

## Quarterly Research Performance Progress Report

**Federal Agency and Organization:** DOE EERE – Geothermal Technologies Program

**Recipient Organization:** Oak Ridge National Laboratory

**Project Title:** Ultrasonic Phased Arrays and Interactive Reflectivity Tomography for Nondestructive Inspection of Injection and Production Wells in Geothermal Energy Systems

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# Table of Contents

<b>EXECUTIVE SUMMARY</b> .....	3
<b>ACCOMPLISHMENTS &amp; MILESTONE UPDATE</b> .....	3
<b>Project Status Summary:</b> .....	3
Task 2 – Modeling and simulation to support design: .....	4
Task 3 – Initial MBIR Reconstruction Code: .....	5
Task 4 – Complete design, fabrication, and testing of acoustic phased array system: .....	6
Task 5 – Design and build simple laboratory testing environment: .....	10
<b>PROJECT MANAGEMENT</b> .....	10
<b>PROJECT OUTPUT</b> .....	11

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## **EXECUTIVE SUMMARY**

For the past quarter, we have placed our effort in implementing the first version of the Model-Based Iterative Reconstruction (MBIR) algorithm, assembling and testing the electronics, designing transducers mounts, and defining our laboratory test samples. We have successfully developed the first implementation of MBIR for ultrasound imaging. The current algorithm was tested with synthetic data and we are currently making new modifications for the reconstruction of real ultrasound data. Beside assembling and testing the electronics, we developed a LabView graphic user interface (GUI) to fully control the ultrasonic phased array, adjust the time-delays of the transducers, and store the measured reflections. As part of preparing for a laboratory-scale demonstration, the design and fabrication of the laboratory samples has begun. Three cement blocks with embedded objects will be fabricated, characterized, and used to demonstrate the capabilities of the system.

During the next quarter, we will continue to improve the current MBIR forward model and integrate the reconstruction code with the LabView GUI. In addition, we will define focal laws for the ultrasonic phased array and perform the laboratory demonstration. We expect to perform laboratory demonstration by the end of October 2015.

## **ACCOMPLISHMENTS & MILESTONE UPDATE**

### **Project Status Summary:**

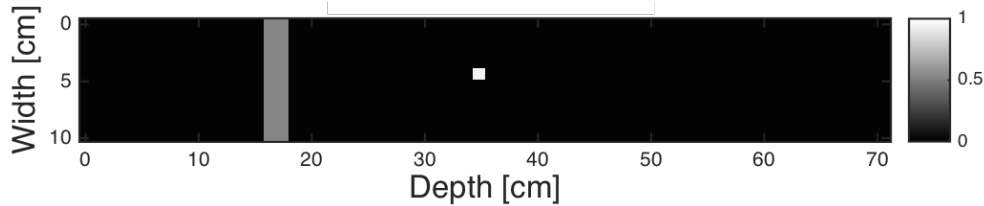
Task	Title	Planned Completion Date	Completion Date or % completion
1	Performance specification for ultrasound system	2/28/2014	100%
2	Modeling and simulation to support design	4/28/2014	100%
3	Initial MBIR Reconstruction Code	6/30/2015	100%
4	Complete design, fabrication and testing of acoustic phased array system	7/30/2015	75%
5	Design and build simple laboratory testing environment	8/31/2015	20%
6	Adapt MBIR algorithm for progressive reconstruction scheme	9/30/2015	0%
7	Experimental analysis and tuning	10/31/2015	0%

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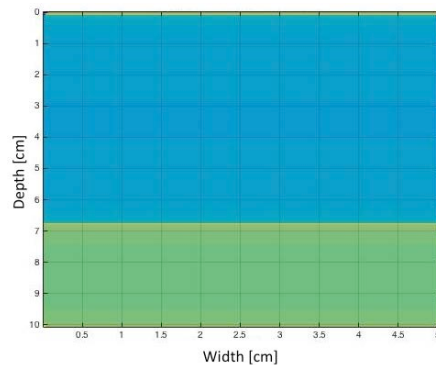
**Status:** *Task 1 was completed and our progress on this task was documented on previous quarterly reports. Tasks 5, 6, and 7 are not part of the reporting period; therefore, they will be discussed on future reports. We provide a preliminary report on progress for Task 5. Below is our progress report for Tasks 2, 3, and 4.*

