CSEM for Geohazard Identification

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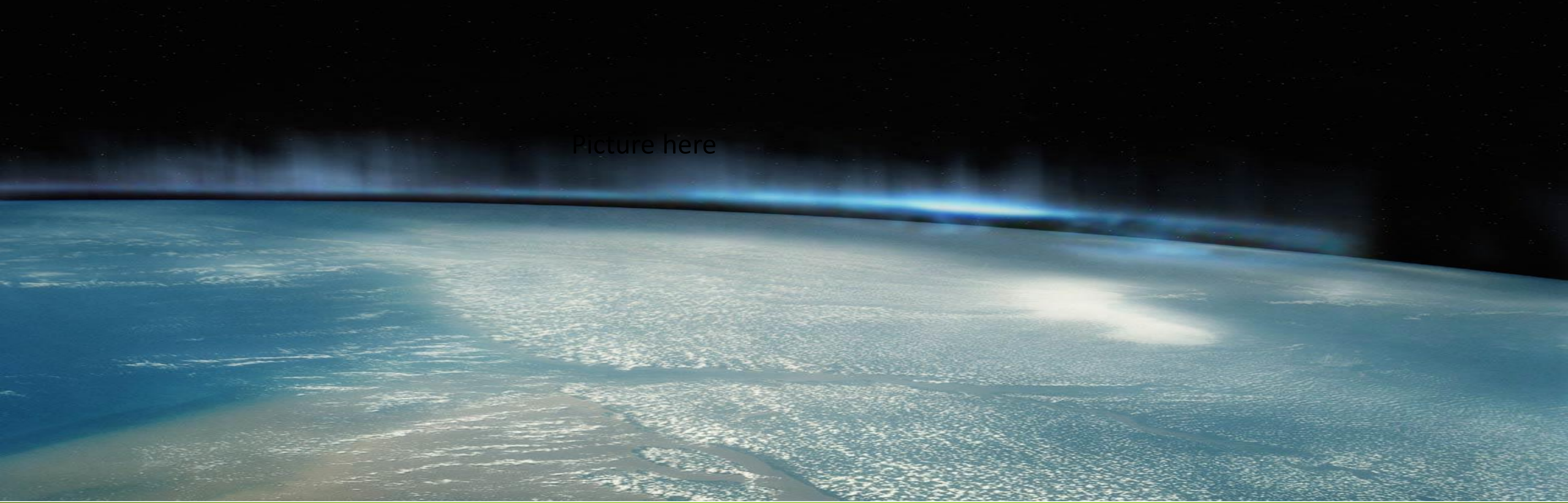
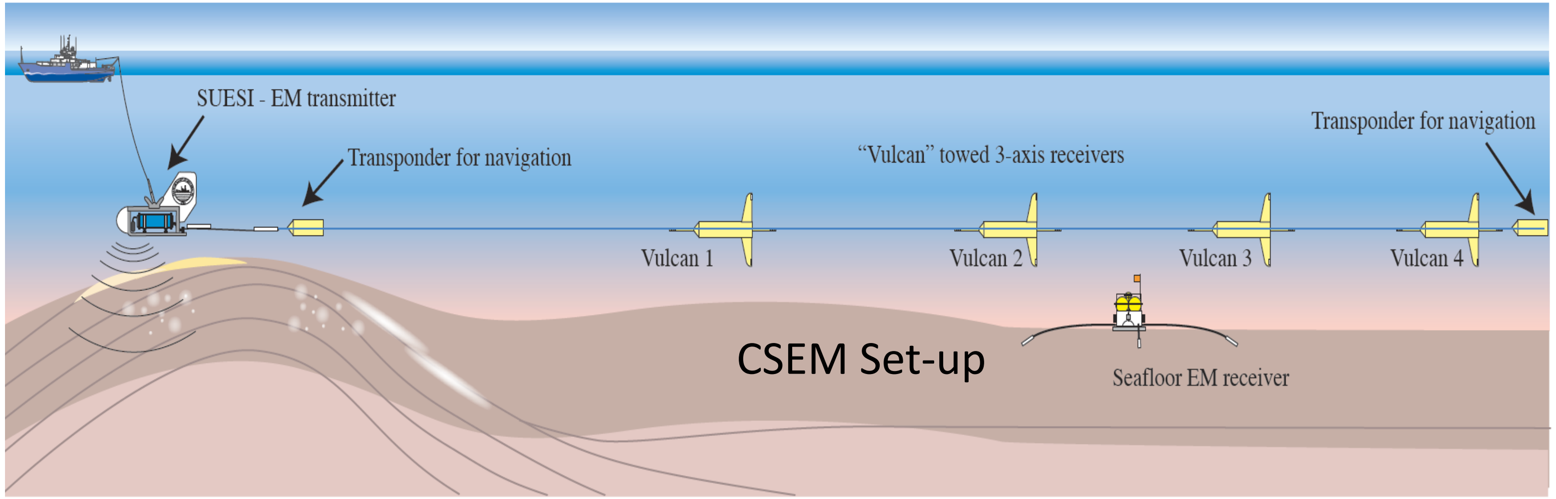


Introduction

CSEM for Geohazard ID

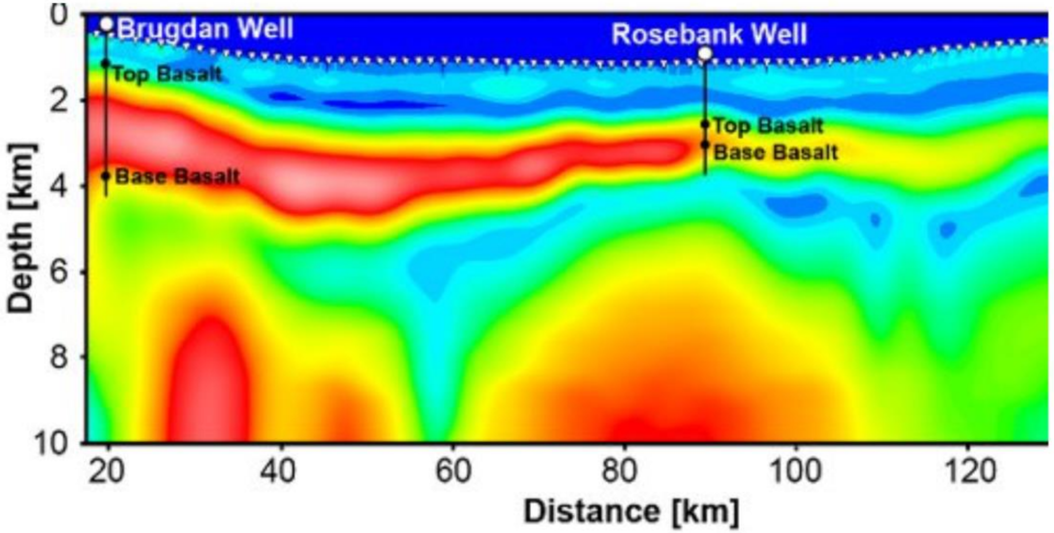
- Controlled source electromagnetic (CSEM) imaging
  1. Use time varying and DC supplied EM power
  2. Use array of electric and magnetic field vector sensors
  3. Invert data to determine subsurface impedances
  4. Interpret data to locate features of interest (e.g. hydrocarbon)



