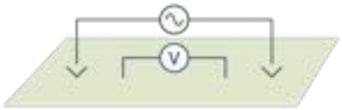
EM: Grounded Sources

DISC

2017

Electromagnetics
Fundamentals and Applications

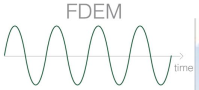


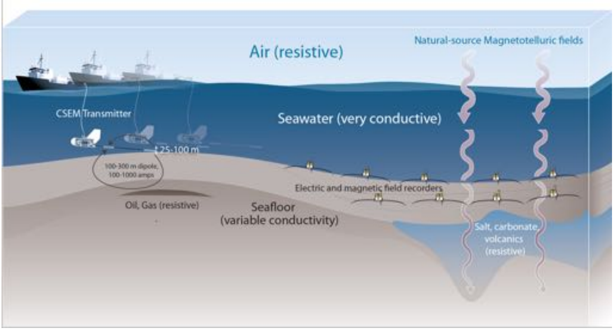
Outline

- Basic experiment
- FDEM: Electric dipole in a whole space
- TDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets: currents and data
- Resistive Targets: currents and data
- Case History: Barents Sea
- Synthetic Example: Gradient Array

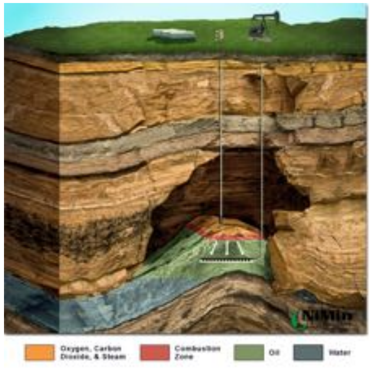
Motivational examples

Marine EM for hydrocarbon





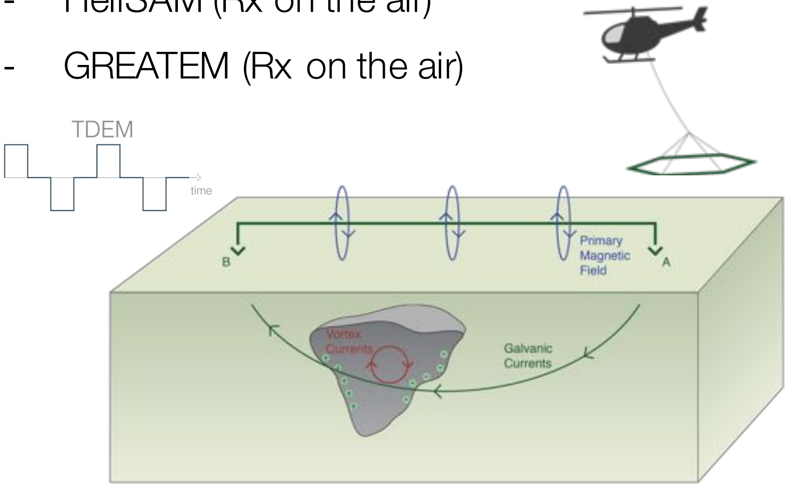
Oil and Gas (EOR)



Gas hydrates

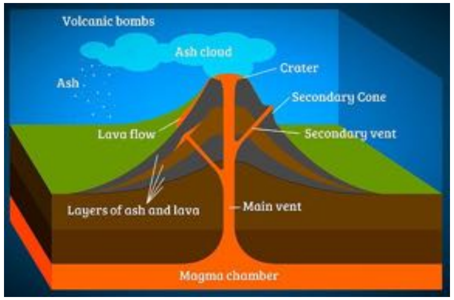
Galvanic source TEM

- LoTEM (ground)
- HeliSAM (Rx on the air)
- GREATEM (Rx on the air)

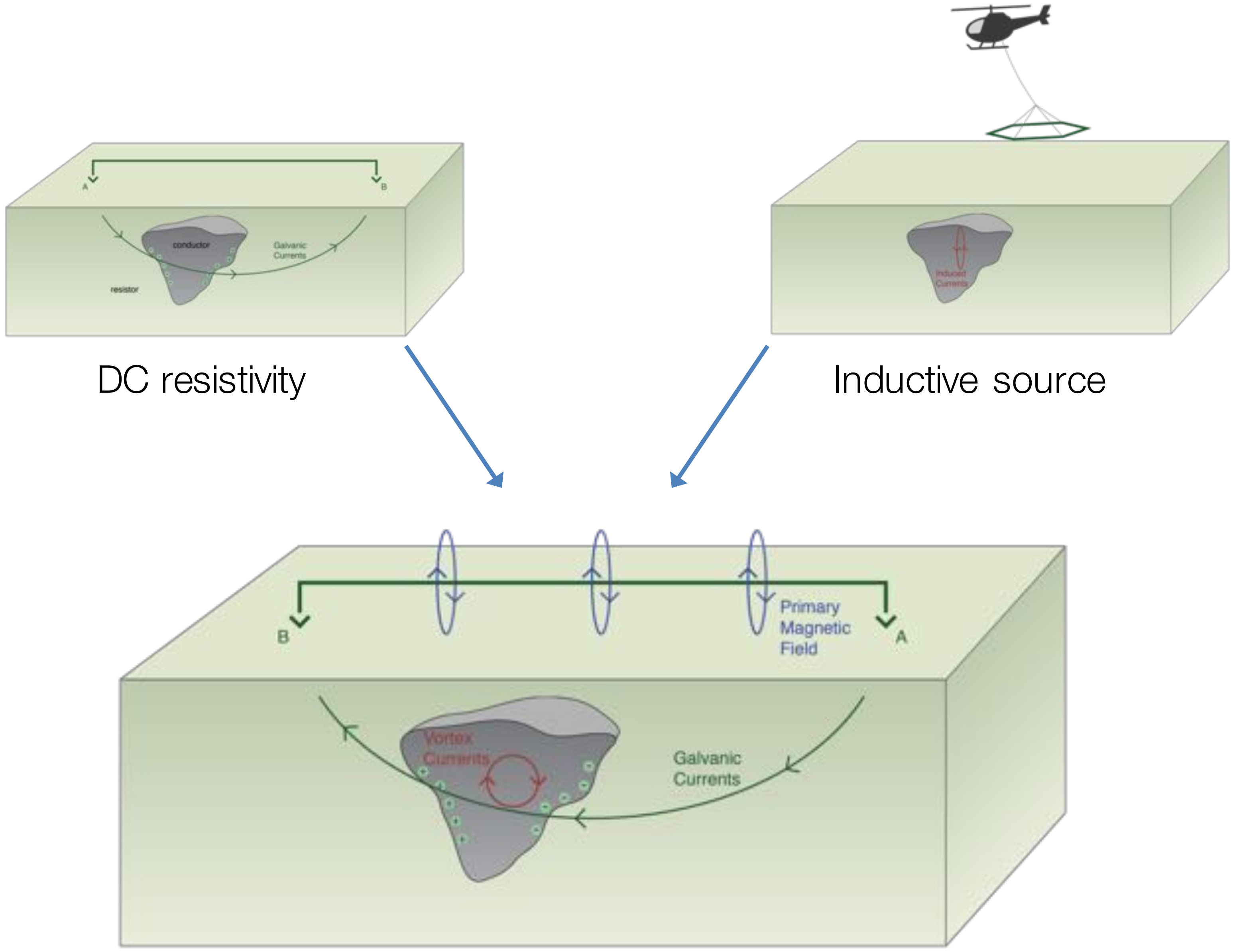


Minerals

Volcanoes



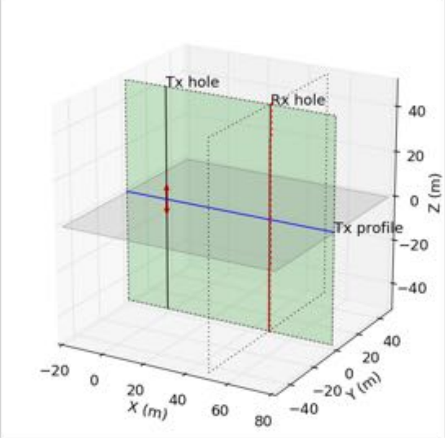
Basic experiment



DC resistivity

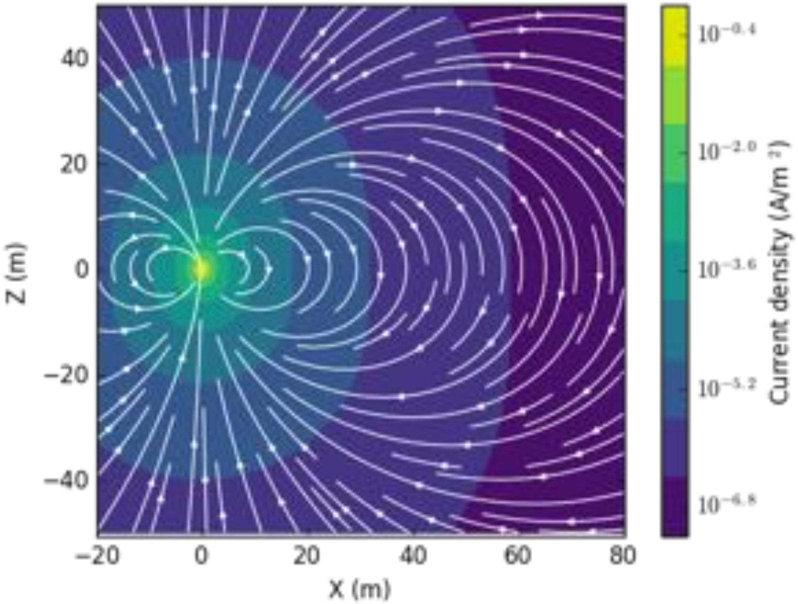
Inductive source

Electric Dipole in a whole space: FDEM



- Electric dipole in a whole space
  - 0 Hz (DC), 0.01 S/m

DC current density



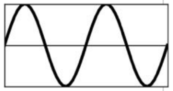
$$\mathbf{E}_{DC}(\mathbf{r}) = \frac{1}{4\pi\sigma|\mathbf{r}|^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m}\right)$$

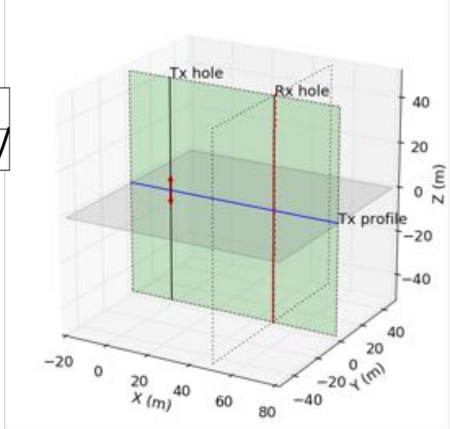
$$\mathbf{J}_{DC}(\mathbf{r}) = \frac{1}{4\pi|\mathbf{r}|^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m}\right)$$

- Geometric decay: $1/r^3$
- Current path is geometric for homogeneous earth, but electric field is dependent upon $\boldsymbol{\sigma}$

Electric Dipole in a whole space: FDEM

Skin depth: $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}.$

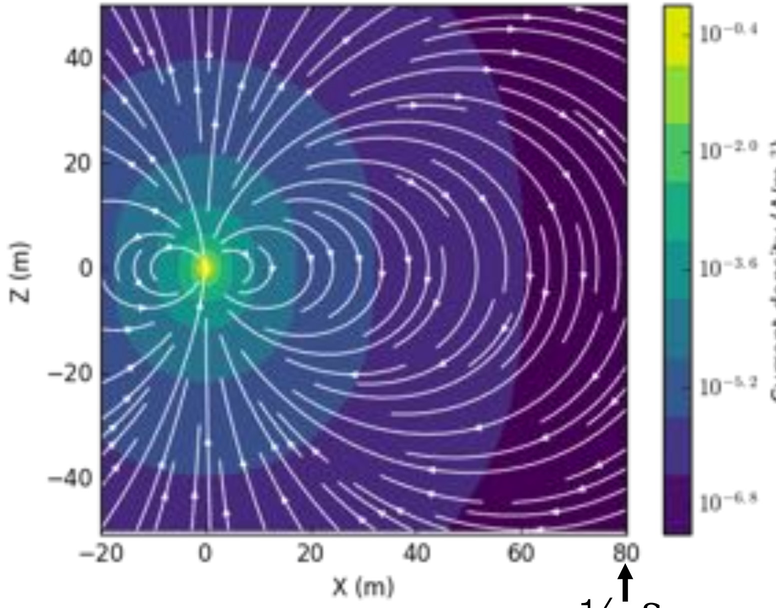


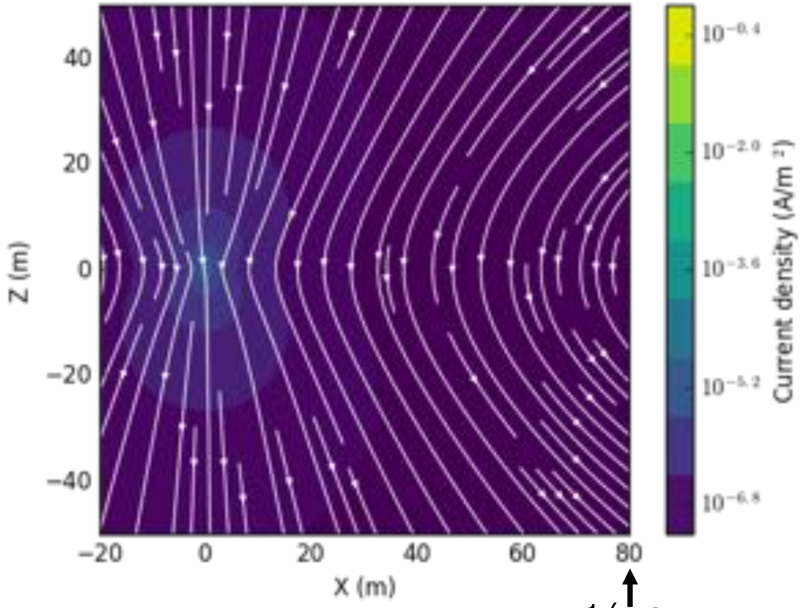


- Electric dipole in a whole space
  - 1000 Hz, 0.01 S/m, δ= 160 m

Current density (Real part)

Current density (Imaginary part)





½ δ

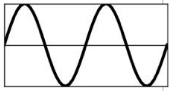
½ δ

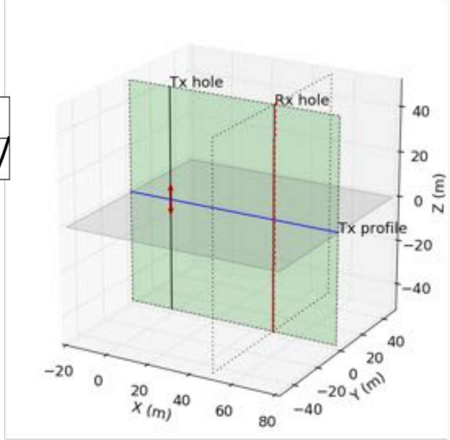
DC + EM induction

EM induction

Electric Dipole in a whole space: FDEM

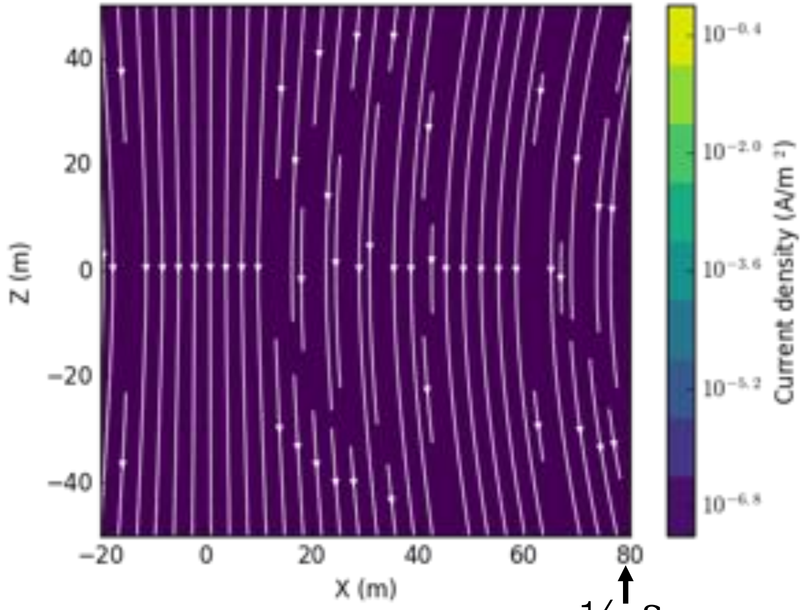
Skin depth: $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}.$





- Electric dipole in a whole space
  - 1 kHz, 0.01 S/m, δ= 160 m

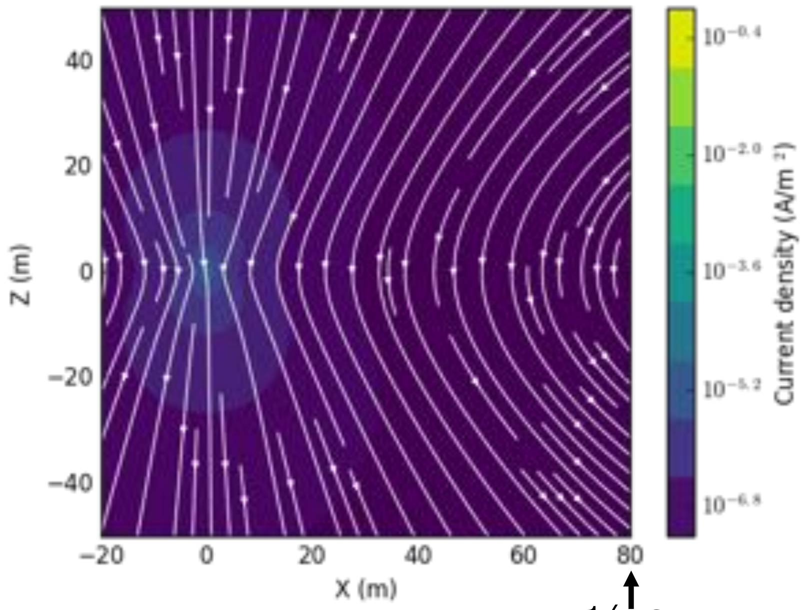
Remove DC part
Re (J) −J^{DC}



½ δ

EM induction

Im (J)

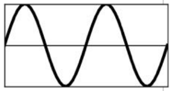


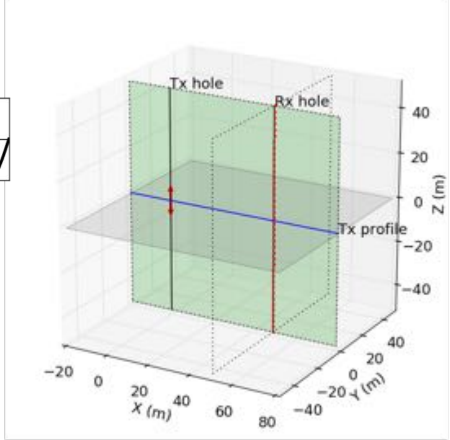
½ δ

EM induction

Electric Dipole in a whole space: FDEM

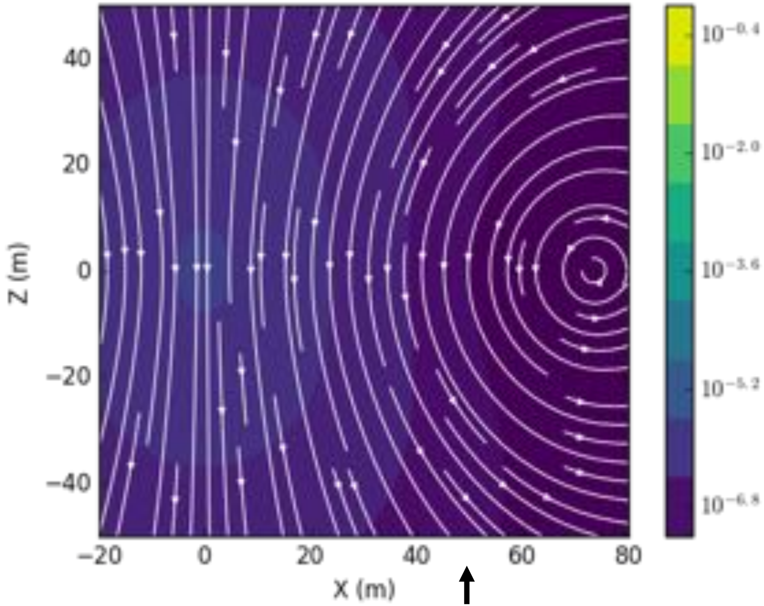
Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\mu\sigma}}.$





- Electric dipole in a whole space
  - 10 kHz, 0.01 S/m, δ= 50 m

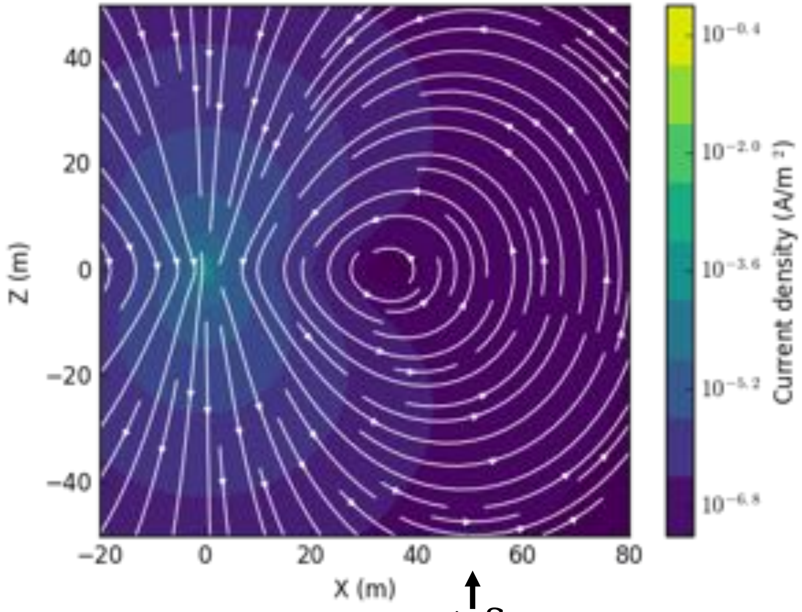
Re (J) –J^{DC}



1 δ

EM induction

Im (J)

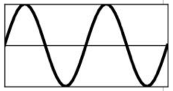


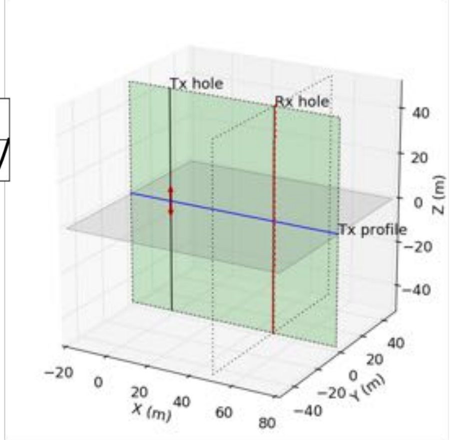
1 δ

EM induction

Electric Dipole in a whole space: FDEM

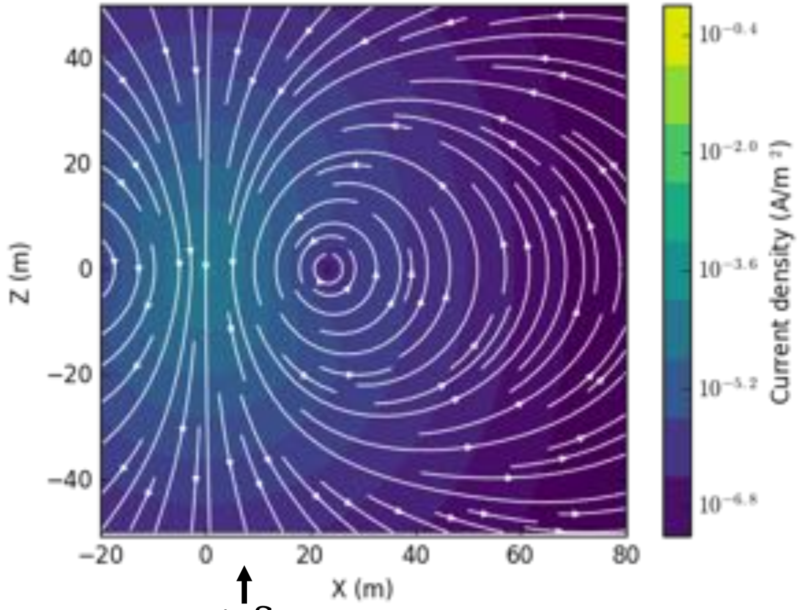
Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\mu\sigma}}.$





- Electric dipole in a whole space
  - 100 kHz, 0.01 S/m, δ= 16 m

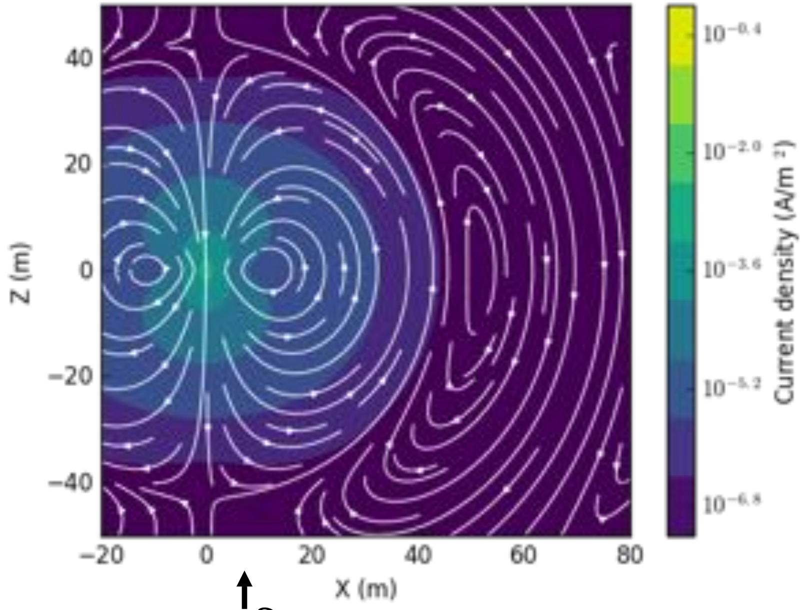
Re (J) –J^{DC}



1 δ

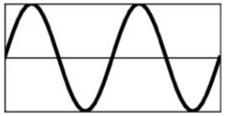
EM induction

Im (J)



1 δ

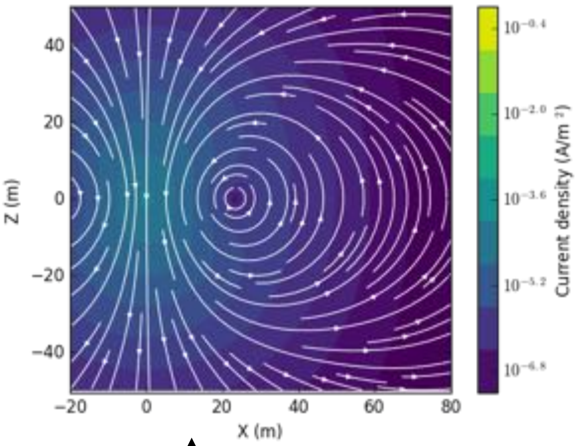
EM induction



Summary:
FDEM Electric Dipole in a whole space

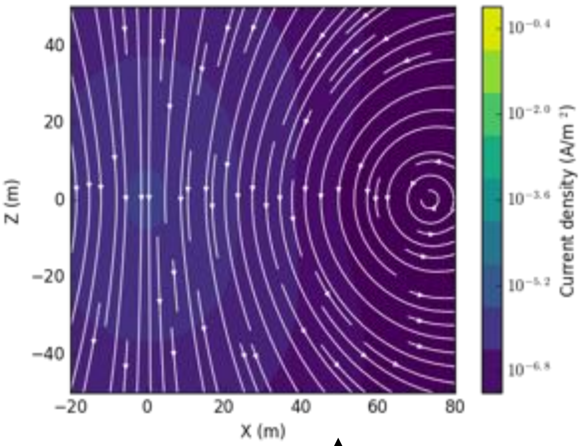
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Re ($\mathbf{J}$) $-\mathbf{J}^{DC}$



