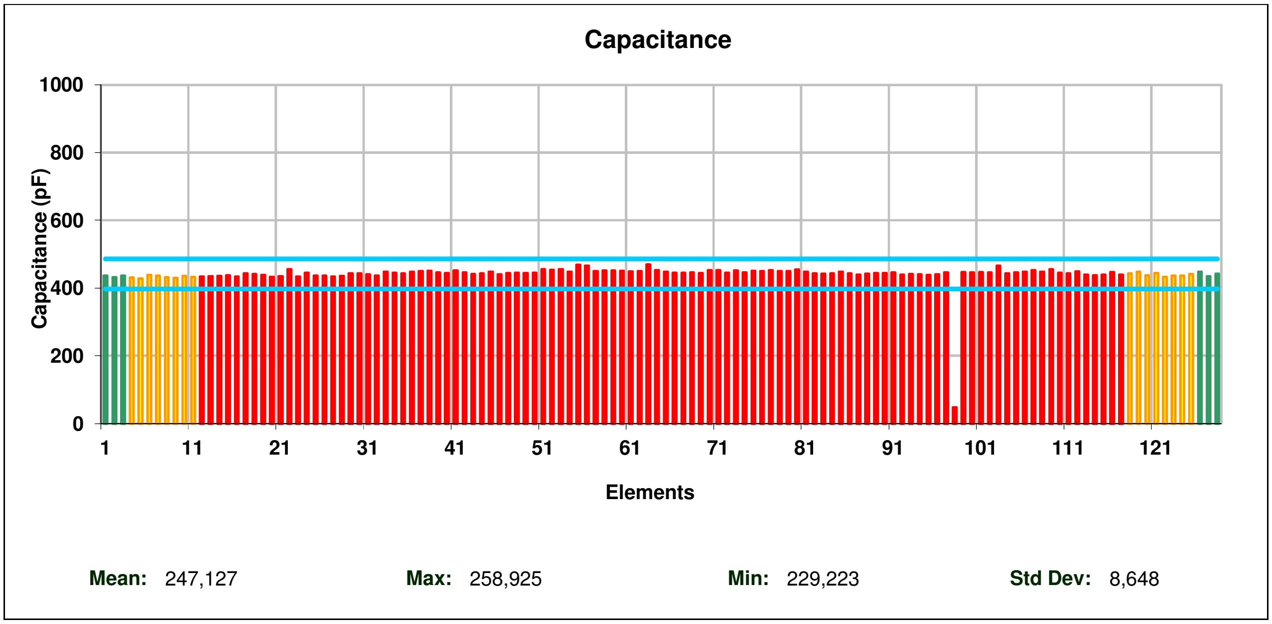

Frequency Spectrum 3
Magnitude (dB)
Frequency (MHz)
0
-10
-20
-30
-40
-50
-60
-70
-80
0
2
4
6
8
10

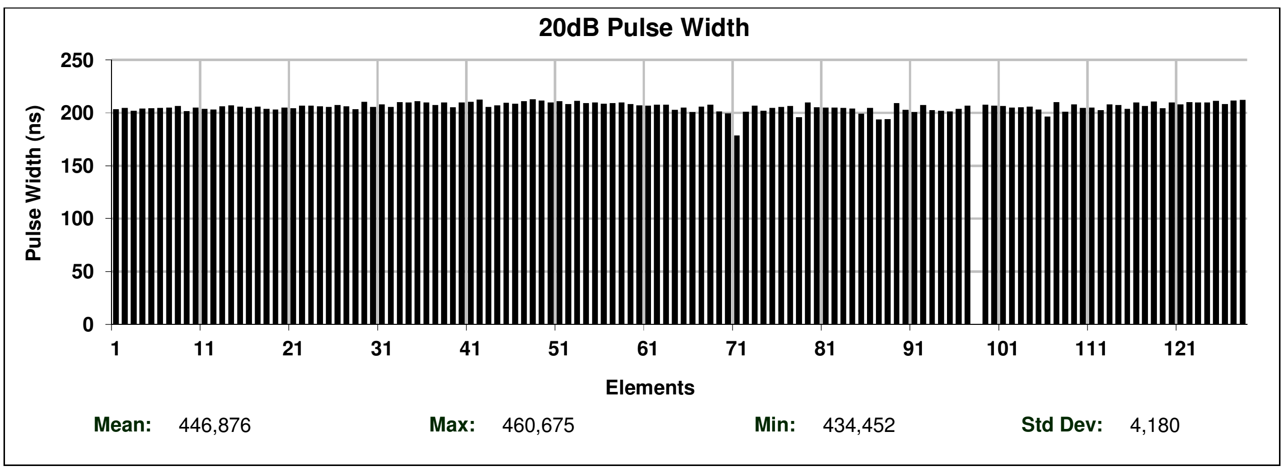
Transducer Evaluation Report

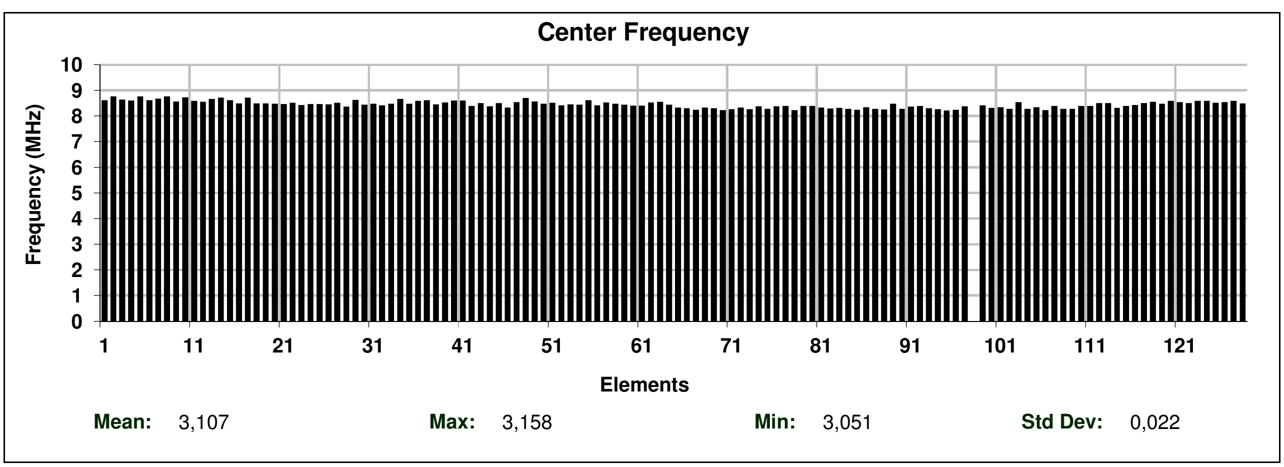
Manufacturer:	Acuson	**Customer:**	Customer			**Contact:**	Contact
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**		**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					

