

A Software Platform for Post-Processing Waveform-Based NDE

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ABSTRACT

Ultrasonic, microwave, and terahertz nondestructive evaluation imaging systems generally require the acquisition of waveforms at each scan point to form an image. For such systems, signal and image processing methods are commonly needed to extract information from the waves and improve resolution of, and highlight, defects in the image. Since some similarity exists for all waveform-based NDE methods, it would seem a common software platform containing multiple signal and image processing techniques to process the waveforms and images makes sense where multiple techniques, scientists, engineers, and organizations are involved. This presentation describes NASA Glenn Research Center's approach in developing a common software platform for processing waveform-based NDE signals and images. This platform is currently in use at NASA Glenn and at Lockheed Martin Michoud Assembly Facility for processing of pulsed terahertz and ultrasonic data. Highlights of the software operation will be given. A case study will be shown for use with terahertz data. The authors also request scientists and engineers who are interested in sharing customized signal and image processing algorithms to contribute to this effort by letting the authors code up and include these algorithms in future releases.

KEY WORDS: Nondestructive Evaluation, Signal Processing, Software

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1. INTRODUCTION

Nondestructive evaluation (NDE) is used to detect flaws and characterize material microstructure in monolithic and composite materials in the aerospace, nuclear, pressure vessel and infrastructure fields (refs. 1 and 2). Many different methods exist, and most can be used in a single-point measurement or scanning fashion, the latter in order to produce images. Pulsed ultrasonic, microwave, terahertz, and radar NDE imaging systems generally require the acquisition of waveforms at each scan point to form an image. For such systems, signal and image processing methods are commonly needed to extract information from the waves and improve resolution of, and highlight, defects in the image. Since some similarity exists for all waveform-based NDE methods, it would seem a common software platform containing multiple signal and image processing techniques to process the waveforms and images makes sense where multiple techniques, scientists, engineers, and organizations are involved. This article describes NASA Glenn Research Center's beta approach in developing a common software platform for processing broadband waveform-based NDE signals and images. This platform is currently in use at NASA Glenn and at Lockheed Martin Michoud Assembly Facility for processing of pulsed terahertz and ultrasonic data. The software was designed with a commercial grade interface and works with waveform-based files, image files, or image series files. A number of the analysis routines were custom built using algorithms obtained from the literature (egs. Principal Component Analysis) and this approach will continue as needed so as to employ the most useful and latest technologies (such as wavelet transformations). Highlights of the software operation will be given in this article and some unique capabilities will be showcased. The software operation is illustrated through use with the terahertz method (refs. 3 to 5). It is hoped at some point to expand the use of this software beyond NASA to industry and academia, and invite engineers and scientists to contribute useful algorithms in the spirit of open source developments that can help all parties involved (ref. 6).

2. GENERAL DESCRIPTION AND SOFTWARE OPERATION

The NASA NDE Signal and Image Processing software was built using the latest versions of (National Instruments) LabVIEW, and its associated Advanced Signal Processing and Vision Toolkits. The software was developed so as to be used on a PC with Windows XP (Microsoft Corporation) but for the most part should be cross-platform and useable on Apple McIntosh (Apple Computer, Inc.) or Linux-based PC (Linus Torvalds). The software was designed with a commercial grade interface as shown in figure 1 in which two main windows are displayed if the user chooses a "waveform file" to display. Within these two main windows, most actions are chosen through logically-conceived run-time menus. In this case, the data shown in figure 1 is from a terahertz scan of a thermal protection system foam sample containing seeded voids. The waveform file consists of header information describing the scan and data parameters followed by the series of waveforms acquired during the scan at each scan location. The Waveform (Waveform, Inc.) window has plots for both the raw time-domain waves and their frequency-domain transformations. The Image Window shows the C-scan image formed from information of the time-domain waveform (such as peak amplitude) or its frequency-domain transformation at each scan location. The user also has the ability to open an image or series of images from a directory that was created during prior waveform file analysis.

