Fracture Diagnostics Using Low Frequency EM Induction and Electrically Conductive Proppant

Mukul M. Sharma

Yaniv Brick, Peng Zhang, Javid Shiriyev,

Ali E. Yilmaz, Carlos Torres-Verdin

University of Texas at Austin

Jeff Gabelmann, Robert Houston

E-Spectrum

DE-FE0024271

Project Objectives

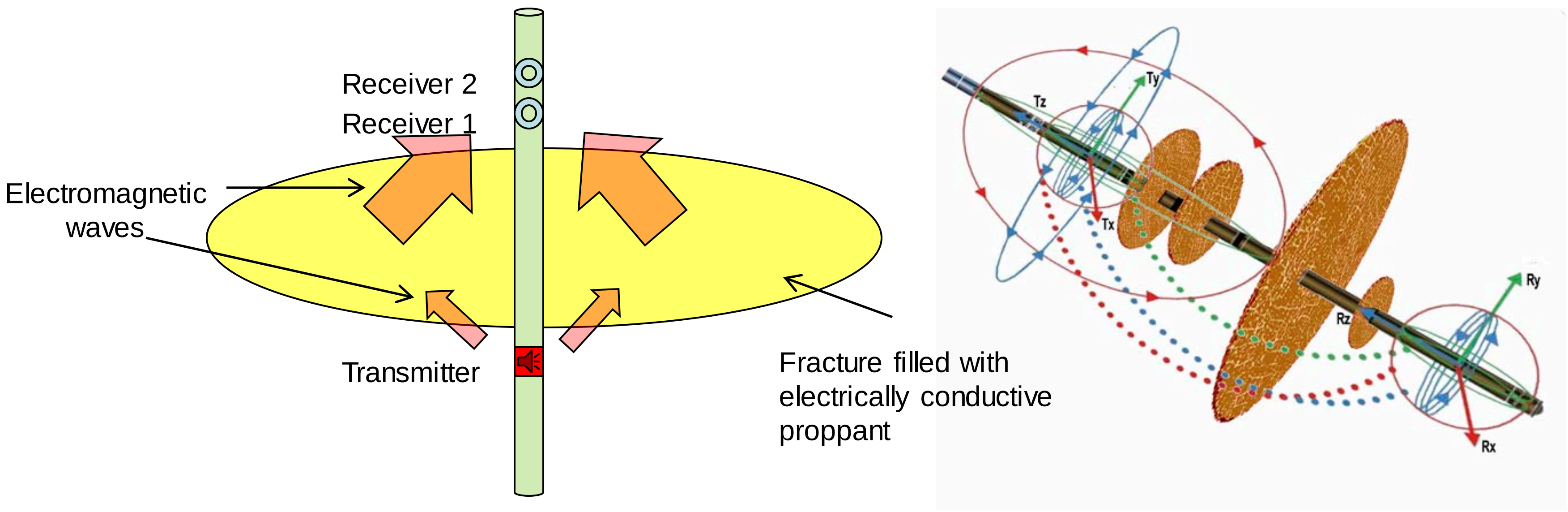
The primary objective of the project is to build and test a downhole fracture diagnostic tool that can be used to estimate the orientation and length of the 'propped' fracture and to map the distribution of proppant in the fracture.

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 field test a prptotype 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.

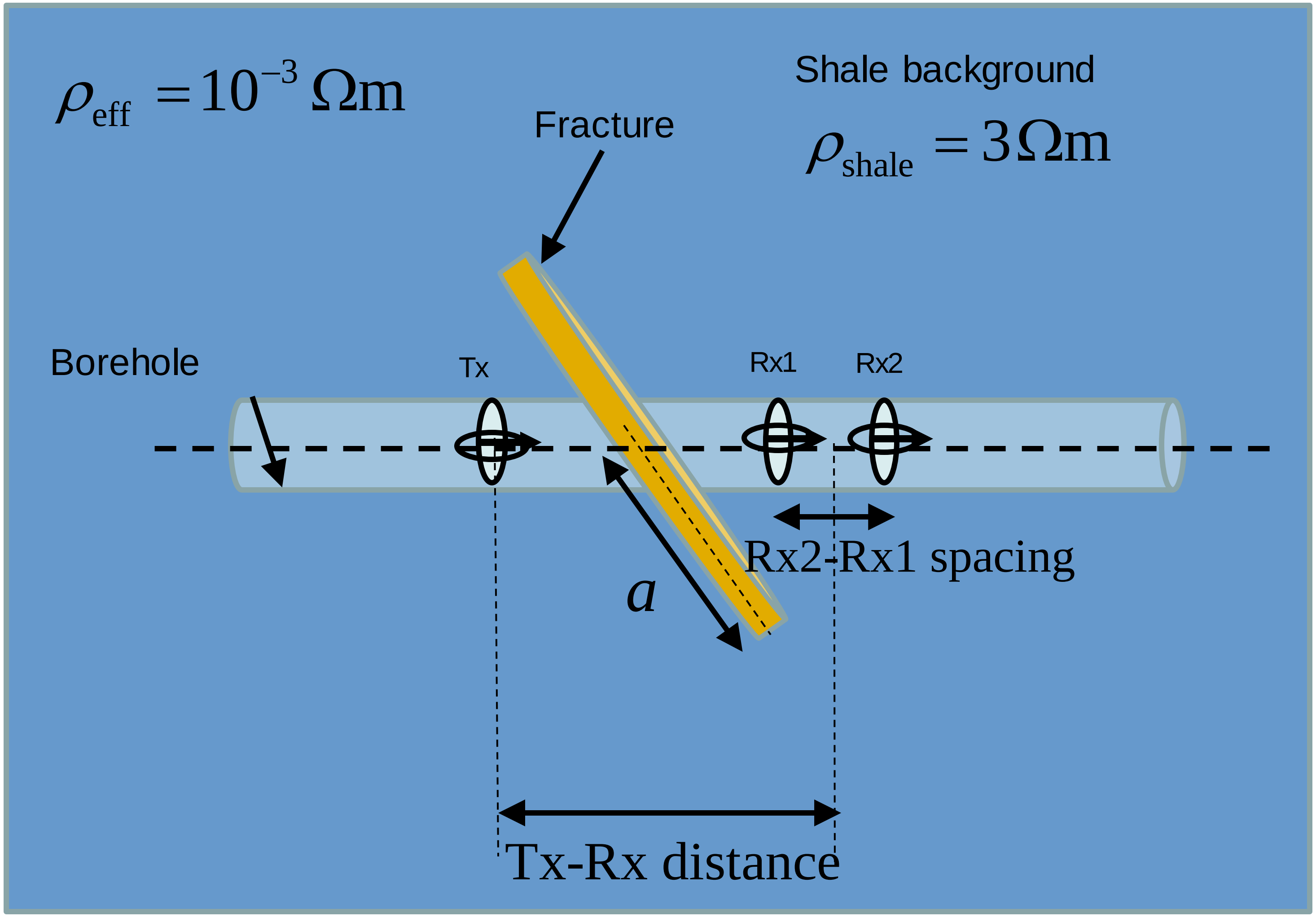
Concept

- Transform a hydraulic fracture into a highly conductive plane using conductive proppants.
- One transmitter, two receiver set to measure electromagnetic response.



Forward Model

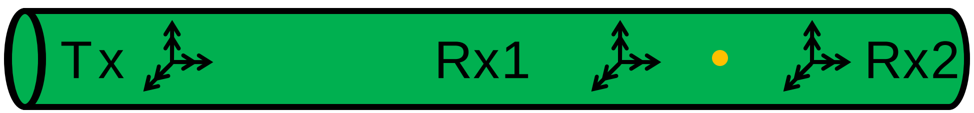
Simulated Scenario



Simulated Scenario

- Primary and bucking coil configuration

- Short-spacing measurement



$r_{Rx1} = 1.2$ m

$r_{Rx2} = 1.5$ m

- Long-spacing measurement

$r_{Rx1} = 18$ m

$r_{Rx2} = 19.2$ m

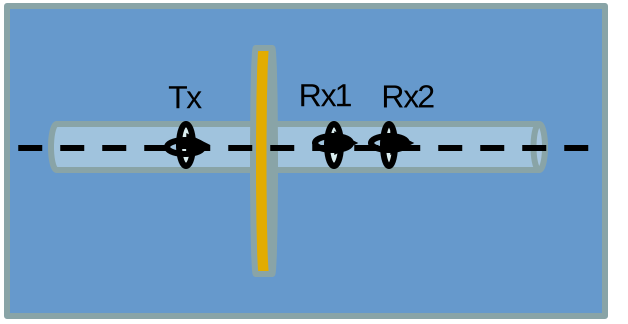
- Center of the receivers

u-component *H* field due to *v*-directed magnetic dipole

$$\Delta H^{uv} = -\left[H^{uv}(\mathbf{r}_{Rx2}) - H^{uv}(\mathbf{r}_{Rx1})(r_{Rx1} / r_{Rx2})^3\right]$$

Simulated Scenario

- Primary (formation) and secondary (fracture) magnetic fields computed for co-axial and co-planar scenarios

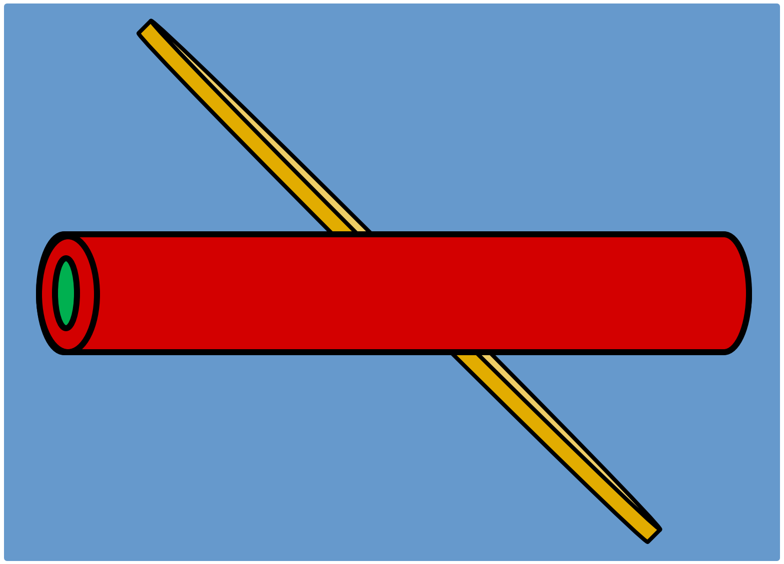


- Field notations: $\mathbf{H}^{v} = \mathbf{H}^{v}_{\text{form}} + \mathbf{H}^{v}_{\text{frac}}$
  - Magnetic field (fracture + formation):
  - uv indicates:
    - aa – co-axial measurement, pp – co-planar measurement
  - Voltage after cancellation [volts]:

$$\Delta U^{uv} = \mathrm{Re}\{-j\omega\mu_0 A N_{\text{turn}} \hat{\mathbf{u}} \cdot [\mathbf{H}^{v}(\mathbf{r}_{\text{Rx2}}) - \mathbf{H}^{v}(\mathbf{r}_{\text{Rx1}}) r^{3}_{\text{Rx1}} / r^{3}_{\text{Rx2}}]\}$$

- Secondary field increases with facture size and effective conductivity and decreases with Tx-Rx distance.