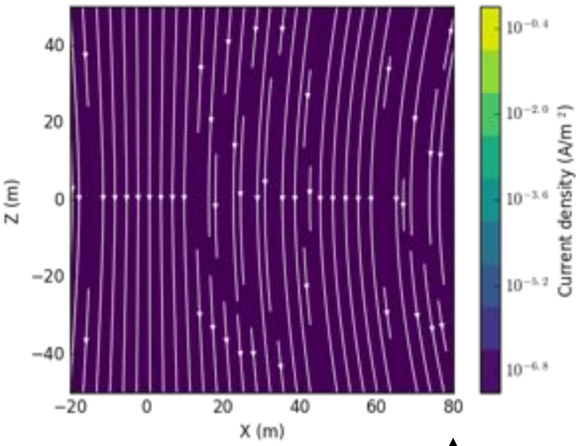
1 δ

100 kHz



1 δ

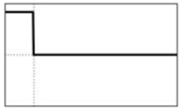
10 kHz



½ δ

1 kHz

In time…



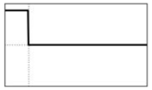
Electric Dipole in a whole space: TDEM

t=10^{-4} ms, $\mathbf{d}$ = 4 m

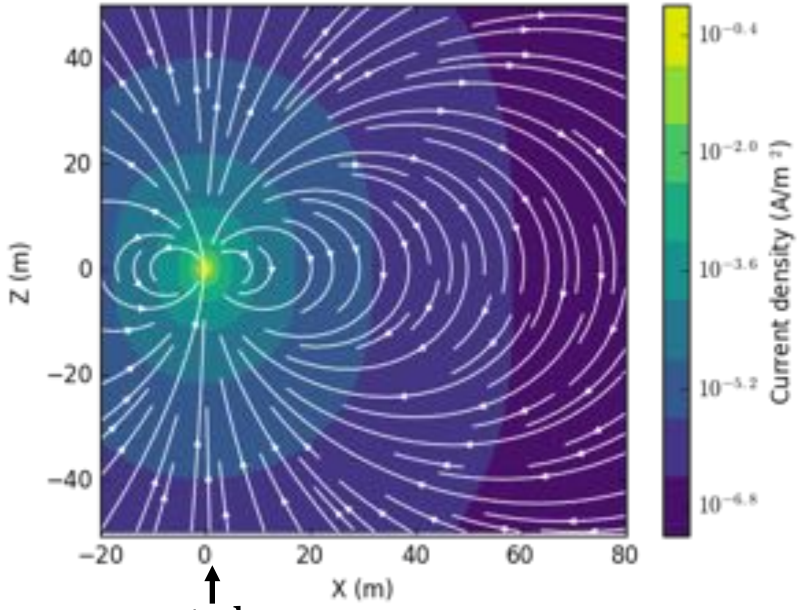
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

f=10^{4} kHz, δ = 2 m

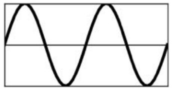
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



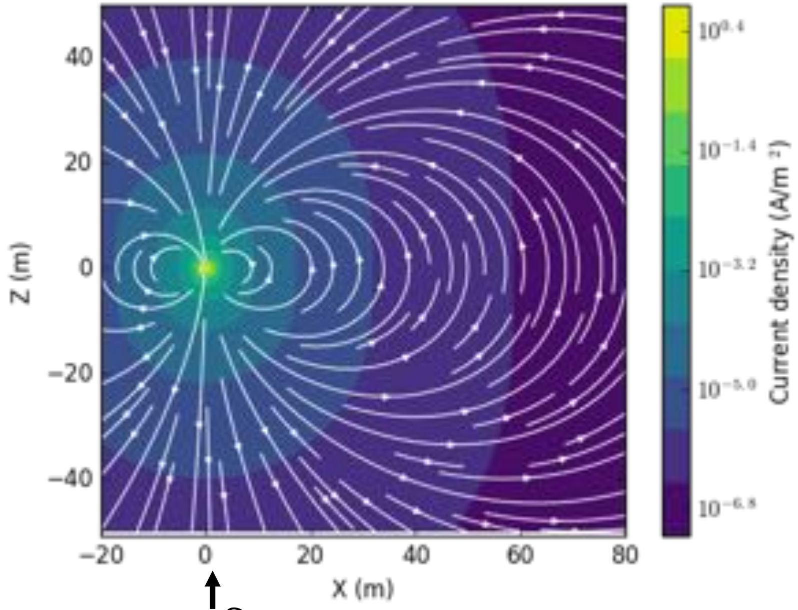
j



1 d



Re (J) – Re(J^{DC})



1 δ

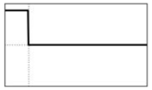
Electric Dipole in a whole space: TDEM

t=10^{-3} ms, $\mathbf{d}$ = 13 m

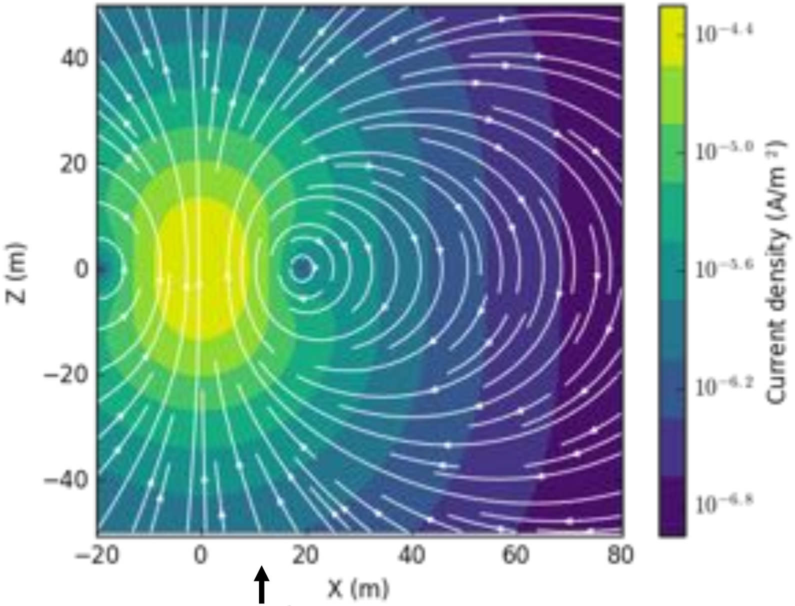
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

f=10^{3} kHz, δ = 5 m

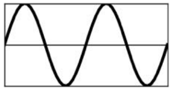
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



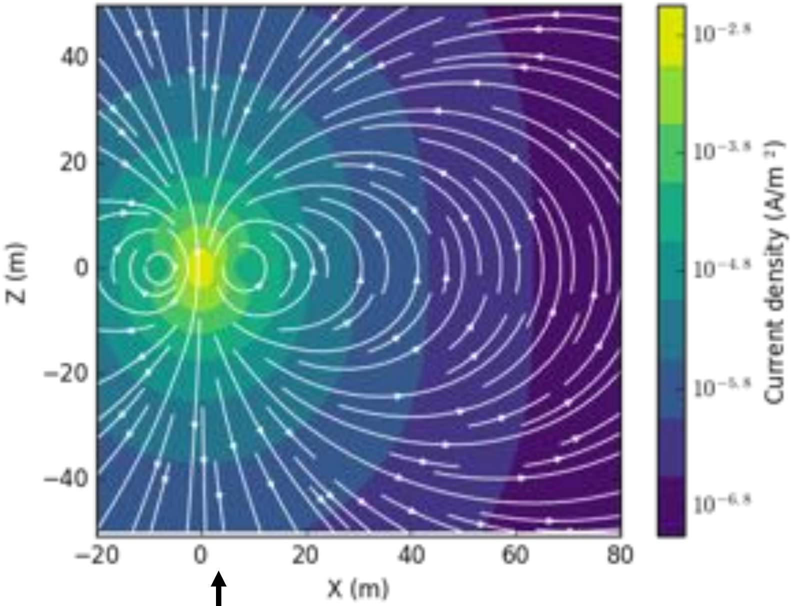
j



1 d



Re (J) – Re(J^{DC})

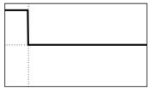


1 δ

Electric Dipole in a whole space: TDEM

t=10^{-2} ms, **d** = 40m

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$



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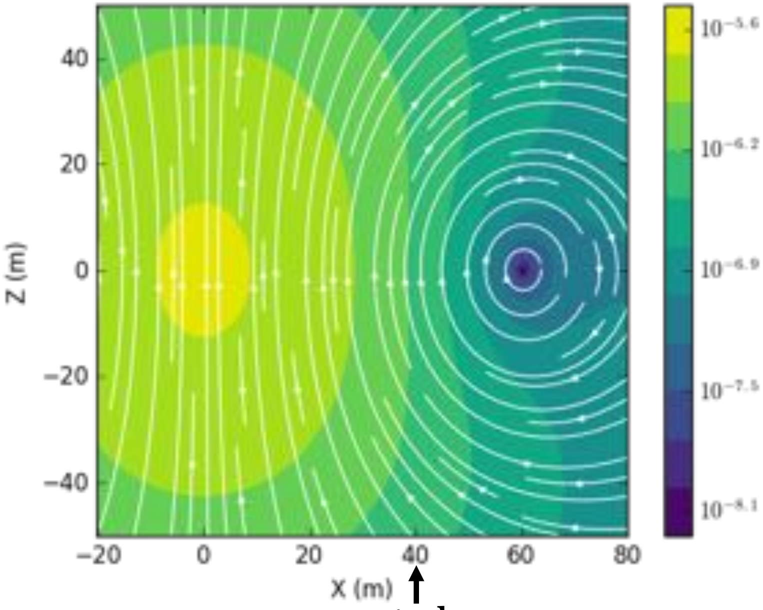
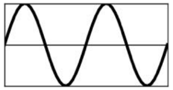


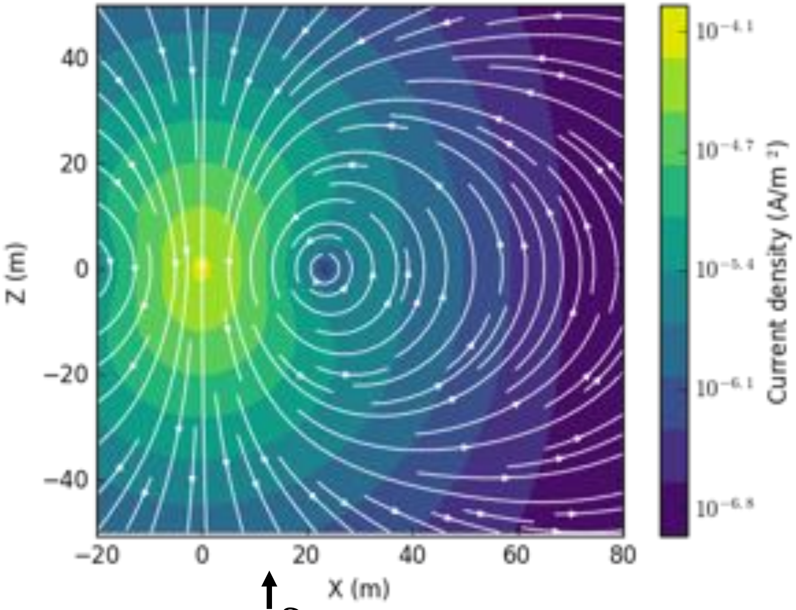
1 **d**

f=10^2 kHz, **δ** = 16 m

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



Re (J) – Re(J^{DC})

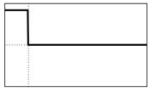


1 δ

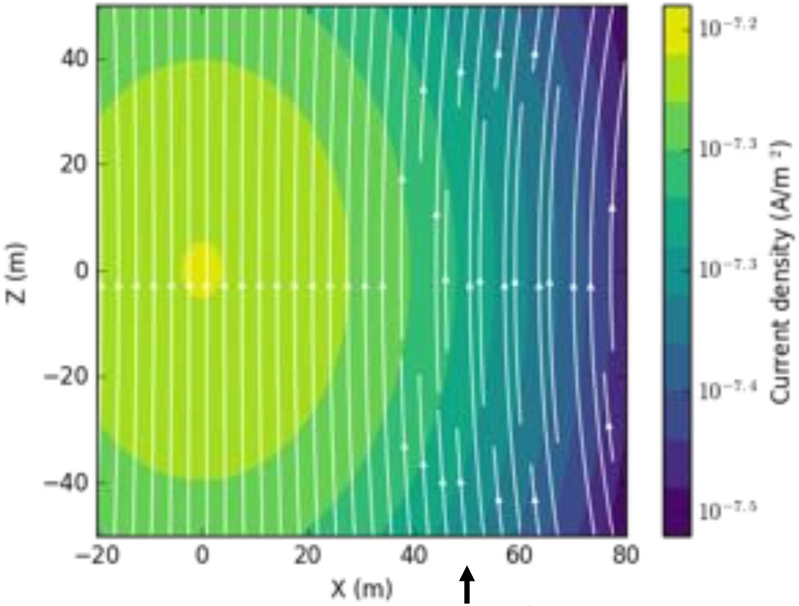
Electric Dipole in a whole space: TDEM

t=10^{-1} ms, $\mathbf{d}$ = 126m

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$



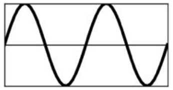
j



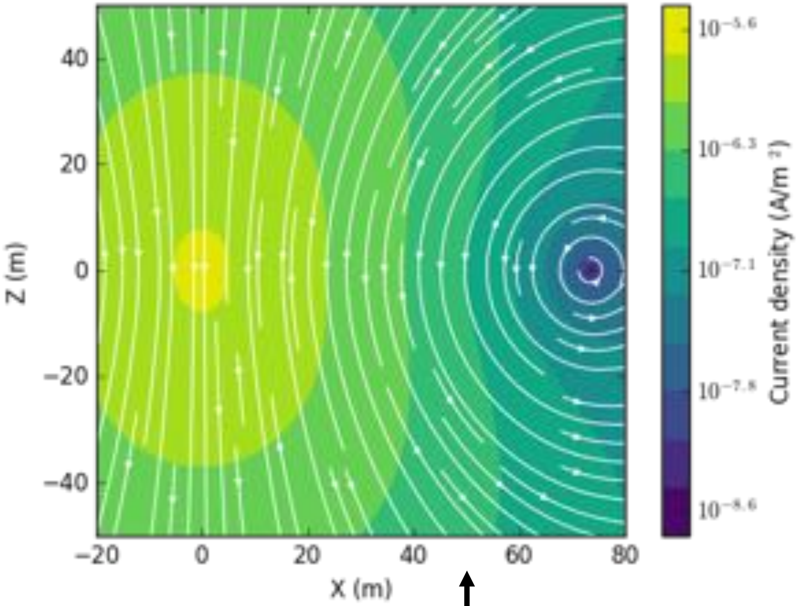
2/5 $\mathbf{d}$

f=10^{1} kHz, δ = 50 m

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



Re (J) – Re(J^{DC})

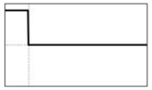


1 δ

Electric Dipole in a whole space: TDEM

t=1 ms, d = 400m

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$



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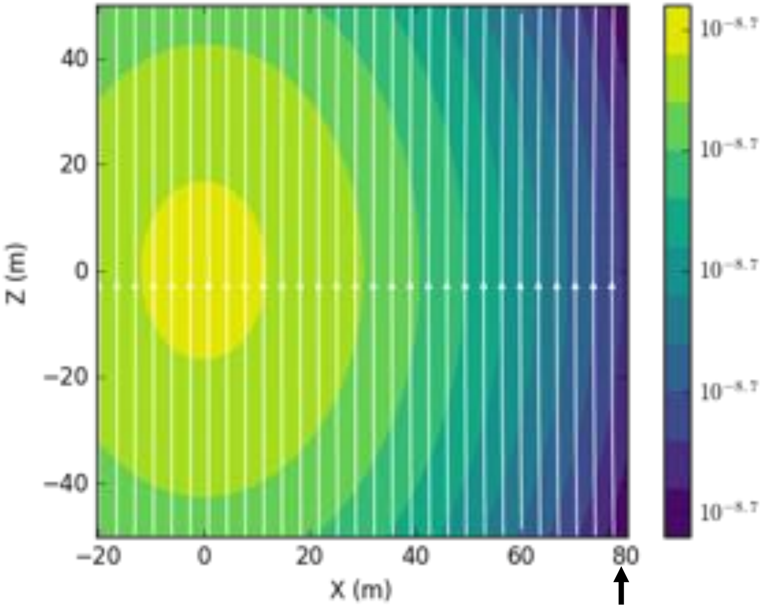
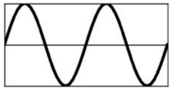


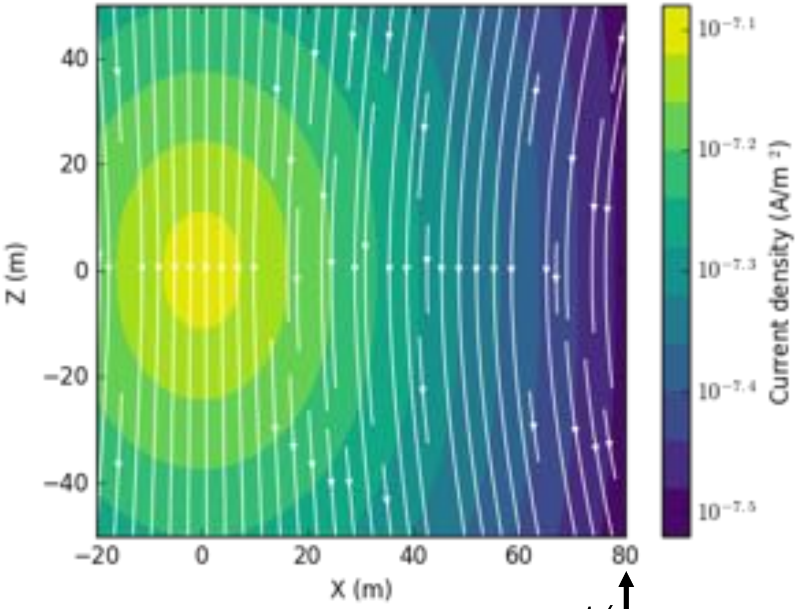
1/5 d

f=1 kHz, δ = 160 m

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



Re (J) – Re(J^{DC})

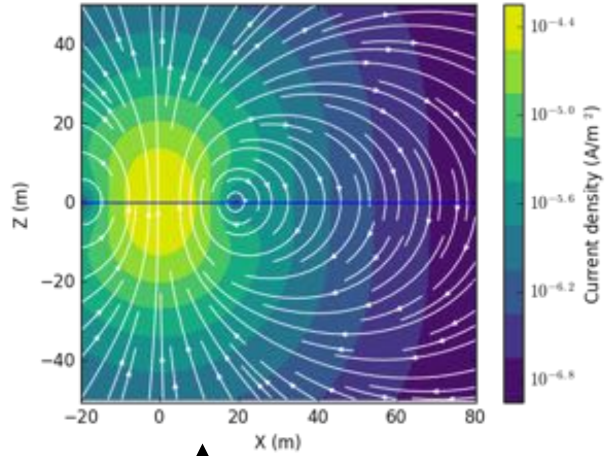


½ δ

Diffusing currents

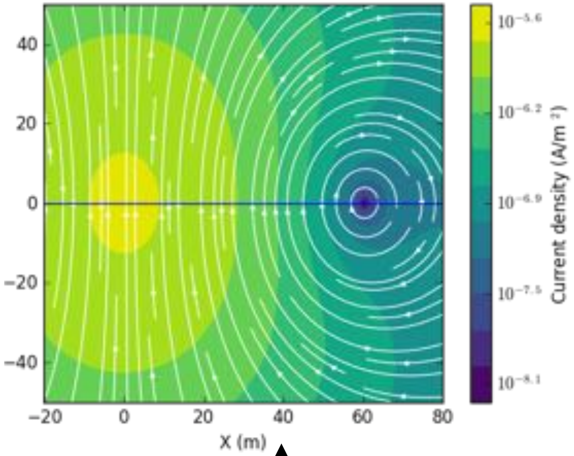
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

10^{-3} ms



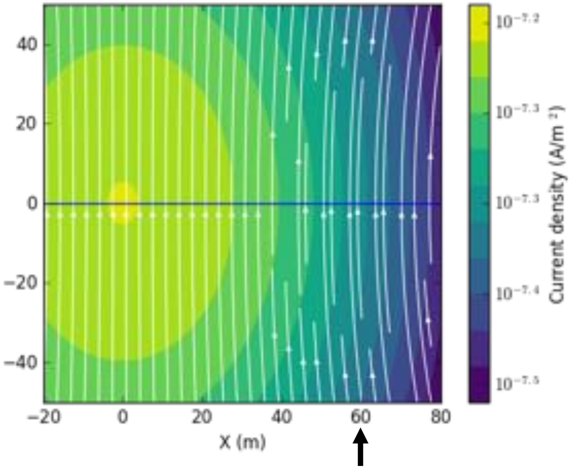
1 d

10^{-2} ms



1 d

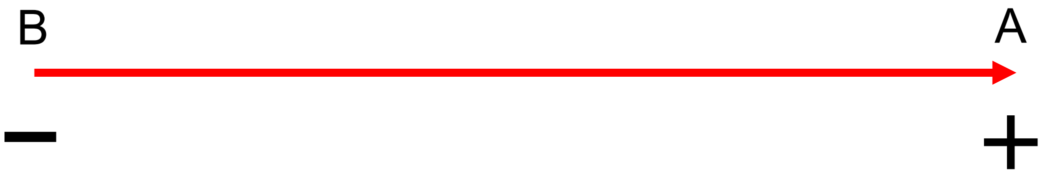
10^{-1} ms



1/2 d

Bipole Sources

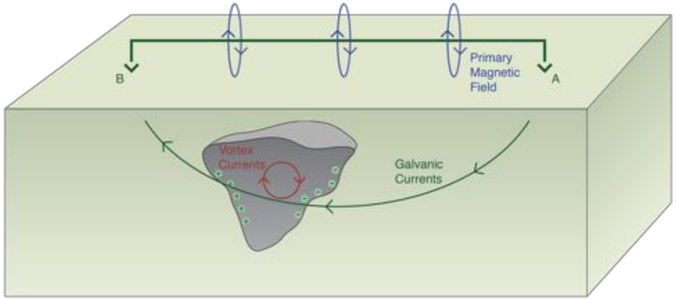
- Extended line sources
  - Grounded term (**galvanic**) + wire path (**inductive**)
  - Straight line



  - Crooked line (horse shoe)

Grounded Sources: On the surface

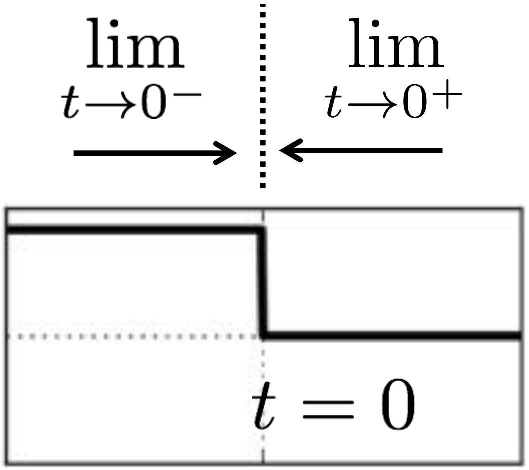
- Ability to detect target depends on
  - Geometry, conductivity of target & host
  - Geometry of TX
  - Frequency or time
  - Fields and components measured
    - e, b, db/dt
  - Location of Tx and Rx with respect to the target

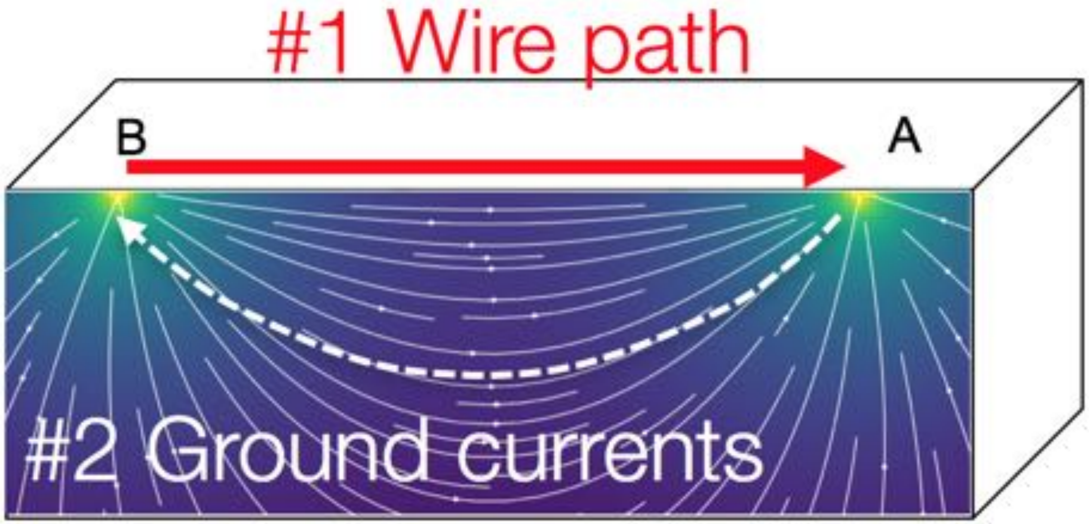


- Lots of variables…
  - Use an example to highlight important concepts

Currents: Grounded System

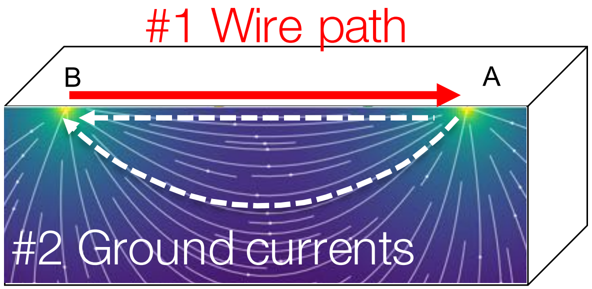
- $t = 0^-$ Steady state
- $t = 0$ Shut off current
- $t = 0^+$ Off-time

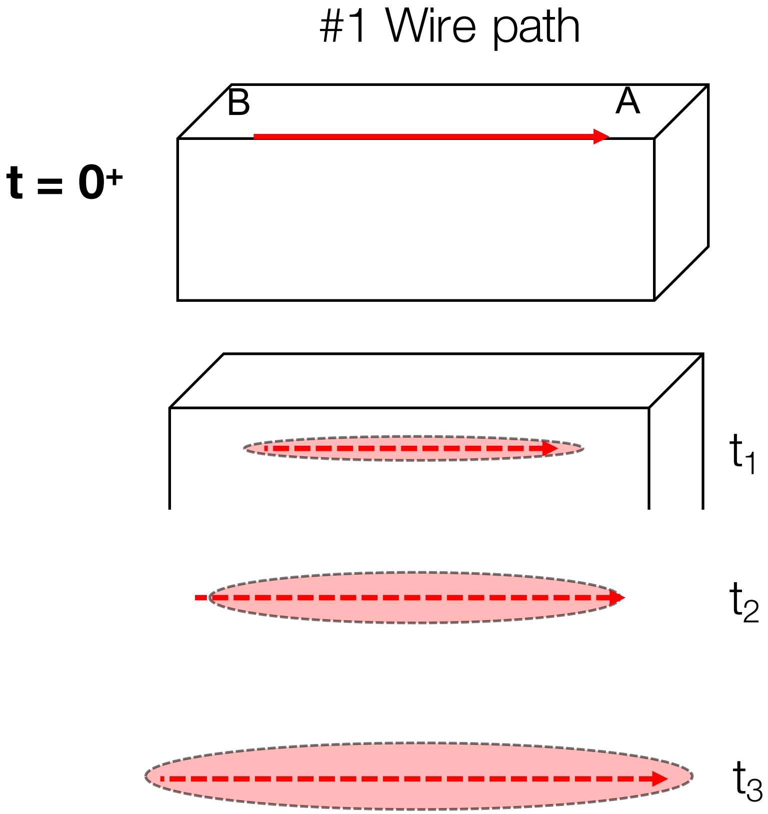




What happens when we shut the system off?