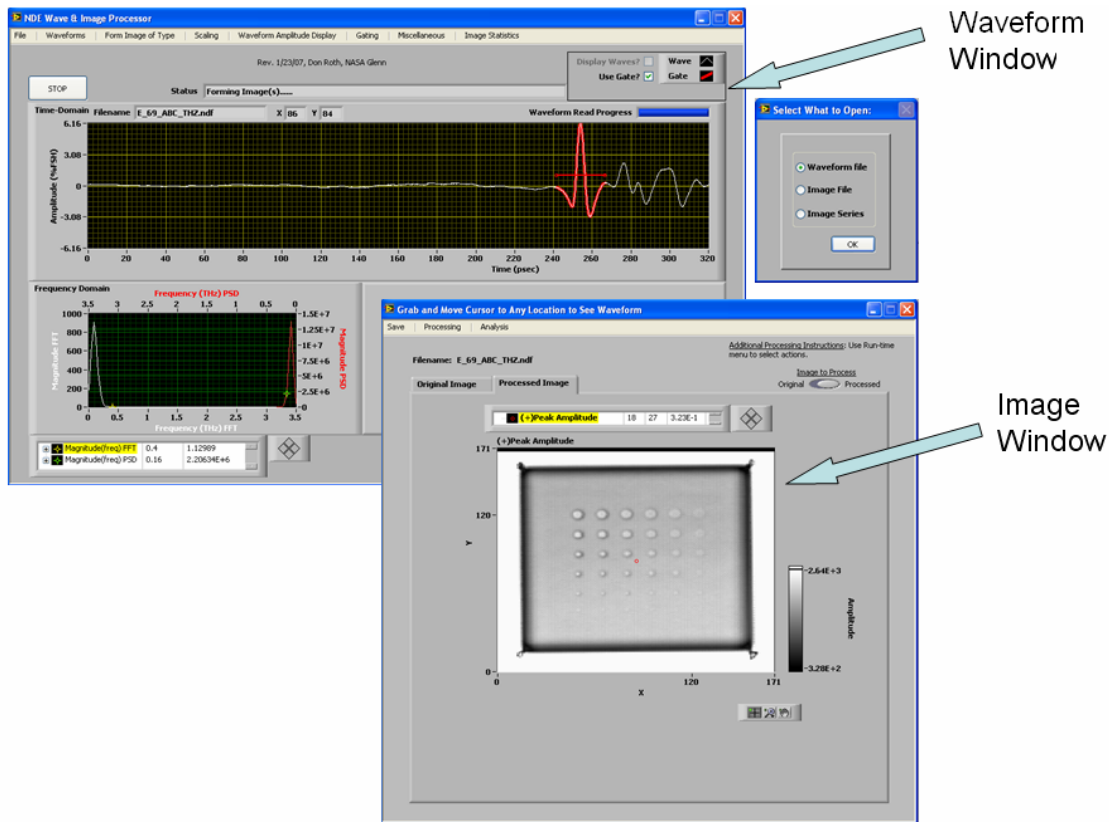


Figure 1.—Software GUI for NASA NDE Wave and Image Processor.

As mentioned, each of the Waveform and Image windows contains menus from which to perform many actions. For example, the menu on the Waveform window allows pre-processing of waveforms prior to image formation, scaling and display of waveforms, formation of different types of images (including unique types such as velocity), gating of portions of waves prior to image formation, and several other miscellaneous and specialized operations (such as wave-based deconvolution). The menu available on the Image Window allows many further image processing and analysis operations, some of which are found in commercially-available image processing software programs (such as Adobe Photoshop) (Adobe Corporation), and some that are not (removing outliers, B-scan information, region-of-interest analysis, line profiles, and precision feature measurements).

3. DATA FORMAT

The data format is shown in table 1 and described here so that scientists and engineers interested to format their data to test the software for potential use with their waveform-based NDE applications can do so. All numerics are written as Little Endian. Data type designations are as follows:

- Integer = 16-bit/2-byte integer
- Long = 32-bit/4-byte integer
- Single = 32-bit/4-byte floating point number

- Double = 64-bit/8-byte floating point number
- String = Ascii character string

The header occupies byte positions 0 – 2047 in the file and is 2048 bytes in length. All strings are preceded by a 16-bit integer that indicates the string length. The waveforms are written next right after the header starting at file position 2048 (referenced to 0). Each waveform is 2048 positions with each position represented in Integer (2 byte) format. The waveforms are stored sequentially with the scan proceeding from left to right (scanaxis or X axis) and from bottom to top (increment axis or Y axis) (scan start location is lower left-hand corner).

TABLE 1. HEADER FORMAT SPECIFICATION

Field	Description	Example Value
File Revision as Long	860243022	860243022
Header Size as Long	2048	2048
Data Type as Long	4	4
Scan Units String Length as Integer	Gives the length of string describing scan units	4 or 10 (depending on whether “inch” or “centimeter”)
Scan Units as String	Contains either “inch” or “centimeter”	either “inch” or “centimeter”
Acquisition Device String Length as Integer	Gives the length of string describing Acquisition Device	Egs. 24
Acquisition Device as String	ID string from DAQ card or Acquisition Device	QA-1000 with Spinner Mod
Data Points as Long	Data Points per Waveform	2048
Sample Rate as Single	Sample rate of acquisition device	Egs. 6.4×10^{12}
Scan Axis String Length as Integer	gives the length of string describing Scan Axis	1
Scan Axis as String	Horizontal or vertical B-scan	=A if horizontal B-scan (=B if vertical B-scan)
Scan Axis Points as Long	number of scan axis points	Egs. 171
Scan Axis Resolution as Double	Scan axis dimension measurement interval	Egs. 0.1
Scan Axis Size as Double	Scan axis points x Scan Axis Resolution	Egs. 17
Incr Axis String Length as Integer	Gives the length of string describing Incr Axis	1
Incr Axis as String	Horizontal or vertical B-scan	=B if horizontal B-scan (=A if vertical B-scan)
Incr Axis Points as Long	number of incr axis points	Egs. 169
Incr Axis Resolution as Double	Incr axis dimension measurement interval	Egs. 0.1
Incr Axis Size as Double	Incr axis points x Incr Axis Resolution	Egs. 16.8
Total Scan Points as Long	Scan Axis Points X Increment Axis Points	Egs. 28899
Acquisition Device Gain as Long	Gives voltage range for acquisition	-1 = +/-10V, 1 = +/-5V, 10 = +/-0.5V, 0 = unknown
Acquisition Program Info. String Length as Integer	Gives the length of string describing Acquisition Program Info.	Egs. 24

Acquisition Program Info. as String	Fill in with Scan Version Number ' app. Major app. Minor app. Revision	Egs. SOFI Scan Version 4.1.32
Acquisition Range Lower as Single	Gives lower voltage range for acquisition	Egs. -10
Acquisition Range Upper as Single	Gives upper voltage range for acquisition	Egs. 10

A key feature of this data format is inclusion of the sampling rate of the method (row 9). The exponent of the sample rate is used to automatically determine whether the method is terahertz, microwave, ultrasonic, or radar data. The graphs are then appropriately formatted to reflect the correct time and frequency units for the graphs presented to the user in the software.

4. SUMMARY OF SIGNAL PROCESSING CAPABILITY

Waveform Type Use of raw waves obtained directly from scan or waves after deconvolution if system wave response is provided. Two types of deconvolution, time-based subtraction (ref. 7) or inverse-filter (ref. 8), can be performed to arrive at a deconvolved wave set.