**Task 2 – Modeling and simulation to support design:**

- Planned Activities:** Develop synthetic samples on an existing linear acoustic simulator (e.g., Field II). The samples will vary in complexity. Beside different media configurations, we will simulate prospective phased array configurations. Initially, synthetic ultrasound signals will be used to test the reconstruction code.
- Actual Accomplishments:** We currently have two methods for generating synthetic ultrasonic signals. The first method consists of back-propagating image phantoms, such as the example in Figure 1, with our wave propagation code. This allow for rapid testing of the MBIR algorithm with irregular interfaces. This method suits better when the medium is assumed homogenous. We can also generate synthetic datasets using the ultrasound simulation engine K-Wave (See Figure 2). This software package is conveniently coded in Matlab. With K-Wave, we can test complex systems that include wave propagation features that are absent in our MBIR forward model in order to provide more realistic test samples. One example is the possibility of simulating shear waves while our current reconstruction code only considers the propagation of longitudinal waves.



**Figure 1:** Illustration of phantom used to generate synthetic ultrasound signals. The intensity of the pixels corresponds to the Intensity Reflectivity Coefficient for the medium at that pixel. Transducers are placed at the left of the image.



**Figure 2:** Heterogeneous sample generated with K-Wave. The blue region corresponds to cement and the green region corresponds to steel. The pixel intensity corresponds to a material category. Each material category links to a set of acoustic properties, such as p-wave speed, s-wave speed, density, attenuation, etc. Transducers are placed at the top of the image.

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3. **Explanation of Variance:** At first, we proposed to use Field II as our simulation engine for ultrasonic waves. We opted for K-Wave because it was implemented in Matlab, the routines are well documented, and it is GPU-capable. The GPU capability significantly reduces computational time.
4. **Plans for Next Quarter:** We will continue generating new synthetic datasets. The goal is to increase the complexity of the samples to find issues with the current implementation and to have better insight about the limitations of the current MBIR forward model.

### Task 3 – Initial MBIR Reconstruction Code:

1. **Planned Activities:** Port X-Ray MBIR code to ultrasound imaging. There will be a progressive development of the reconstruction algorithm. At first, the mathematical models for sound propagation will be simple and as we move forward these models will increase in complexity
2. **Actual Accomplishments:** For a full documentation of our progress developing the MBIR algorithm, we included with the report a draft of the paper we presented at the Review of Progress on Quantitative Nondestructive Evaluation (QNDE) Conference. We have developed an initial implementation of the reconstruction algorithm for ultrasonic signals. The current software assumes isotropic sources and sensors and models longitudinal waves (i.e., p-waves) propagating in a homogenous medium. The code was tested with synthetic samples and performed as expected. For the prior model, we selected a q-Generalized Gaussian Markov Random Fields (q-GGMRF), which has shown to greatly improve image quality for other modalities. In addition, we selected Iterative Coordinate Descent (ICD) as the optimization algorithm. Typically, this algorithm shows fast and stable convergence. Usually, the algorithm is initialized with a low frequency (i.e., blurred) version of the object. The low frequency initial object estimate could be obtained from back projection or from other reconstruction techniques such as SAFT. ICD emphasizes high frequency components during convergence.

Figure 3 illustrates a snapshot of the forward model system matrix coefficients for the row corresponding to 133us. The forward model was generated for a single transducer pair located at the bottom-left and top-left of the propagation plane. The input signal  $s(t)$  is a five-cycle sine wave tapered with a Hanning Window. As expected, the coefficients' amplitudes are constant at equal propagation distances. Similarly, the coefficients at system matrix rows corresponding to a longer propagation time are smaller due to attenuation.