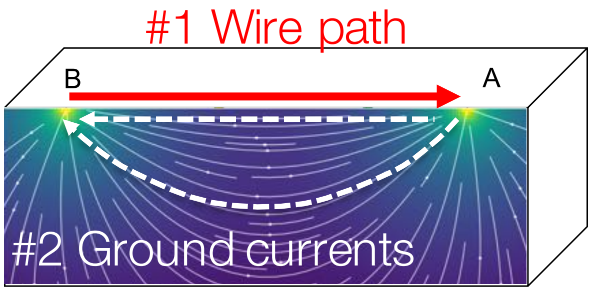
Currents: Grounded System





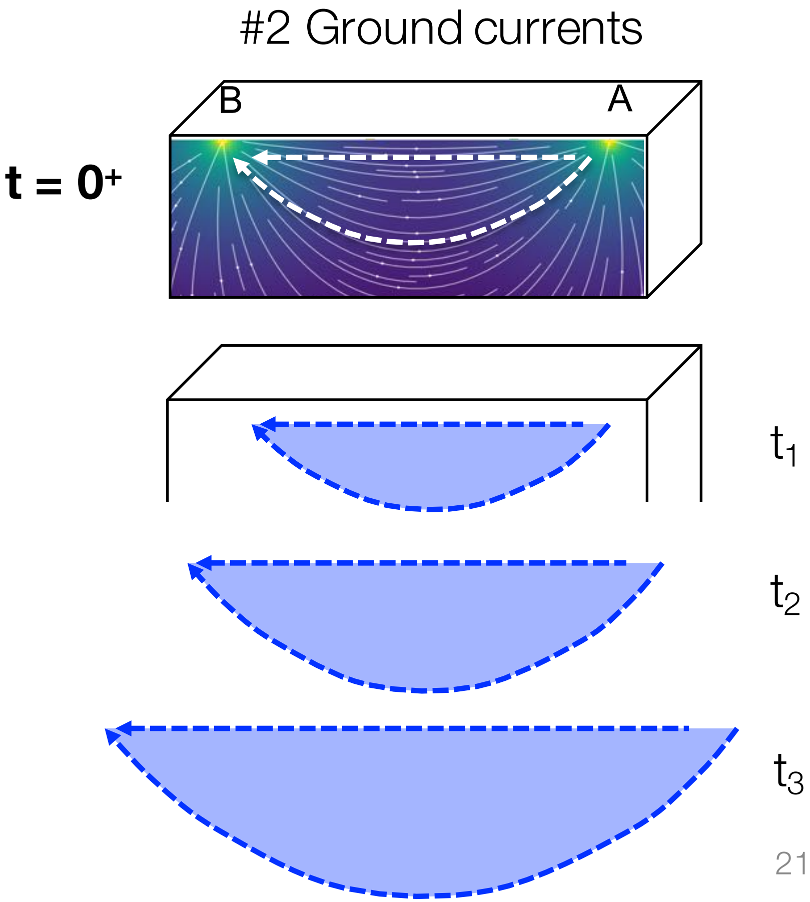
- Immediately after shut off: image current at the surface
- Successive time: currents diffuse downwards and outwards

Currents: Grounded System

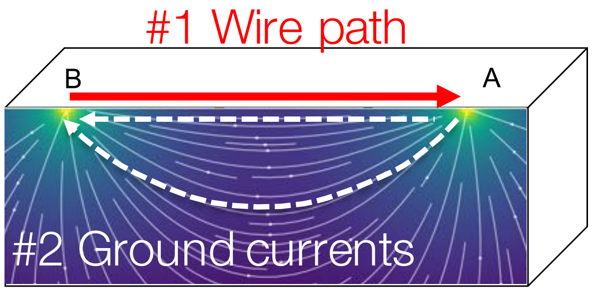


- Immediately after shut off: ground currents are still there

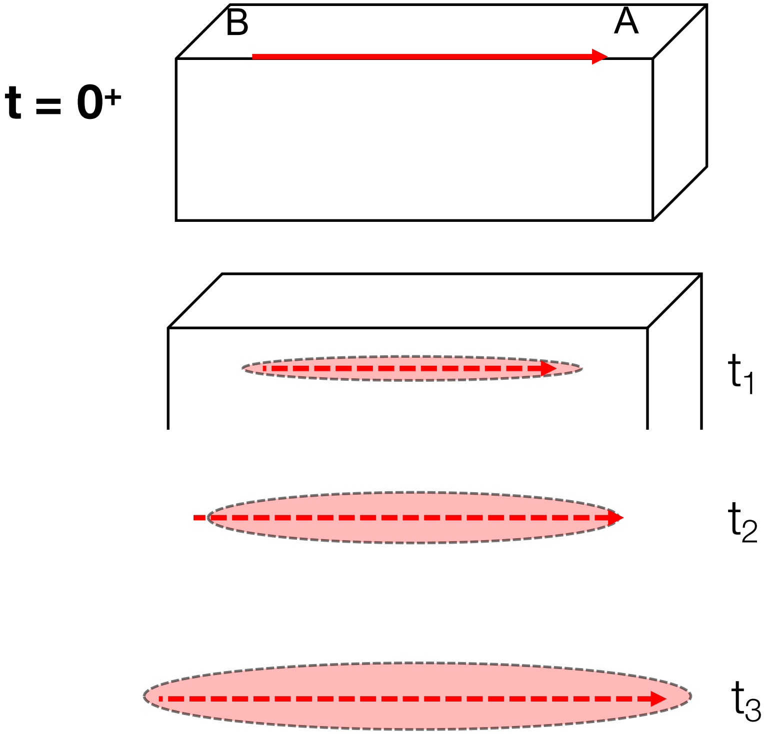
- Successive time: currents diffuse downwards and outwards



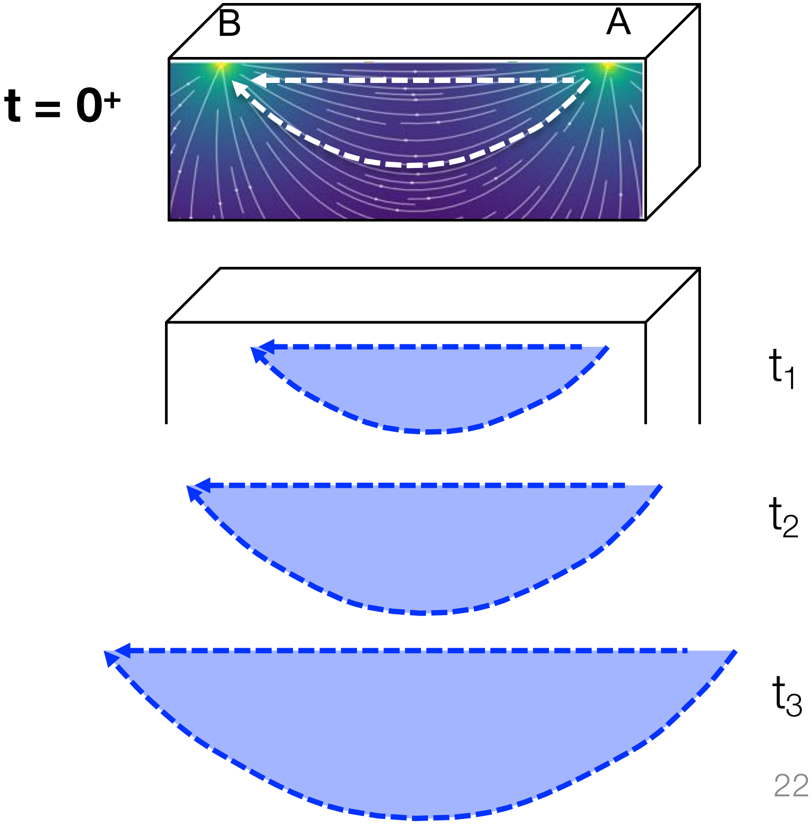
Currents: Grounded System



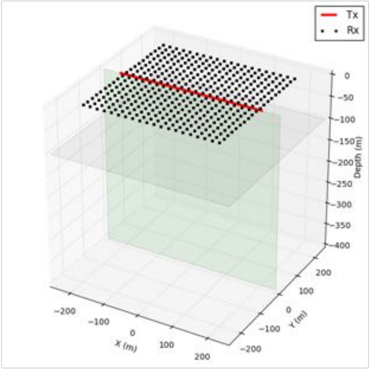
#1 Wire path



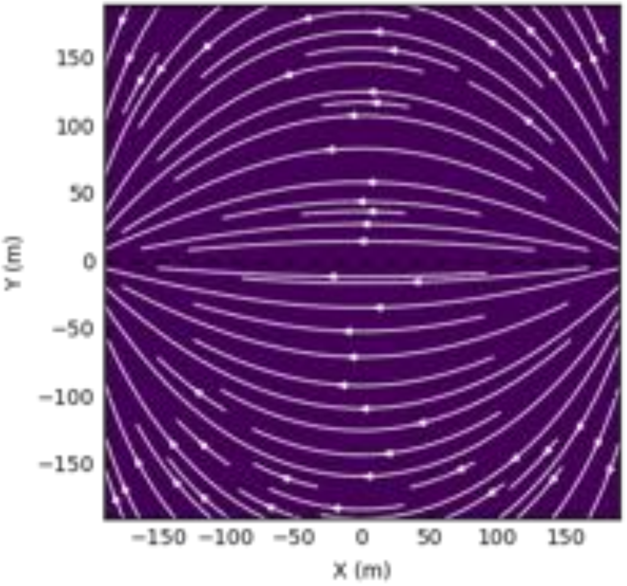
#2 Ground currents

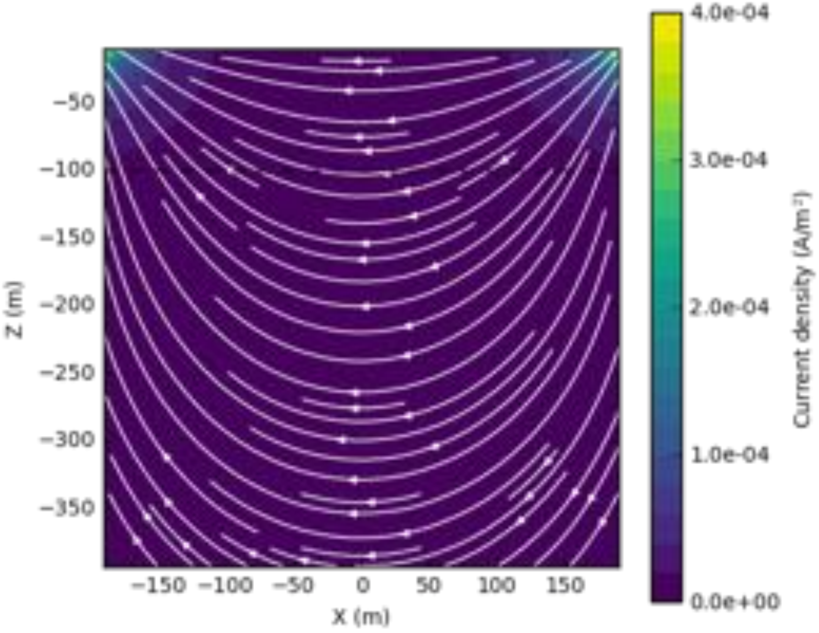


Grounded Source: Halfspace Currents



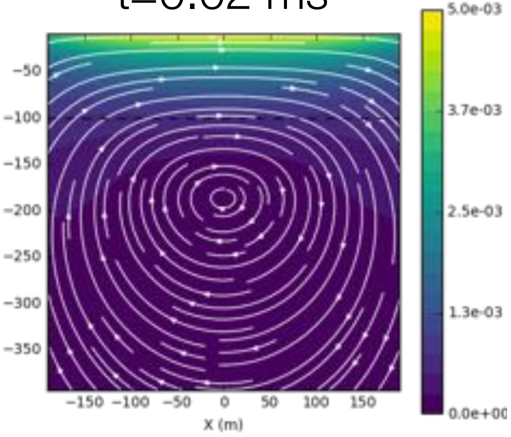
- Parameters:
  - halfspace (0.01 S/m)
  - **t=0$^-$**, steady state


XY plane at Z=-100 m

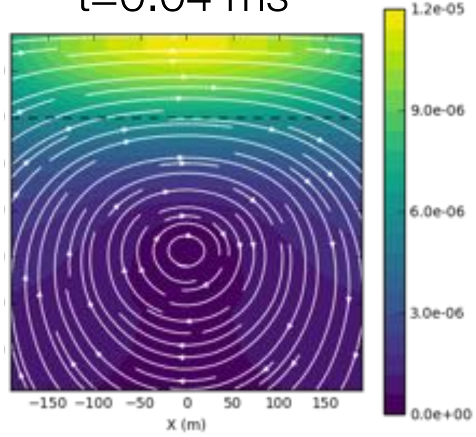

XZ plane at Y=0 m

Grounded Source: Halfspace currents

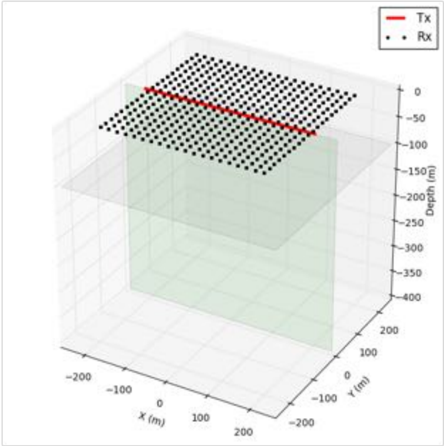
- Cross section of currents, t = 0.04 to 10 ms

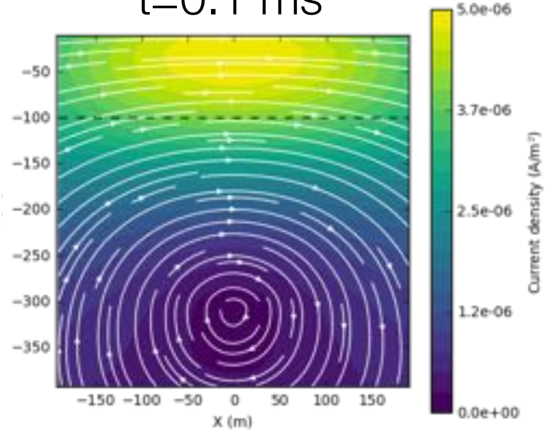


t=0.02 ms

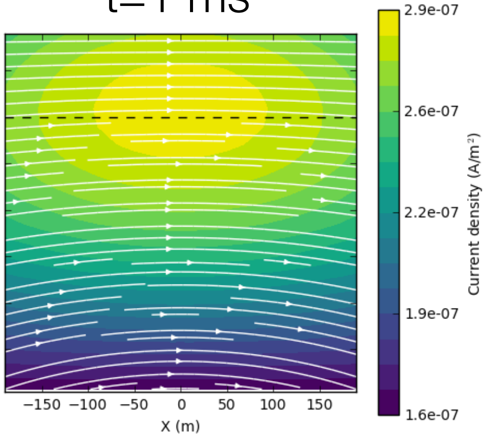


t=0.04 ms

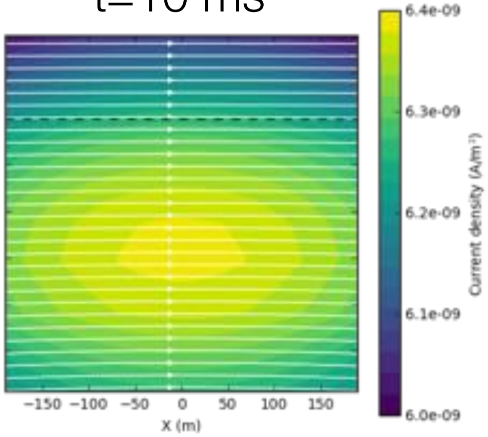




t=0.1 ms



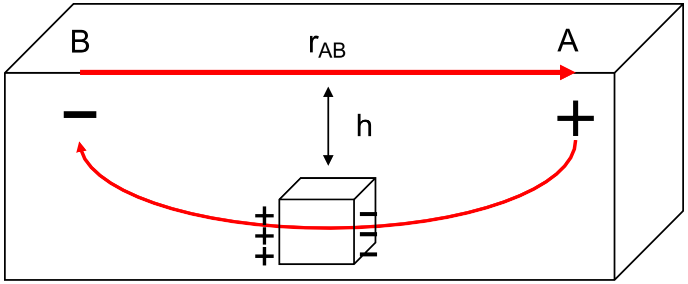
t=1 ms



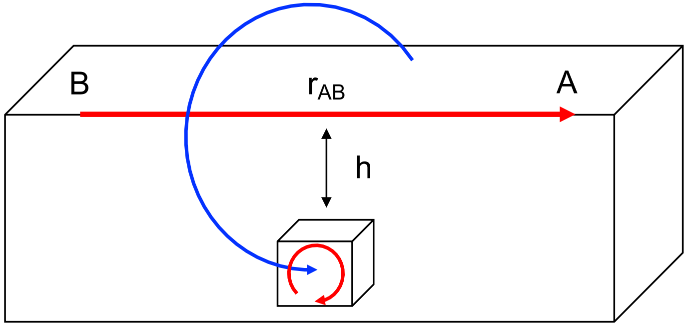
t=10 ms

Grounded sources: with a target

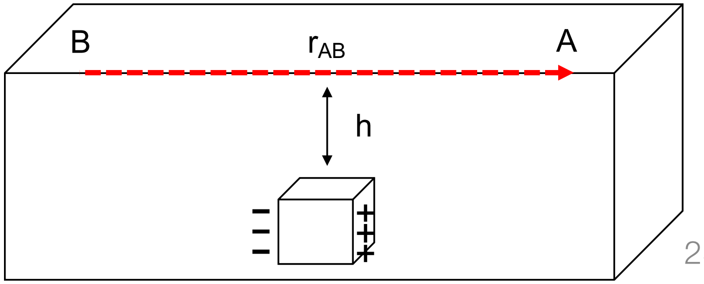
- Block in a halfspace
  - DC
    - Good coupling if h < r_{AB}



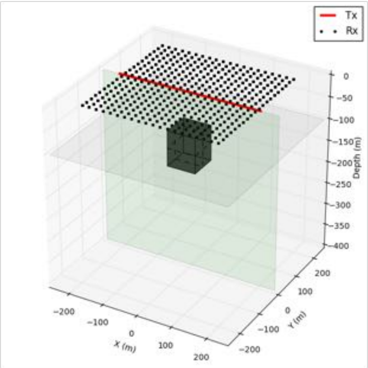
  - Vortex currents
    - Good coupling (magnetic fields)
    - Good signal for conductor
    - Resistor more difficult



  - Galvanic currents
    - Good coupling (electric fields)
    - Good signal for conductor and resistor

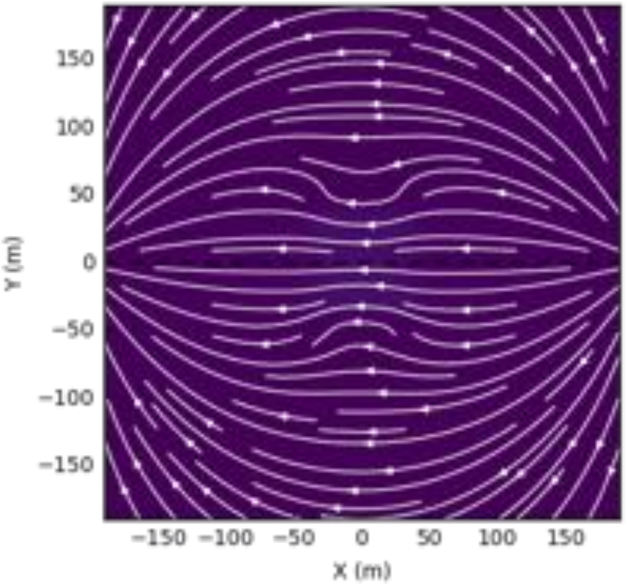


Conductor: currents

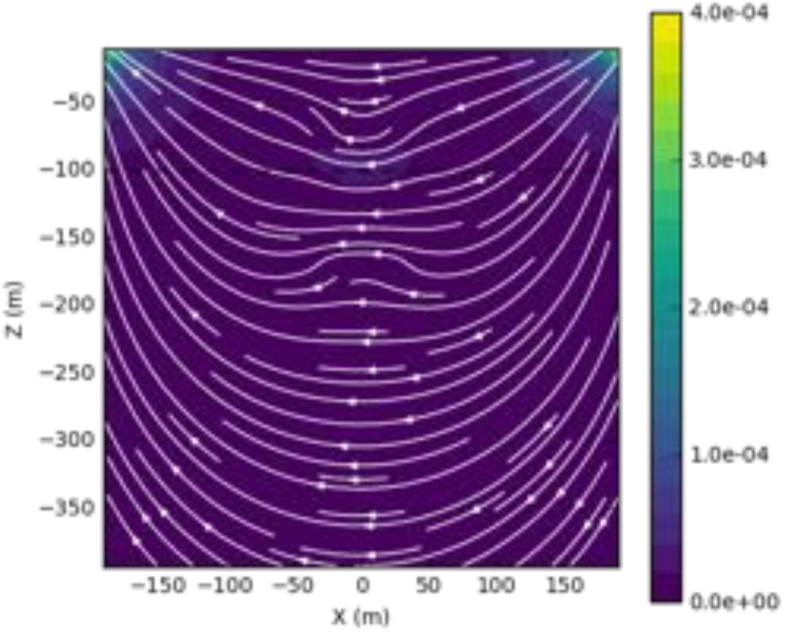


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **t=0$^-$**, steady state

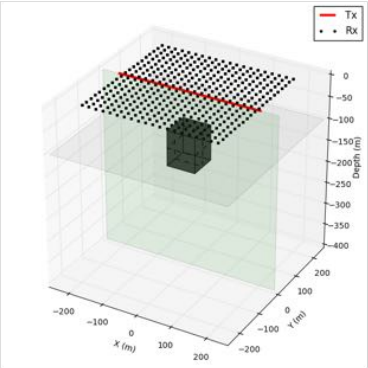
XY plane at Z=-100 m



XZ plane at Y=0 m

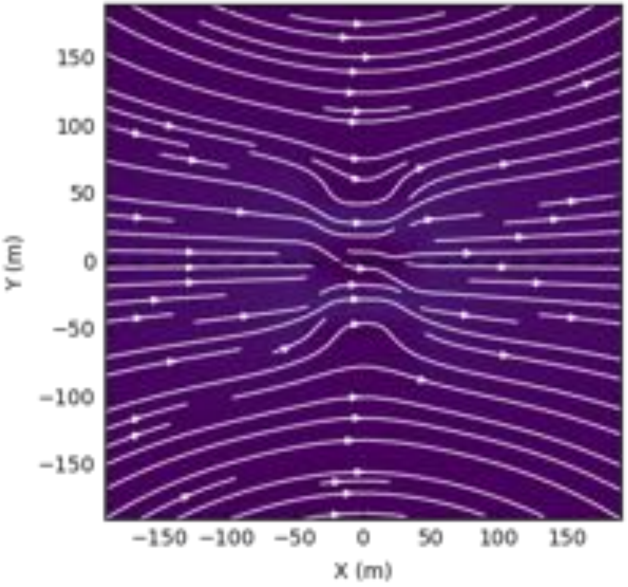


Conductor: currents

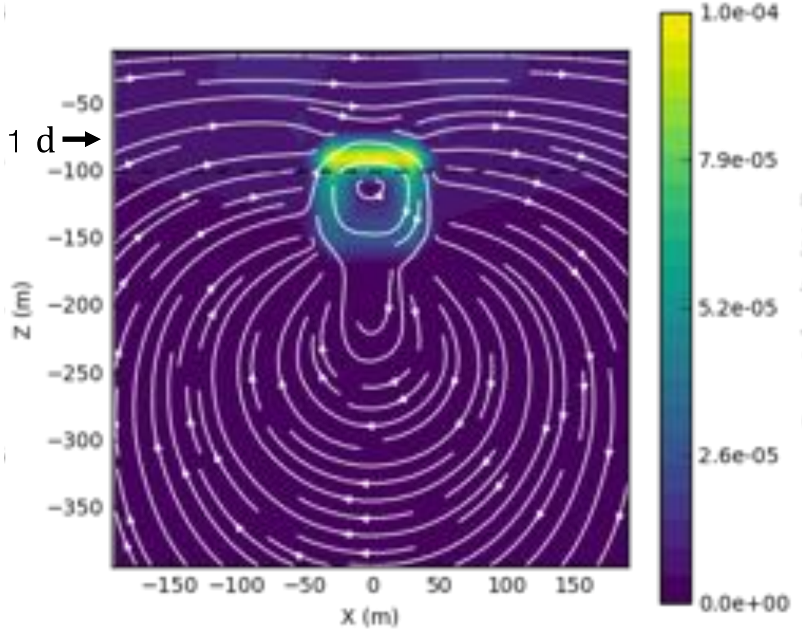


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

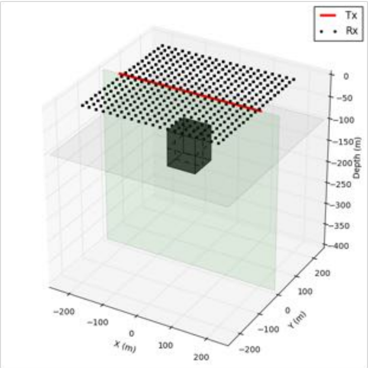
XY plane at Z=-100 m



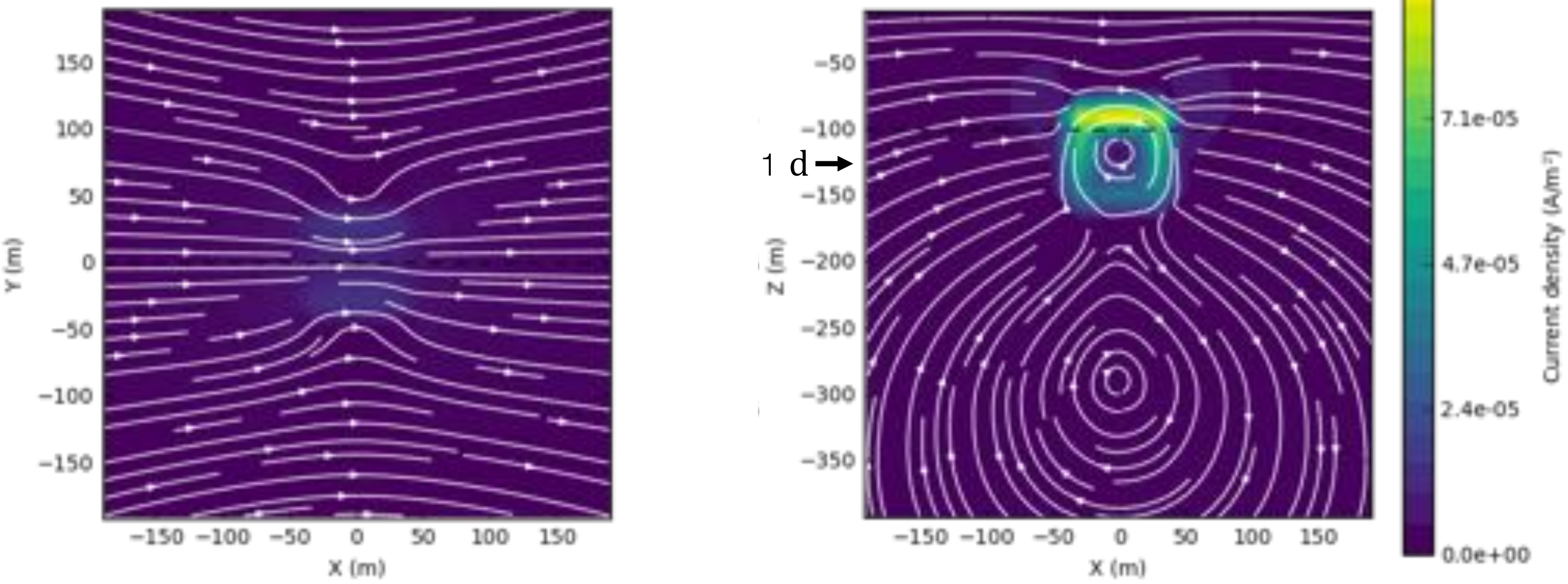
XZ plane at Y=0 m



Conductor: currents



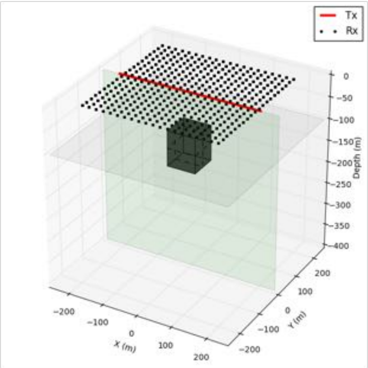
- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m



