Autonomous Monitoring of Wellbore Integrity Applying Time-Reverse Nonlinear-Elastic Wave Spectroscopy and Fiber Optic Sensing and Communication

Project Number (FWP-FE-853-17-FY17)

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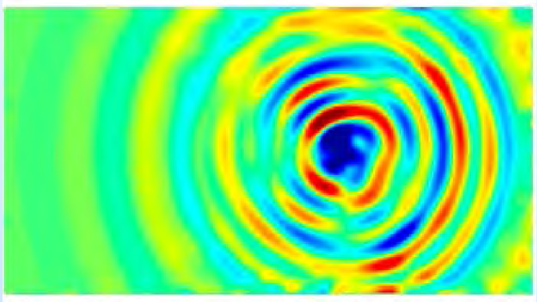
LA-UR-18-27674

U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 13-16, 2018

Presentation Outline

- Objective
- Collaborators and Background
- Approach
- Impact
- Technical status
- Accomplishments to date
- Lessons learned
- Synergy opportunities
- Project summary



Project Overview

Goals and Objectives

Goals and Objective: Development of an autonomous system that can be deployed in wells for unattended long-term (e.g., decades) to monitor both wellbore integrity and stress changes around the borehole

- Need: affordable, robust, autonomous system for monitoring wellbore integrity, especially post closure
- Need: detect leakage signatures for long term CO_2 monitoring

Innovation: Combination of:

(i) Fiber optic sensing to track near-borehole anomalous stress evolution associated with damage

(ii) Active acoustics using embedded sensors and Time Reverse Nonlinear Elastic Wave Spectroscopy (TR-NEWS) to probe for localized damage

(iii) Machine learning to extract passive seismo-acoustic signals for long term monitoring of associated with leakage;

Collaborators and Background

Team

Los Alamos National Lab (project lead)

- P. Johnson (PI), G. Guthrie (co-PI), J. TenCate, C. Donahue, M. Remillieux, B. Carey, M. Stuber-Geesey
- Acoustics (nonlinearity, time reversal, signals from noise); machine learning; wellbore integrity; lab-scale experiments; project integration

Lawrence Berkeley National Lab

- K. Nihei, S. Nakagawa
- Acoustics; fiber optics

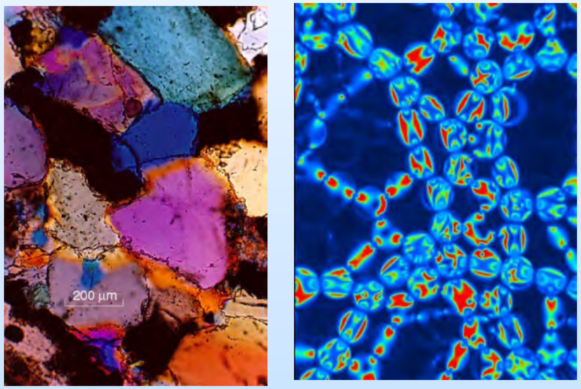
Clemson University

- L. Murdoch, L. Hua, H. Xiao, S. DeWolf
- Fiber optics, geomechanics, acoustics

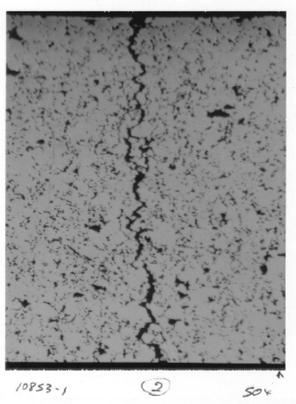
Chevron, ETC

- H. Goodman
- Field application needs

“Distributed”



“Localized”

