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Author(s): Pantea, Cristian

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High-Resolution 3D Acoustic Borehole Integrity Monitoring System

May 7, 2018

PI: Cristian Pantea
**Los Alamos National
Laboratory**

Topic Area 1

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Cristian Pantea¹, Eric S. Davis^{1,2}, Dipen N. Sinha¹, Craig Chavez¹, Vamshi Chillara¹,
Bill Carey¹,
Yu Chen¹, Lianjie Huang¹,
Barbara Kutchko³, Dustin Crandall³, Roger Chen⁴,
Douglas A. Blankenship⁵, Jiann-Cherng Su⁵,
Hector J. Santos-Villalobos⁶, Yarom Polsky⁶, Roger Kisner⁶

¹Los Alamos National Laboratory, Los Alamos, NM 87545

²University of Houston, Department of Physics, Houston, TX 77204

³National Energy Technology Laboratory, Pittsburgh, PA 15236

⁴West Virginia University, Department of Civil and Environmental Engineering, Morgantown, WV 26506

⁵Sandia National Laboratories, Albuquerque, NM 87185

⁶Oak Ridge National Laboratory, Oak Ridge, TN 37831

Sandia
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Main objective: develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment

- Challenges addressed: imaging, with high-resolution, of defects/fractures beyond casing
- Costs – similar to existing technology
- Performance – improved performance, better resolution
- Applications – wellbore integrity assessment
- Markets – any underground borehole
- Innovative aspects: low frequency, collimated beam.
 - Combination of a unique source with advanced image processing
 - An approach that can be deployed to characterize foamed cements in-situ
→ identify acoustic-based metrics from comparison with CT scans

Relevance to Industry Needs and SubTER Objectives

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Office of Fossil Energy

Main objective: develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment

The Problem:

Defects/fracture detection beyond casing with high resolution. No current techniques.

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

Comparison of existing techniques and the present approach

Method	Frequency (kHz)	Range (m)	Resolution (mm)
Standard borehole sonic probe, e.g. BARS (Borehole Acoustic Reflection Survey)	0.3-8	15	~ 300
Present approach	10-150	~ 3	~ 5
Ultrasonic probe, e.g. UBI (Ultrasonic Borehole Imager)	>250	casing	4-5

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

Relevance to Industry Needs and SubTER Objectives

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The Proposed Solution:

Novel technique that fills this technology gap.

1. Collimated beam for increased resolution

2. Low frequency for deeper penetration

Relevance to Industry Needs and SubTER Objectives

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Relevance to the SubTER pillars:

Comprehensive solutions to wellbore integrity monitoring and improved near wellbore fracture detection are needed in multiple energy sectors (CO₂ Storage, Geothermal, Oil & Gas, Nuclear).

Wellbore Integrity

Subsurface Stress and Induced Seismicity

Permeability Manipulation

New Subsurface Signals

Subsurface Control for a Safe and Effective Energy Future

Adaptive Control of Subsurface Fractures and Fluid Flow

Geothermal Technologies Office's goals targeted by this project

- Overcoming technical obstacles and mitigating risk
- Overcoming deployment barriers
- Collaborating on solutions to subsurface energy challenges

Multi-lab project

Inter-lab collaboration and teaming arrangements/partnerships

- 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.

Long-term objectives:

Develop a high-resolution 3D imaging system, based on:

- unique acoustic source (low frequency, highly collimated, broad-band: 10-150 kHz, high power)
- advanced image processing.

Investigate effectiveness of next generation wellbore completion technology such as foamed cements.

Outcome:

- improved imaging resolution around the borehole, and
- extended investigation range - beyond the wellbore casing

Schematic representation of the 3D imaging system:

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)

(3)

conventional

enhanced

- **Foamed cements (w/ NETL)**
 - limited information on foamed cement behavior at conditions specific to wellbores exists at present and
 - conventional methods have difficulty detecting foamed cement due to low impedance contrast.

Acoustic (LANL) $\leftrightarrow$ CT (NETL)

Acoustic characterization: sound speed, attenuation, acoustic nonlinearity, elastic moduli

- **Realistic environments (w/ Sandia)**
 - Perform imaging experiments in more realistic simulated wellbore environments

* From JPT, vol. 67, no. 1, Jan 2015

Acoustic Sources

- **Parametric Acoustic Source:**
 - Low frequency (10-150 kHz)
 - Large bandwidth (140 kHz)
 - Frequency-independent beam width
 - No side lobes
 - Beam divergence < 6 degrees
 - Patented
- **Bessel-like Acoustic Source:**
 - Low frequency (10-150 kHz)
 - Frequency-independent beam width
 - Limited diffraction during propagation
 - Reduced side lobes
 - IP process underway
- **Compact Parametric Acoustic Source:**
 - Very compact source; can be fitted in boreholes 1-2 in ID
 - IP process underway

Transducer surface profile of a Bessel-like source

Examples for low-frequency beam profiles in H₂O for a Bessel-like source

Radial modes of a Bessel-like transducer

Bessel-like Acoustic Source

First four radial modes of a piezoelectric disc transducer

Beam profile in water for the 3rd radial mode RM-3; free transducer (left) and clamped transducer (right)

Technical Accomplishments and Progress

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Measurement system

Simulated borehole:
metal casing embedded in cement.

