E-Spectrum Technologies

The University of Texas at Austin
Petroleum and Geosystems Engineering

DOE Project Number DE-FE0024271

Fracture Diagnostics Using Low Frequency Electromagnetic Induction and Electrically Conductive Proppants

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Participants: Javid Shiriyev, Peng Zhang, Yaniv Brick, Ali Yilmaz, UT Austin.

J. Gabelmann, Robert Houston, ESTI

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Motivation for Research

- Microseismic monitoring is the most common fracture diagnostic method in use today. It tracks shear failure events associated with the opening of the main fracture.
- Micro-seismic events do not reflect the propped fracture length nor do they inform us about the spatial distribution of proppant.
- Shear failure events that generate microseisms are often associated with regions of the reservoir that have no propped conductivity.
- It would be very useful to have a single well, far field method that measures the propped fracture length, orientation and proppant distribution in the fracture after hydraulic fracturing.

Project Objectives

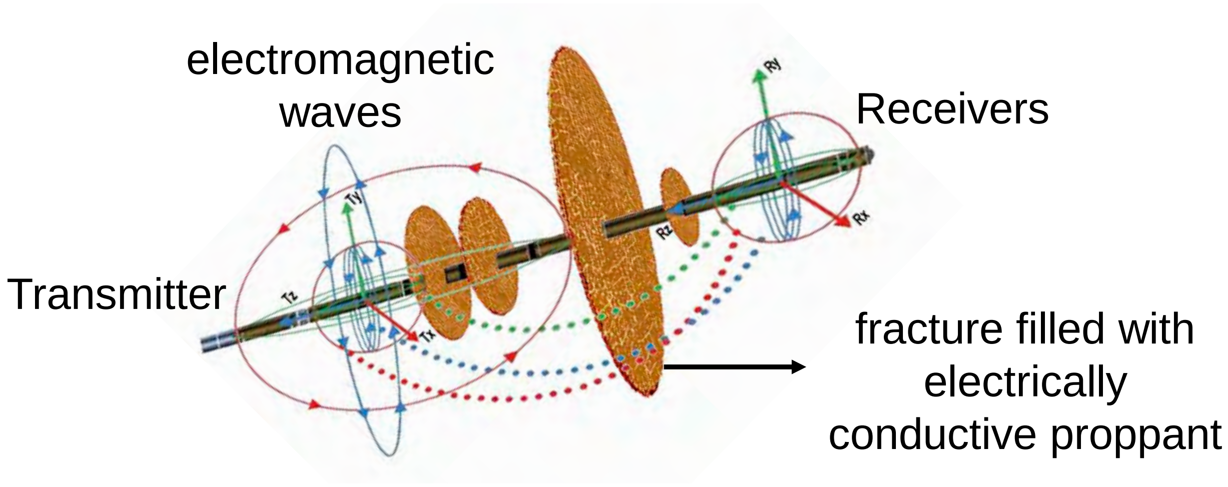
The primary objective of the project is to build and test a prototype downhole fracture diagnostic tool that can be used to estimate the orientation and length of the 'propped' fracture and to map the distribution of proppant in the fracture.

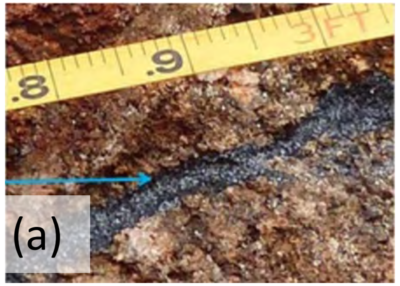
Specifically, our objectives are to:

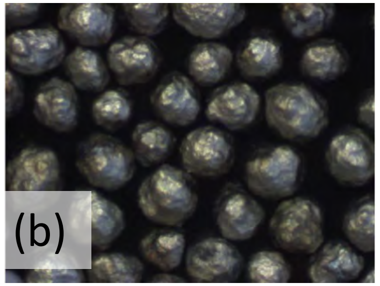
- Develop a forward model for the proposed technology taking into account real geological and reservoir constraints.
- Test proppants in the laboratory for electrical and material properties for their suitability in deployment in the field.
- Design, build and test a prototype low frequency electromagnetic tool.
- Invert the field data to estimate the propped fracture geometry, and present a map showing the distribution of proppant in the fracture.

The Basic Idea

- Transform a hydraulic fracture into a highly conductive plane using conductive proppants
- Use a logging tool (with downhole sources and receivers)







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Key Questions

- ❑ Are inexpensive conductive proppants available?
- ❑ How far can we image the proppant in the fracture?
- ❑ Is the signal to noise ratio sufficient to provide us with a reliable measurement?
- ❑ Can the measured signal be inverted to provide fracture dimensions and orientation?

Project Impacts

- The proposed technology is a potential game changer for fracture diagnostics as it provides information on the proppant distribution in the fracture, information that is currently not available to operators.
- It is less expensive, simpler to run and provides more direct information about the propped fracture than other far field diagnostic methods such as micro-seismic monitoring.
- It is anticipated that the technology will be widely used by operators to better understand where the proppant has been placed.

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Key Deliverables / Expected Outcomes

Periodic, Topical and Final reports are being submitted in accordance with the "Federal Assistance Reporting Checklist" and the instructions accompanying the checklist. In addition the specific deliverables for each Task are listed below.

Task 1: Project Management Plan

1. A Project Management Plan.

Tasks 2-4: Development and Construction of Prototype Tool and Proppant Selection

1. A Topical Report outlining the results of the main simulations of the forward model and sensitivity analysis performed, the laboratory test results of proppant testing, and design of EM tool.
2. Test results that allow us to select a suitable electrically conductive proppant.
3. Design of a prototype electromagnetic tool. This will include the basic drawings and specifications of the tool.

Tasks 5: Testing of Prototype Tool

1. A Report outlining the results and the main conclusions of the trial.

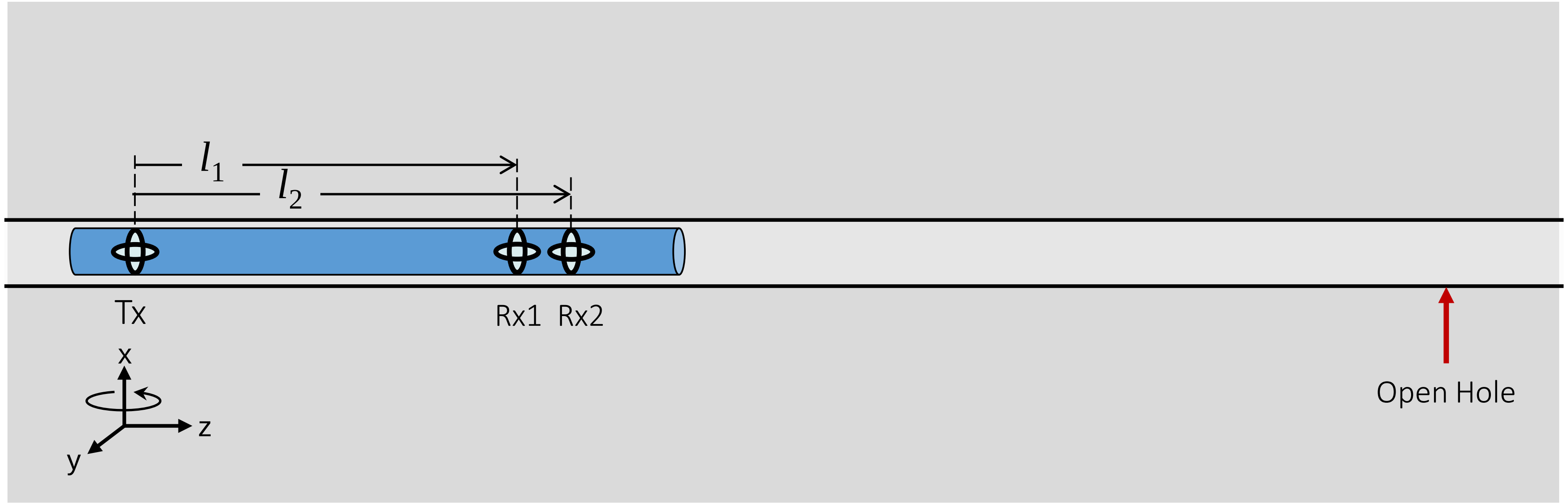
Tasks 6: Data Inversion

1. Final Report.

Tasks

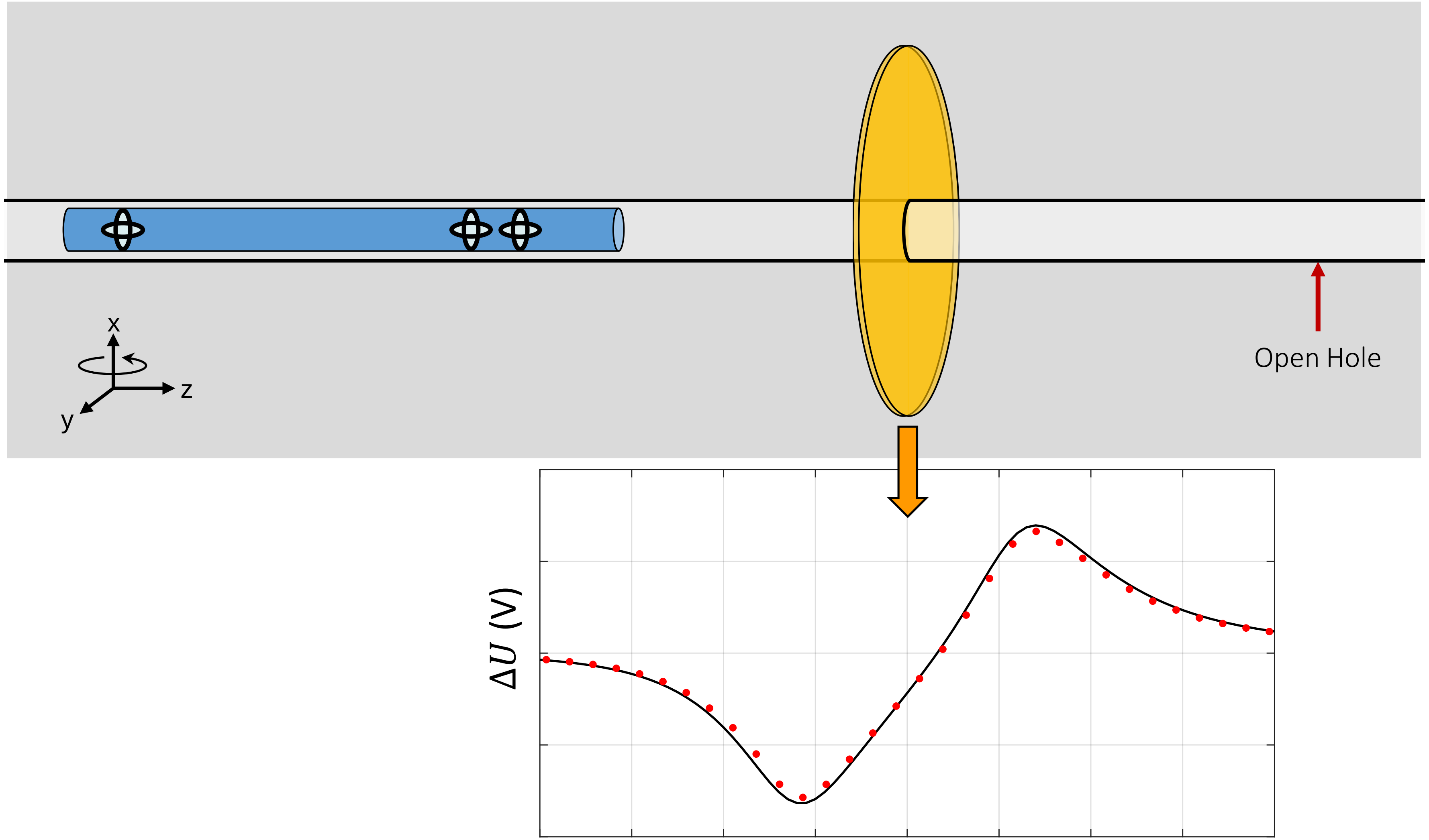
- Task 1.0 – Project Management Plan
- Task 2.0 – Development of forward model for the proposed tool and different fracture geometries
- Task 3.0 – Lab testing of available proppants in the market for electrical and material properties
- Task 4.0 – Final design and construction of low frequency electromagnetic tool
- Task 5.0 – Laboratory and field testing of prototype tool
- Task 6.0 – Inverting data to obtain the fracture geometry

EM Induction Logging Tool



$$\Delta U^{uv} = \mathrm{Re}\left\{-j\omega\mu_o A_{\mathrm{RX}} N_{\mathrm{RX}} \hat{\mathbf{u}} \cdot \left[\mathbf{H}^{v}\left(\mathbf{r}_{\mathrm{Rx2}}\right) - \mathbf{H}^{v}\left(\mathbf{r}_{\mathrm{Rx1}}\right)\frac{l_1^3}{l_2^3}\right]\right\}$$

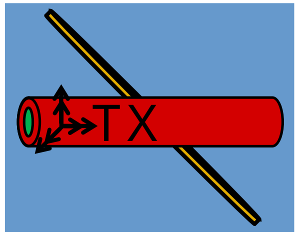
EM Induction Logging Tool



Numerical Simulation – VIE

Electric-field integral-equation

* Simplest coil model
* reference: current source



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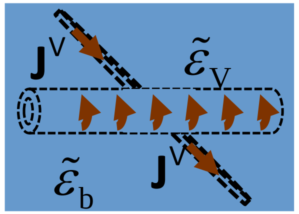


$$\tilde{\mathbf{D}}(\mathbf{r}) = \tilde{\varepsilon}_V(\mathbf{r})\mathbf{E}(\mathbf{r}) \rightarrow \frac{\tilde{\mathbf{D}}(\mathbf{r})}{\tilde{\varepsilon}_V(\mathbf{r})} + \mathrm{L}\left(j\omega\chi\tilde{\mathbf{D}},\mathbf{r}\right) = \mathbf{E}^{\mathrm{inc}}(\mathbf{r}) \ \forall \mathbf{r} \in V$$

$$\mathrm{L}(\mathbf{J}^V,\mathbf{r}) = j\omega\iiint_V \mu_0 G(\mathbf{r},\mathbf{r}')\mathbf{J}^V(\mathbf{r}')dv' - -\nabla\iiint_V G(\mathbf{r},\mathbf{r}')\frac{\nabla'\cdot\mathbf{J}^V(\mathbf{r}')}{j\omega\tilde{\varepsilon}_b}dv'$$

$$\tilde{\varepsilon}_V(\mathbf{r}) = \varepsilon_V(\mathbf{r}) + \sigma_V(\mathbf{r})/j\omega$$

$$\mathbf{J}^V(\mathbf{r}) = \underbrace{\left(1 - \frac{\tilde{\varepsilon}_b}{\tilde{\varepsilon}_V(\mathbf{r})}\right)}_{\chi(\mathbf{r})} j\omega\tilde{\mathbf{D}}(\mathbf{r})$$

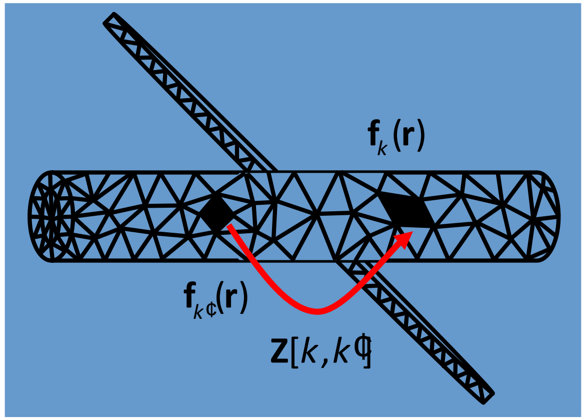
$$0 < |\chi| < 1$$

$$G(\mathbf{r},\mathbf{r}') = \frac{e^{-\gamma_b|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}, \ \gamma_b = j\omega\sqrt{\mu_0\tilde{\varepsilon}_b}$$

- **Discretize geometry expand unknowns**

$$\tilde{\mathbf{D}}(\mathbf{r}) \cong \sum_{k'=1}^{N}\mathbf{I}[k']\mathbf{f}_{k'}(\mathbf{r})$$

$$\frac{\mathbf{J}^V(\mathbf{r})}{j\omega} \cong \sum_{k'=1}^{N}\chi_{k'}(\mathbf{r})\mathbf{I}[k']\mathbf{f}_{k'}(\mathbf{r})$$



- **Galerkin testing**

$$\left\langle \chi_k(\mathbf{r})\mathbf{f}_k(\mathbf{r}), \frac{\tilde{\mathbf{D}}(\mathbf{r})}{\tilde{\varepsilon}_V(\mathbf{r})} + \mathrm{L}(j\omega\chi\tilde{\mathbf{D}},\mathbf{r})\right\rangle = \left\langle \chi_k(\mathbf{r})\mathbf{f}_k(\mathbf{r}), \mathbf{E}^{\mathrm{inc}}(\mathbf{r})\right\rangle$$

- **System of linear equations**

$$\mathbf{Z}_{N\times N}\mathbf{I}_{N\times 1} = \mathbf{V}^{\mathrm{inc}}_{N\times 1}$$

- **Multiple tool positions**

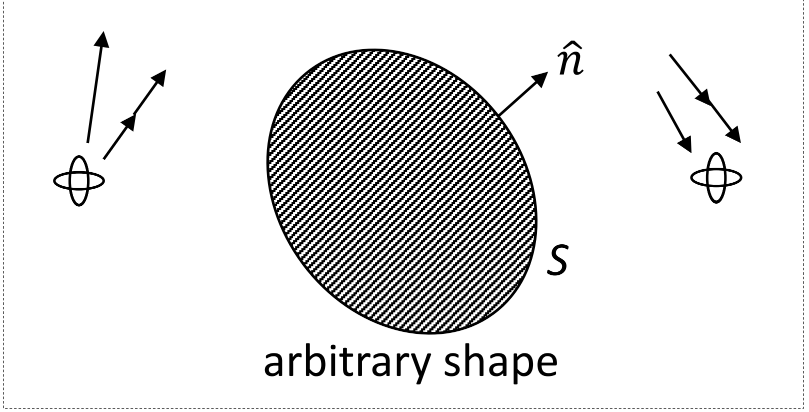
$$\mathbf{Z}[\mathbf{I}_1 \cdots \mathbf{I}_{N_{\mathrm{rhs}}}] = [\mathbf{V}_1^{\mathrm{inc}} \cdots \mathbf{V}_{N_{\mathrm{rhs}}}^{\mathrm{inc}}]$$

More details on the Volume Integral Equations EM forward-modeling:

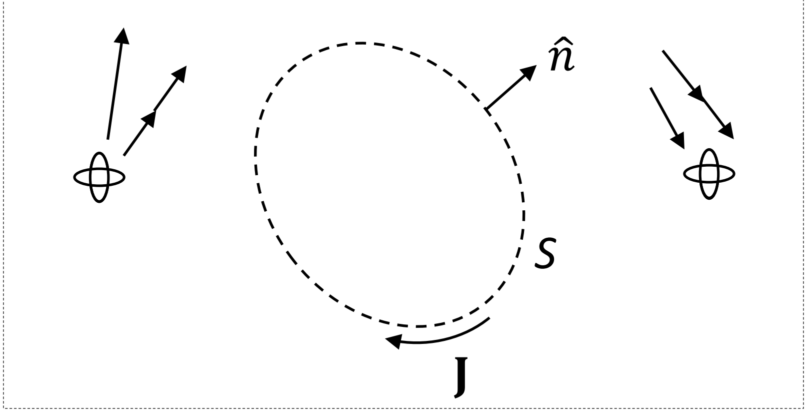
[1] P. Zhang, J. Shiriyev, Y. Brick, J. Massey, C. Torres-Verdin, A. E. Yılmaz, and M. M. Sharma, "Fracture diagnostics using a low frequency electromagnetic induction method," in *Proc. ARMA*, June 2016

Numerical Simulation – SIE/IBC

Original Problem



Equivalent Problem



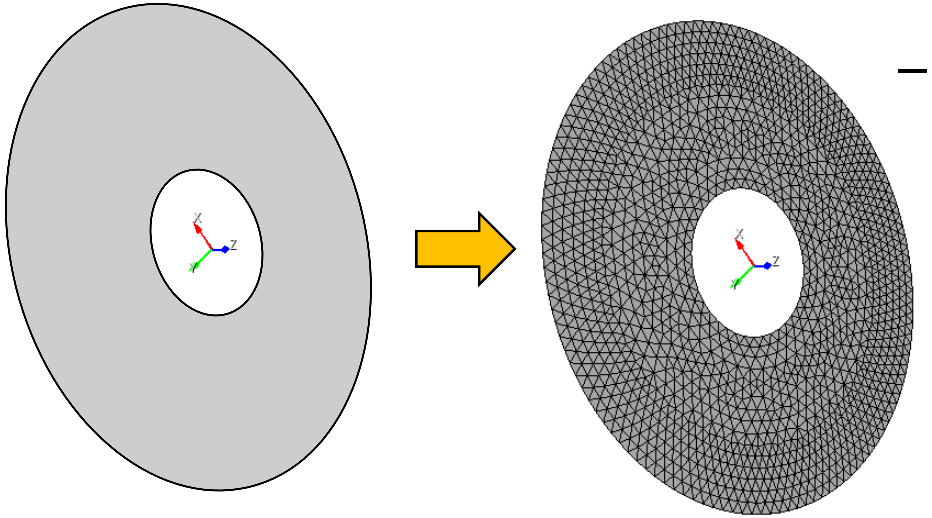
Maxwell Equations:

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H} - \mathbf{M}$$
$$\nabla \times \mathbf{H} = j\omega\varepsilon\mathbf{E} + \mathbf{J}$$
$$\nabla \cdot (\varepsilon\mathbf{E}) = \rho_e$$
$$\nabla \cdot (\mu\mathbf{H}) = \rho_m$$

$$\mathbf{E}^{sca} = -j\omega\mu \iint_S G(\mathbf{r},\mathbf{r}')\mathbf{J}(\mathbf{r}') + \frac{\nabla G(\mathbf{r},\mathbf{r}')}{k^2}\nabla' \cdot \mathbf{J}(\mathbf{r}')\, dS'$$

$$\mathbf{H}^{sca} = \iint_S \nabla G(\mathbf{r},\mathbf{r}') \times \mathbf{J}(\mathbf{r}')\, dS'$$

Numerical Simulation – SIE/IBC



$$-\hat{n} \times \hat{n} \times \mathbf{E}^{\text{sca}} - \frac{\mathbf{J}}{\sigma t} = \hat{n} \times \hat{n} \times \mathbf{E}^{\text{inc}}(\mathbf{r}) \quad \mathbf{r} \in S$$

and $$\mathbf{J}(\mathbf{r}) \cong \sum_{n=1}^{N} I_n \mathbf{\Lambda}_n(\mathbf{r})$$

$$\mathbf{Z}\mathbf{I} = \mathbf{V}^{\text{inc}}$$

- Once unknown coefficient vector is found, scattered fields are calculated for two observation points.
- This procedure is repeated for each tool position and only incident field vector is regenerated.
- S-EFIE constrain unknowns to only currents on anomalous regions.
- No artificial/approximate boundary conditions are required.