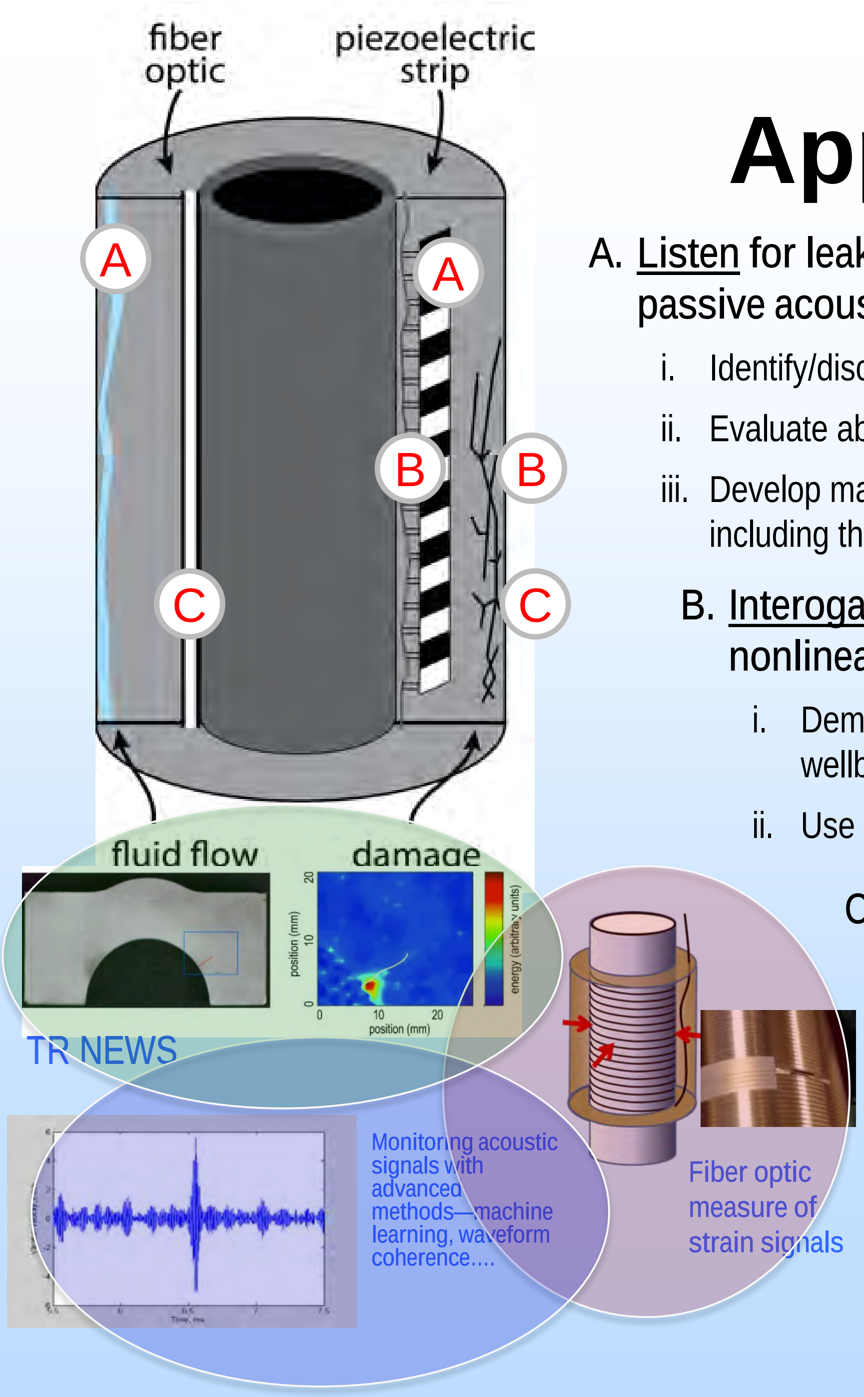


Background to Approach

Our previous work has demonstrated:

- Machine-learning algorithms can extract small seismo-acoustic signatures from noisy backgrounds;
- Nonlinear acoustic methods can probe damage (distributed & localized) in complex earth materials;
- Acoustic time-reversal methods can be used to focus energy (including within earth materials);
- Fiber optic sensors can be used to monitor strain at high resolution;
- Microwave photonics can measure distributed strain with optical fiber using non-proprietary methods.

Approach



Monitoring acoustic signals with advanced methods—machine learning, waveform coherence….

Fiber optic measure of strain signals

A. Listen for leakage related signatures in the near-wellbore region using passive acoustic methods (specific objective 1; task 3)
   i. Identify/discover signatures
   ii. Evaluate ability of embedded acoustic sensors to detect signature(s)
   iii. Develop machine-learning algorithms to extract signature(s) autonomously, including the extraction of signal from noise

B. Interogate and locate damage regions with time-reversal nonlinear elasticity wave spectroscopy (TR-NEWS)
   i. Demonstrate the ability to focus acoustic energy at specific points along a wellbore using time reversal (specific objective 2; task 4)
   ii. Use time-reversal to locate damage (specific objective 3; task 5)

C. Monitor strain/stress evolution in near-wellbore region using fiber optic sensing
   i. Demonstrate the ability of an embedded fiber optic cable to detect strain tied to loss of integrity in the near-wellbore region (specific objective 4; task 6)
   ii. Evaluate the feasibility of measuring distributed strain and acoustic spectra using non-proprietary fiber optic techniques

Task 3—Detection of Fluid-Flow in a Damaged Wellbore

Distributed Acoustic Signals: Coherence Microwave Photonic Interferometry (CMPI)

Objective

Develop/demonstrate optical methods for measuring acoustical signals

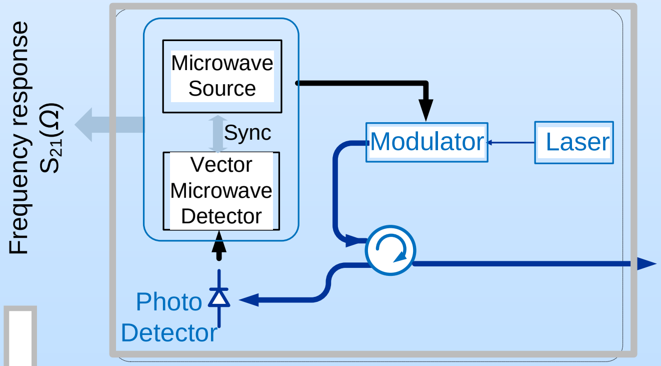
- Frequency to 20 kHz
- Spatially distributed
  - Many locations
  - High spatial resolution
  - High strain sensitivity
- Potential for low cost implementation
- Off-the-shelf components
- Open source signal processing

Prototype
CMPI Interrogator

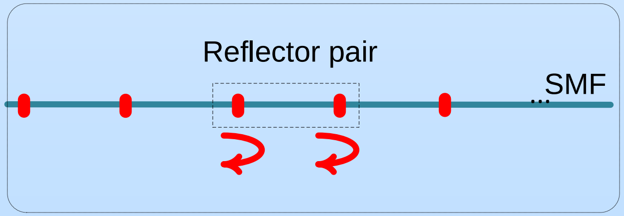
Approach

- Microwave photonics: Novel optical method developed at Clemson University
- Improve speed and resolution → CMPI

CMPI interrogator: open source, portable



- Pairs of reflectors interrogated as optical interferometer
- Measure local strain induced by acoustic wave



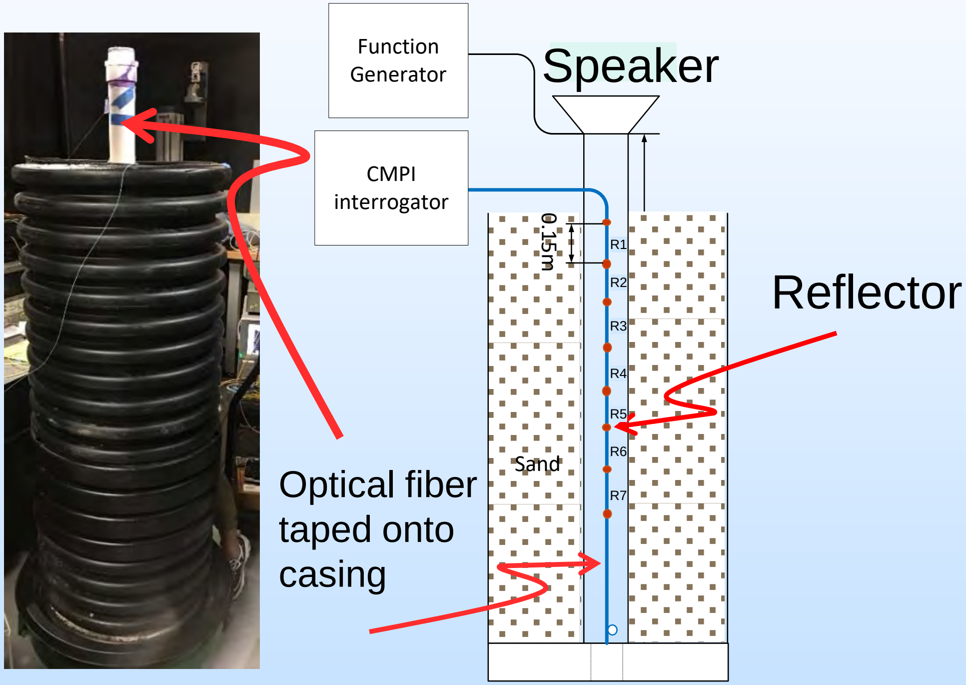
Signal Processing

- Microwave phase to locate reflector pairs in time domain
- Optical interference pattern in time domain
- Correlate interference intensity to acoustic wave amplitude and frequency

Task 3—Detection of Fluid-Flow in a Damaged Wellbore

Proof-of-concept CMPI lab experiments

Objective: Demonstrate that CMPI can measure frequency and amplitude of an acoustic signal at multiple locations along a casing.