- CSEM can distinguish between electrically conductive fluids (e.g. brine) and resistive fluids (e.g. oil)

- Works well in salt and basalt settings

- MT + CSEM with same equipment
  - CSEM better for resistive, MT for conductive

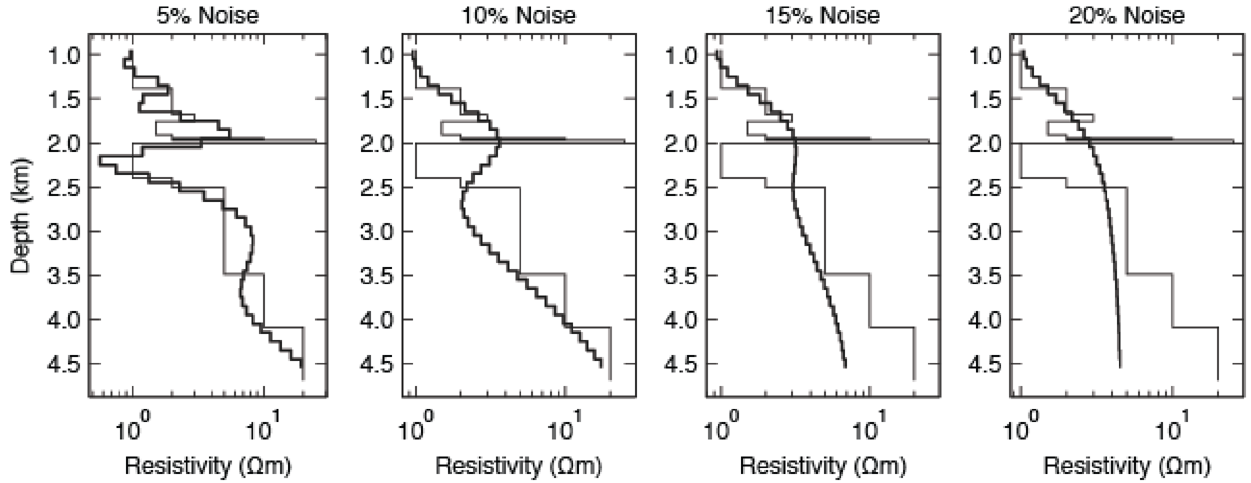


Market and Benefit

Offshore CSEM/MT

- Applications
  - Exploration mapping tool
  - De-risking tool
- CSEM/MT different data then seismic
  - Increasing market impact; importance of seal + charge in exploration
- Can be used in conjunction with seismic survey
- CSEM imaging is limited by the signal to noise (S/N) ratio.
  - Better S/N ratio = Improved feature detection
- Improved CSEM S/N ratio needed for deep exploration

	Trap	Reservoir	Charge	Seal	Volume
2D Seismic	+	+	+		
3D Seismic	+	+	+		+
CSEM			+	+	+



Project Objectives & Background

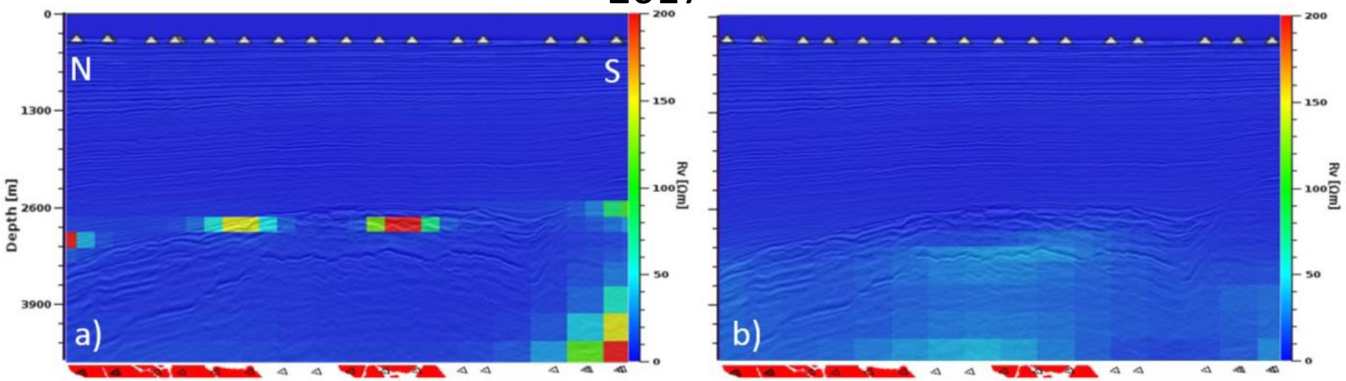
Improving CSEM for Geohazard ID

- Project Goal: Develop a technological leap in CSEM imaging resolution (>10x improvement)

- Project Objectives
  - Review, analyze and assess current CSEM S/N and performance
  - Scope and design new MHD based power supply approach for CSEM
  - Quantify improved S/N performance benefits to CSEM and geohazard ID

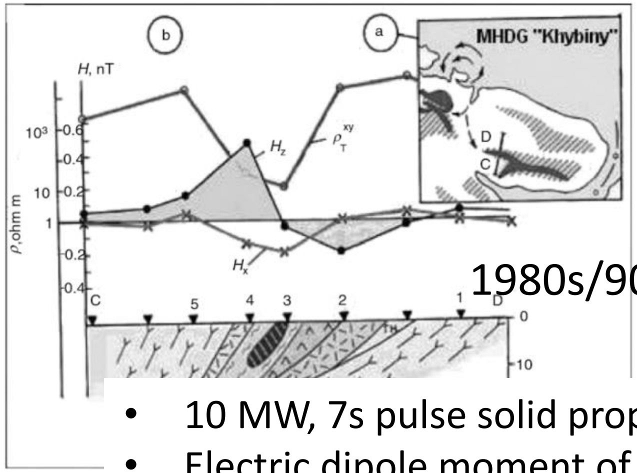
- Background
  - Higher power CSEM shows benefits
  - MHD generators used before for on-shore CSEM imaging