More details on the Surface Integral Equations EM forward-modeling can be found on the appendix of:

[2] J. Shiriyev, Y. Brick, P. Zhang, A.E. Yilmaz, C. Torres-Verdin, M.M. Sharma, T. Hosbach, M.A. Oerkfitz, and J. Gabelmann, "Experiments and simulations of a prototype tri-axial electromagnetic induction logging tool for open-hole hydraulic fracture diagnostics", Geophysics, 2018

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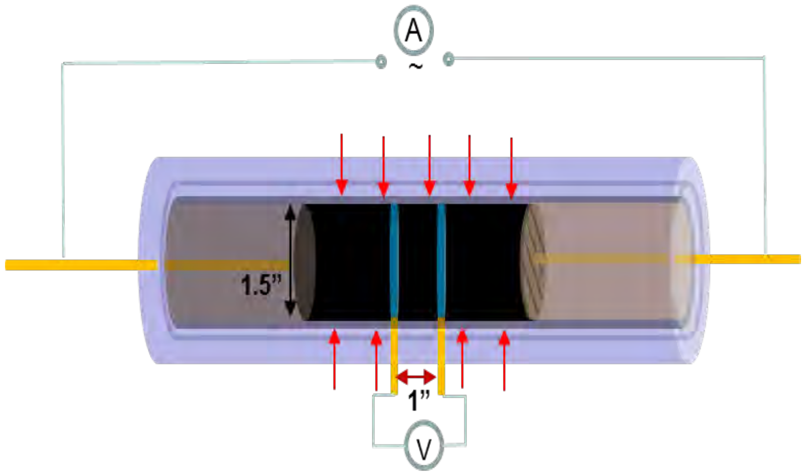
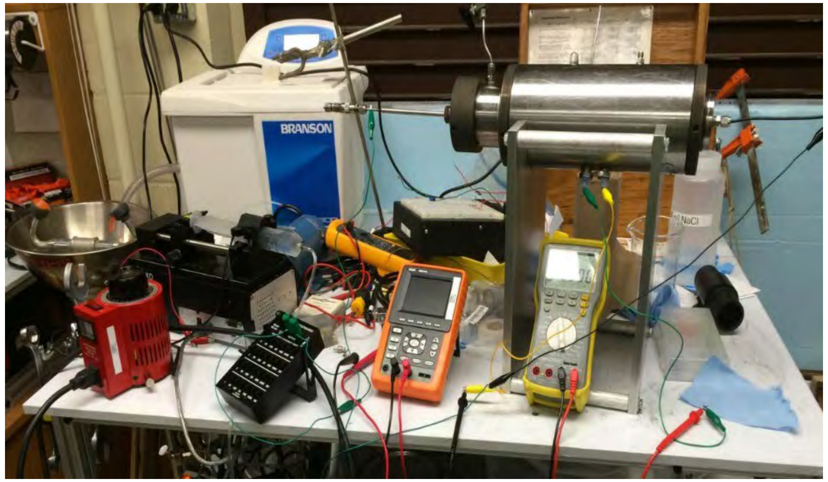
Tasks

- Task 1.0 – Project Management Plan
- Task 2.0 – Development of forward model using proposed tool and different fracture geometries
- Task 3.0 – Testing of available proppants in the market for electrical and material properties (Peng Zhang, Rod Russell, and Mukul Sharma)
- Task 4.0 – Final design and construction of low frequency electromagnetic tool
- Task 5.0 – Laboratory and field testing of prototype tool
- Task 6.0 – Inverting data to obtain the fracture geometry

Experimental Method for Resistivity Measurements





- A **4-point probes method** was used to do the measurements in a core holder.
- Alternating current (**AC**) was applied on the current-carrying electrodes, while the voltage was measured on the voltage-sensing electrodes.
- **Confining pressure** can be applied. Saturation fluid could be tuned.

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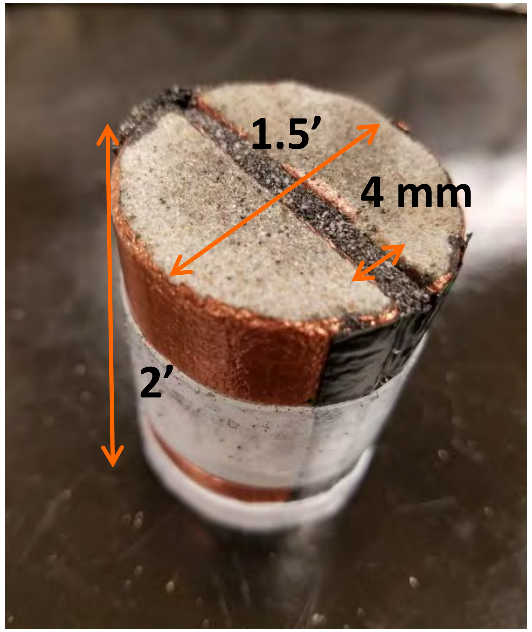
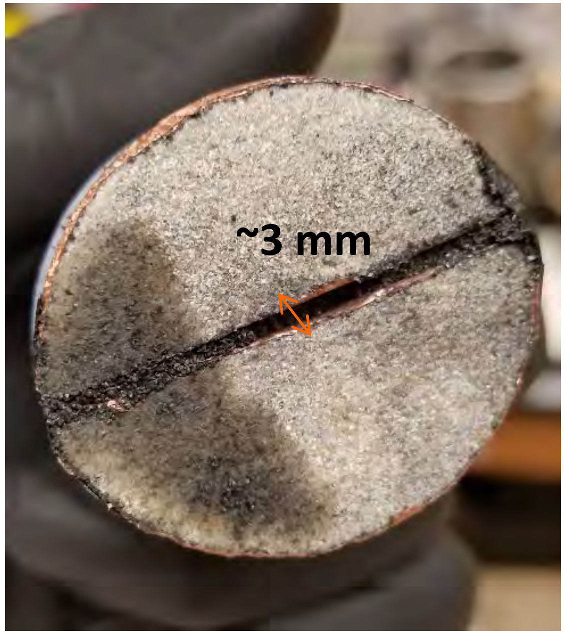
Experimental Method for Resistivity Measurements



Before measurement



After measurement

- 0% sand + 100% coke
- 25% sand + 75% coke
- 50% sand + 50% coke
- 75% sand + 25% coke

The ratio is based on **mass.**

Size: 40-70 mesh & 70-100 mesh
Coke Density: ~2 g/cm^3

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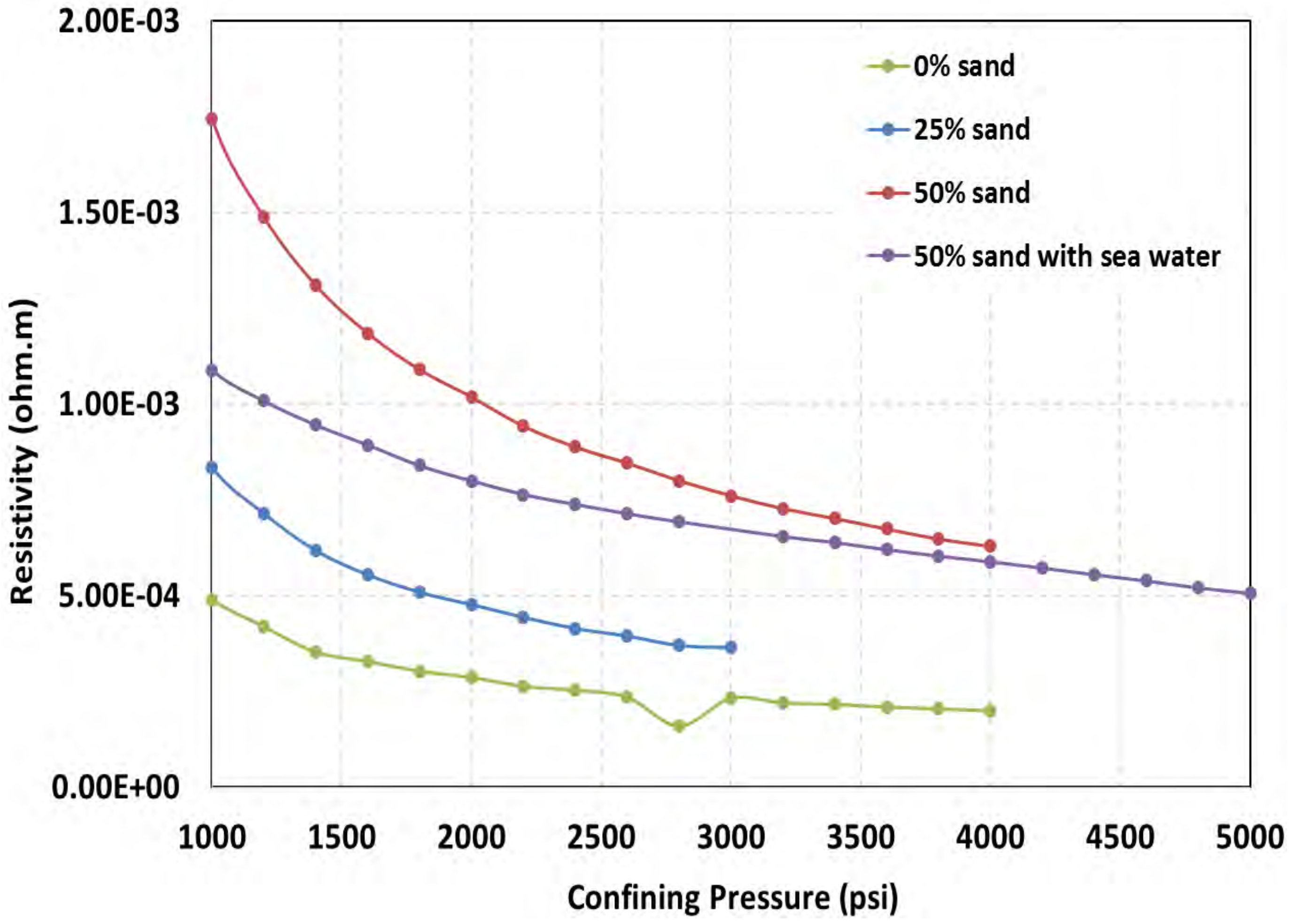
Electrical Resistivity: 40/70 mesh



0% sand	$1.99 \times 10^{-4}\ \Omega \cdot m$ @4000 psi
25% sand	$3.64 \times 10^{-4}\ \Omega \cdot m$ @3000 psi
50% sand	$6.28 \times 10^{-4}\ \Omega \cdot m$ @4000 psi
50% sand (sea water)	$5.06 \times 10^{-4}\ \Omega \cdot m$ @5000 psi

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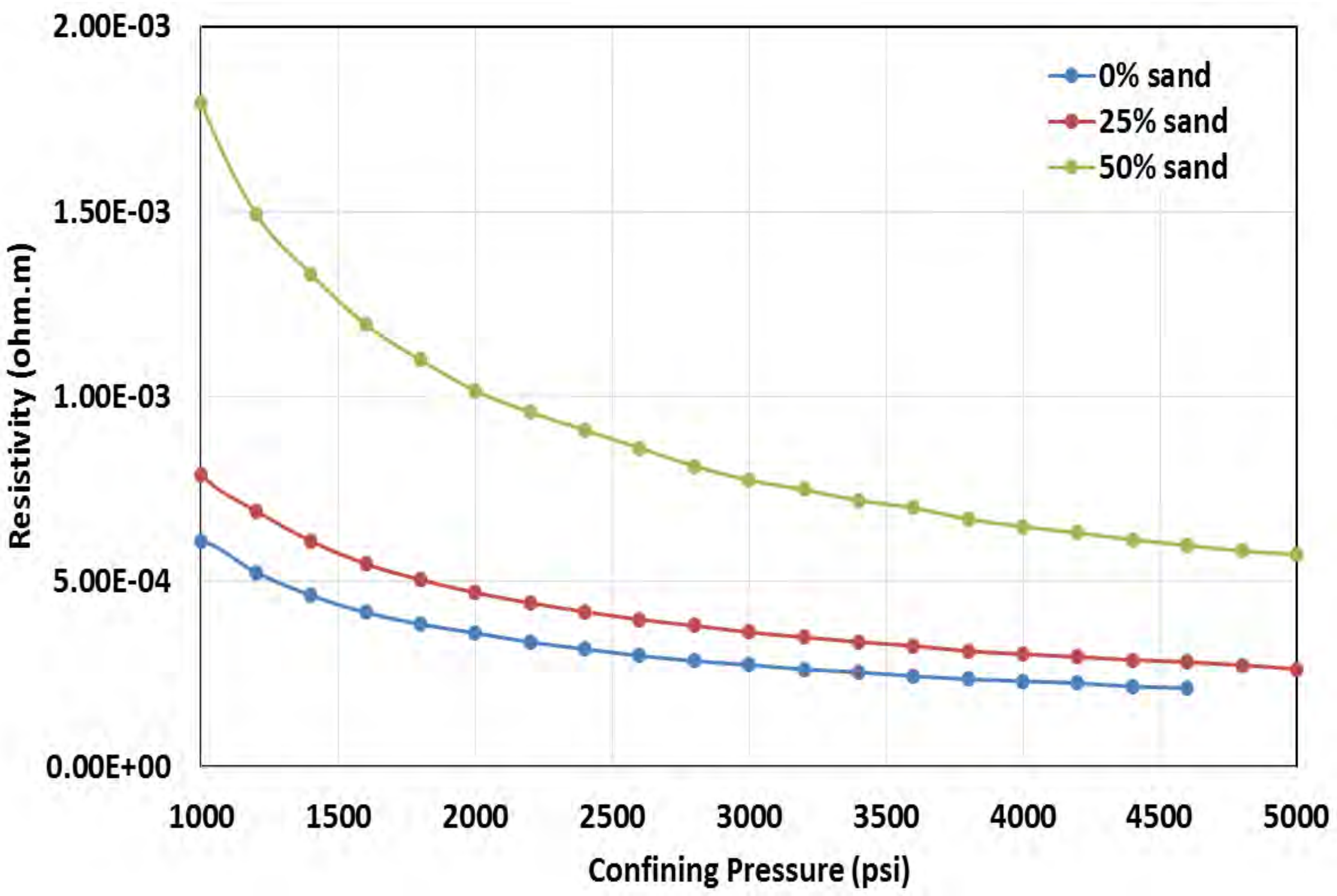
Electrical Resistivity: 70/100 mesh



All with sea water

0% sand	$2.12 \times 10^{-4}\ \Omega \cdot m$ @4600 psi
25% sand	$2.64 \times 10^{-4}\ \Omega \cdot m$ @5000 psi
50% sand	$5.73 \times 10^{-4}\ \Omega \cdot m$ @5000 psi

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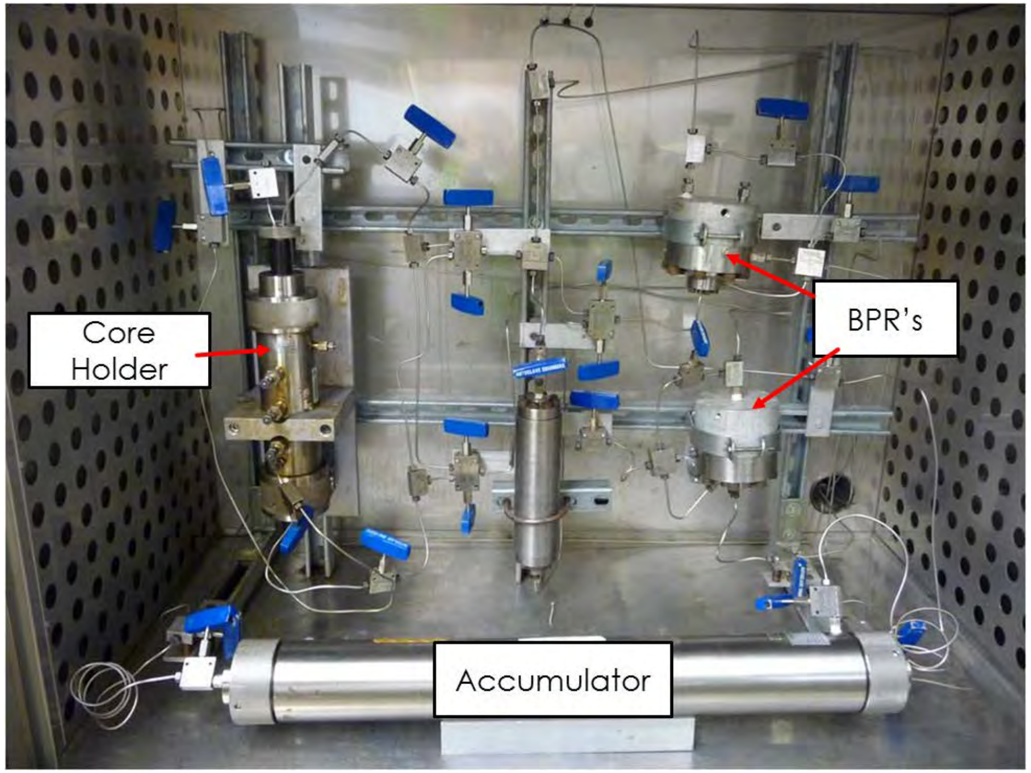
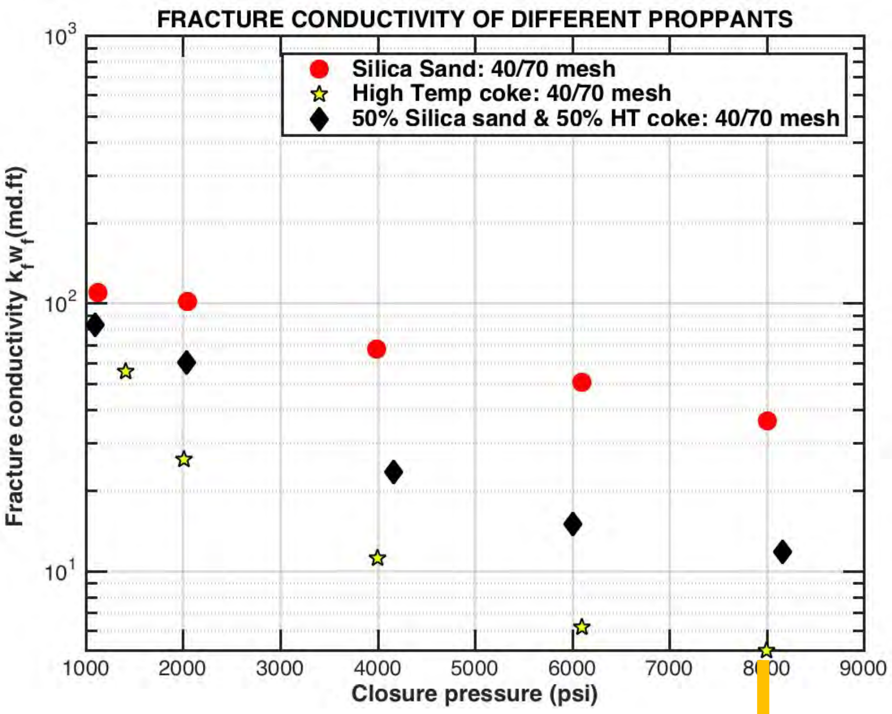
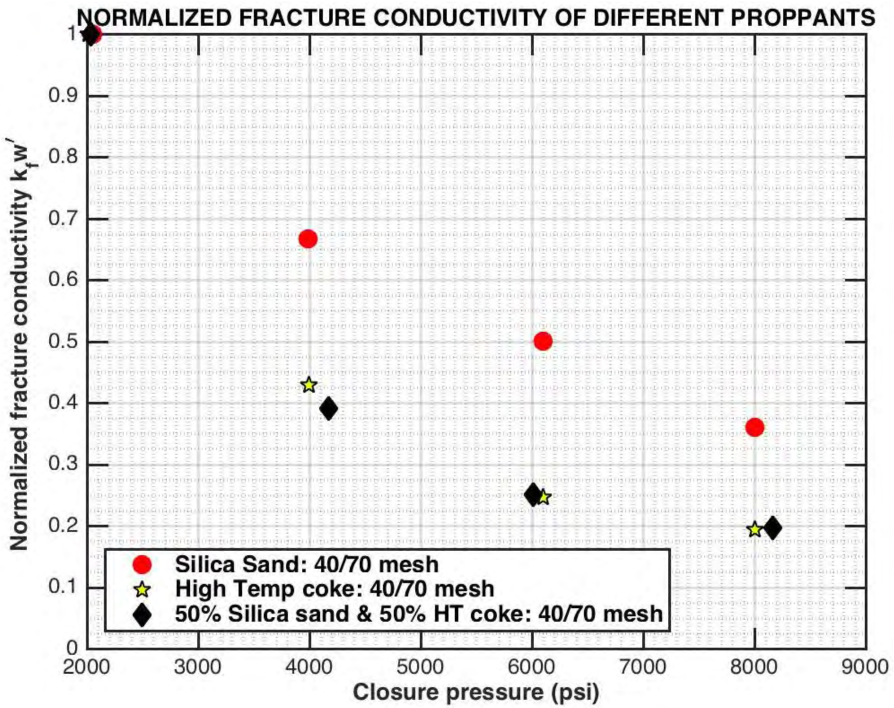
Experimental Method for Fracture Conductivity Measurements

- A Berea sandstone core of 1'' diameter by 8'' length was prepared with a fracture width of 1mm.
- The core was placed inside a Hassler sleeve core holder and **evacuated** to remove trapped air.
- Confining closure stress was applied for 24 hours, after which 3% brine solution was pumped through the core at a range of **constant flow rates**.
- For each closure stress applied, the **pressure drop** across the core was measured and used to calculate the fracture conductivity using Darcy's Law.
- This procedure was repeated for incremental closure stresses from 1000 – 8000 psi.



