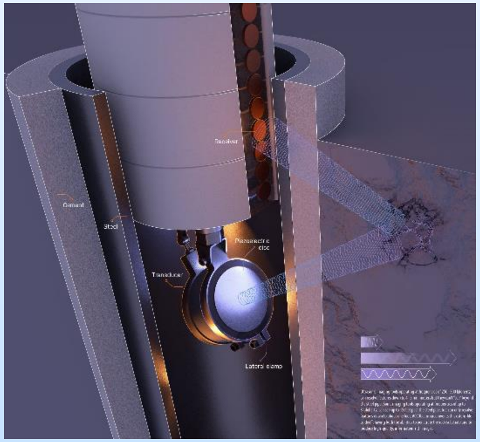
High-Resolution 3D Acoustic Borehole Integrity Monitoring System

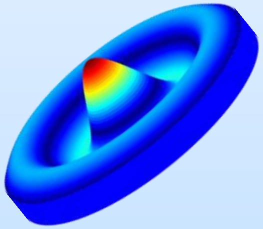
Project Number: FWP-FE-855-17-FY17



Cristian Pantea

Acoustics and Sensors Lab

Los Alamos National Laboratory



U.S. Department of Energy

National Energy Technology Laboratory

CARBON STORAGE PROJECT REVIEW MEETING

Virtual Meeting

September 8-11, 2020

LA-UR-20-26929

Partners/Collaborators

Cristian Pantea[1], Eric S. Davis[1], Craig Chavez[1], Vamshi Chillara[1], Bill Carey[1],
David Li[1], Kai Gao[1], Lianjie Huang[1],
Barbara Kutchko[2], Dustin Crandall[2], Richard Spaulding[2], Roger Chen[3],
Douglas A. Blankenship[4], Jiann-Cherng Su[4],
Hector J. Santos-Villalobos[5], Singanallur Venkatakrishnan[5]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545
[2]National Energy Technology Laboratory, Pittsburgh, PA 15236
[3]West Virginia University, Morgantown, WV 26506
[4]Sandia National Laboratories, Albuquerque, NM 87185
[5]Oak Ridge National Laboratory, Oak Ridge, TN 37831

Presentation Outline

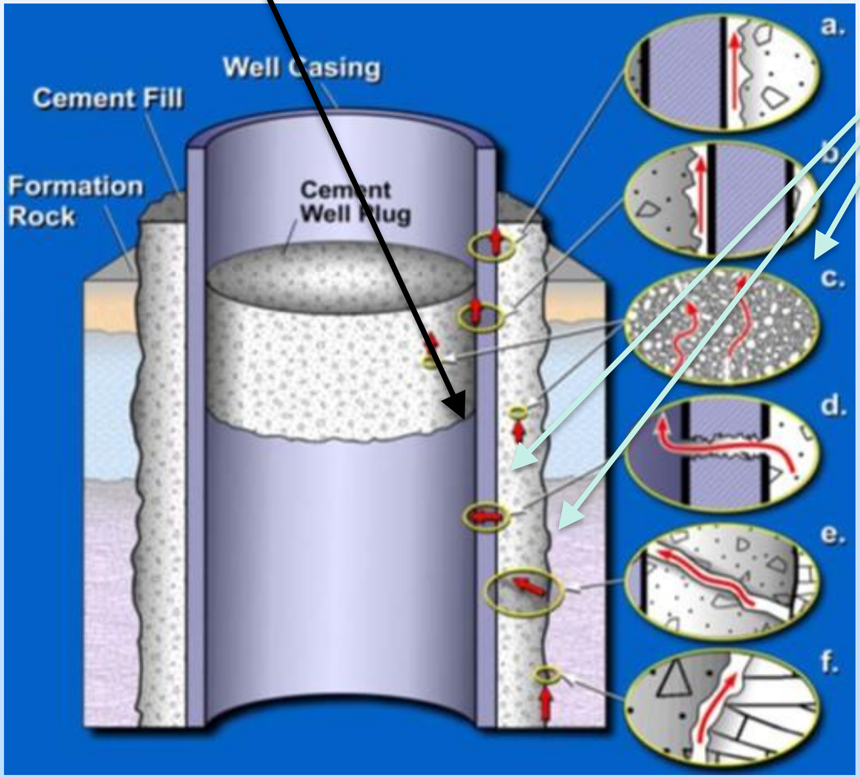
- Technical Status
- Accomplishments
- Project Summary

Technical Status

Develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment

Existing ultrasonic tools work well for casing inspection

Extend applicability to: (1) casing-cement interface, (2) cement-formation interface, and (3) out in the formation (up to ~ 3 meters).



Performed a comprehensive literature/existing technology study for wellbore integrity monitoring tools.

Comparison of existing techniques and the present approach

Method	Frequency (kHz)	Range (m)	Resolution (mm)
Sonic probe	0.3-8	15	~ 300
Present approach	10-150	~ 3	~ 5
Ultrasonic probe	>250	casing	4-5

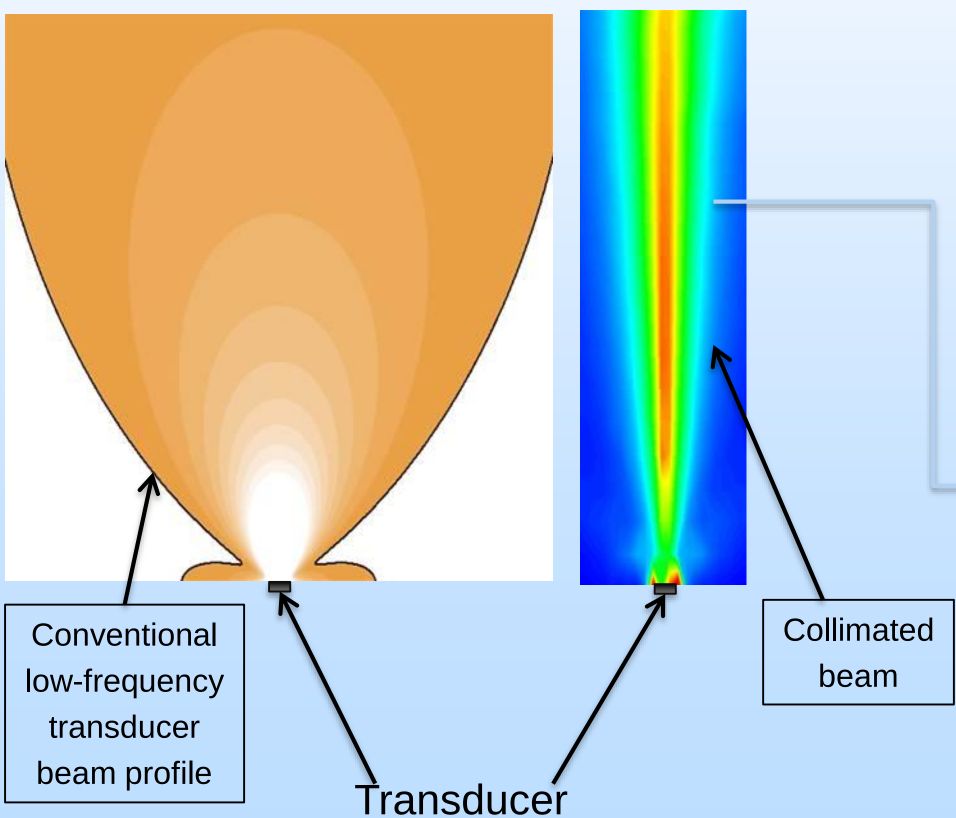
** Picture adapted from S.E. Gasda, Environ Geol (2004) 46: 707-720*

Technical Status

The Proposed Approach:

Novel technique that fills this technology gap.

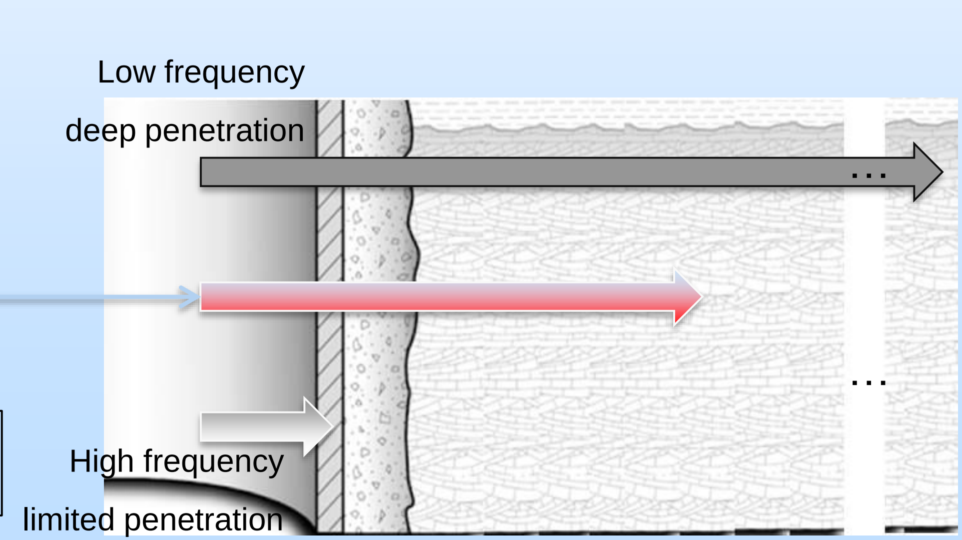
1. Collimated beam for increased resolution