2017



Resistivity with a dipole source of 2.5 *10^6 Am

Resistivity with a dipole source of 3.5 *10^5 Am



1980s/90s

- 10 MW, 7s pulse solid propellent MHD system built on truck
- Electric dipole moment of 1.2 * 10^8 A-m achieved

Top Picture Source: Hanssen et.al. 2017; Bottom: Active Geophysical Monitoring

CSEM signal to noise ratio analysis

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Analysis

- Marine CSEM has electronic noises (electrodes and amplifier), environmental noises (motion of seawater/instrument sensors), and uncertainties of transmitter/receiver location.
- Except for positional uncertainties, the noise sources are decreased by "stacking" recorded time series and/or by increasing a dipole moment.
- Stacking is not effective as higher dipole source as it decreases noise by $1/\sqrt{n}$ when the number of data is stacked n times.
- If a dipole moment of the order of 10^5 kAm were generated, the noise floor would be 7.7 x 10^{-19} V/Am2. To achieve the same S/N ratio by the state-of-the-art transmitter, a survey ship need to go through survey lines more than 700 times to decrease by stacking

	Dipole moment [kAm]
EMGS dipole	3,600
Proposed MHD based dipole	10^5

~27x Improvement

Power Generation Options

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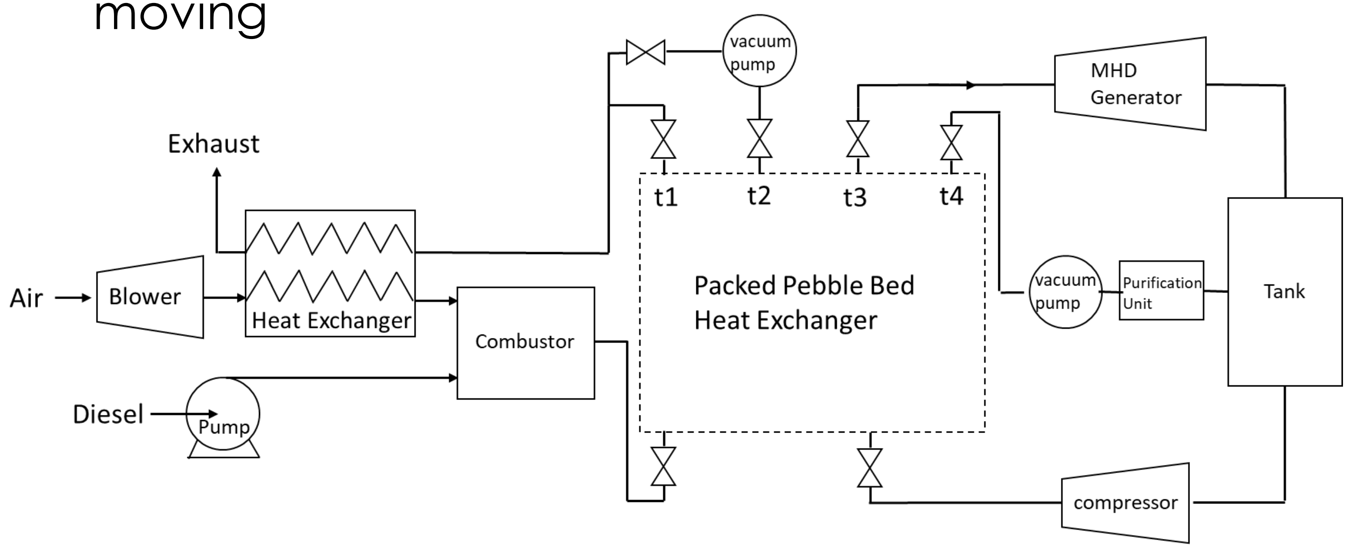
MHD Power Advantages

- OCMHD (e.g. Russian Sakhalin Generator) approach has shown low efficiency and longevity at target size (10MWe)
- CCMHD more efficient at smaller scale, and no rocket exhaust containing alkali elements
- Conceptual design for an CCMHD MHD power source and powering scheme pursued

- $10MW_e$ Power Output
- Diesel powered air combustion w/regenerative heating
- MHD Generator is on board ship, replaces diesel generator
- Rectify for ~100,000 Amps and ~100 Volt pulse in underwater EM transmitter
- ~ 2-minute duty cycle with 10s pulse
- Eliminates need for "pulse stacking" while ship is moving



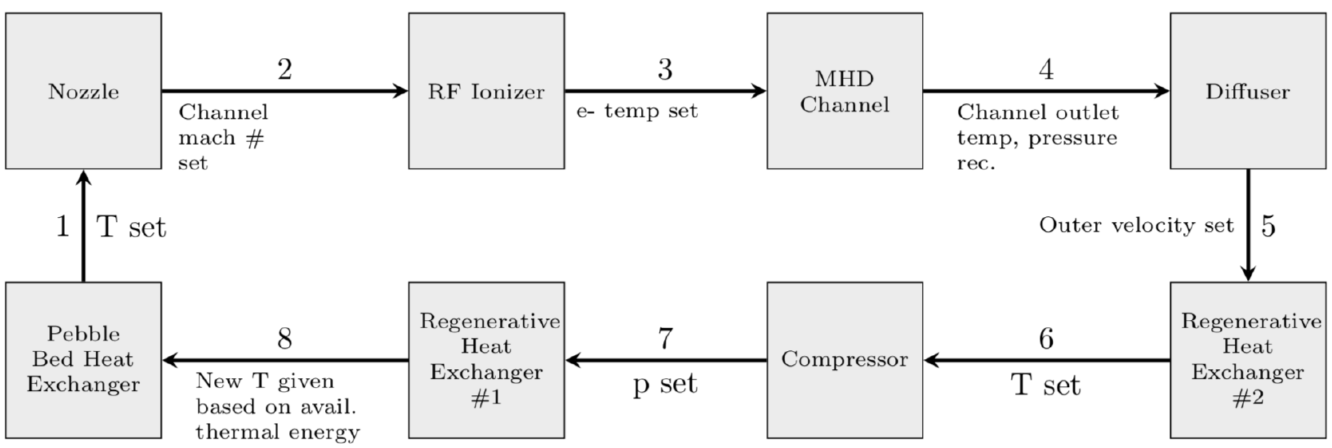
MHD performance analysis

The set-up

CCMHD Power generator

- Uses a noble gas
- Uses a RF pre-ionizer

- Energy storage in packed pebble bed when not generating electrical power
- Integrated Heat Exchangers with Compressor
- Compressor gets loop running prior to electrical power generation



Block flow diagram (MHD power loop shown) for newly developed closed cycle MHD code to predict and optimize power generation