Fracture Conductivity and Normalized Conductivity – Sand and Coke: 40/70 mesh





$$F_{CD} = k_f w_f / L_f k = 5 / 250E{-}4$$

$$F_{CD} = 200$$

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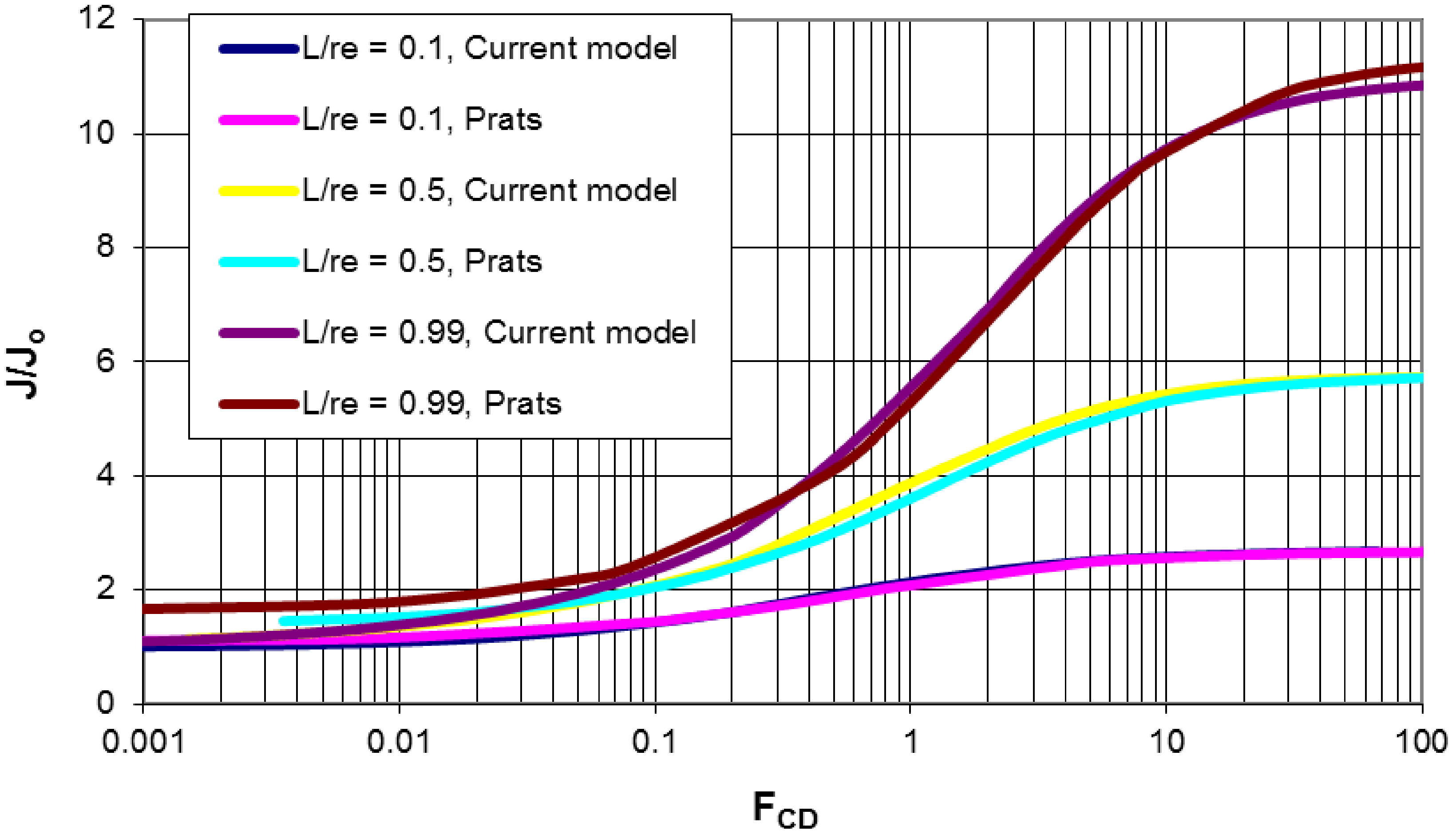
Productivity Index: Fractured Vertical Wells



(Friehauf and Sharma, 2009)

Summary of Lab Measurements

- The electric resistivity of the PC, under confining stress, was measured to be in the range of 2 x $10^{-4}\ \Omega \cdot m$
- Size does not affect the electrical resistivity but does affect the permeability.
- It is feasible to use mixtures of sand and PC if fracture conductivity is a concern (large in-situ stresses).
- Both resistivity and permeability increase with increasing mass percentage of sand at a given confining pressure.
- Brine has a minor effect on the measured resistivity because it is usually much more resistive ($\sim 0.2\ \Omega \cdot m$) than petroleum coke.

Tasks

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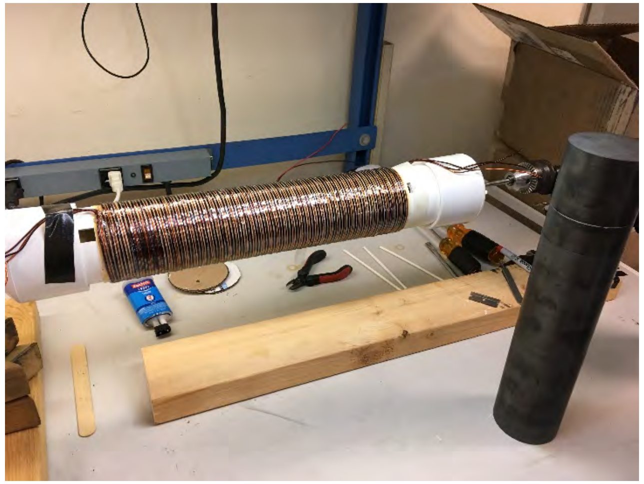
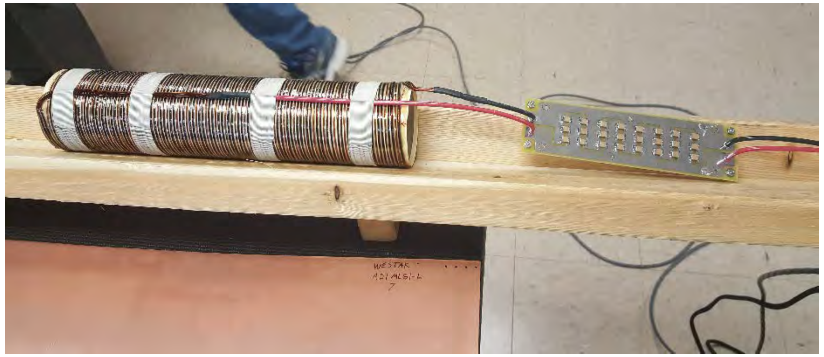
Tool Construction and Lab Testing

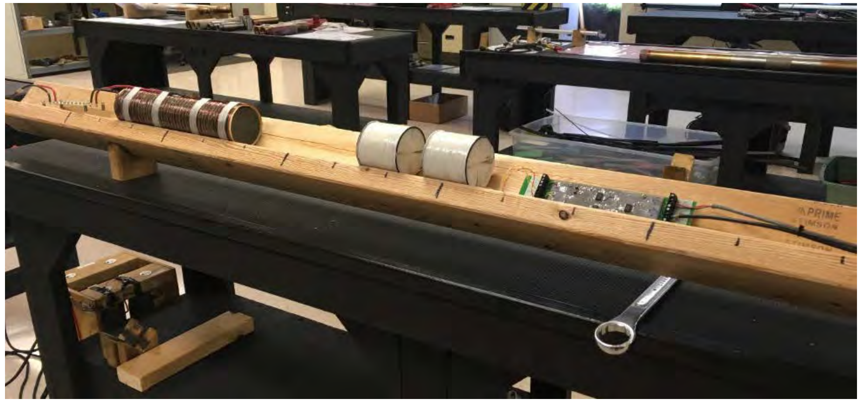


Axial TX coil on winding fixture with ferrite core to the side

Co-planar coil after construction

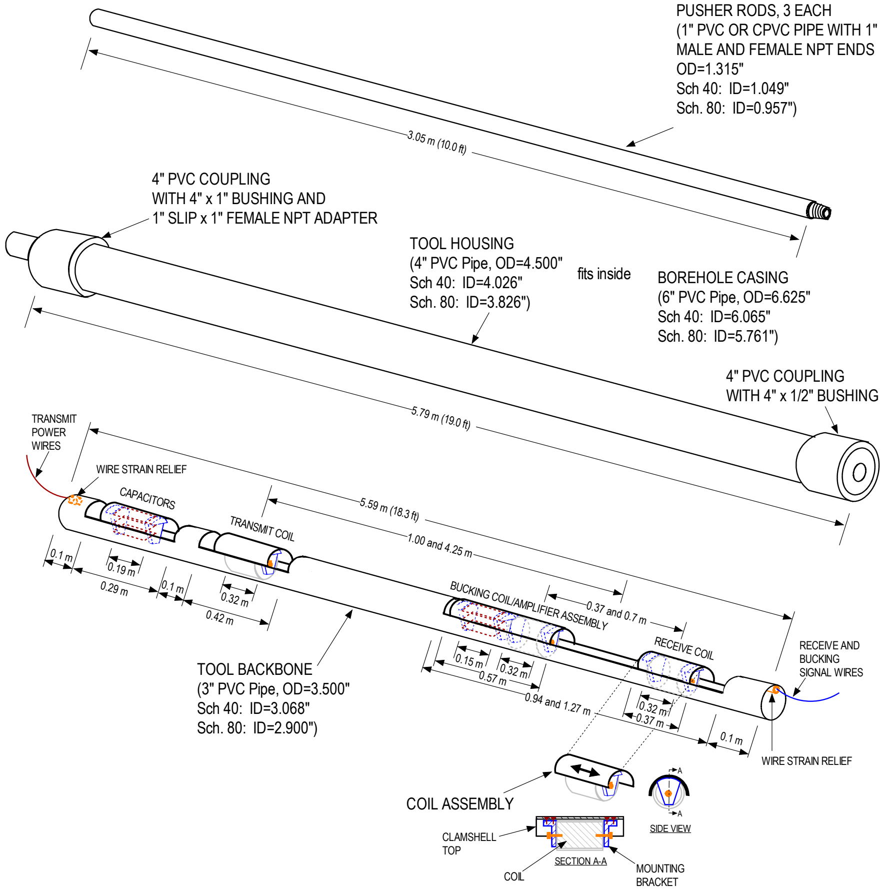


Tank circuit, transmit coil with capacitor board on the right



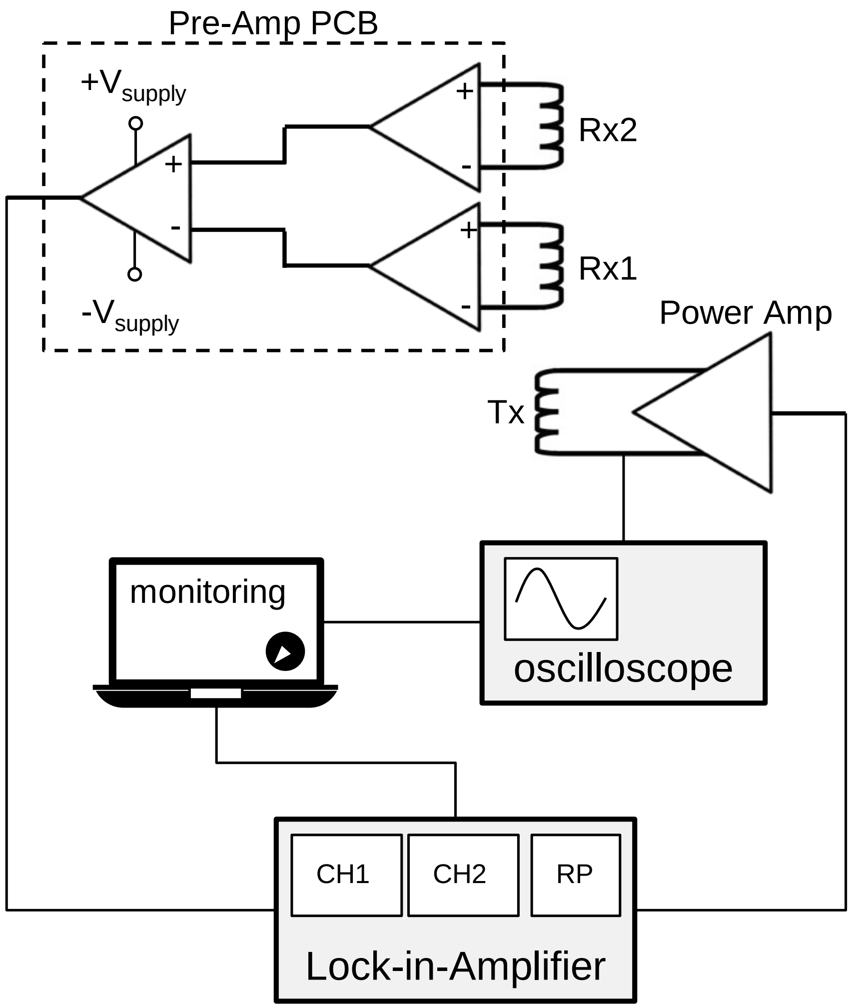
Initial bench testing of TX-RX coil setup

RX coils:
z-coil (right)
x/y coil (left)



Lab test fixture diagram for LFIE tool

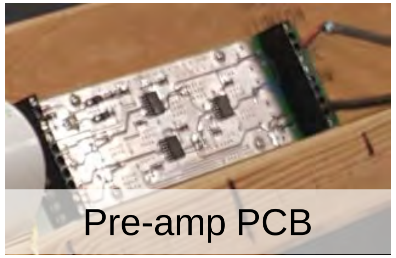
Lab Test Setup



Tx coil (x,y)

Tx coil (z)

Rx coil (x,y,z)


Pre-amp PCB

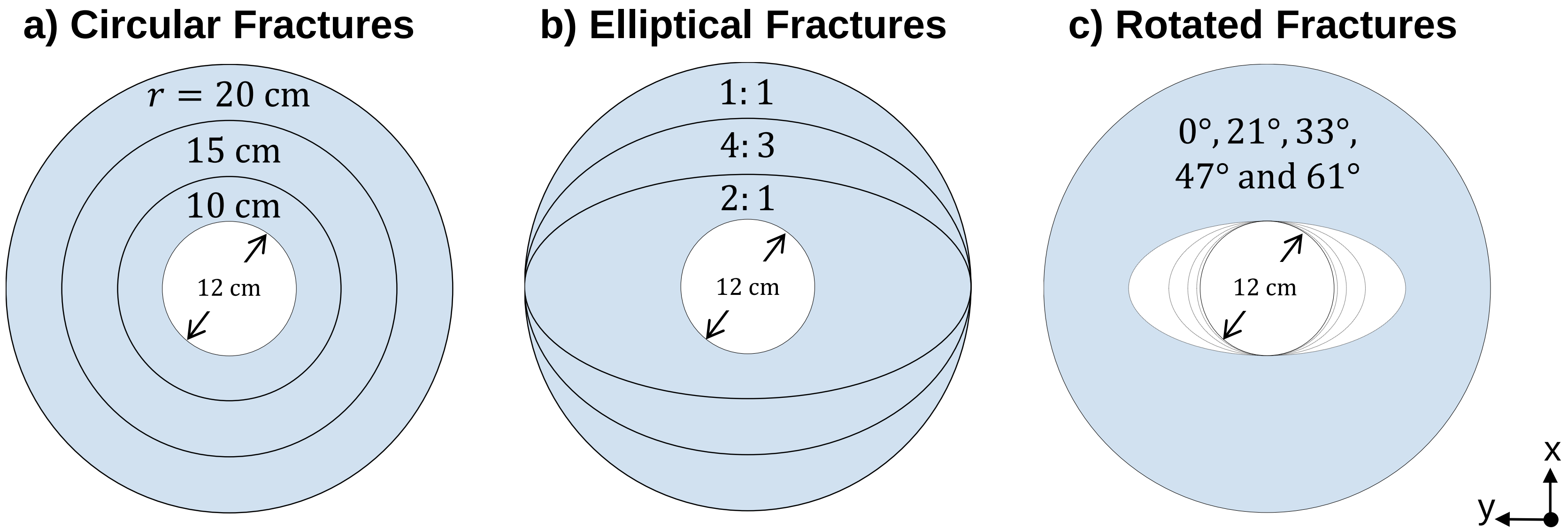

Power Amplifier


Tektronix MSO-scope 2024


SR830 DSP Lock-in-Amplifier

Lab Test Fracture Models

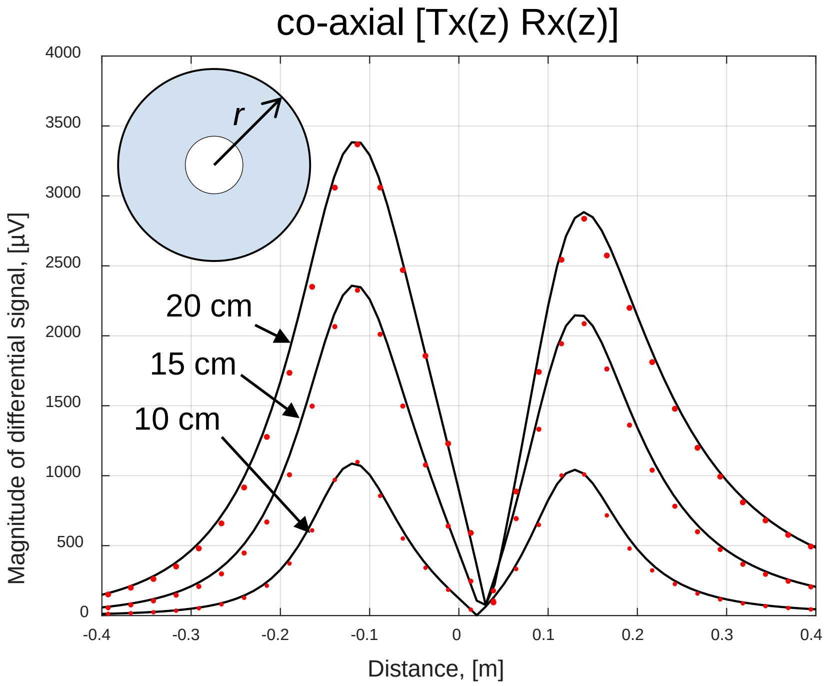
– **Industrial Aluminum Foil**
Conductivity at 20°C is 33.4 – 35.8 MS/m
Thickness is 25.4 ± 10% μm
(also verified with micrometer measurement)
– **Experiment setup**
Plexiglass, PVC pipes, nylon rod and Lexan
– **Comparison to real size hydraulic fractures**

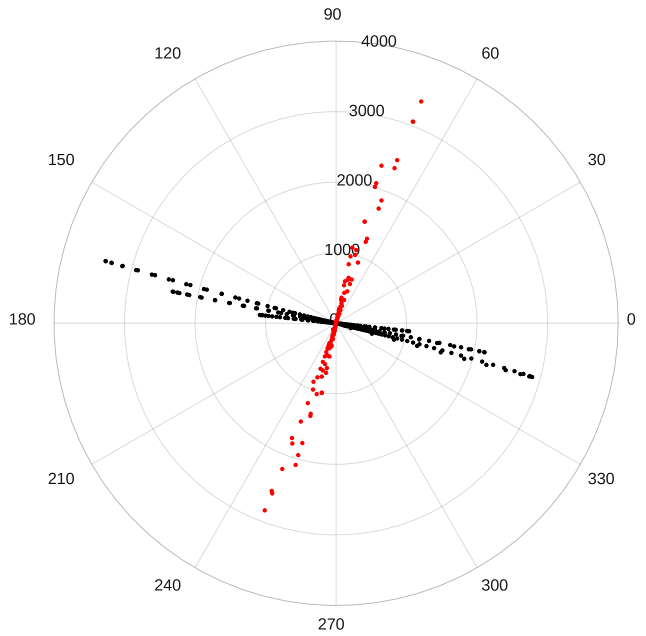


Lab Measurements

- All coils were tested to verify specs.
- A single coil configuration is tested at a time.
- Transmitter coil currents are measured during tests and results are normalized with respect to currents.
- At every sampling point data were recorded for a minute or more and signal to noise ratio is shown to be strong.
- Signals are referenced with respect to voltage around the transmitter coil. Reference phase is used to rotate the output channels to get in-phase (real) and quadrature (imaginary) components of received signals.