2. Low frequency for deeper penetration

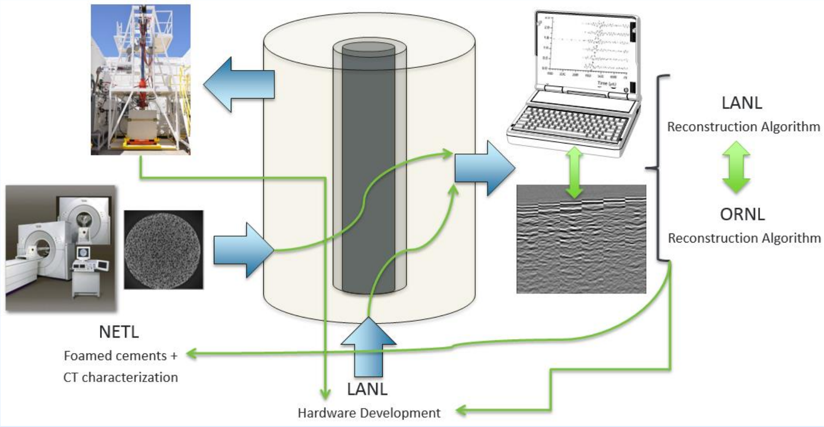
$$Attenuation \sim f^{n}$$

f = frequency, n = 1-2



Technical Status

Multi-lab project



Inter-lab collaboration and teaming arrangements/partnerships

- Develop acoustic source, imaging system, and image processing.
- Investigate acoustic metrics for foamed cements. Incorporate new metrics for wellbores in the field.
- Explore different image processing approaches.
- Perform experiments in more realistic boreholes. Incorporate data from realistic borehole and compare resolution with lab experiments.

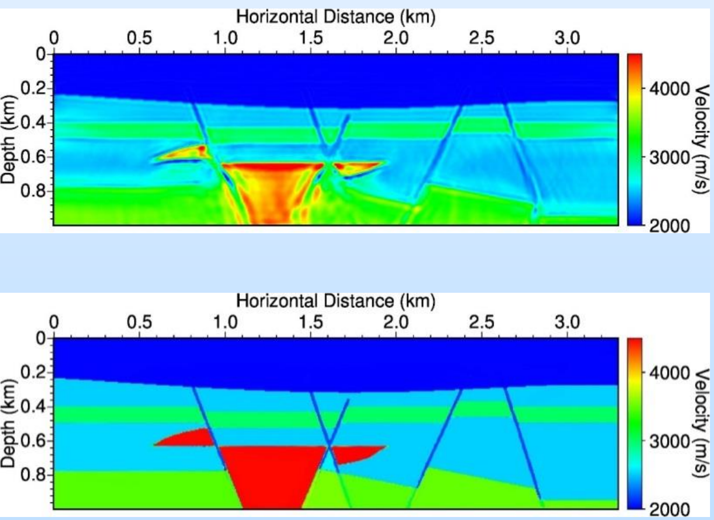
Technical Status

Advanced image processing techniques:

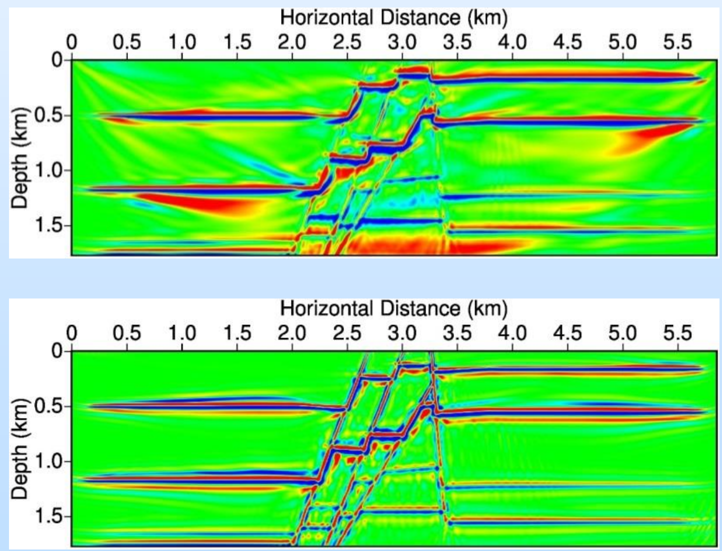
(1) LANL’s Elastic-Waveform Inversion,

(2) LANL’s Least-Squares Reverse-Time Migration techniques,

(3) ORNL’s model-based iterative reconstruction (MBIR).



(1)



(2)

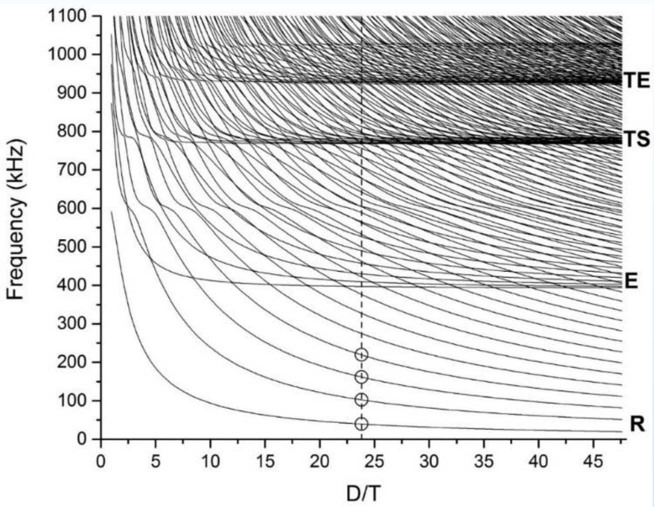
conventional

enhanced

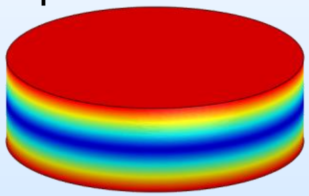
(3)

Accomplishments

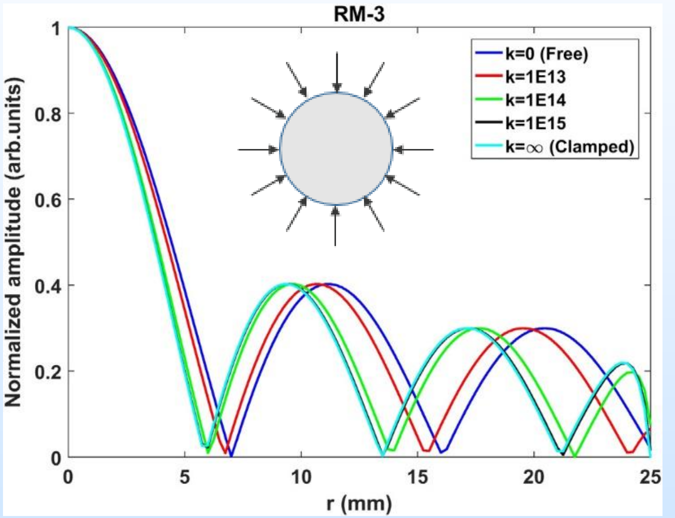
Generate collimated beam by exciting radial modes of piezoelectric disk
Clamp disk edges to focus energy into collimated beam

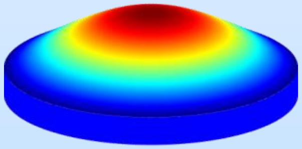


Traditional acoustic source "piston mode"

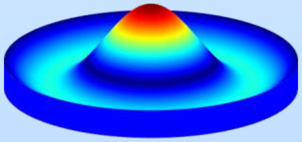


Normalized out-of-plane displacement on the surface of the disc for RM-3 for different lateral stiffness k (N/m3)

