In Situ Acoustic Measurements: A Wave Focusing and Fracture Characterization Feasibility Study

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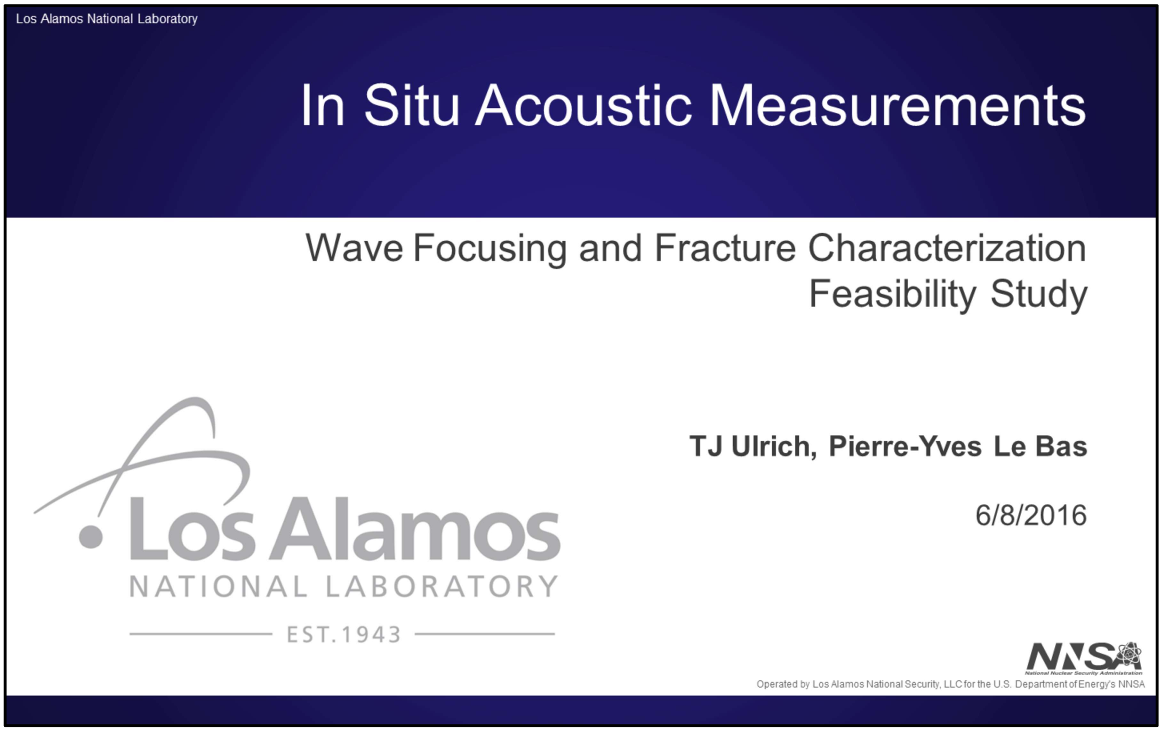
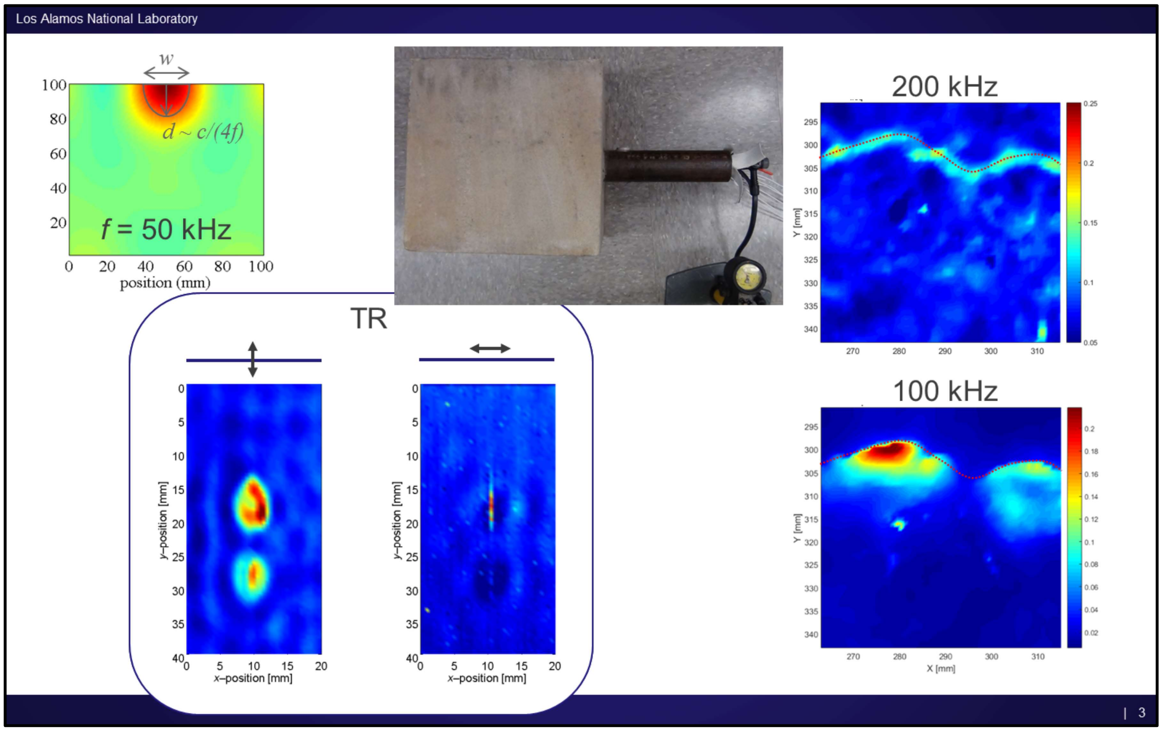
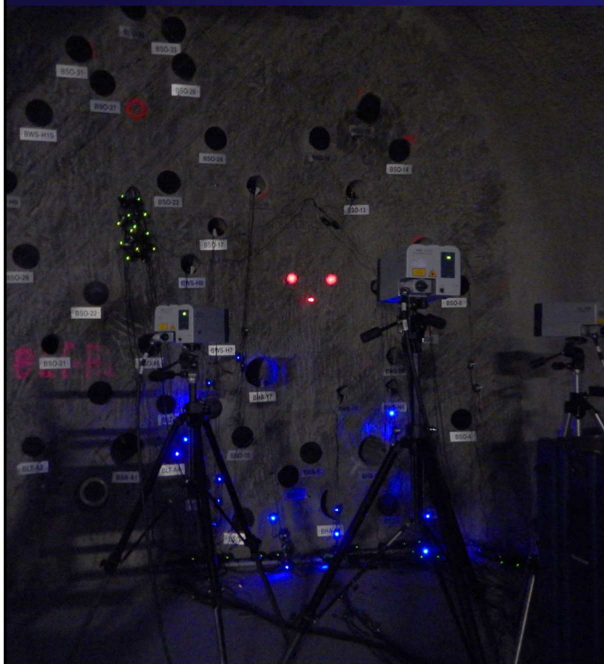