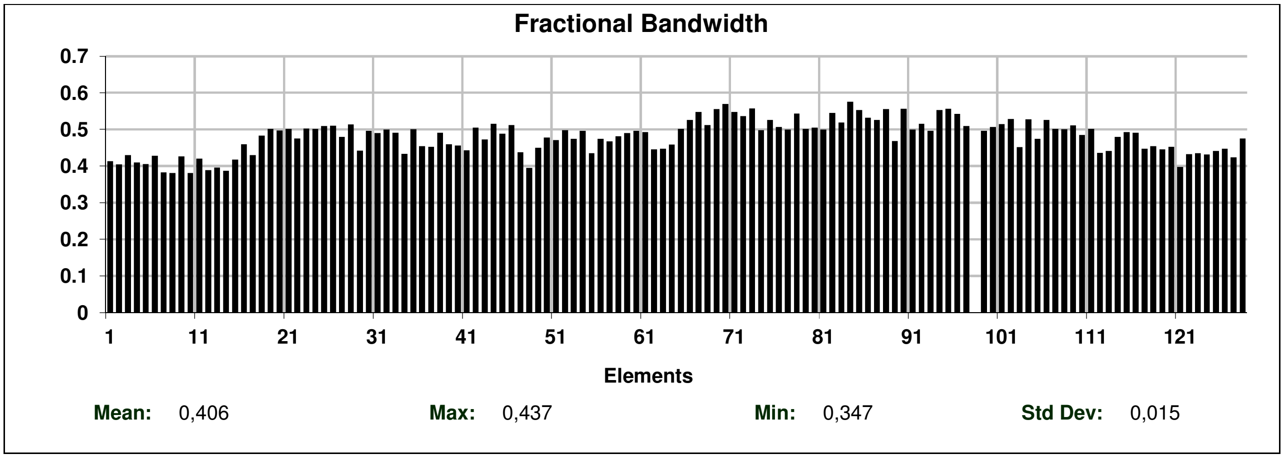


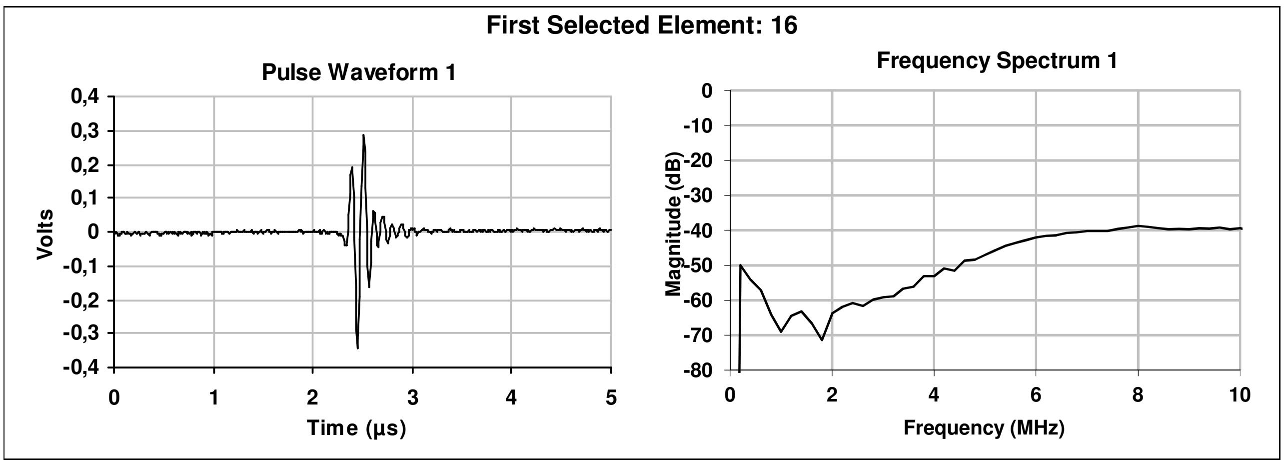
Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB

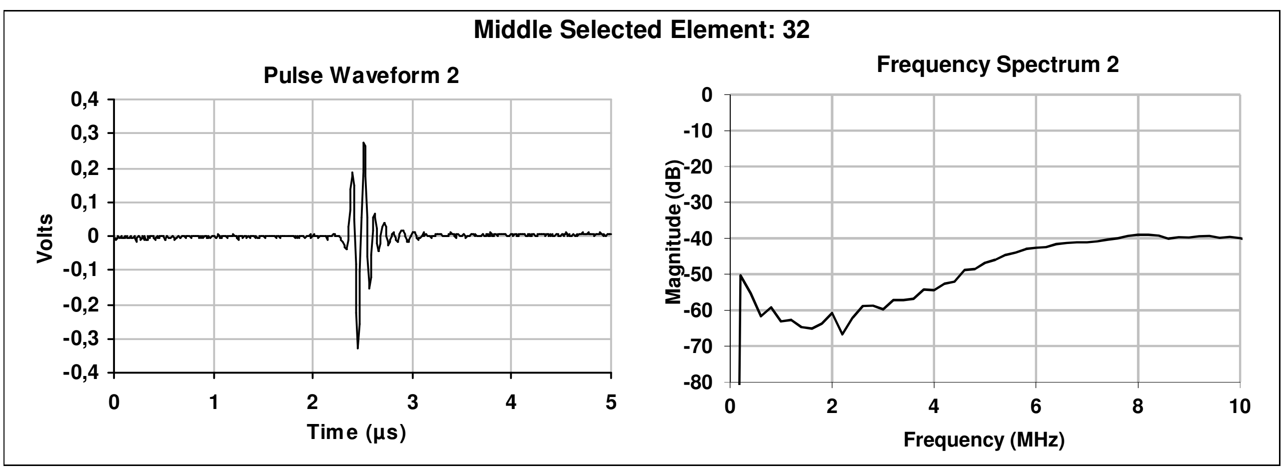

Capacitance
1000
800
600
400
200
0
Capacitance (pF)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 247,127
Max: 258,925
Min: 229,223
Std Dev: 8,648


20dB Pulse Width
250
200
150
100
50
0
Pulse Width (ns)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 446,876
Max: 460,675
Min: 434,452
Std Dev: 4,180

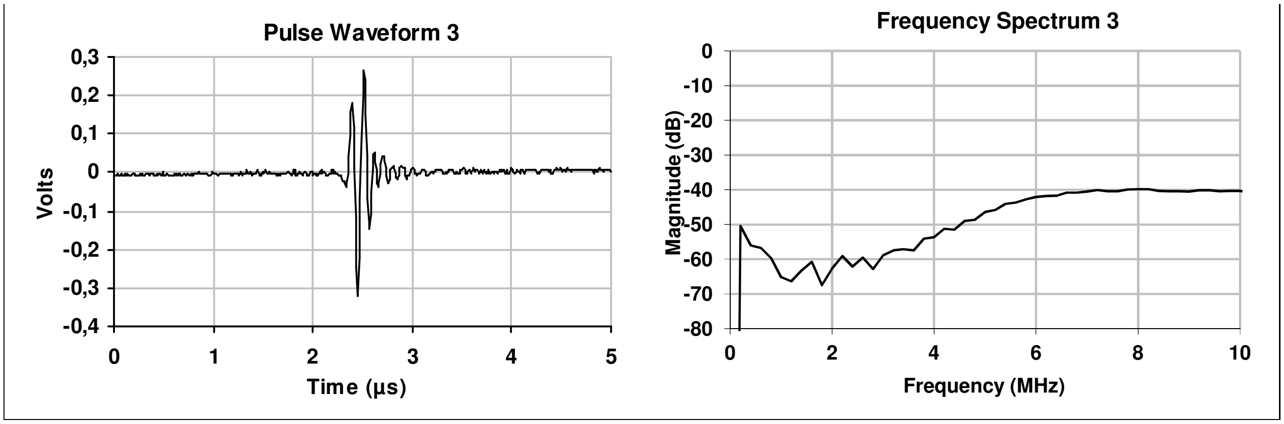

Center Frequency
10
9
8
7
6
5
4
3
2
1
0
Frequency (MHz)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 3,107
Max: 3,158
Min: 3,051
Std Dev: 0,022