Column filled with sand with axial casing

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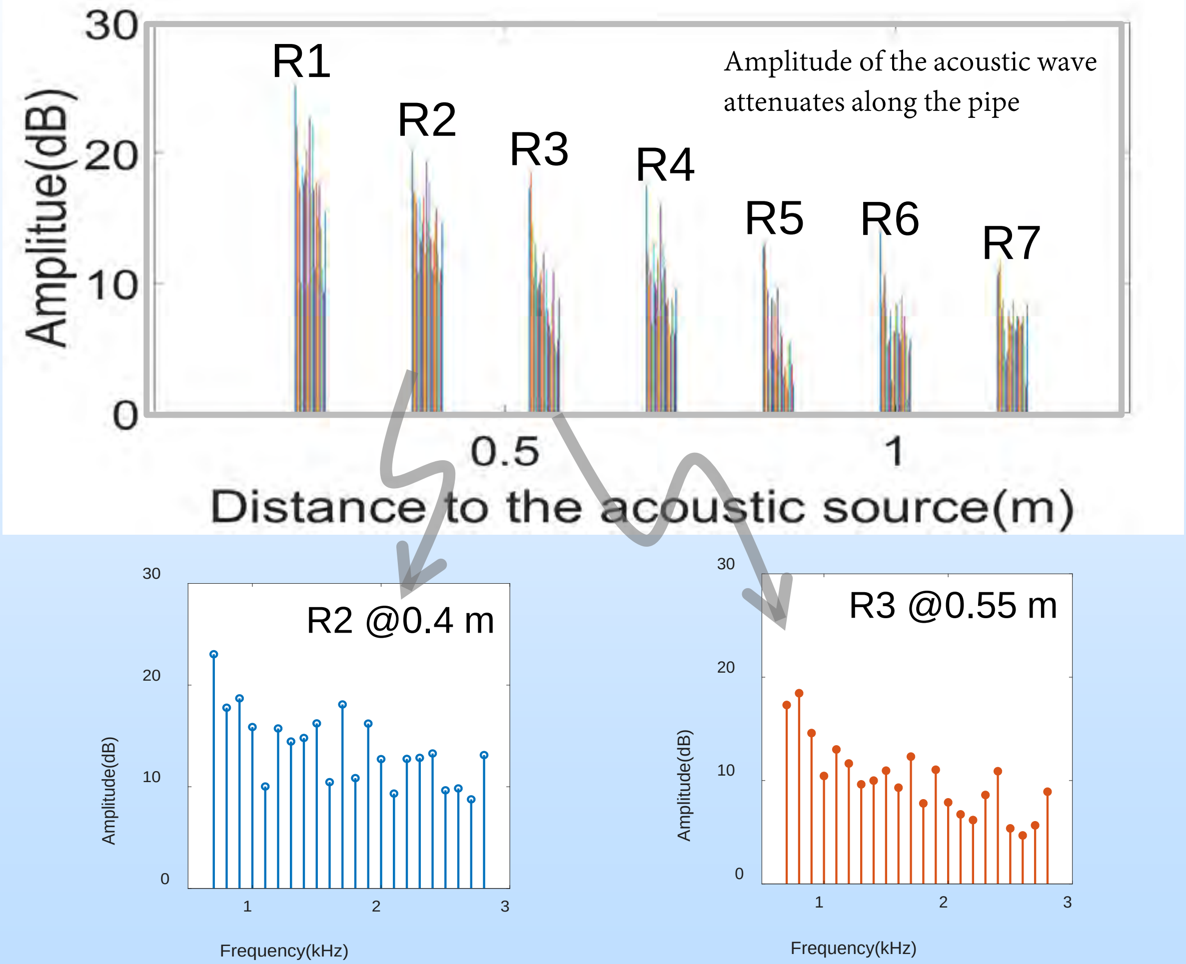
- Reflectors spaced 0.15m apart used as sensors to measure acoustic signals at 7 locations along a casing in sand
- A speaker produces acoustic signals of different frequencies, so the acoustic spectrum at various locations can be measured by the distributed sensors

Task 3—Detection of Fluid-Flow in a Damaged Wellbore

Proof-of-concept CMPI lab experiments

Acoustic spectra at 7 fiber reflector locations



Example acoustic spectra at reflectors R2 and R3

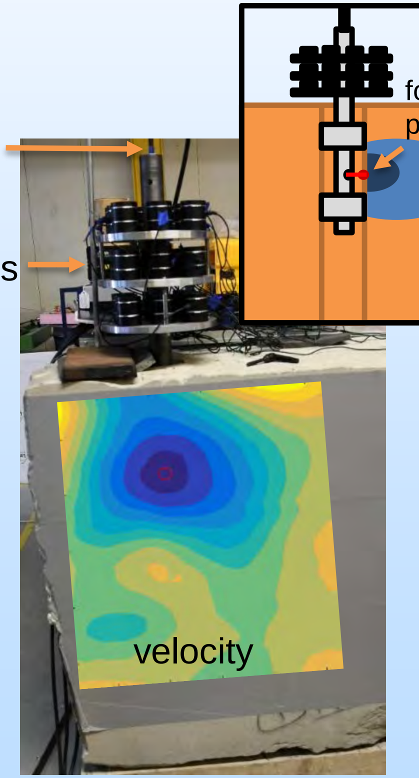
Task 4—Use of Time Reversal to Focus Energy along a Wellbore

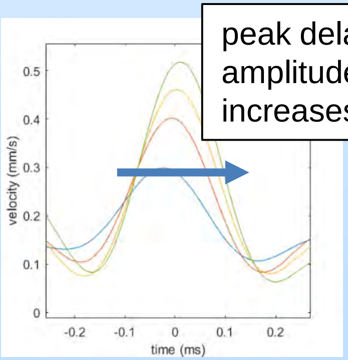
Time reversal experiments in a lab-scale borehole

The first step is to see if we can focus acoustic waves next to an experimental wellbore. It works!