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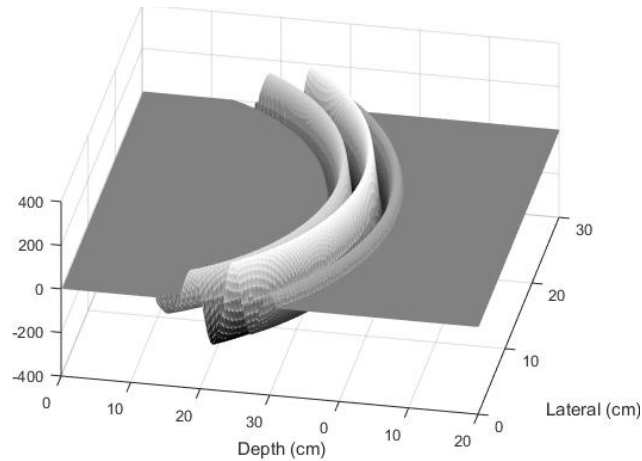


Figure 3: Illustration of system matrix coefficient amplitudes for two transducers at time 133us.

3. **Plans for Next Quarter:** Continue improving the forward model and test the system with more complex synthetic samples. In addition, we will start integrating the reconstruction code to our ultrasound system software package.

**Task 4 – Complete design, fabrication, and testing of acoustic phased array system:**

1. **Planned Activities:** The transducers and control system will be assembled and functional testing of the electronics will be performed.
2. **Actual Accomplishments:**

**Hardware**

We have assembled and tested the analog pulser/receiver driver and the analog to digital converter board (See Figure 4). We also tested all 16 transducers and started the characterization process (See Figure 5).

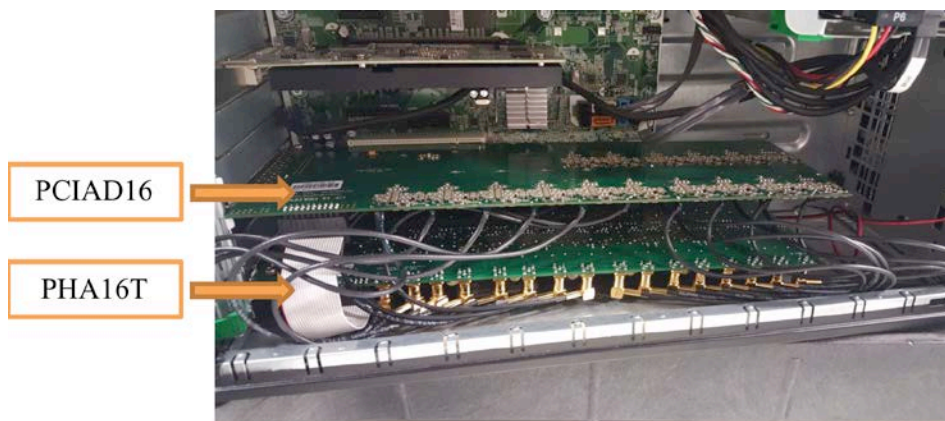


Figure 4: US Ultratek 16-channel PCIAD1650 analog to digital converter board with simultaneous acquisition, and 16-channel PHA16T ultrasonic pulser/receiver and phased array board.

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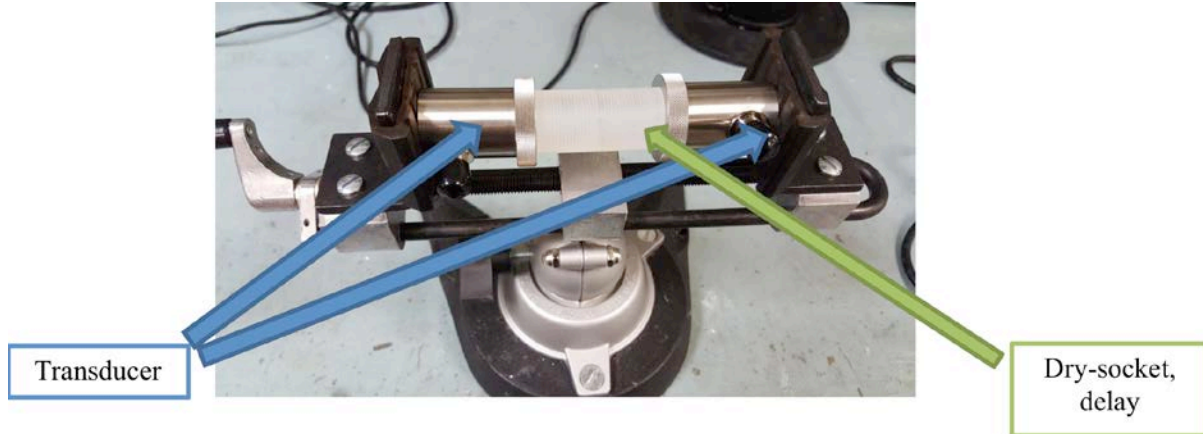


Figure 5: The Ultran Group GRD100-D19 100kHz Delayed Contact Transducers with 19 mm active diameter.