Model: Volume Electric Field Integral Equation (VEFIE)



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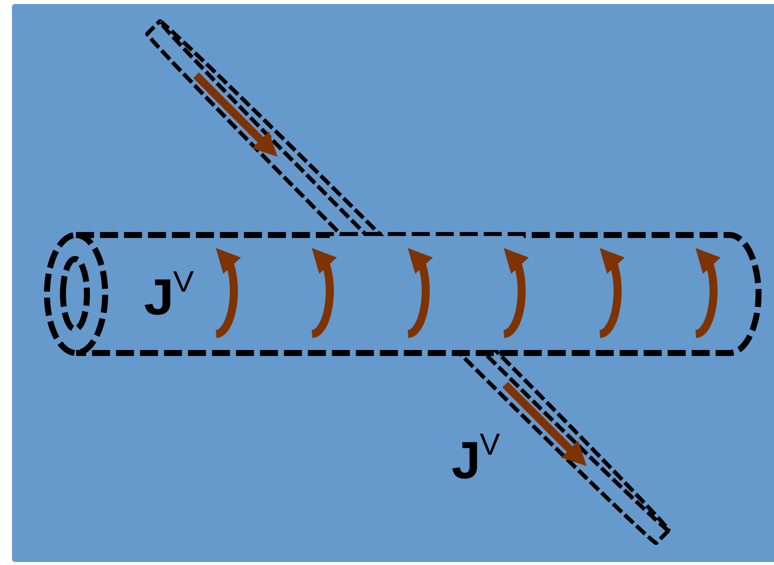
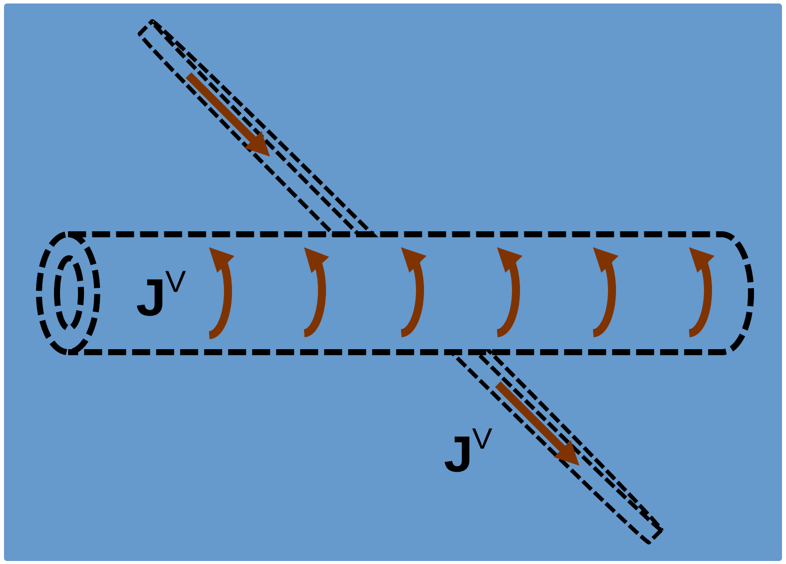


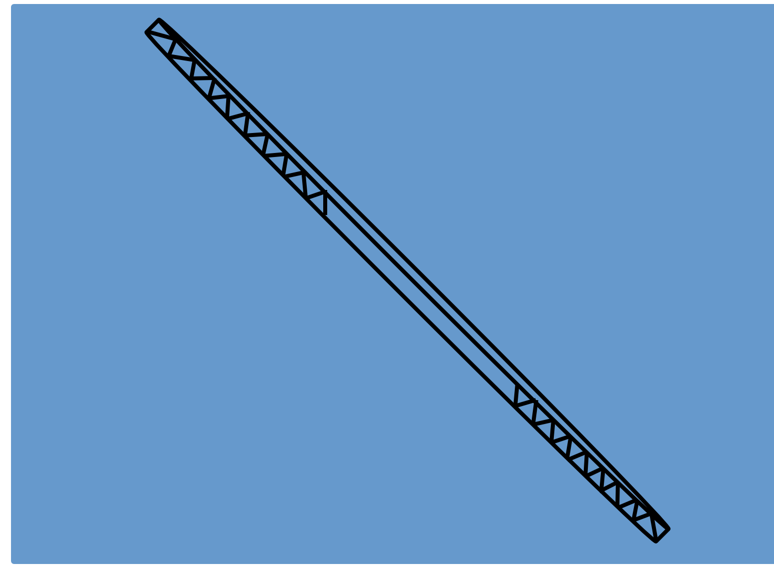
- Scattered (secondary) electric field

$$\mathbf{E}_{frac}(\mathbf{J}^V)$$

Model: Method-of-Moments (MoM)



$\Rightarrow$



- Basis and Galerkin testing

$$\left.\begin{aligned} \mathbf{E}_{\mathrm{form}} &= \frac{\mathbf{J}^V}{\sigma_V - \sigma_{\mathrm{shale}}} - \mathbf{E}_{\mathrm{frac}}(\mathbf{J}^V) \\ \mathbf{J}^V(\mathbf{r}) &\approx \sum_{n=1}^{N} I[n]\,\mathbf{f}_n(\mathbf{r}) \end{aligned}\right\} \xrightarrow{\text{Galerkin testing}} \mathbf{Z}_{N\times N}\mathbf{I}_{N\times 1} = \mathbf{V}_{N\times 1}$$

Computational cost: $O(N^3)$ (direct method)

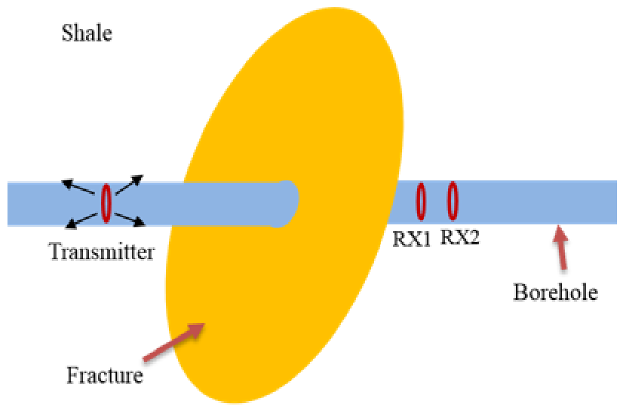
$(N \sim 70\,000 \sim 250\,000)$ $O(N^2)$ (iterative method)

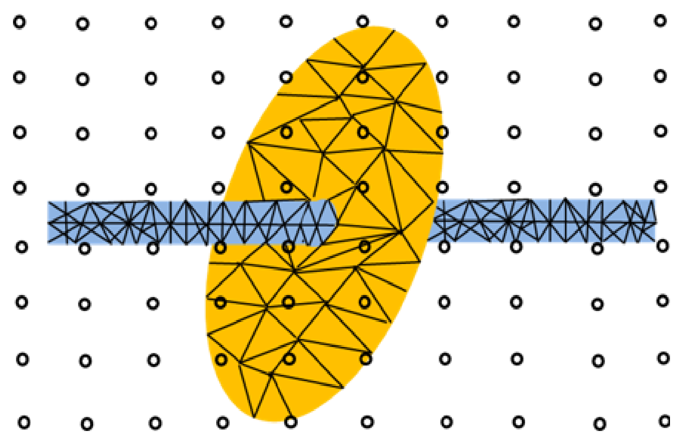
Model: Numerical Solution and Fast Solver

- Method of Moments
  - Discretization of the integral equation

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

  - Computational cost $O(N_{\text{iter}} N^2)$
- Adaptive integral method:
  - Auxiliary 3-D regular grid
  - A 4-step procedure to approximate MOM matrix
  - Translational invariance
  - 3-D FFTs
  - Computational cost $O(N_{\text{iter}}(N + N_C \log N_C))$





Computational Complexity

- MoM iterative solver performance (presented **last year**) $\boxed{\rho = 0.1\Omega\text{m}}$
  - Problem: circular fracture (*a*=30m):
  - Number of unknowns: ~189k
  - Storage: ~546GB
  - 512 cores
  - Matrix fill time: 28 min (238 hr. if serial)
  - Solution per excitation average time: 45 sec. (6 hr. if serial)
  - For 2x200 excitations: 5 hr. (for a single fracture)

- AIM iterative solver performance (new) $\boxed{\rho = 0.01\Omega\text{m}}$
  - Problem: circular fracture (*a*=30m):
  - Number of unknowns: **~1.9M** (dictated by higher conductivity)
  - Storage: ~**91GB** (~54.6TB with MoM)
  - 512 cores
  - Matrix fill time: 2.2 min (19 hr. if serial)
  - Solution per excitation average time: 8.3 sec. (1.18 hr. if serial)
  - For 2x200 excitations: 0.9 hr. (for a single fracture)

Simulations Summary

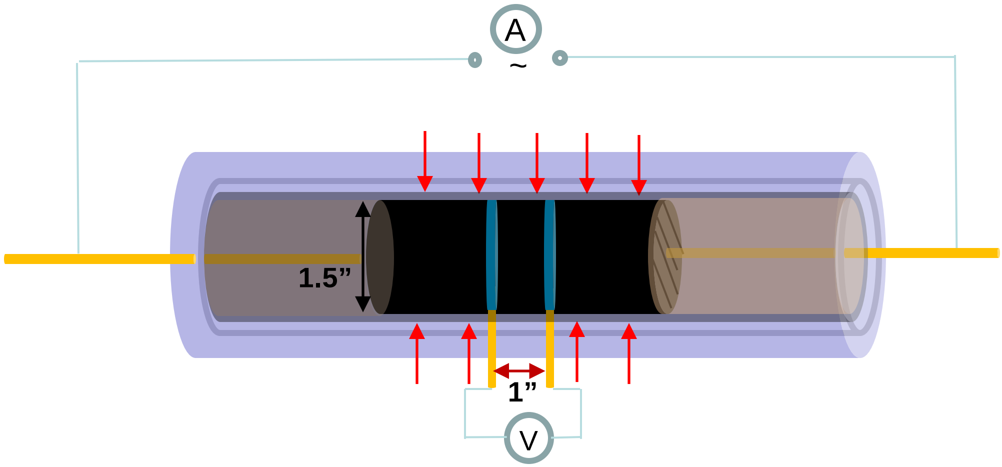
- Simulations are required for evaluation of tool design as well as for forward model as part of an inverse solver
- Integral equation-based solvers obviate the need in modelling formation background, larger fractures can be analyzed
- Adaptive Integral Method (AIM)-based **fast iterative solver** enable analysis of larger, more detailed fractures, with higher proppant conductivity
- Removal of borehole has little effect on the results while enabling optimal performance of AIM (greater acceleration)
- Fast run-time per excitation - corner stone of the **inverse solver in progress**

Simulations Summary

- High conductivity contrasts cause ill conditioning – results are scaled with fracture conductivity in post processing
- Hence, results are obtained with “pessimistic” proppant resistivity values and scaled to match values extracted from lab-experiment
- Planned:
  - **Fast direct solver**– (in progress) suitable for multiple forward solutions and high conductivity contrasts
  - **Inversion algorithm** relying on a fast direct solution
  - Advanced formulation and complex modeling for **cased wells** tools