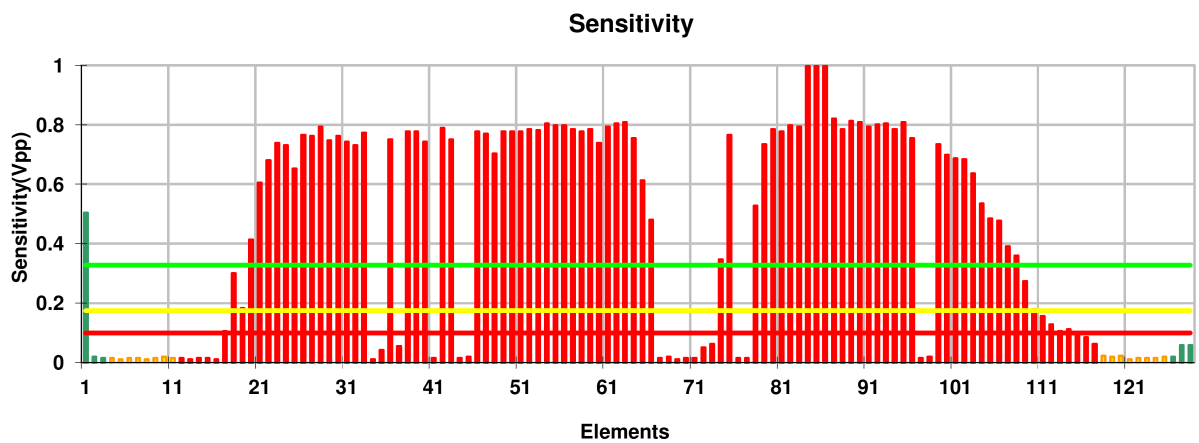
Last Selected Element: 48


Pulse Waveform 3
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
Volts
0
1
2
3
4
5
Time (µs)
Frequency Spectrum 3
0
-10
-20
-30
-40
-50
-60
-70
-80
Magnitude (dB)
0
2
4
6
8
10
Frequency (MHz)

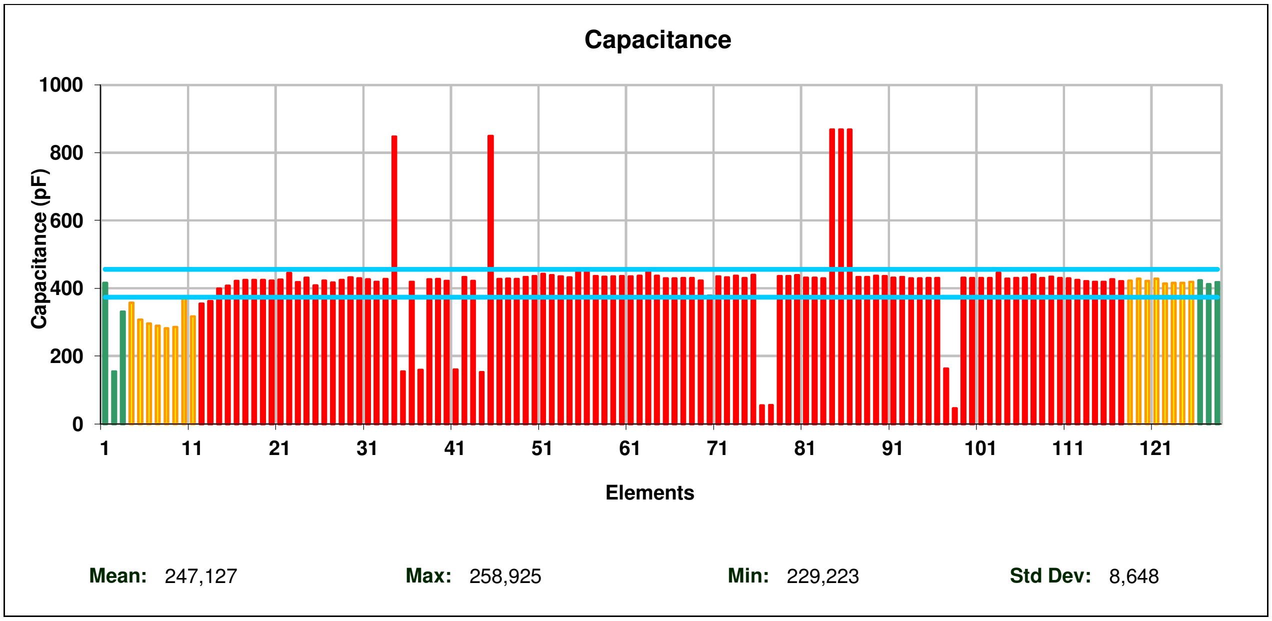
Appendix F – Test report – L7 – Defective

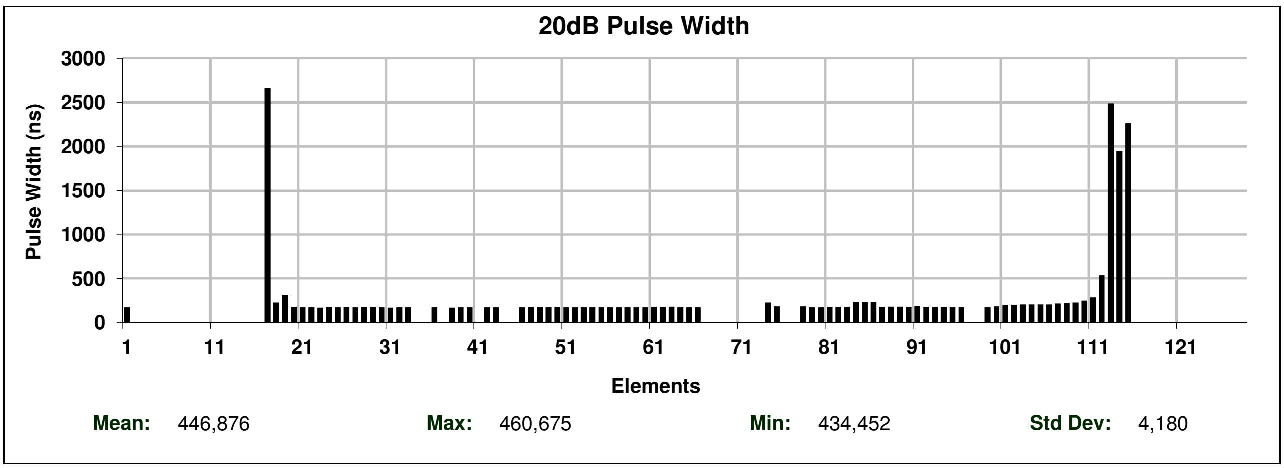
Transducer Evaluation Report

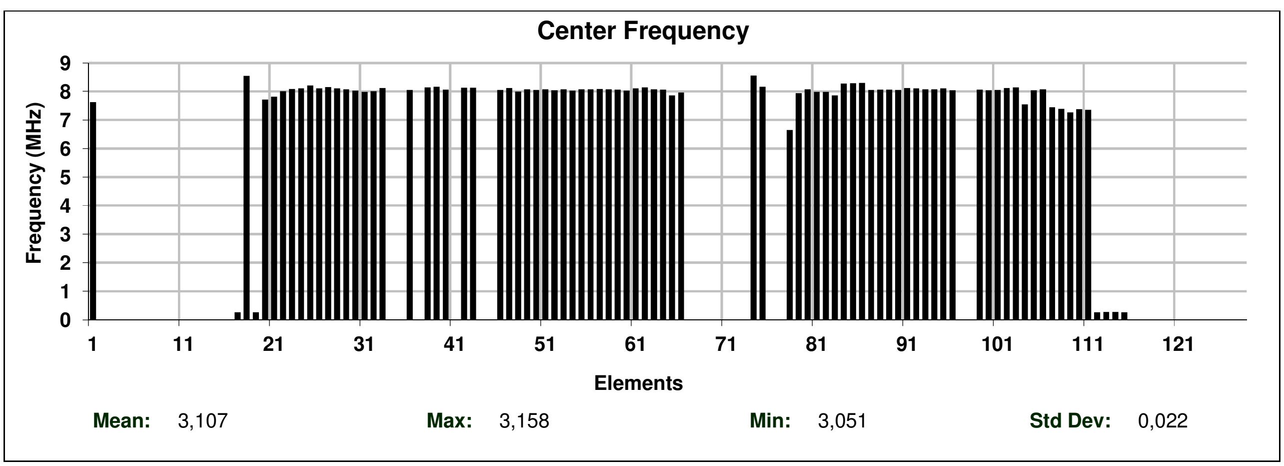
Manufacturer:	Acuson	**Customer:**	Customer			**Contact:**	Contact
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**		**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					