XY plane at Z=-100 m

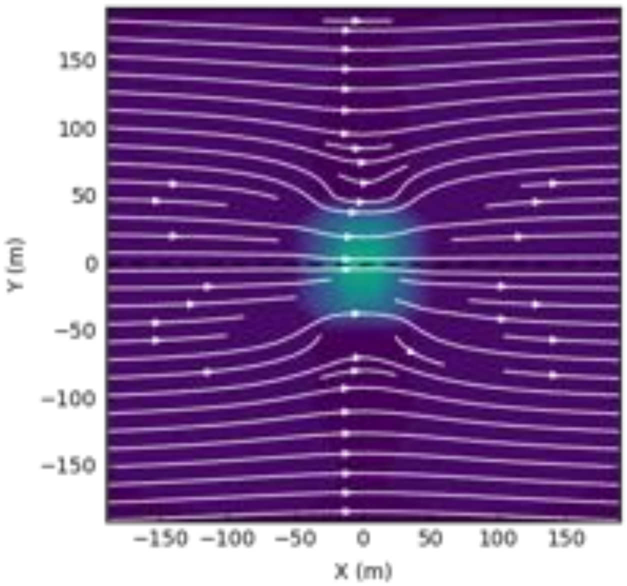
XZ plane at Y=0 m

Conductor: currents

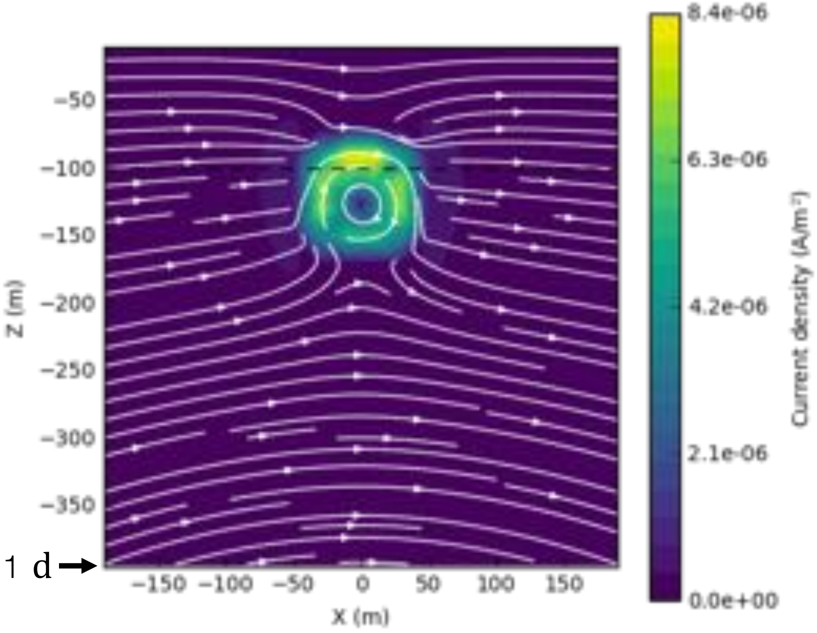


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - 1 ms, d = 400 m

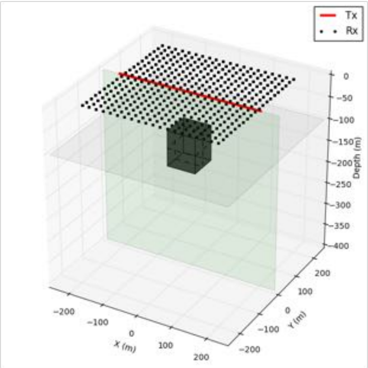
XY plane at Z=-100 m



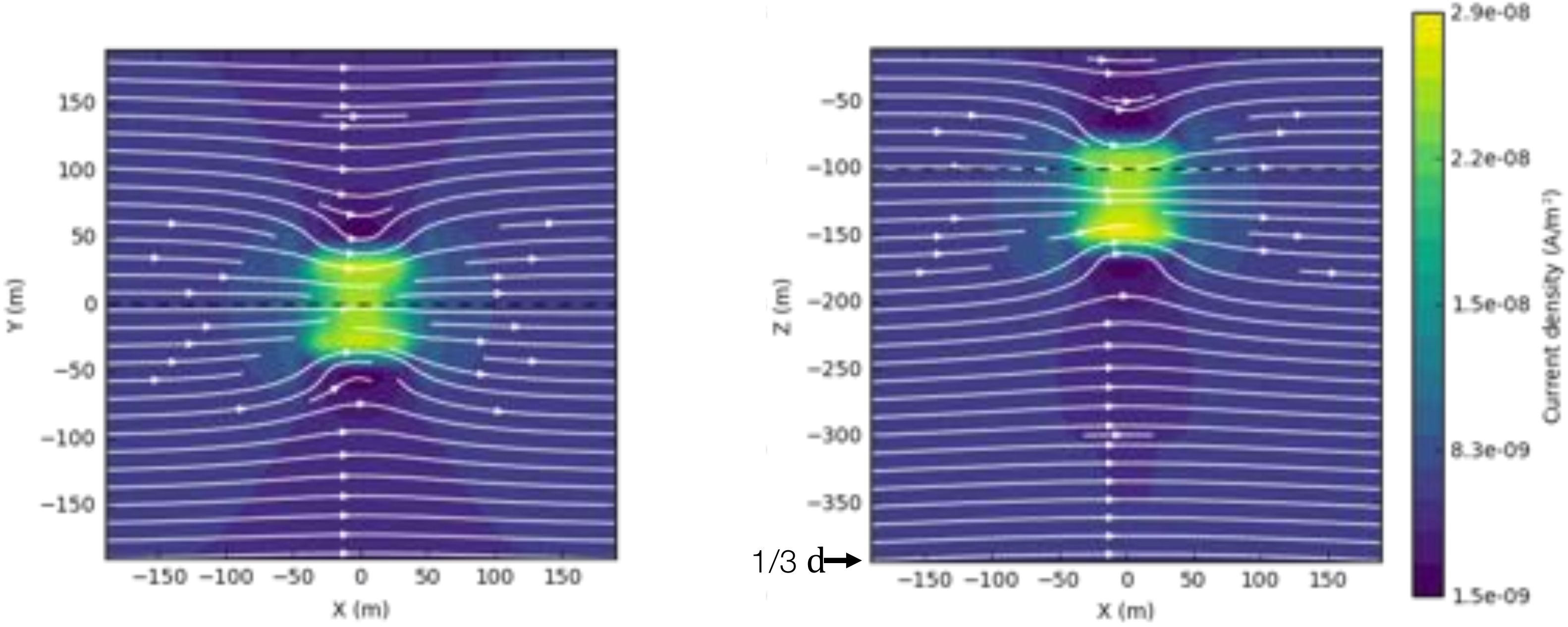
XZ plane at Y=0 m



Conductor: currents



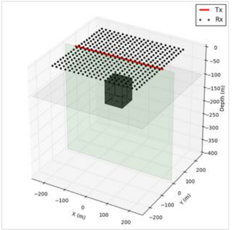
- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m


XY plane at Z=-100 m

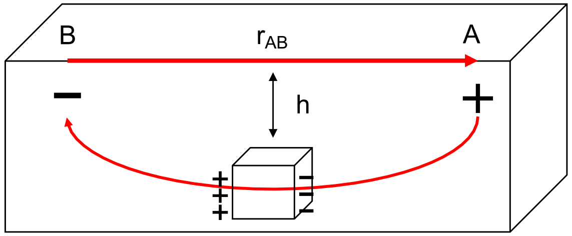
XZ plane at Y=0 m

1/3 d→

Conductor: currents

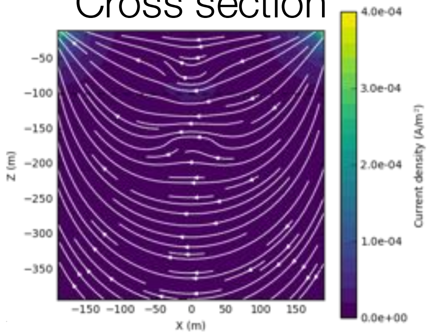


Steady State (galvanic current)

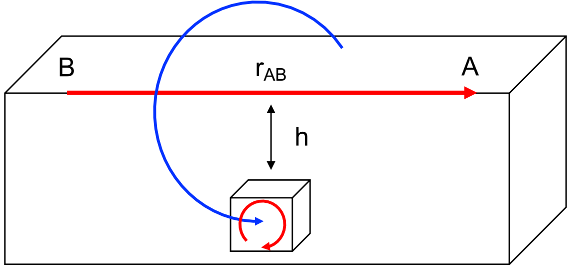


Galvanic current
$t = 0^-$

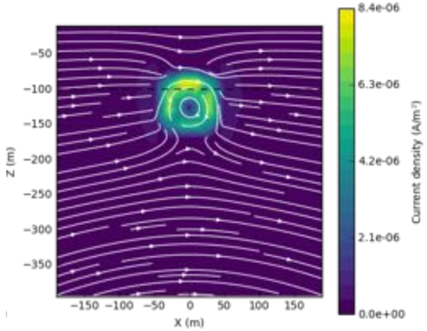
Cross section



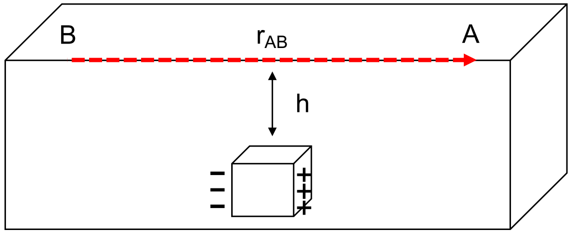
EM induction (vortex current)



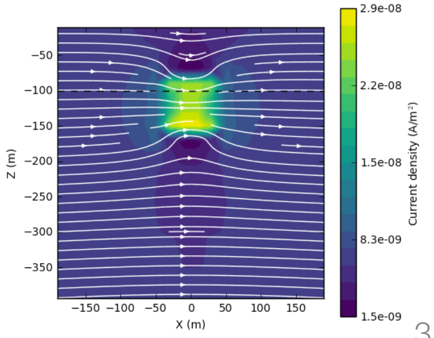
Vortex current
$t = 1$ ms



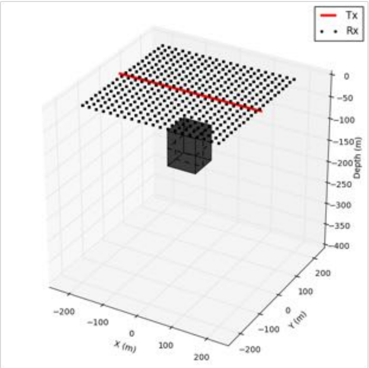
EM induction (galvanic current)

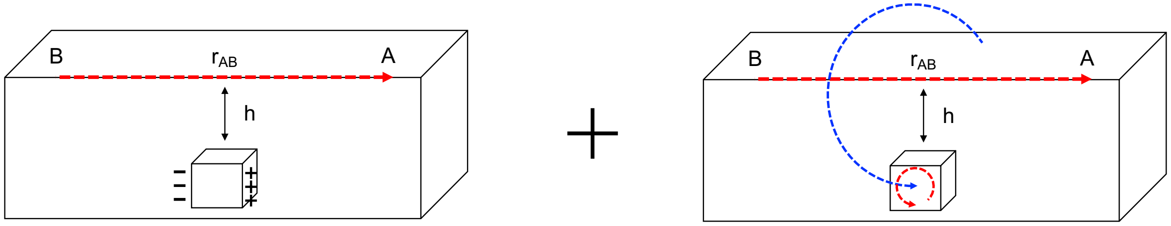


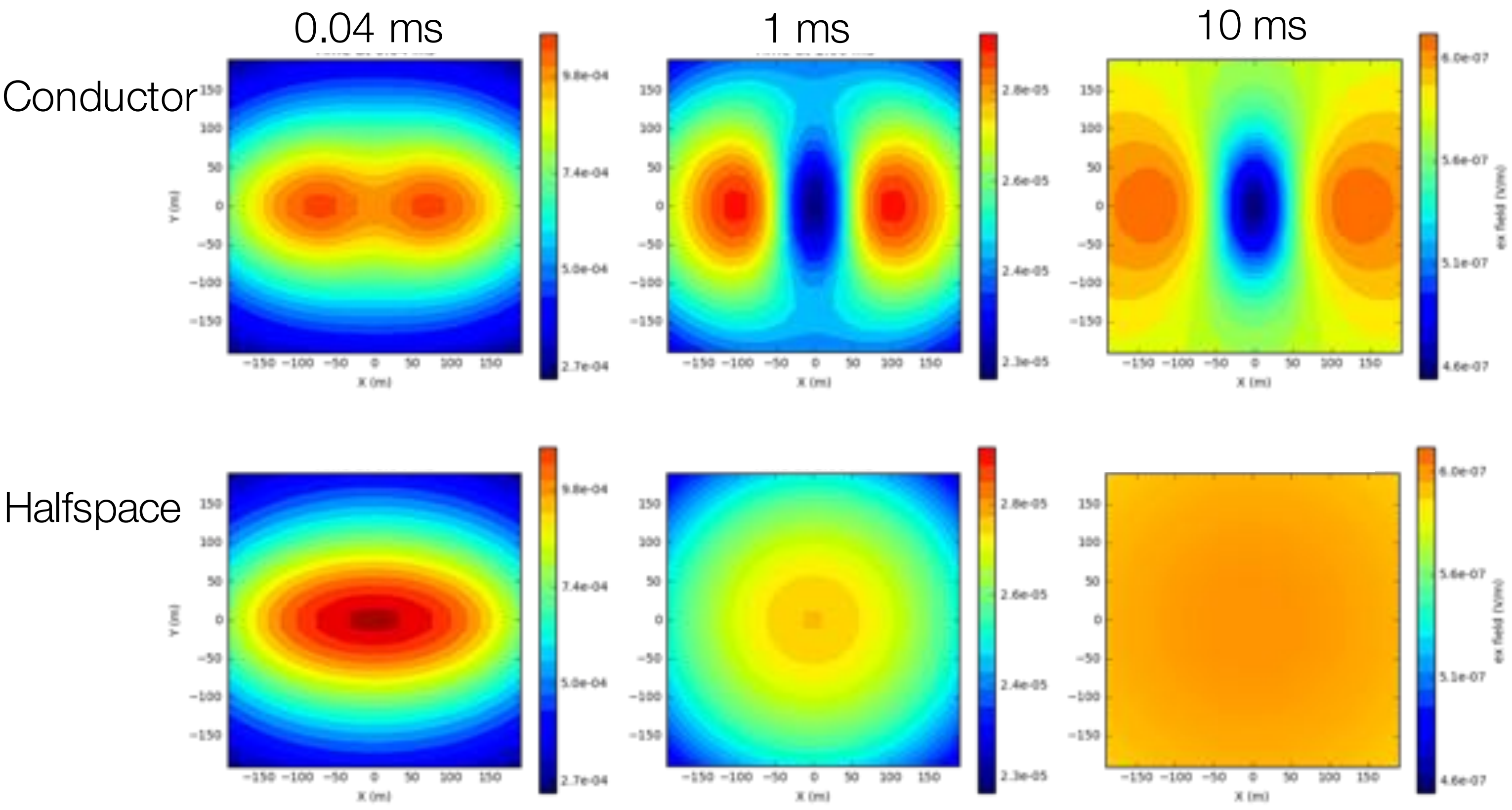
Galvanic current
$t = 10$ ms



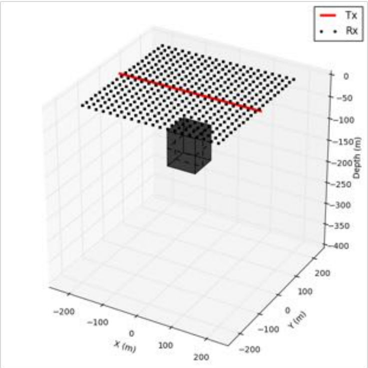
Data: e_x field

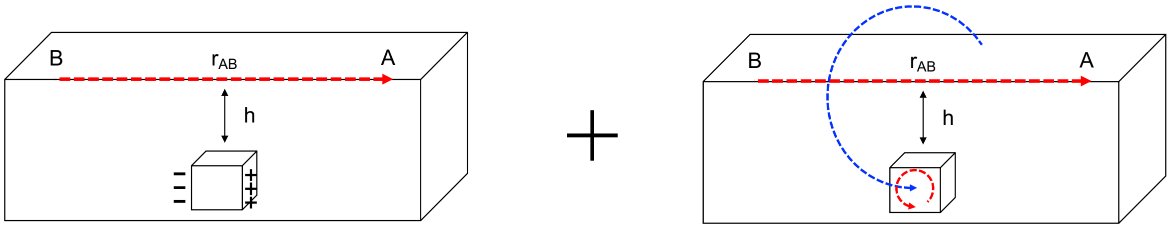


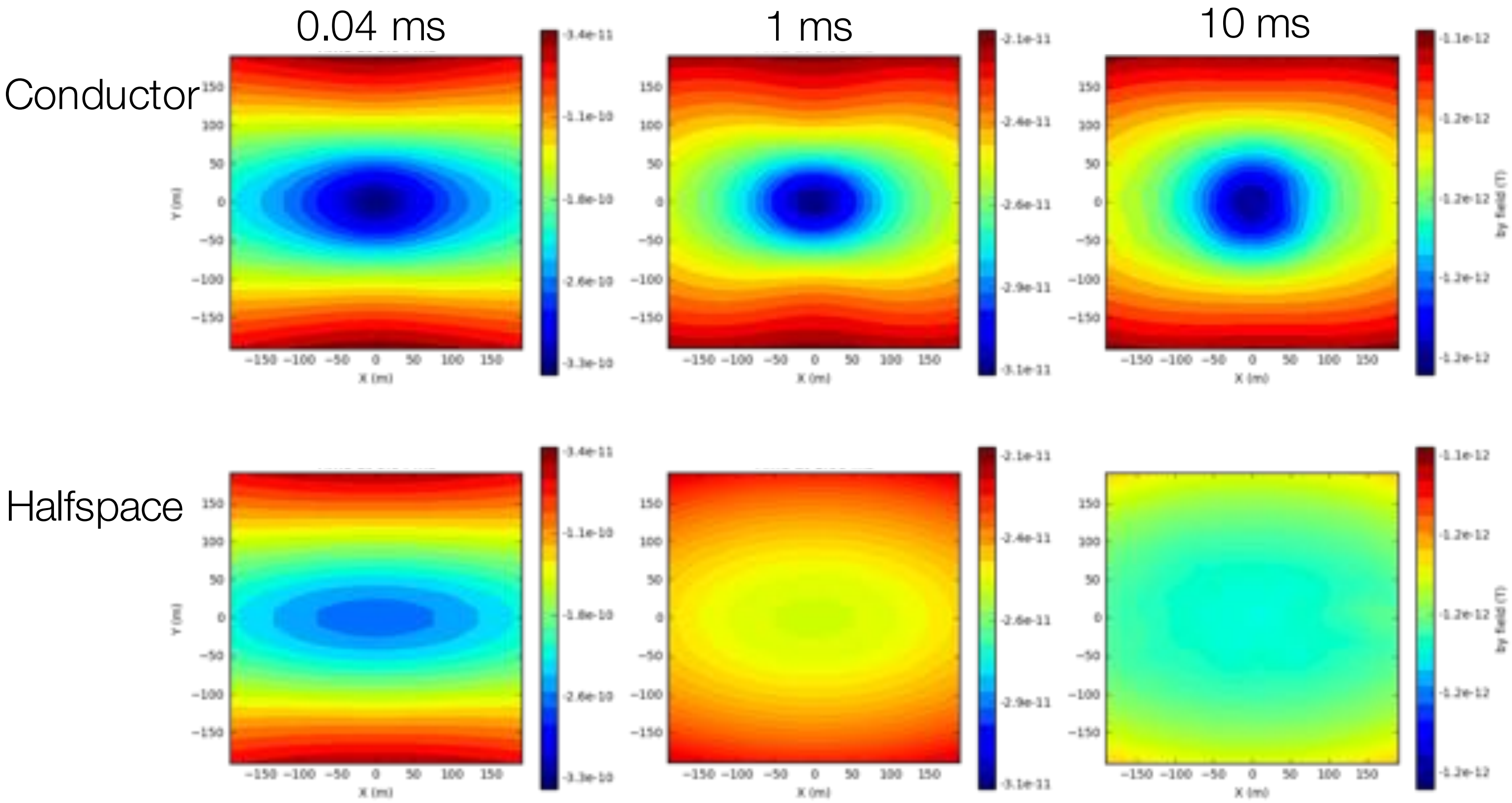




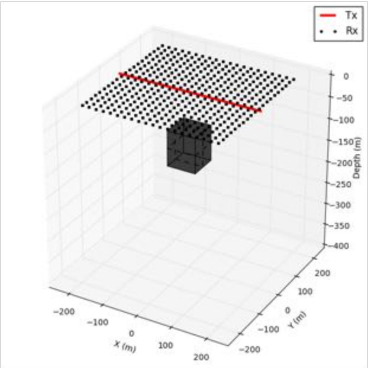
Data: b_y field

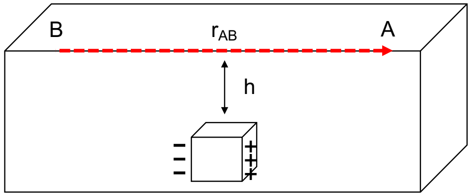






Data: b_z field





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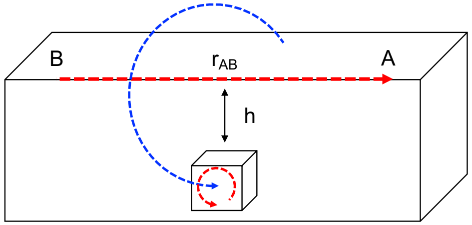
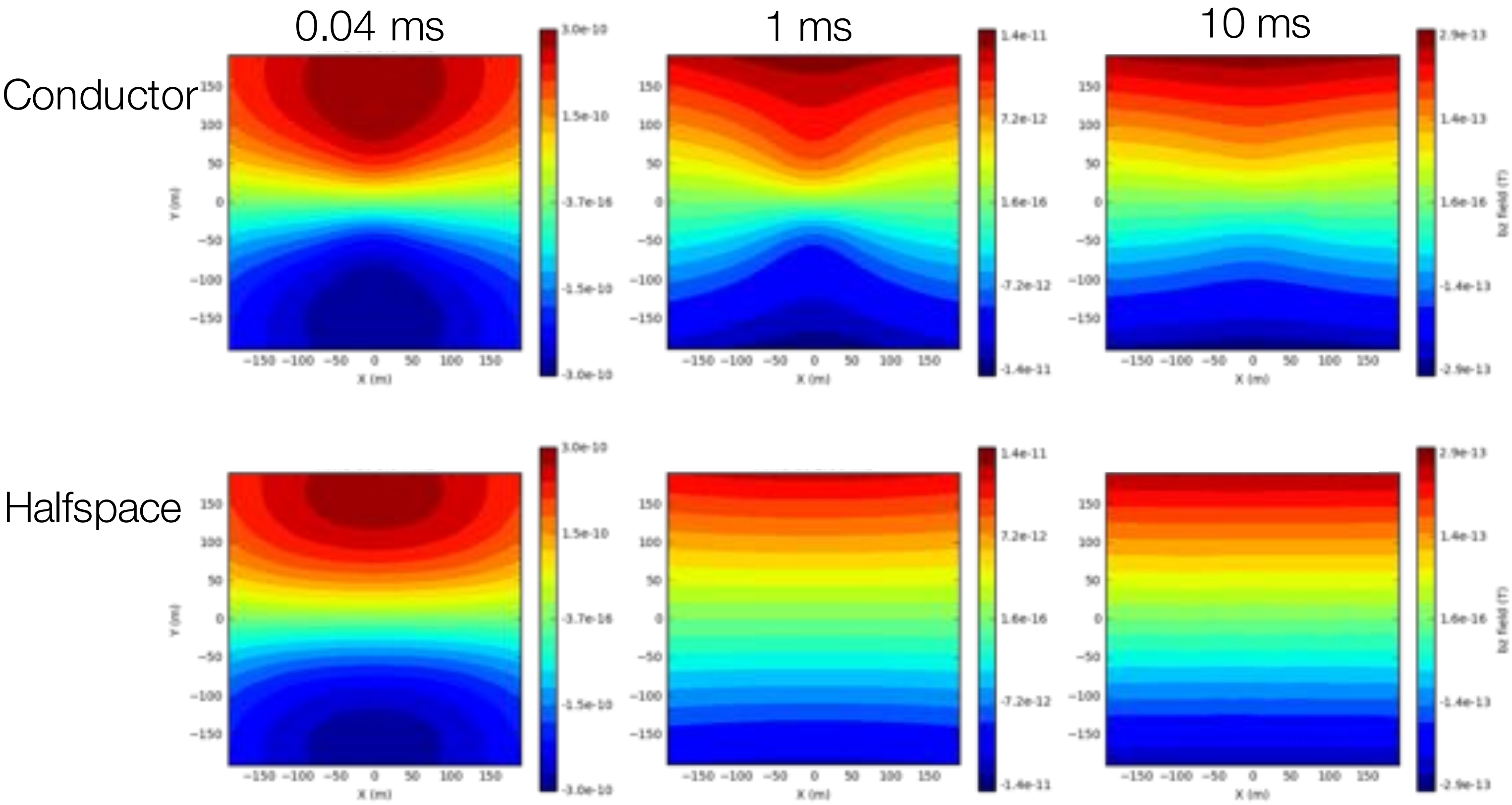
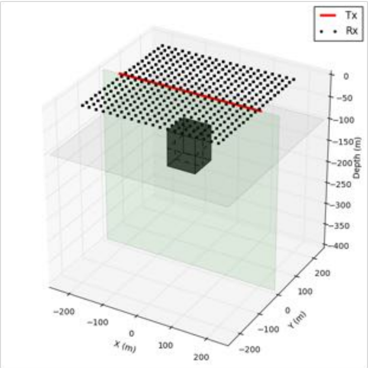