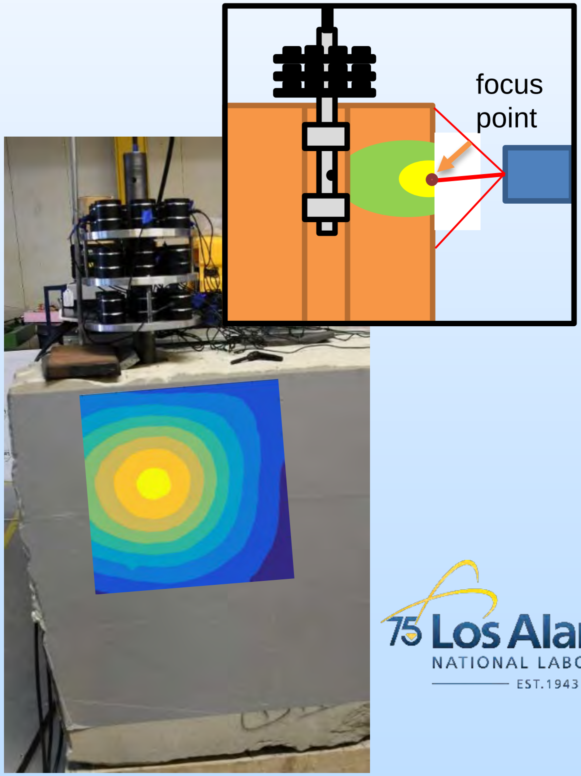
fiber optic vibrometer

transducers





peak delayed as amplitude increases

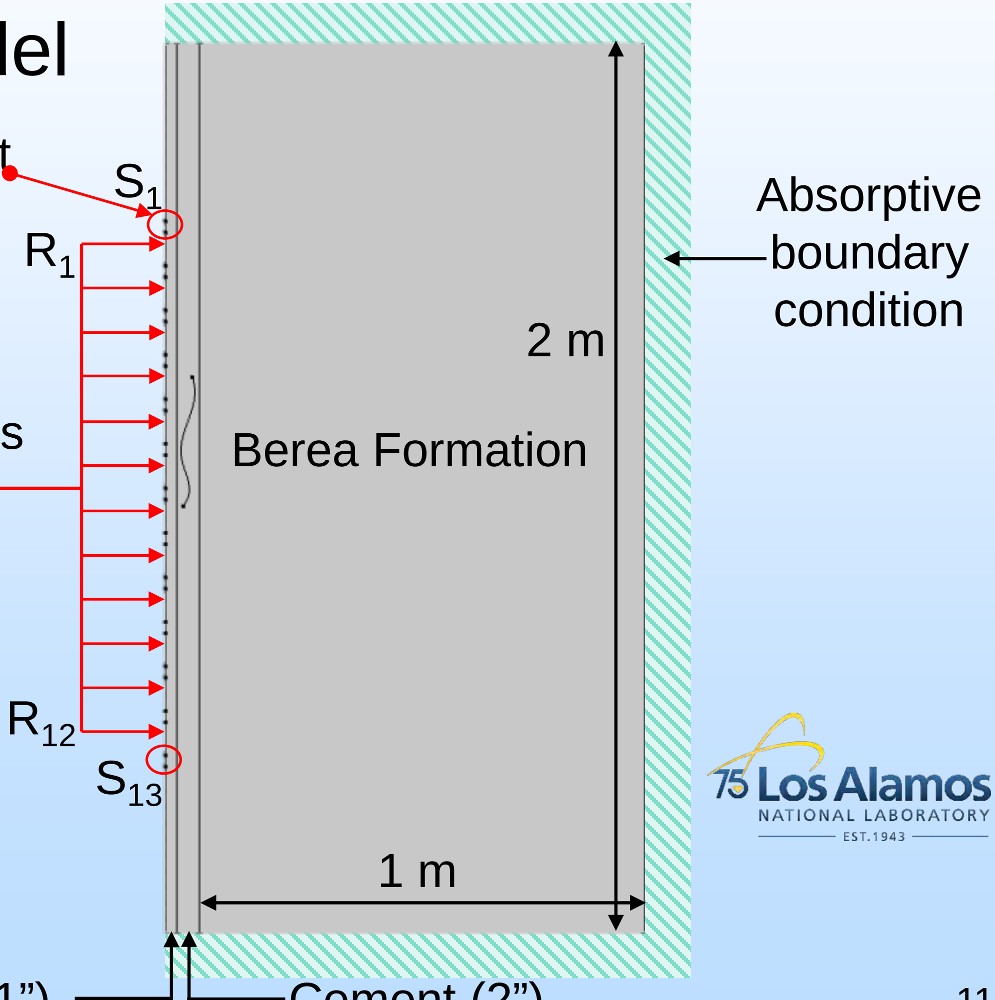


Initial focus: Use synthetic data to assess nature of a nonlinear signal in a damaged wellbore system.

2D Cement-Crack Model

- Arbitrary geometry crack in cement
- Sources (S_1-S_{13}) are 1” in length and distributed every 0.1 m along outer edge of steel casing
- Receivers (R_1-R_{12}) are point probes located between sources
- Rayleigh damping in cement (α = 500, β= 1.27e-7)

	E **[GPa]**	$\boldsymbol{\nu}$	$\boldsymbol{\rho}$ **[kg/m³]**
Casing	206	0.28	8500
Cement	10	0.20	2200
Berea	10	0.10	2000



Steel Casing (1”)

Cement (2”)