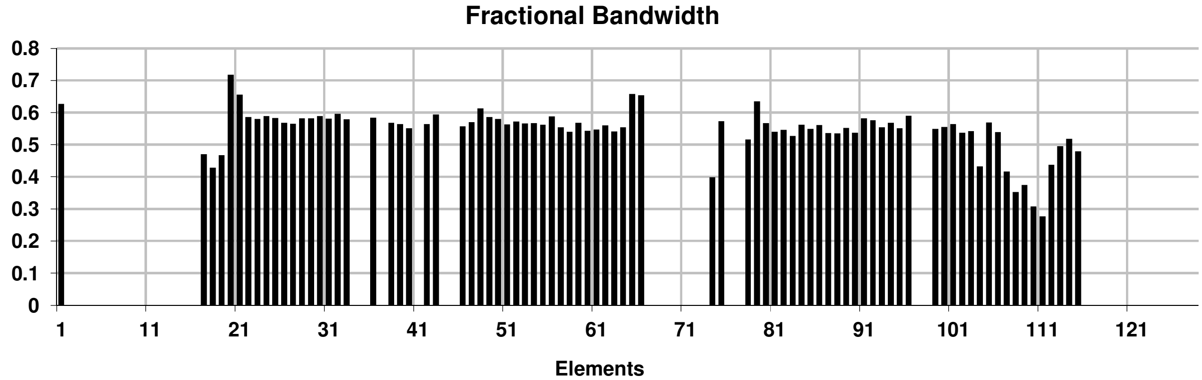


Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB


Capacitance
1000
800
600
400
200
0
Capacitance (pF)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 247,127
Max: 258,925
Min: 229,223
Std Dev: 8,648

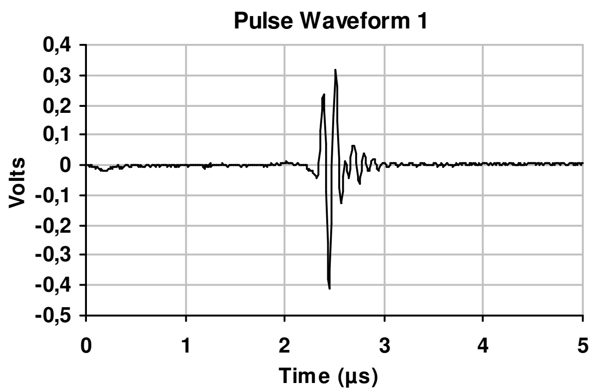

20dB Pulse Width
3000
2500
2000
1500
1000
500
0
Pulse Width (ns)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 446,876
Max: 460,675
Min: 434,452
Std Dev: 4,180

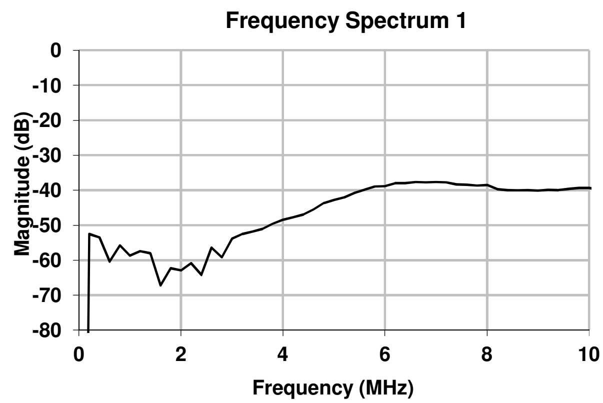

Center Frequency
9
8
7
6
5
4
3
2
1
0
Frequency (MHz)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 3,107
Max: 3,158
Min: 3,051
Std Dev: 0,022



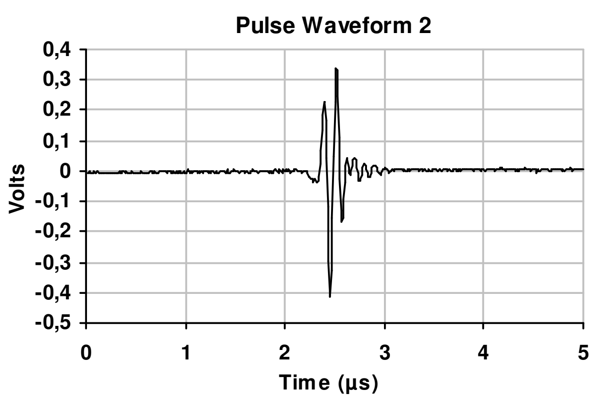
Mean: 0,406 **Max:** 0,437 **Min:** 0,347 **Std Dev:** 0,015

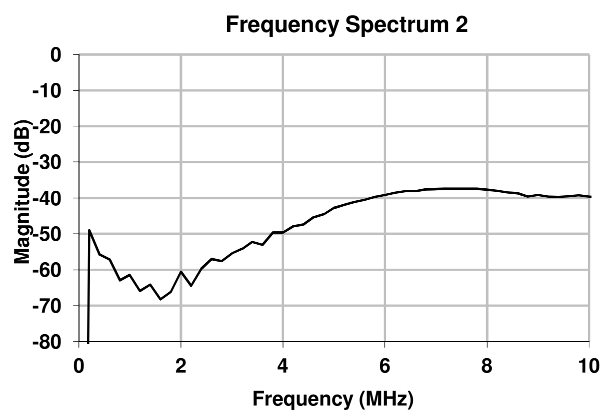
First Selected Element: 16



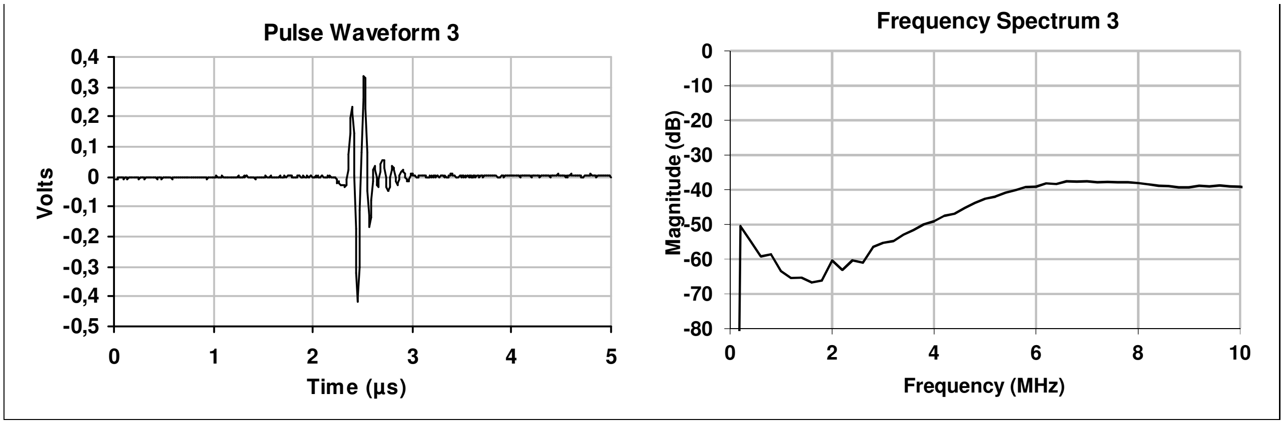


Middle Selected Element: 32





Last Selected Element: 48


Pulse Waveform 3
Volts
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
-0,5
0
1
2
3
4
5
Time (µs)
Frequency Spectrum 3
Magnitude (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
0
2
4
6
8
10
Frequency (MHz)