### Computer Software

We developed a Graphical User Interface (GUI) in LabVIEW to download parameters, initiate signals, acquire return transmissions, and display/format data. We can control the following parameters: sampling rate, high and low-pass filters, buffer length (number of samples), trigger delay, data type (8 or 10-bit data), amplifier gain, DC offset, pulse delay, transducer mode (single: pulse and receive with one transducer, dual: pulse and receive with two transducers), pulse voltage, tone burst frequency, tone burst polarity, number of half-cycles (number of pulses). This program can control up to 16 transducers with live-signal display. The transducers and boards went through several tests. For example, Figure 6, Figure 7, and Figure 8 show testing of the boards without any transducer attached to them. We ran the board diagnostic tools to make sure that the electronics meet the manufacturer specifications. Figure 7 and Figure 8 show the developed GUI displaying two channels and the system parameters and displaying 16 channels, respectively.

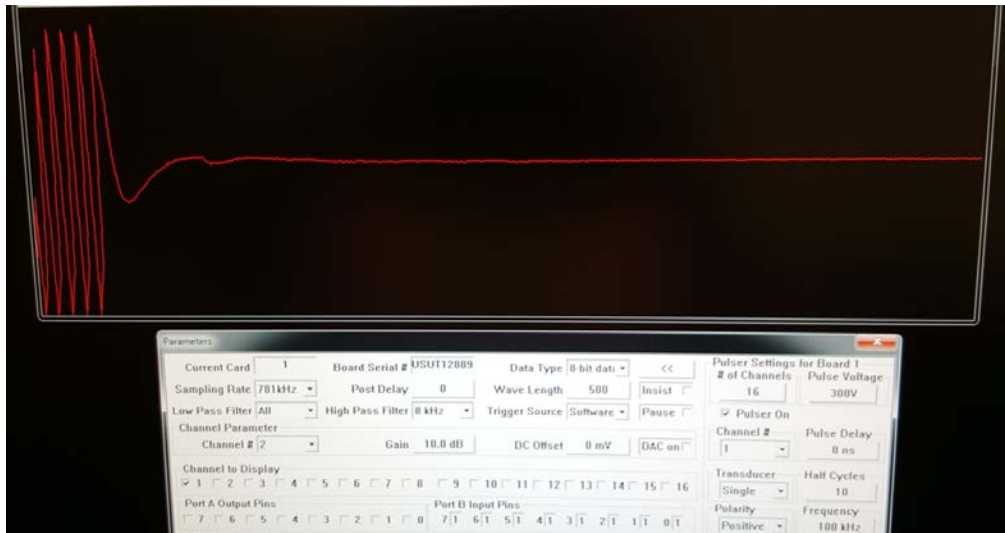


Figure 6: Testing signal output with no transducer connected.

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Figure 7: System parameters and 2-Channel Display

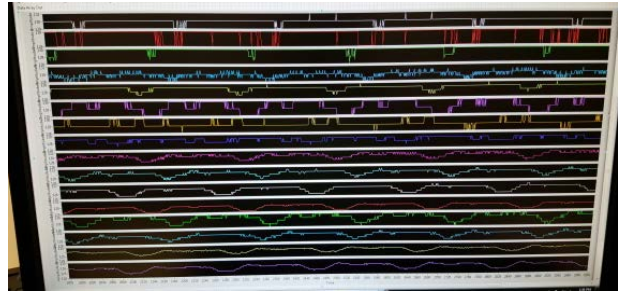


Figure 8: GUI for 16-Channel Display

The next step was to connect the transducers and perform calibration tests. Our first test was to measure the received voltage with a high-end oscilloscope. Figure 9 shows probing the output signal with an oscilloscope, using a 10x-probe. The oscilloscope results (See Figure 10) showed a peak voltage of approximately 150 V (pulse voltage was 300 V peak-peak), with frequency of 100 KHz. We also performed over the air, through a 1inch polyethylene plate (Figure 11), and direct-contact (Figure 13) transmission tests. All test resulted in the expected behavior.