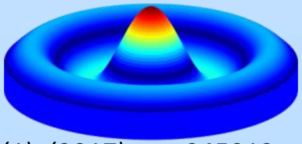




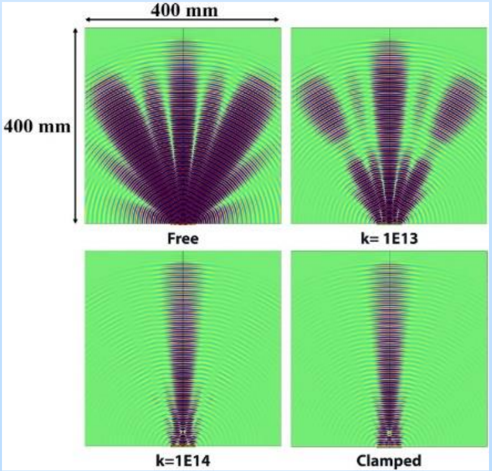
Radial mode 1



Radial mode 2

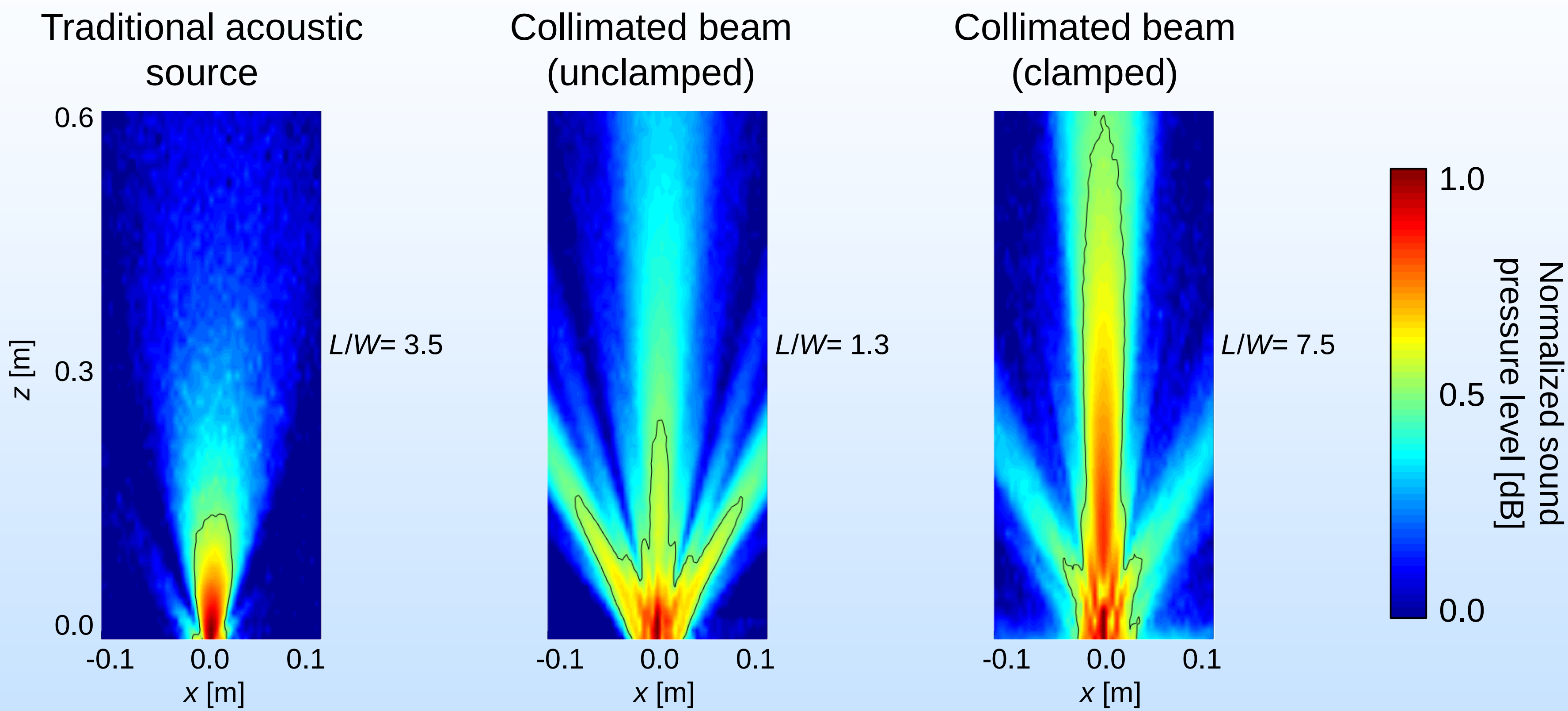


Radial mode 3



Smart Mater. Struct., 2020, vol. 29, 085002
Ultrasonics, 2019,vol. 96, no. 7, pp. 140-148
AIP Conf. Proc., 2019, vol. 2102, pp. 040013
Appl. Phys. Lett., 2018, v. 113, issue 7, p. 071903
Wave Motion, 2018, vol. 76, p. 19-27
Appl. Phys. Lett., 2017, v. 110, issue 6, p. 064101
Proceedings of SPIE, 2017, v. 10170, p. 1017024
Proceedings of Meetings on Acoustics (POMA), vol. 32(1), (2017), pp. 045013

Accomplishments



Collimated beam provides:

- Reduction in beam width → higher image resolution, more control over directivity
- Increased beam length → longer detection/communication range

Accomplishments

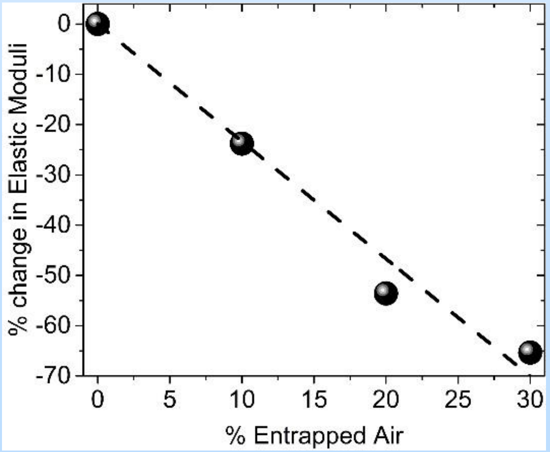
Elastic Properties of Foamed Cement

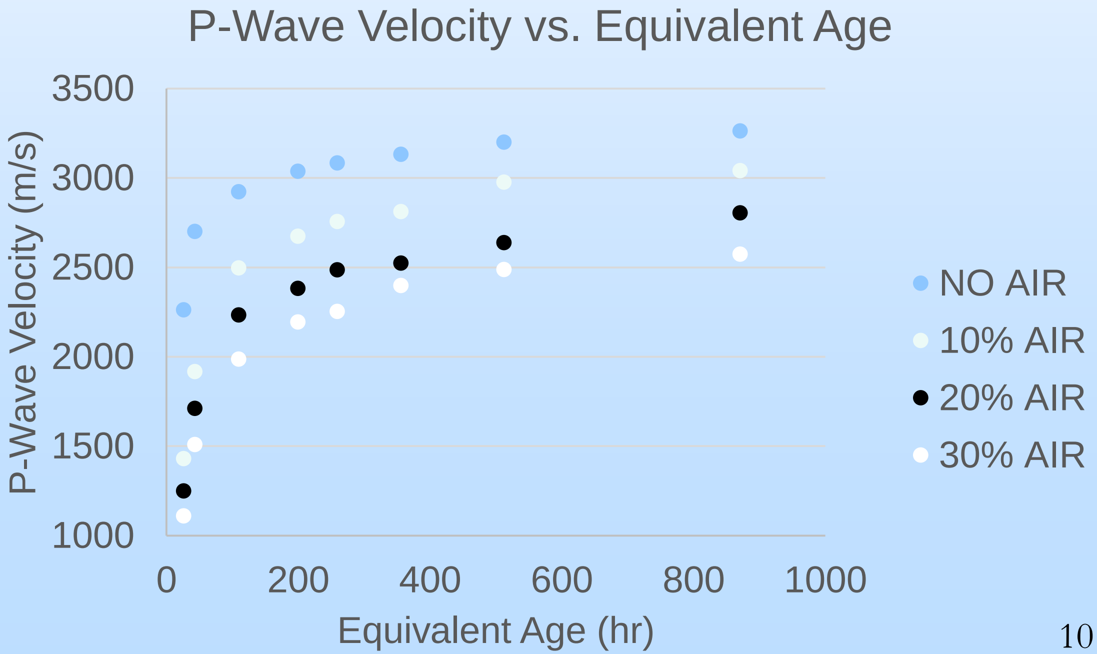
- Ultrasonic testing of Foamed Cement cylinder specimens with size approximately 25 mm (diameter) x 110 mm.
- Equivalent Age was calculated using the Arrhenius equation with an Activation Energy of 35,418 J/mol.