Proppant Resistivity Measurements

Experimental Configuration

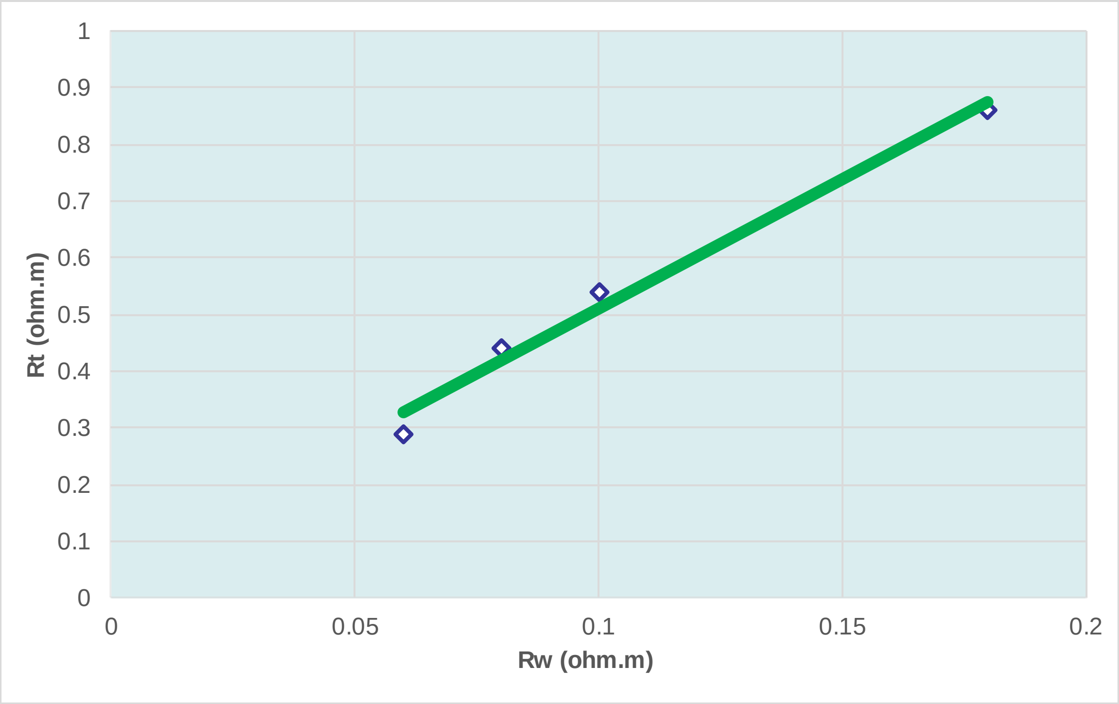


Conductive Proppant: Petroleum Coke

- A 4-point probe 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

Verification of the Experimental Method

Sand pack saturated with brine



Archie's Equation

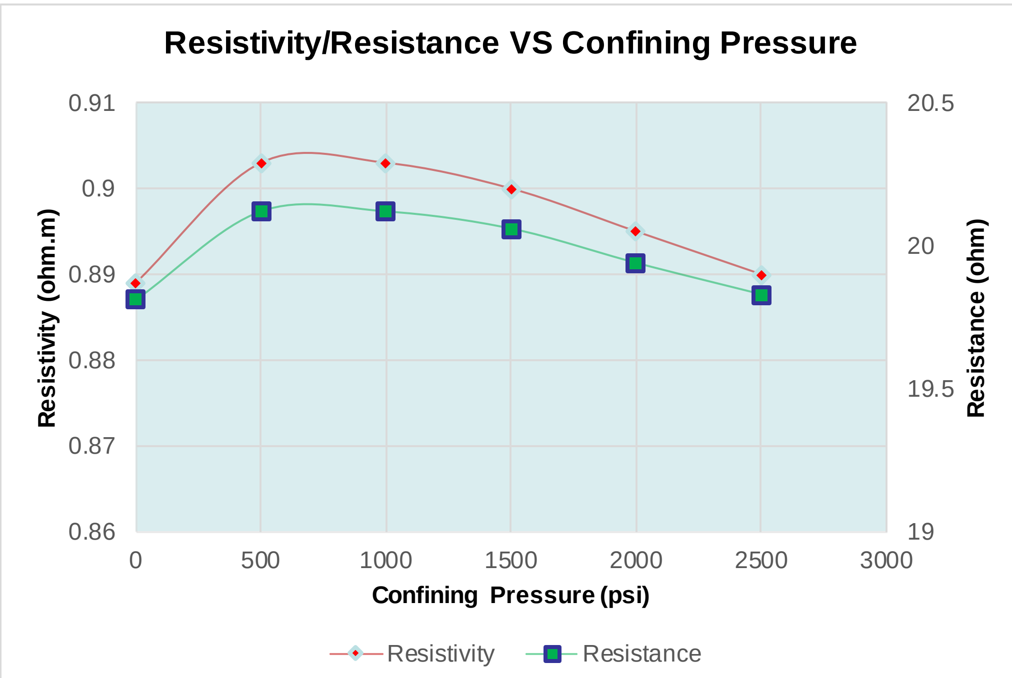
$$Rt = Rw(a\Phi^{-m})Sw^{-n}$$

m	1.3
Sw	1
Φ	25.2%
FF	4.55
a	0.76

A good fit to Archie's Law

Verification of the Experimental Method

Confining pressure applied



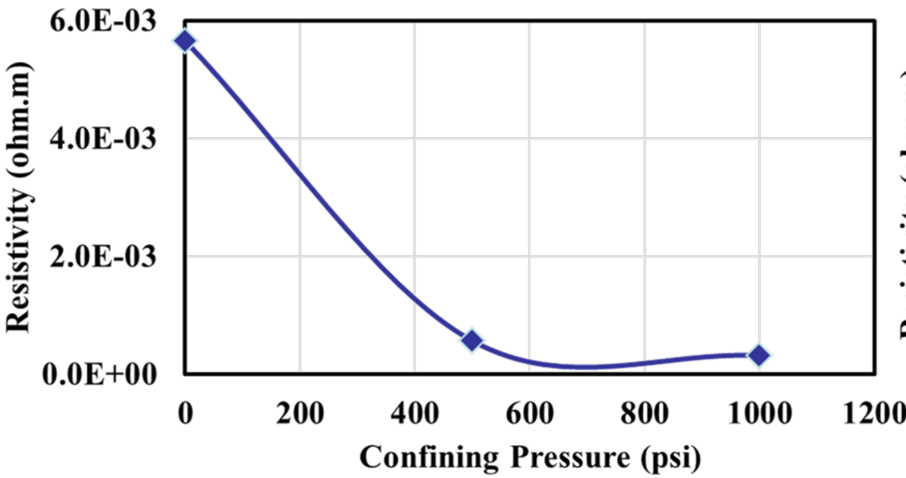
Φ=24.2%

Sea Water (Rw=0.18 ohm.m)

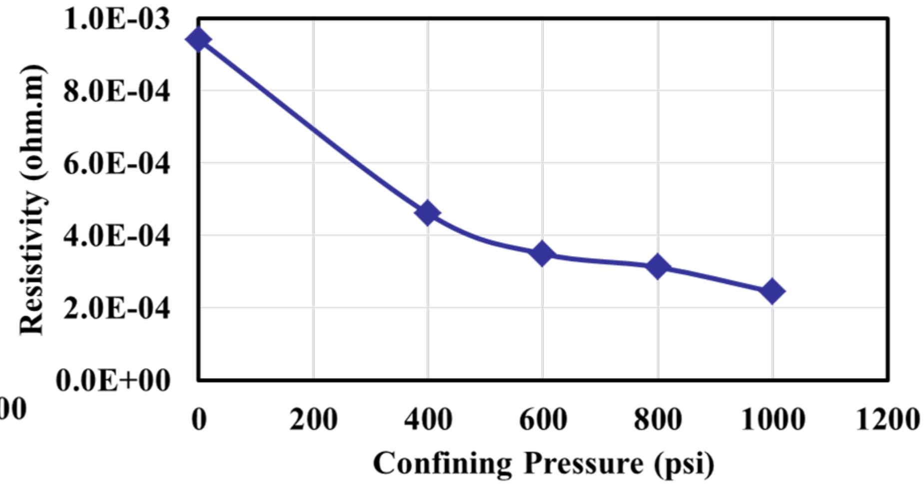
The setup works properly when confining pressure is applied, although the contraction of the sleeve has a small effect on the calculations.

Preliminary Results

Resistivity measurements of petroleum coke with air



(a)



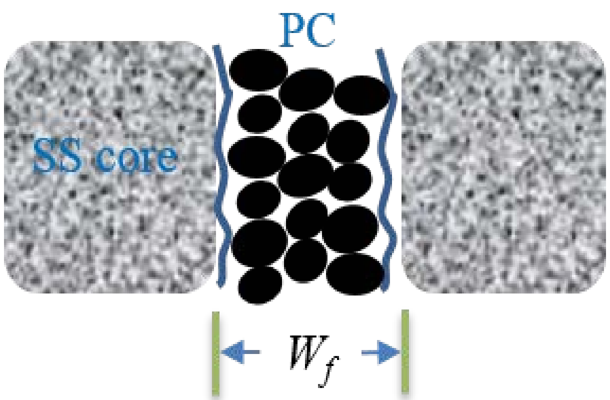
(b)

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

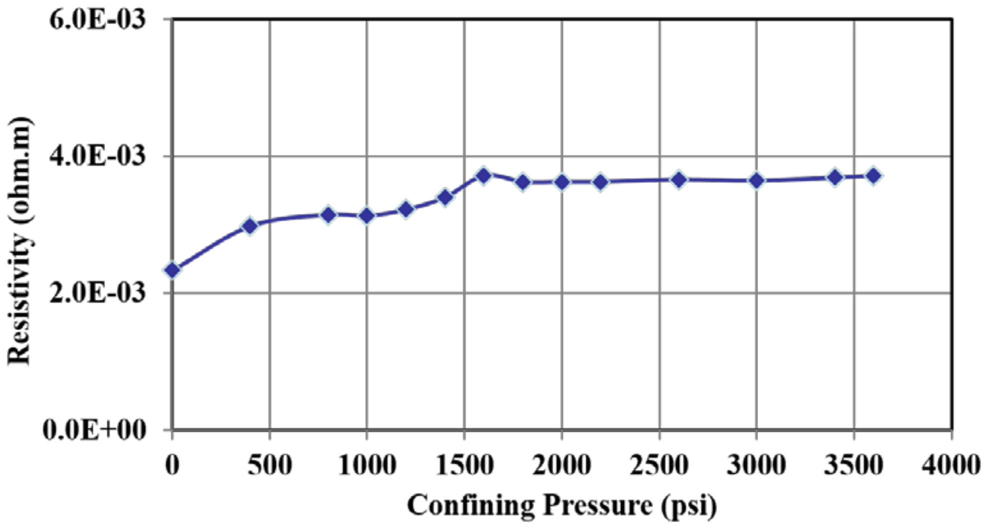
Density: 1.27 g/cm^3
Porosity: 37.6%
End point: 2.4x10^{-4} $\Omega \cdot m$

Preliminary Results

Resistivity measurements of petroleum coke in a fracture



$W_f = 1\ \mathrm{mm}$



The resistivity remains relatively steady around $3\times10^{-3}\ \Omega\cdot\mathrm{m}$, i.e., an order of magnitude higher than that obtained for the cylindrical pack.

Key Observations

- The electric resistivity of the proppant we plan to use, under confining stress, was measured to be in the range of $2 \times 10^{-4}\,\Omega \cdot m$.
- This value is four orders of magnitude smaller than the resistivity of a typical shale. This is very important since it provides an excellent resistivity contrast with the shale.
- The initial packing density affects the resistivity at low stress but not at high stress.
- The resistivity is not very sensitive to the fluid saturation since the conductance is controlled by the conductivity of the solid grains.

Towards a Parametric Inversion Algorithm

Before Inversion

- In order to do inversion, we need to know:
  - What information the tool offers corresponding to different fracture geometries
  - What signals should be used for inversion in order to recognize different model parameters
- We already know from simulations of simple fracture geometries:
  - The voltage detected ΔU^{uv} are proportional to fractures' conductivity
  - ΔU^{uv} increases as the fracture area increases, until it reaches to a saturation point
  - Coaxial measurements ΔU^{zz} are more sensitive to fracture's conductivity, area, shape and position, while cross-polarized measurements (ΔU^{xz} …) are more sensitive to fractures' angle

Yang, K., C. Torres-Verdin, and A.E. Yilmaz. 2015. *IEEE Transactions*, 53(8), 4605-4615.

Before Inversion

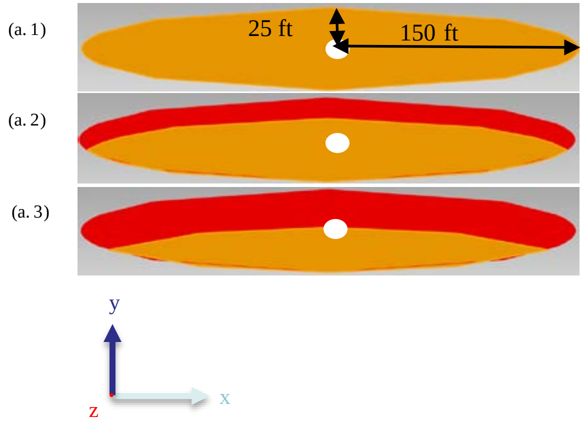
Towards more realistic fractures:

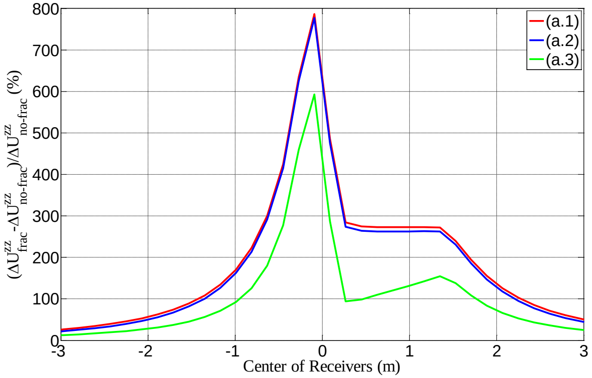
- Asymmetrical proppant distributions
- Complex fractures
- Curved fractures
- Lab measured proppant conductivity

Can the tool differentiate these fractures?