- The following pages contain slides presented during the lightning talk round of the deep borehole session at the 2016 annual UFD meeting in Las Vegas, NV, held June 7-9. Each slide is included here with a brief annotation describing the content and important points. For more information please contact TJ Ulrich at Los Alamos National Laboratory. (tju@lanl.gov)

- The purpose of the preliminary study was to demonstrate the ability to implement laboratory, i.e., bench-top, developed techniques in situ for site characterization purposes. The selected technique is generally referred to as the Time Reversed Elastic Nonlinearity Diagnostic (TREND), which utilizes focused elastic waves to probe the material for mechanical defects and/or degradation, e.g., fractures. A tool under development would be deployable in tunnel and borehole environments for detecting and imaging fractures, among other mechanical degradation features.



- **This slide contains examples of TREND applications as follows:**
  - (top left) the ability to probe into the material from the surface (orientated at the top of the figure) of the borehole or tunnel to a depth relative to the chosen wavelength (governed by the frequency of the wave f, and the speed of sound, c, in the material).
  - (top center) a bench top demonstration of the concept. The tool is emplaced inside the pipe casing which is embedded into a sandstone block. This system was used as a proof of concept to demonstrate the ability to conduct TREND measurements in a confined space.
  - (lower left) the ability to detect and image features and their orientation, by focusing different directions of wave motion (indicated directly above each image. These images are delaminations (left) and a penetrating crack (right) in the same composite plate at the same location but only visible when the appropriate focused excitation is used.
  - (right top & bottom) Images of the same crack as measured using TREND on a stress corrosion crack in a metallic welded specimen. Top image uses high frequencies (i.e., small penetration depth) to image the near surface opening of the crack. Bottom image uses lower frequencies to penetrate deeper into the material and image the downward turning of the crack as it penetrates below the surface.



