EM: Grounded Sources

DISC

2017

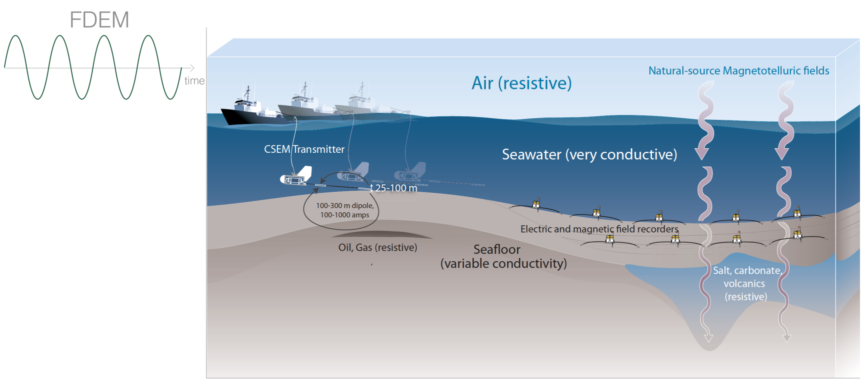
Electromagnetics
Fundamentals and Applications

Outline

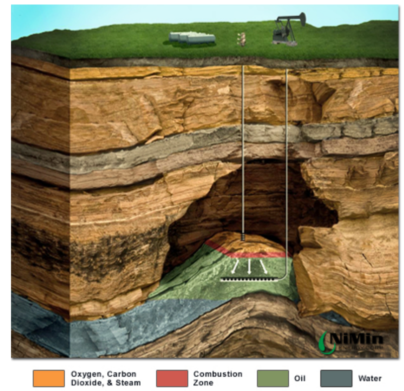
- Basic experiment
- FDEM: Electric dipole in a whole space
- TDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets: currents and data
- Resistive Targets: currents and data
- Case History: Barents Sea
- Synthetic Example: Gradient Array