Electronics

Acoustic source
+
receivers array

Beam pattern through concrete

Experimental setup for beam pattern determination after propagation through concrete

Reflective
Tape / Concrete
Barrel

Laser
Doppler
Vibrometer

- 6 dB power beam pattern on the face of the
concrete barrel

Excitation beam

Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)

Reflection seismology – Common azimuth representation

Excitation:

29 kHz shaped pulse

Azimuthal data collected every
5 deg, for a 180 deg span.

Groove
location

LANL image processing

Open borehole configuration (Plexiglas-lined cement barrel)

Least-squares reverse-time migration

Excitation:

10-150 kHz Gaussian pulse

Azimuthal data collected every 5 deg, for a 180 deg span.

LANL image processing

Open borehole configuration (Plexiglas-lined cement barrel)

Multi-scale acoustic full-waveform inversion algorithm for velocity model

Excitation: 29-112 kHz Bessel-like Acoustic Source

Data collected using fixed azimuth, and vertical translation of source and receivers.

Defects detection – Bessel-like Source

Cased borehole configuration (Steel-lined cement barrel)

Reflection seismology – Common receiver representation

Cement OD: 460 mm
Cement ID: 170 mm
Steel pipe ID: 148 mm
Steel pipe thickness: 10 mm
Groove depth: 50 mm
Plastic pipe location: 25 mm

Groove Detachment Water-filled pipe

Defects detection – Bessel-like Source

Steel casing barrel – Bessel-like Source

Resolution determination

Steel casing barrel – Parametric Source

Calculations:

- Sound speed: ~ 5.8 km/s
 - Thickness: ~ 10 mm
- **Steel**

Resolution determination

Plexiglas casing barrel – Parametric Source

Calculations:

- Sound speed: ~ 2.8 km/s
- Thickness: ~ 3 mm

→ **Plexiglas**

- **First CT scans acquired of well/cement/rock system in early 2016**
 - Well thickness varied to ensure minimal imaging artifacts during scanning. Scan resolution 27.8 micron.
 - Multiple voids/fractures created in cement during process to test ability to capture imperfections in cement

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/m ³)	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

LANL got similar values.

Poisson ratio was determined to be ~0.25, for both longitudinal and shear propagation modes.

Large change in elastic moduli with air content → significant softening

⁺ measured, ^{*} assumed

P-Wave Velocity vs. Equivalent Age

Granite Block Samples – Sandia National Laboratory

Rock sample in
drilling facility

4 holes: 6" dia x ~40.5" deep

Targeted Casing Defects:

- Wall thinning
 - Pre-machine thin section in casing prior to cementing
- Casing eccentricity
 - Offset casing with jig during cementing
- Channeling
 - Removable insert
- Delamination
 - Thin-layer Silicone insert

Quartered Granite block

Summary (seedling + sapling)

- Built and experimentally validated three different acoustic sources that provide a collimated beam of low frequency.
- Beam collimation is maintained after passing through an inhomogeneous scattering medium (concrete barrel).
- Gained insight into understanding foamed cements, by determining elastic properties and performing CT scans.
- Demonstrated imaging capabilities of the system, in both open- and cased-borehole, for different induced defects (groove, detachment, fluid-filled void pocket, casing).
- Determined spatial resolution as low as 3 mm.
- Long-term plan: refine and enhance the capabilities of the 3D imaging system for more realistic environments, and extend investigation range beyond the wellbore casing.

- Industry/academic engagement that is taking place under this project.
 - multi-lab project: LANL, SNL, NETLS, ORNL
 - West Virginia Univ, through NETL
 - industry: contacted an oil & gas company. They're interested in a future collaboration for “real-world use”

Project Directions

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

Project Status Summary:

Task	Title	Planned Completion Date	Completion Date or % completion
1	Investigation of existing technology	03/31/2018	100%
2	Define metrics	03/31/2018	100%
3	Industry partners/technology maturation plan	03/31/2018	100%

Task 1. Investigation of existing technology

- Baseline performance of existing technologies, validated through elicitation of industry input, case studies, and/or literature review.
- Performed a comprehensive literature/existing technology study for wellbore integrity monitoring tools.