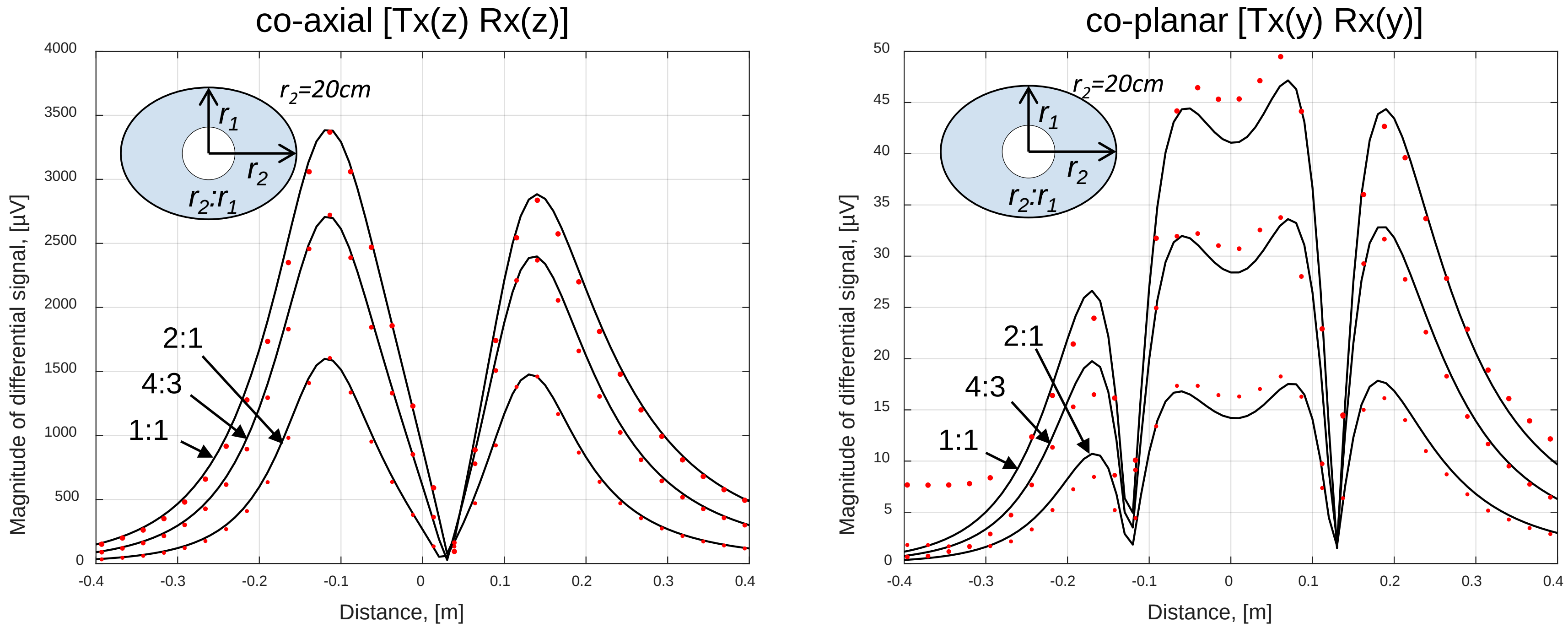
Results – Lab Measurements





Parameter	Co-Axial	Co-Planar	Cross-Polarized
Surface Area	>100 μV	>10 μV	<1 μV
Aspect Ratio	>100 μV	>10 μV	<1 μV
Dip Angle	>100 μV	>100 μV	>100 μV

Results – Lab Measurements



Parameter	Co-Axial	Co-Planar	Cross-Polarized
Surface Area	>100 μV	>10 μV	<1 μV
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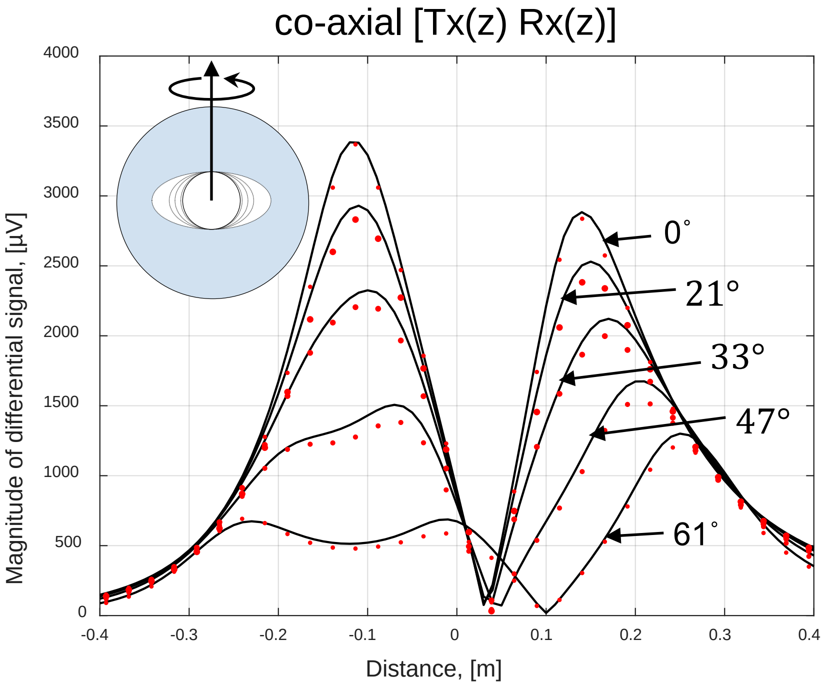
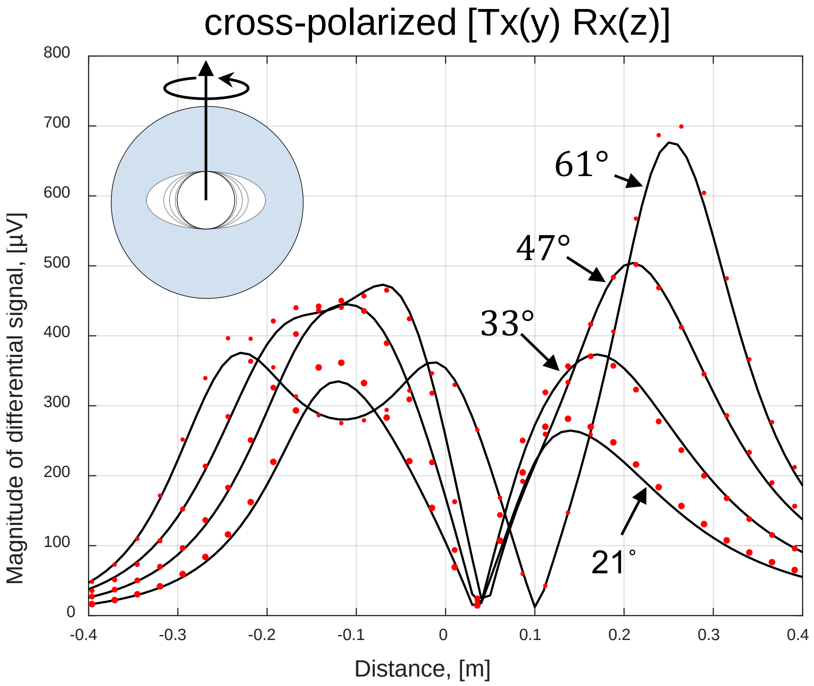
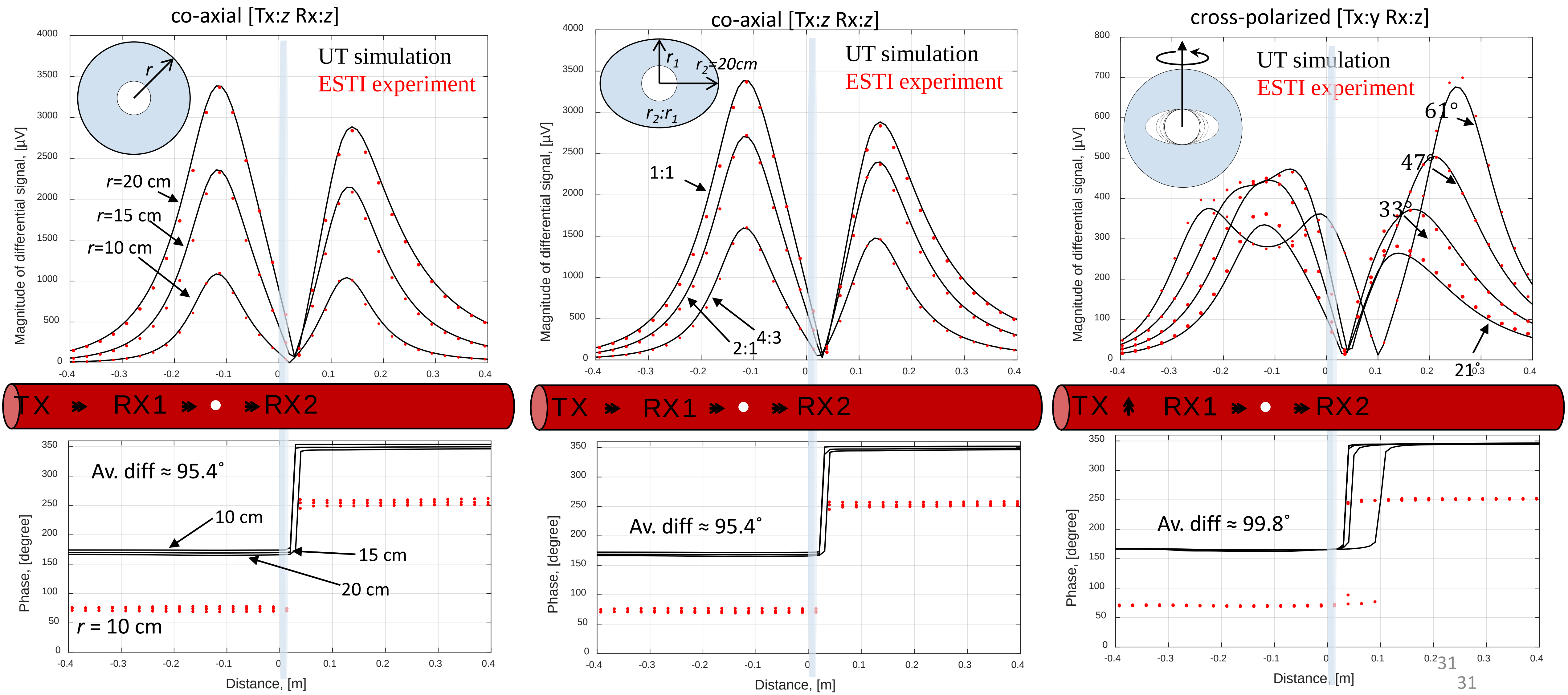
Results – Lab Measurements





Parameter	Co-Axial	Co-Planar	Cross-Polarized
Surface Area	>100 µV	>10 µV	<1 µV
Aspect Ratio	>100 µV	>10 µV	<1 µV
Dip Angle	>100 µV	>100 µV	>100 µV

Comparison of Lab Results with Simulations



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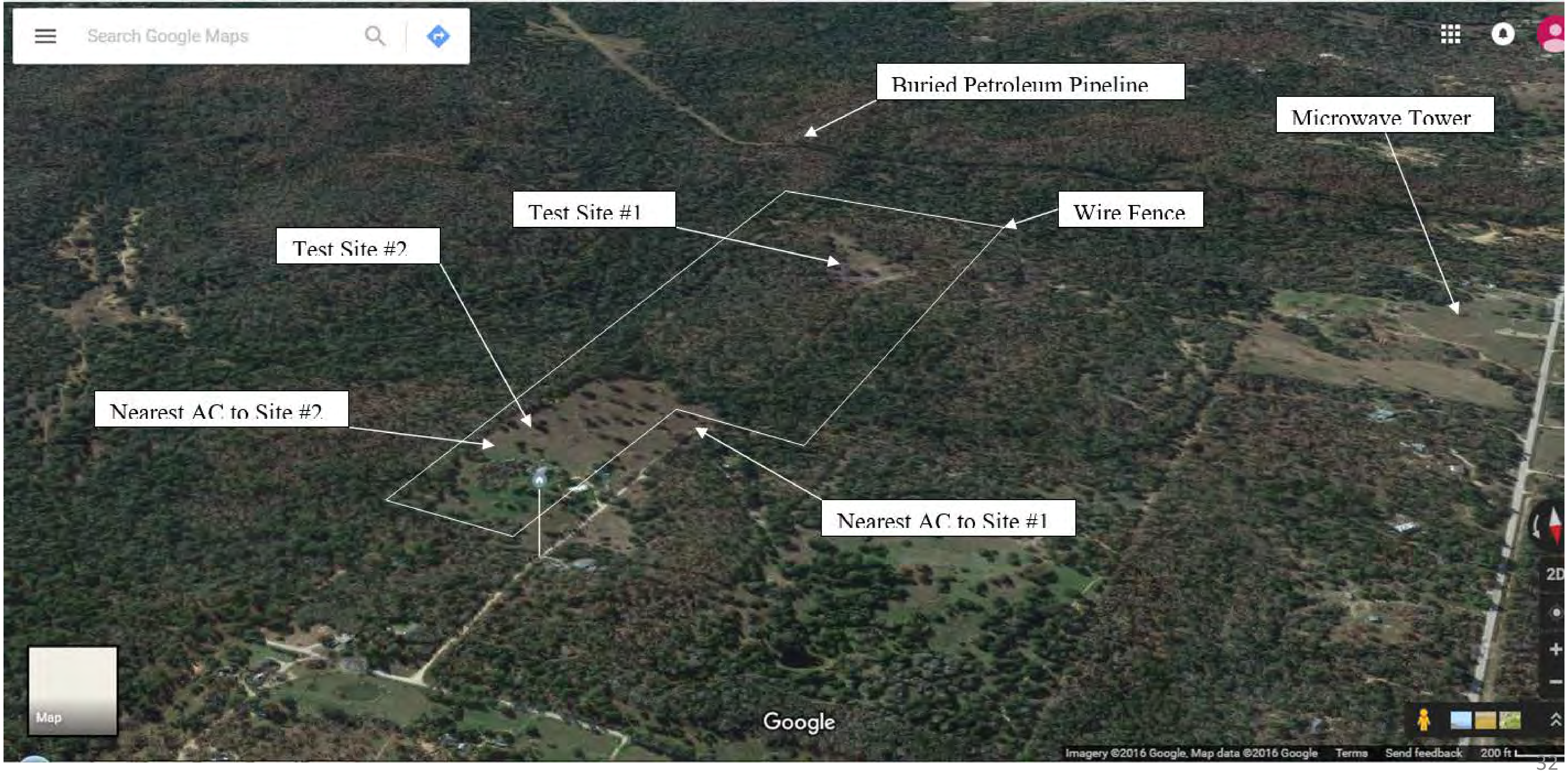
Near-surface field testing



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Near-surface field testing

Uncovering the partially collapsed slot box and installing the 2X10 support beams.

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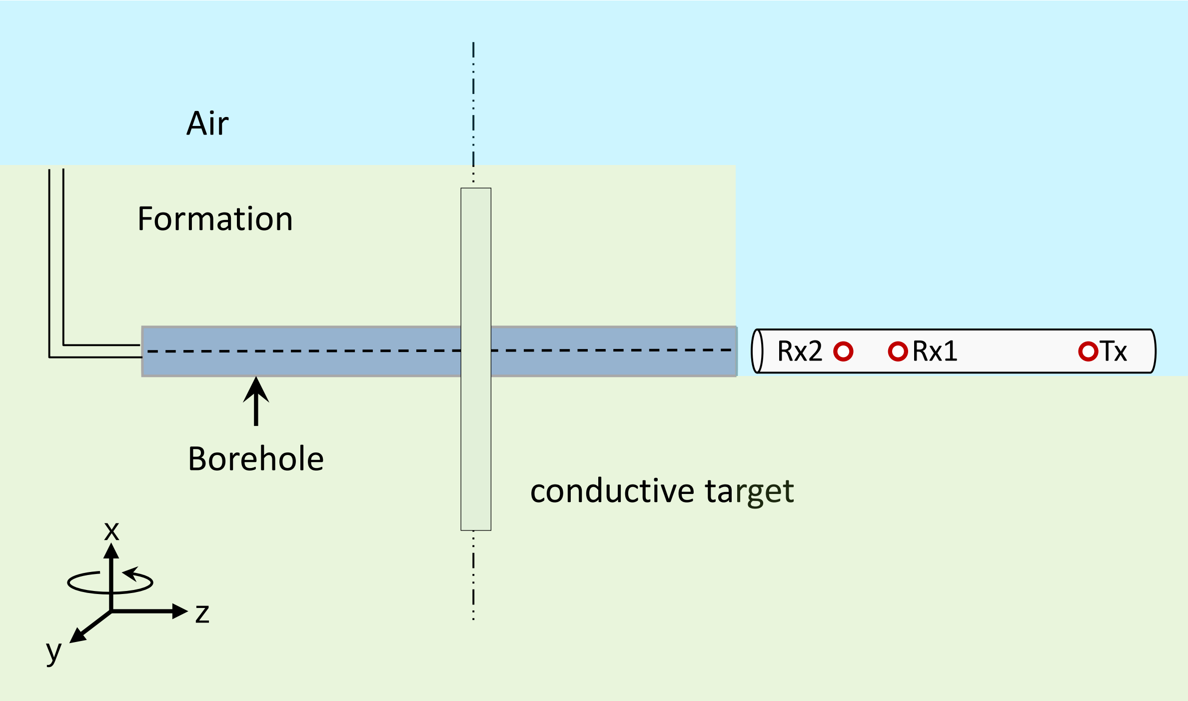
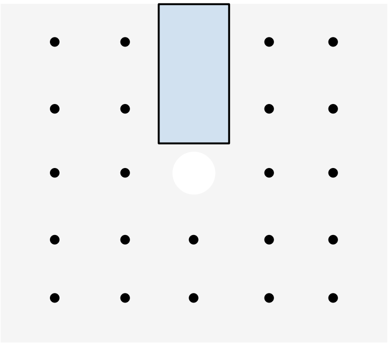
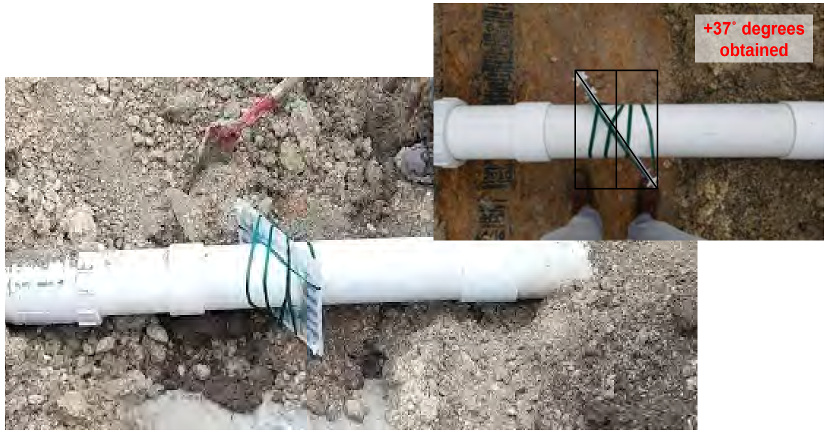
Near-surface field testing

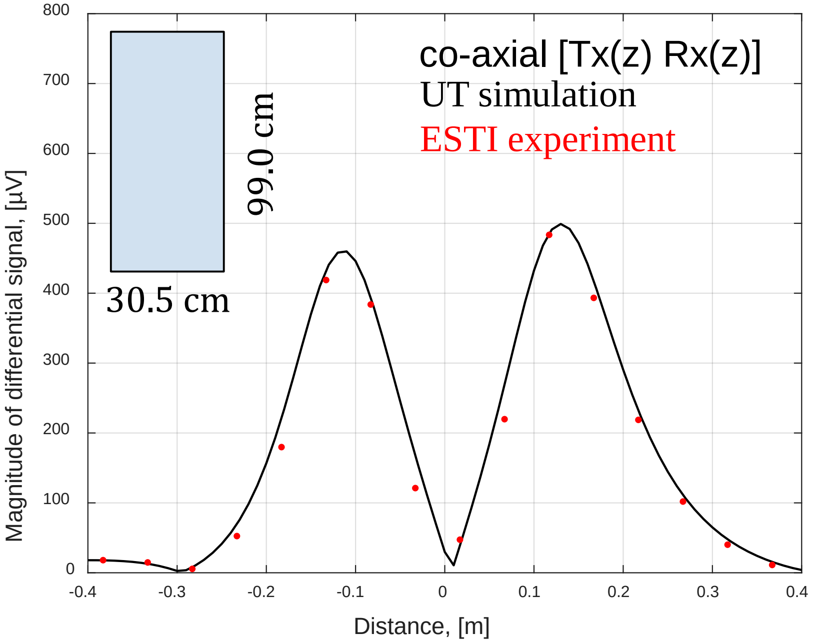


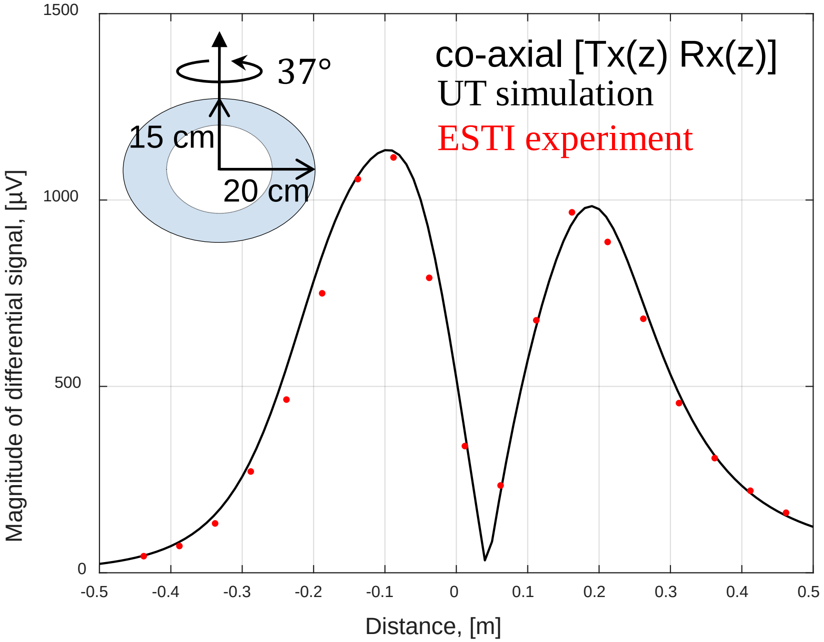
Results – Near-surface Field Test

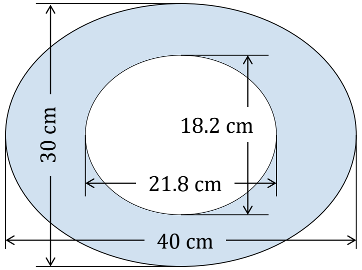
fracture slot











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Summary of Experiments

- A lab prototype tool (transmitters and bucked receivers) has been built and tested in the lab and a near-surface test site.
- Excellent agreement is obtained between the model predictions and the lab measurements for different T-R configurations.
- The results from the tests suggest that a commercial tri-axial EM tool can be built that has the potential to map the geometry of hydraulic fractures in open-hole completions.
  - The prototype induction tool is shown to differentiate surface area, aspect ratio and dip angle of the fracture models used.
  - The highest signal levels occur when the primary magnetic field is perpendicular to the plane of the target.
  - From the principle of reciprocity, the response is the same if the source and receivers are interchanged.
  - Simulations suggest that we can see fractures out to 300 ft away from the wellbore.