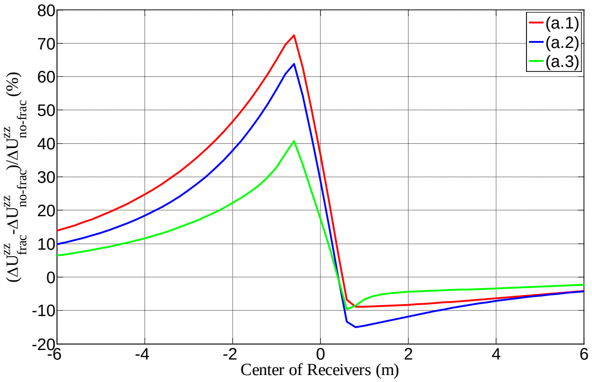
Example - Proppant Distribution

Effect of proppant distribution (coaxial measurements)





Short spacing, coaxial

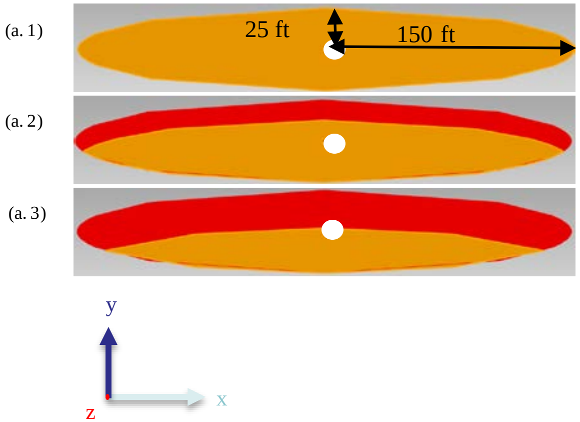


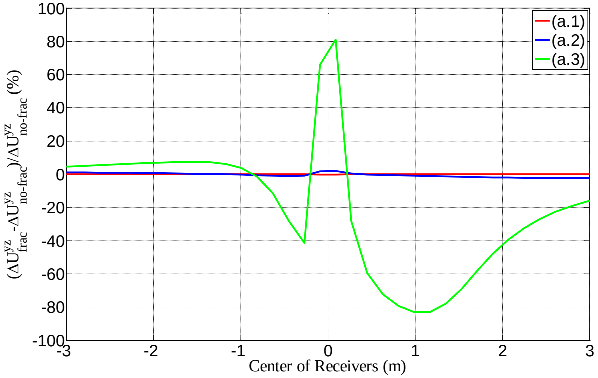
Long spacing, coaxial

- The curves reach their peak values when the center of the two receivers is roughly at zero ⟶ *ability to detect fracture's location*
- The relative signal strength decreases as the propped area reduces⟶*proportionality of the secondary fields to fracture size*
- The separation of the curves for the long-spacing configuration is more pronounced. The long-spacing detector is more sensitive to longer fractures.

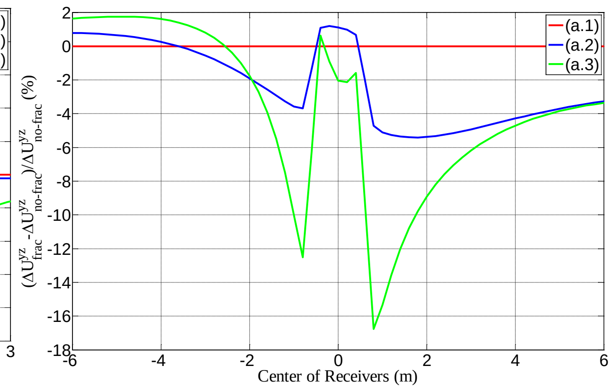
Example - Proppant Distribution

Effect of proppant distribution (cross-polarized measurements)





Short spacing, cross-polarized



Long spacing, cross-polarized

- The cross-polarized measurement is less sensitive to the propped fracture's area
- The more symmetrical fractures induce significantly lower voltage levels at the receiver compared to that of the single sided distribution (less symmetrical induced stronger signals)
- This configuration is more sensitive to the fracture's asymmetry, and it provides complementary information that can improve shape classification of the propped fracture

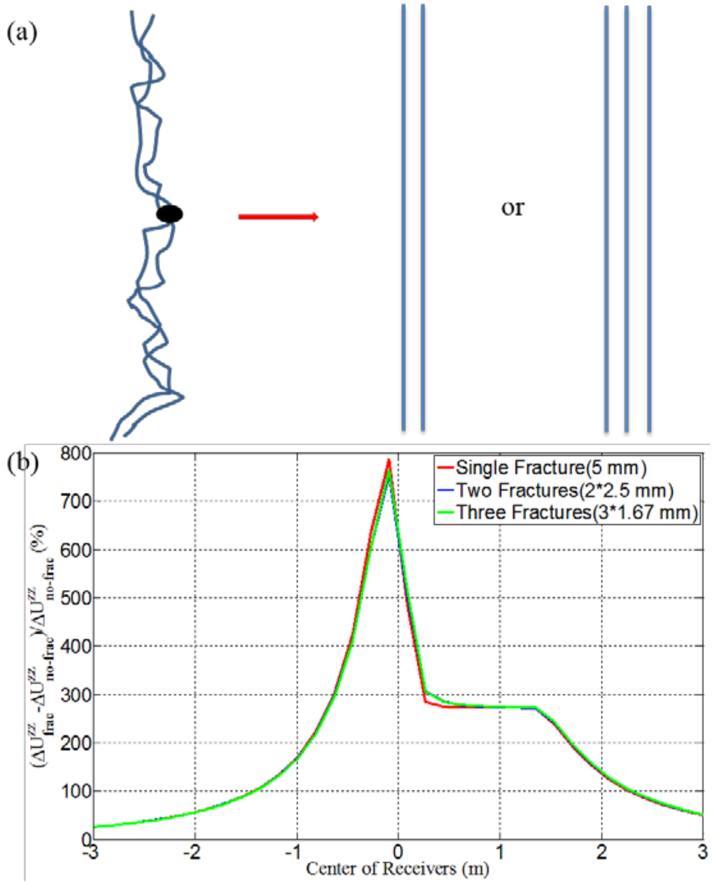
Example - Proppant Distribution

Key conclusions:

- the EM logging technique enables the differentiation between different spatial distributions of proppant.
- To detect spatial asymmetry in fractures, a combination of co-axial and cross-polarized measurements should be used.
- While co-axial measurements provide information on fracture area, distinguishing asymmetrical fractures from symmetrical ones is possible based on cross-polarized measurements.
- Long-spacing configuration is preferred to distinguish between various spatial distributions of proppant in large-size fractures.

Example - Complexity of Fractures

Complex fractures VS planar fractures

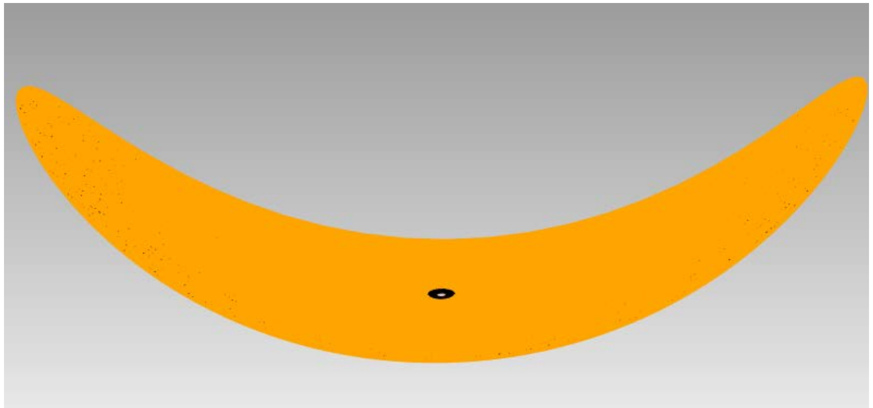


Short spacing, coaxial

- Use multiple planar elliptical fractures of a 5mm total width and a 1 cm separation to approximate the complex fracture.
- No significant difference is observed between the various cases. The tool's response depends only on the propped fracture volume, and not on its complexity.

Therefore, it is sufficient to model a thin complex fracture as a single thin bulk volume of a constant effective thickness

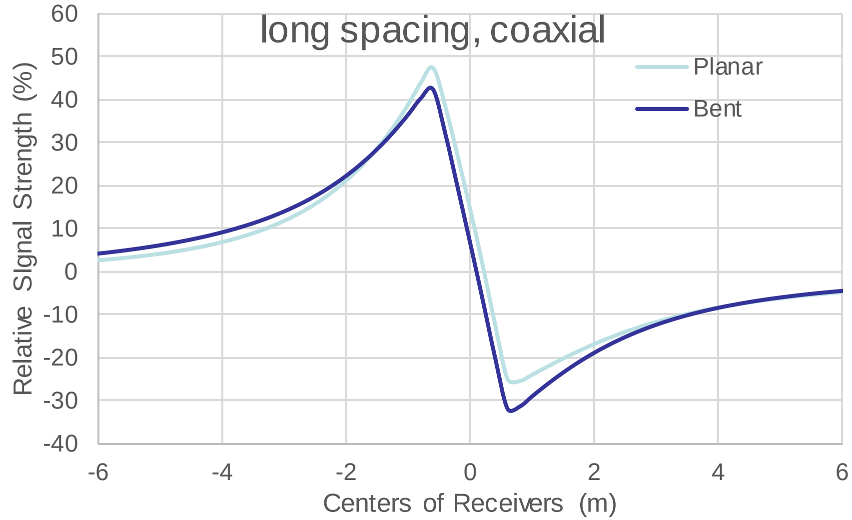
Example - Curved Fractures

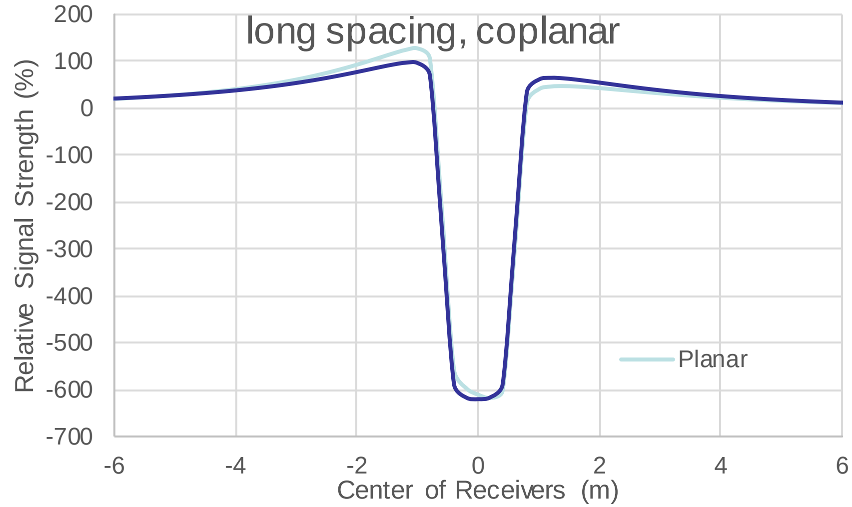


Curved fracture VS planar fracture

Major radius 10m, minor radius 3m
Two wings are bent 30 º

- Measurement with long-spacing configuration shows some differences in both coaxial and coplanar measurements.
- These differences are more likely effects of differences in area





Parametric Inversion Approach

Objective function

$$E(\overline{m}) = \frac{\sum_{i=1}^{n} [F_i(\overline{m}) - F_i(\overline{m}_{true})]^2}{\sum_{i=1}^{n} [F_i(\overline{m}_{true})]^2}$$