Case (Foam Quality)	0%	10%	20%	30%
P-Wave Velocity+ (m/s)	3371.5	3060.4	2877.6	2661.8
Mass Density+ (kg/m3)	2120.9	1853.2	1650.3	1468.4
Poisson's Ratio*	0.18	0.18	0.19	0.2
Young's Modulus (GPa)	22.2	15.48	11.9	8.8

+ measured, *assumed

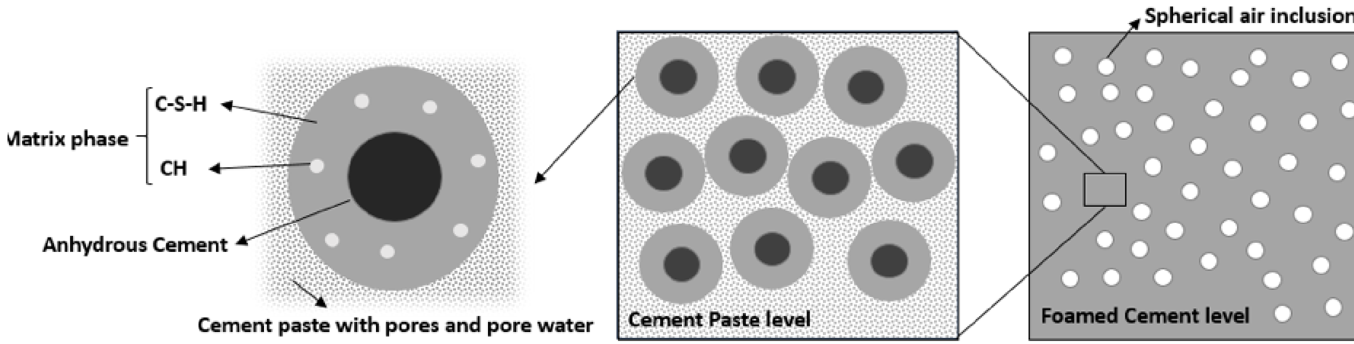
LANL got similar values for v_p. Measured v_s. Poisson ratio was determined to be ~0.25, using measurements of both longitudinal and shear propagation modes.
Large change in elastic moduli with air content → significant softening



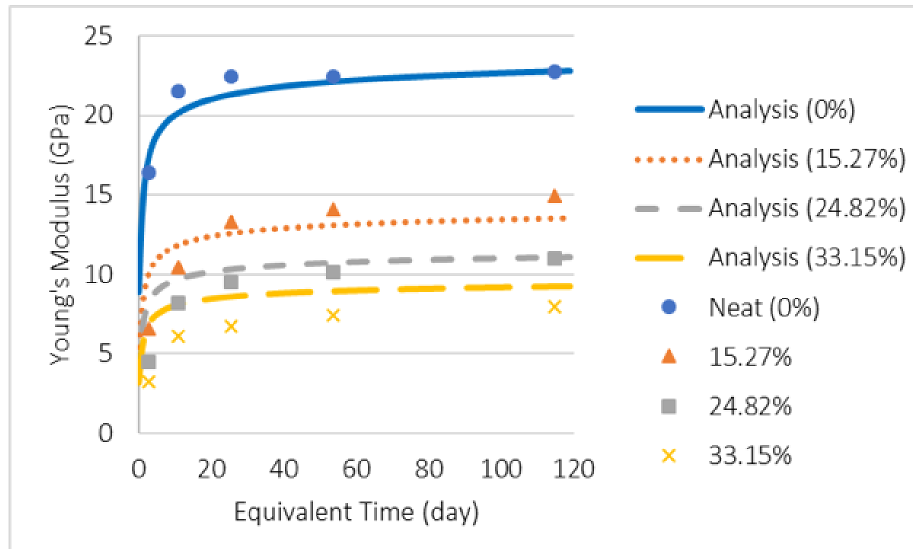


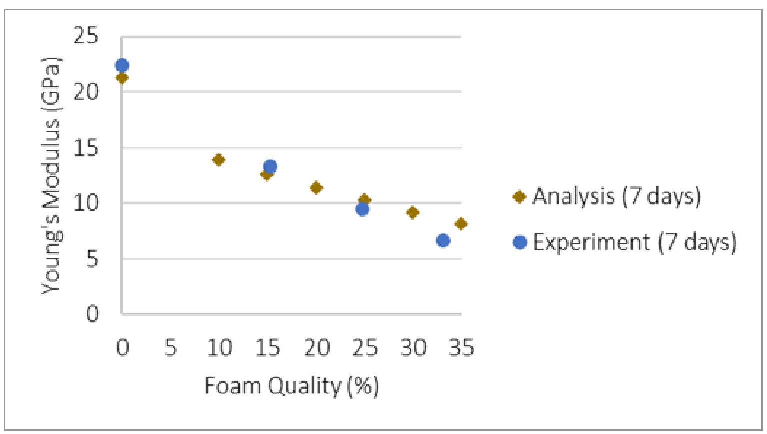
Accomplishments

Modeling of Mechanical Properties



- The effective medium theory was used to calculate Young's modulus of cement paste and foamed cement with different foam qualities.
- Both analytical and experimental results show that the Young's modulus tends to reduce as the foam quality increases.





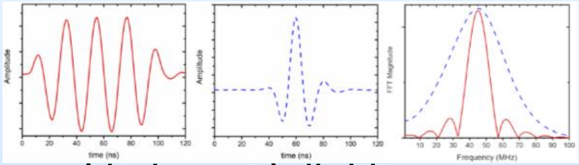
	0%	10%	20%	30%
ρ(g/ml)	2.0631	1.7481	1.5510	1.3791
Air%	-	15.27%	24.82%	33.15%

Accomplishments

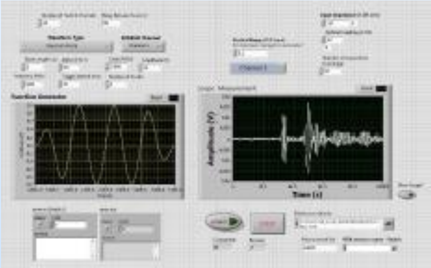
Tool improvement:

- Increased efficiency by ~2 orders of magnitude
    - Previous source based on nonlinear mixing (~0.1% efficiency)
    - New source based on clamped radial modes

- Increased data collection speed by ~2 orders of magnitude
    - Shaped waveform with large bandwidth



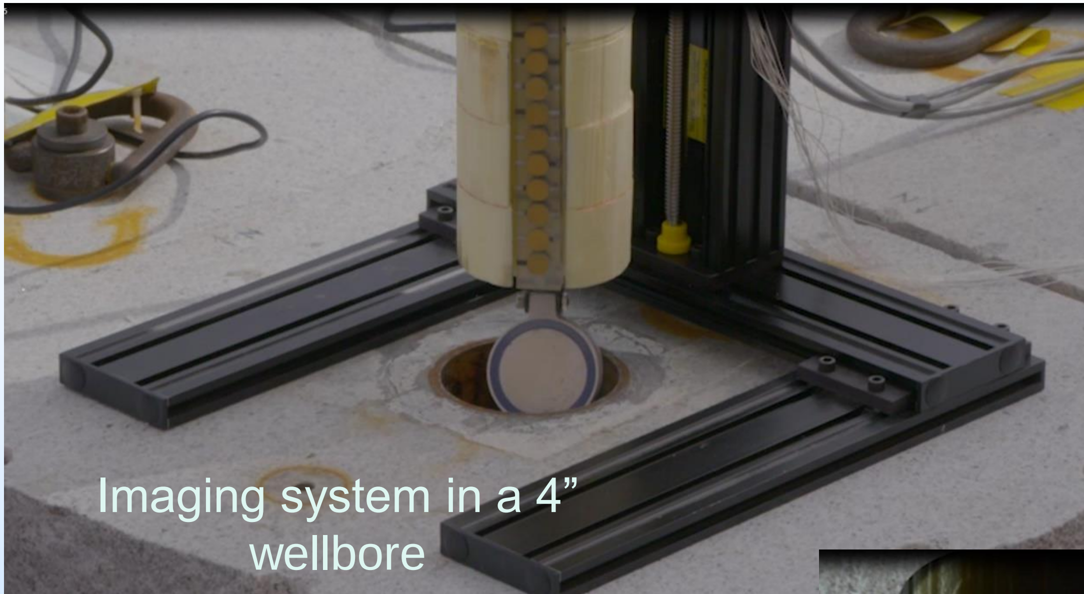
    - NI multi-channel digitizer
      (leveraging on a high-explosive project)



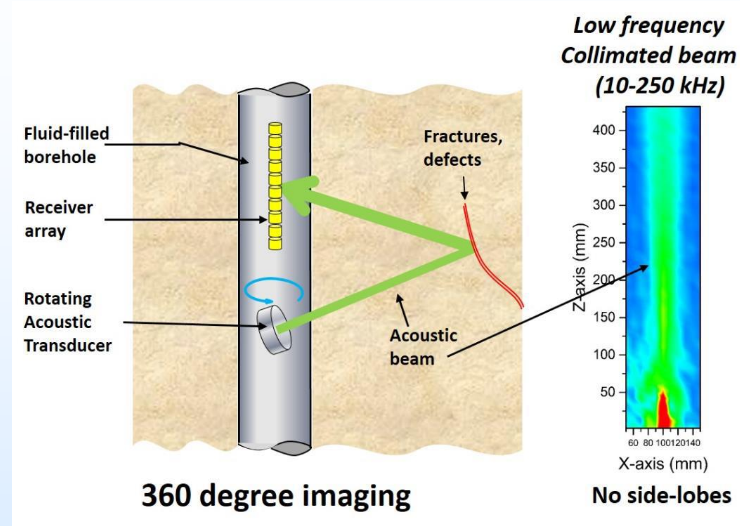
- Ruggedized tool
    - Stainless steel and ceramic parts for sensor packaging and cables

Rev. Sci. Instrum., 2020, vol. 91, 075115
2019 IEEE IUS, Glasgow, UK, 2019, pp. 1663-1665
2019 IEEE IUS, Glasgow, UK, 2019, pp. 1666-1669