More details of the Lab and Near-Surface Test:

[2] J. Shiriyev, Y. Brick, P. Zhang, A.E. Yilmaz, C. Torres-Verdin, M.M. Sharma, T. Hosbach, M.A. Oerkfitz, and J. Gabelmann, “Experiments and simulations of a prototype tri-axial electromagnetic induction logging tool for open-hole hydraulic fracture diagnostics”, Geophysics, 2018

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Tasks

- Task 1.0 – Project Management Plan
- Task 2.0 – Development of forward model for the proposed tool and different fracture geometries
- Task 3.0 – Lab testing of available proppants in the market for electrical and material properties
- Task 4.0 – Final design and construction of low frequency electromagnetic tool
- Task 5.0 – Laboratory and field testing of prototype tool
- Task 6.0 – Inverting data to obtain the fracture geometry

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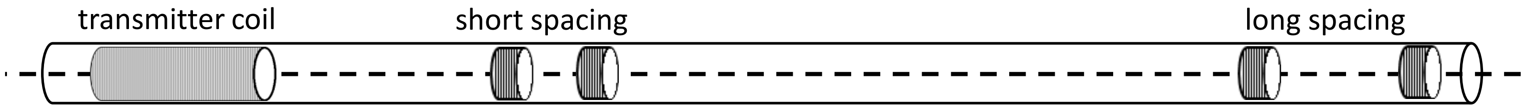
Derivative Free Directional Search

Simulated Annealing & Neighbor Approximation

Randomly generate first set of models
↓
Compute E for old generation
↓
Update parameters for each model in the generation
↓
Estimate error based on history or calculate it
↓
Accept new parameter if conditions are satisfied
↓
New generation of models

stop if max num. of iter. is achieved

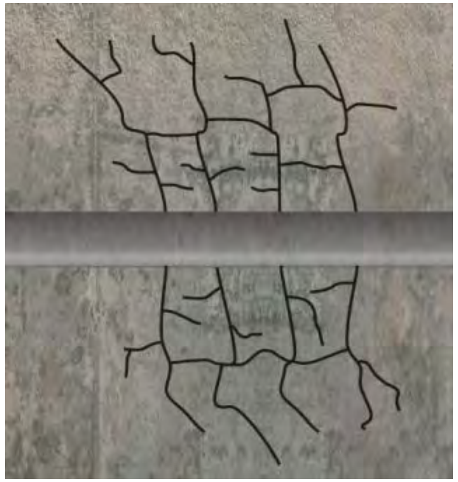


A model consists of
- Fracture width
- Fracture length
- Fracture orientation

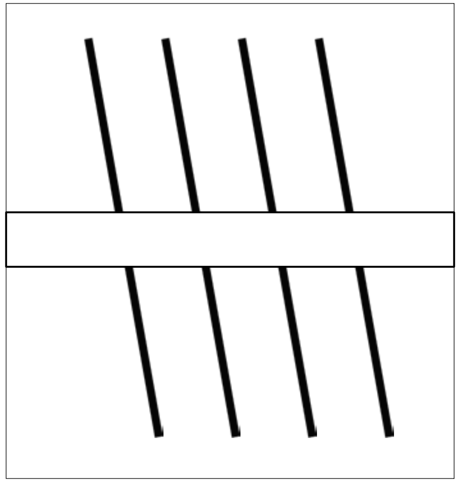
$$E = \left(E_{zz} + E_{yz}\right)^{\text{short}} + \left(E_{zz} + E_{yz}\right)^{\text{long}}$$

$$E_{uv} = \sum_i \left(\frac{V_{uv}^i - \tilde{V}_{uv}^i}{\tilde{V}_{uv}^i}\right)^2$$

Reality



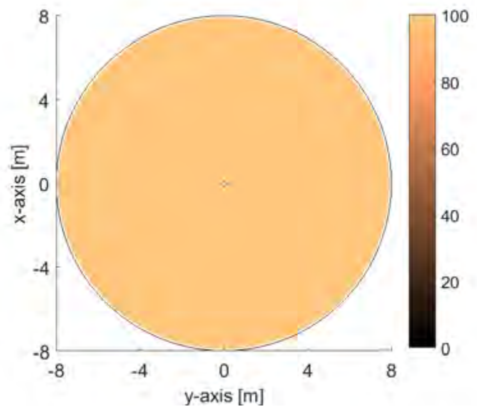
Inversion result

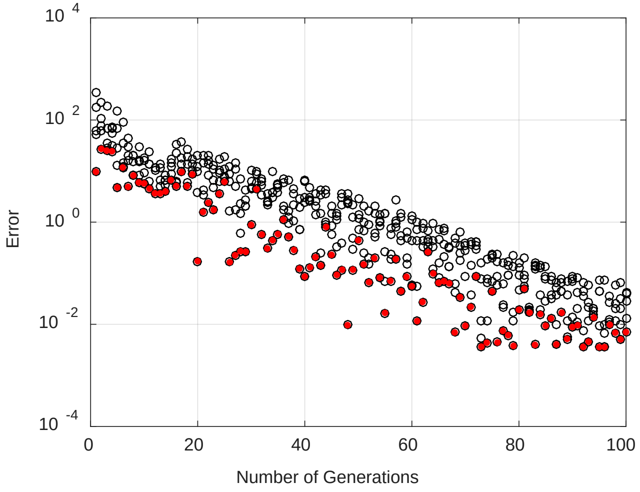


Single Fracture Analysis

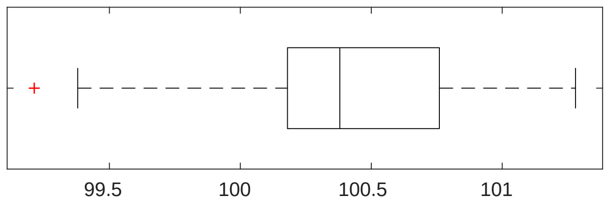
- Circular Fractures
- Rotated Fractures
- Elliptical Shape
- Distributed Conductivity

true model

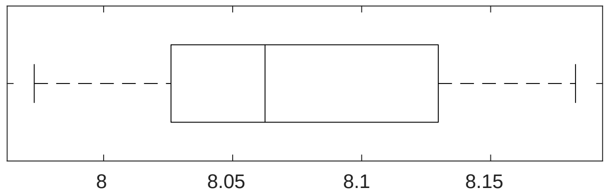


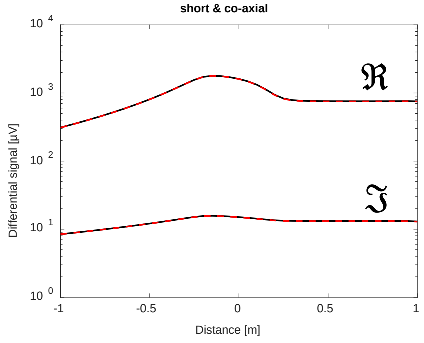


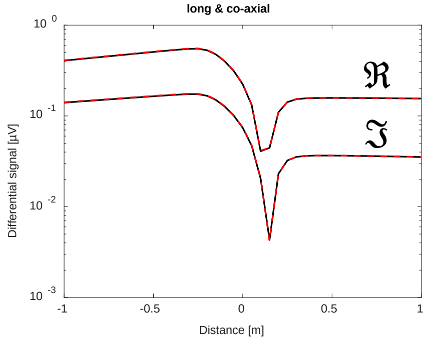
conductivity [S/m]



fracture radius [m]







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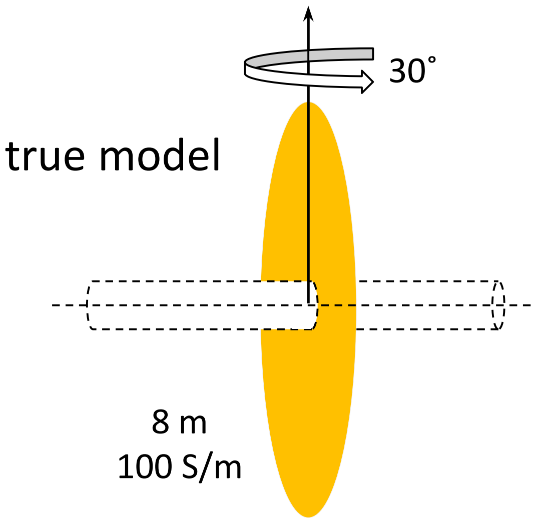
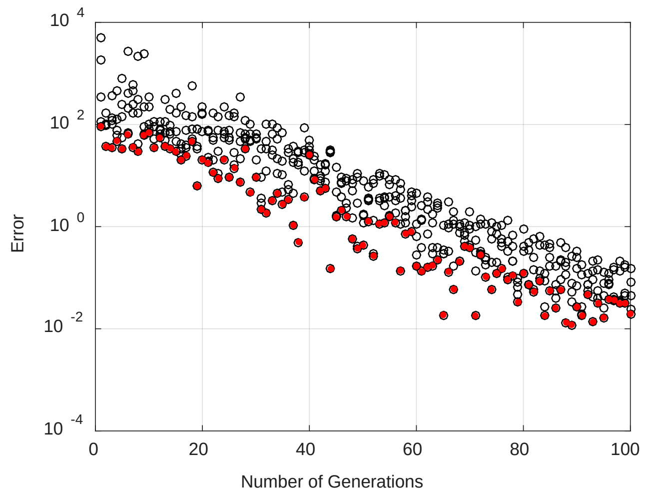
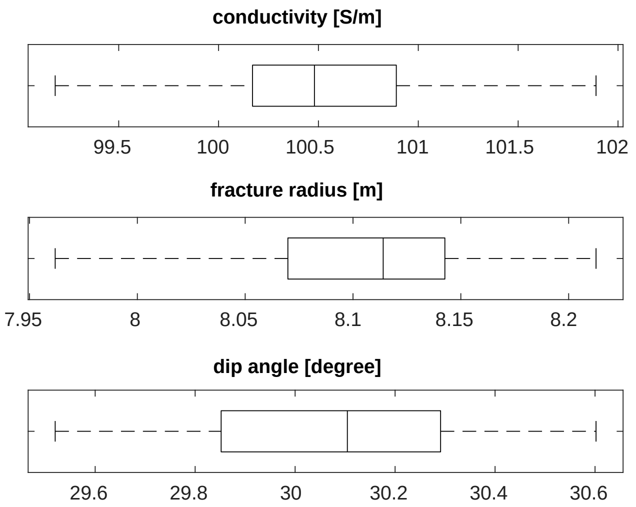
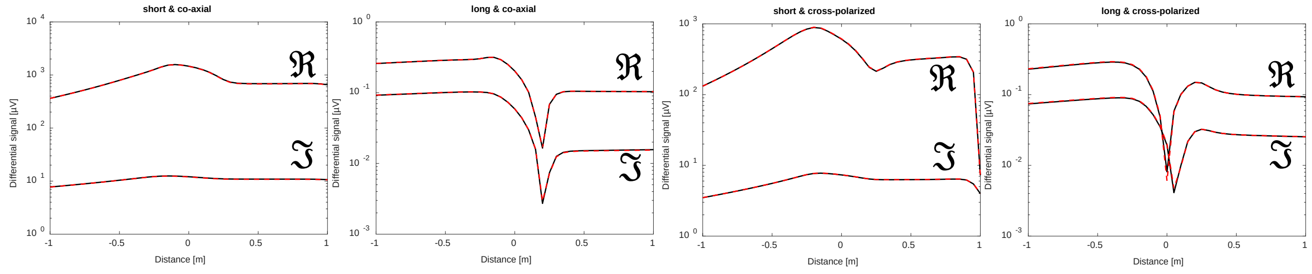
Single Fracture Analysis

- Circular Fractures
- Rotated Fractures
- Elliptical Shape
- Distributed Conductivity









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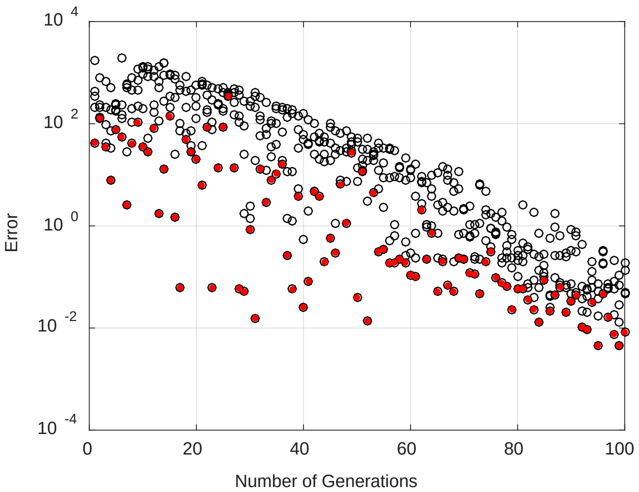
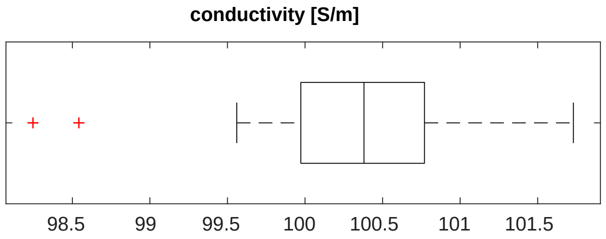
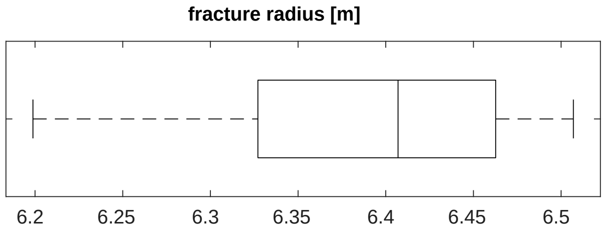
Single Fracture Analysis

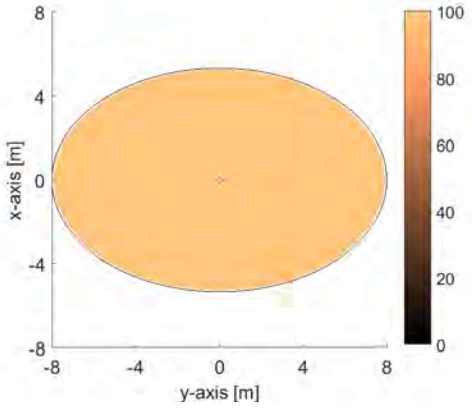
- Circular Fractures
- Rotated Fractures
- **Elliptical Shape**
- Distributed Conductivity

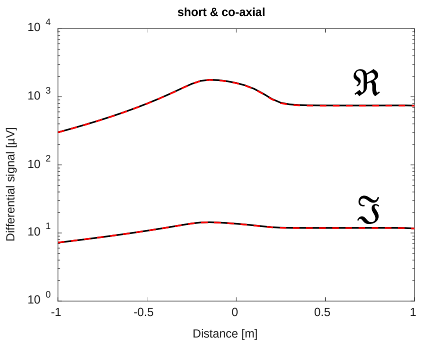


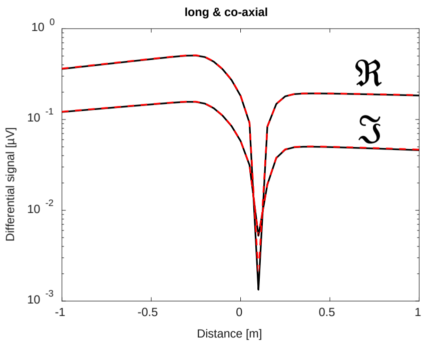




true model







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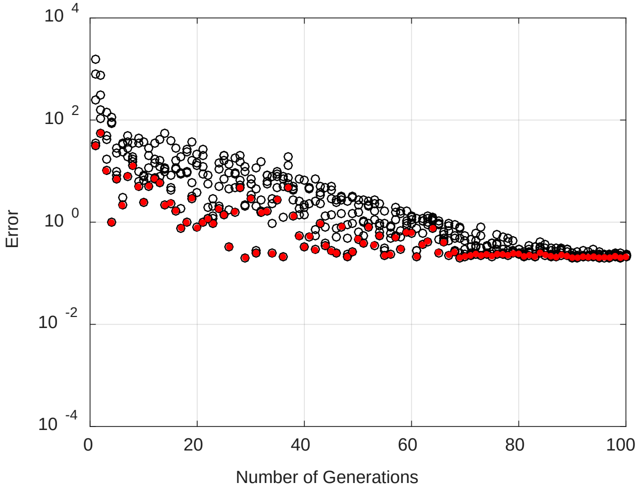
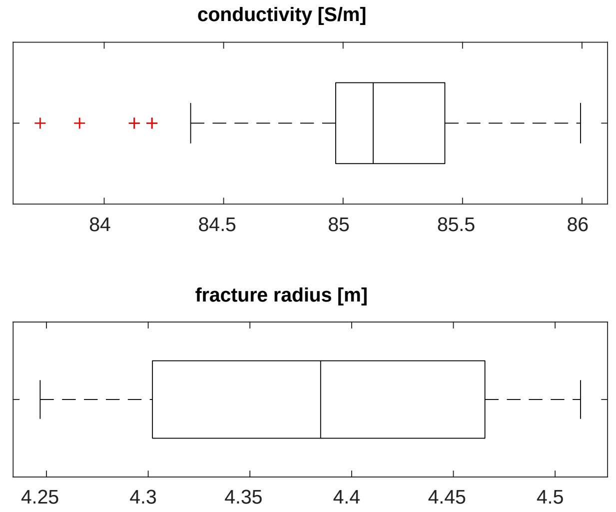
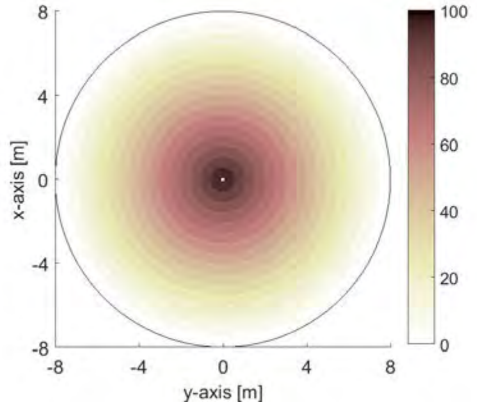
Single Fracture Analysis

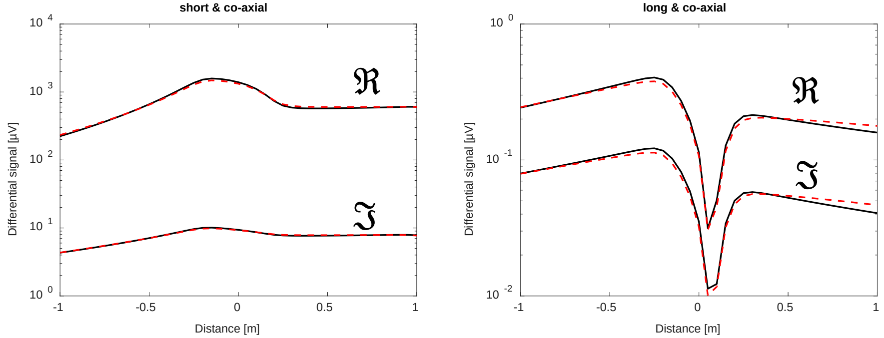
- Circular Fractures
- Rotated Fractures
- Elliptical Shape
- **Distributed Conductivity**