Conservation Equations

Mass	$\frac{d}{dx}(\rho u A) = 0$
Species	$\rho u \frac{dY_k}{dx} = R_k W_k$
Momentum	$\rho u \frac{du}{dx} + \frac{dP}{dx} = F_{EM} - F_{friction}$
Energy	$\rho u \left(u \frac{du}{dx} + \frac{dh}{dx} \right) = P_{EM} - Q_{wall}$
Lorenz	$F_{EM} = J_y B_z$
EM power	$P_{EM} = J_y E_y + J_x E_x$

Generalized Ohm's Law

$$J_x = \frac{\sigma}{1+\beta_H^2}\left[E_x - \beta_H\left(E_y - uB_z\right)\right]$$

$$J_y = \frac{\sigma}{1+\beta_H^2}\left[\beta_H E_x + E_y - uB_z\right]$$

Electrode configuration (Faraday Shown)

$J_x = 0$

$E_y = K_L u B_z$

$E_x = -\beta_H u B_z (1-K)$

$J_y = -\sigma u B_z (1-K)$

MHD performance analysis

Results

- Computationally optimized the performance of the proposed system
  - ~2.8 gallons diesel per needed per 10MW_e 10s pulse (@ full power)
  - Power cycle efficiency can be ~30%
  - Approx. uses same energy input (fuel) as current CSEM systems, but ~27x improvement in CSEM from higher total power over 10s and no stacking.
- Identified Tech Challenges
  - RF ionizer efficiency
  - Possible Ion-slip in generator
  - Thermal management in cycle
  - Pebble bed losses
  - Antenna design
  - Power conditioning

Fixed Parameters	Value
T_nozzle	2200K
u	50 m/s
B_z_chan	6 T

Minimization Parameters	Value
p_nozzle	0.9 MPa
K_L_chan	0.5

Maximization Parameters	Value
E_rf	10000 V/m
E_chan	8500 V/m
M_chan	0.6 Mach
B_z_rf	0.7 T
mdot	10 kg/s

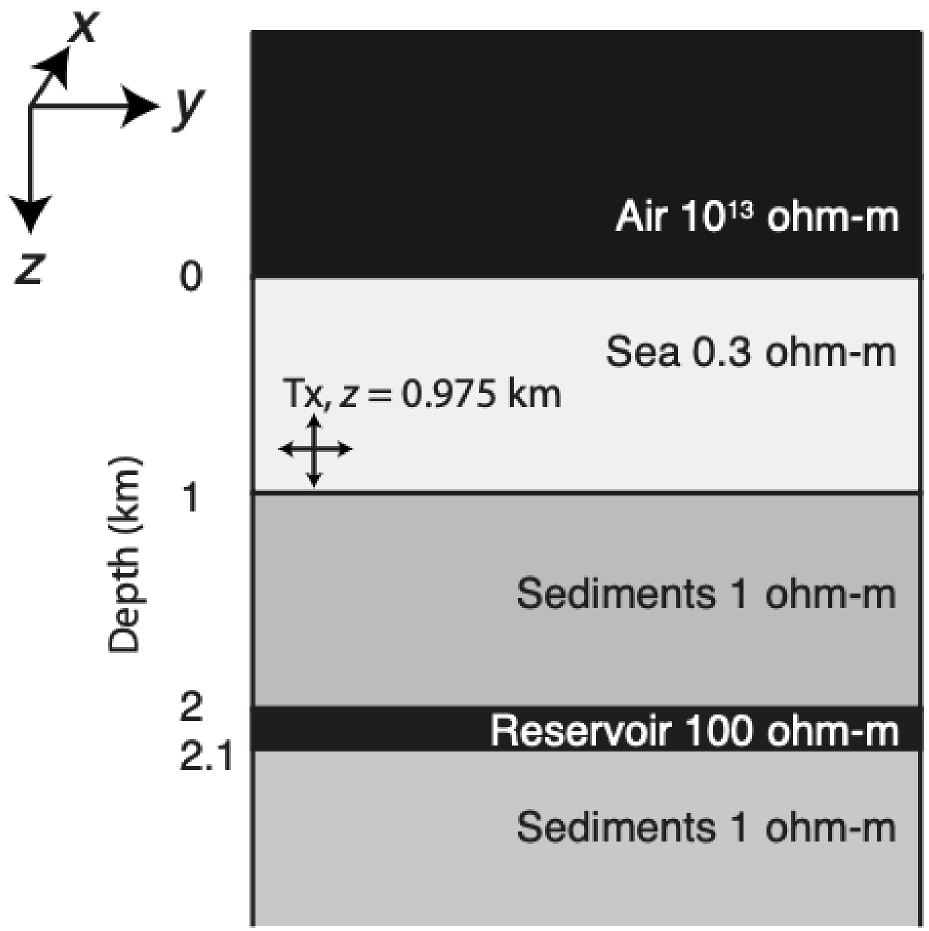
Simulated CSEM/MT Imaging

With MHD power supply

- Evaluated CSEM performance with simulated sub-surface
- Reconstructed 2D images and explored impacts of reservoir detection at various depths
  - Ey-transmitter and Ey-receiver (inline component).
  - Tx-Rx offsets are from 0.05km to 20km.
  - Changed depth of reservoir from 2-5km.
  - 2% noise relative to the response amplitude and generated separately for real and imaginary component.
  - A minimum absolute noise level was set to 10^{-15} V/Am^2 for the traditional source and 10^{-17} for the MHD source.