Accomplishments & Milestone Update

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Tools available on the market:

Technique	Company	Range	Frequency	Resolution
FMI – Fullbore Formation Microimager	Schlumberger	30 inches	N/A	5 mm both
IBC – Imaging Behind Casing	Schlumberger	Casing-formation interface	~200 kHz	102 mm vert 30 mm azim
CBL – Cement Bond Log (multiple tools)	Schlumberger	Casing-cement interface	20 kHz	Poor - ~.91m
USI – Ultrasonic Imager	Schlumberger	Casing-cement interface	200 – 700 kHz	30 mm lateral ² 15.24 cm vert
UBI – Ultrasonic Borehole Imager	Schlumberger	Full Borehole, all standard sizes	250, 500 kHz	"high"
OBMI – Oil-Based MicroImager	Schlumberger	3.5 in	N/A	Features as small as 1 cm
ARI – Azimuthal Resistivity Imager	Schlumberger	~100 in?	N/A	8 inches vert/ 60° azim angle for 1 inch standoff
AIT - Array Induction Imager Tools (multiple)	Schlumberger	10-90 in	N/A	.61m or .30m smooth borehole
Isolation Scanner Tool	Schlumberger	Casing and annulus up to 3 in	~200kHz	1.52 cm vert
Sonic Scanner	Schlumberger	formation	wide	<1.82 m
XMAC F1	Baker Hughes	100 feet	Low frequency dipole source	low
Array Dielectric eXplorer formation evaluation service	Baker Hughes	6 in	N/A ("multiple")	3 in
High-Resolution Vertilog	Baker Hughes	5.3 in to 9.425 in depending on hole diam (casing tool)	N/A	?
Digital MagneLog (DMAG)	Baker Hughes	Casing	multi	?
Acoustic Cement Bond Log	Baker Hughes	Casing-Cement Interface	?	?
Imaging Caliper Log	Baker Hughes	Casing	N/A (mechanical)	.003 in azim .14 in vertical at 11 $\frac{11}{16}$ in casing
Segmented Bond Tool (SBT)	Baker Hughes	Casing-Cement interface	Ultrasonic range	3 in vertical
Radial Analysis Bond Log (RAL)	Baker Hughes	Casing-Cement Interface	?	Similar to other CBL
Integrity eXplorer Cement Evaluation	Baker Hughes	Casing-Cement Interface	?	?
STAR Imager	Baker Hughes	Into Reservoir?	N/A	.2 inch both
Circumferential Borehole Imaging Log	Baker Hughes	?	250 kHz	?
UltrasonicXplorer Imaging Service	Baker Hughes	?	250 kHz	"high"
GeoXplorer Imaging Service	Baker Hughes	Near-wellbore	N/A	.8 in vert .3 in azim
Wellbore Geometry Instrument (WGI) Measurement Service	Baker Hughes	Casing only	N/A	1 in vert
MR eXplorer	Baker Hughes	2.1-3.8 in	~500-1000 kHz (magnetic resonance)	high
Circumferential Acoustic Scanning Tool (CAST)	Halliburton	Casing and Cement	?	1.8° azim openhole 3.6° casedhole, .3 in vert
Multifinger Imaging Tool (MIT)	Halliburton	Casing	N/A	?
Acoustic Conformance Xaminer® (ACX™)	Halliburton	Casing and Cement?	?	high
Electromagnetic Pipe Xaminer® V (EPX™ V) Tool	Halliburton	Casing only	N/A	.015 inch accuracy defect detection
Xaminer® Sonic Imager Service (also Full Wave Sonic Tool (FWS))	Halliburton	formation	low?	Low?
Radial Cement Bond Log (RCBL™)	Halliburton	Cement-Formation Interface	?	?
SPACE Panorama	Archer	Casing	3.5 MHz	.39 in vert 1.25° azim
ABI-40 Televue/WellCAD	Advance Logic Technology	2" to 20" diameter depending on mud conditions	~1.2MHz	Caliper Resolution: 0.08 mm