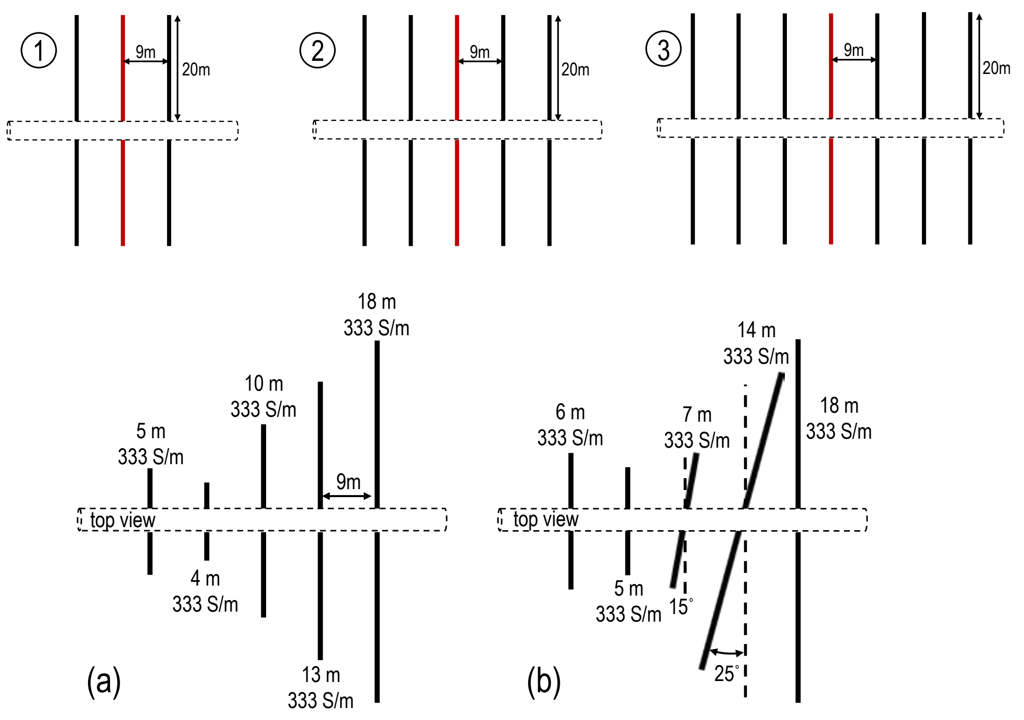
true model

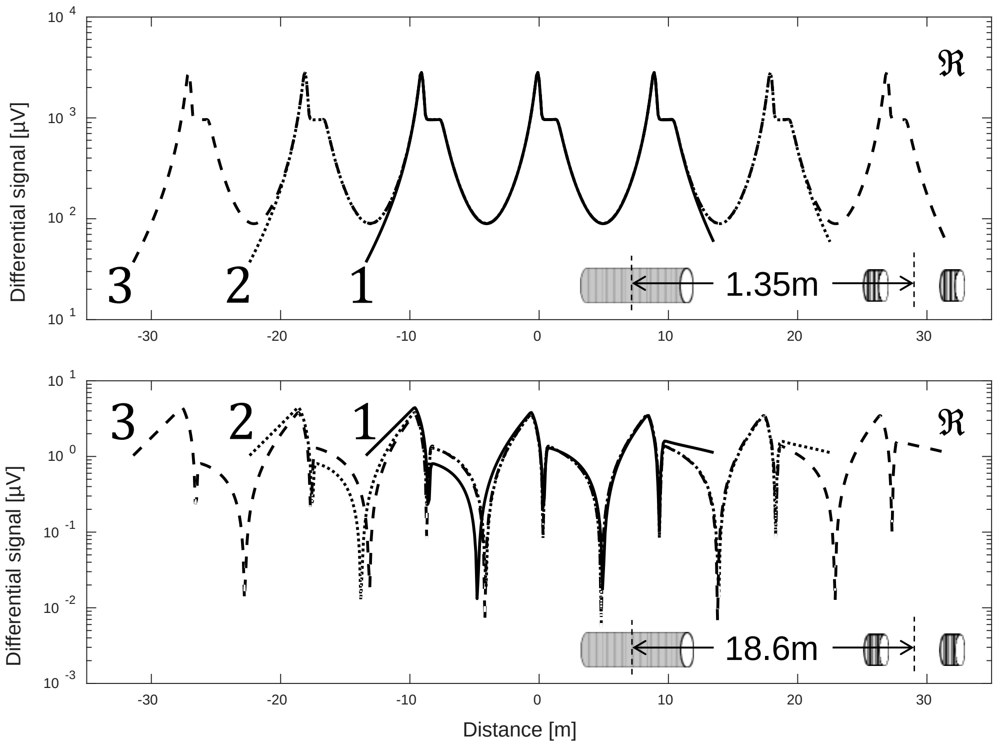




Multiple Fractures

- The effect of neighboring fractures on the signal of interest is observed on the long spacing receiver:



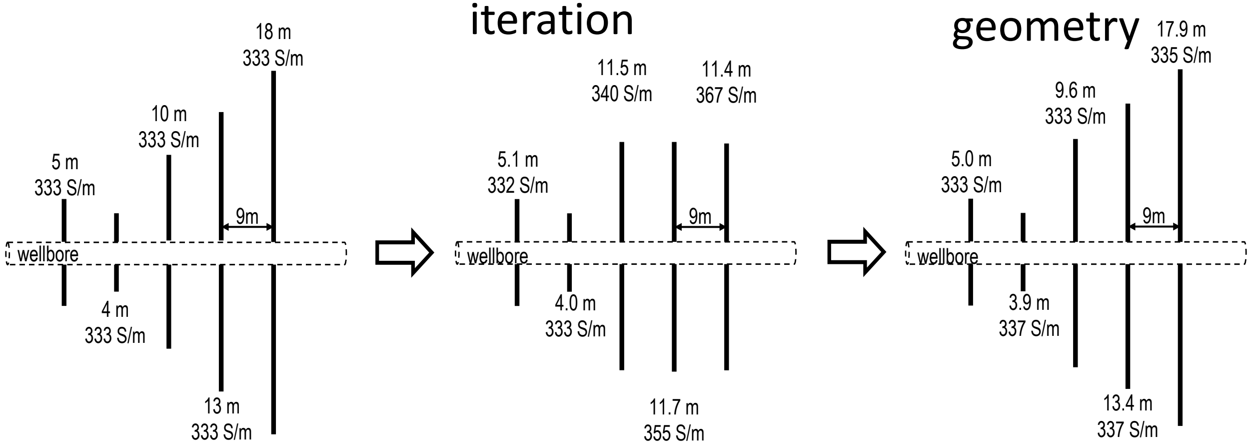


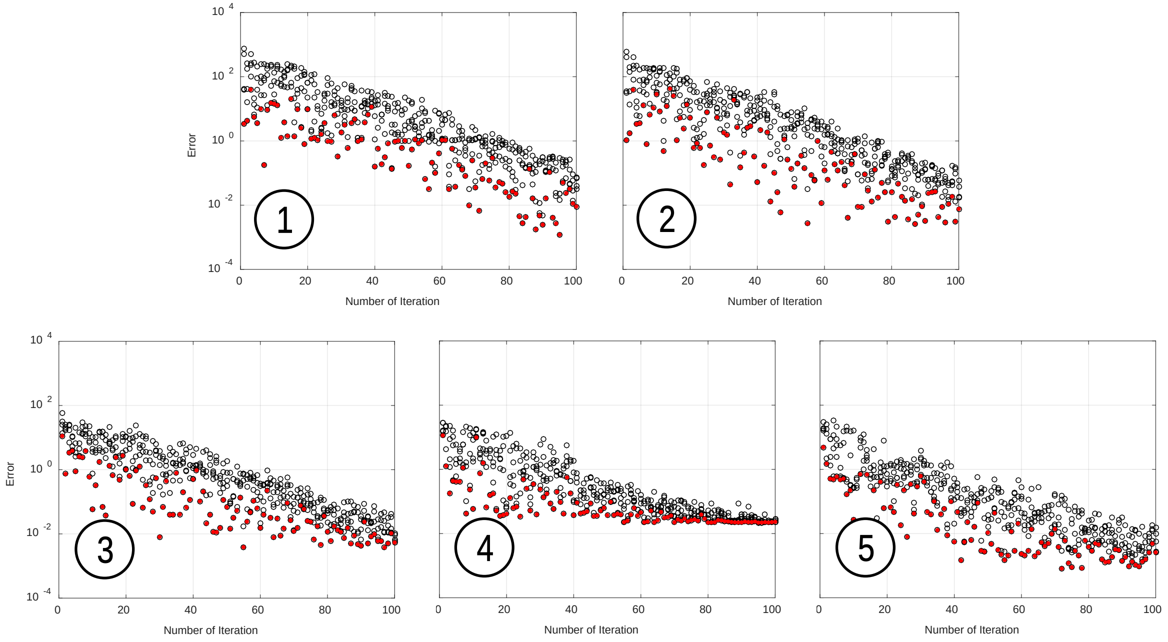
Multi-Fracture Inversion

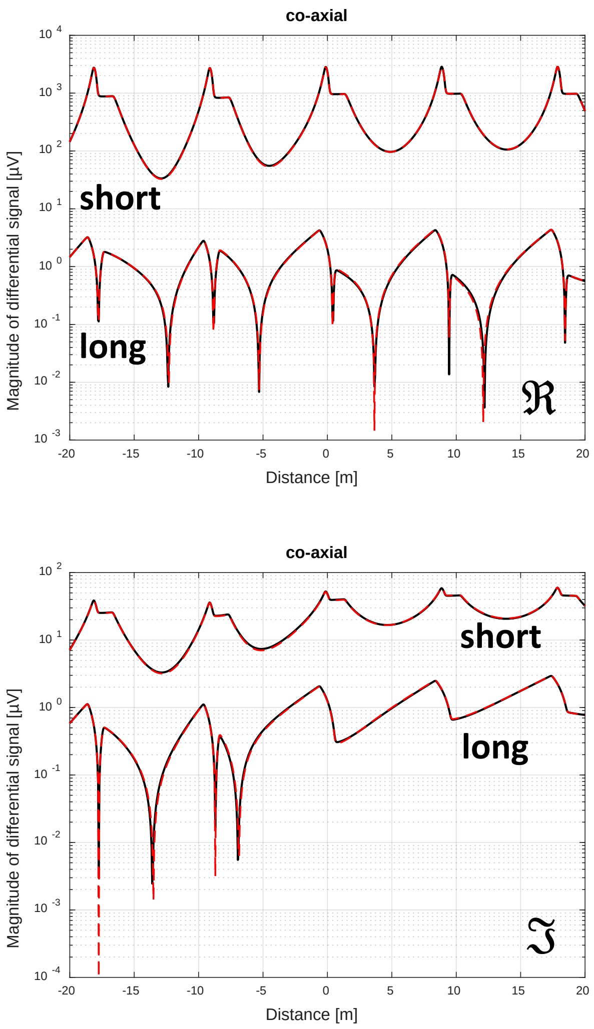
True geometry

Intermediate iteration

Final predicted geometry







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Multi-Fracture Inversion

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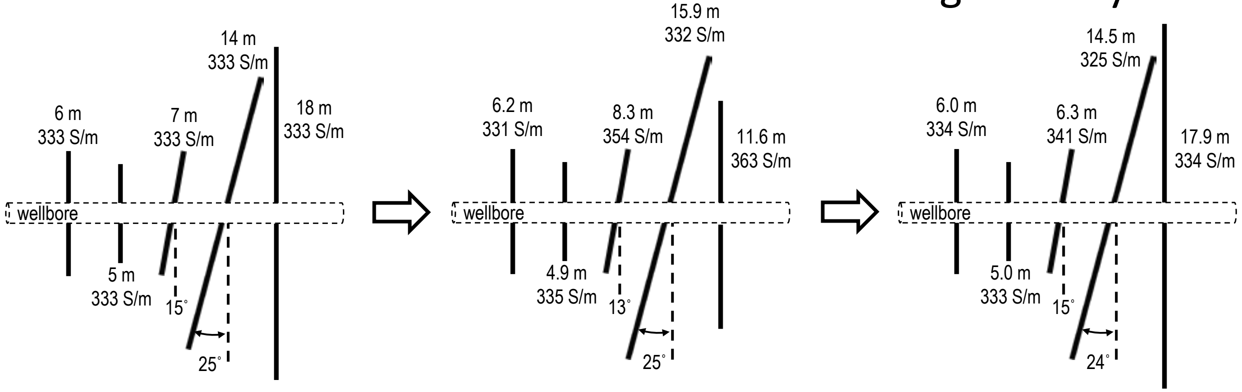
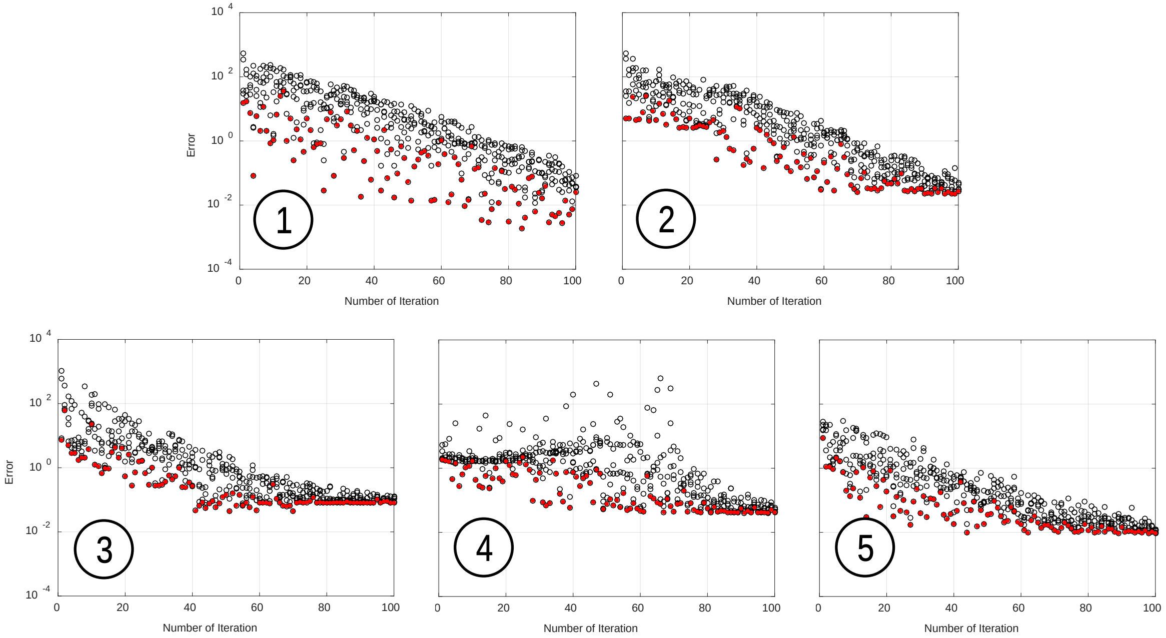
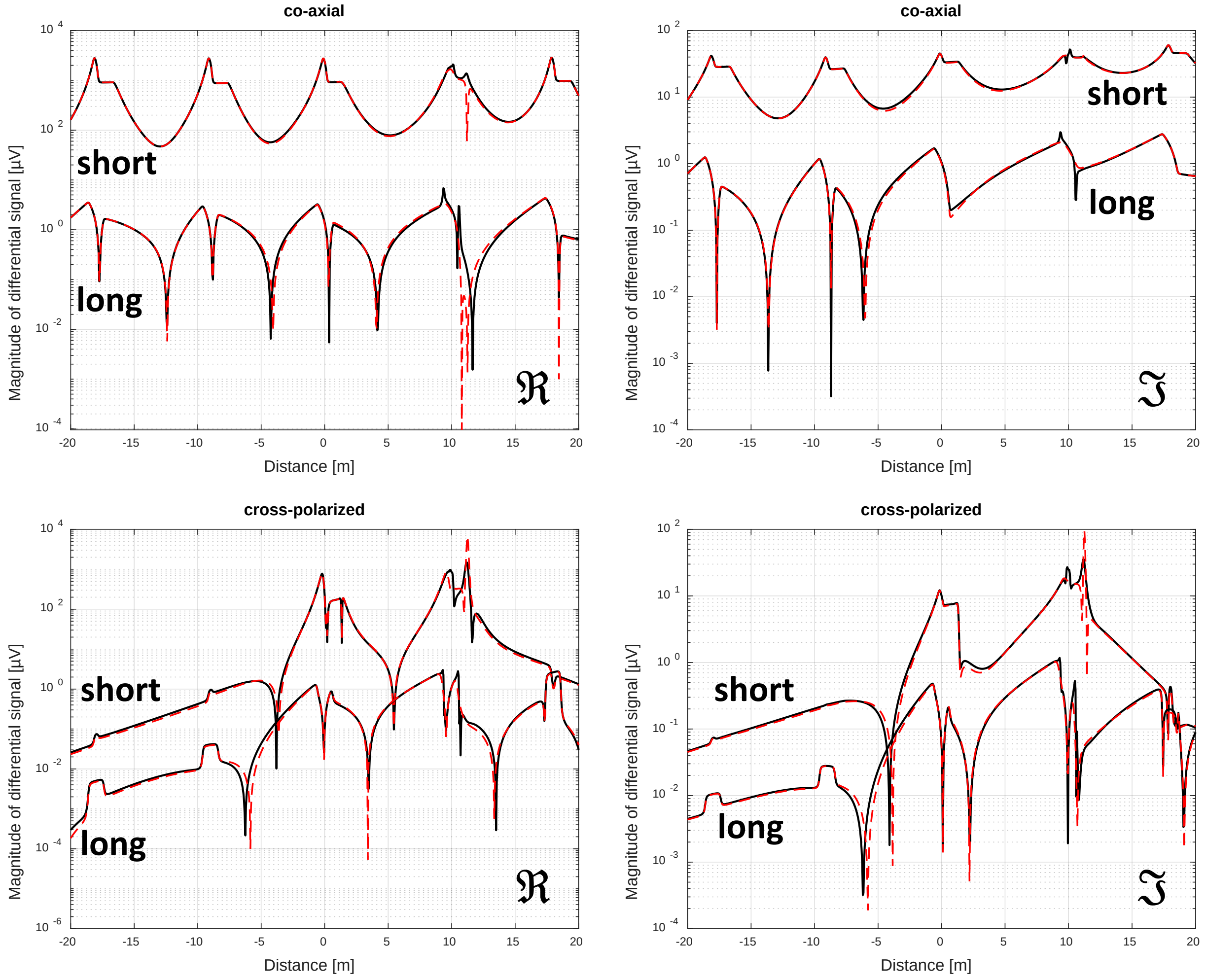
True geometry | Intermediate iteration | Final predicted geometry







Summary of Inversion Analysis

- The three-component induction measurements provide us the ability to map the length, width and orientation of multiple propped hydraulic fractures.
- An inversion algorithm has been built and tested with synthetic data.
- Excellent agreement is obtained between the “true” and estimated model.
- Inversion results show that data from the prototype tri-axial EM tool that has been built can map the geometry of multiple hydraulic fractures:
  - The induction tool is capable of measuring fracture conductivity (width), surface area (length), and dip angle for planar fractures.
  - Data from the tool can also be accurately inverted to obtain the fracture geometry for each cluster in each stage along the wellbore.

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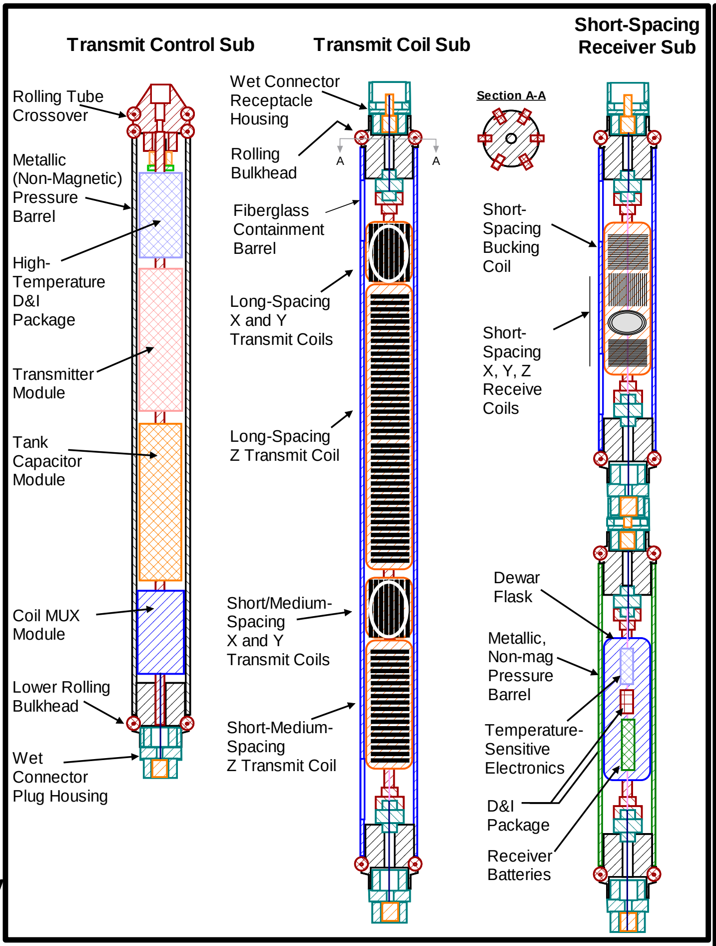
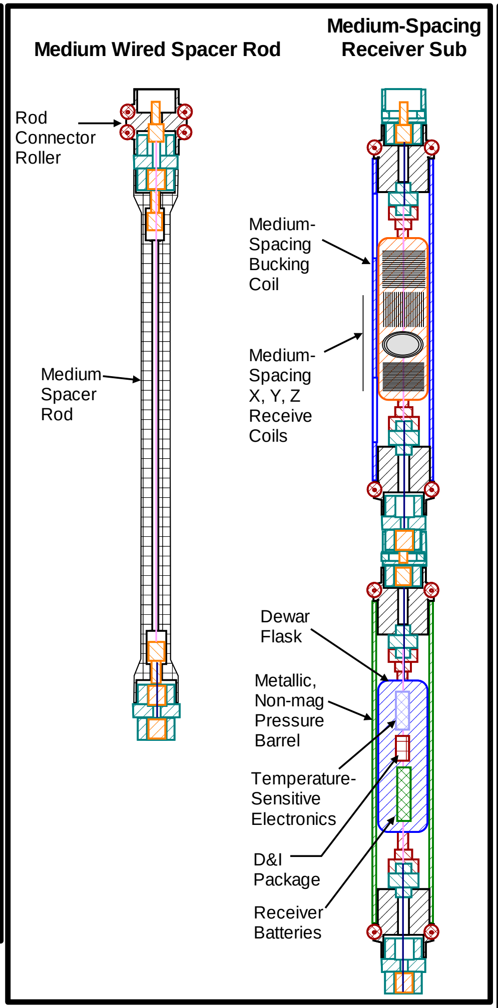
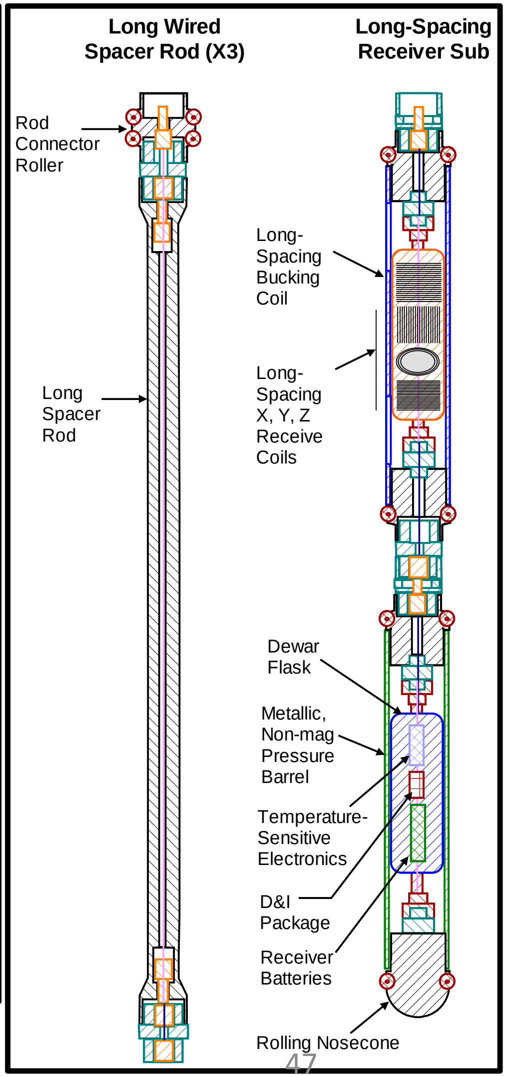
Commercial Tool Specifications