Waveform Pre-Processing prior to Image Formation Subtraction of DC component and Wavelet Denoising (ref. 9) facility are currently provided (that latter interface is shown in figure 2.)

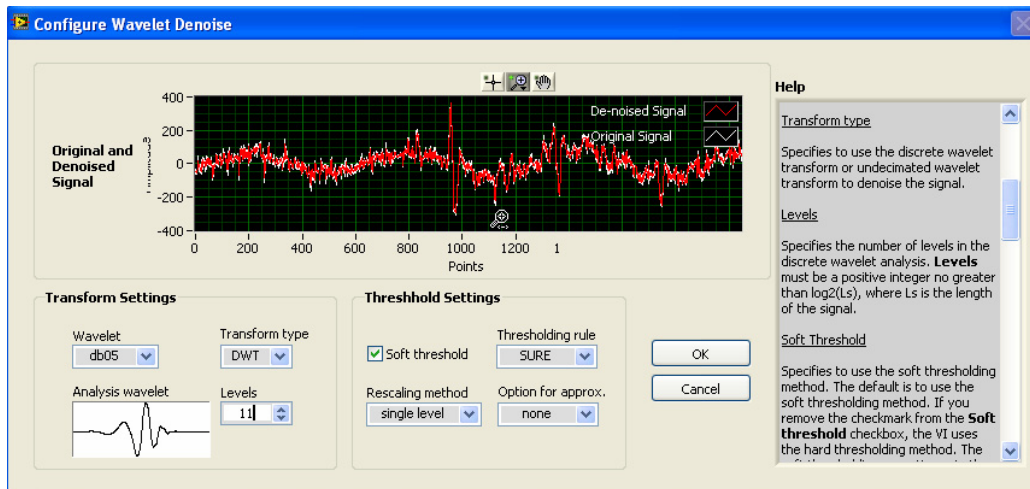


Figure 2.—Wavelet Denoising Facility to remove noise from waveforms. A similar facility for trend extraction and for 2D image denoising and trending using wavelets is also planned. Wave is from a front surface terahertz reflection off of foam.

Feature to Extract from Waveform from Which to form Image A very large set of features are available for both the time-domain waves and their frequency domain transformations. These include amplitude- and time-based features for the time-domain waves and magnitude- and phase-based features for their frequency-domain transformations.

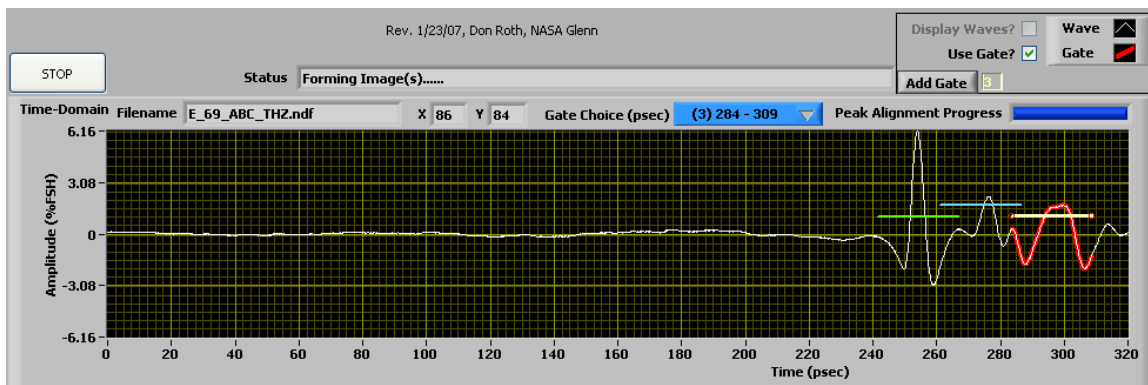
Gating In many cases, the user will want to gate, or window, a certain region(s) of the waveform and then calculate the image from features of the waveform within the region. The user grabs the gate on the waveforms display to move and lengthen it. This software provides several unique gate types including:

- Static gate: Gate stays in the same time position for entire scan set
- Smart gate: Gate tracks a feature of the echo, such as positive peak amplitude, for entire scan set
- Sliding gate: Data set is first peak-aligned by shifting all echoes with respect to the peak of a reference echo. Then the user can grab and move the gate across the waveform and image formation will occur once the gate is released.
- Multiple gates: The user can set up to 16 gates to window various regions of the waveform. Image sets will be created for all set gates for the selected image parameter.