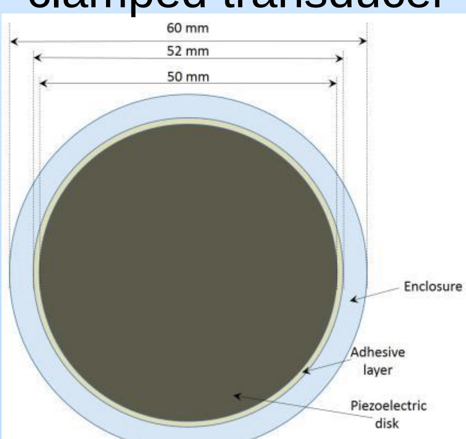
Accomplishments



Imaging system in a 4” wellbore



Drawing of front face of clamped transducer



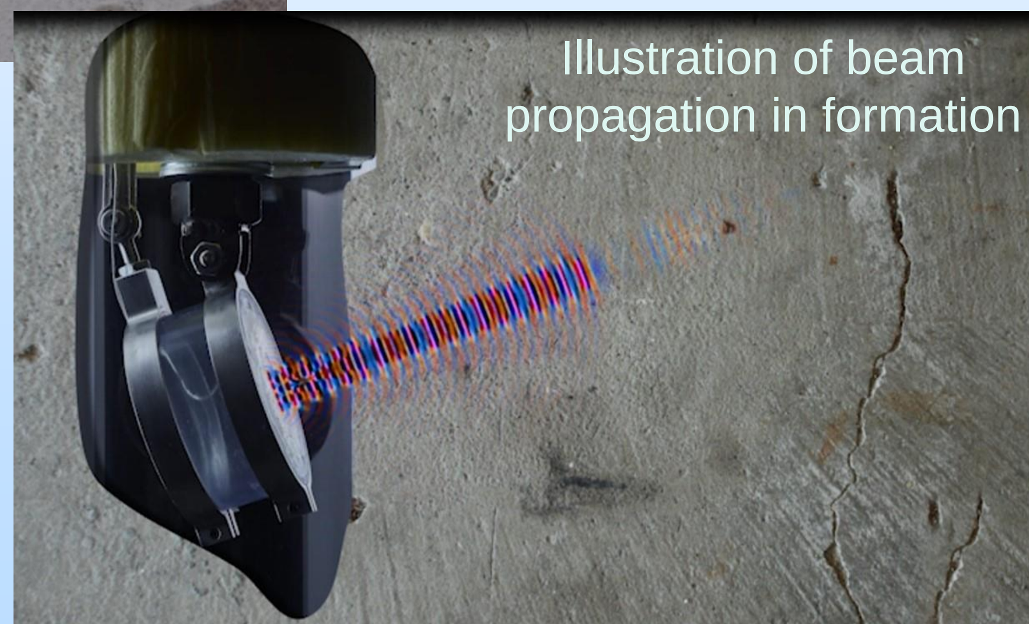


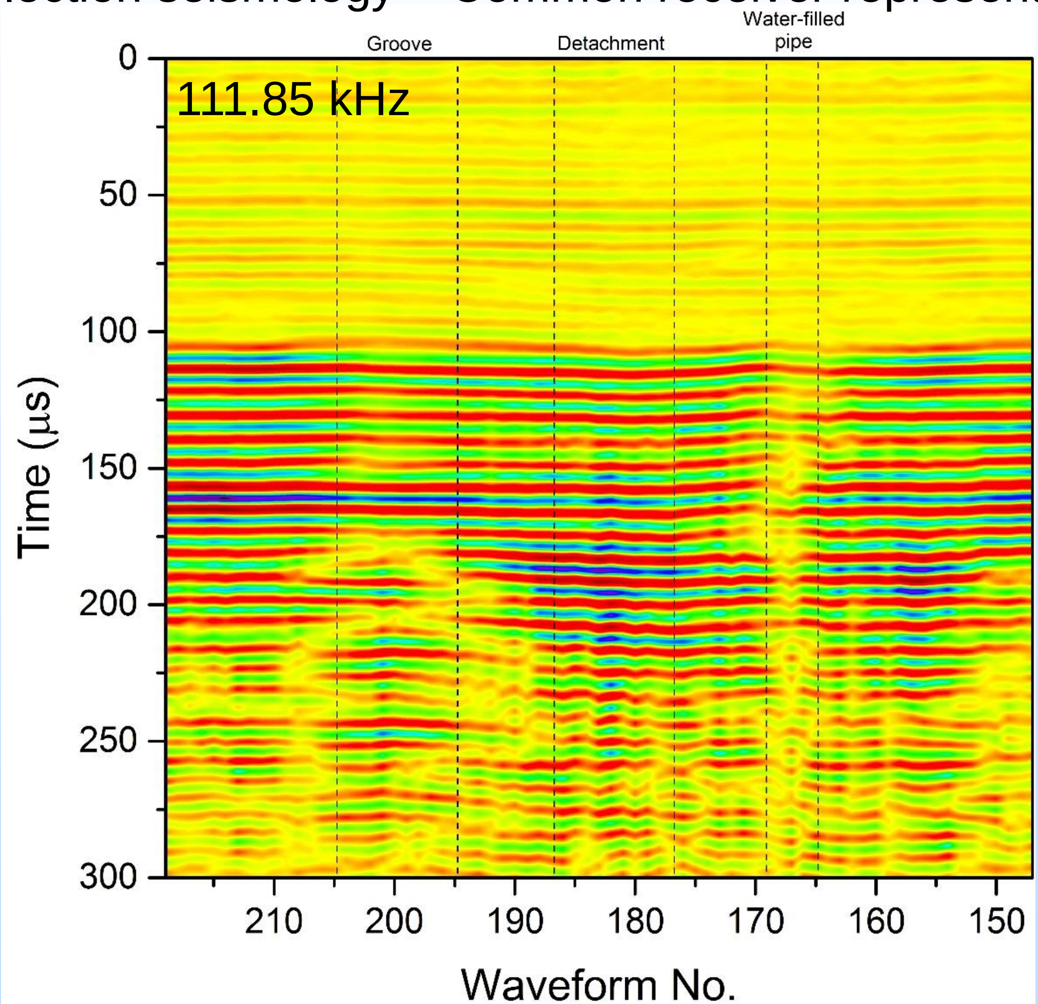
Illustration of beam propagation in formation

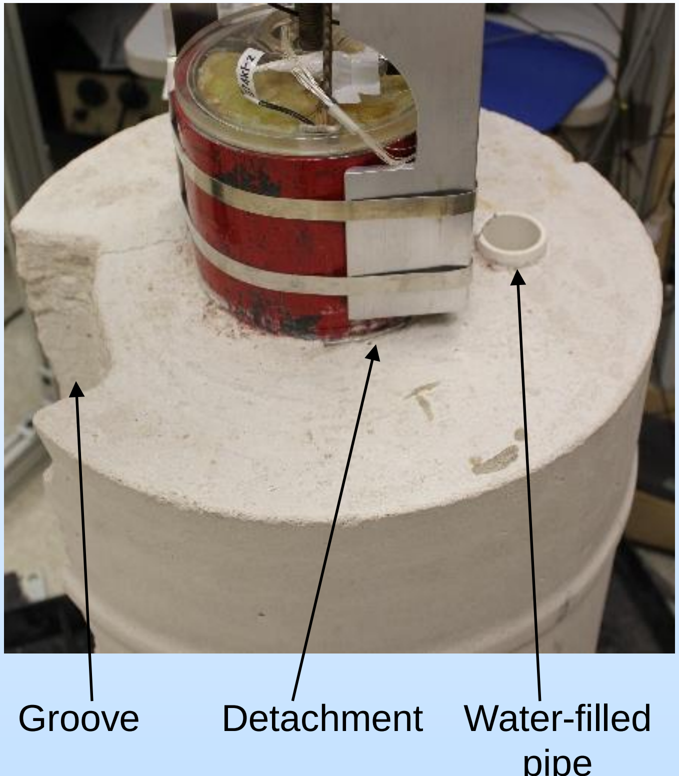
Accomplishments

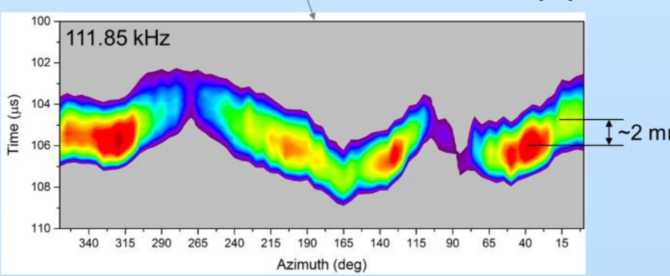
Defects detection

Cased borehole configuration (Steel-lined cement barrel)