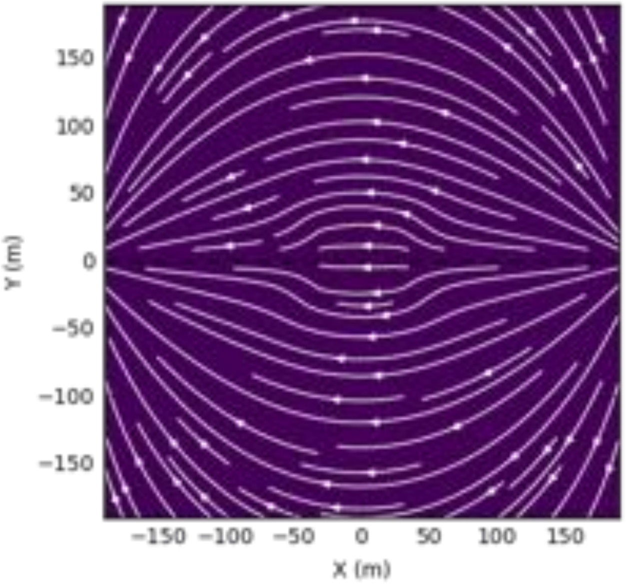


Resistor: currents

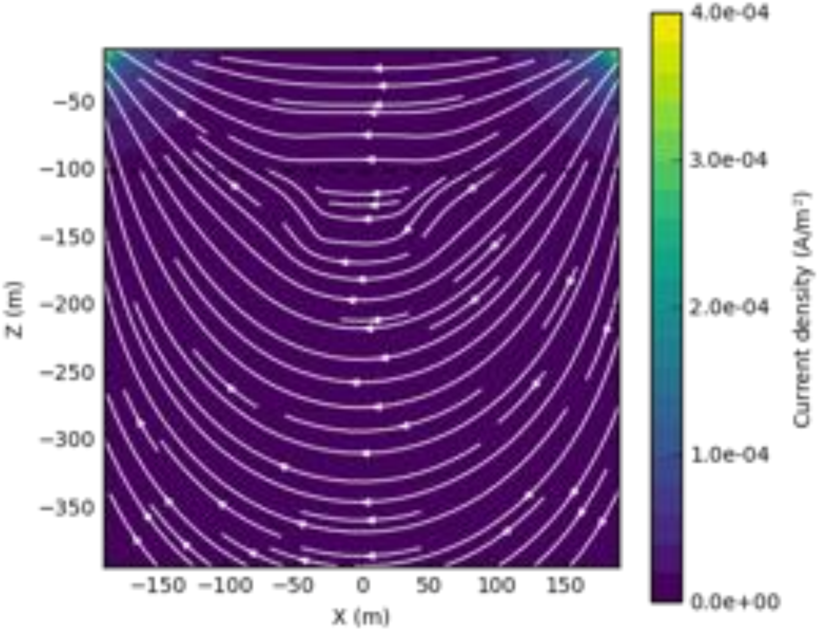


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **t=0^{-}**, steady state

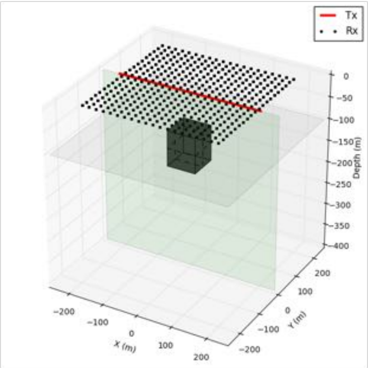
XY plane at Z=-100 m



XZ plane at Y=0 m

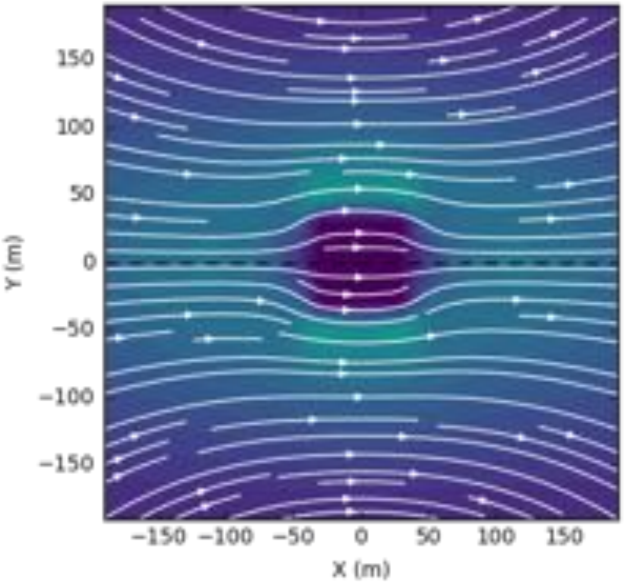


Resistor: currents

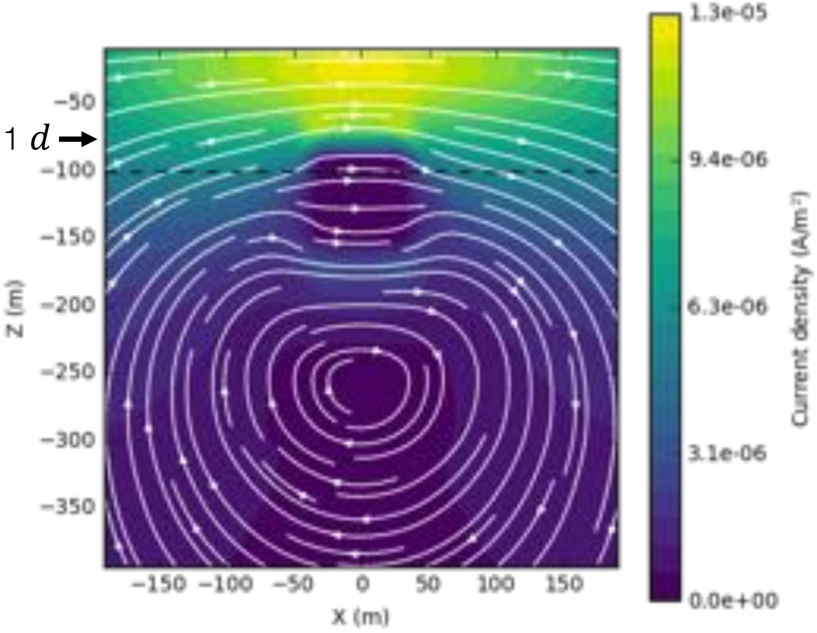


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

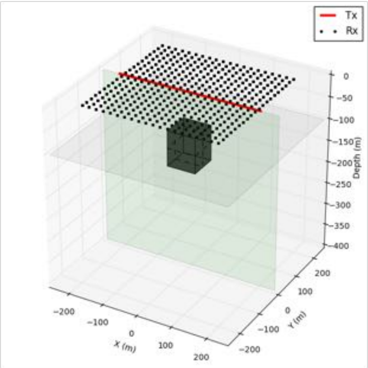
XY plane at Z=-100 m



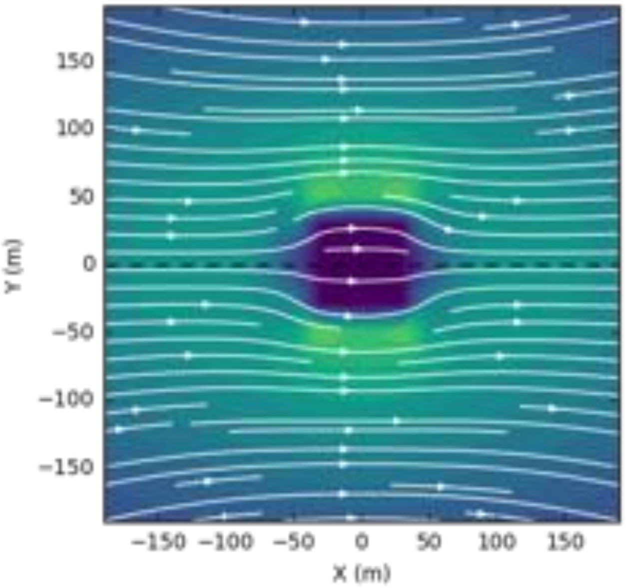
XZ plane at Y=0 m

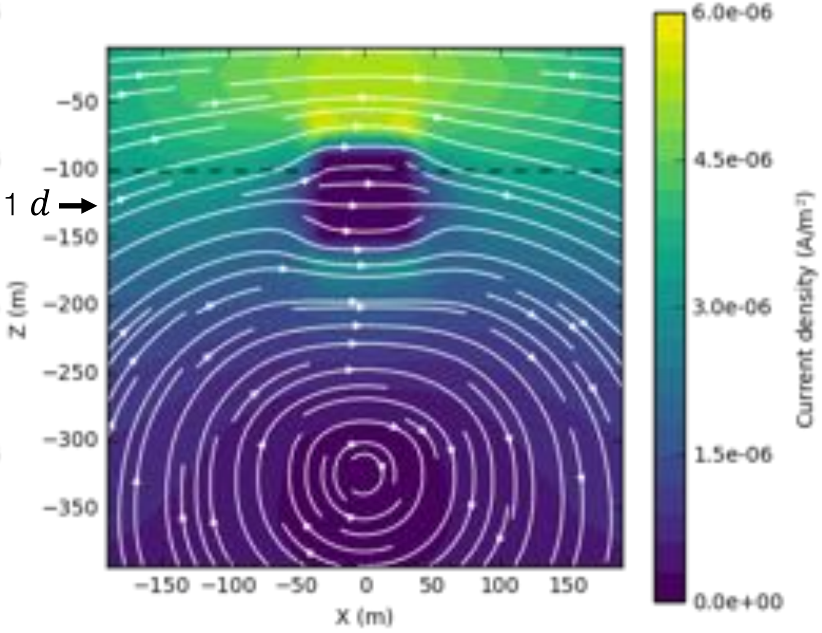


Resistor: currents

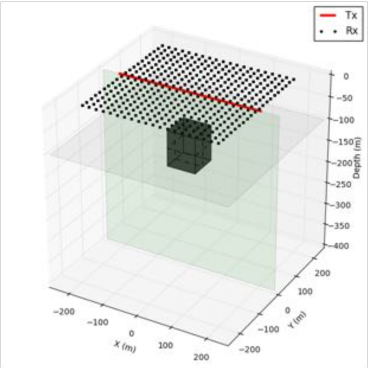


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m

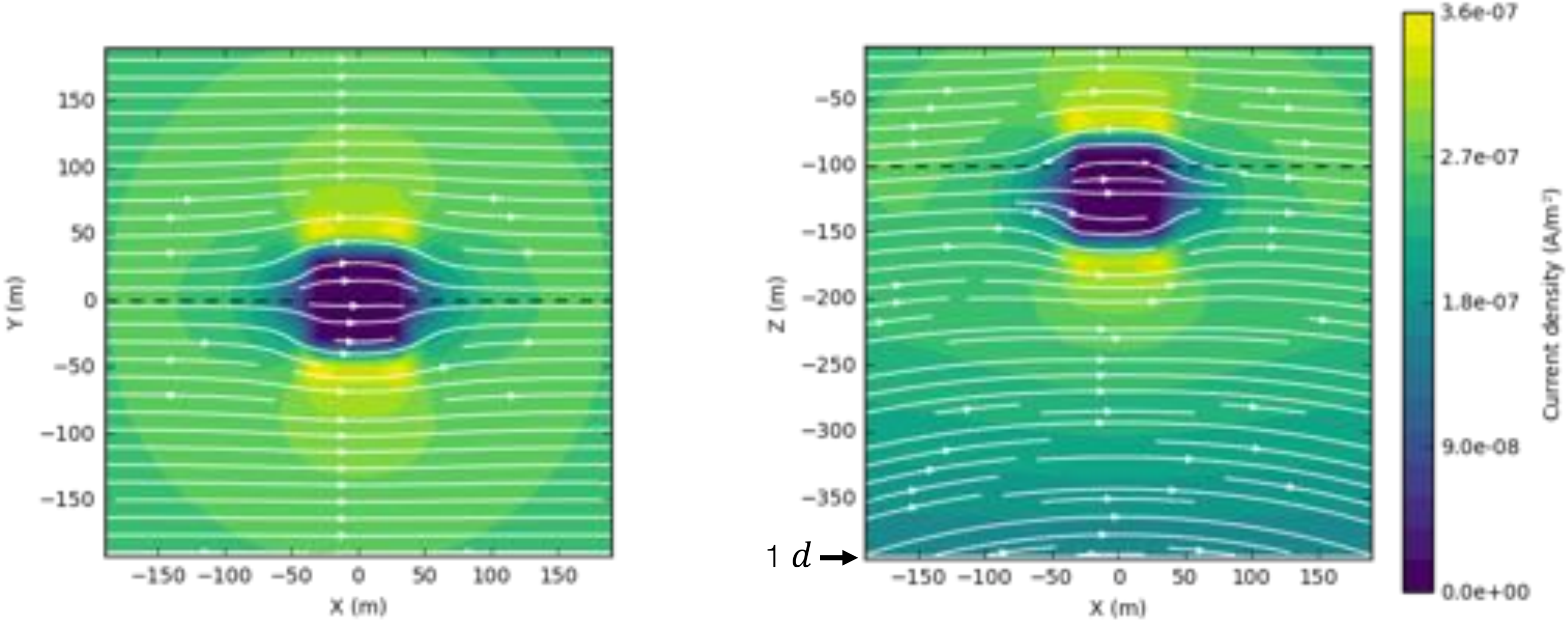

XY plane at Z=-100 m


XZ plane at Y=0 m

Resistor: currents

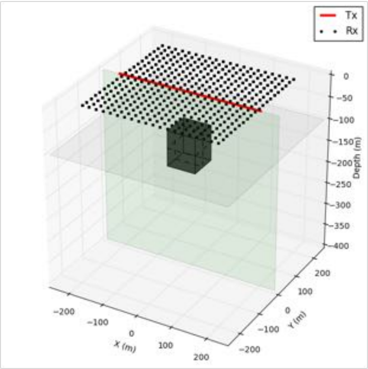


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **1** ms, d = 400 m

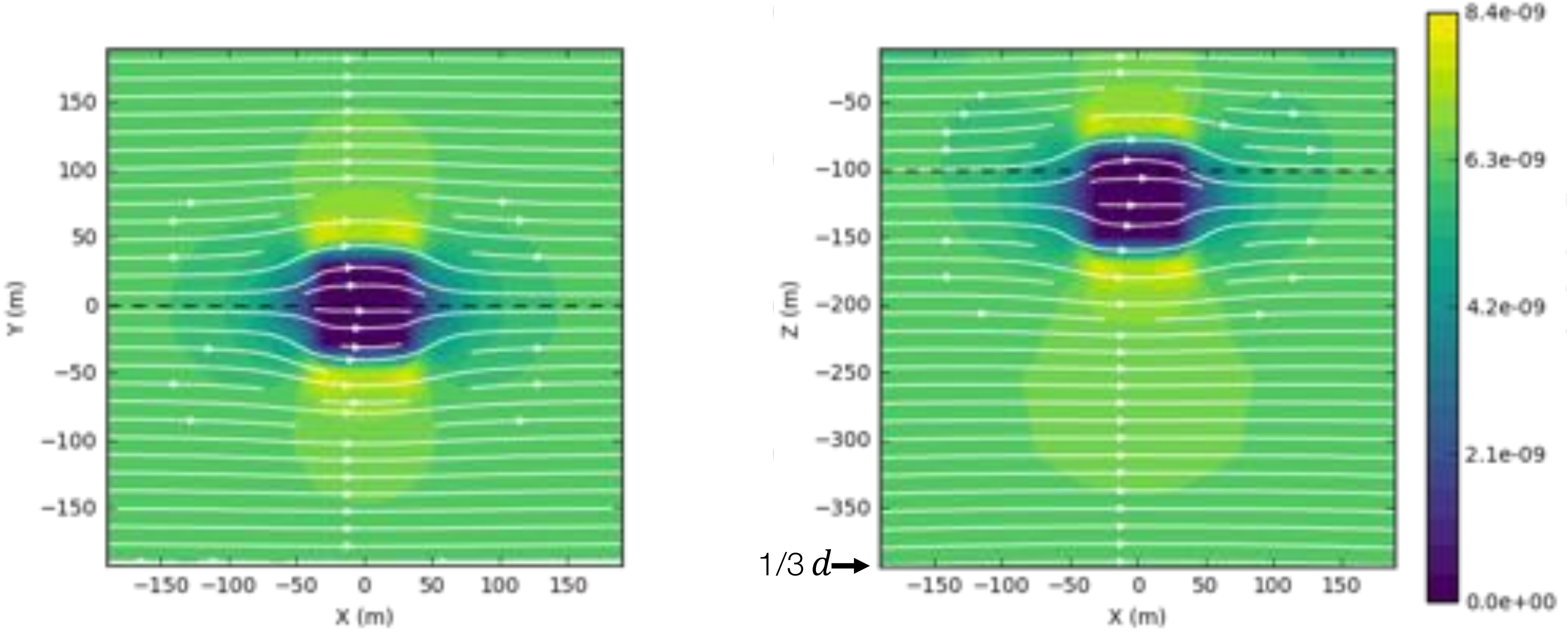

XY plane at Z=-100 m

XZ plane at Y=0 m

Resistor: currents



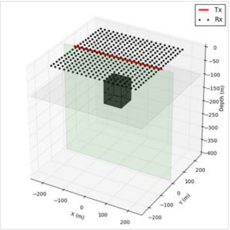
- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m


XY plane at Z=-100 m

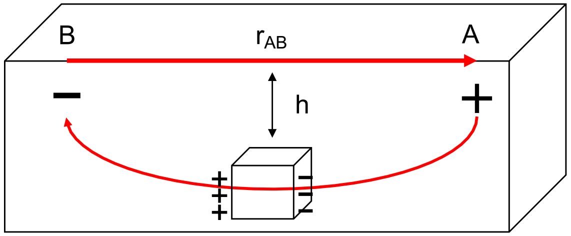
XZ plane at Y=0 m

1/3 *d*→

Resistor: currents

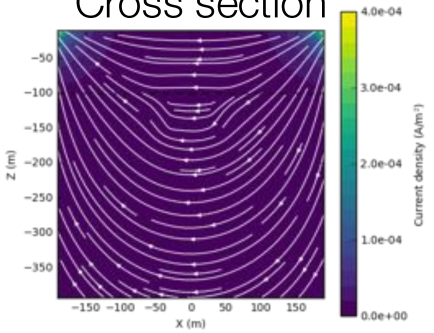


DC (galvanic current)

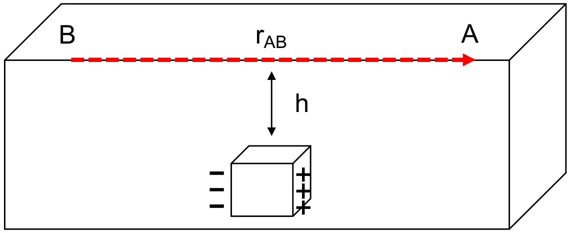


Galvanic current
$t = 0^-$

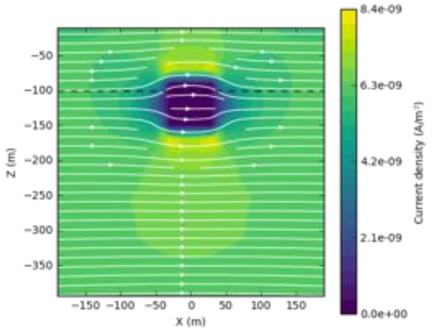
Cross section



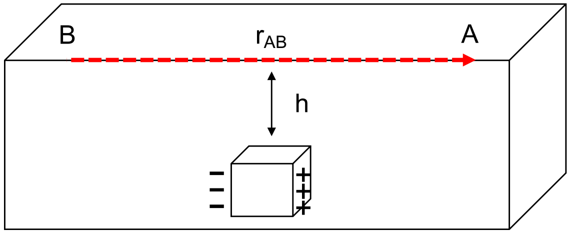
EM induction (galvanic current)



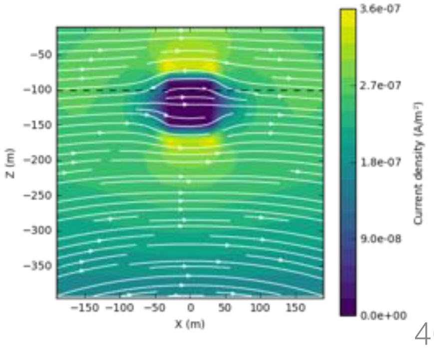
Galvanic current
$t = 1$ ms



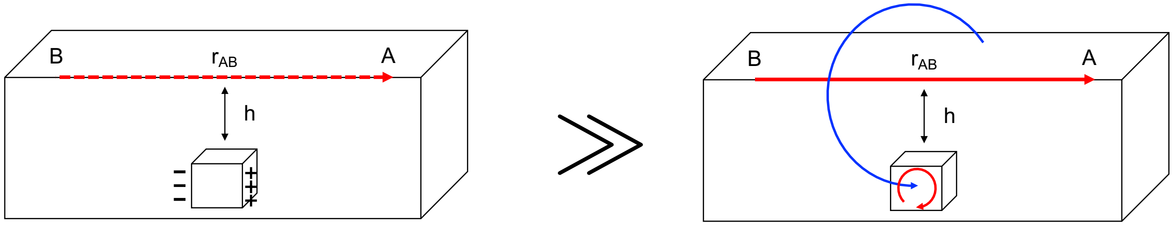
EM induction (galvanic current)