Relative signal strength

$$F_i(\overline{m}) = \frac{\Delta U_{i(\text{frac})}^{zz/xz}(\overline{m}) - \Delta U_{i(\text{no-frac})}^{zz/xz}(\overline{m})}{\Delta U_{i(\text{no-frac})}^{zz}(\overline{m})} \times 100\%$$

Model parameters

$$\overline{m} = [\alpha; \zeta; \sigma; A; \lambda]$$

α : angle (º)

ζ : position (m)

σ : conductivity (S/m)

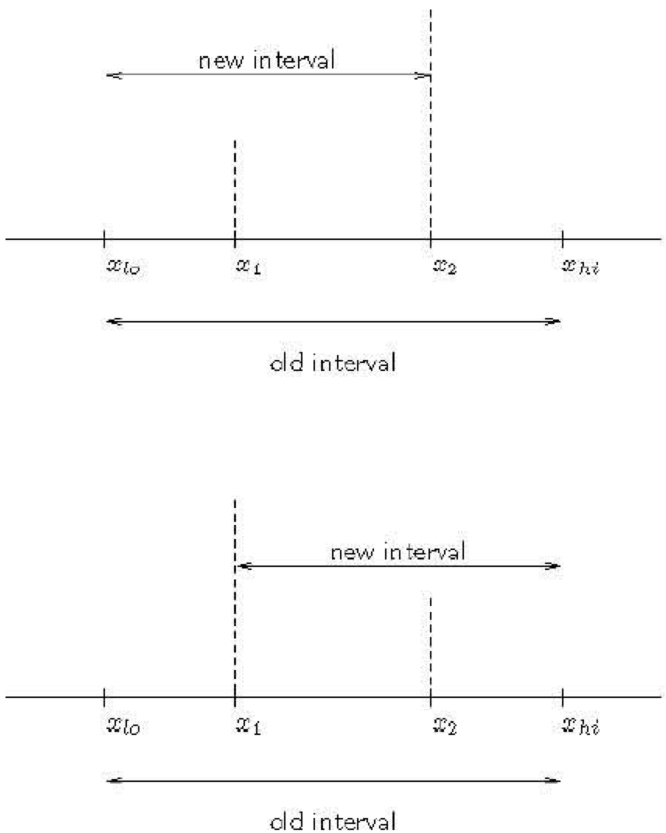
A : area (m^2)

λ : aspect ratio (m)

Goal: Minimize the objective function w.r.t all model parameters !

Optimization Algorithm - GSS

Golden section search (GSS)



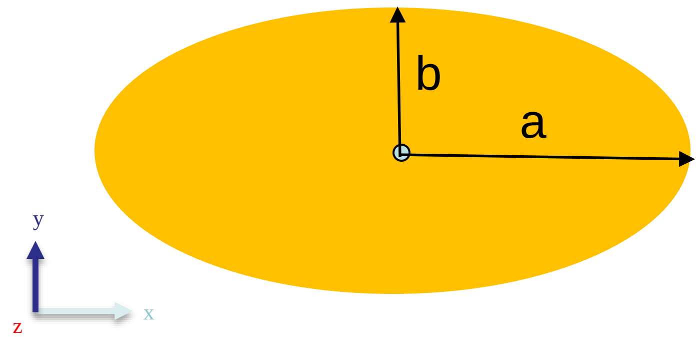
- To find the minimum of $f(x)$ in the interval $[x_{lo}, x_{hi}]$

1. Let $[x_{lo}, x_{hi}]$ be the initial interval
2. Set $x_1 = cx_{lo} + (1-c)x_{hi}$
3. Set $x_2 = (1-c)x_{lo} + cx_{hi}$
4. If $f(x_1) < f(x_2)$, $x_1, x_2 \rightarrow x_2, x_{hi}$; else $x_1, x_2 \rightarrow x_{lo}, x_1$
5. If (stopping criteria met) return; else go to Step 3

Example for Inversion

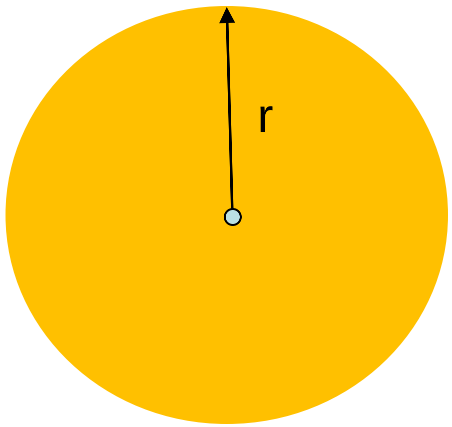
Starting from a simple case

True model



Position: 0 m
Conductivity: 30 S/m
Orientation: 0°
Area: $\pi \times 10 \times 3\ m^2$
Aspect Ratio: 3.33

Initial guess



Position: 3 m
Conductivity: 100 S/m
Orientation: 0°
Area: $\pi \times 7^2\ m^2$
Aspect Ratio: 1

The Order of Searching

Start searching using short-spacing configuration

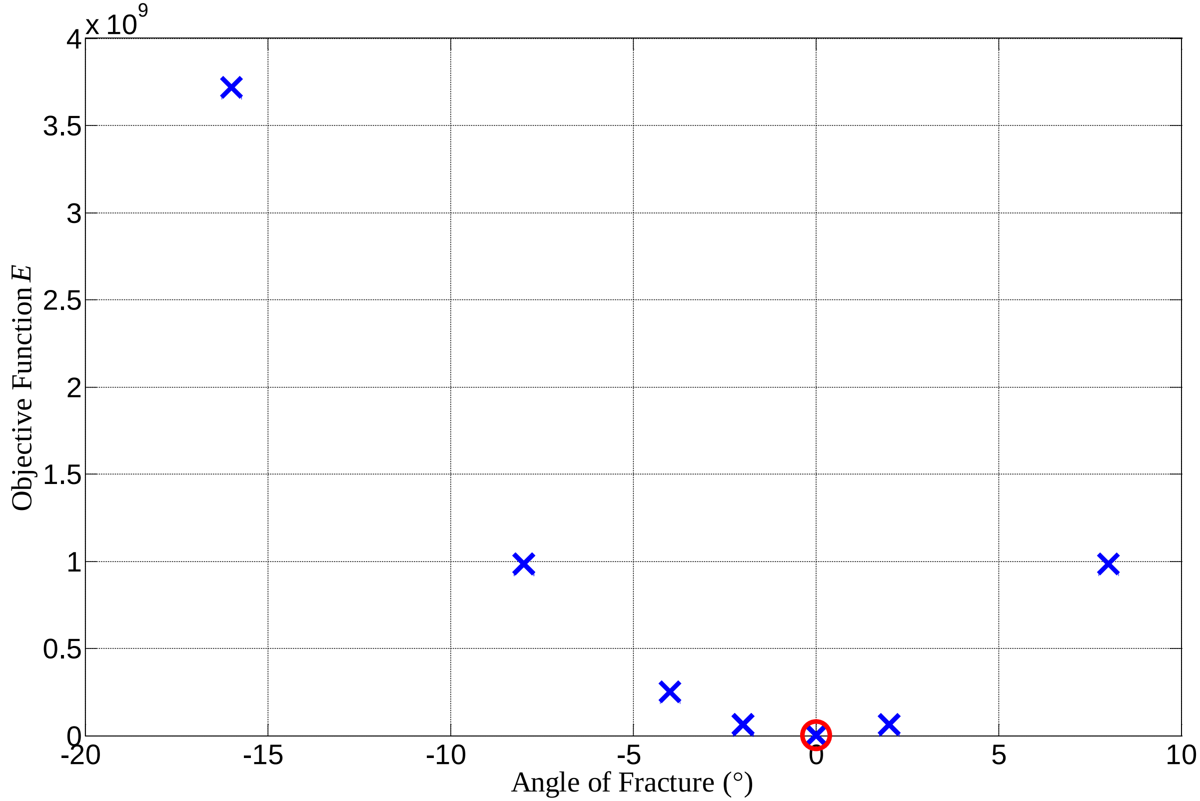
$$\left|\frac{\partial E}{\partial \alpha}\right| = 0.044 \qquad \left|\frac{\partial E}{\partial Z}\right| = 7.532 \qquad \left|\frac{\partial E}{\partial \sigma}\right| = 0.298$$

$$\left|\frac{\partial E}{\partial A}\right| = 0.007 \qquad \left|\frac{\partial E}{\partial \lambda}\right| = 0.254$$

$\alpha \quad z \quad \sigma$ are independent model parameters

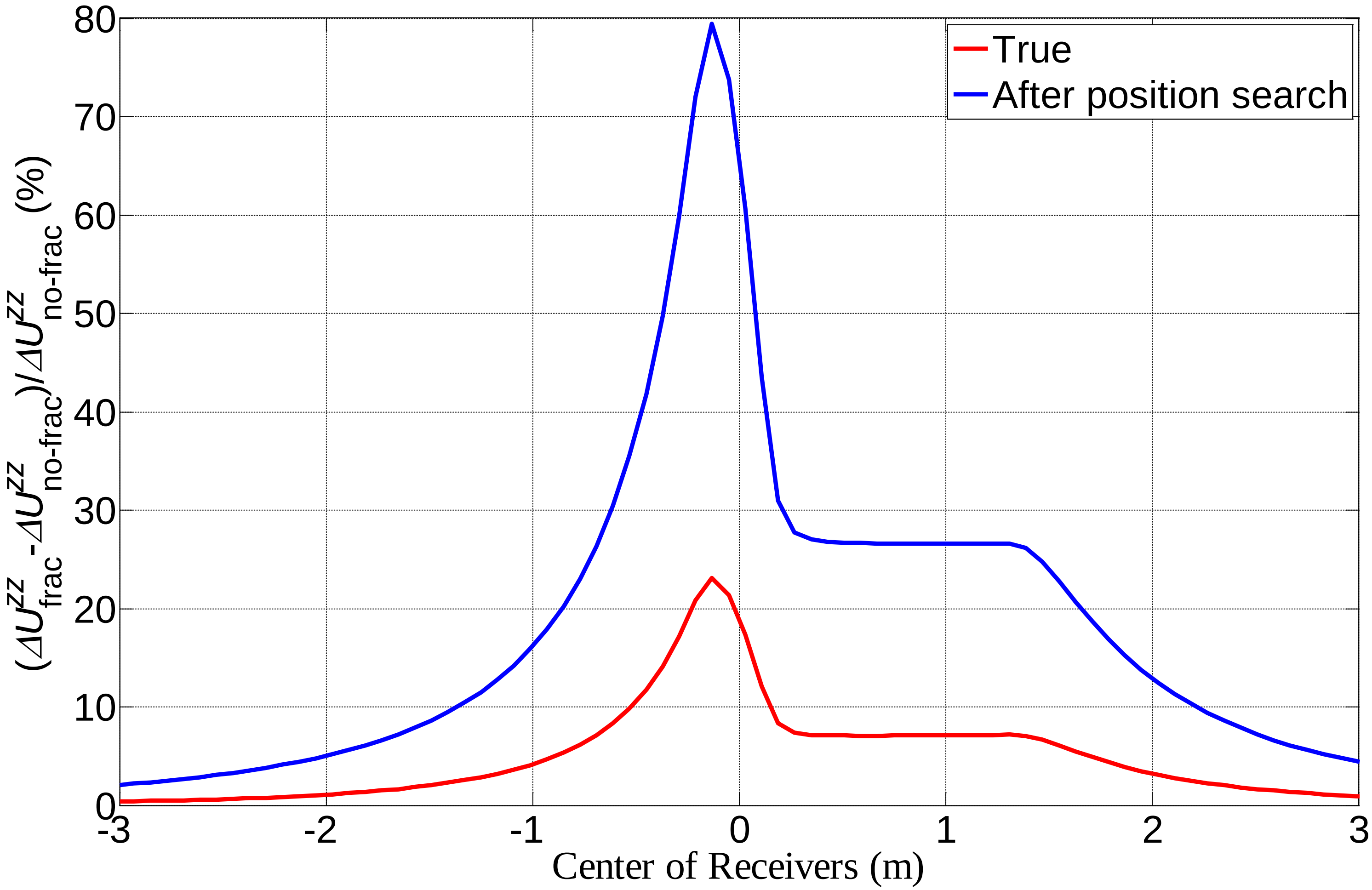
$A \quad \lambda$ are coupled model parameters