In Situ Experiments

- Purpose
- Setup
- First results

- An image of the tunnel wall (TT niche at Mont Terri) where the in situ underground measurements were conducted. The 3 laser spots (red) emanate form the Polytec 3D scanning laser Doppler vibrometer, which is used to measure the full elastic wave field throughout the experiments in the region of interest (ROI). The blue lights are power indicators for the acoustic source amplifiers. The acoustic sources (16 used) were placed in the horizontal boreholes surrounding the ROI. The ROI is roughly the center of the photo and was approiximately 1.5m X 1.5m. Green lights are power indicators for the acoustic sources. Large black circles are openings of horizontal boreholes.

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Purpose

- **Test our ability to scale lab measurement to field for both instrumentation deployment and frequency range change**
  - ✓ Tests were done at the Mont Terri Underground Laboratory, Switzerland in shale
  - ✓ Equipment shipped from LANL
  - ✓ Low Frequency sources used for larger scale experiment
- **Primary goal: focus acoustic waves in the formation**
- **Secondary goal: measure nonlinear signature from formation fractures**

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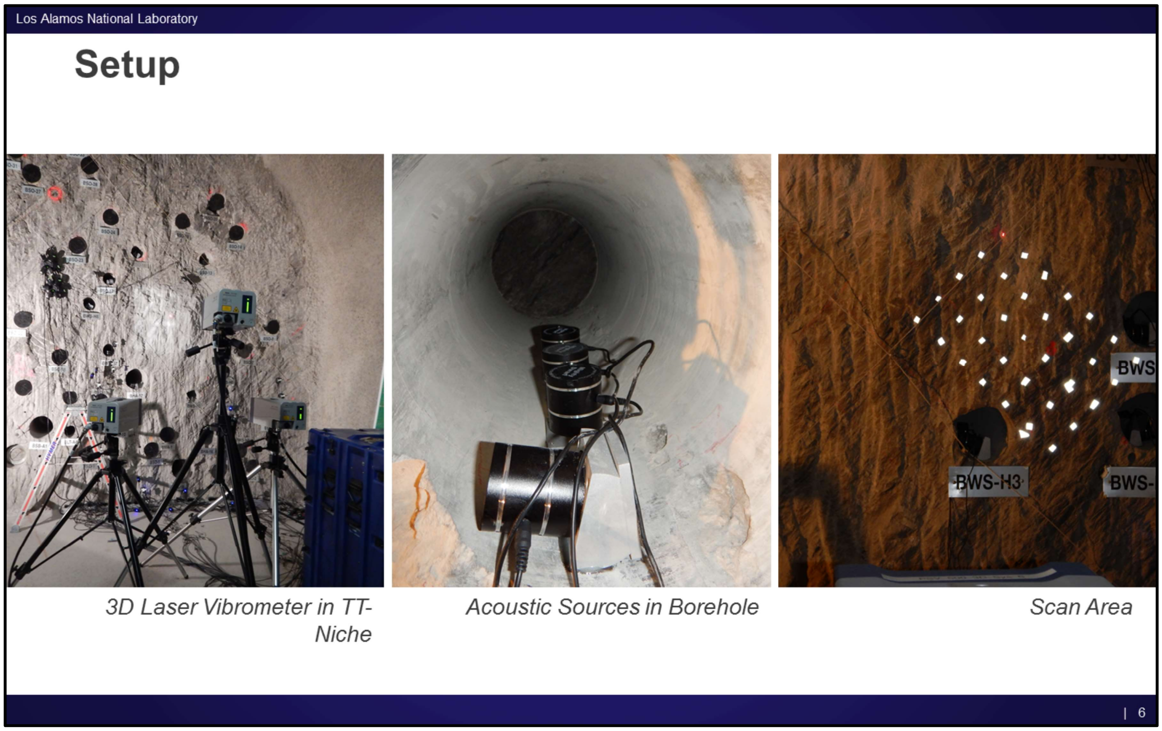
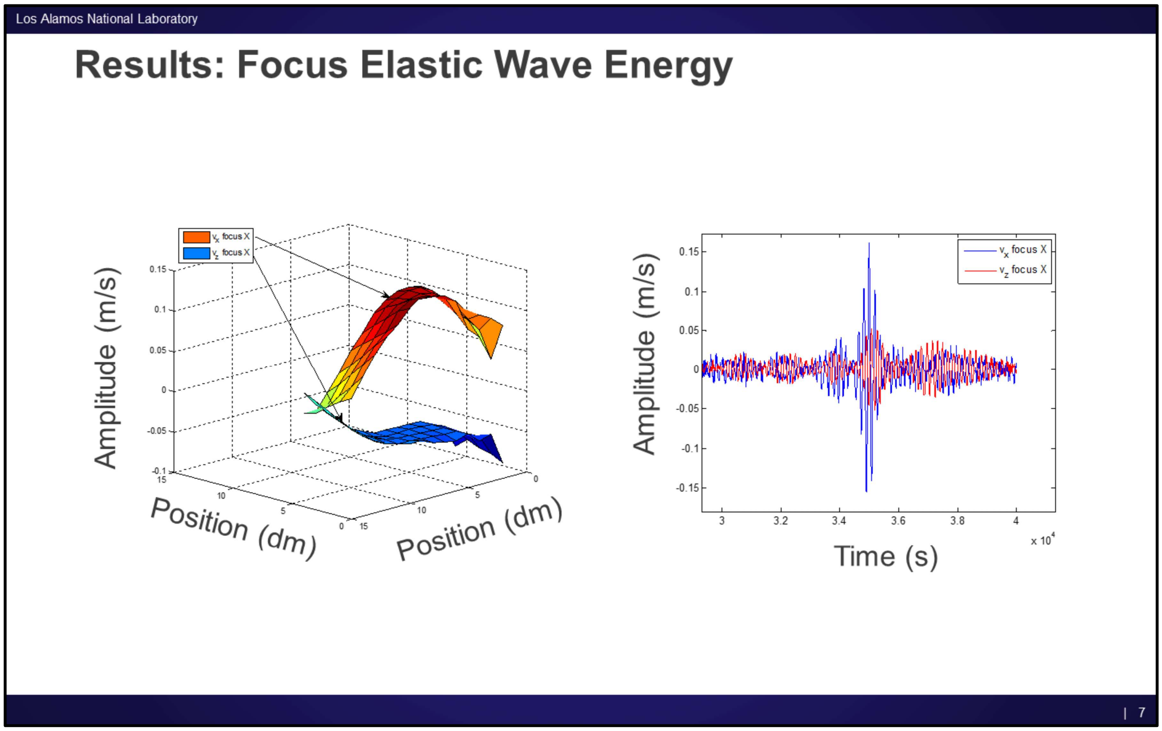
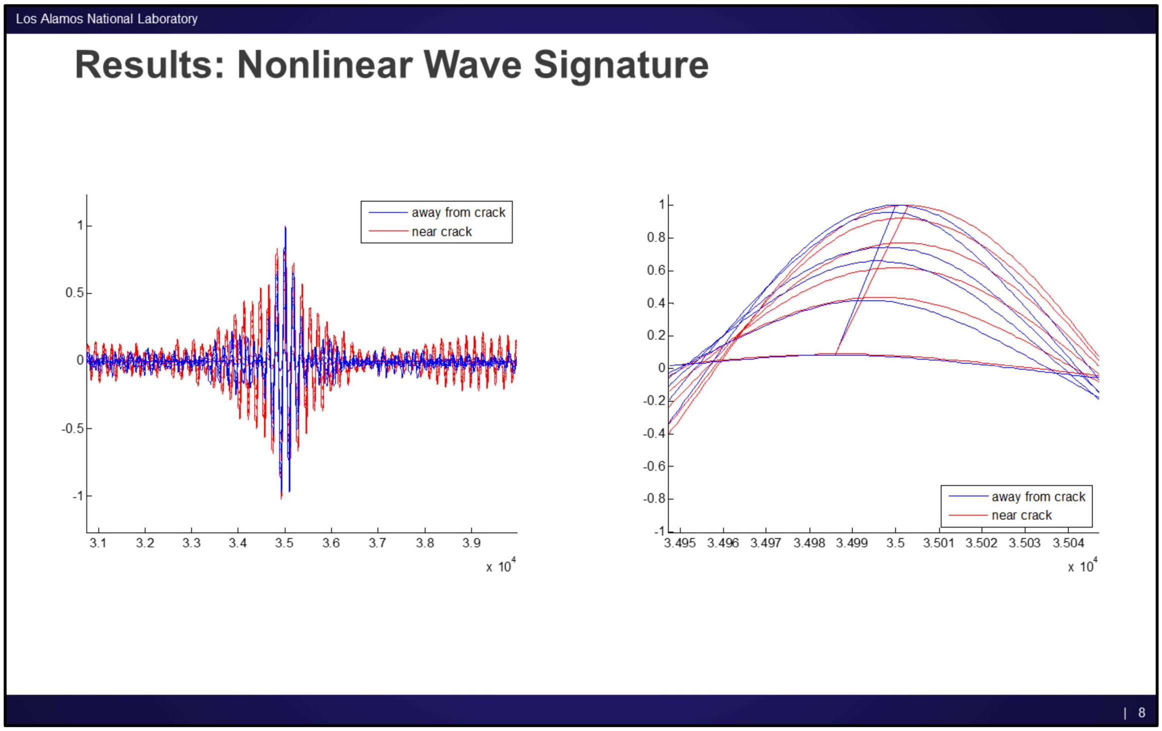
- **Measurements were conducted at Mont Terri Underground Laboratory near St. Ursanne, Switzerland. As stated, the purpose was two-fold: 1) to assess deployability, 2) to determine if the sensitivity of the measurement allows for discrimination between fractured and non fractured regions when conducted in situ.**