Task 5—Nonlinear Responses Associated with Damage

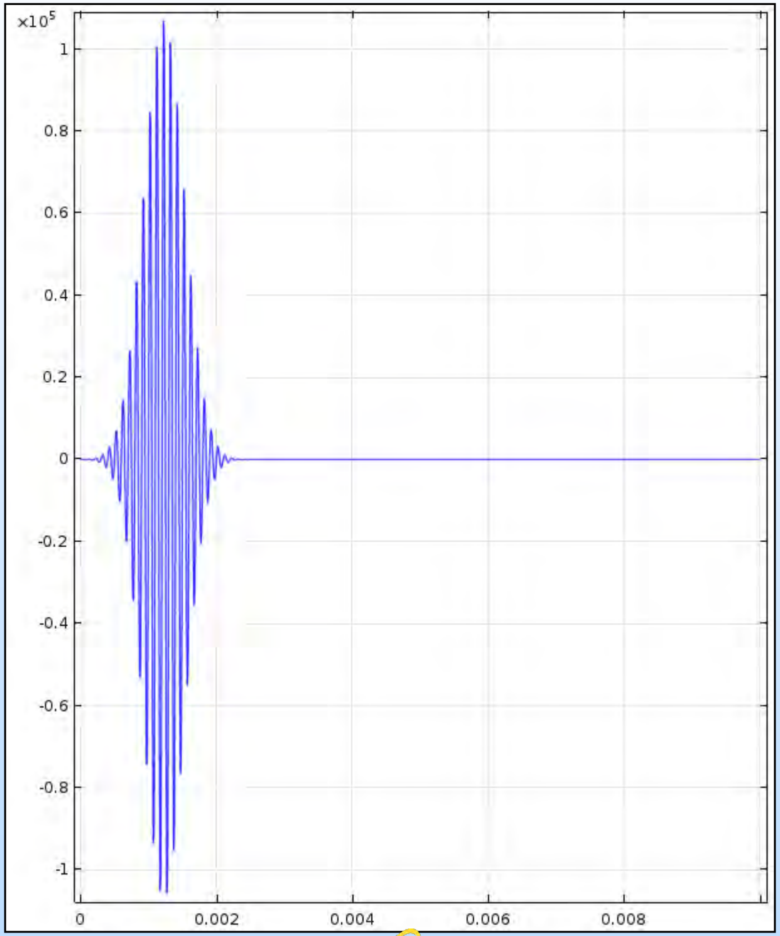
2D Cement-Crack Model

Source Signal

- Centered at 10 kHz
- Pulse is sent at one source
- A simulation will be run for each source
- Received signal is recorded at all receiver locations (R_1-R_{12}) during each simulation

Time

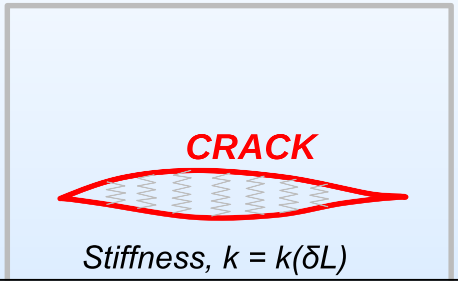
- Each simulation models 20 ms of behavior with Δt = 1e-7 s

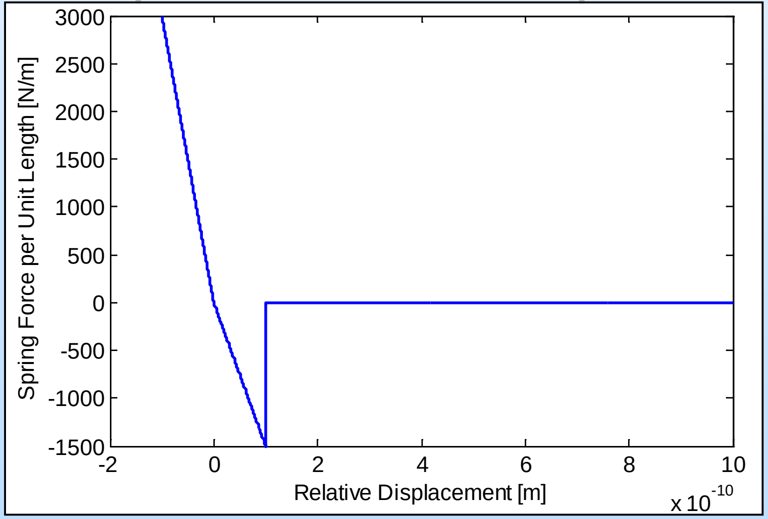


Task 5—Nonlinear Responses Associated with Damage

Modeling a Crack

- A crack is modeled by a nonlinear spring at the interface.



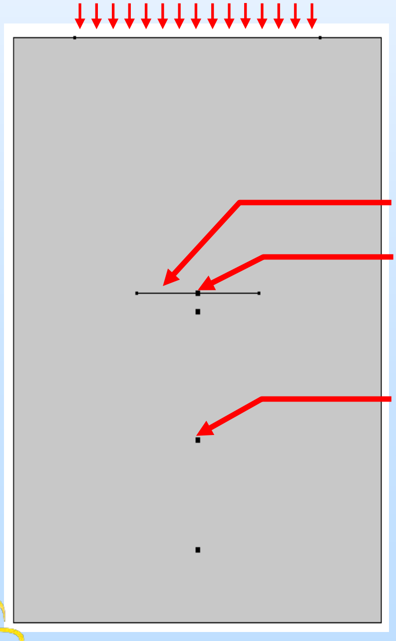


- The spring force is distributed over the crack interface
- At one instant, one portion of the crack may be closed while another may be open, depending on the loading
- The spring force depends on the elongation between the crack faces

Task 5—Nonlinear Responses Associated with Damage
Modeling a Crack

- Propagation of a wave with sufficiently large amplitude through a crack generates a nonlinear elastic response

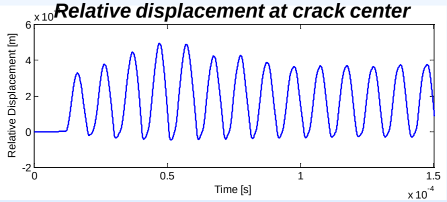
Distributed Load: Sine wave centered at 100 kHz