Reflection seismology – Common receiver representation



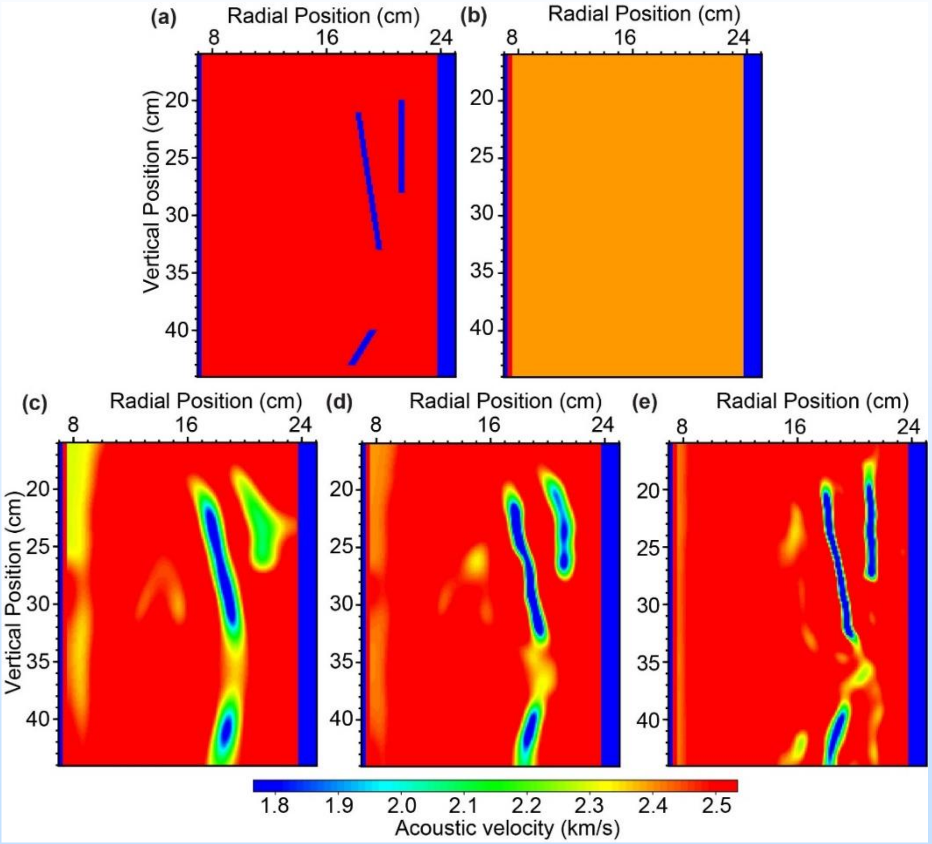




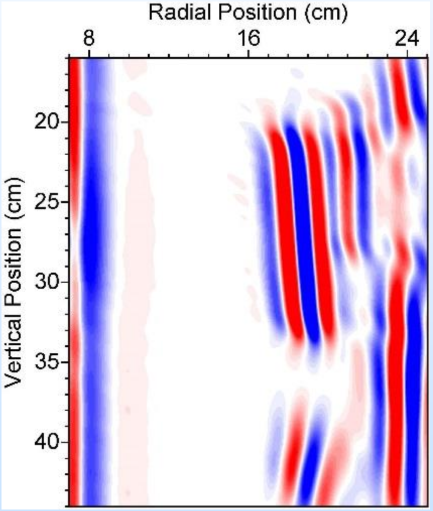
Accomplishments

LANL’s imaging approach – based on Least-square reverse-time migration

*Lianjie Huang

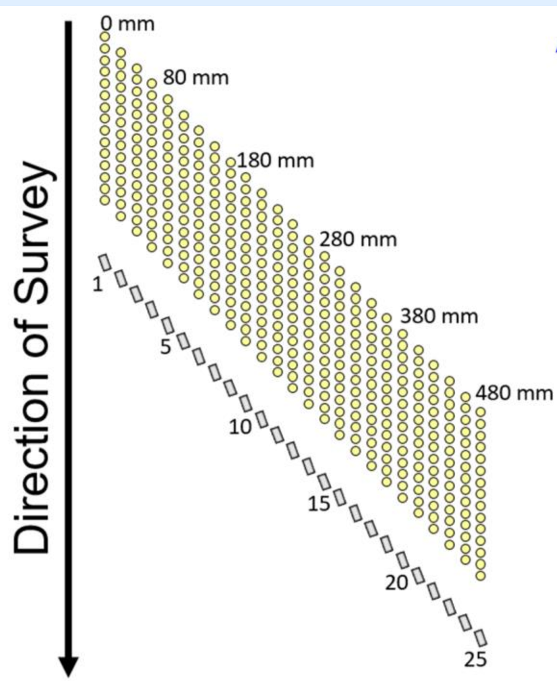


(a) Velocity model based on experimental data; (b) Initial velocity model used for full-waveform inversion; (c-e) Results of full-waveform inversion obtained using the center frequencies of 29 kHz (c), 42 kHz (d), and 58 kHz (e).



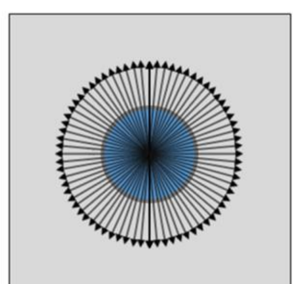
Least-squares reverse-time migration image obtained using synthetic ultrasonic data and the velocity model of full-waveform inversion

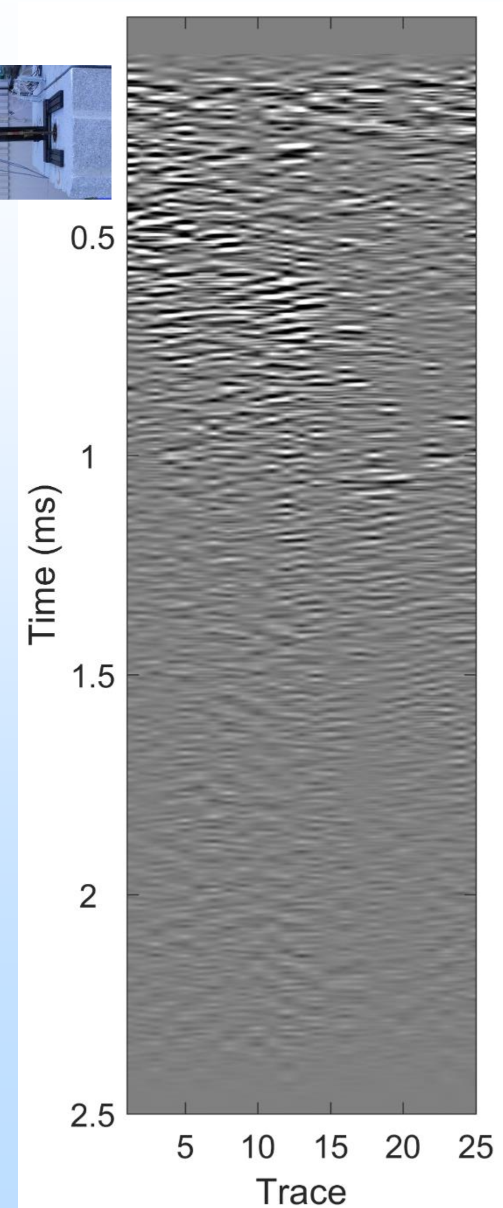
Accomplishments



Acquisition Geometry

- 72 azimuths: 0° to 355°; 5° spacing
- 4 shot angle: 8°,12°,16°,20°
- 25 shot positions: 0-480 mm; 20 mm shot spacing
- 2 source frequencies: 40 kHz & 125 kHz