- **More photos from Mont Terri:**
  - (left) laser system for full wavefield measurements.
  - (center) acoustic source (~2” tall, 1.5” diameter) emplaced in the borehole with minimal coupling.
  - (right) A scanning grid in the ROI.

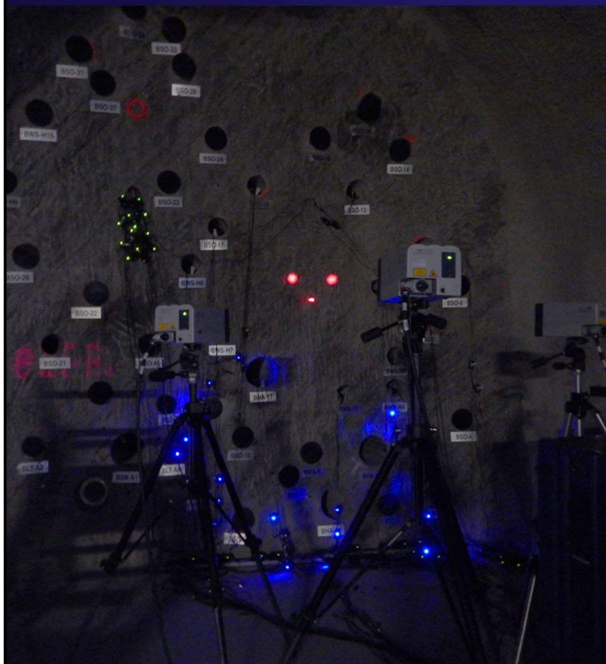


- **Elastic wave focusing in the highly attenuative and scattering medium (i.e., the rock formation) was successfully achieved using Time Reversal (TR). The focusing can be observed 1) spatially in the ROI (i.e., localized high amplitude in the left image), 2) temporally (right image, high amplitude only for a short period of time), and 3) only in the selected component of motion (i.e., high amplitude in the x-component of motion but not in the z-component, visible in both plots). In short, the TR focusing technique performed as expected and is suitable as an in situ elastic wave focusing technique. The frequencies of the waves focused in these measurements were in the range of 3-10 kHz, producing a localized focal region approximately 0.5m in diameter.**



- To determine whether or not the TREND technique is suitable for in situ fracture detection, imaging, and characterization, it is necessary to compare the nonlinear elastic signature at a location away from a fracture and another at the fracture location. In this case, the figure of merit is the focal time delay as a function of the strain amplitude induced by the elastic waves. This implies a material softening as a function of elastic strain (strains ~ 10^-6 to 10^-5). Increased softening at fracture locations is expected and observed, however, some degree of elastic softening is also inherent in the undamaged formation. This is also expected, but must be quantified as a baseline out of which fractured regions should rise.

- (left) Full focal signals at both locations at a given strain level (i.e., acoustic source strength).
- (right) zoom just around the focal time showing the increased focal time delay as a function of the strain. More delay is seen in the focal time near the crack than away.



Conclusion

- TR focusing is possible in the formation.
- Nonlinear elastic wave signatures are present at/near fractures in the formation.
- Learned valuable information on the deployment of these techniques at this scale.

Plan Forward

- Additional lab-scale measurements to characterize fractures in granite.
- Return to MT for expanding measurements to EDZ.

- **In summary, the TR focusing technique was successfully demonstrated in situ, as was the ability to see an increased nonlinear elastic response (i.e., the focal time delay) near real fractures. In addition, we were able to determine a parameter space (e.g., frequencies, wavelengths, strain levels) for operating in these situations, which allows for improved planning and optimization of future measurements. Future measurements are recommended to transform TREND from a laboratory technique into a field deployable tool for fracture detection, characterization and imaging.**