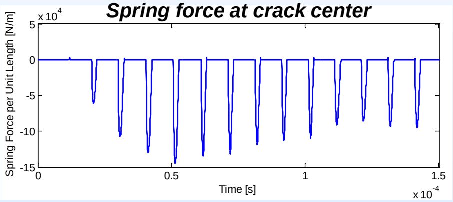
Crack

Probes for relative displacement and spring force

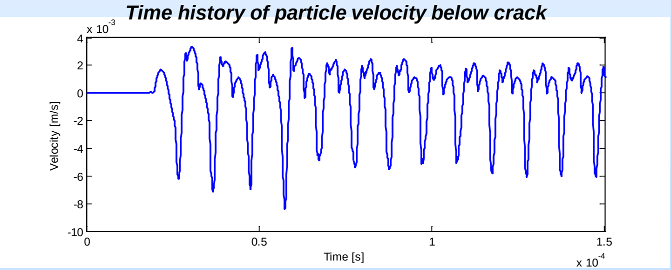
Probe for particle velocity



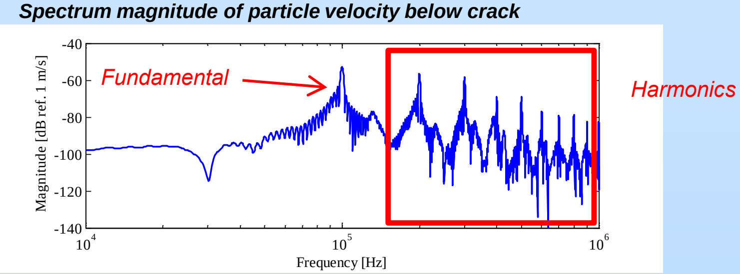
Relative displacement at crack center



Spring force at crack center



Time history of particle velocity below crack



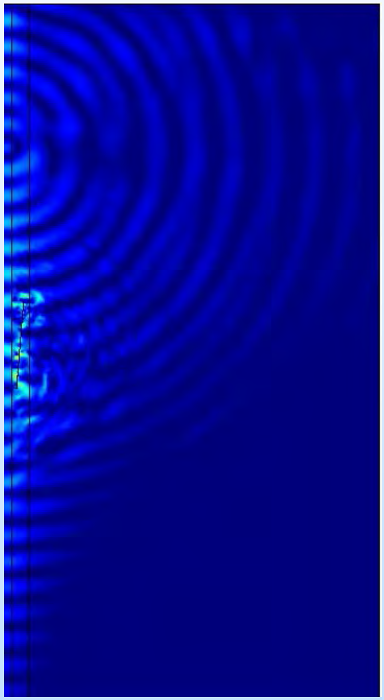
Spectrum magnitude of particle velocity below crack

Task 5—Nonlinear Responses Associated with Damage

Preliminary Results: Particle Velocity

High-amplitude crack-wave interaction

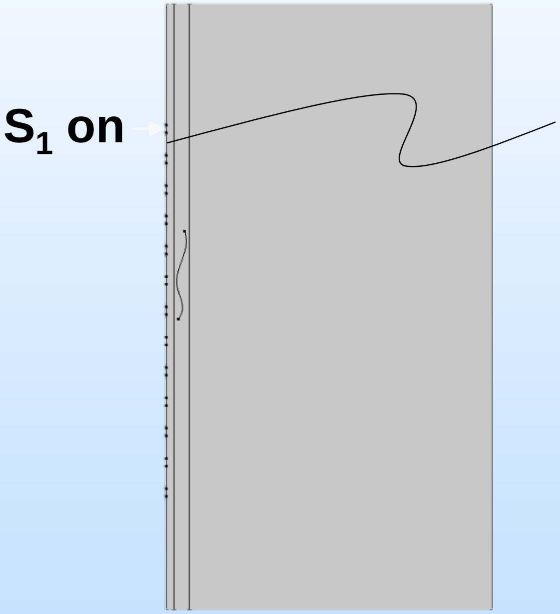
S_1 on

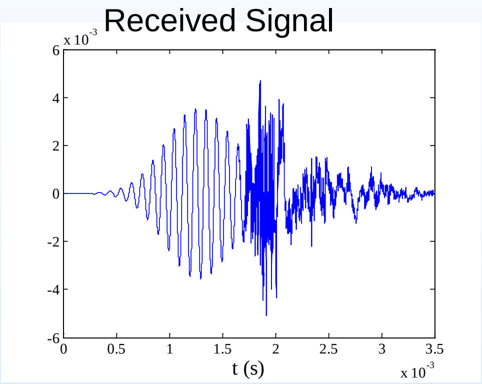


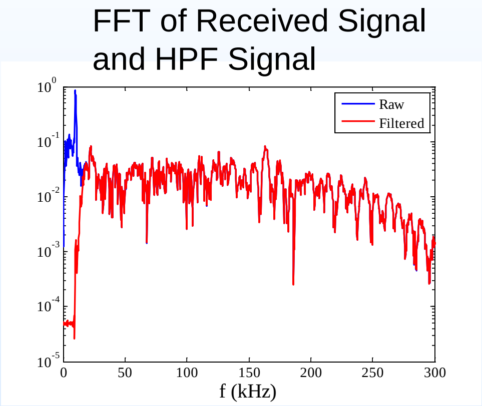
- Propagation of a wave with sufficiently large amplitude through a crack generates a nonlinear elastic response. Towards the end of the simulation, we see the crack acting as a secondary source of high-frequency vibration.

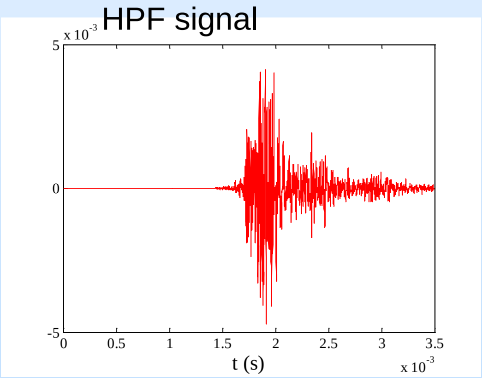
Task 5—Nonlinear Responses Associated with Damage

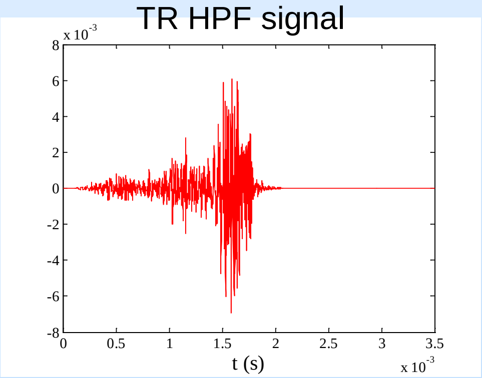
Preliminary Results: NL TR Processing




Received Signal


FFT of Received Signal and HPF Signal

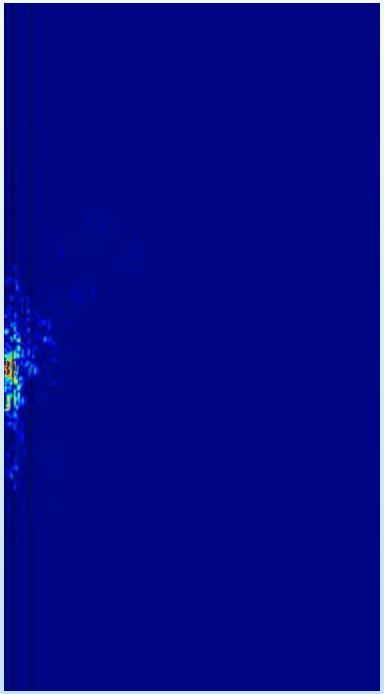

HPF signal


TR HPF signal

- We repeat this process for all 12 receivers that are going to be used as sources during the TR process

Task 5—Nonlinear Responses Associated with Damage

Preliminary Results: TR Imaging



- The elastic wave energy emitted by the original receivers - now acting as sources and broadcasting the high pass filtered TR signals - refocuses on the crack, giving us a clear indication of where the source of nonlinearity is.