LFEI Tool Design Specifications

- Consists of 7 sections assembled at wellhead
- First 3 sect. connect rigidly at fixed orientation
- Transmit Control Sub powered by monocable, controls electrical impulses sent to TX coils
- Transmit Coil Sub contains long-spacing TX coils and short/medium-spacing TX coils
- Short-Spacing Receiver Sub contains short-spacing bucking and RX coils, Dewar flask holding temperature-sensitive RX electronics, D&I package, RX batteries
- Medium- and Long-Spacing Receiver Subs similar to short-spacing receiver sub
- Medium Wired Spacer Bar spaces receiver sub so that medium-spacing RX coils are 20 ft away from *z* TX coil
- Long Wired Spacer Bars (3 ea) space receiver sub so that long-spacing RX coils are 60 ft away from the *z* TX coil
- Tool Wiring Bus extends through each spacer bar and allows communication between Transmitter Control Sub and each receiver sub







- Rolling Bulkheads on end of each sub reducing sliding friction against tool in horizontal wellbores

Answers to Key Questions

- Are inexpensive conductive proppants available?
  - Yes
- How far can we image the proppant in the fracture?
  - About 300 ft. from the wellbore in OH
- Is the signal to noise ratio sufficient to provide us with a reliable measurement?
  - Yes
- Can the measured signal be inverted to provide fracture dimensions and orientation?
  - Yes

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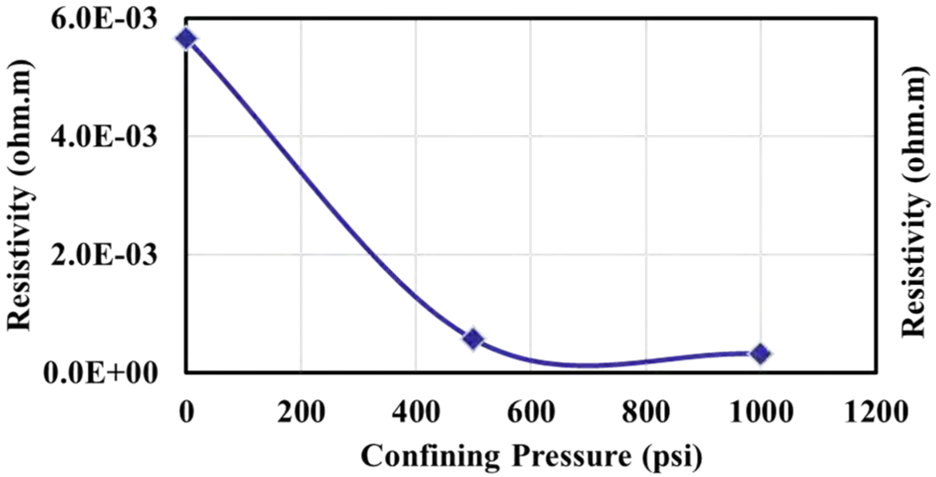
Thank you & Questions

Thanks to DOE for funding the project
DE-FE0024271

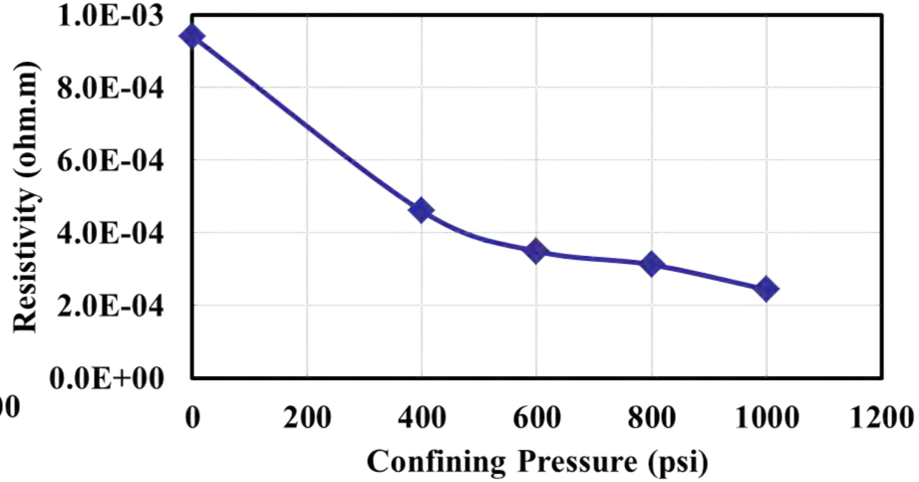
Proppant: Experimental Results

Resistivity measurements for electrically conductive proppant



(a)

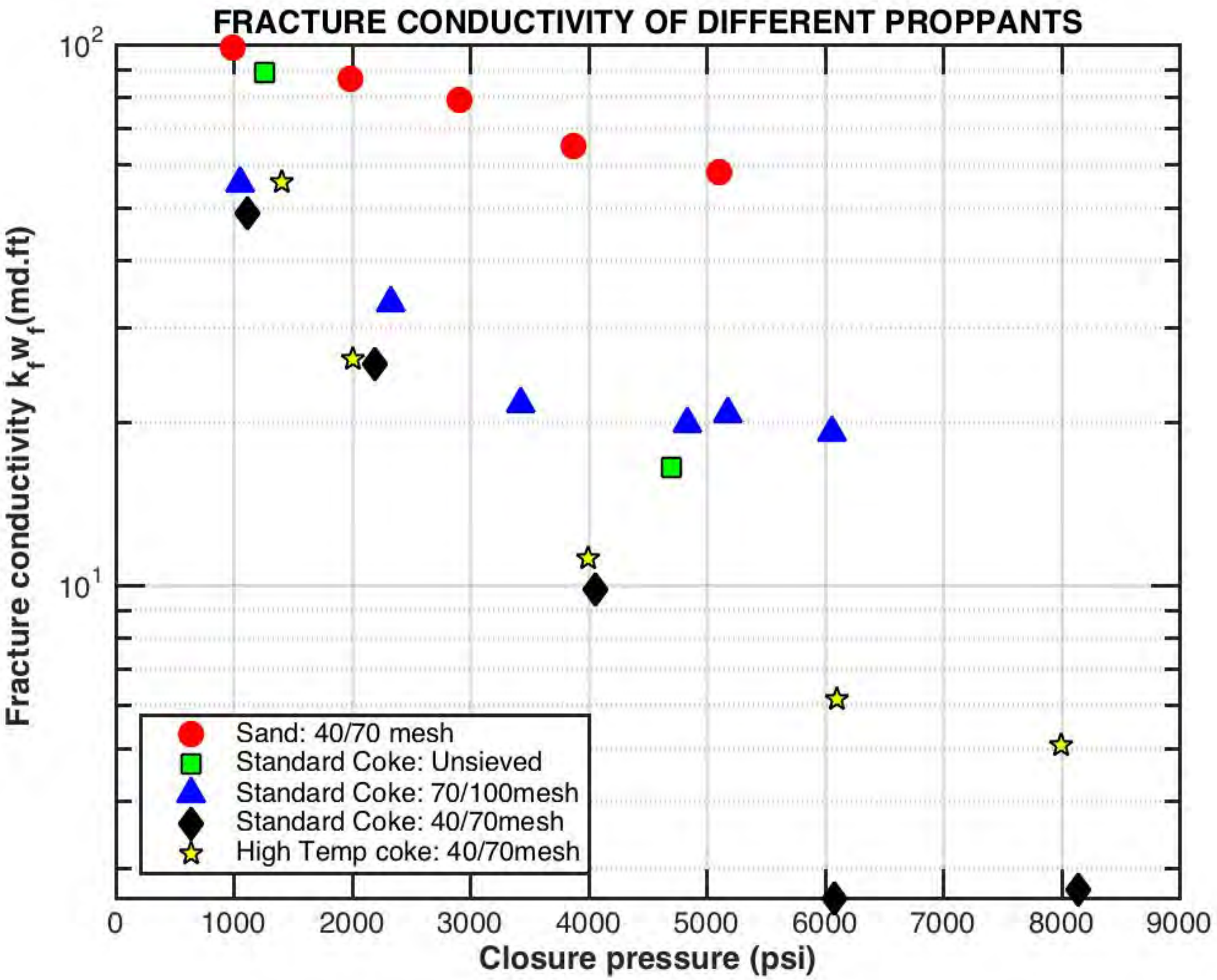
Density: 1.14 g/cm^3
Porosity: 43.9%
End point: 3.2x10^{-4} $\Omega \cdot m$



(b)

Density: 1.27 g/cm^3
Porosity: 37.6%
End point: 2.4x10^{-4} $\Omega \cdot m$

Fracture Conductivity and Normalized Conductivity for Sand and EC-Proppant



$F_{CD} = k_f * w / L_f * k$

$F_{CD} = 5 / (500 * 10^{-4})$

$F_{CD} = 100$

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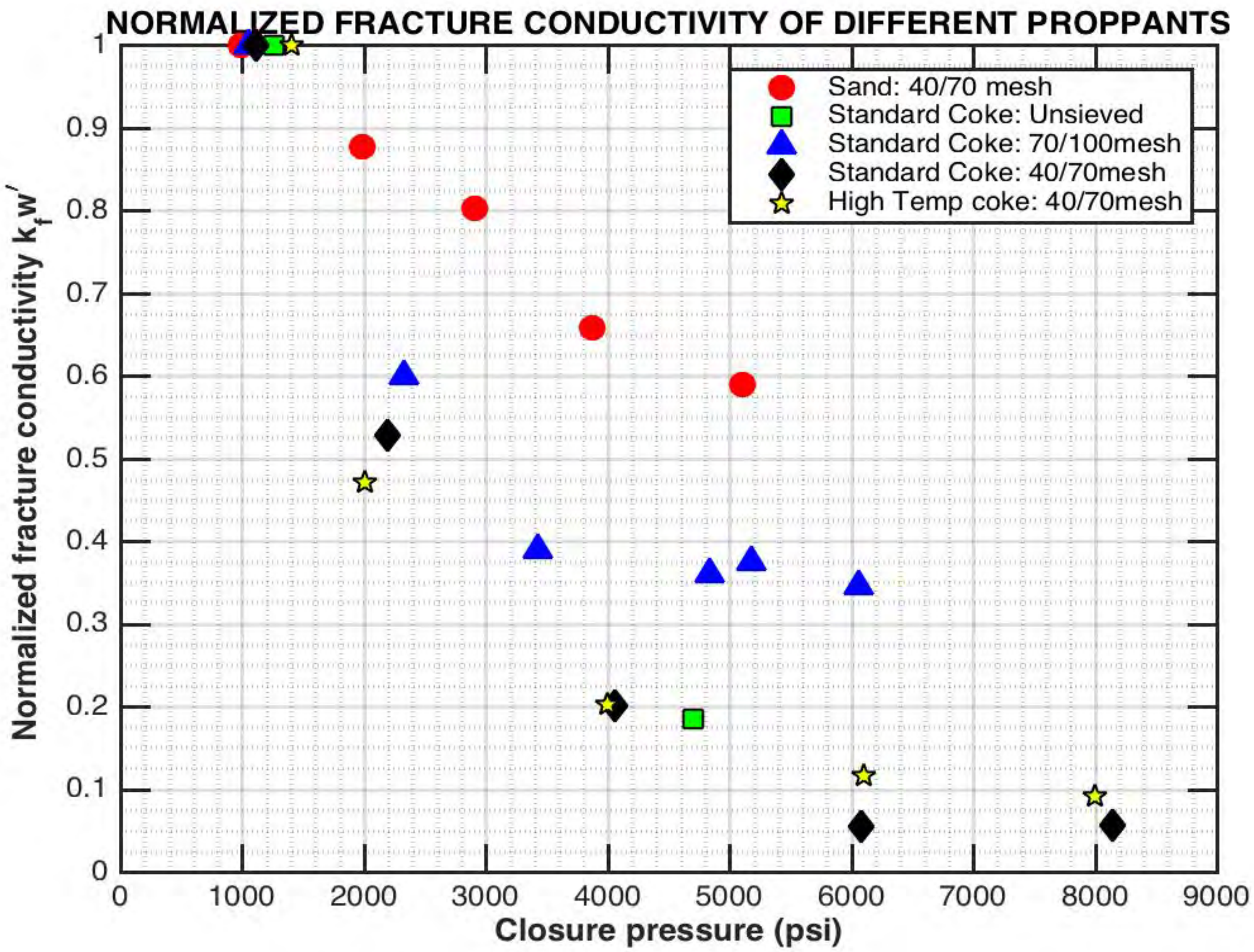
Normalized Conductivity for Sand and EC-Proppant



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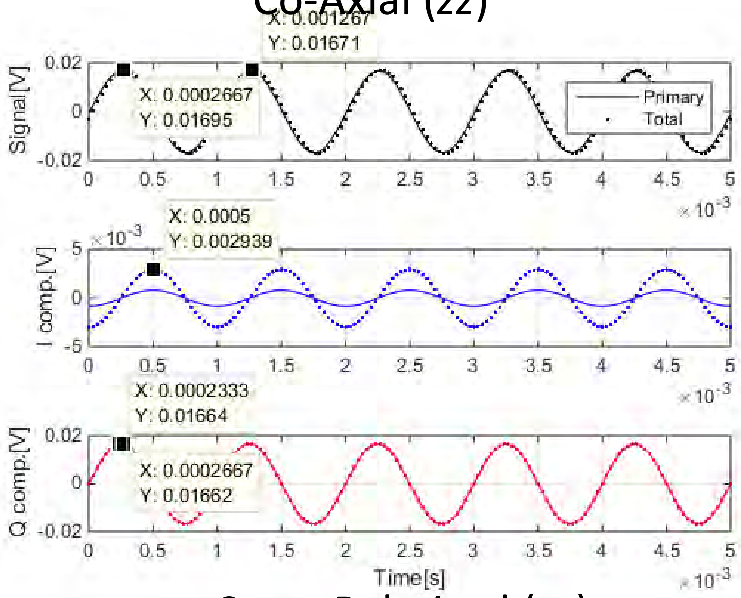
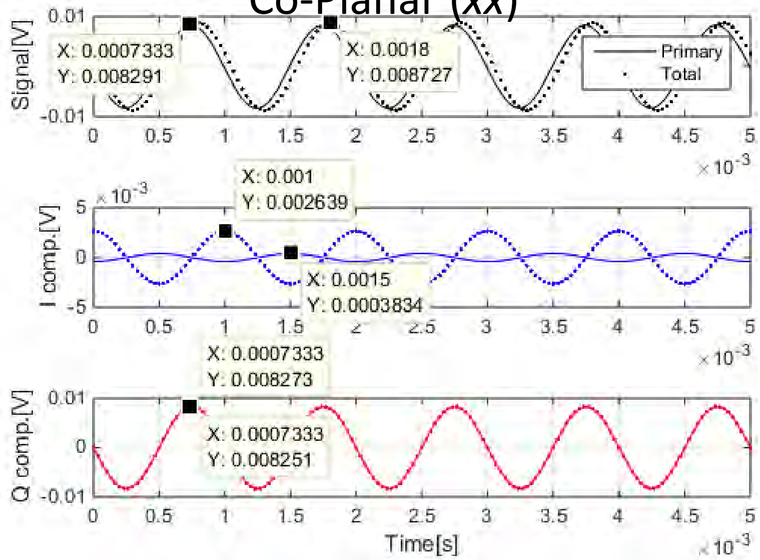
Bucked Signal, Short Spacing, Fracture: 3m radius, 5mm thickness

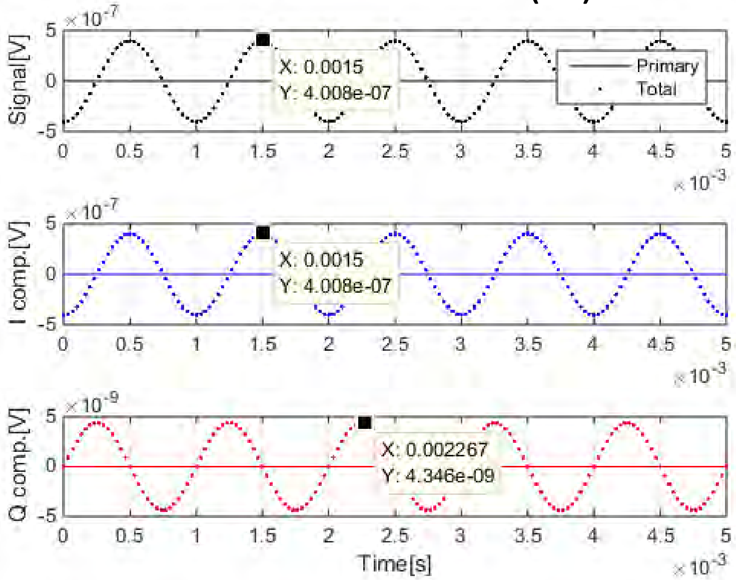
Co-Axial (*zz*)



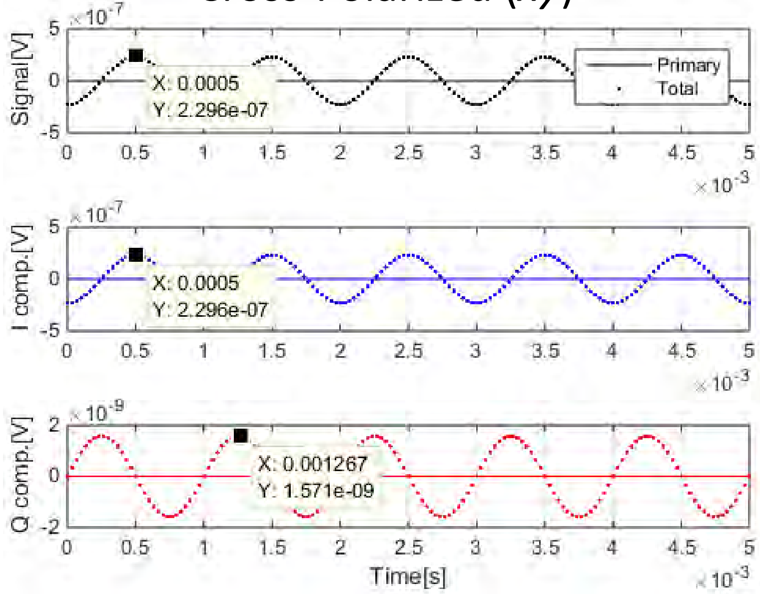
Co-Planar (*xx*)



Cross-Polarized (*xz*)



Cross-Polarized (*xy*)



$\sigma_{\text{frac}} = 333\ \text{S/m}$
$\sigma_{\text{bg}} = 0.333\ \text{S/m}$