Searching for Angle

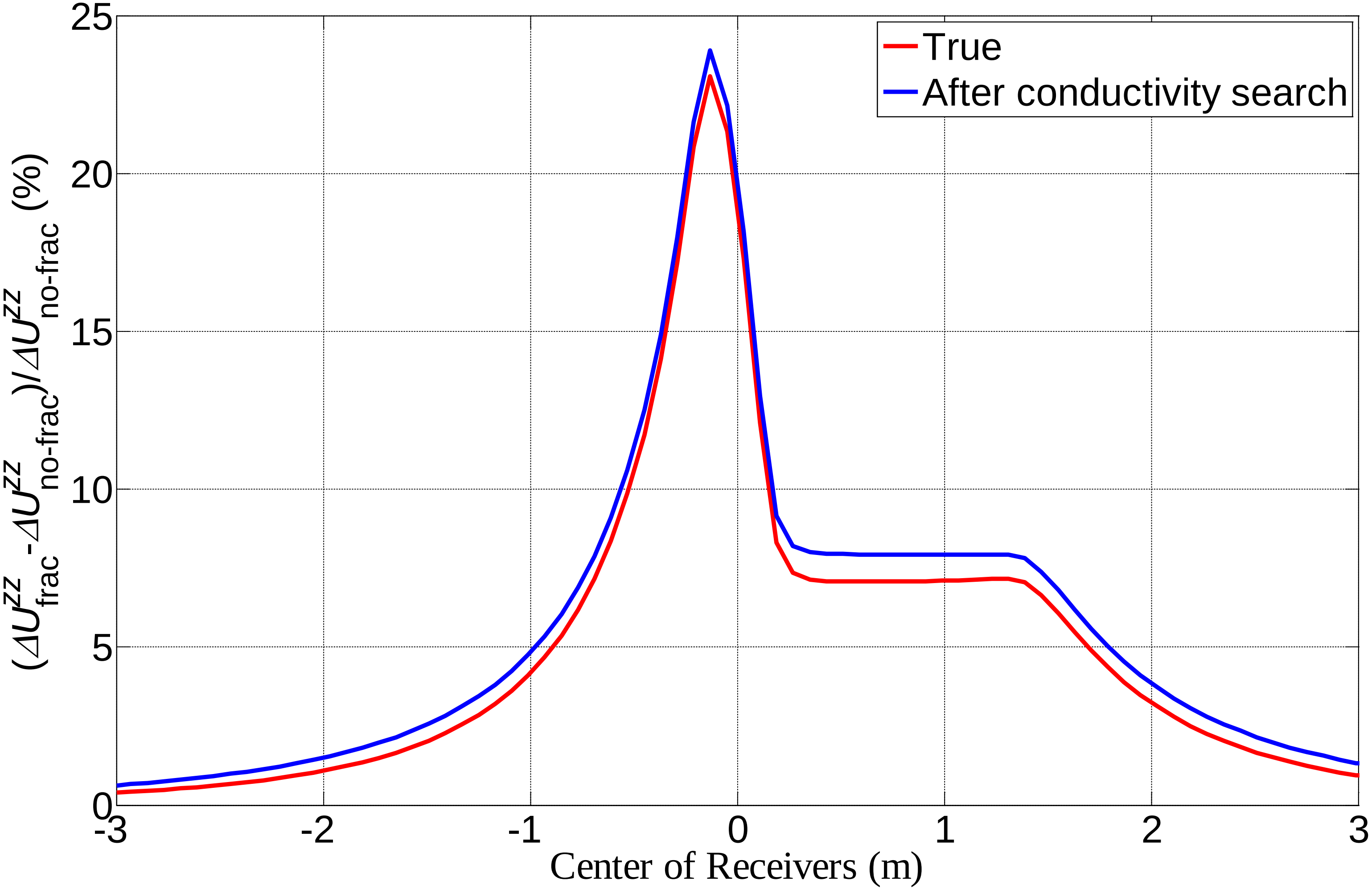


- Cross-polarized results
- Searching interval: [-30, 30]
- Accuracy: 2
- Number of forward Simulations: 7

Searching for Location



Searching for Conductivity



Searching for Area and Aspect Ratio

$A \quad \lambda$ are coupled model parameters !

- Inversion results (stops after one iteration)

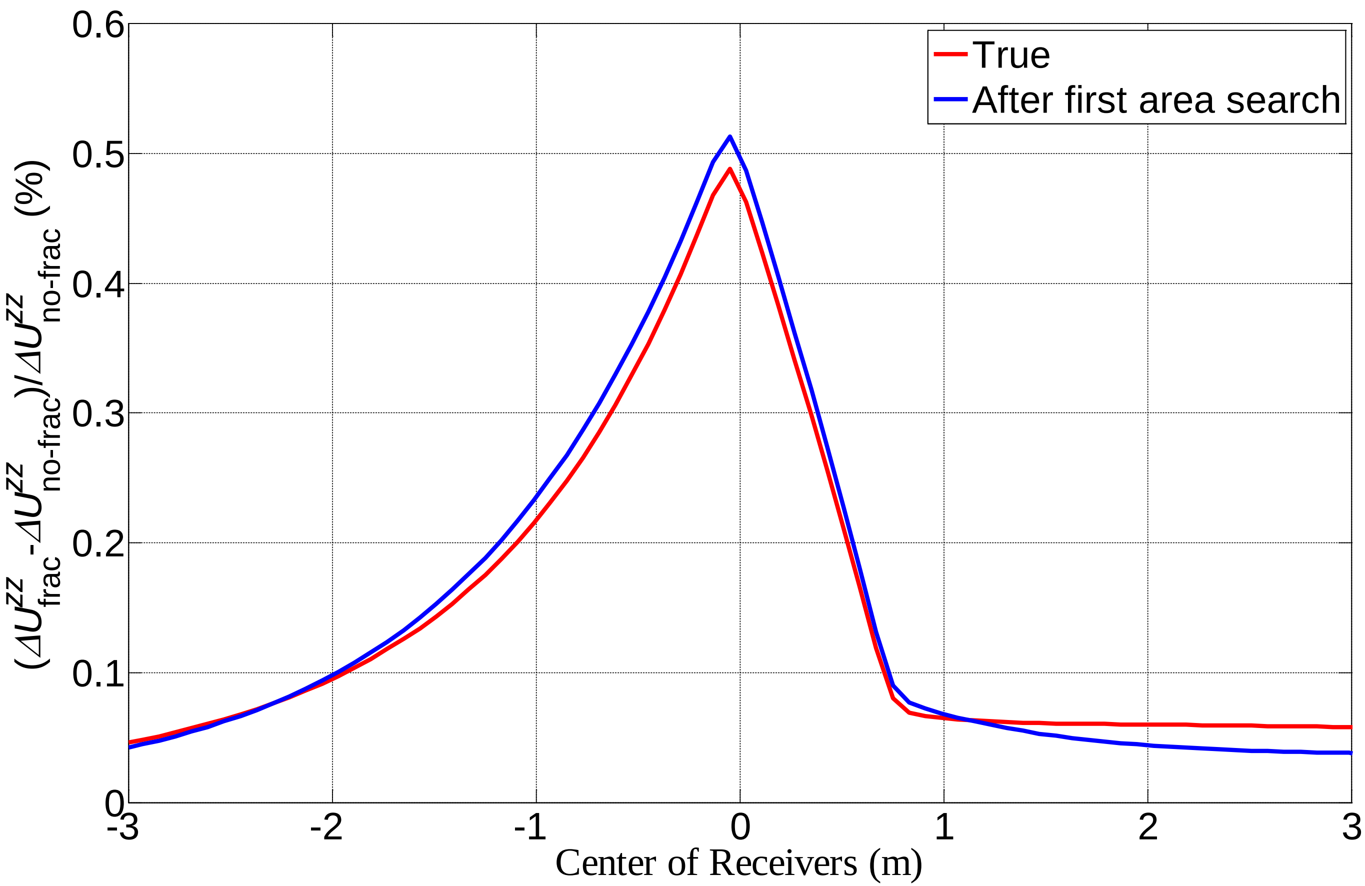
$$A = 55 \text{ m}^2 \qquad \lambda = 1$$

$$A = 94 \text{ m}^2 \qquad \lambda = 3.3 \qquad \text{(True)}$$

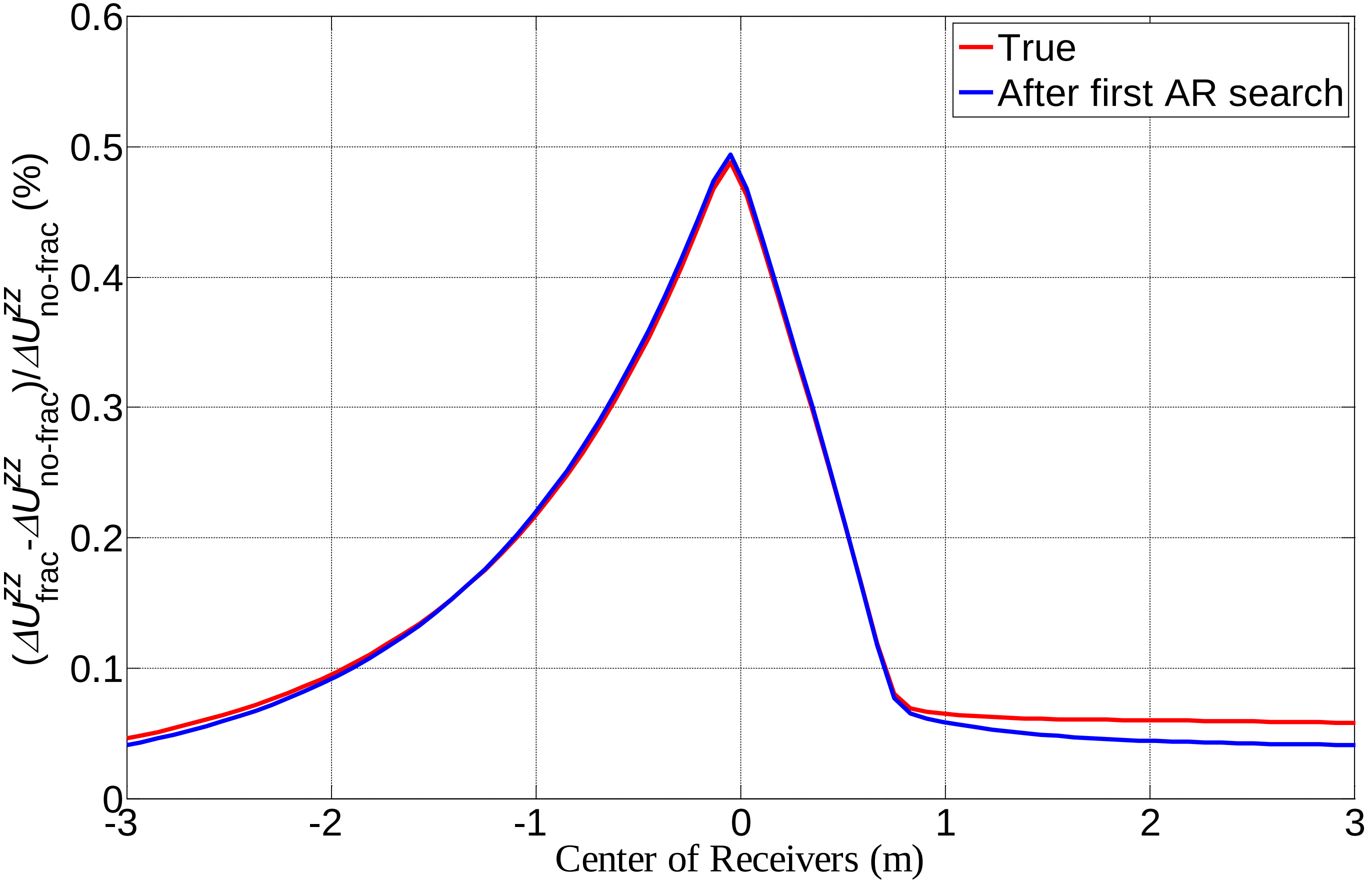
Reason: data from short-spacing configuration doesn't provide information about proppant far from wellbore.