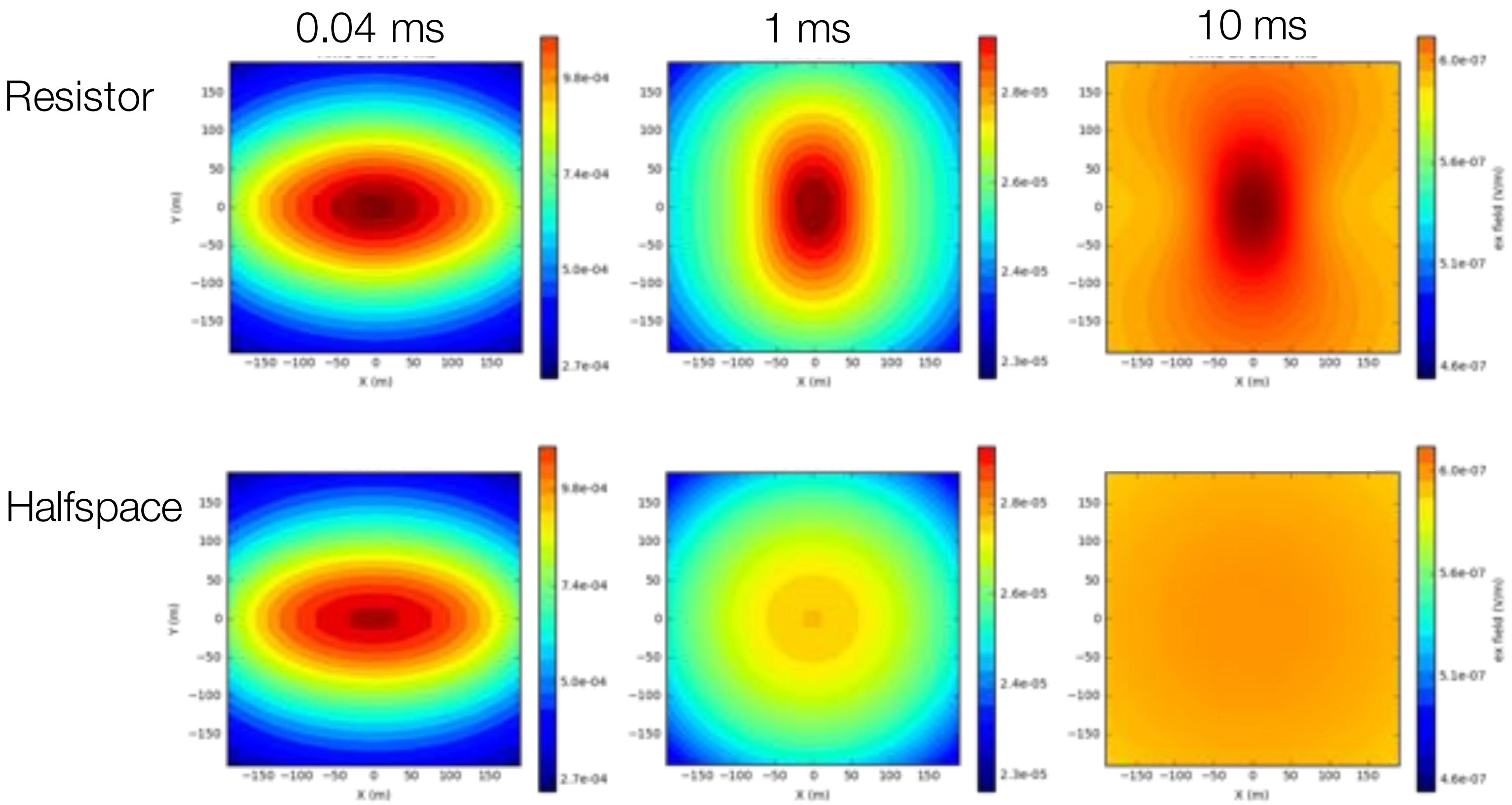


Galvanic current
$t = 10$ ms



Data: e_x field




0.04 ms

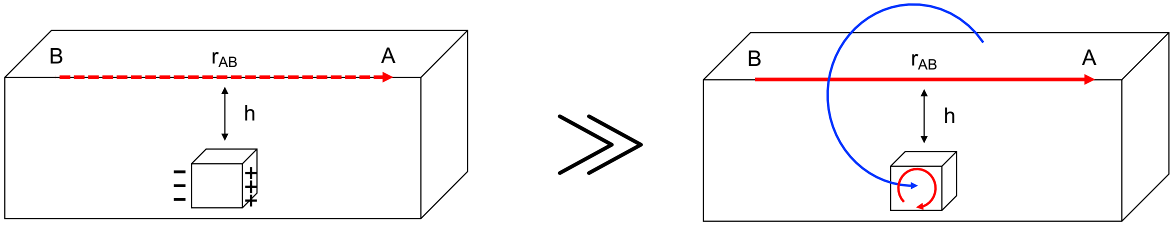
1 ms

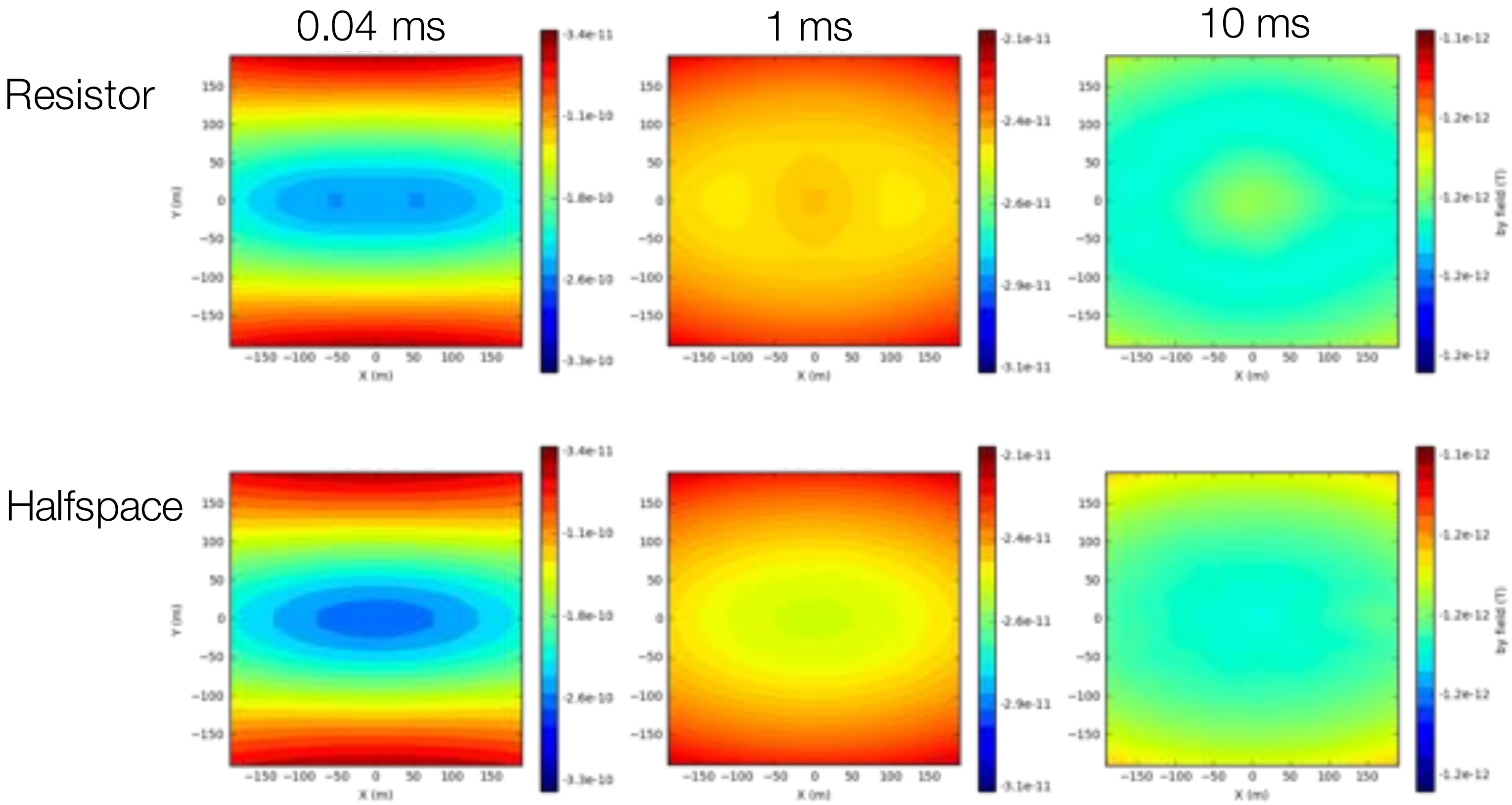
10 ms

Resistor

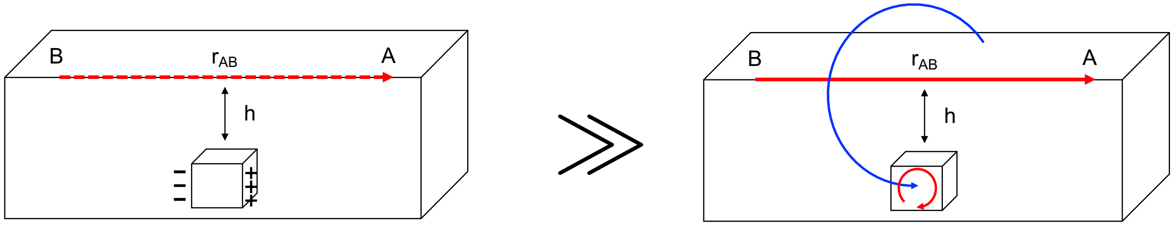
Halfspace

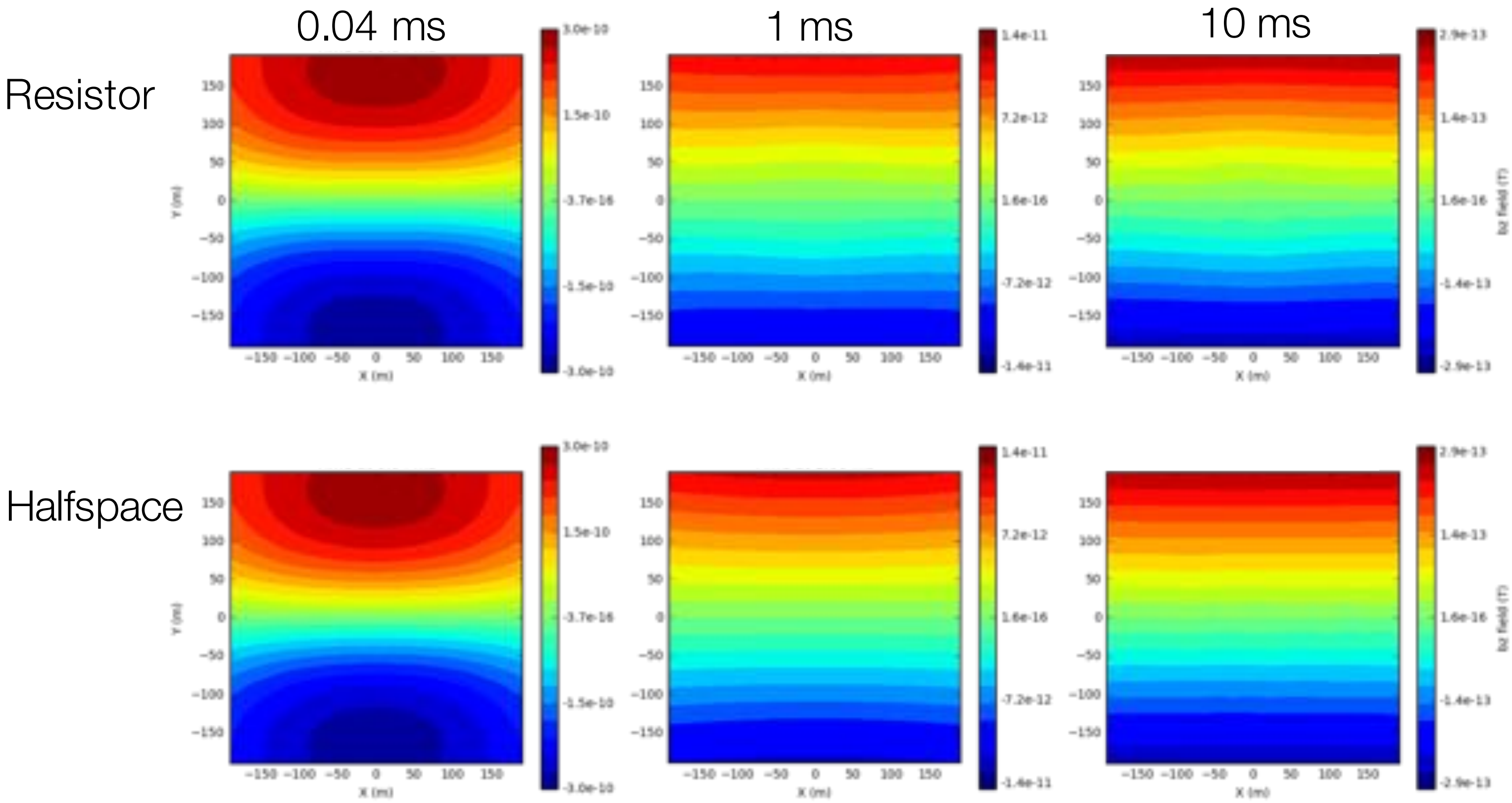
Data: b_y field





Data: b_z field





Data summary

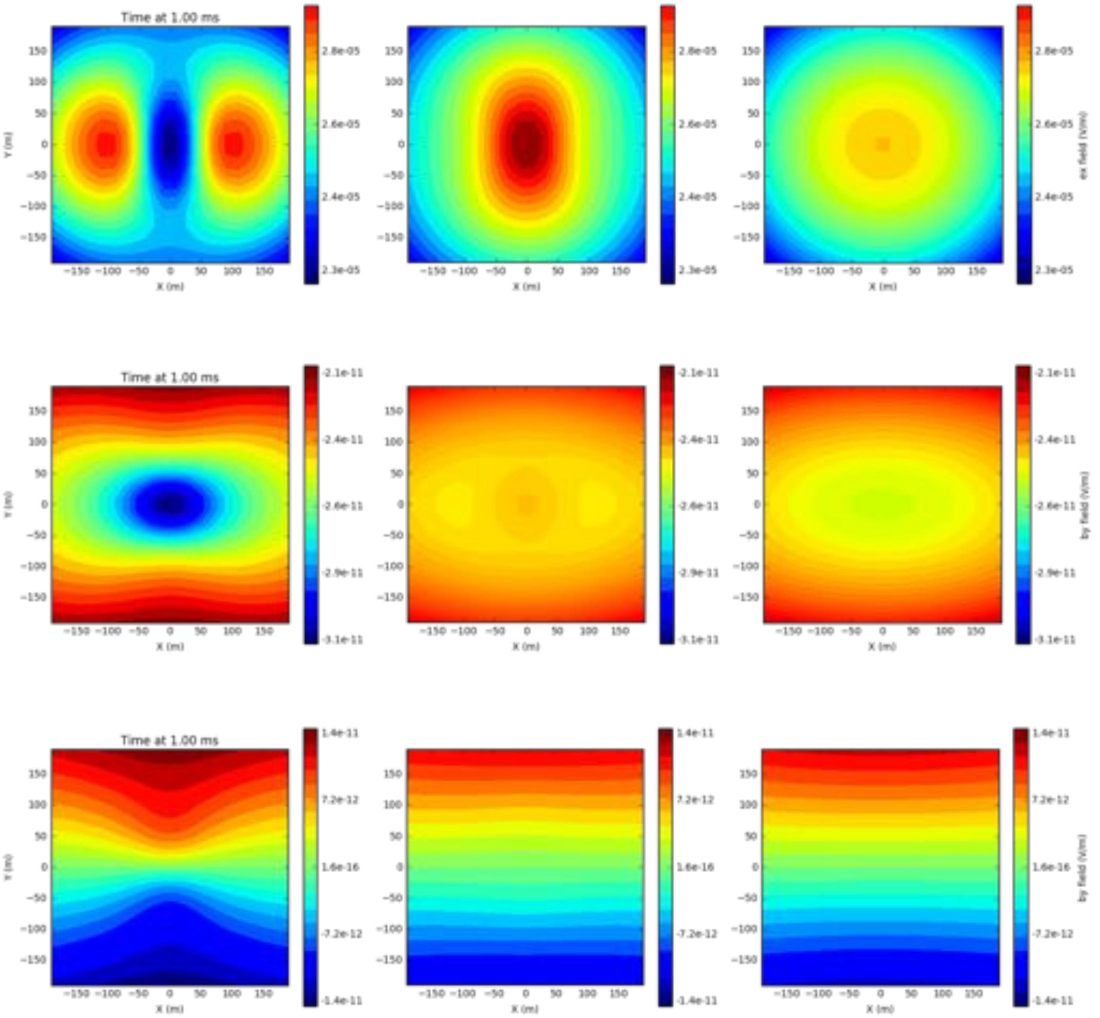
t = 1ms

Conductor Resistor Halfspace

e_x

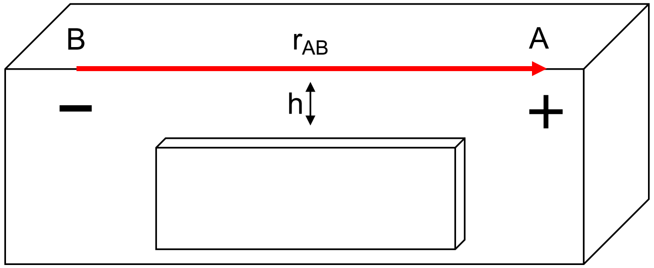
b_y

b_z

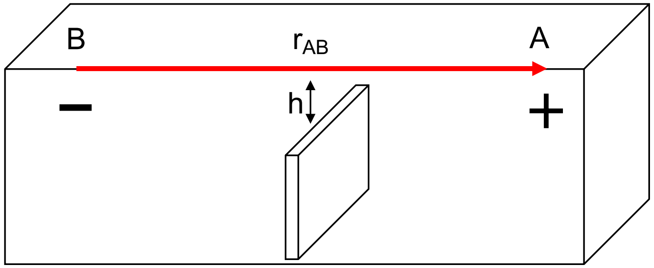


Geometric Complexities

- Coupling: Back to finding thin plates…



- DCR: good coupling
- EM: good coupling



- DCR: poor coupling
- EM: poor coupling

- Arbitrary target requires multiple excitation directions
- Forward simulations necessary

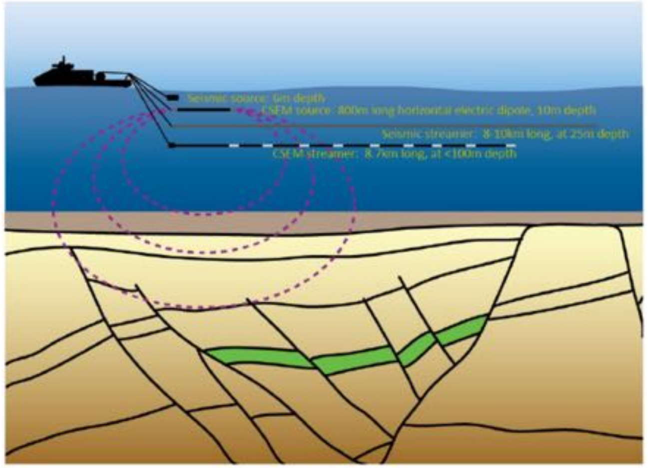
Grounded Sources: Summary

- Basic experiment
- FDEM: Electric dipole in a whole space
- TDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets: currents and data
- Resistive Targets: currents and data

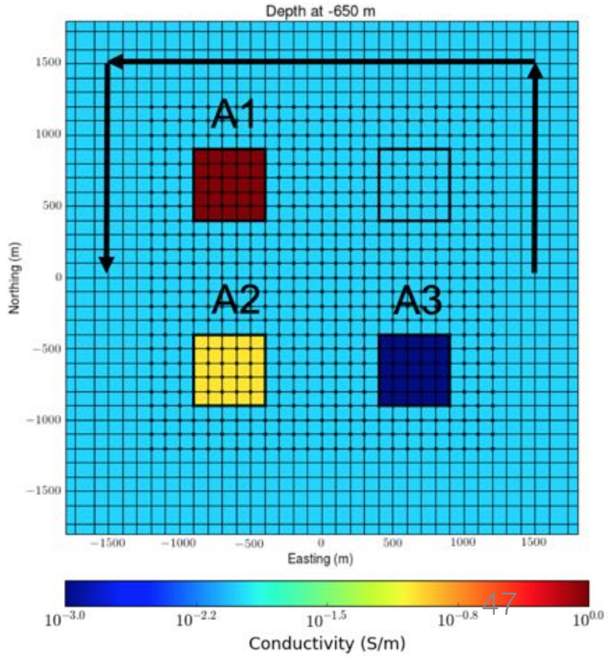
- Questions
- Case History: Barents Sea
- DC/EM Inversion

Grounded sources: two examples

- Marine EM (towed Tx, Rx array)
  - Multiple transmitters, frequencies
  - Looking for a resistive target



- DC/EM inversions (gradient array)
  - Single transmitter
  - Traditionally only DC data used
  - Wires have a large EM effect (contaminates "DC data")
  - EM signal contains useful information…

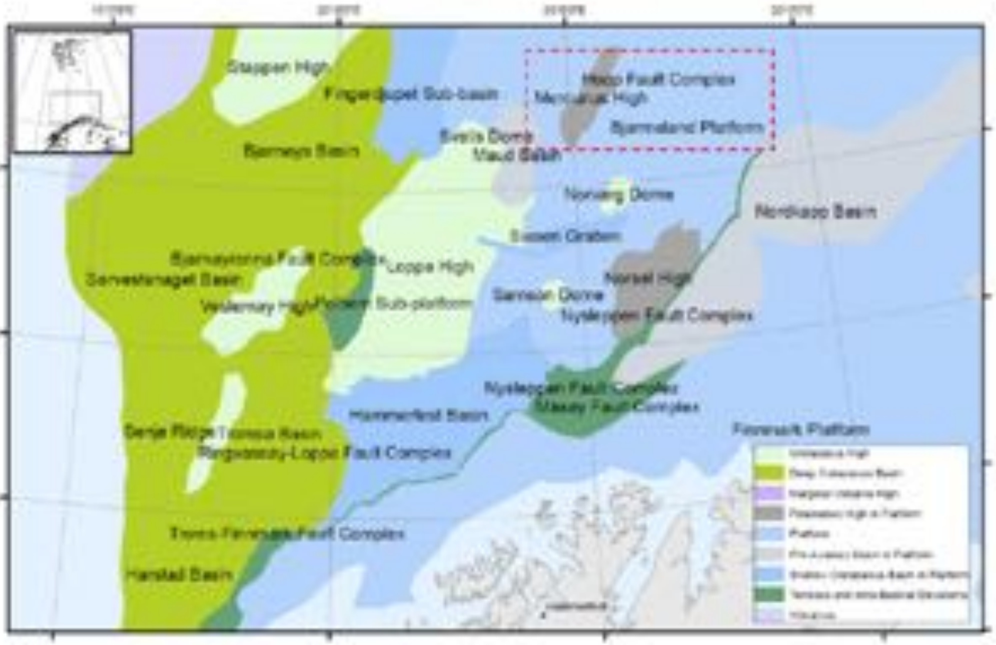


Case History: Barents Sea

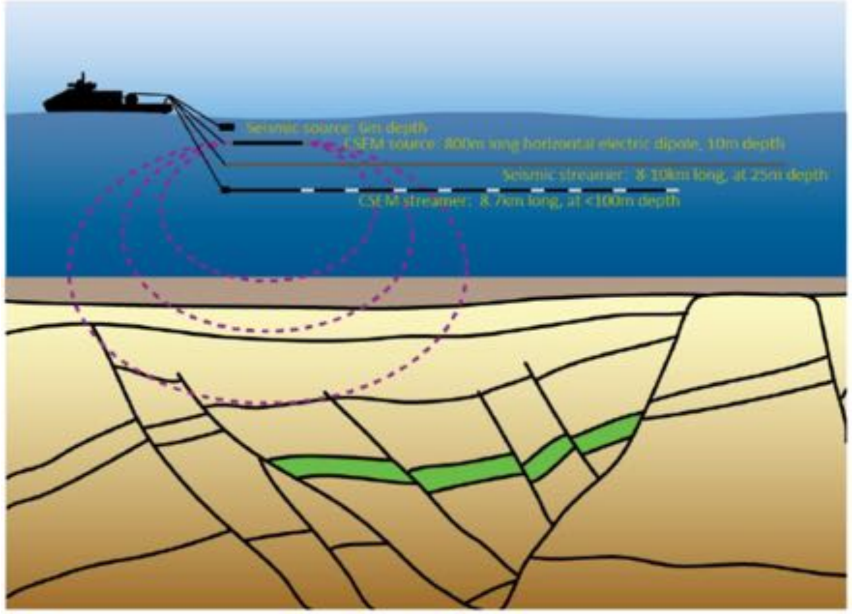
Alvarez et al., 2016. Rock Solid Images

Setup

Hoop Fault Complex, Barents Sea

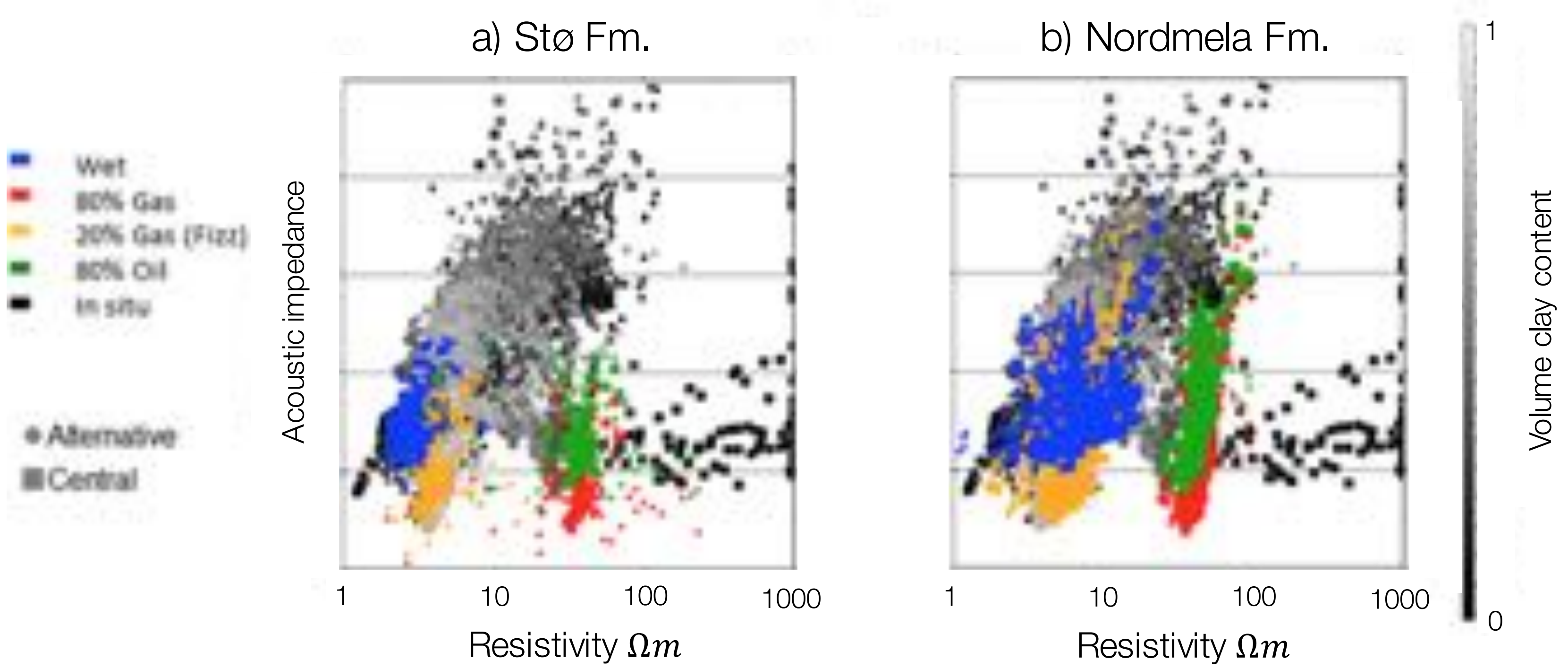


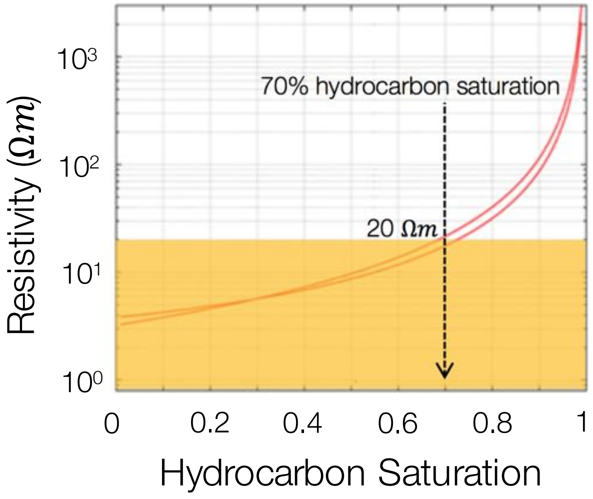
Marine CSEM



- Known hydrocarbon reservoirs within the Hoop Fault Complex, Barents Sea.
- Seismic can locate oil and gas reservoirs but cannot always determine hydrocarbon saturation (in particular fizz gas)
- Seismic, borehole and CSEM data used to characterize reservoir
  - fluid, porosity, clay content, and hydrocarbon saturation

Properties

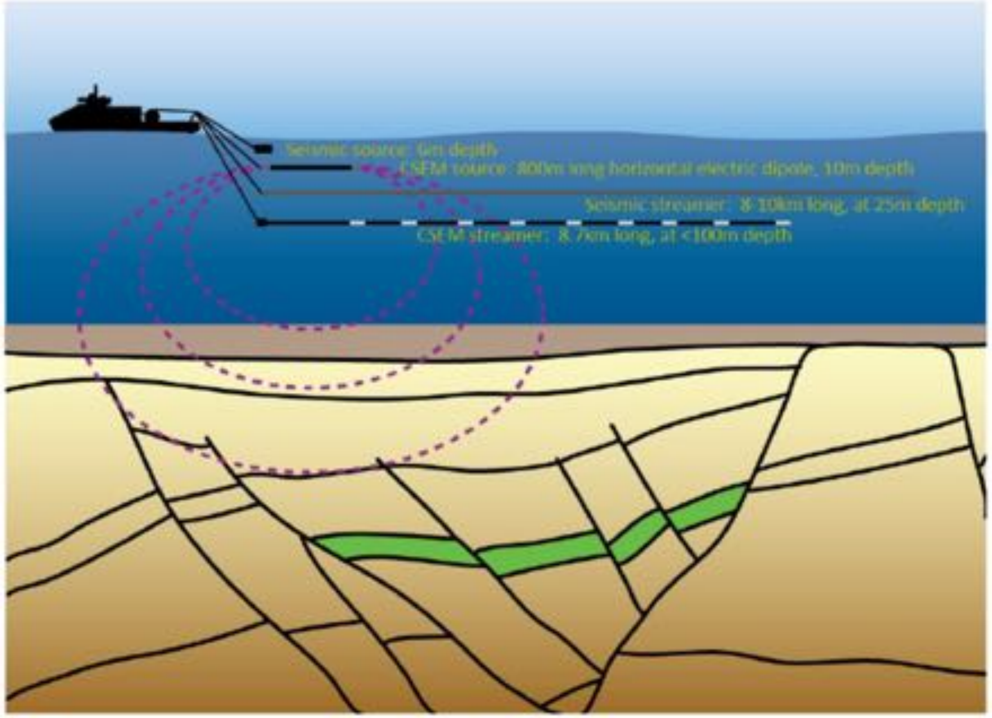




- Highly hydrocarbon-saturated reservoir (< 30% water-wet) significant resistivity
- CSEM can differentiate high from low quality reservoirs

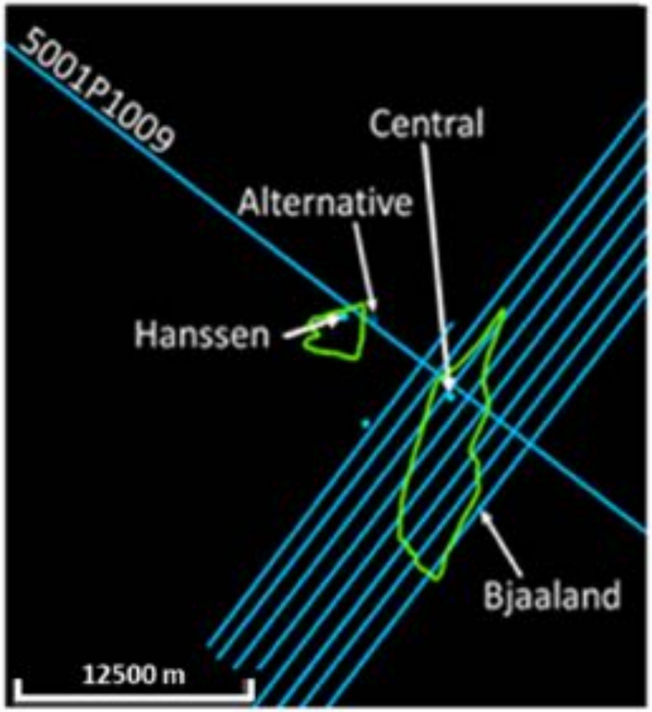
Survey

Towed CSEM and 2D seismic



- 6 lines of 2D seismic and towed streamer CSEM data.
- 72 receivers collected CSEM data
    - offsets from 31m to 7.8 km
- CSEM frequencies: 0.2 Hz to 3 Hz.

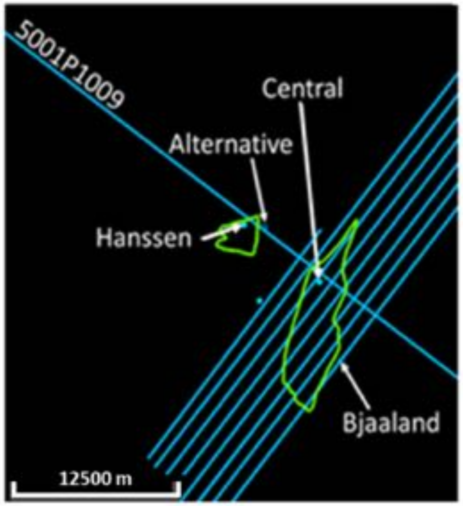
Survey lines



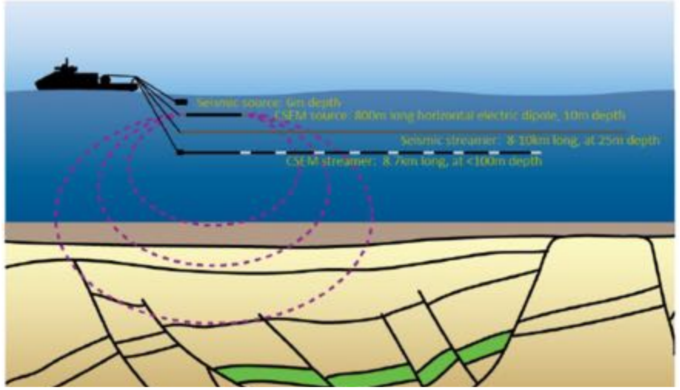
Alternative	Control well, dry
Central	Control well, productive
Hanssen	Validation well
Bjaaland	Validation well

CSEM Data

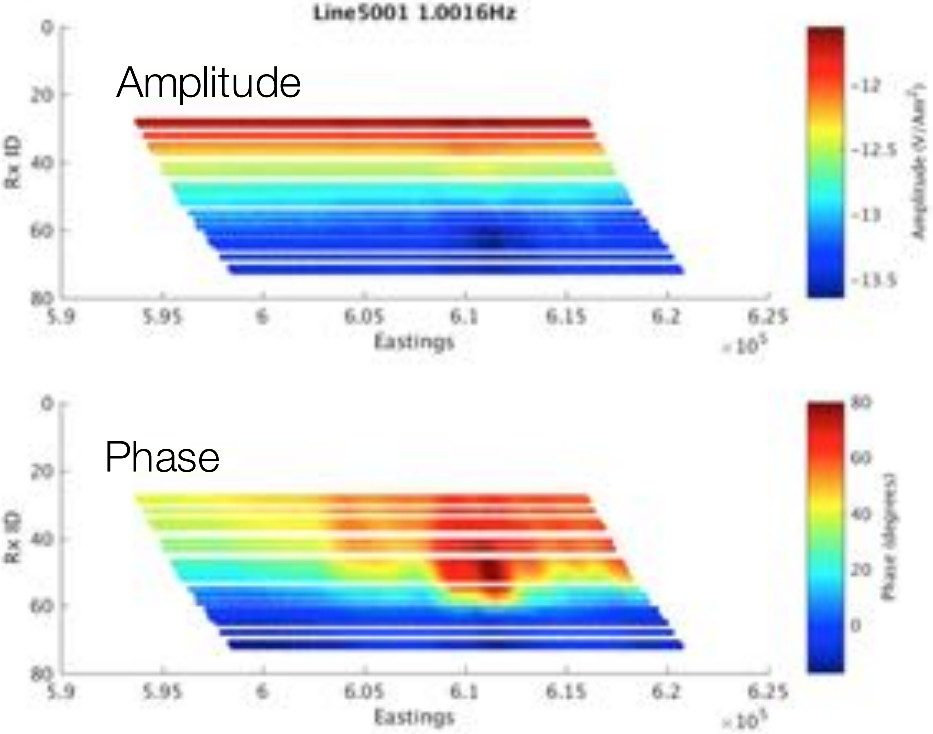
Survey lines



Towed-streamer EM



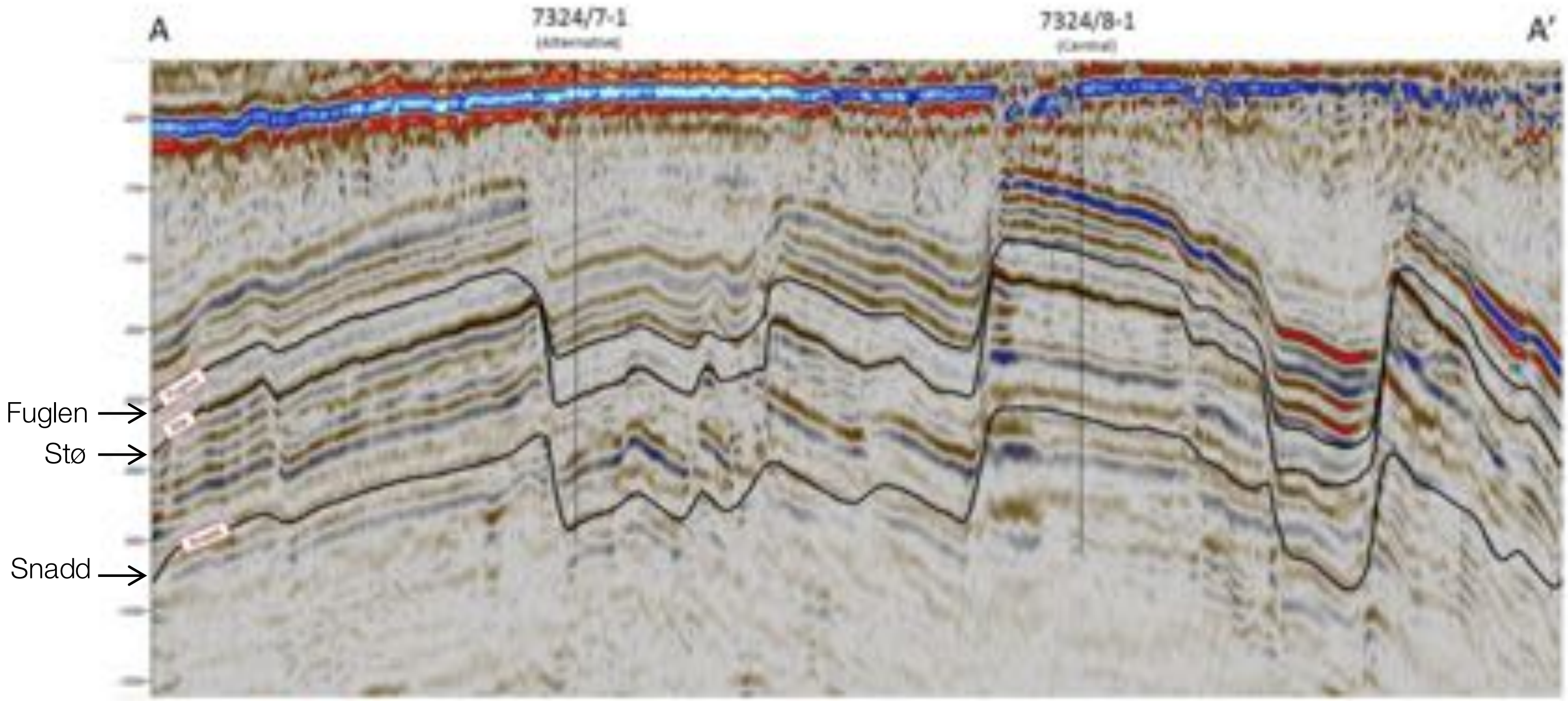
CSEM data over central reservoir (1 Hz)

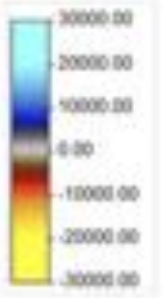


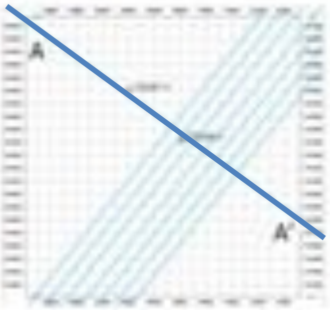
- Significant phase response over Central reservoir