$$\nabla^2 E = \mu\sigma \frac{\partial E}{\partial t}$$

- Low freq, quasi-static
- solve in frequency domain

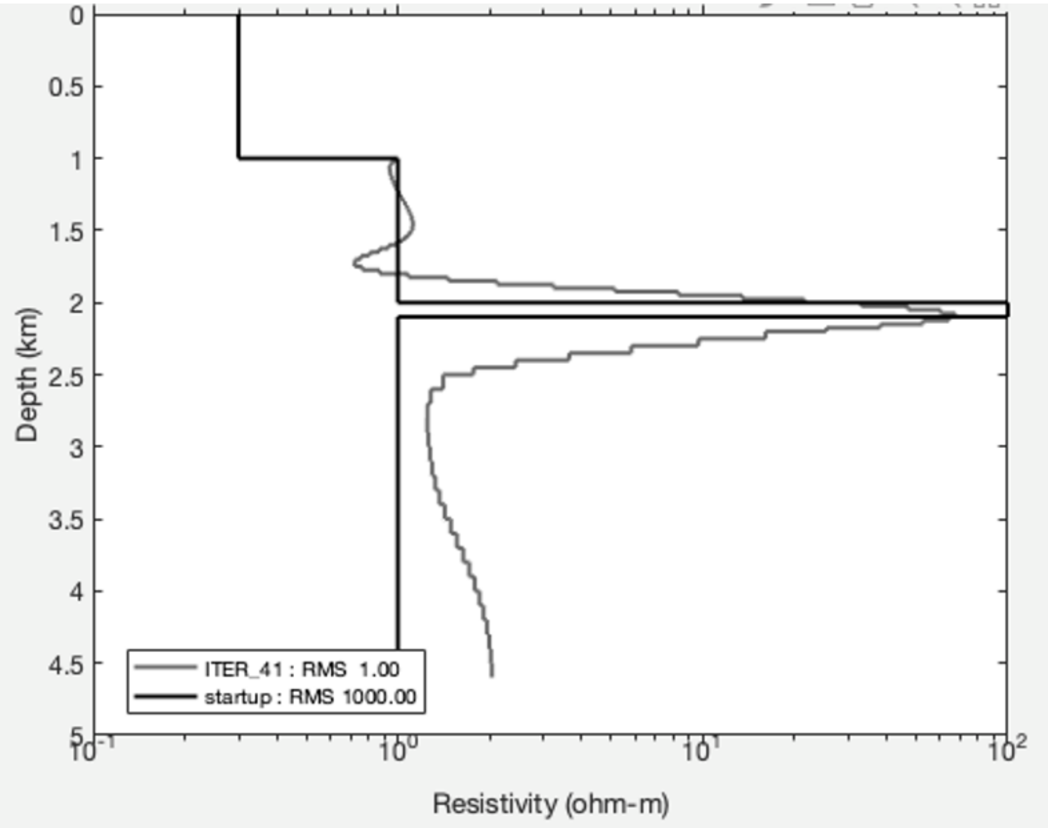


Simulated CSEM imaging results

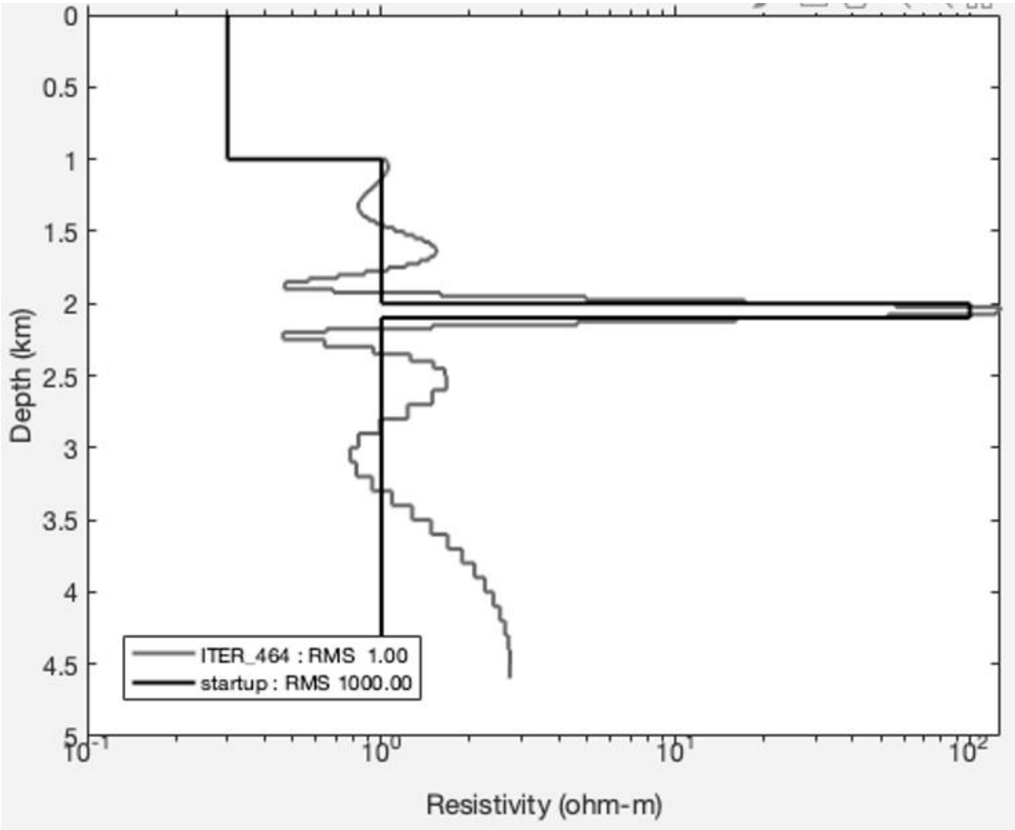
2 km depth

Used frequencies: 0.25, 1.0 [Hz]

Traditional CSEM source (10^{-15} V/Am^2)



MHD source (10^{-17} V/Am^2)