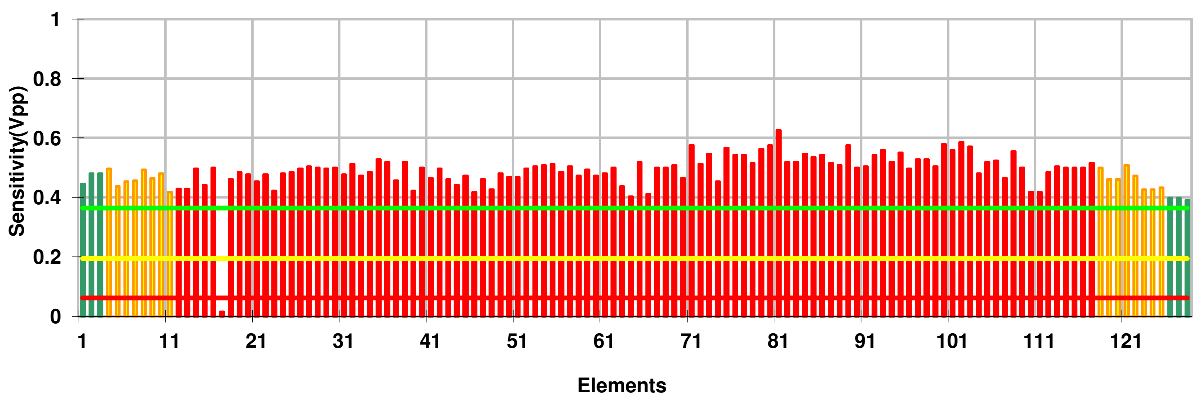
Appendix G – Test report – UST9123 – Functional

FirstCall aPerio Sonora

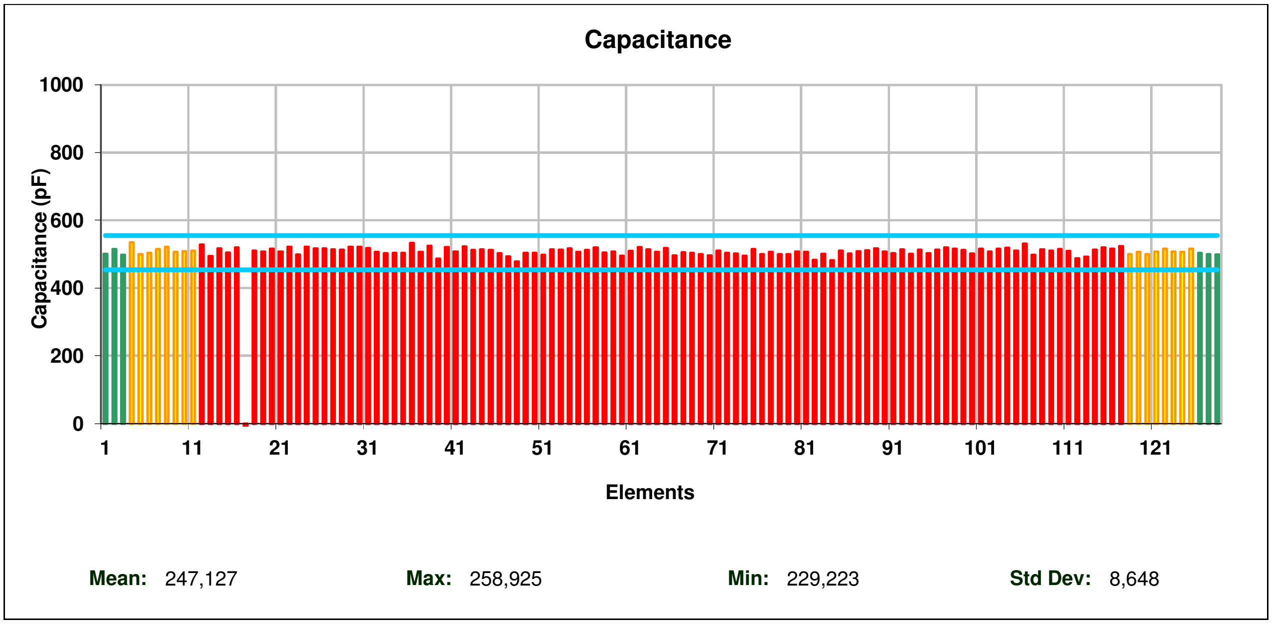
Transducer Evaluation Report

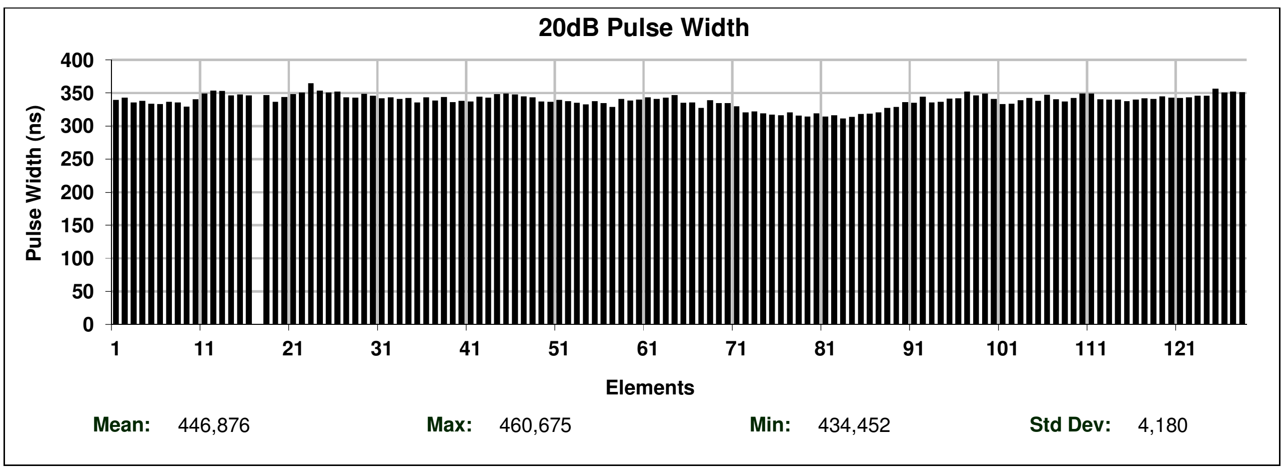
Manufacturer:	Acuson	**Customer:**	Customer	**Contact:**	Contact		
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**		**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					