Seismic data

Seismic section: Line 5001





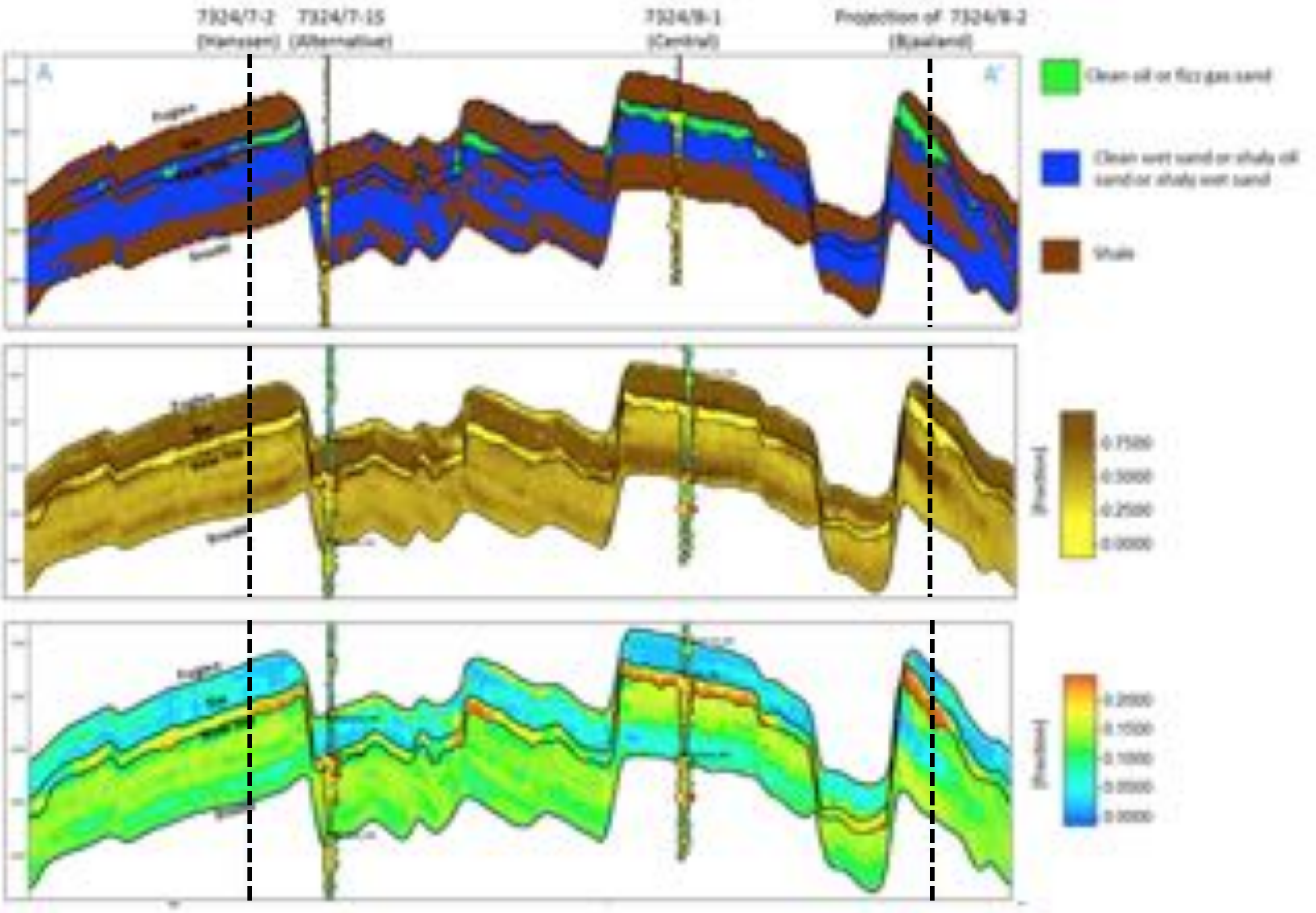


Well-Log and Seismic Inversion

Litho-fluid Facies

Clay Content

Total Porosity



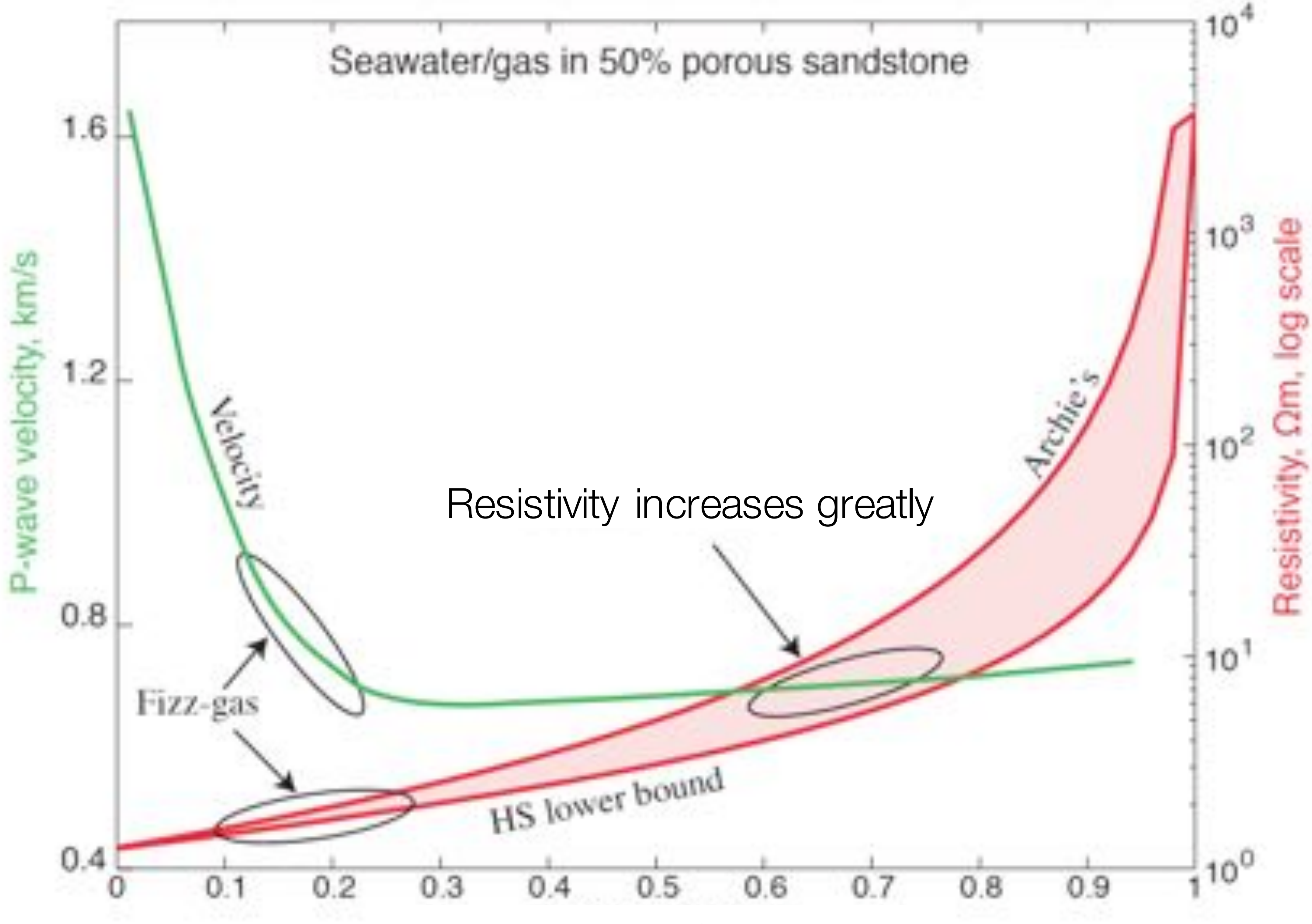
Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

Bjaaland
Validation well

Revisiting physical properties

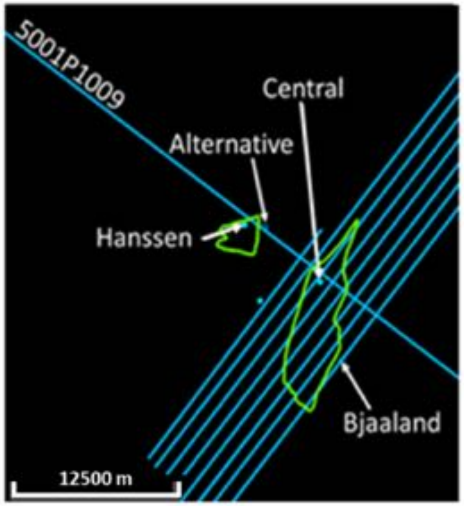


Resistivity increases greatly

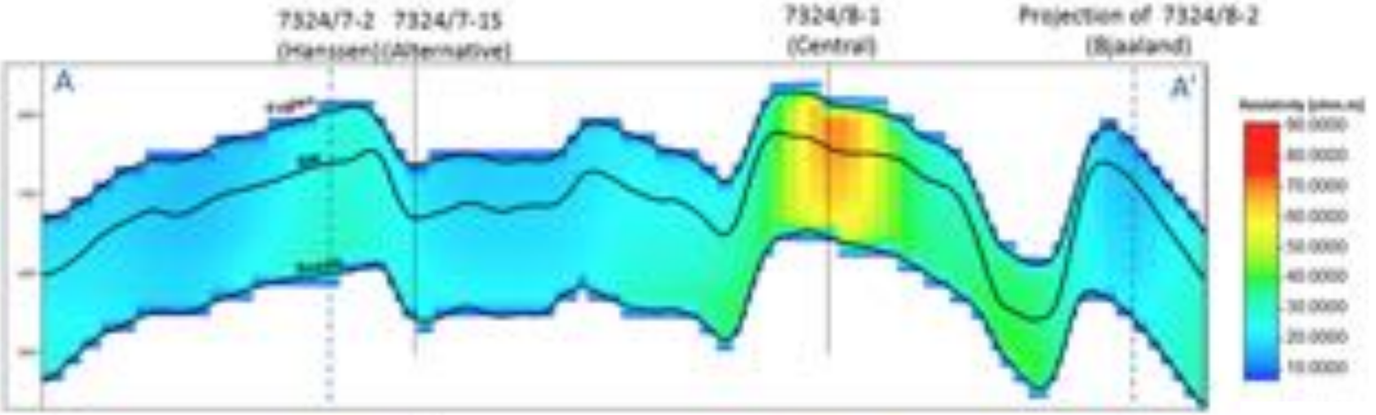
Hydrocarbon Saturation

Processing: CSEM Inversion

Survey lines



Vertical resistivity section along profile line 5001



Hanssen
Validation well

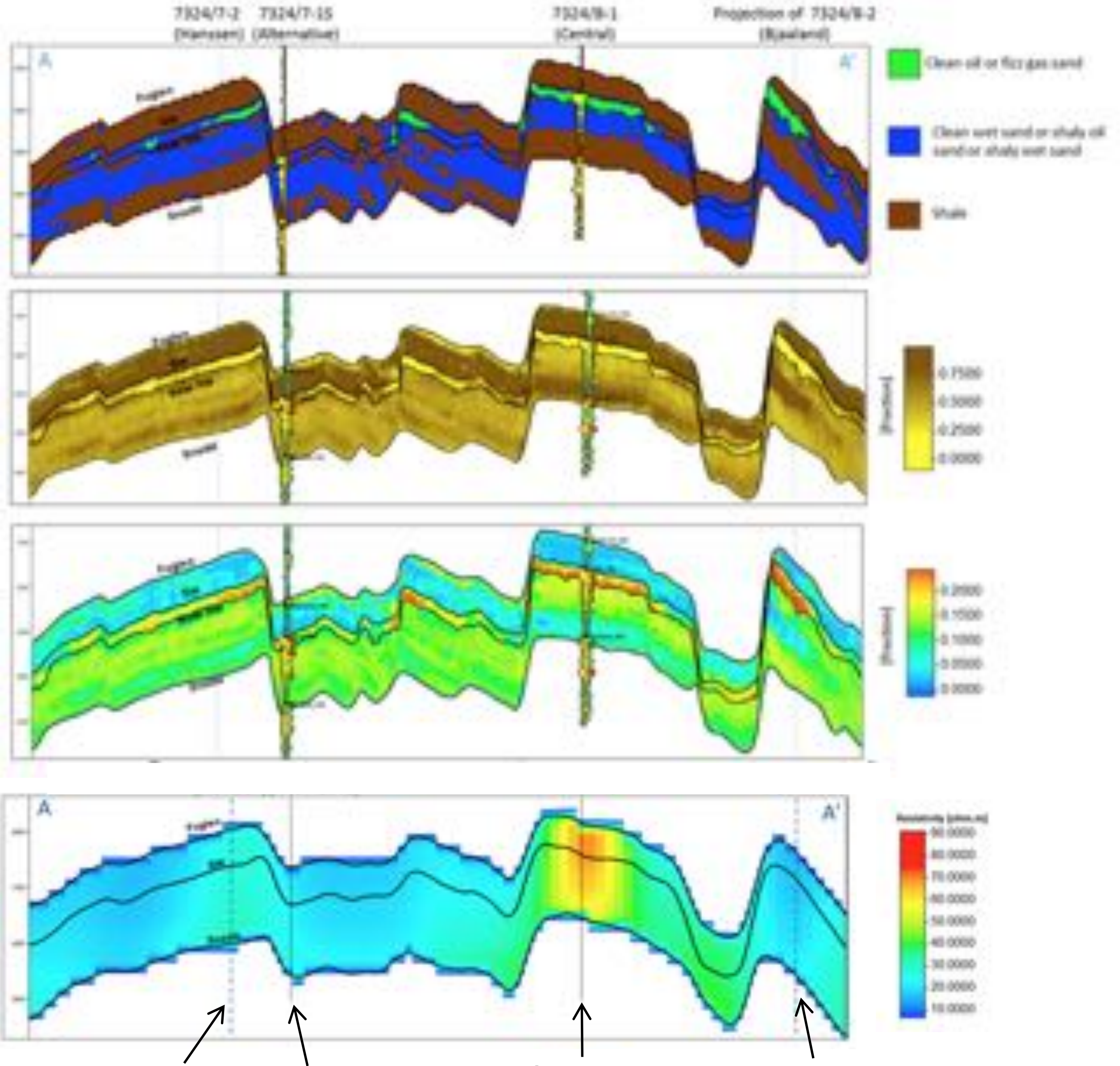
Alternative
Control, dry

Central
Control, productive

Bjaaland
Validation well

- Inversion shows strong resistor at Central and a secondary resistor at Hanssen.

Processing: Multi-physics Approach



Litho-fluid Facies

Clay Content

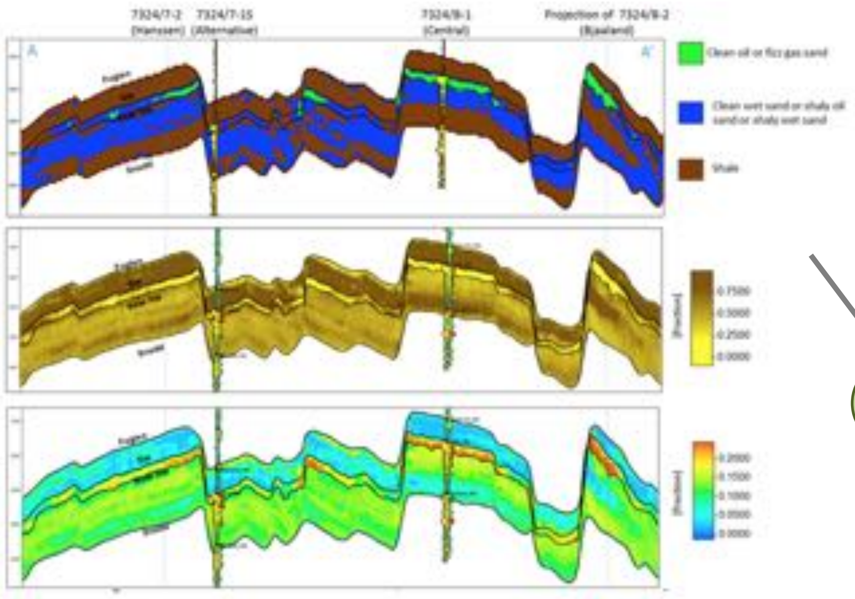
Total Porosity

Resistivity

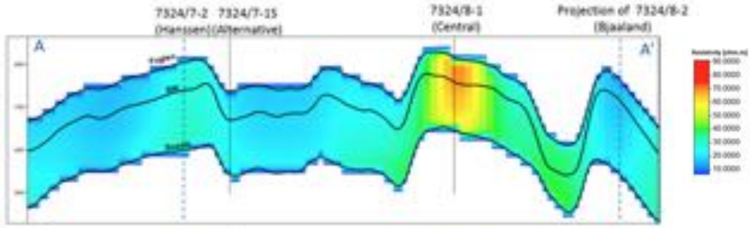
Hanssen **Alternative** **Central** **Bjaaland**

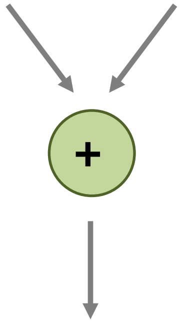
Interpretation & Synthesis

Seismic

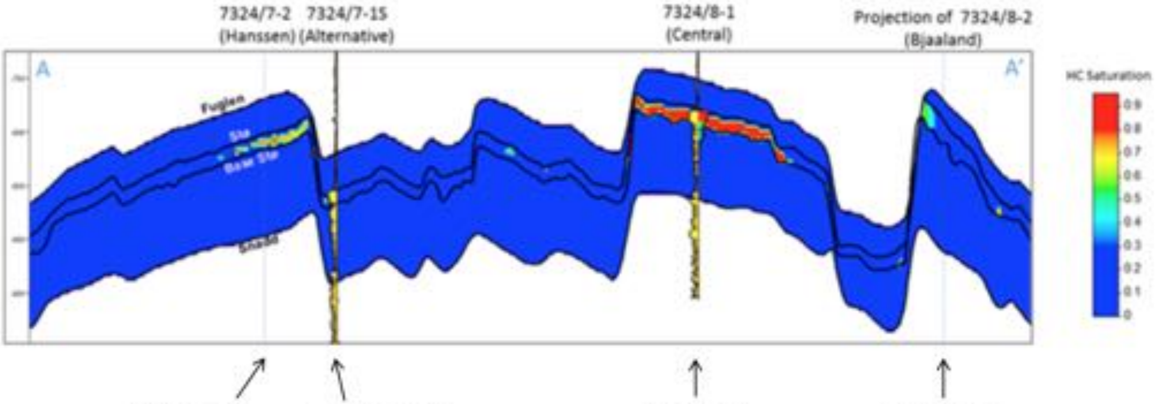


EM





Hydrocarbon saturation



Hanssen
Validation well
productive

Alternative
Control, dry

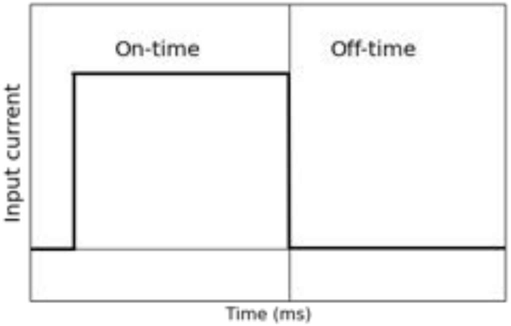
Central
Control, productive

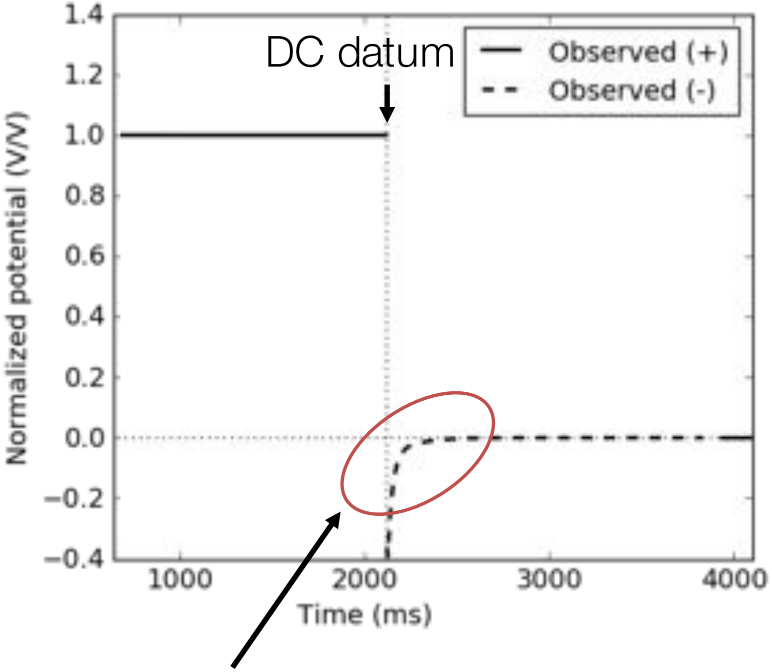
Bjaaland
Validation well
dry

DC/EM Inversion

DC/EM: Goals

- Standard DCR time domain waveform
- Compare:
  - Inversions from DC data
  - Inversions from EM data
- Illustrate the value of data which is often discarded
- Numerical example from a gradient array



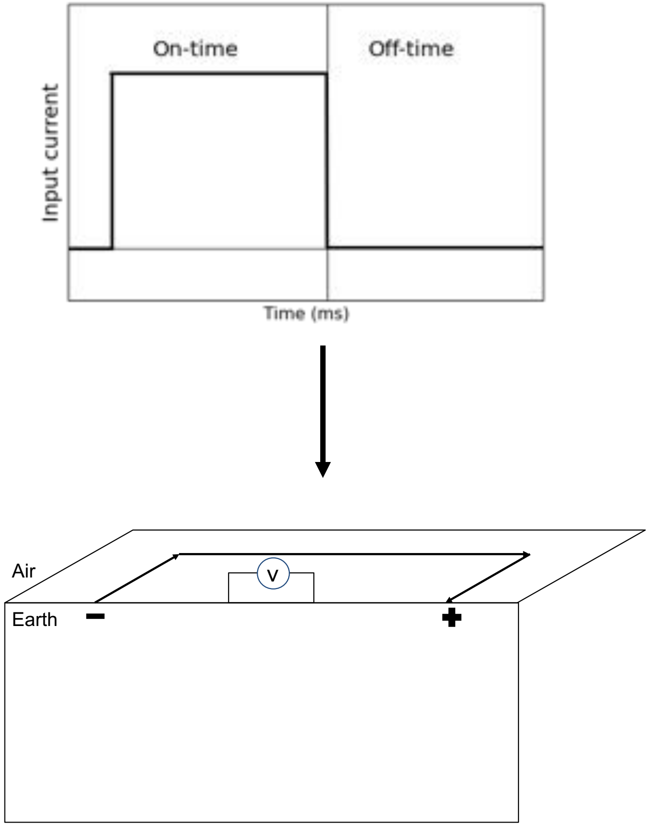


DC datum

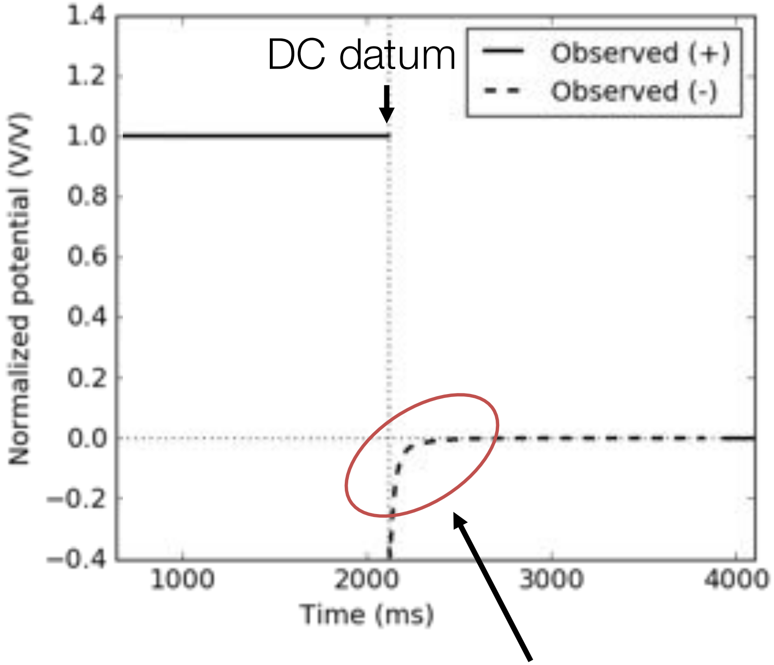
EM portion
Generally considered noise

Survey and Data

Transmitter



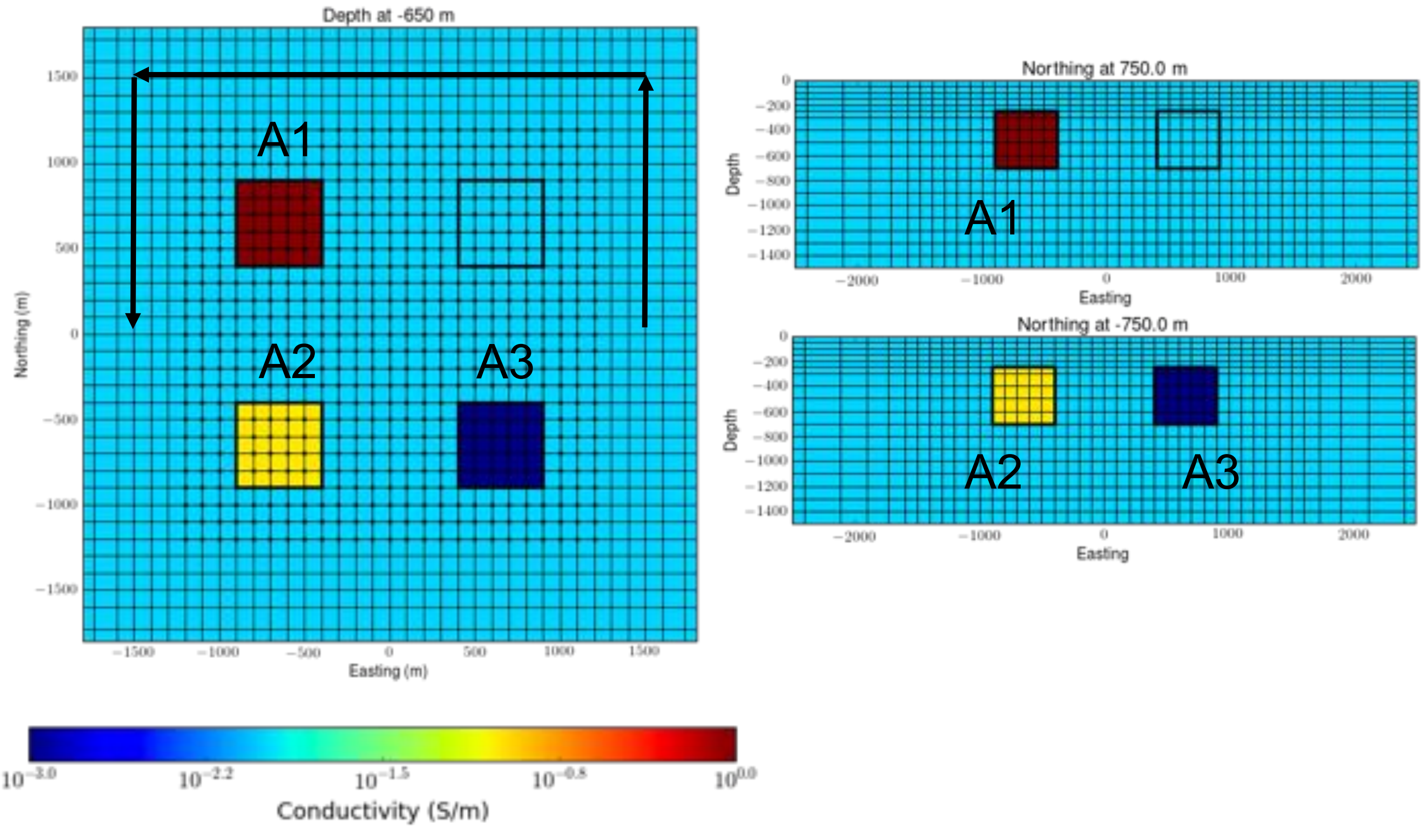
Measured Voltage



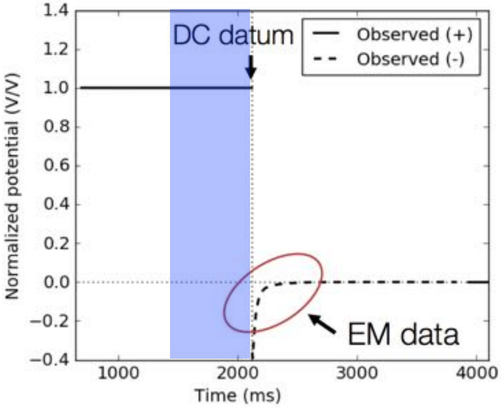
EM portion
Generally considered noise

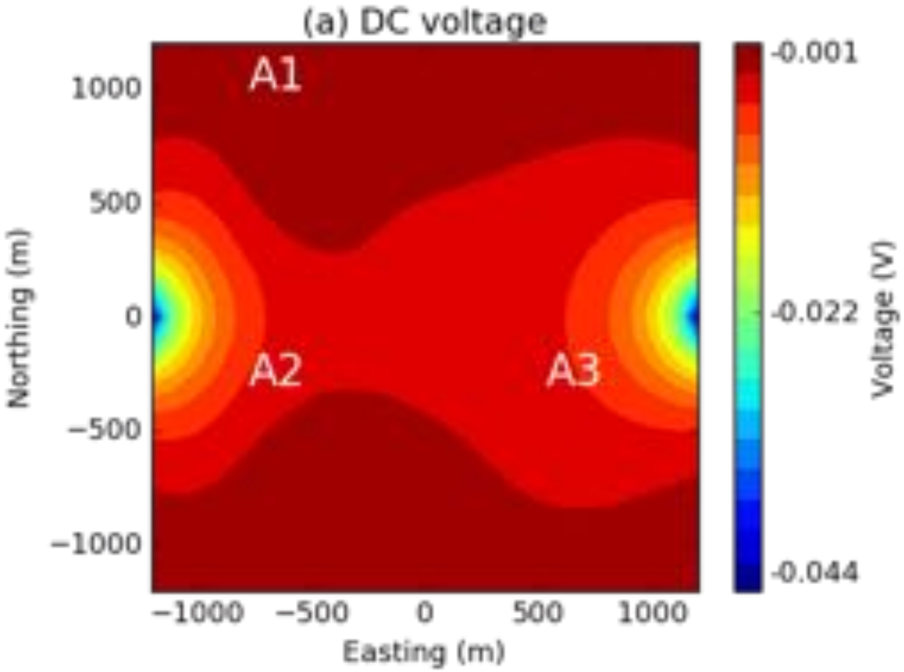
Gradient array

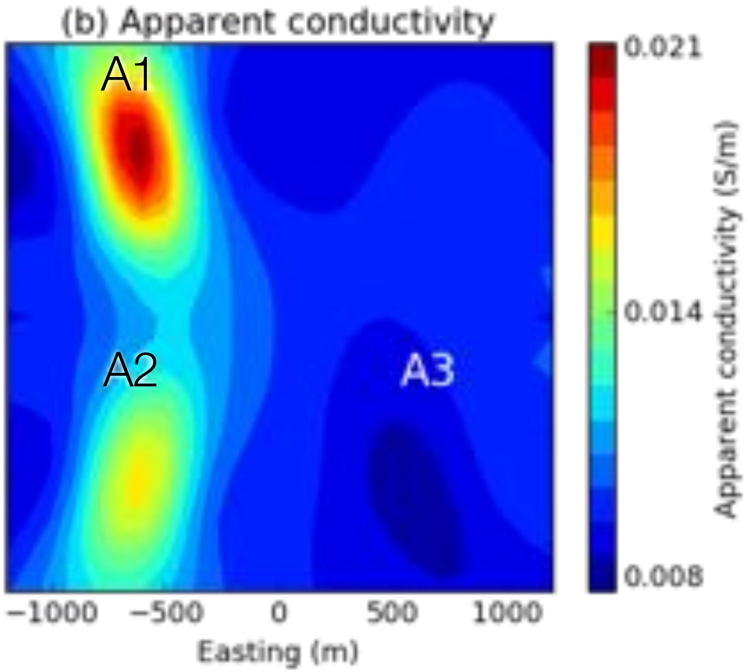
- Model
  - A1: high conductivity
  - A2: moderate conductivity
  - A3: resistive
- Survey
  - 200m bi-pole (625 data)
  - times: 1-600ms