What if we switch to data from long-spacing configuration?

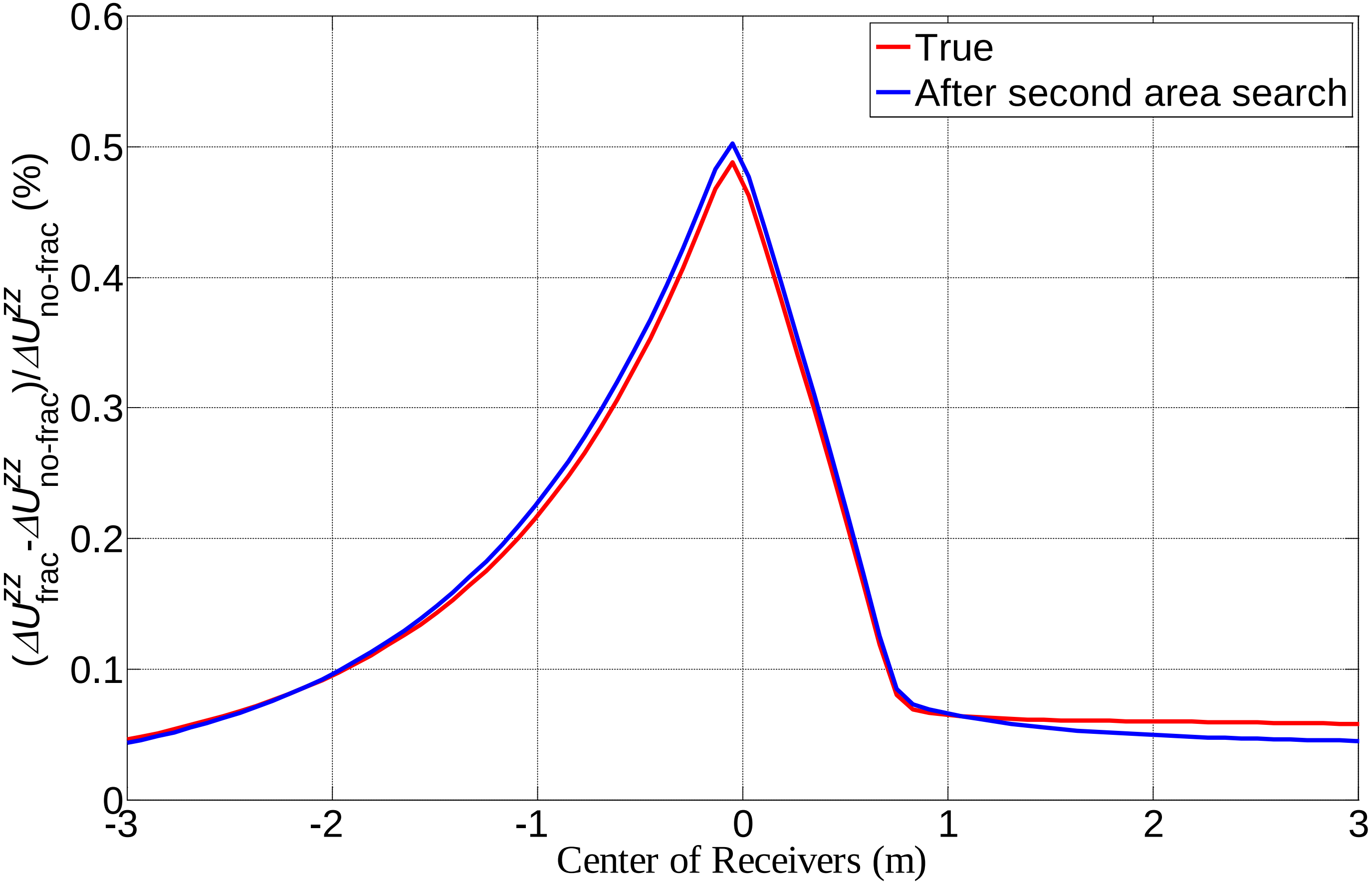
Searching for Area



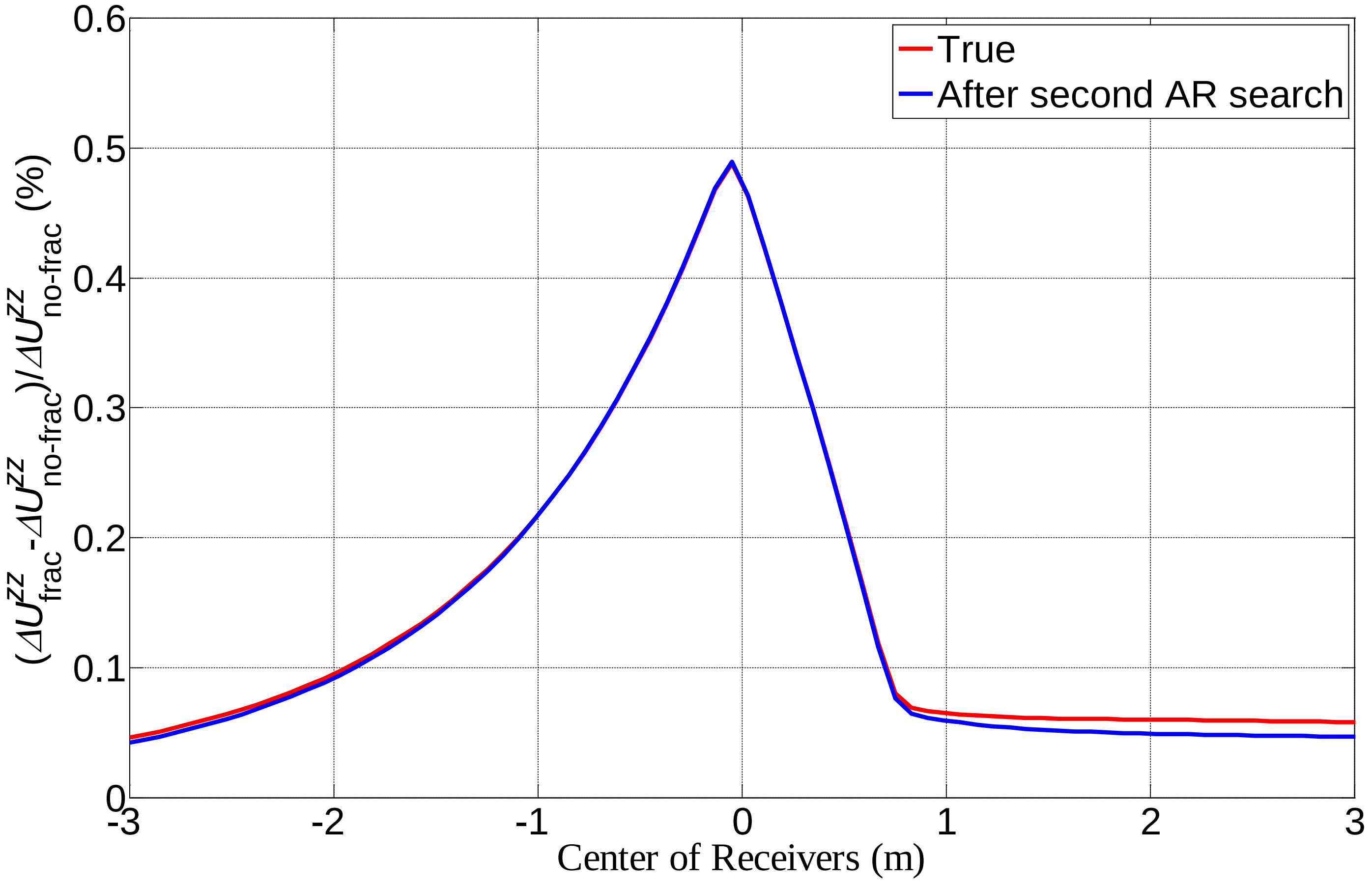
Searching for Aspect Ratio



Searching for Area (2nd)



Searching for Aspect Ratio (2nd)



Inversion Summary

True	Inversion
Position: 0 m	Position: 0 m
Conductivity: 30 S/m	Conductivity: 30 S/m
Orientation: $0°$	Orientation: $0°$
Area: 94 m^2	Area: 84 m^2
Aspect Ratio: 3.33	Aspect Ratio: 2.5

- Total number of forward simulations is 41
- Total computational time needed ~50 min (256 processors)
- Data should be chosen based on the rough estimation of fracture size especially for inversion of fracture size and aspect ratio

Future plans for inversion:

- Automation of searching
- Adding noise to synthesized data
- Using real data (recorded by experiments)

Shallow Earth Experiment for Prototype Tool

Prototype Tool: Shallow Earth Experiment

- Smaller scale experiment in a controlled environment (not field deployable)
- Necessary for:
  - Refining/Improving design towards a field deployable tool
  - Verifying measurement methodology
  - Recording realistic data to be used by inverse algorithms in development

Test Site Tool Specifications

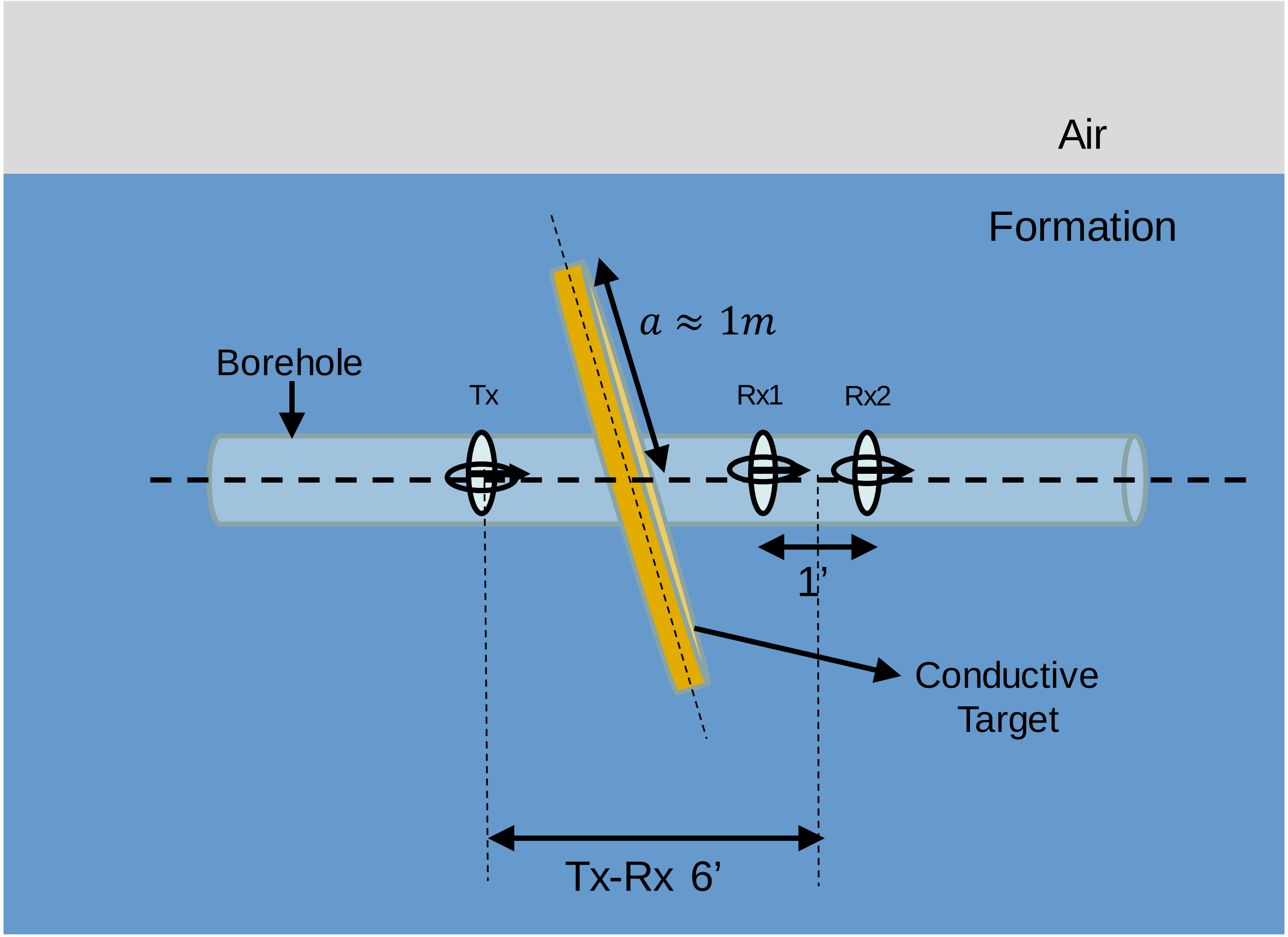
Requirements:

- *Magnetic dipole moment:* Preferably at least $N*S*I$ = 150 Am^2
- *Three receivers:* short (6'), intermediate (20'), long Tx-Rx spacing (60')

Constraints:

- *Wellbore Size Limitation:* diameter of the coil is restricted to 4"
- *Thickness of Wire used in transmitter and receiver*
- *Eccentricity:* misalignment of receiver axis with respect to transmitter axis can result in errors due to different signal level in different configurations
- *Target Frequency:* Larger fractures require lower frequencies.