Task 5—Nonlinear Responses Associated with Damage

Next Steps

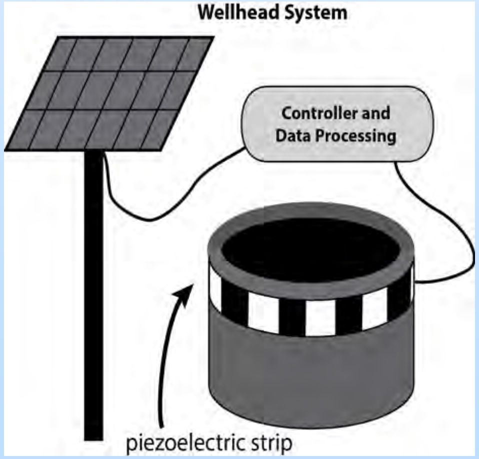
- Repeat TR process with different sources (we fired a total of 13 sources but did the TR imaging process with only one so far, just to see if it works)

- Put a crack in the formation. Can we image that far with all the layers (casing, cement, formation, fluid, etc.) between the tool and the crack?

- Change frequency. Right now we have used a source signal center at 10 kHz. Can we still image at 5kHz, 1kHz, 100Hz? Lower frequency means larger penetration depth and propagation distance.

Lessons Learned

- Research gaps/challenges: so far, none
- Unanticipated research difficulties: so far, none
- Technical disappointments: so far, none
- Changes that should be made next time: so far, none



Synergy Opportunities

DOE-FE Carbon Storage Program

- Nonlinear Acoustic Methods for the Detection and Monitoring of CO2/Brine Leakage Pathways in Wellbore Systems – Pierre-Yves Le Bas & Carly Donahue. Signatures discovered in this project will be shared with our project to guide discovery of signatures with embedded sensor arrays.
- Novel methods to detect small leaks over large areas – Youzuo Lin. Some signatures discovered and algorithms developed in this effort may be relevant to our project—lessons learned will be shared.
- Robust in situ strain measurements to monitor carbon dioxide storage – Larry Murdoch. Optical methods developed in this effort to measure strain using microwave photonics at higher frequency for acoustic applications will be used by our project
- Characterizing and interpreting the in situ strain tensor during CO2 injection – Larry Murdoch. Strain and changes in in-situ stress resulting from injection evaluated during this project will contribute to understanding wellbore integrity for our project.

LANL Laboratory Directed Research and Development (LDRD)

- Critical Stress – Paul Johnson. This project is exploring the physics of systems at a critical state of stress, including many that involve fluid flow. Signatures and insights discovered in this effort will be shared with our project.

Accomplishments to Date

Key Findings:

- The TR Experiments work in a laboratory borehole
- TR NEWS computer simulations show the procedure in full
- Fiber optics have been demonstrated in a tube

Next Steps:

- Begin ‘leak listening’ studies applying machine learning. Laboratory and simulation.
- Advance the fiber optic sensors for borehole use
- Continue simulations
- Test TR+ NEWS in experiment

Appendix: Timeline

10/24/17: Telecon, Introductions, Nuts and Bolts

11/13/17: GTO Program Review: Paul Johnson, Project Introduction *

11/30/17: Subcontract paperwork with Clemson University complete; sent out for review and approvals

12/21/17: Telecon to discuss timeline for rest of quarter

01/19/18: Paul Johnson, Telecon to introduce background Time Reversal research to the greater project team *

02/01/18: Harvey Goodman, CVX Gorgon Project briefing; CVX needs **

02/15/18: Larry Murdoch, Telecon to introduce Clemson's Fiber Optic sensing research and their group to the greater project team *

02/26/18: Clemson subcontract awarded and in place ($$)

03/05/18: Telecon to discuss patent research to date

03/10/18: Meeting with CVX and HAL; detecting wellbore leakage **

04/09/18: LBNL visit to LANL; joint telecon with Clemson, fiber optic experiments

04/26/18: Tour of HAL research facilities courtesy CVX **

05/01/18: Beginning LANL TR borehole experiments

06/01/18: Beginning TR NEWS simulations

07/02/18 Telecon: TR NEWS Simulation update

Impact and Tech Transfer

Impact

Development of an autonomous system for long-term monitoring of wellbore integrity and leakage addresses a key cost-driver for post-injection site care.

This system could also have impacts outside of CO_2 storage, particularly for subsurface operations concerned with controlling the behavior and control of fluid flow in fracture dominated reservoirs.

Technology Transfer

The participation of Chevron as a collaborating partner on the effort will help to focus our technology development on needs of an end user.

The project team has extensive prior experience engaging commercialization partners on successfully developed technology; we anticipate being in a position to engage commercialization partners by the end of year 3.

Benefit to the Program

- GOAL: development of autonomous system that can be deployed in wells for long-term (e.g., decades), unattended monitoring both wellbore integrity and associated stress changes (Topic Area 2).
- If successful in achieving the overarching R&D goal, the outcome would be a cost-effective option (hardware and software) for long-term autonomous monitoring of wells.
- This technology would have broad application in subsurface operations, where maintaining and monitoring wellbore integrity is central to reservoir management strategies (including geothermal operations, oil/gas operations, injection operations). However, the largest benefit to national subsurface energy interest likely lies in post-closure monitoring of wellbore integrity, as needed for CO2 storage operations. This system would be a cost-effective autonomous option to provide the data necessary to ensure that wellbore integrity is being maintained, targeting a central need in any CO2 storage.