Comparison Matrix

Parameter	ACCObeam Acoustic Collimated Beam (our approach)	Standard borehole sonic probe, e.g. BARS SCHLUMBERGER	Ultrasonic probe, e.g. UBI SCHLUMBERGER	SPACE Panorama ARCHER
Frequency	10-250 kHz	0.3-8 kHz	250, or 500 kHz	3.5 MHz
Comments: Low frequency is needed for deeper penetration, but conventional low-frequency sources have a very large beam spread, which decreases resolution. Our approach provides a low-frequency beam that is still collimated and has no side lobes.				
Penetration Range	3 m	15 m	Casing (< 10 mm)	Casing only
Comments: ACCObeam is collimated and has a much longer investigation range than other high-frequency sources, which leads to good understanding of both the borehole and the surrounding environment. Although it does not currently penetrate as far as standard probes, ACCObeam's collimation means that it surpasses standard probes in critical ways, namely imaging resolution (ACCObeam's resolution is 60-100 times better than standard sonic probes) and power efficiency. ACCObeam is also adaptable for numerous other applications.				
Resolution	3-5 mm	300 mm	4-5 mm	10 mm
Comments: ACCObeam has the deep penetration advantage of a low-frequency source, but it maintains the same resolution as higher-frequency sources. This resolution is critical because even small fractures, delaminations, and other defects can lead to catastrophic failure of a borehole.				

Comparison Matrix

Parameter	ACCObeam Acoustic Collimated Beam (our approach)	Standard borehole sonic probe, e.g. BARS SCHLUMBERGER	Ultrasonic probe, e.g. UBI SCHLUMBERGER	SPACE Panorama ARCHER
Collimation	< 6 deg	Monopole/dipole >180 deg	< 15 deg	< 6 deg
Comments: Our source has a very similar collimation/beam spread as its high-frequency competitors, even though it generates a low-frequency beam that penetrates much deeper than any high-frequency source. Please note the huge difference when compared with the standard borehole sonic probe.				
Cost	\$	\$\$\$\$	\$\$\$\$	\$\$\$\$
Comments: All other products are offered as a service/package operated by a specific company, so the cost of using their source is thousands of dollars . ACCObeam costs \$50-\$200 to manufacture and is compatible with virtually any imaging software or hardware.				
Imaging through highly attenuating materials	Y	Y	N	N
Comments: The only other product able to image clearly and beyond casing in highly attenuating media (such as concrete, drilling mud, rock, and bone) is the low-frequency standard borehole sonic probe. However, standard probes have an extremely low spatial resolution and can miss important small features. On the other hand, our source works well in highly attenuating media while maintaining the resolution characteristic of high frequency.				

Comparison Matrix

Parameter	ACCObeam Acoustic Collimated Beam (our approach)	Standard borehole sonic probe, e.g. BARS SCHLUMBERGER	Ultrasonic probe, e.g. UBI SCHLUMBERGER	SPACE Panorama ARCHER
Size	Small/compact	Large	Small/compact	Small/compact
Comments: ACCObeam is similar in size to high-frequency sources, but much smaller than a typical low-frequency source.				
Collimated beam at multiple frequencies	Y (several)	N	N	N
Comments: The UBI ultrasonic probe can provide either a somewhat collimated 250 kHz beam or a more collimated 500 kHz beam, but our source images at numerous frequencies ranging from 10–250 kHz while maintaining a tight collimation.				
Simple manufacturing process	Y	N	N	N
Comments: ACCObeam's design requires radial clamping, achieved by gluing a piezoelectric transducer into casing made of any strong material. Comparative technologies require filler material and a small matching inductor for "loading" the back of the transducer, making the packaging process more sophisticated.				
Images through various media	Y	N	N	N
Comments: No competing source can be used to image in assorted media. Since our source operates at a low frequency, it can transmit or receive in liquids, solids, gases, and air.				

Project Status Summary:

Task 2. Define metrics

Identified key performance metrics.

Year 1

Phase 2 SMART milestone (end of year 1)

Go/No-Go2: Detect defects at the cement-formation interface, with high resolution (5 mm, or better).

Year 2

Phase 3 SMART milestone (end of year 2):

Go/No-Go3: Tool survival in adverse conditions of corrosiveness, high temperature and high pressure (brines specific to geothermal wells, at temperatures of at least 250C, and high pressures of 45 kpsi);

Go/No-Go4: Imaging capabilities out in the formation, up to 3 meters.

Year 3

2nd quarter progress measure: 1st version of the prototype is functional in laboratory tests.

Final success metrics:

Prototype in field functionality similar to the one observed in tests in the laboratory.

Project Status Summary:

Task 3. Industry partners/technology maturation plan

- Identified Chevron as potential future partner for further developing the proposed technique. Obtained Support Letters from Chevron, on two different occasions: once when the proposal was submitted, and when we submitted an R&D100 application.
- Technology maturation plan
 - Develop an engineering prototype. The prototype has to meet the standards required for CO₂ sequestration and geothermal industry, in terms of resistance to corrosion, high temperature and high pressure.
 - Develop robust operation & analysis software, for near real-time 3D imaging by speeding up the measurement and analysis process.

Main objective: develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment

The Problem:

Defects/fracture detection beyond casing with high resolution. No current techniques.

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

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