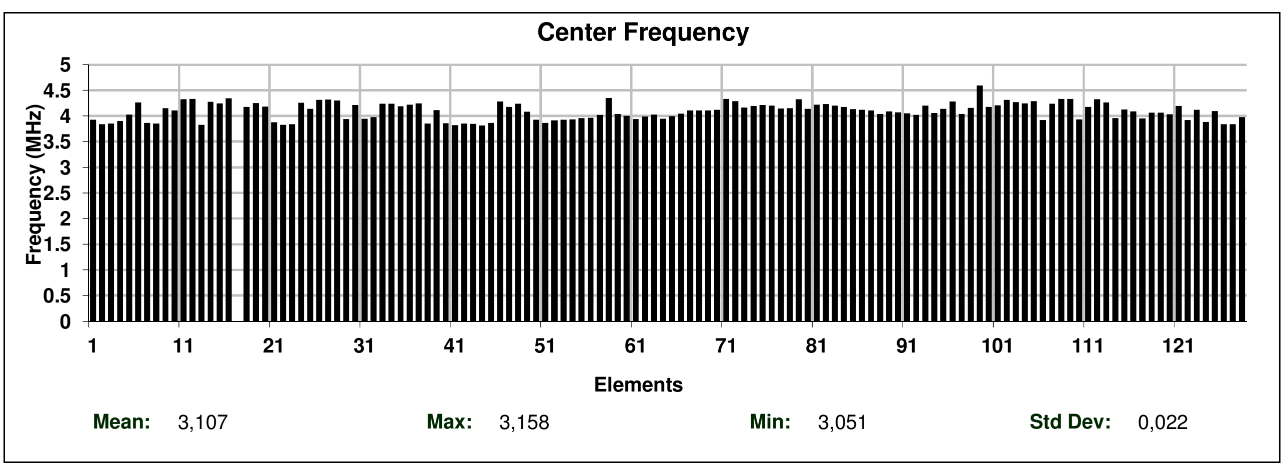
Sensitivity

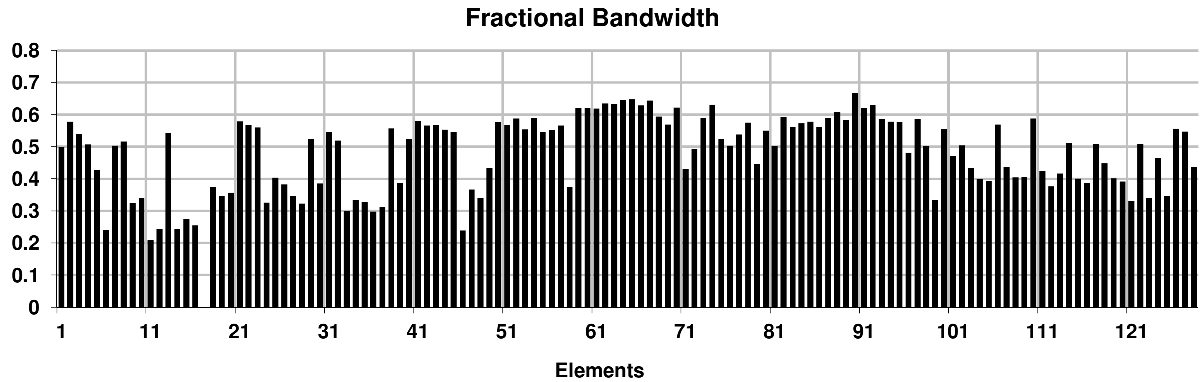


Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB


Capacitance
1000
800
600
400
200
0
Capacitance (pF)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 247,127
Max: 258,925
Min: 229,223
Std Dev: 8,648

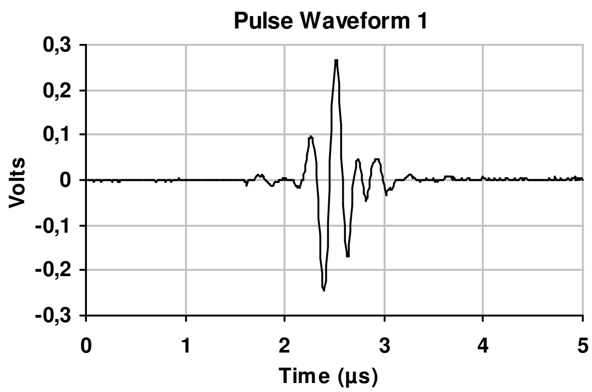

20dB Pulse Width
400
350
300
250
200
150
100
50
0
Pulse Width (ns)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 446,876
Max: 460,675
Min: 434,452
Std Dev: 4,180

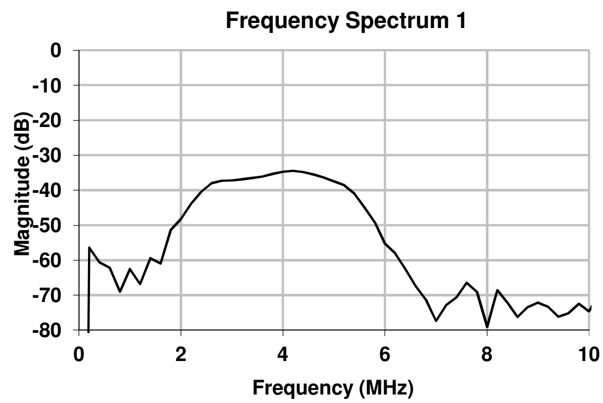

Center Frequency
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Frequency (MHz)
1
11
21
31
41
51
61
71
81
91
101
111
121
Elements
Mean: 3,107
Max: 3,158
Min: 3,051
Std Dev: 0,022



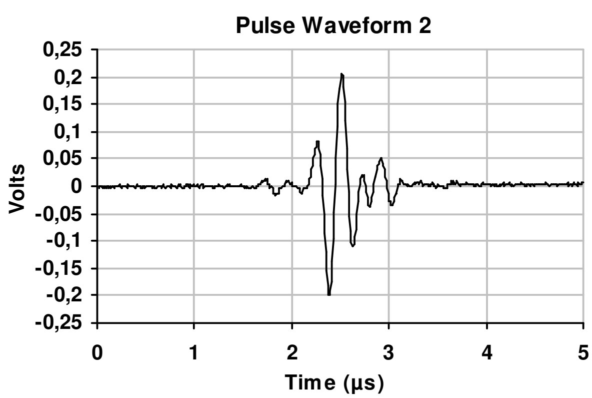
Mean: 0,406 **Max:** 0,437 **Min:** 0,347 **Std Dev:** 0,015