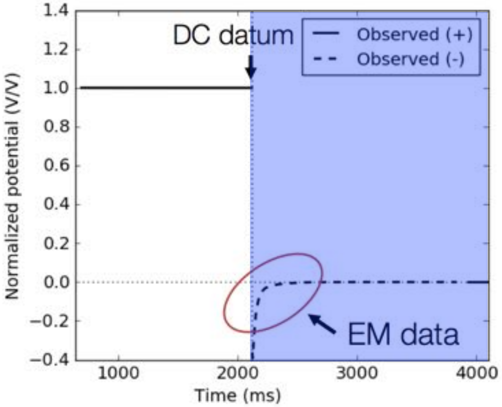
DC data



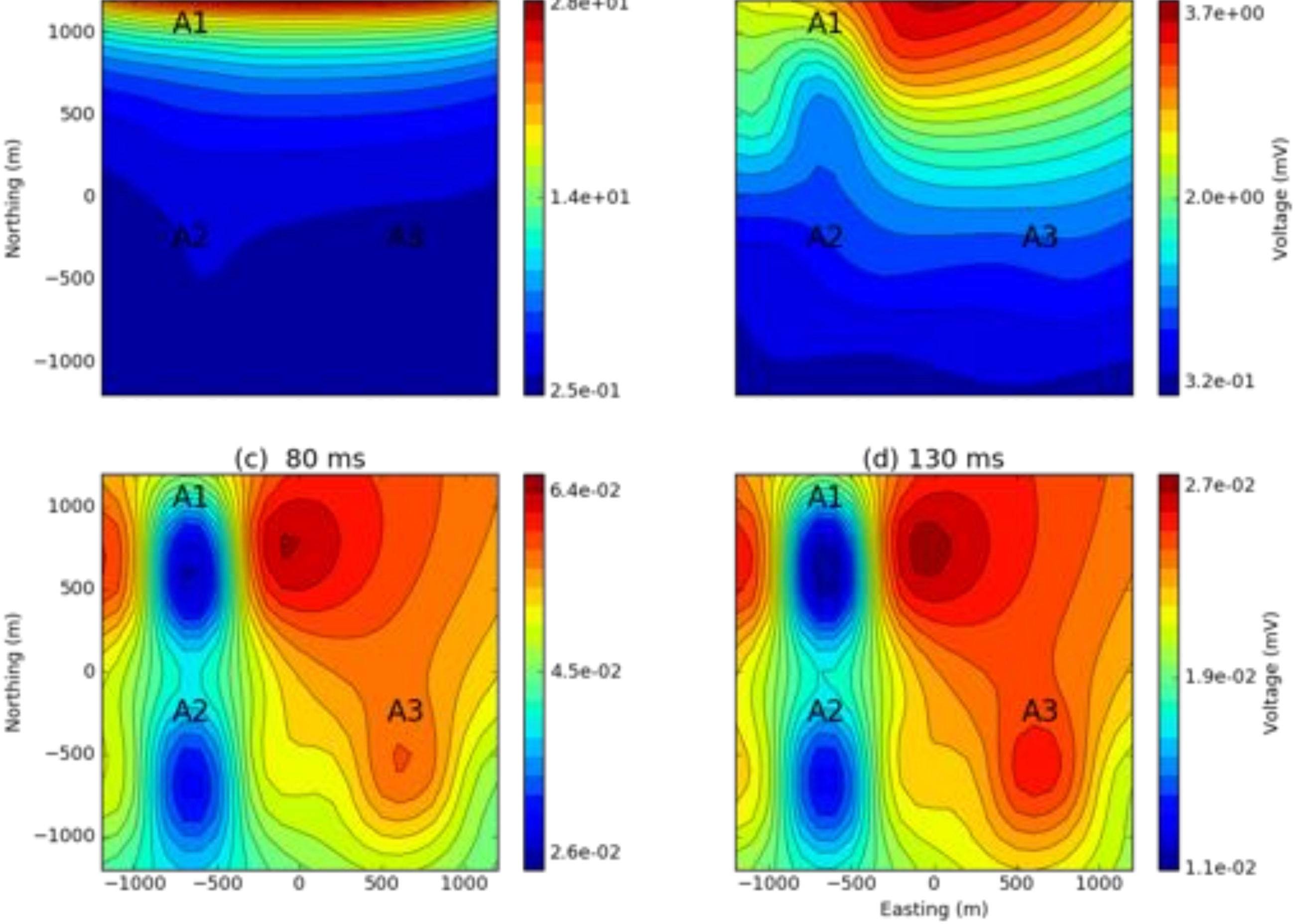

(a) DC voltage


(b) Apparent conductivity

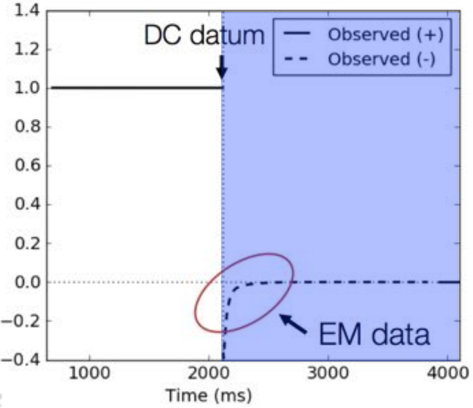
Off-time data



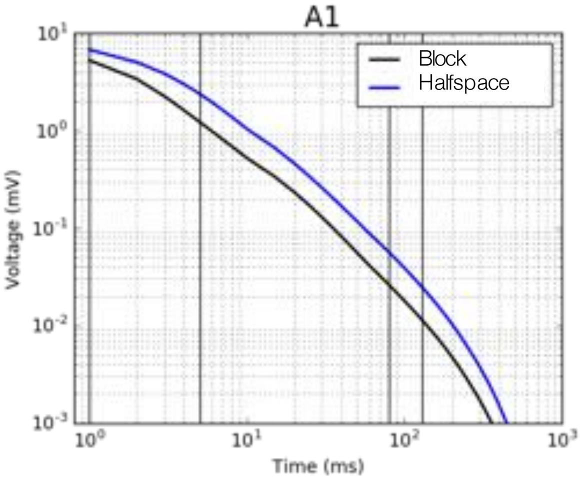
- TDEM data

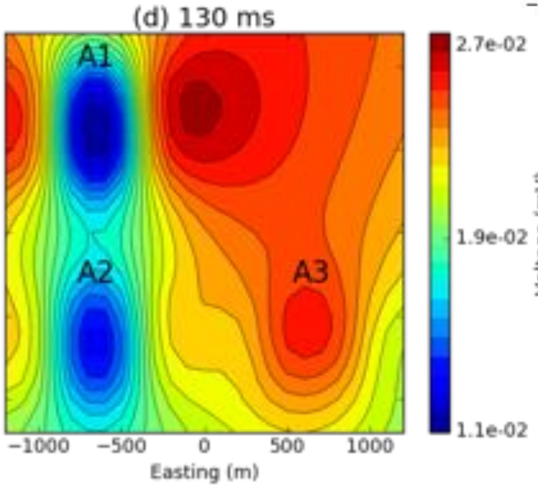


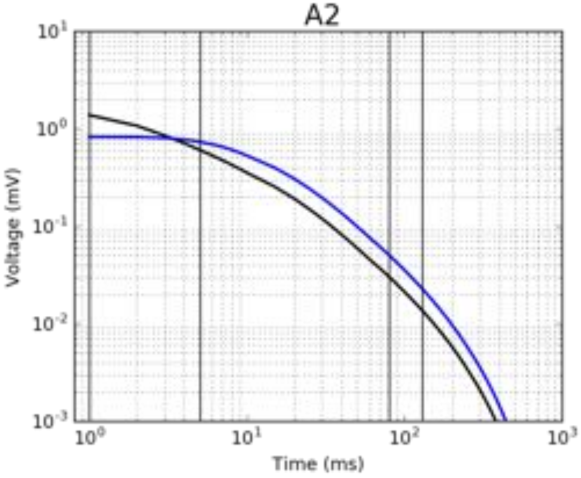
Off-time data

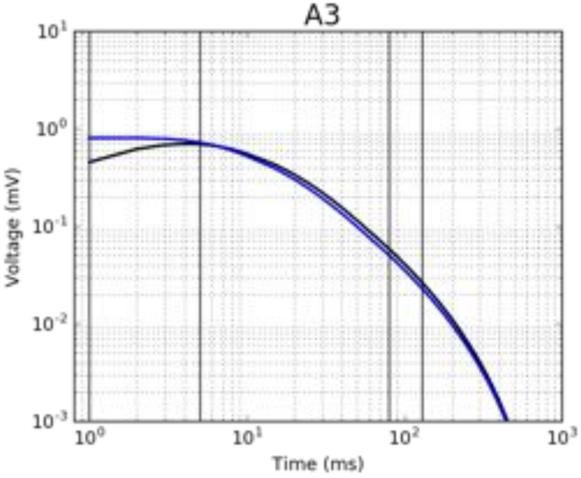


- E_x Decay curves at A1-A3


A1


(d) 130 ms

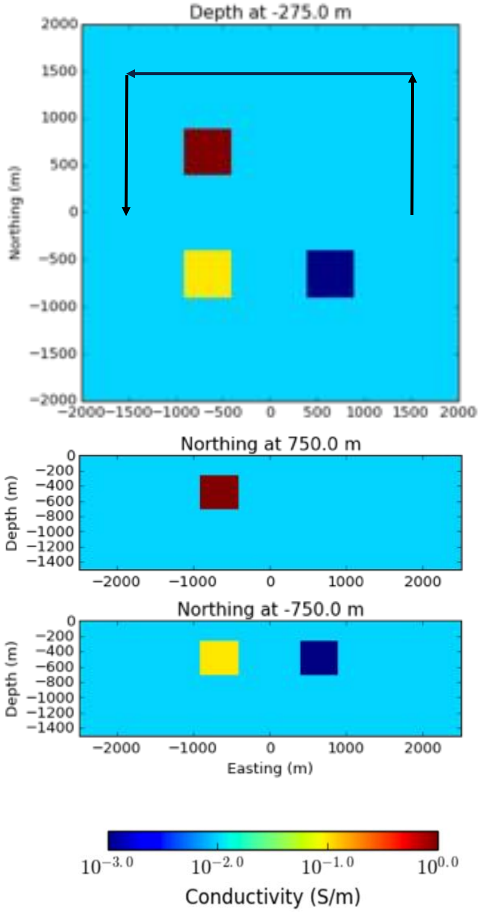

A2


A3

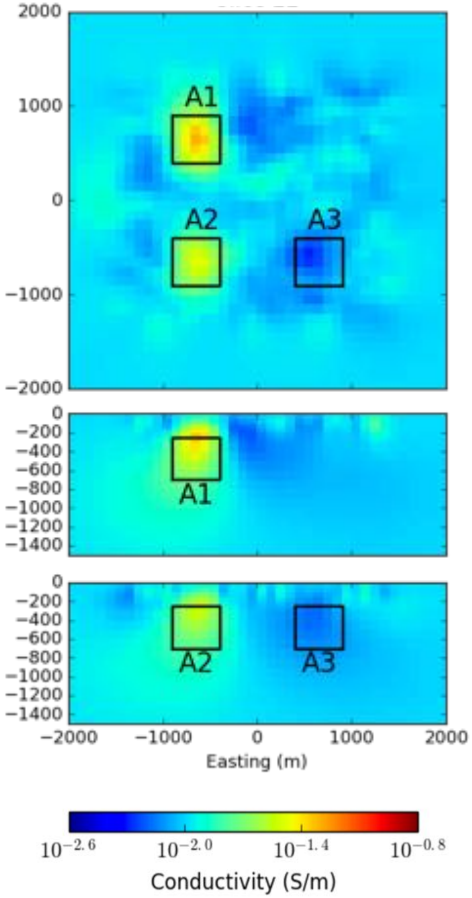
DC inversion

- Recovered 3D conductivity

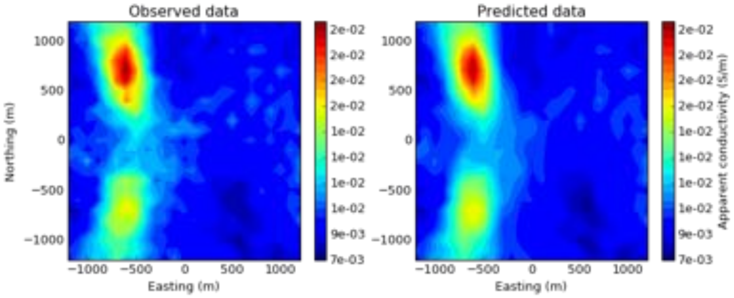
True



Recovered



Apparent conductivity

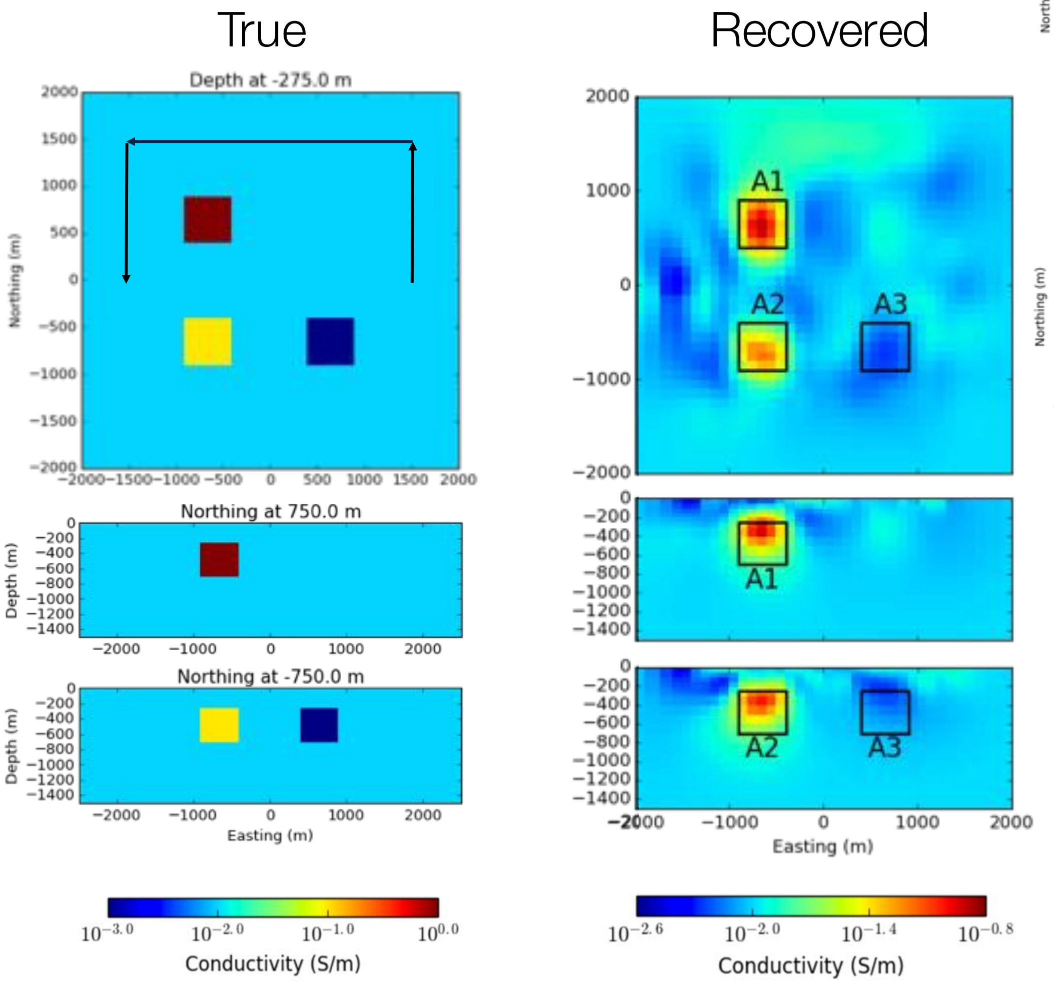


- Depth weighting
  - Compensate for high sensitivity near surface (similar to mag.)

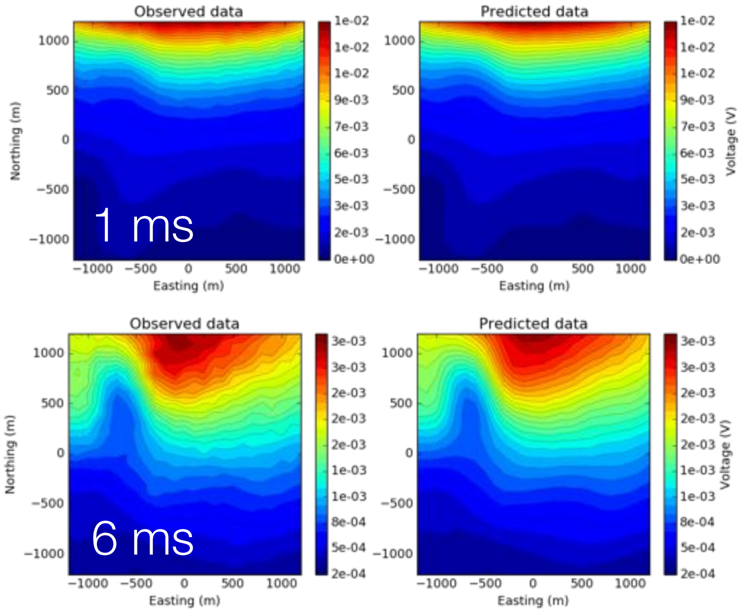
$$\frac{1}{(z - z_0)^3}$$

EM inversion

- Recovered 3D conductivity

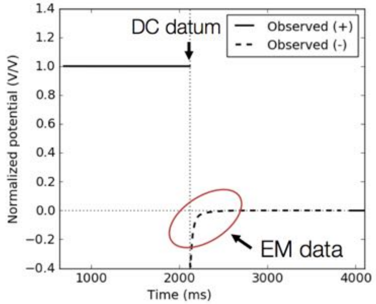

True

Recovered

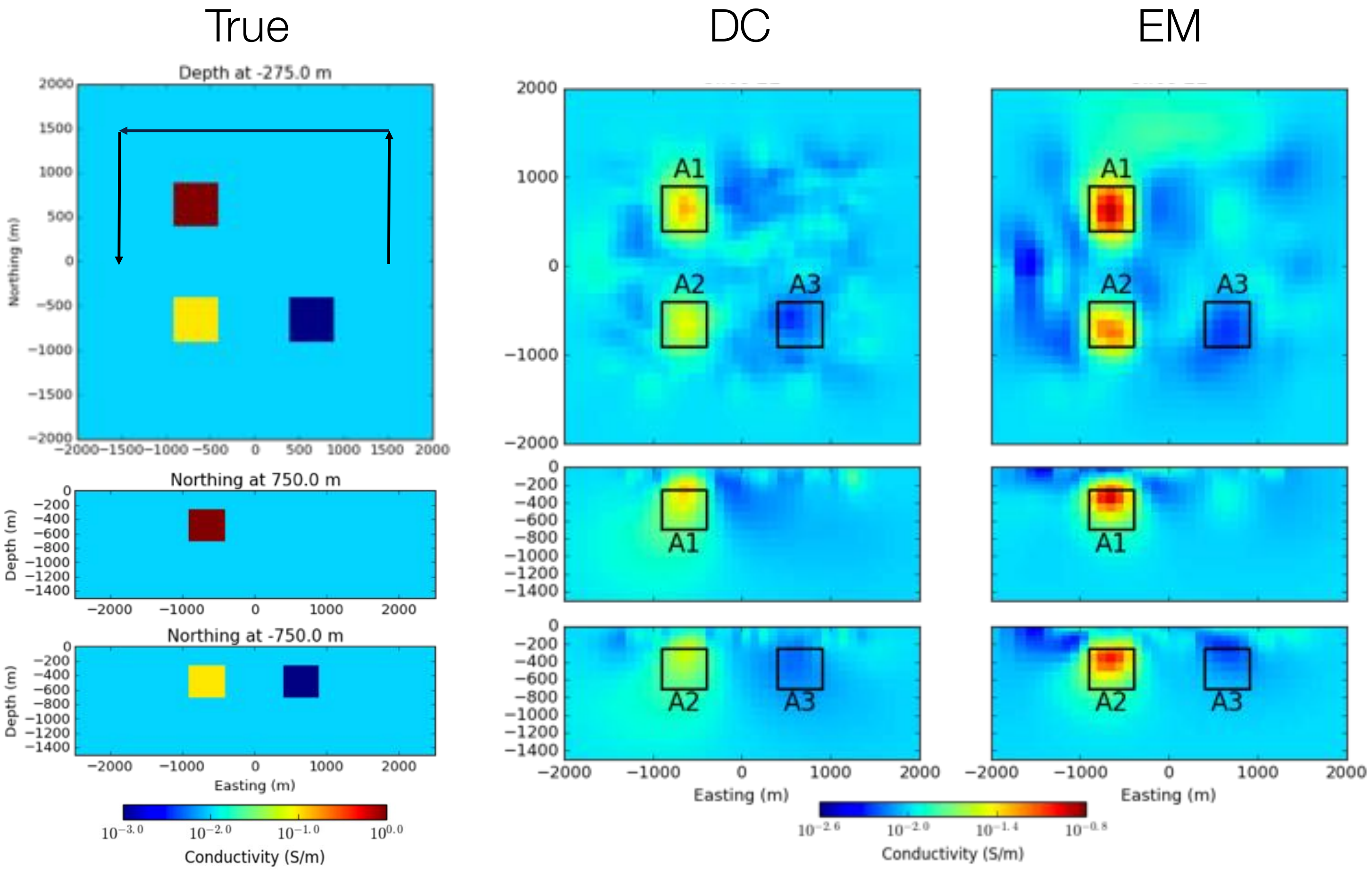


- No depth weighting

Conductivity models



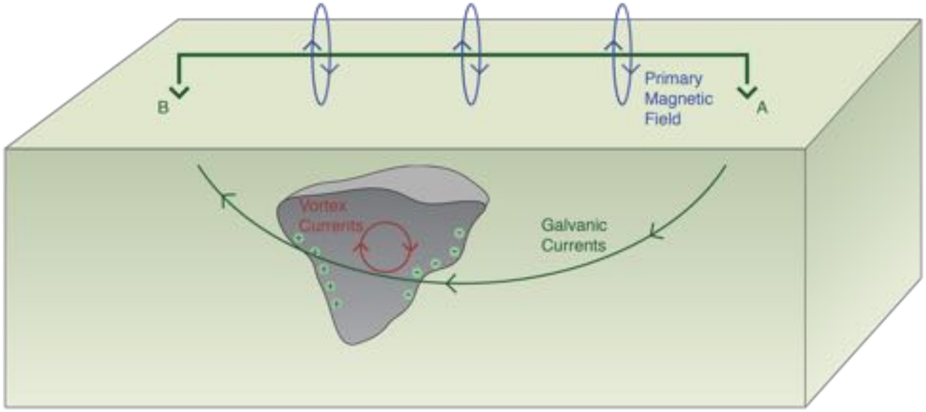
- True, DC, and TEM conductivities



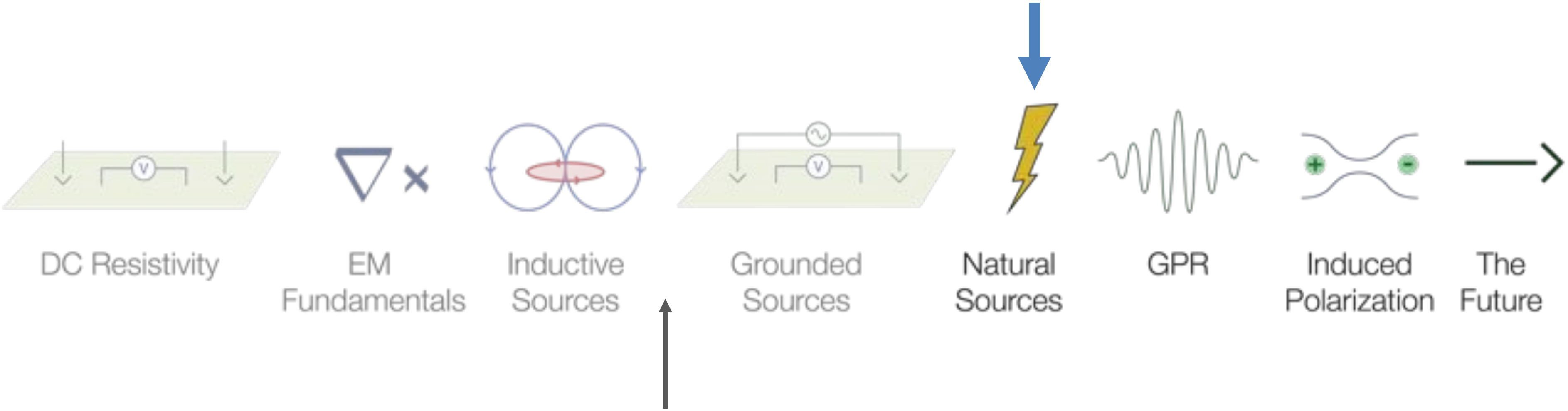
EM data contain signal

Summary

- Basic experiment
- FDEM: Electric dipole in a whole space
- TDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets: currents and data
- Resistive Targets: currents and data
- Case History: Barents Sea
- DC/EM Inversion



End of Grounded Sources



Next up

DC Resistivity

EM Fundamentals

Inductive Sources

Grounded Sources

Natural Sources

GPR

Induced Polarization

The Future

Lunch: Play with apps