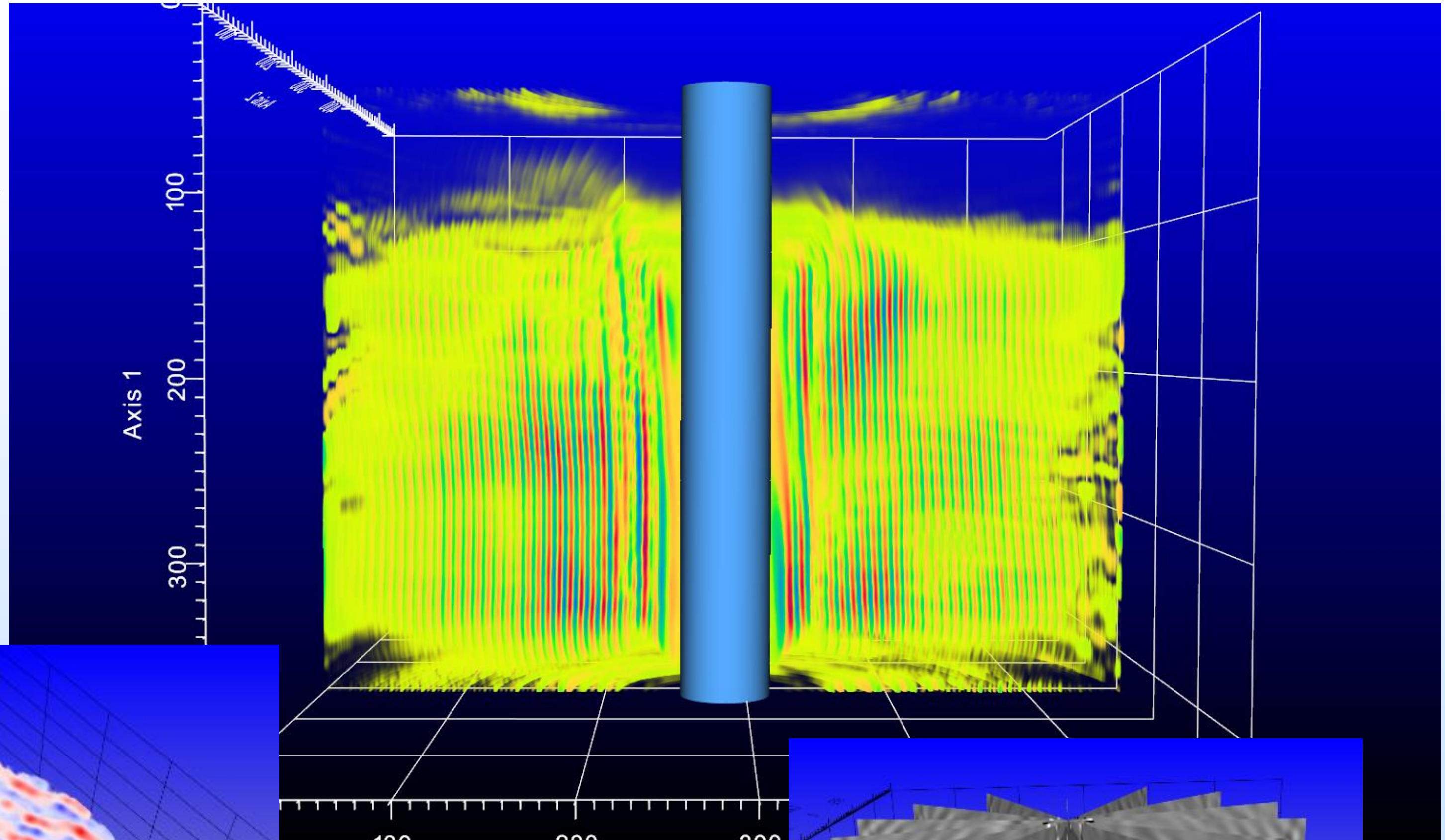


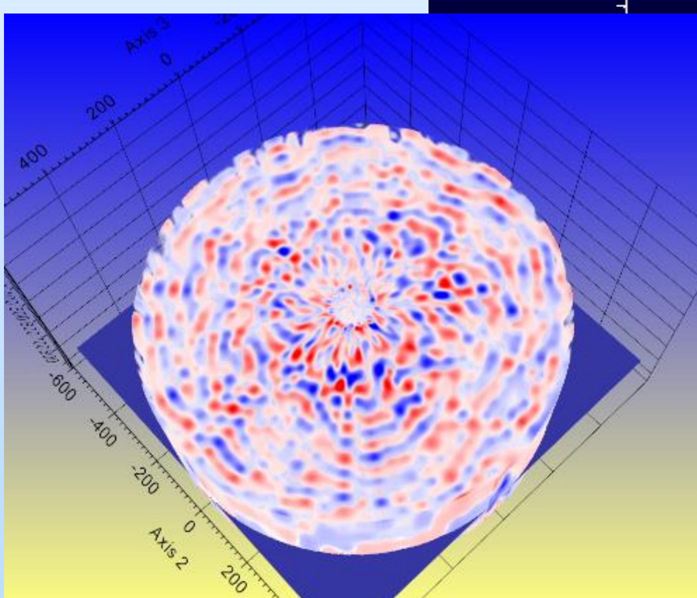


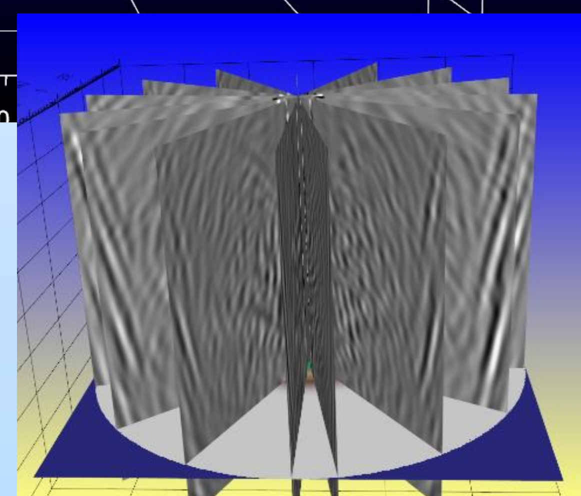
Los Alamos
NATIONAL LABORATORY
EST. 1943

Accomplishments

Block III
Eccentricity – lean
from N to S



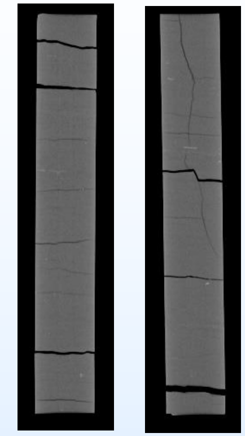




Accomplishments

- Mancos shale samples for lab-scale testing
- 18” DIA x 6” ID X 36” tall
- 4.5” OD x 4.0” ID casing
- Grouted with neat and “foam” cement

Mancos Shale cores - CT scans

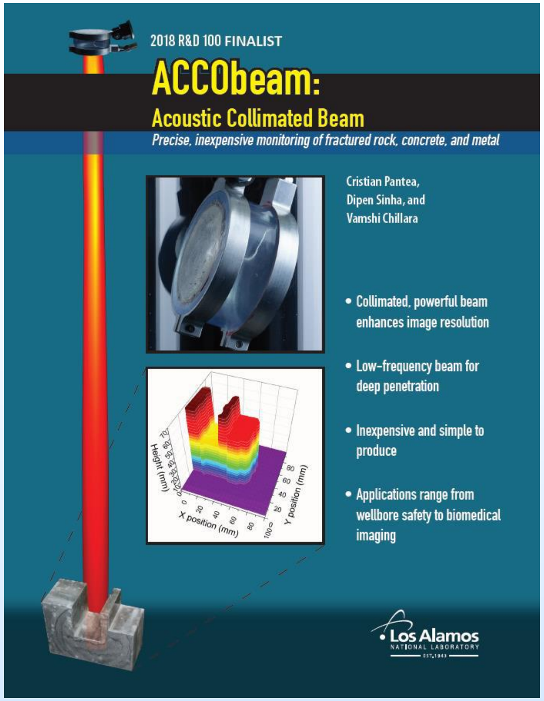


- Preparing test borehole at New Mexico Tech
  - Blue Canyon Dome in Socorro, NM
  - 2” core to 30’
  - 6.0” borehole to 30’
  - 4.5” OD X 4.0” ID casing to 30’
  - Drilling scheduled for late Sept 2020

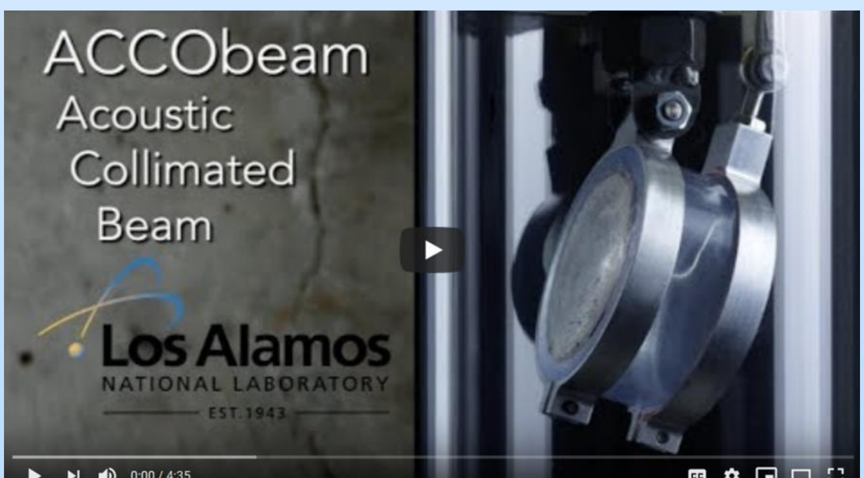
Project Summary

- There are no commercial acoustic sources that provide a collimated beam over a frequency range of 10–250 kHz in a small package that works in different media
- Developed robust operation software, speeding up data collections by about two orders of magnitude
- Developed improved acoustic source, significantly more powerful than its predecessor (~ two orders of magnitude)
- Enhanced receivers sensitivity
- Ruggedized tool for harsh conditions (high temperature, high pressure, corrosiveness, etc.)
- High azimuthal and longitudinal resolution (< 5mm)
- Extended investigation range beyond the wellbore casing