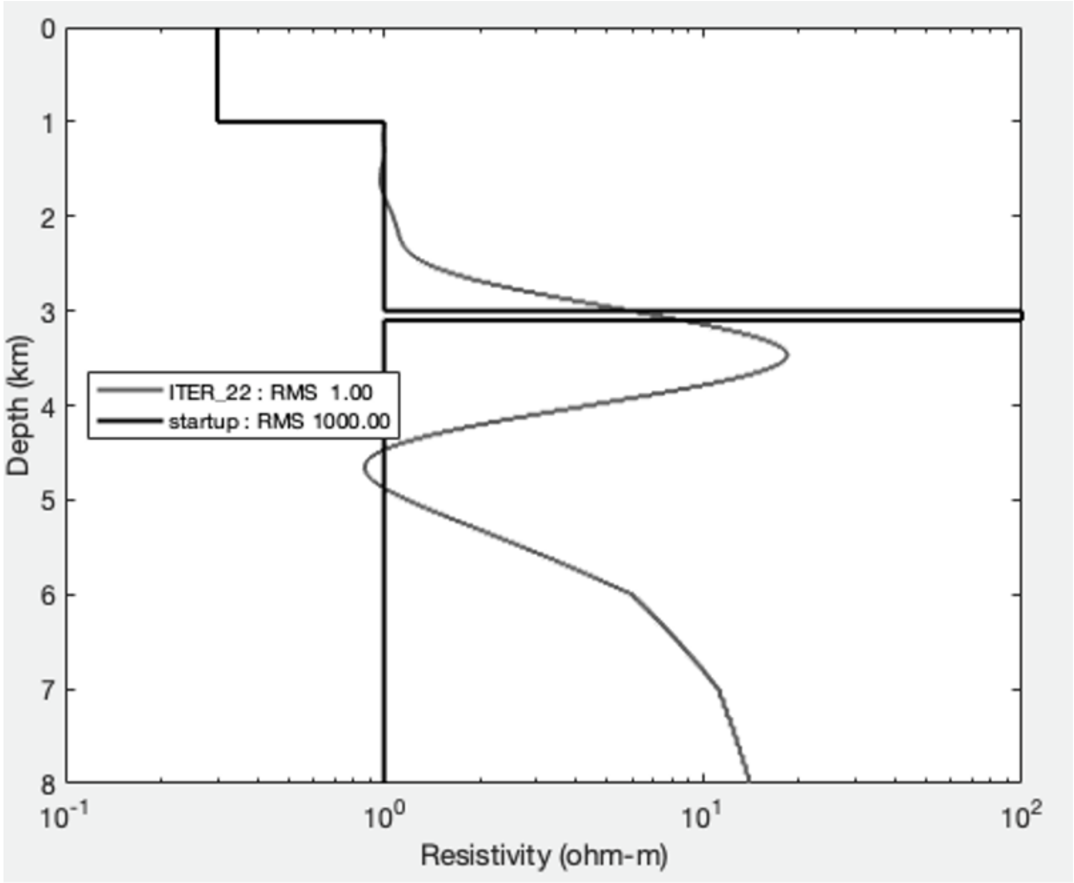
Reservoir detected in both cases

Simulated CSEM imaging results

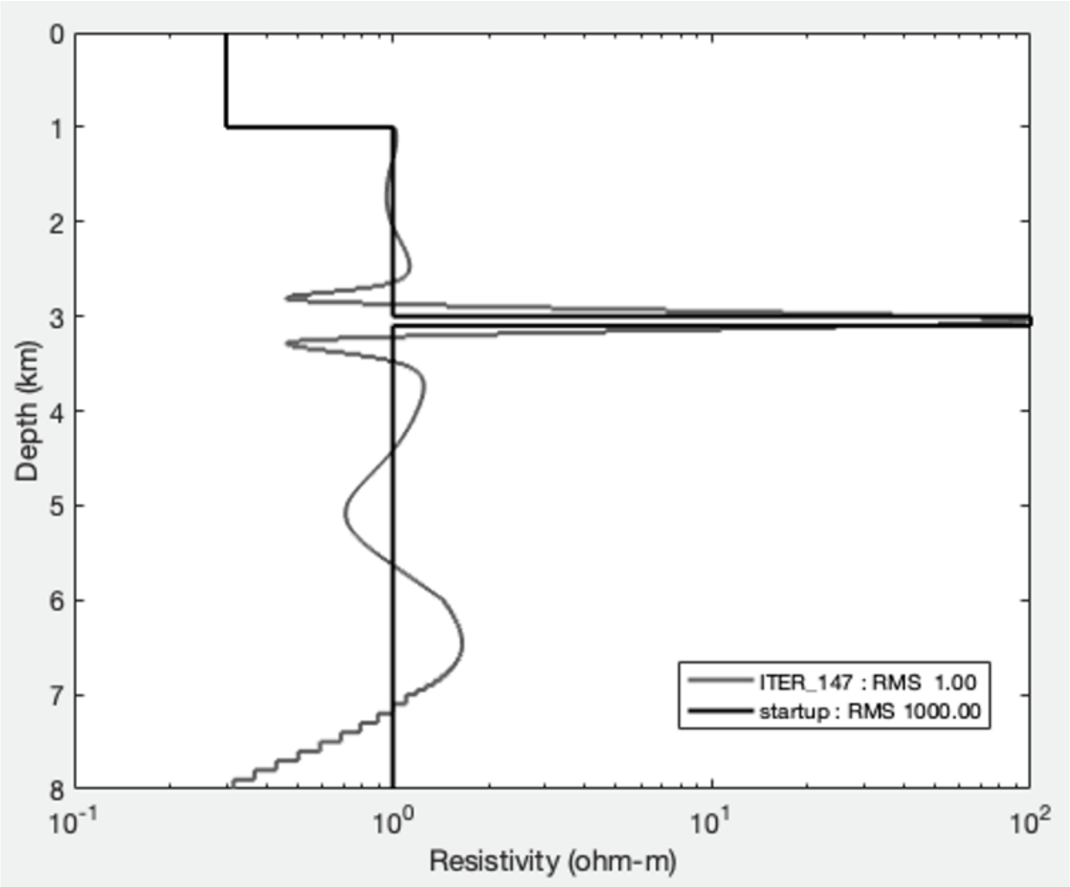
3 km depth

Used frequencies: 0.05, 0.25, 1.0 [Hz]

Traditional CSEM source (10^{-15} V/Am^2)



MHD source (10^{-17} V/Am^2)



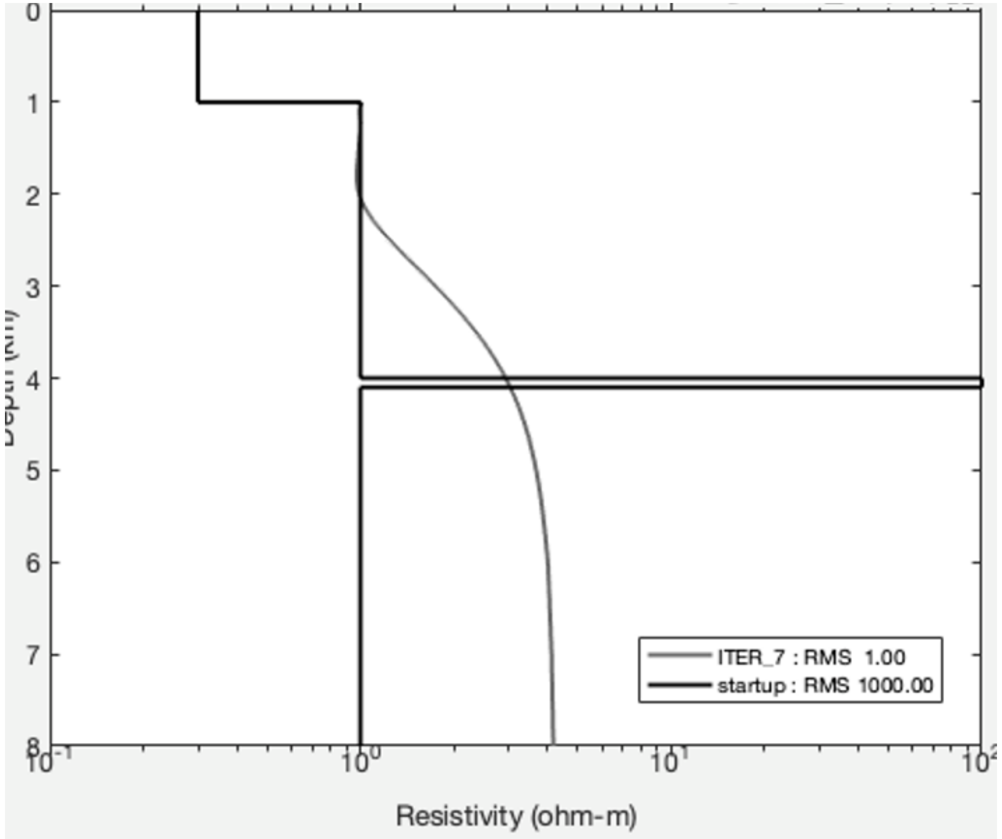
Unclear reservoir location detected with traditional source