Organization Chart

LANL: overall lead

LANL and LBL: TR NEWS simulation and experiment

LANL: Machine learning applied to leak signals, experiment and simulation

Clemson: Fiber optic borehole detection

Chevron: consultation on R and D, and application

Gantt Chart

(project initiated late Q1 FY18)

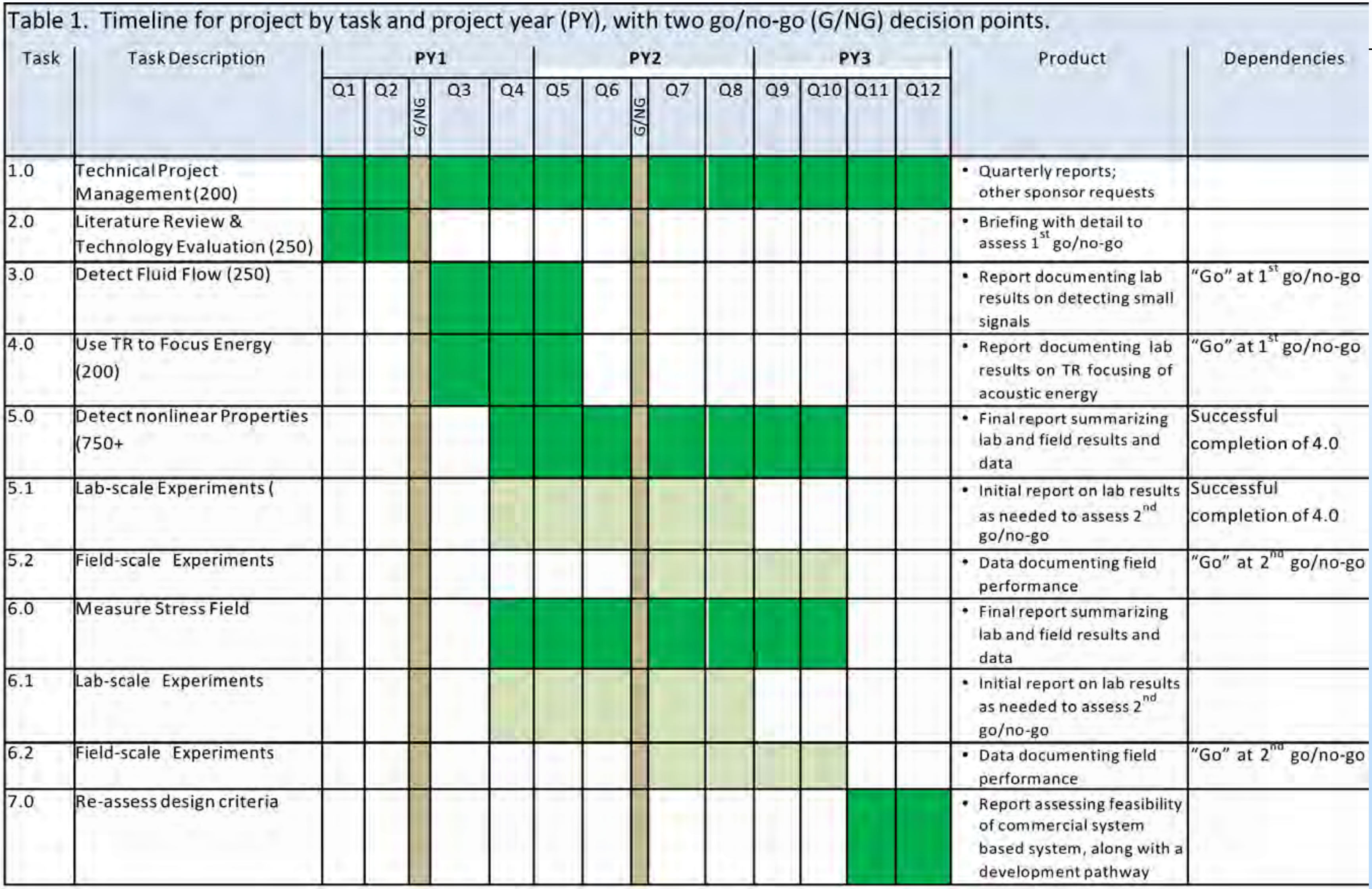


Table 1. Timeline for project by task and project year (PY), with two go/no-go (G/NG) decision points.

Task	Task Description	PY1					PY2					PY3				Product	Dependencies
		Q1	Q2	G/NG	Q3	Q4	Q5	Q6	G/NG	Q7	Q8	Q9	Q10	Q11	Q12		
1.0	Technical Project Management (200)	🟩	🟩	🟫	🟩	🟩	🟩	🟩	🟫	🟩	🟩	🟩	🟩	🟩	🟩	• Quarterly reports; other sponsor requests	
2.0	Literature Review & Technology Evaluation (250)	🟩	🟩	🟫					🟫							• Briefing with detail to assess 1st go/no-go	
3.0	Detect Fluid Flow (250)			🟫	🟩	🟩	🟩		🟫							• Report documenting lab results on detecting small signals	"Go" at 1st go/no-go
4.0	Use TR to Focus Energy (200)			🟫	🟩	🟩	🟩		🟫							• Report documenting lab results on TR focusing of acoustic energy	"Go" at 1st go/no-go
5.0	Detect nonlinear Properties (750+			🟫		🟩	🟩	🟩	🟫	🟩	🟩	🟩	🟩			• Final report summarizing lab and field results and data	Successful completion of 4.0
5.1	Lab-scale Experiments (			🟫		▨	▨	▨	🟫	▨	▨					• Initial report on lab results as needed to assess 2nd go/no-go	Successful completion of 4.0
5.2	Field-scale Experiments			🟫					🟫	▨	▨	▨	▨			• Data documenting field performance	"Go" at 2nd go/no-go
6.0	Measure Stress Field			🟫		🟩	🟩	🟩	🟫	🟩	🟩	🟩	🟩			• Final report summarizing lab and field results and data	
6.1	Lab-scale Experiments			🟫		▨	▨	▨	🟫	▨	▨					• Initial report on lab results as needed to assess 2nd go/no-go	
6.2	Field-scale Experiments			🟫					🟫	▨	▨	▨	▨			• Data documenting field performance	"Go" at 2nd go/no-go
7.0	Re-assess design criteria			🟫					🟫					🟩	🟩	• Report assessing feasibility of commercial system based system, along with a development pathway	

Bibliography

- In Progress

Summary Slide

Take Away

- Develop an autonomous system for long-term deployment in wells for unattended monitoring wellbore integrity and associated stress changes
- System consisting of wellhead and downhole components based on the combined signals of piezoelectric and/or optical sensors
- Signal target: (i) seismo-acoustic signals associated with moving (leaking) fluids; (ii) the stress field along the wellbore where changes in stress may presage damage and leakage; (iii) nonlinear properties in the near-wellbore region that arise when damage develops and progresses.