$f = 1\ \text{kHz}$
$NI^{\text{peak}}A_{\text{TX}} = 150\ \text{Am}^2$

$N_{\text{RX}} = 1500\ \text{turns}$
$A_{\text{RX}} = 0.01\ \text{m}^2$

$\Delta U = \frac{U_2}{n} - \frac{C_2}{C_1}U_1 n,$

$n = 1.01$ – mismatch factor

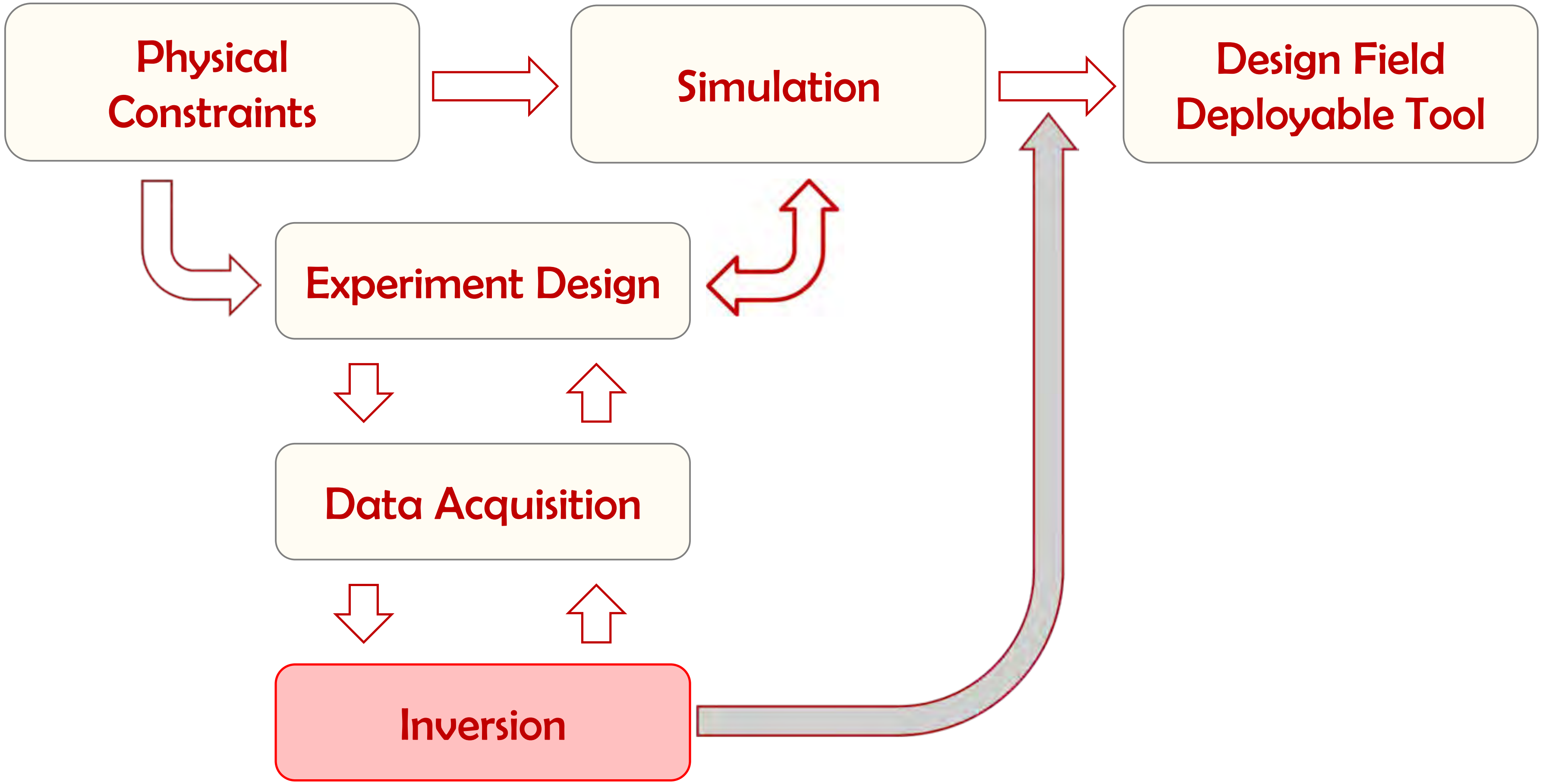
$\frac{C_2}{C_1}$ – coefficient for perfect bucking

Project Schedule

Task/Milestones	Assigned resources/ year	Qtr 4	Year 1 (2015) Qtr 1	Qtr 2	Qtr 3	Qtr 4	Year 2 (2016) Qtr 1	Qtr 2	Qtr 3	Qtr 4	Year 3 (2017) Qtr 1	Qtr 2	Qtr 3	Qtr 4
Task 1: Project Management and Planning	1 PI	■	■											
M1: Project Management Plan	1 PR		●											
VM1: Project Management Plan	1 GRA		▲											
Task 2: Development of forward model	1 PI		■	■	■	■	■							
Subtask 2.1. Matrix and well formulation	1 GRA		■	■										
Subtask 2.2 Fracture formulation	1 PR		■	■										
M2: Model of fracture in well completed				●										
Subtask 2.3 Tool formulation				■	■									
Subtask 2.4 Forward modeling				■	■									
M3: Forward model to observe signal					●									
Subtask 2.5 Sensitivity analysis						■	■							
M4: Important operational parameters							●							
VM2: Publication 1 (Illustrating the forward model and the sensitivity analysis)							▲							
Task 3: Lab testing of available proppants	1 PI		■	■	■	■	■							
M5: Identify the best proppants for their electrical conductivity and strength.	1 GRA						●							
Task 4 – Construction of low frequency electromagnetic tool	1 PI							■	■	■				
M6: Low Frequency Electromagnetica tool built and lab-tested according to well specifications	1 GRA									●				
VM3: Lab test report will be provided for review										▲				
Task 5: Field testing of tool	1 PI										■	■		
M7: Built tool deployed in well.	1 PR										●			
M8: Results from tool compared to other field diagnostics like microseismic.	1 GRA											●		
VM4: Publication 2 (Comparison of tool signal with other microseismic results)												▲		
Task 6: Inverting the obtained field data for SRV	1 PI										■	■	■	■
M9: Invert the tool signal to obtain stimulated rock volume map.	1 PR												●	
VM5: Publication 3 (Illustrate the new technology as a fracture diagnostic tool)	1 GRA													▲

M = Milestone = ● , VM = Verification Method = ▲
GRA = Graduate Research Assistant; PR = Postdoctoral Research Associate, PI = Principal Investigator

Development Plan



Capabilities and Limitations of Current Fracture Diagnostic Methods

Research Challenges and Technology/Knowledge Advances

Techniques: can determine / may determine / cannot determine

Group	Fracture Diagnostic Method	Main Limitations	Ability to Estimate: Length	Height	Asymmetry	Width	Azimuth	Dip	Volume	Conductivity
Far field, during fracturing	Surface tiltmeter mapping	• Cannot resolve individual and complex fracture dimensions • Mapping resolution decreases with depth (fracture azimuth ±3° at 3,000-ft depth and ±10° at 10,000-ft depth)	may determine	may determine	may determine	cannot determine	can determine	can determine	can determine	cannot determine
Far field, during fracturing	Downhole tiltmeter mapping	• Resolution in fracture length and height decreases as monitoring-well distance increases • Limited by the availability of potential monitoring wells • No information about proppant distribution and effective fracture geometry	can determine	can determine	can determine	may determine	may determine	cannot determine	can determine	cannot determine
Far field, during fracturing	Microseismic mapping	• Limited by the availability of potential monitoring wells • Dependent on velocity-model correctness • No information about proppant distribution and effective fracture geometry	can determine	can determine	can determine	cannot determine	can determine	may determine	cannot determine	cannot determine

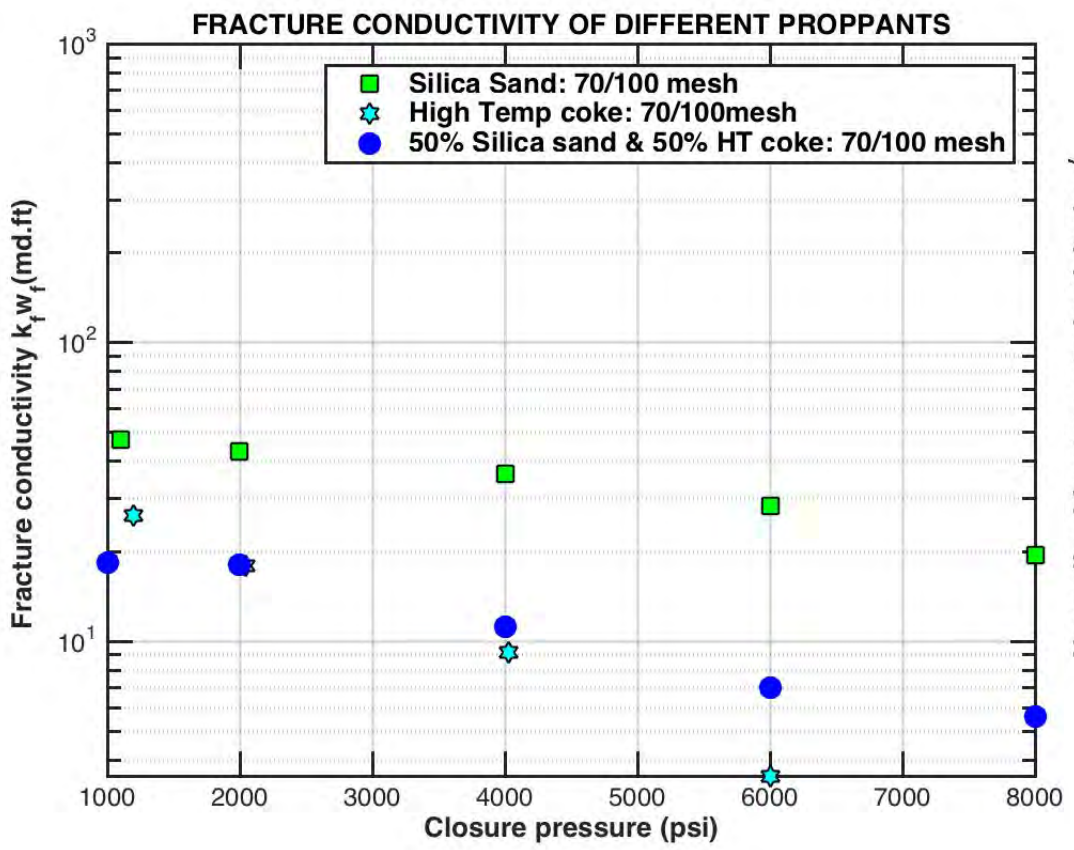
Near wellbore, after fracturing	Radioactive tracers	• Measurement in near-wellbore volume • Provides only a lower limit for fracture height if fracture and well path are not aligned								
	Temperature logging	• Thermal conductivity of different formations can vary, skewing temperature log results • Post-treatment log requires multiple passes within 24 h after the treatment • Provides only a lower limit for fracture height if fracture and well path are not aligned								
	Production logging	• Provides only information about zones or perforations contributing to production in cased-hole applications								
	Borehole image logging	• Run only in open hole • Provides fracture orientation only near the wellbore								
	Downhole video	• Run mostly in cased holes and provides information only about zones and perforations contributing to production • May have openhole applications								
Model based	Net-pressure fracture analysis	• Results depend on model assumptions and reservoir description • Requires "calibration" with direct observations								
	Well testing	• Results dependent on model assumptions • Requires accurate permeability and reservoir pressure estimates								
	Production analysis	• Results dependent on model assumptions • Requires accurate permeability and reservoir pressure estimates								

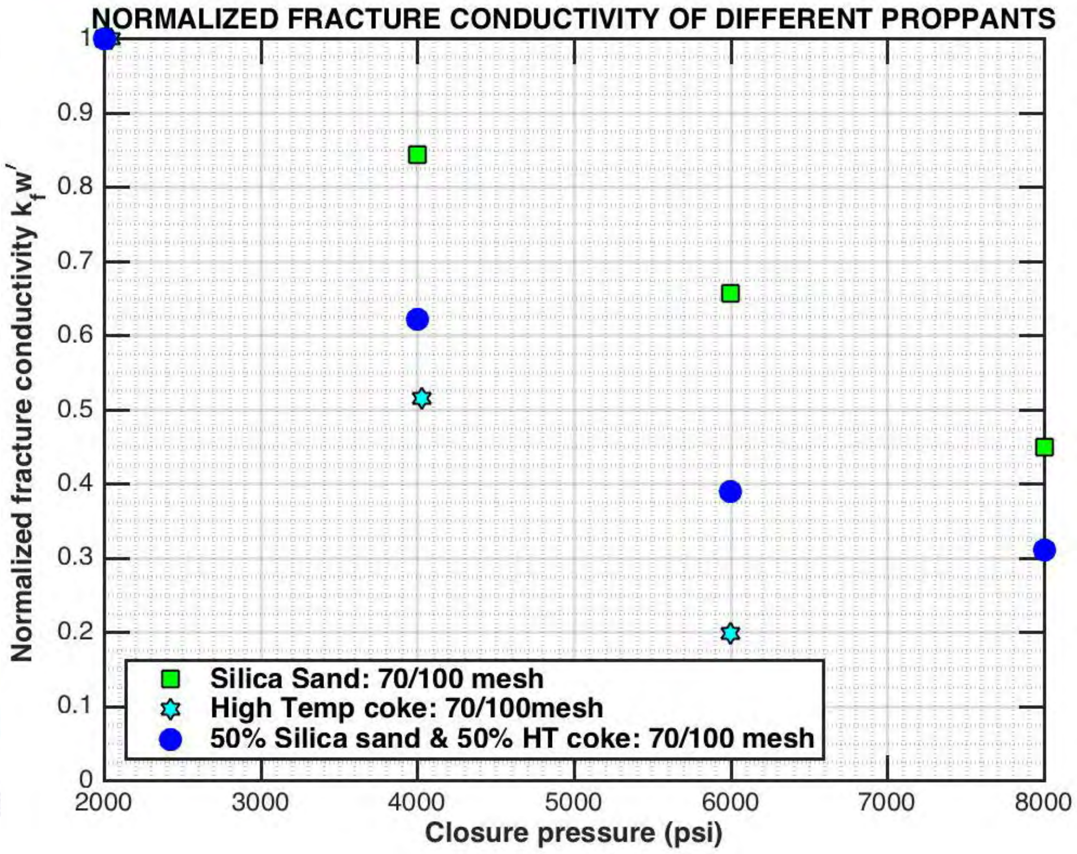
- Capabilities and limitations of indirect and direct hydraulic fracture diagnosis techniques (Adapted from Cipolla and Wright, 2000)

Project Summary

- Goals/Objectives
- Schedule (Gantt Chart)
- Summary of progress to date
- Budget by Year/Phase/Budget Period
- Anticipated Products/Expected Outcomes/Key Deliverables
- Impacts

Fracture Conductivity and Normalized Conductivity – Sand and Coke – 70/100 mesh

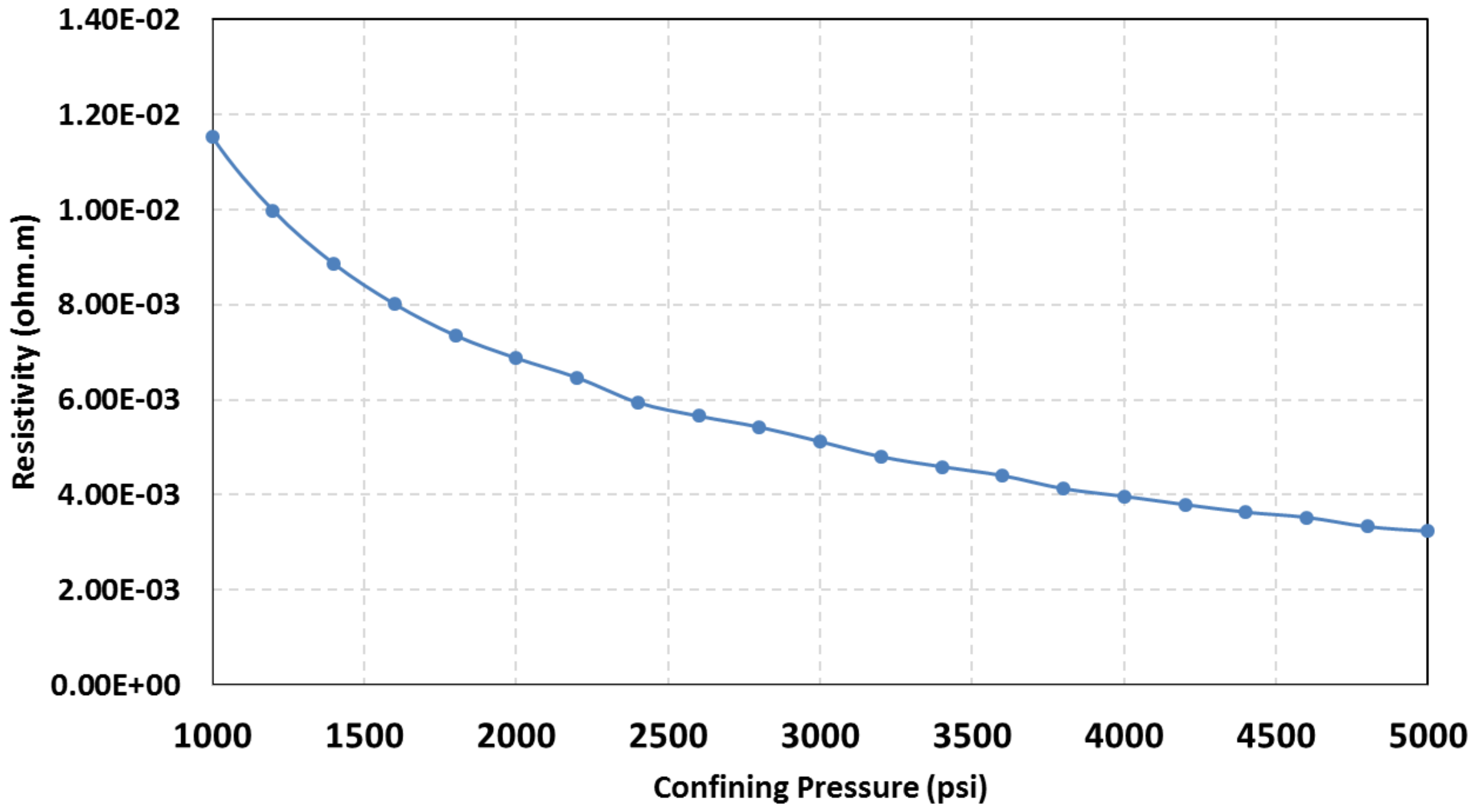




E-Spectrum Technologies

The University of Texas at Austin
Petroleum and Geosystems Engineering

Electrical Resistivity: 40/70 mesh

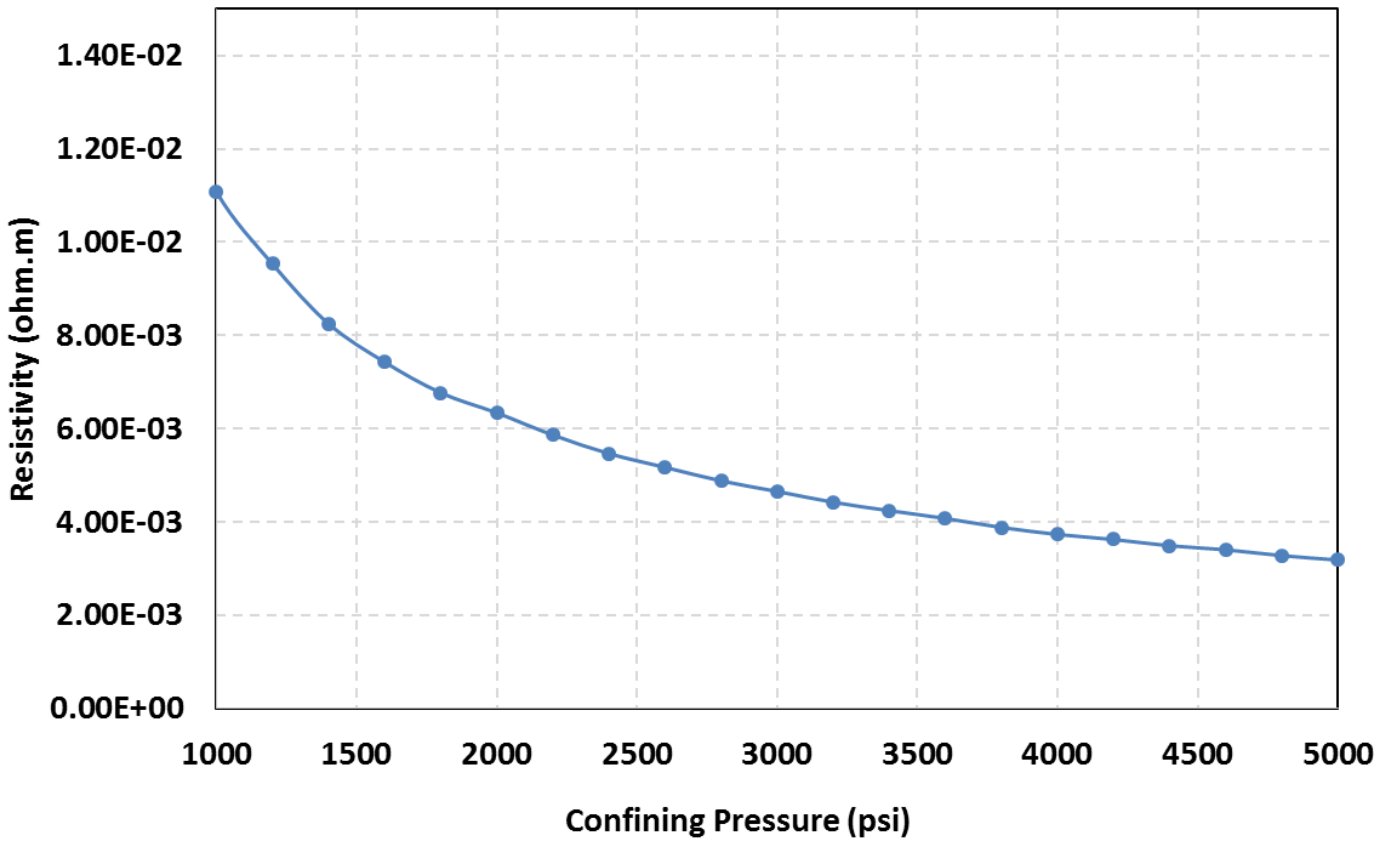


75% sand (seawater)	$3.24 \times 10^{-3}\ \Omega \cdot m$ @5000 psi

The University of Texas at Austin
Petroleum and Geosystems Engineering

E-Spectrum Technologies

Electrical Resistivity: 70/100 mesh



75% sand (sea water)	$3.18 \times 10^{-3}\ \Omega \cdot m$ @5000 psi