Simulated CSEM imaging results

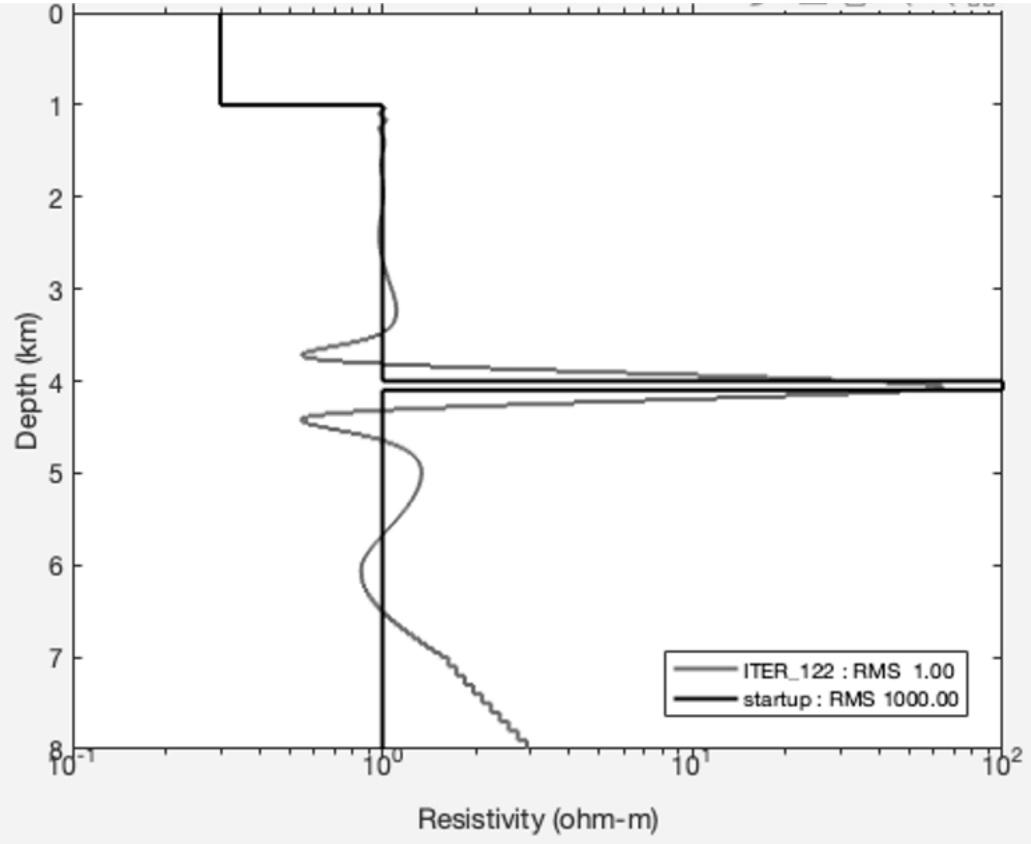
4 km depth

Used frequencies: 0.05, 0.25, 1.0 [Hz]

Traditional CSEM source (10^{-15} V/Am^2)



MHD source (10^{-17} V/Am^2)



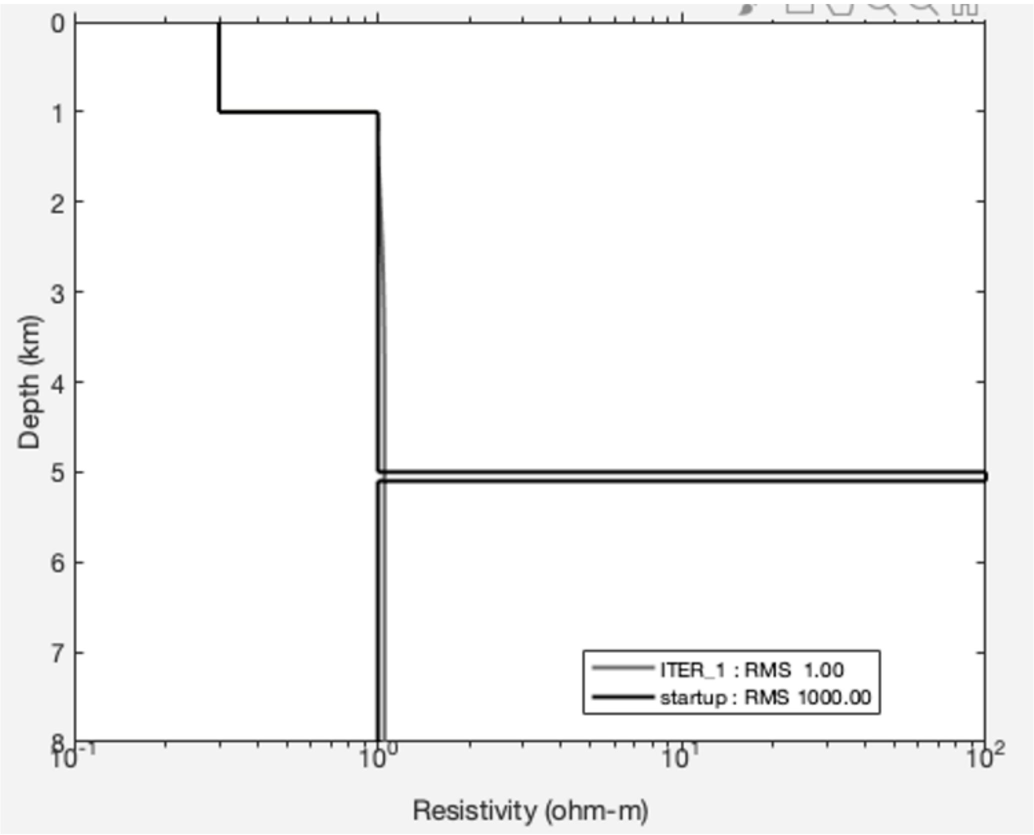
Location of reservoir not reliably detected with traditional source