Figure 9: 10x oscilloscope probe.

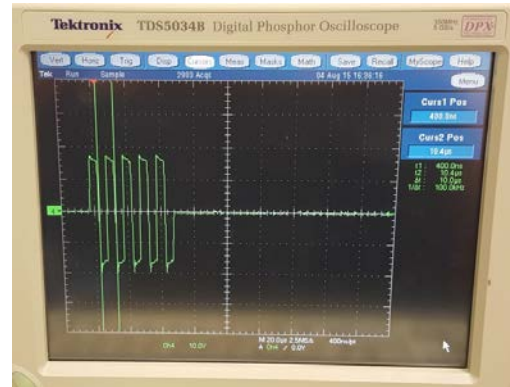


Figure 10: Oscilloscope display showing approximately 300V peak to peak



Figure 11: Transducer 1 pressed against 1 inch-thick polyethylene



Figure 12: Output of polyethylene test.

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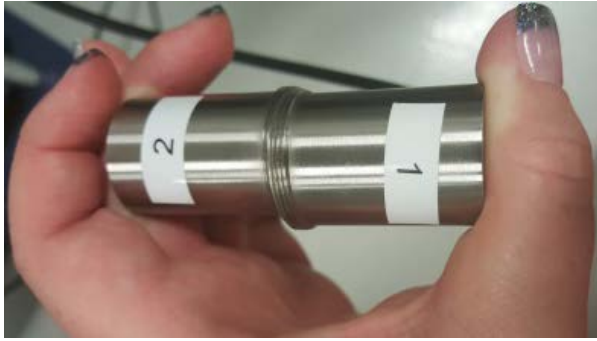


Figure 13: Direct-contact transducer test.

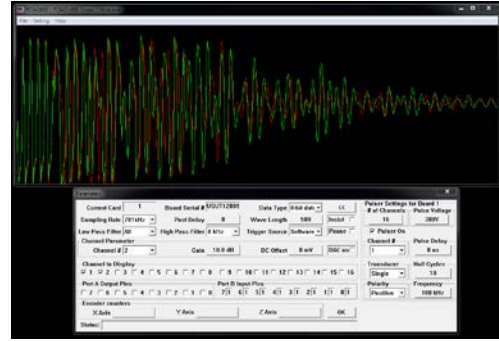


Figure 14: Output of direct-contact test.

Finally, we also designed a few configurations for the phased array rig prototype. Figure 15 shows a 2D configuration with two rows of eight transducers. The rig design allows for easy adjustment of the transducer center-to-center pitch and the distance between the transducers rows.