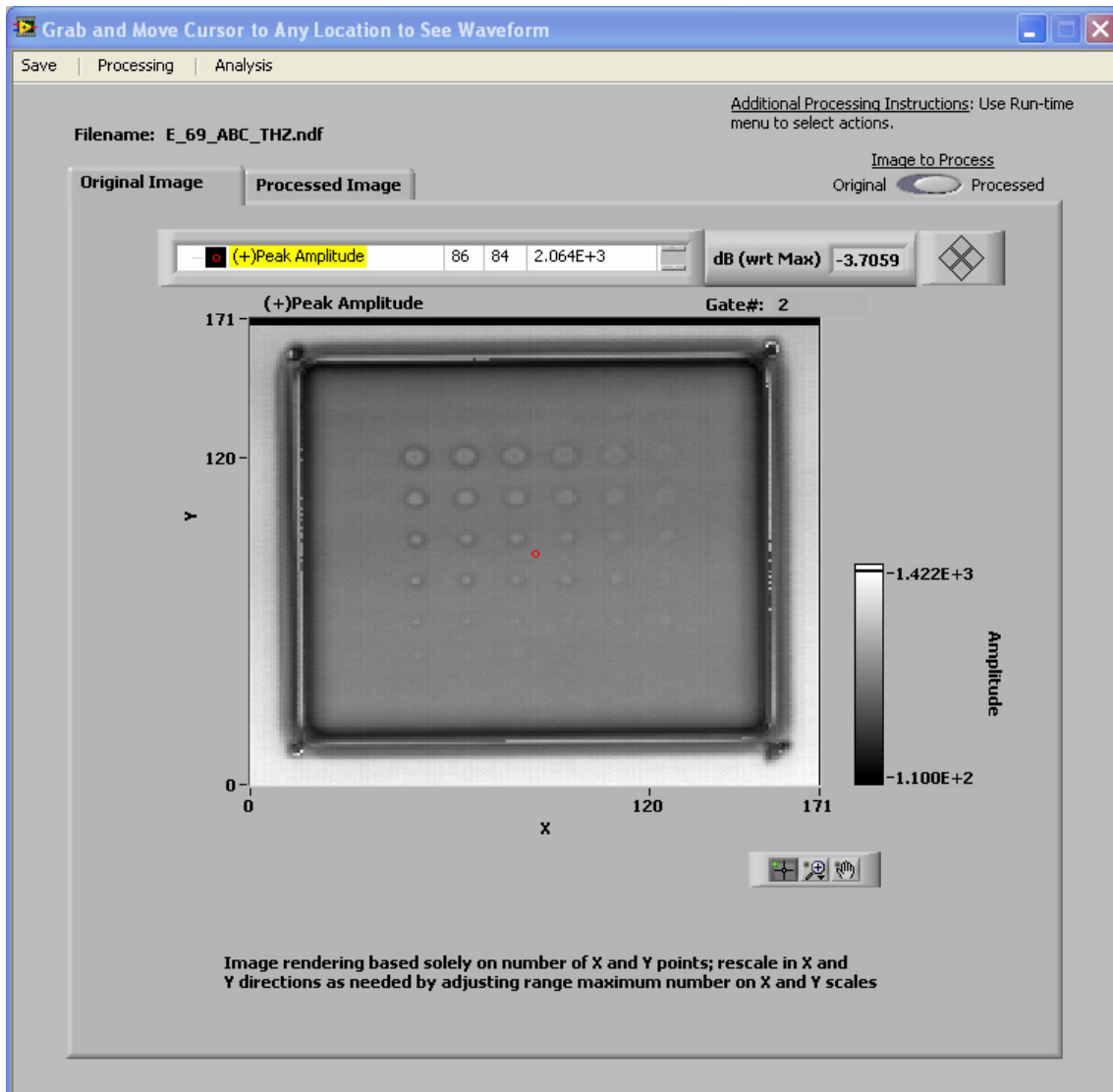
The portion of the waveform within the gate(s) can have the following processing applied prior to image formation:

- Phase Flip (180° shift)
- Full-wave rectification
- Amplification
- DC subtraction
- Time Shift
- Wavelet Denoising

Each gate can have its own set of parameters so that, for example, different amplification factors can be applied for different gates. This flexibility is especially useful when a change in waveform parameters in two gates are involved in an image calculation and one gate has a very weak signal. In figure 1, the gate can be seen as a red horizontal line in the Time-domain waveforms window and the portion of the waveform is highlighted that is encompassed by the gate. Figure 3 shows an example of analysis with three gates set; the user can click near any gate to display the image at that gate, for the selected waveform feature. The user can move a cursor across the image which will display waveforms in the time- and frequency-domain waveform windows at the positions the cursor is being moved to.



(a)



(b)

Figure 3.—(a) Time-domain waveform display showing gating of three areas in waveform. Terahertz wave is from reflection off of a metal substrate after passing through foam sample. Image window showing gate 2 positive peak amplitude image that appears by clicking near gate 2 on waveform display.

Image Types The time-domain waveform and frequency-domain representations have many features that can be extracted to form images from. Additionally, the capability to use multiple gates allows some unique properties such as velocity and thickness to be calculated from time information off of sample front and back surfaces. Image types available include:

- Time-domain
 - Amplitude-based
 - (+)Peak Amplitude
 - (-)Peak Amplitude
 - Peak-to-Peak Amplitude

- Relative Peak Reduction with respect to (wrt) Reference (Ref) Wave
 - Cross-Correlation (ref) Max wrt Ref Wave
 - Amplitude Loss in dB as compared to highest image value
 - Root Mean Square (RMS) Image
 - Relative Power Loss
 - Relative thickness (from attenuation versus thickness relationship)
 - Time-based
 - Centroid Mean Time
 - Time to (+)Peak
 - Time to Gate 1 Threshold (location where echo first intersects gate1 height)
 - Cross-Correlation delay at Max wrt Ref Wave
 - Relative Time Delay wrt Ref Wave
 - Spectrally-weighted Time Delay
 - Velocity/Thickness
 - Delta time between gates 1 and 2 (Peak-to-Peak)
 - Delta time between gates 1 and 2 (Cross-correlation)
 - Peak-to-Peak Velocity
 - Cross-correlation Velocity
 - Peak-to-Peak Thickness
 - Cross-correlation Thickness
 - Thickness-Independent Velocity
 - Microstructure-Independent Thickness
- Frequency Domain
 - Magnitude-based
 - Fast Fourier Transform (FFT) Peak Magnitude
 - Power Spectral Density (PSD) Peak Magnitude
 - Centroid (FFT)
 - Centroid (PSD)
 - Zeroth Moment¹⁰
 - First Moment
 - Second Moment
 - Fourth Moment
 - RMS Image
 - First Harmonic Nonlinearity Parameter
 - FFT Magnitude series (Magnitude as a function of frequency)
 - FFT Power Ratio series
 - PSD Magnitude series
 - Relative Power Loss series
 - Absorption/Refractive Index series
 - Phase-based
 - Phase Velocity (Velocity as a function of frequency)
 - Phase Delay wrt Ref Wave series