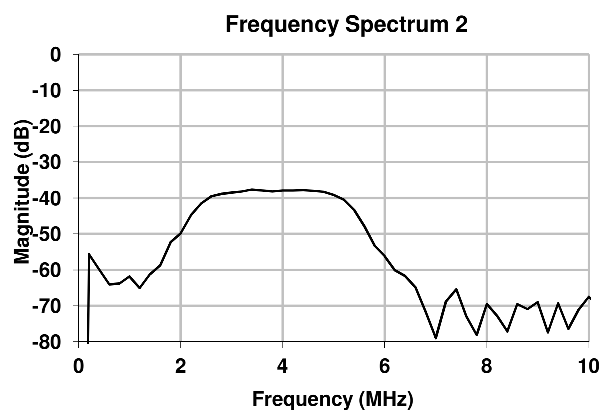
First Selected Element: 16



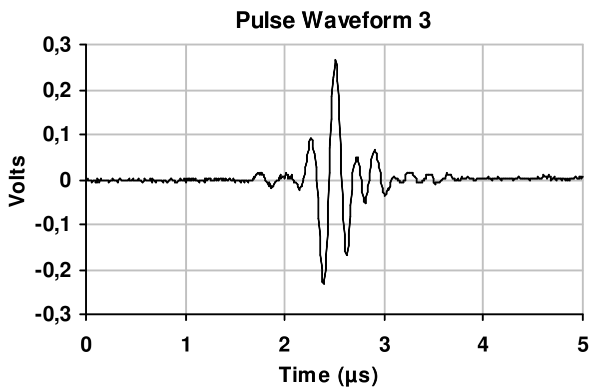


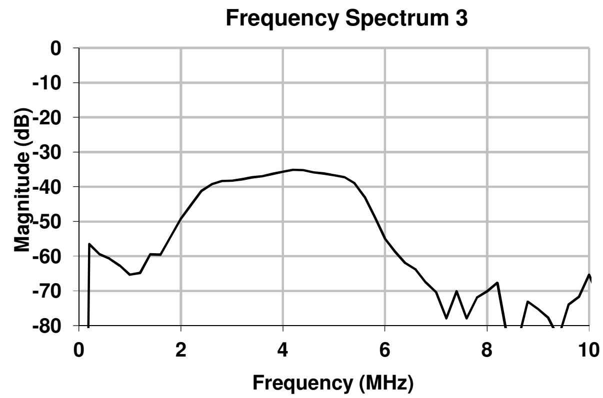
Middle Selected Element: 32





Last Selected Element: 48

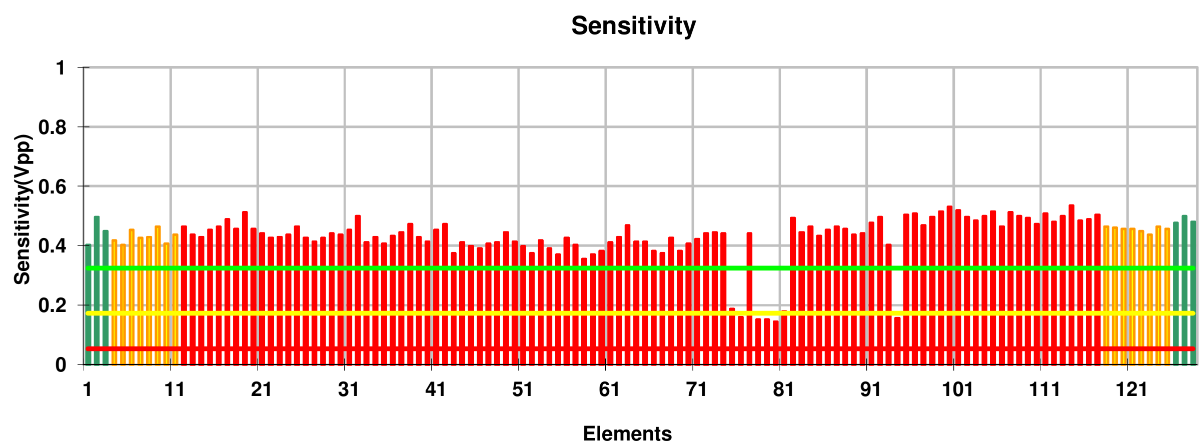

Pulse Waveform 3
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
Volts
0
1
2
3
4
5
Time (µs)


Frequency Spectrum 3
0
-10
-20
-30
-40
-50
-60
-70
-80
Magnitude (dB)
0
2
4
6
8
10
Frequency (MHz)

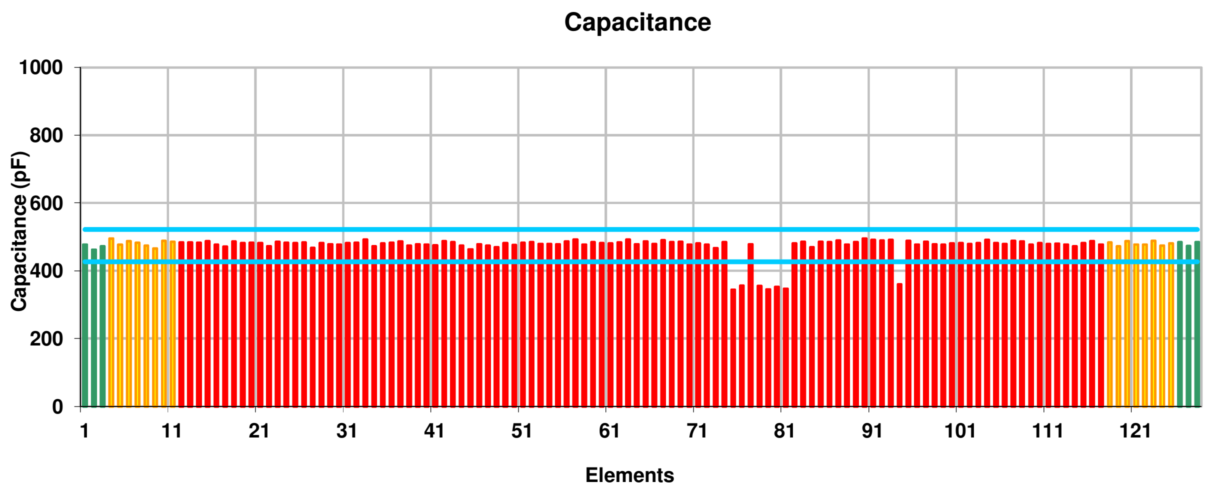
Appendix H – Test report – UST9123 – Defective

Transducer Evaluation Report

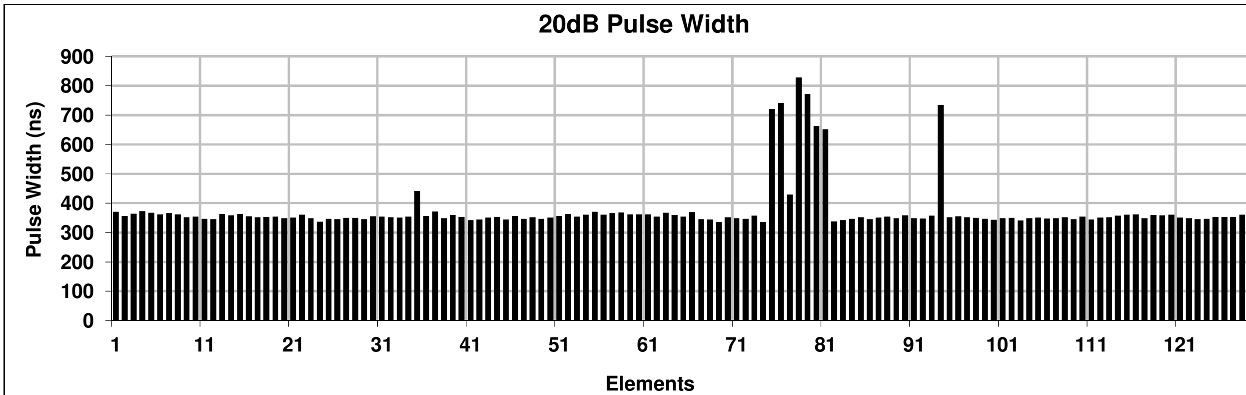
Manufacturer:	Acuson	**Customer:**	Customer			**Contact:**	Contact
Probe Model:	Sequoia_3V2c	**Address:**	Address				
Serial Number:	91202738	**City:**	City	**State:**	CO	**Zip Code:**	Zip
Test Date:	2010-07-05 14:28			**Phone:**	Phone	**Fax:**	Fax
Test ID:	1037	**Operator:**		**aPerio Serial:**	B00091	**Cal. Due Date:**	Oct. 2010
Purpose:	Test Type	**DX/Comments:**					



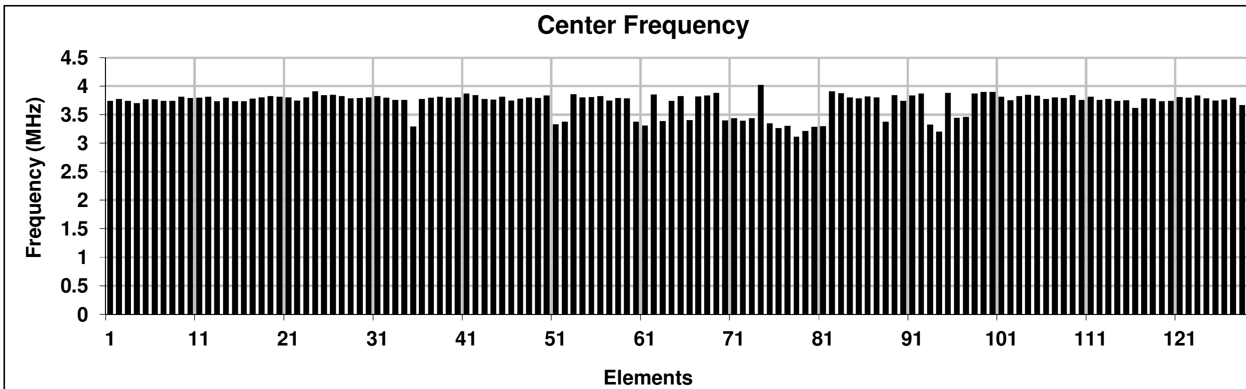
Mean: 0,612 **Max:** 0,700 **Min:** 0,551 **Std Dev:** 0,025 **Gain:** 20 dB