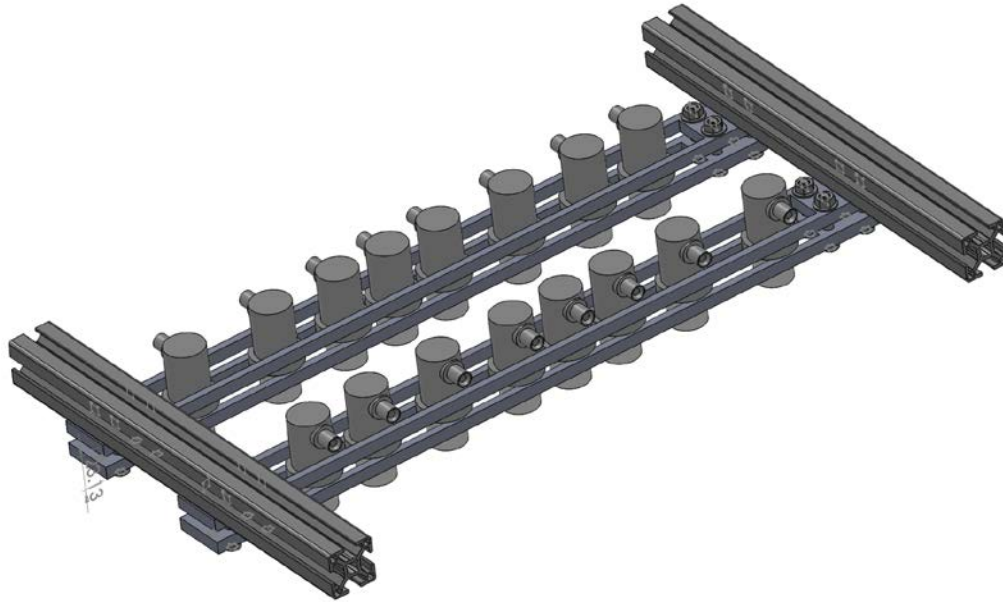


Figure 15: Phased array prototype rig.

3. **Explanation of Variance:** The plan was executed successfully.
4. **Plans for Next Quarter:** The transducers will be tested together as a phased array and characterized. Ultrasound focal laws will be defined and software will be developed to dynamically control the focal laws of the phased array.

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## Task 5 – Design and build simple laboratory testing environment:

1. **Planned Activities:** This task will focus on designing and building a sensor characterization and testing environment.
2. **Actual Accomplishments:** We started the design process for our laboratory test samples. Figure 16 shows one sketch of three laboratory samples that will be fabricated in the next few weeks. The laboratory sample is a cement slab with a 0.25 inch thick steel plate at 100mm from the surface and a one-inch diameter steel sphere 165mm from the surface. The Oak Ridge National Laboratory (ORNL) acronym was engraved in the steel plate with 6mm deep grooves.

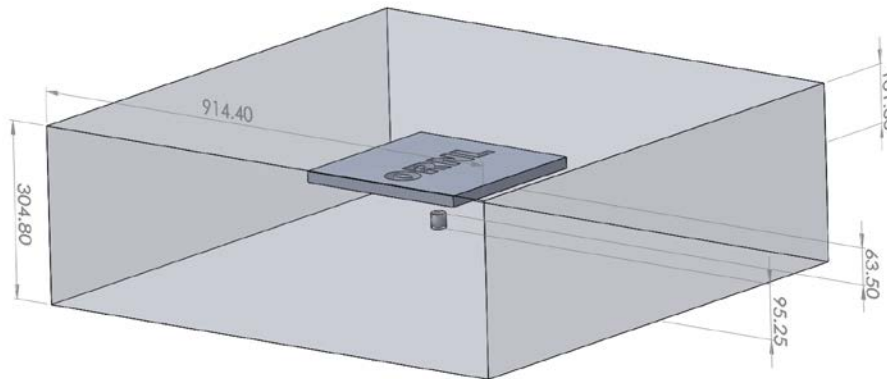


Figure 16: Illustration of one of the laboratory test samples. The unit scale for the sketch is in mm.

3. **Explanation of Variance:** The planned completion date is outside this reporting period.
4. **Plans for Next Quarter:** We will fabricate the laboratory samples and define the experiments that will be performed.

## PROJECT MANAGEMENT

**Issues, Risks, and Mitigation (If Applicable):** After we build the laboratory samples in Task 5, we will be able to assess the compatibility of the current MBIR forward model with the real system (e.g., transducer beam pattern, transducer receiving pattern, propagation model, etc.). If the real system deviates significantly from the mathematical models, we need to modify our current MBIR implementation. This may delay our final demonstration for a couple weeks, but should have no impact on project expenditures and/or changes in scope.

**Changes in Approach (If Applicable):** There have been no changes in the technical approach and we do not envision any near future changes.

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**Key Personnel (If Applicable):** There have been no changes to key personnel. We added three more students to the team. Currently, Prof. Bouman has two Ph.D. students helping with the development of MBIR and the ORNL team has two interns helping with the ultrasound system communication and control software and characterizing the transducers.

### **PROJECT OUTPUT**

**Publications:** We presented a paper at the 2015 Review of Progress in Quantitative Nondestructive Evaluation Conference sponsored by the American Institute of Physics last July. We are currently preparing an abstract submission for the Electronic Imaging Conference at San Francisco, and will submit another abstract to present our work at the 41st Stanford Geothermal Workshop.

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