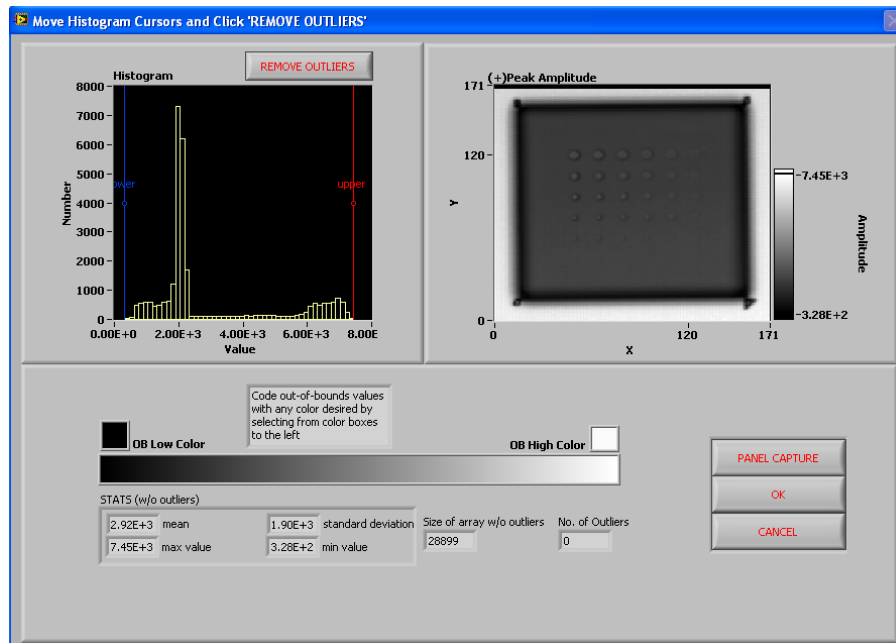
Details on these algorithms can be obtained by contacting the authors. New image types will be added as needed.

5. SUMMARY OF IMAGE PROCESSING AND ANALYSIS CAPABILITY

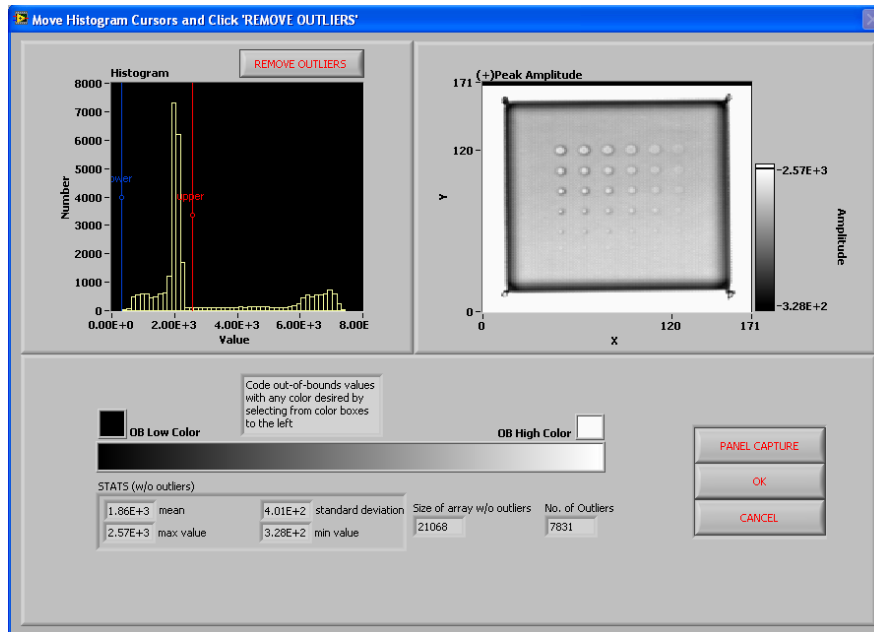
The Image Window shown in figure 1 again has logically-derived run-time menus from which actions are chosen. The ability to save an image or image series after their formation in various formats such as .bmp, .png, etc. and .txt spreadsheet format is provided. The Image Window contains two tabs, one with the original image and one with the processed image (after processing with functions listed below). This facilitates easy comparison between processed and original images. Processing steps can continue successively on the processed image, or the user can choose to always process the original image so only one processing step is applied.

Image Processing Functions The following functions are available to process the image or image series shown in the Image Window:

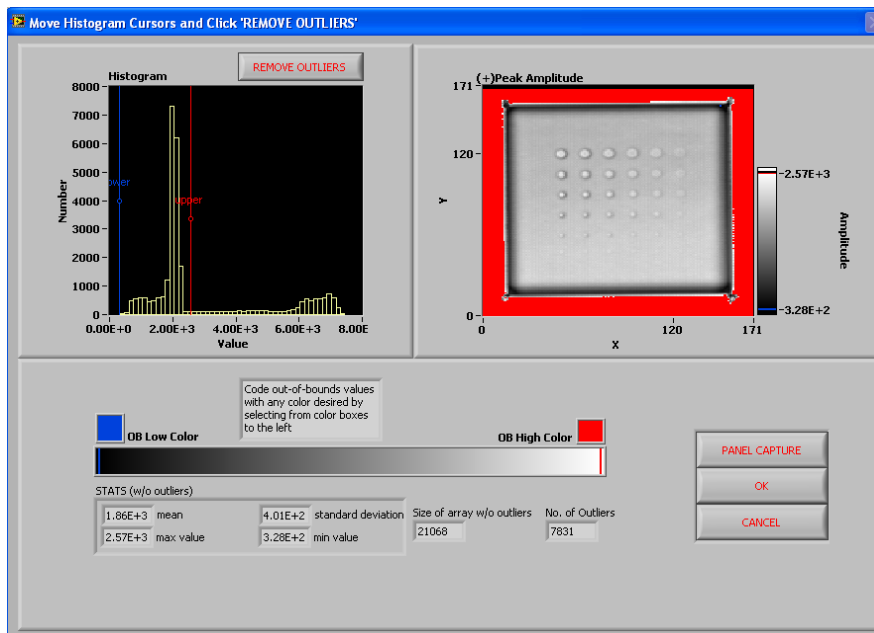
- Normalization
- Gray Scale Balance (brightness, contrast, gamma)
- Custom Color Table Creation
- Bad Pixel (outlier) removal (see fig. 4)
- Image Equalization
- Three-dimensional surface graph representations of images
- Orientation Modifications (flips, mirror, transpose, rotation)
- Edge Detection
- Smoothing
- Convolution
- Deconvolution (Inverse Filter, Weiner) (ref. 8) given a Point Spread Function