Proposed Experiment



Proposed Experiment

Not necessarily large size low conductivity target, **induction number** can be kept constant for fracture

$$\delta = \sigma\mu\omega l^2$$

σ: conductivity of target
μ: electric permeability
ω: angular frequency
l: length of target

$$T_x - R_x = 6 \text{ ft}$$

$$r_{Rx2} - r_{Rx2} = 1 \text{ ft}$$

$$N = 60$$

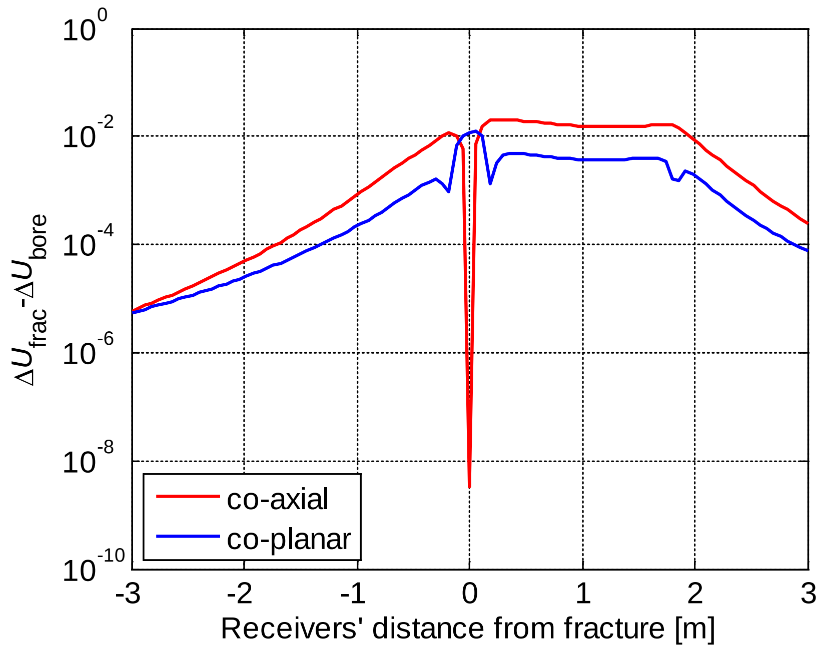
$$A = \pi \cdot 0.06^2 \text{ m}^2$$

$$f = 100 \text{ Hz}$$

$$m = 150 \text{ Am}^2$$

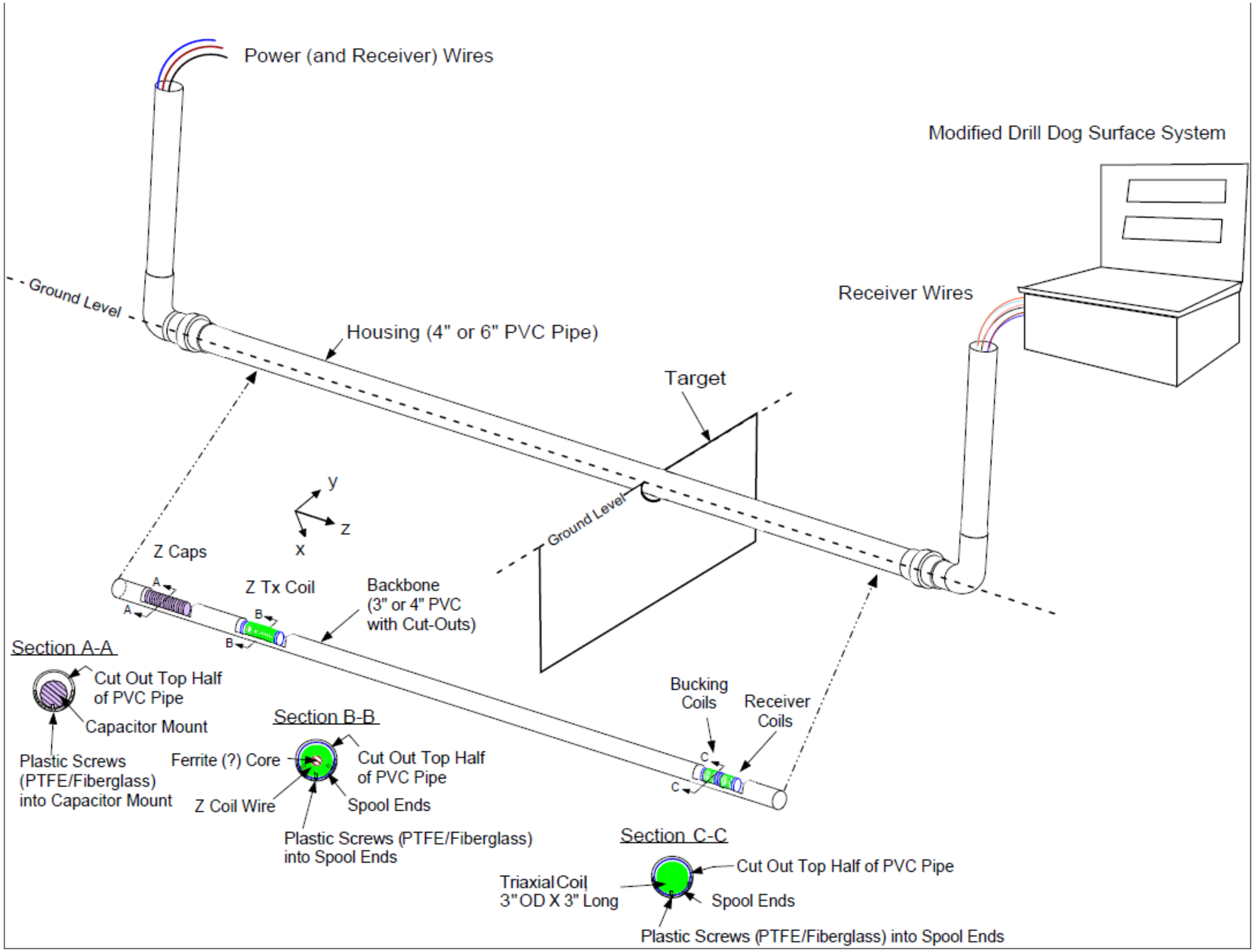
$$\rho_{target} = 10^{-7}\ \Omega\text{m}$$

$$\rho_{background} = 3\ \Omega\text{m}$$

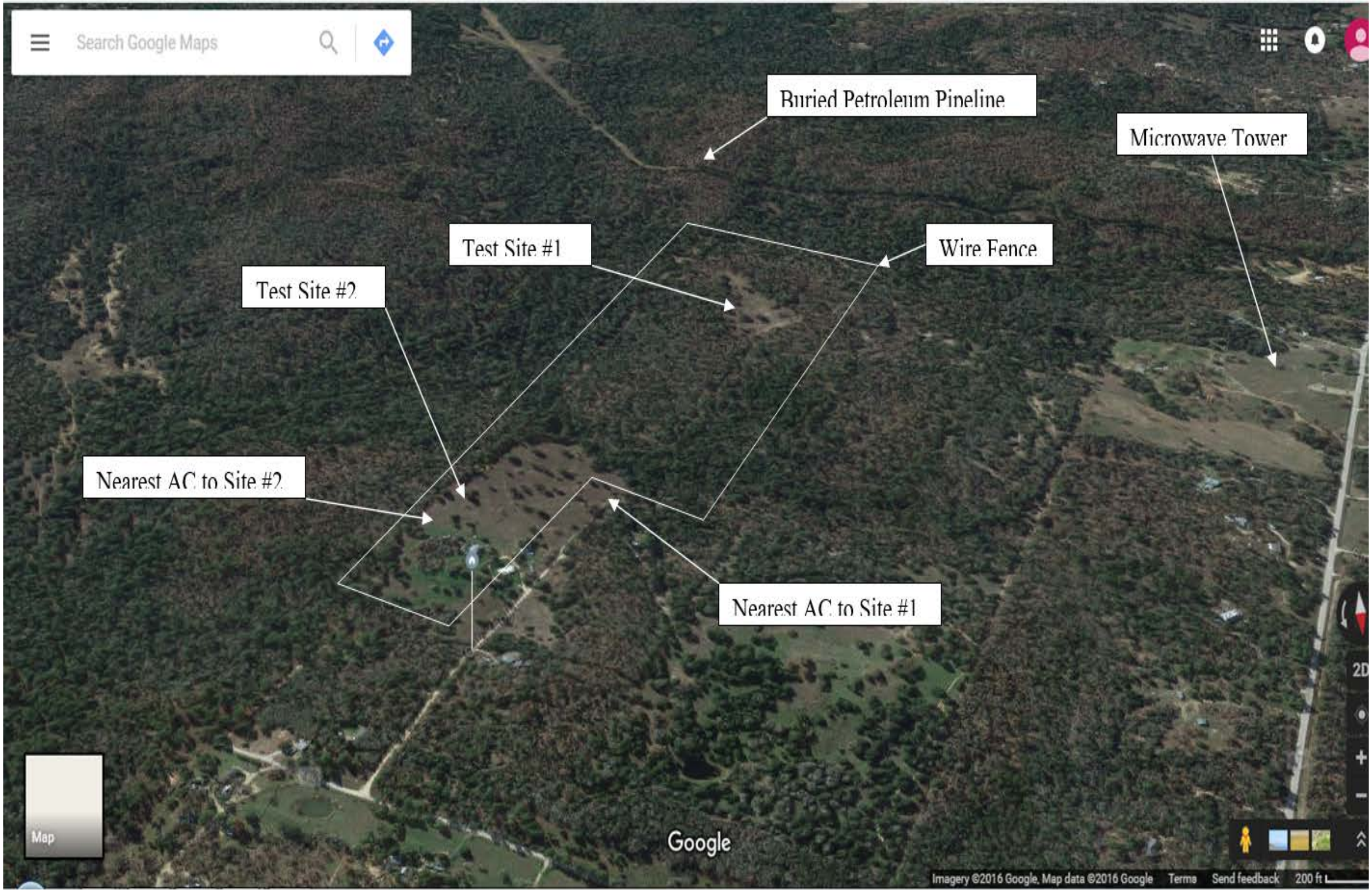


Detectable signal level is ~*10 μV*

Induction Coil Shallow Earth Test



Field Test Facility:



Transmitter and Receiver

Tri Axial Receiver Coils

Mono Axis Transmitter Coil

Modified Drill Dog Surface System

Key components:

- Electronics for driving the transmitter
- Novel electronics and software for high resolution signal processing

Conclusion

- A new numerically efficient simulator was built to solve Maxwell's equations in 3-D.
- Simulations were conducted to show that induction measurements can be used to detect electrically conductive proppant in fractures.
- For these highly conductive targets, measurements are expected to be sensitive to all target parameters, i.e. fracture location, propped fracture area, length and orientation.
- A Field Deployable Prototype Tool is being built.
- A shallow earth experiment is being planned to test the prototype tool.

Thank DOE for funding the project

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