Mean: 247,127 **Max:** 258,925 **Min:** 229,223 **Std Dev:** 8,648

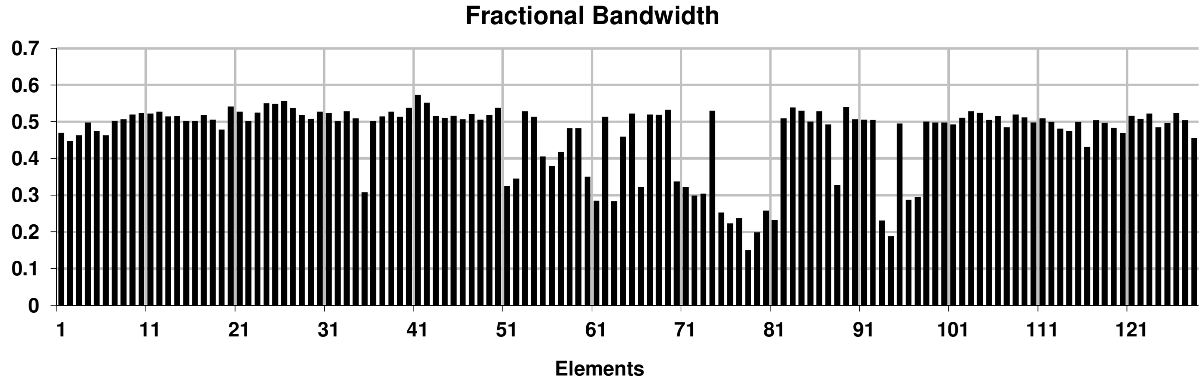


Mean: 446,876 **Max:** 460,675 **Min:** 434,452 **Std Dev:** 4,180



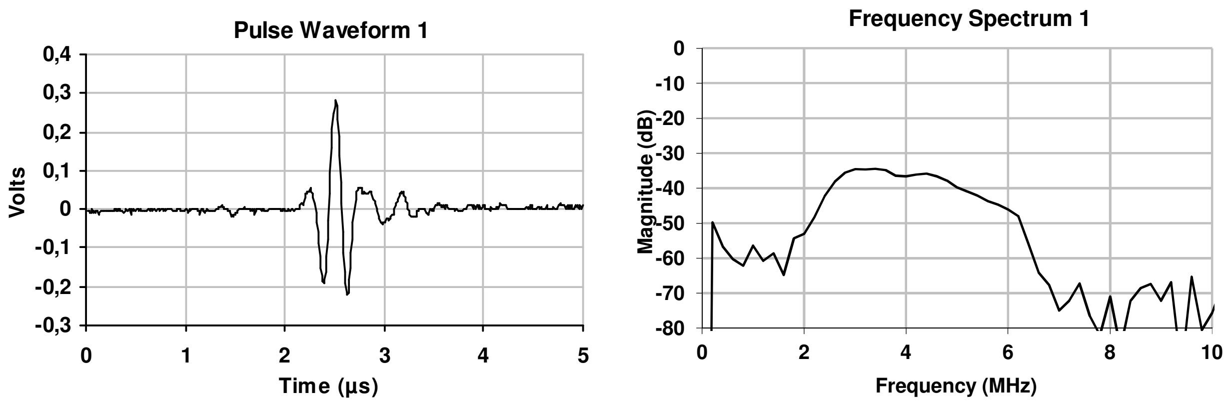
Mean: 3,107 **Max:** 3,158 **Min:** 3,051 **Std Dev:** 0,022

Fractional Bandwidth

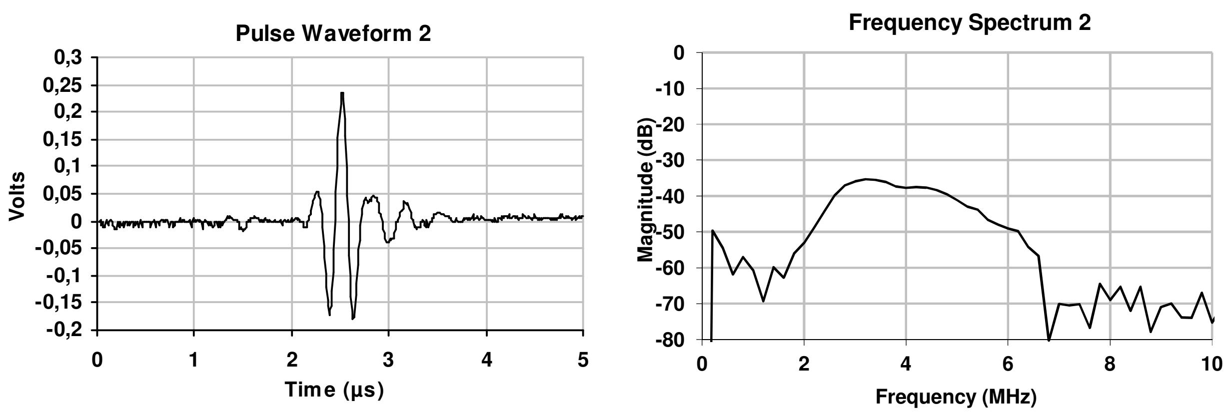


Mean: 0,406 **Max:** 0,437 **Min:** 0,347 **Std Dev:** 0,015

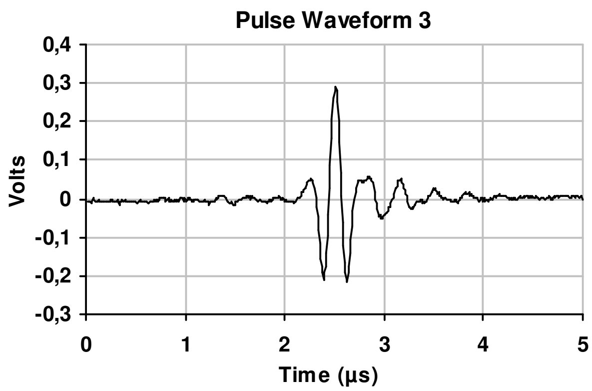
First Selected Element: 16

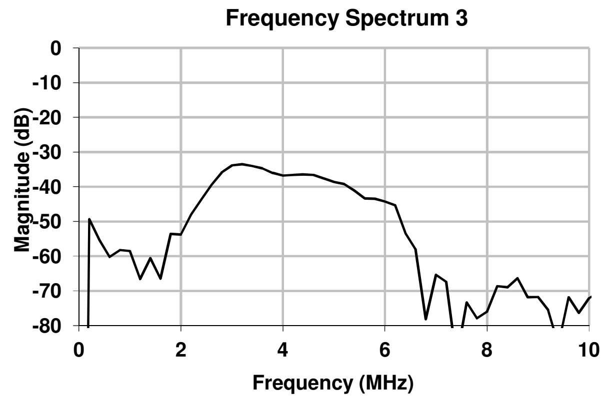


Middle Selected Element: 32



Last Selected Element: 48


Pulse Waveform 3
Volts
Time (µs)


Frequency Spectrum 3
Magnitude (dB)
Frequency (MHz)