(a)



(b)



(c)

Figure 4.—The Outlier Removal Facility uses a histogram to show the values in the image. By moving the lower bound (blue) and upper bound (red) cursors to the right and left, respectively, pixel values outside of the cursors are set equal to out-of-bounds low and high colors, respectively. This facility is used to effectively increase contrast that is dulled by outliers or background pixels. (a) Prior to removing outliers. (b) After removing outliers, out-of-bounds low and high colors are black and white, respectively. (c) After removing outliers, out-of-bounds low and high colors are blue and red, respectively.

It is expected to soon add wavelet denoising among other capability to the image processing functions.

Image Analysis Functions The following functions are available to process the image or image series shown in the Image Window:

- B-Scan (ref) Display (see fig. 5)
- Image Math (for Image Series such as from a series of time gates or frequency analysis) (additions, subtractions, divisions, scale factor)
- Images Average (for Image Series)
- Principal Component Analysis (for Image Series) (see fig. 6)
- Region-of-interest processing and means testing (see fig. 7)
- Line Profile and Feature Measurement (see fig. 8)

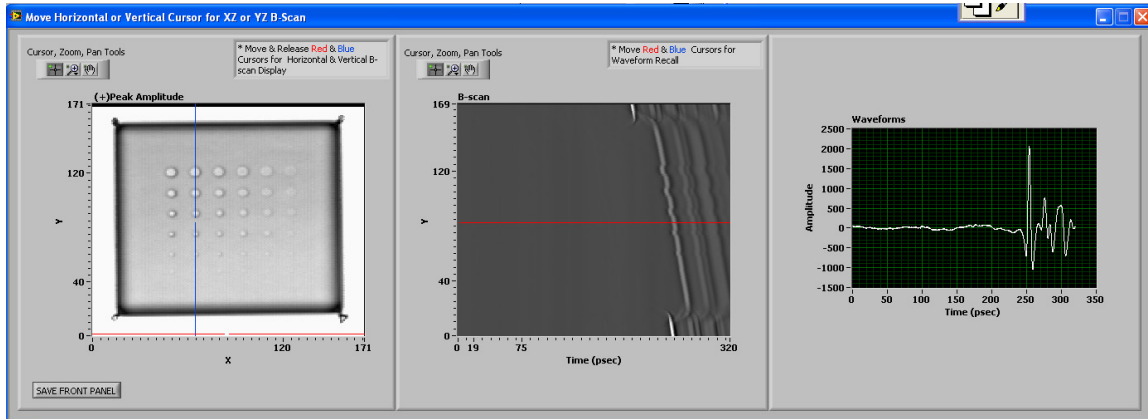


Figure 5.—B-scan facility that allows XZ and YZ ultrasonic slices.