Simulated CSEM imaging results

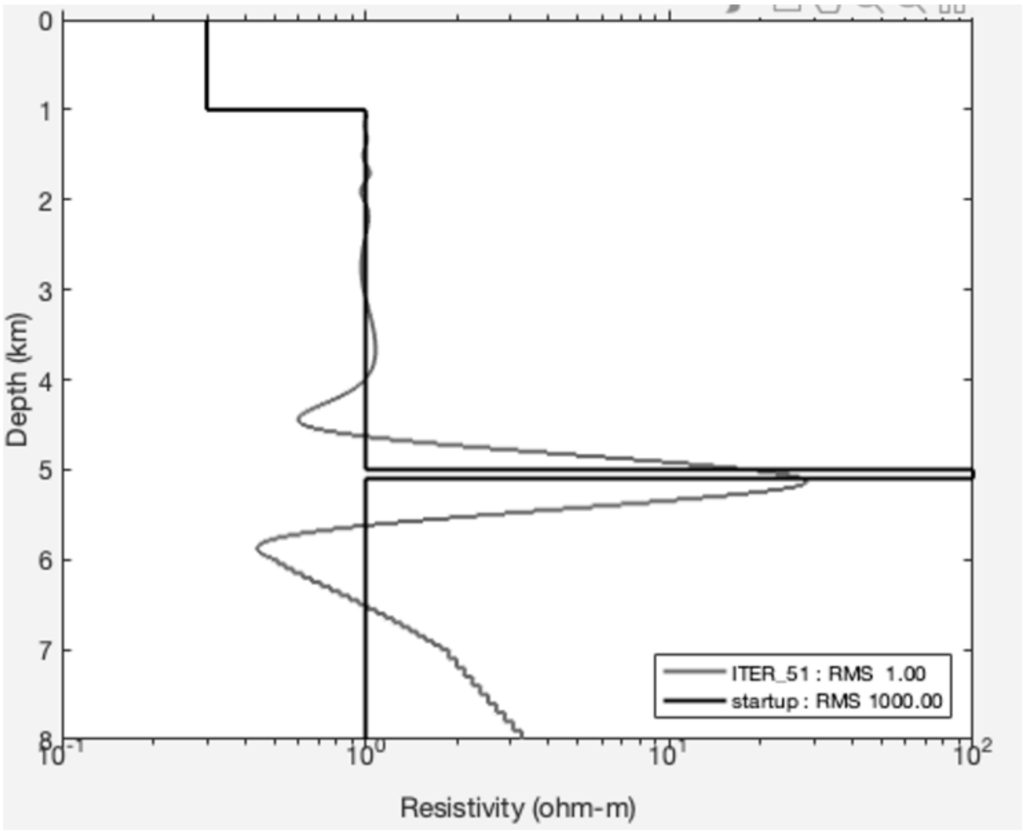
5 km depth

Used frequencies: 0.05, 0.25, 1.0 [Hz]

Traditional CSEM source (10^{-15} V/Am^2)



MHD source (10^{-17} V/Am^2)



Reservoir not detected with traditional source

MHD Generator Analysis

For potential "ion-slip" issue

- "Ion-slip" has been shown to be issue in "high interaction" CCMHD generators
  - β_e is electron Hall parameter, β_i is Ion Hall parameter
  - Added this to our MHD models
  - Engineering strategies needed to overcome losses/instability
- Mathematical analysis for existence and uniqueness of solutions shown
- Converted equations into format that can be solved using commercial EM software (COMSOL)
  - Solve ohm's law for electric current paths
  - What 3D impact does ion slip have on power extraction?
  - Major assumptions in model
    - Constant B field in one direction
    - Constant velocity (u) in one direction
  - Computational verification demonstrated for known case

Electrostatics: Maxwell + Ohm's law

$$\nabla \times \mathbf{E} = 0$$

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) + \frac{\beta_e}{||\mathbf{B}||}(\mathbf{J} \times \mathbf{B}) + \frac{\beta_i}{||\mathbf{B}||^2}((\mathbf{J} \times \mathbf{B}) \times \mathbf{B})$$

$$\nabla \cdot \mathbf{J} = 0$$

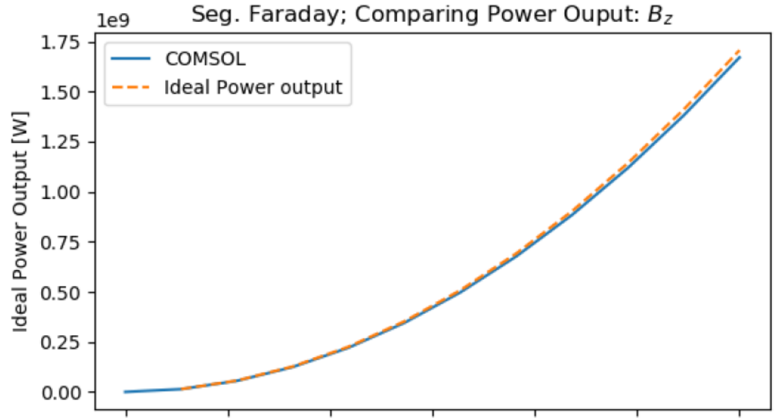
Computationally shown to reduce to the following for implementation using established solvers:

$$\mathbf{J}_i = \underline{\sigma}\mathbf{E} + \mathbf{J}_e$$

$$\mathbf{J}_e = \underline{\sigma}(\mathbf{u} \times \mathbf{B})$$

$$\mathbf{E} = \nabla \mathcal{V}$$

$$\underline{\sigma} = \sigma \frac{1}{1 - 2\beta_i + \beta_i^2 + \beta_e^2} \begin{bmatrix} 1-\beta_i & -\beta_e & 0 \\ \beta_e & 1-\beta_i & 0 \\ 0 & 0 & 1 - 2\beta_i + \beta_i^2 + \beta_e^2 \end{bmatrix}$$



Project Next Steps

Planned for Completion in EY2020

- MHD Power Generator Evaluation & Design
  - Perform parameter sweep of expected ion and electron Hall parameters
  - Assess impact of generator design with ion-slip
  - Update 1D performance evaluation & efficiency estimate with new info on loss mechanisms
  - Develop 3D CFD model of generator design
- CSEM
  - Simulate geohazards of interest with new S/N ratio
  - Investigate sensitivity to size and depth of geohazards

Conclusion

Thanks for your attention

- In CSEM, increasing S/N by reducing instrument noise has diminishing benefits due to background noise sources
  - Traditional CSEM uses signal “stacking” (averaging) to overcome
  - Improved positioning/position monitoring of detectors and antenna could have some benefits
- Increasing S/N by increasing signal level has shown significant benefits in the past
- Increasing signal could allow reduction or elimination of signal stacking
  - Significant improvement (~30x) possible with same fuel use when adopting a pulse power generator
- MHD power generators can achieve the desired dipole strength in compact system
- A CCMHD based pulse generator could have comparable efficiency to diesel generators
- CCMHD is not developed or proven in field use as a continuous cycle
  - Issues to overcome in design

Questions?

Acknowledgements

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