Accomplishments



www.youtube.com/watch?v=qzaPYDWXLbE



Publications

1. Rev. Sci. Instrum., 2020, vol. 91, 075115
2. Smart Mater. Struct., 2020, vol. 29, 085002
3. Ultrasonics, 2019,vol. 96, no. 7, pp. 140-148
4. 2019 IEEE IUS, Glasgow, UK, 2019, pp. 1663-1665
5. 2019 IEEE IUS, Glasgow, UK, 2019, pp. 1666-1669
6. AIP Conf. Proc., 2019, vol. 2102, pp. 040013
7. Appl. Phys. Lett., 2018, v. 113, issue 7, p. 071903
8. Wave Motion, 2018, vol. 76, p. 19-27
9. 52nd U.S. Rock Mech/Geomech Symp, 2018, ARMA
10. Appl. Phys. Lett., 2017, v. 110, issue 6, p. 064101
11. Proc of Meet on Acoustics, vol. 32(1), (2017), pp. 045013
12. Proceedings of SPIE, 2017, v. 10170, p. 101702

few more papers submitted

Conferences

- 2019 IEEE International Ultrasonics Symposium (IUS)
- 52nd U.S. Rock Mechanics/Geomechanics Symposium, 2018
- Sixth International Congress on Ultrasonics, 2017

IP

- 1 patent application (Resonance-based Nonlinear Source)
- 1 patent application (Bessel-like Acoustic Source)
- 1 provisional patent (Imaging Technique with Low-frequency Beam)

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Los Alamos NATIONAL LABORATORY EST. 1943

Benefits to Program

- Program goals being addressed:
  - Develop and validate technologies to ensure 99 percent storage permanence.
  - Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
- Project benefits statement:

The research project is developing a Borehole Integrity Monitoring System to reduce the risk of release of CO_2 around the well casing and cement. The technology, when successfully demonstrated, will provide an improvement over current wellbore diagnostics and integrity assessment techniques. This technology contributes to the Carbon Storage Program's effort of improving reservoir storage efficiency while ensuring containment effectiveness.

Project Overview

Goals and Objectives

- Project goals and objectives in the Statement of Project Objectives.
  - The main objective of this project was to develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment, with the ultimate goal to develop a commercially deployable technology.
  - Wellbore integrity monitoring and characterization of the near wellbore environment are in need of novel technologies for better, faster and safer characterization methods. Some of the goals of these methods are: (1) improved resolution, (2) extended characterization range, and (3) in-situ/real-time monitoring. We worked in parallel to address all these three requirements, such that we can provide a more complete solution for wellbore diagnostics and integrity assessment.

Project Overview

Goals and Objectives

- Project goals and objectives in the Statement of Project Objectives.
  - How the project goals and objectives relate to the program goals and objectives:
    - We looked into providing a complete solution for wellbore diagnostics and integrity assessment. As mentioned on a previous slide, this technology contributes to the Carbon Storage Program's effort of improving reservoir storage efficiency while ensuring containment effectiveness.

Project Overview

Goals and Objectives

- Project goals and objectives in the Statement of Project Objectives.
  - Identify the success criteria for determining if a goal or objective has been met:
    - Identified and assessed existing commercial technology.
    - Determined resolution for channeling outside casing.
    - Performed successful tests on wellbores with foamed cements, with similar resolution as for neat cements.
    - Ruggedized tool for work in adverse conditions.
    - Demonstrated progress toward experimental technique and image processing refinement.
    - Improved detection range through foamed cements (these are more attenuating than neat cements).
    - ***Final success metrics*: *Prototype in field functionality similar to the one observed in tests in the laboratory.***

Organization Chart

- Describe project team, organization, and participants.
  - LANL: Develop acoustic source, imaging system, and image processing.
  - NETL: Investigate acoustic metrics for foamed cements. Incorporate new metrics for wellbores in the field.
  - ORNL: Explore different image processing approaches.
  - SNL: Perform experiments in more realistic boreholes. Incorporate data from realistic borehole and compare resolution with lab experiments.

Gantt Chart

Task	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Phase 1 - Feasibility study												
Task 1 – Investigation of existing technology		M2										
Task 2 – Define metrics	M1											
Task 3 – Industry partners/technology maturation plan												
	GoNoGo1											
Phase 2 - Evaluate method on more complex wellbore environments												
Task 1 - Channeling outside casing			M3									
Task 2 - Hardware/software refinement												
Task 3 - Speed-up measurement & analysis												
Task 4 - Method testing on more complex wellbore environments				M4								
Task 5 - Foamed cements manufacturing												
Task 6 - CT of foamed cements												
Task 7 - Acoustics metrics of foamed cements												
Task 8 - Tests on simulated wellbores with foamed cements				M4								
			GoNoGo2									
Phase 3 - Extend method beyond wellbore												
Task 1 - Acoustic source improvement					M5							
Task 2 - Receivers enhancement												
Task 3 - Ruggedized tool							M7					
Task 4 - Image processing refinement						M6						
Task 5 - Technique refinement								M8				
Task 6 - Enhance capabilities for foamed cements												
							GoNoGo3					
							GoNoGo4					
Phase 4 - Technology Development and Verification												
Task 1 - Prototype development									M9			
Task 2 - Prototype verification at lab scale and in field											M11	
Task 3 - Hardware/software enhancement and refinement										M10		

Go/No-Go1 (end Q2Y1)

Tabulate commercial 3D imaging techniques for borehole integrity

- no commercial technologies for high-res 3D imaging technology with similar depth of penetration (~3 m) and resolution (< 5 mm)

Go/NoGo2 (end Y1)

Detect defects at the cement-formation interface, with high resolution- defects detection at the cement-formation interface with a resolution of at least 5 mm

Go/No-Go3 (end Y2)

Tool survival in adverse conditions of corrosiveness, high temperature and high pressure (brines, 250°C, 45 kpsi)

- imaging system can survive in adverse conditions of temperature, pressure and corrosiveness

Go/No-Go4 (end Y2)

Imaging capabilities out in the formation, up to 3 meters

- defects/features (up to ~ 3m) can be resolved in the received signal

Bibliography

Peer reviewed publications generated from the project:

1. A broadband wavelet implementation for rapid ultrasound pulse-echo time-of-flight measurements, B.T. Sturtevant, N. Velisavljevic, D.N. Sinha, Y. Kono, and C. Pantea, Rev. Sci. Instrum., vol. 91, (2020) 075115.
2. Ultrasonic waves from radial mode excitation of a piezoelectric disc on the surface of an elastic solid, V.K. Chillara, J. Greenhall, and C. Pantea, Smart Mater. Struct., vol. 29, (2020), 085002.
3. Ultrasonic Bessel beam generation from radial modes of piezoelectric discs, V.K. Chillara, E.S. Davis, C. Pantea, and D.N. Sinha, Ultrasonics, vol. 96, no. 7, (2019), pp. 140-148.
4. Full-waveform inversion and least-squares reverse-time migration imaging of collimated ultrasonic-beam data for high-resolution wellbore integrity monitoring, Y. Chen, K. Gao, E.S. Davis, D.N. Sinha, C. Pantea, and L. Huang, Appl. Phys. Lett., vol. 131, issue 7, (2018), 071903.
5. Radial modes of laterally stiffened piezoelectric disc transducers for ultrasonic collimated beam generation, V.K. Chillara, C. Pantea, and D.N. Sinha, Wave Motion, vol. 76, (2018), pp. 19-27.
6. Low-frequency ultrasonic Bessel-like collimated beam generation from radial modes of piezoelectric transducers, V.K. Chillara, C. Pantea, and D.N. Sinha, Appl. Phys. Lett., vol. 110, issue 6, (2017), 064101.
7. Beam Profile Characterization for Thickness Mode Transducers versus Radial Modes, E. S. Davis, V. Chillara, C. Chavez, D. N. Sinha and C. Pantea, 2019 IEEE International Ultrasonics Symposium (IUS), Glasgow, United Kingdom, 2019, pp. 1663-1665.
8. Development of a 3D Acoustic Borehole Integrity Monitoring System, C. Chavez, E. S. Davis, V. Chillara, D. N. Sinha and C. Pantea, 2019 IEEE International Ultrasonics Symposium (IUS), Glasgow, United Kingdom, 2019, pp. 1666-1669.
9. Collimated acoustic beams from radial modes of piezoelectric disc transducers, V.K. Chillara, E.S. Davis, C. Pantea and D.N. Sinha, AIP Conf. Proc., vol. 2102, (2019), pp. 040013.
10. Temperature-dependent elasticity of common reservoir rocks, E.S. Davis, D.N. Sinha, C. Pantea, 52nd U.S. Rock Mechanics/Geomechanics Symposium, 17-20 June, Seattle, Washington, 2018. American Rock Mechanics Association.
11. Low-frequency ultrasonic collimated beam generation from piezoelectric discs, V.K. Chillara, C. Pantea and D.N. Sinha, Proceedings of Meetings on Acoustics (POMA), vol. 32(1), (2017), pp. 045013.
12. Coupled electromechanical modeling of piezoelectric disc transducers for low-frequency ultrasonic collimated beam generation, V.K. Chillara, C. Pantea and D.N. Sinha, Proceedings of SPIE, vol. 10170, (2017), Article no. 1017024.
13. On the bandwidth and beam profile characteristics of a simple low frequency collimated ultrasound beam source, John Greenhall, Vamshi Krishna Chillara, and Cristian Pantea, under review.