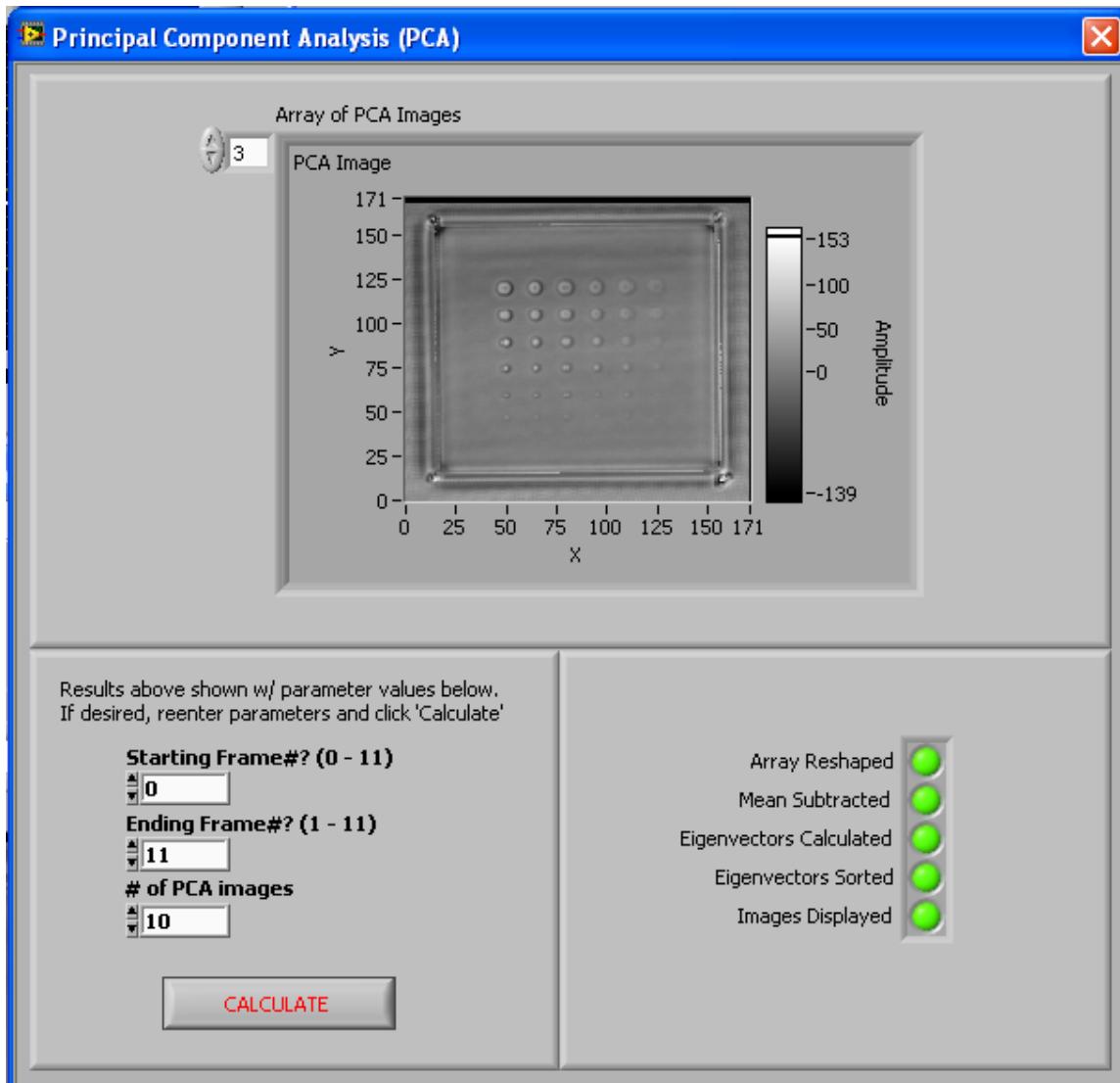


Figure 6.—Principal Component Analysis (ref) to extract feature patterns in image series such as FFT Magnitude series.

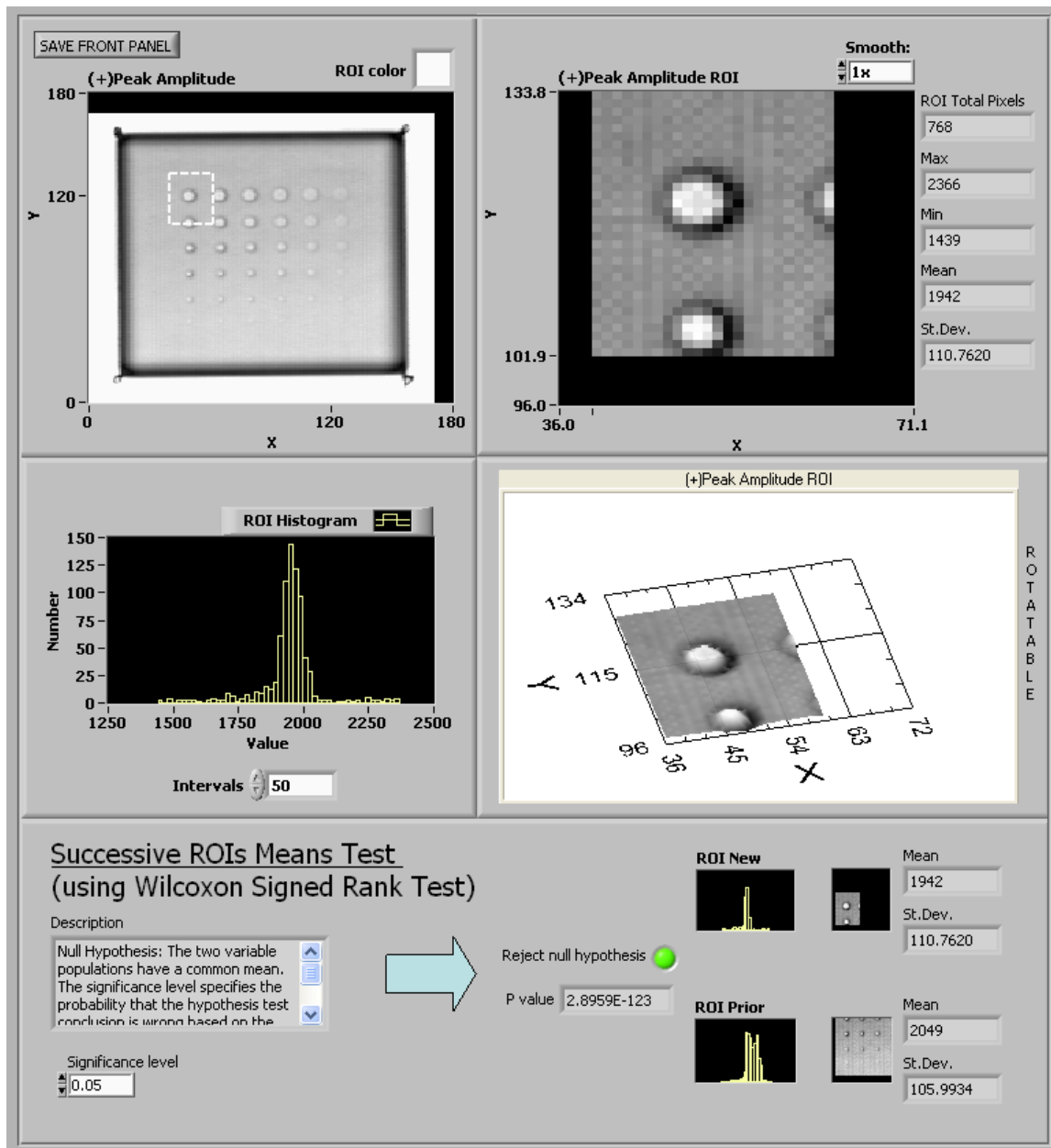
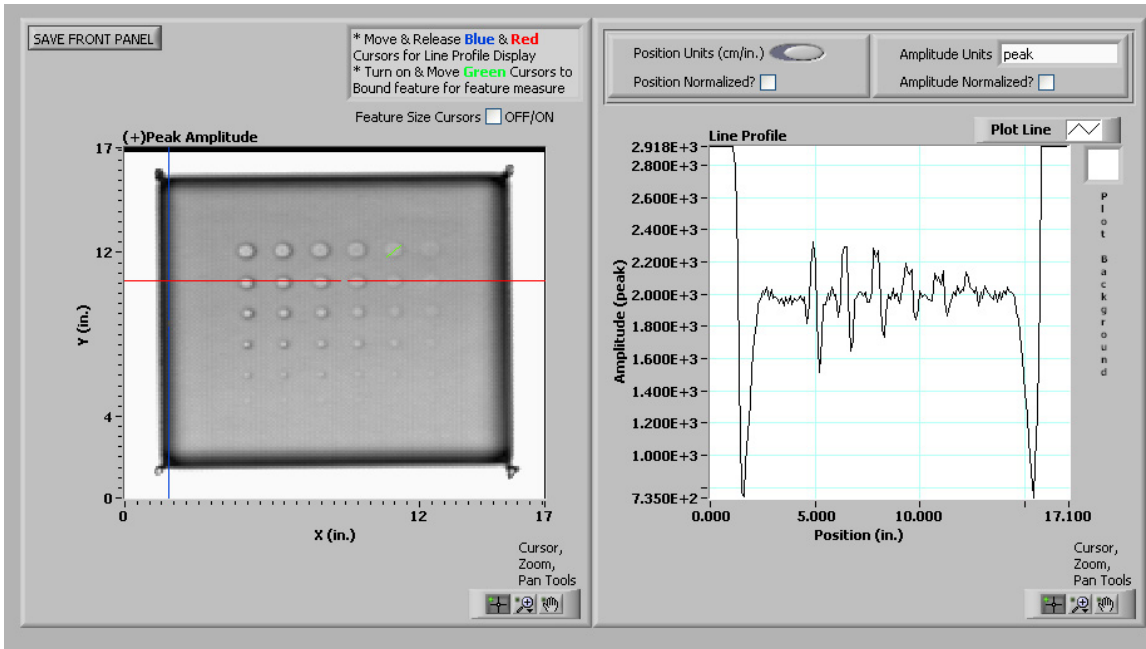
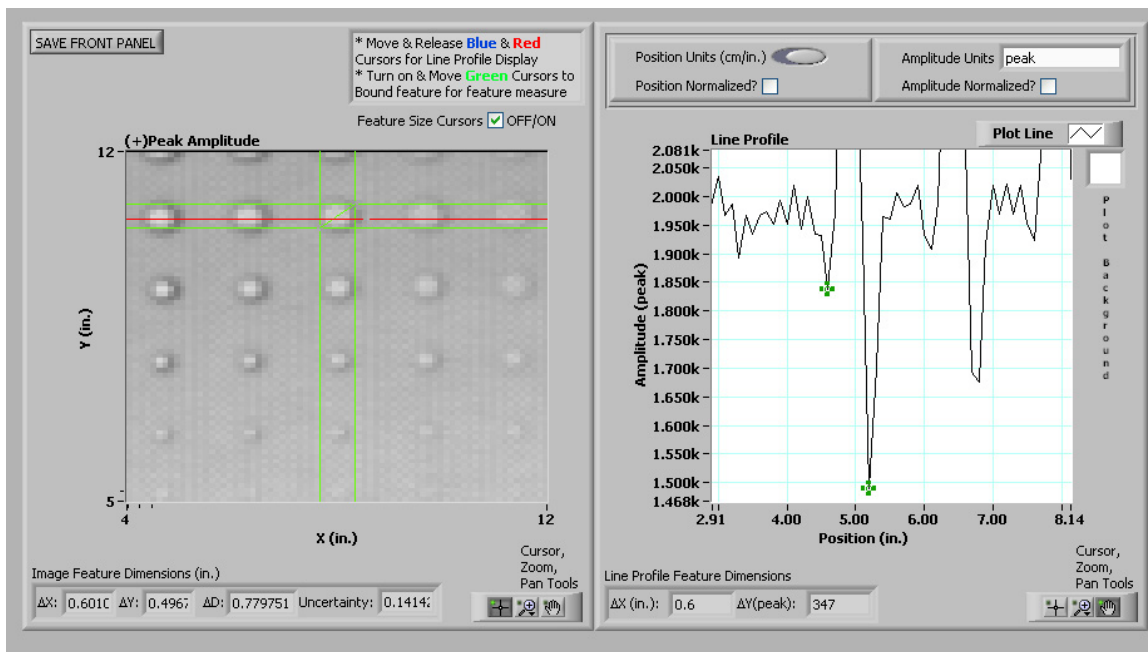


Figure 7.—Region-of-Interest (ROI) Image Analysis facility. Statistical means testing of various ROIs can be used to validate subjective differences observed or test for visually unobservable differences in high density images.



(a)



(b)

Figure 8.—(a) Line Profile and Feature Measure Image Analysis facility. Line profiles can be formed for both horizontal and vertical lines through image. (b) Precision dimensional measurements of features such as void diameter can be made, either using cursors on image or cursors on line profile.

6. FUTURE WORK

It is planned to continue to add common and unique capability to this software through collaborations with other scientists and engineers both at NASA and in the external community. Additionally, with so many image choices available, how does one select the best image or the one with most contrast? NASA is currently engaged in implementation of algorithms to “grade” various signal processing methods by providing a quantitative measure well correlated to the ability to subjectively distinguish flaw data from noise or background data (ref. 11).

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