Motivational examples

Marine EM for hydrocarbon



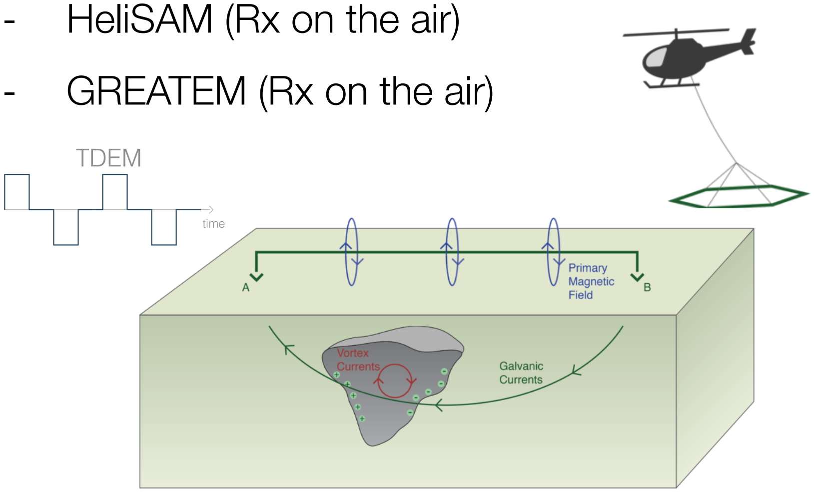
Oil and Gas



Gas hydrates

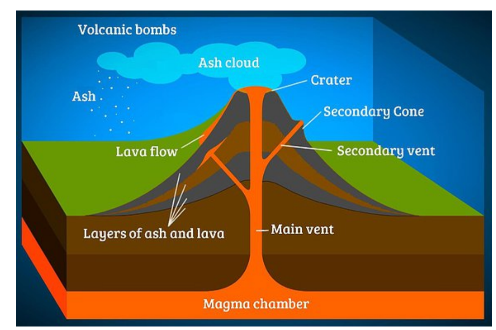
Galvanic source TEM

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

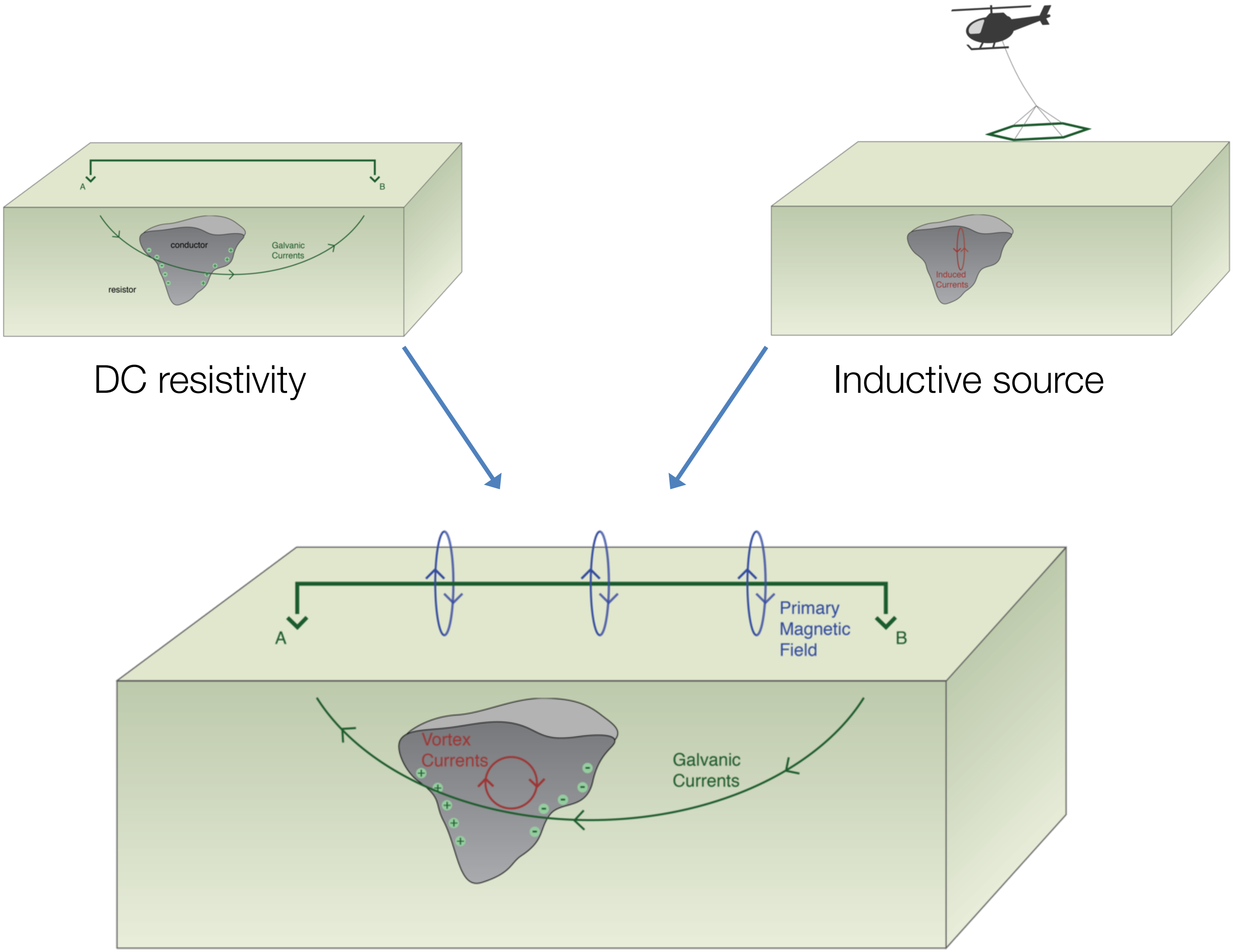


Minerals

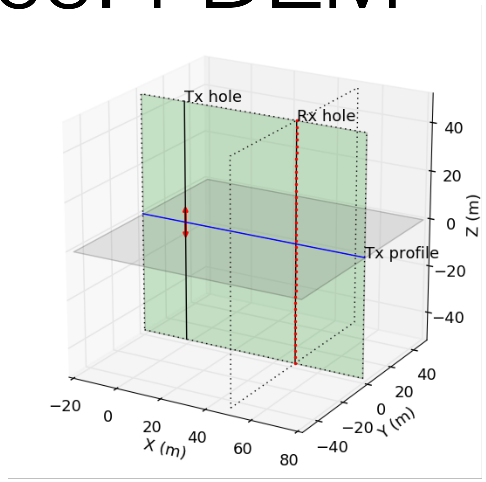
Volcanoes



Basic experiment

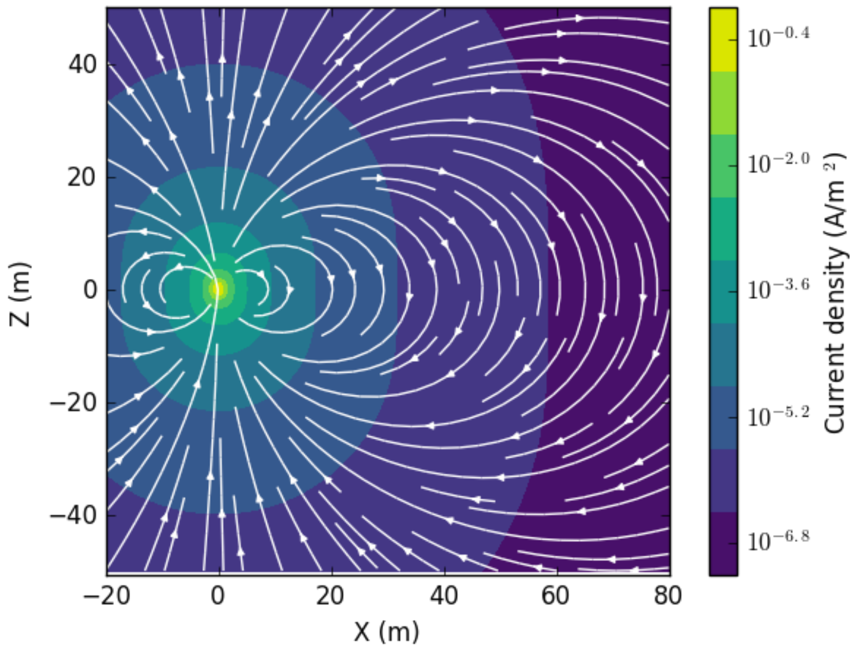


Electric Dipole in a whole space: FDEM



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

DC current density



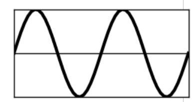
$$\mathbf{E}_{DC}(\mathbf{r}) = \frac{1}{4\pi\sigma|\mathbf{r}|^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m}\right)$$

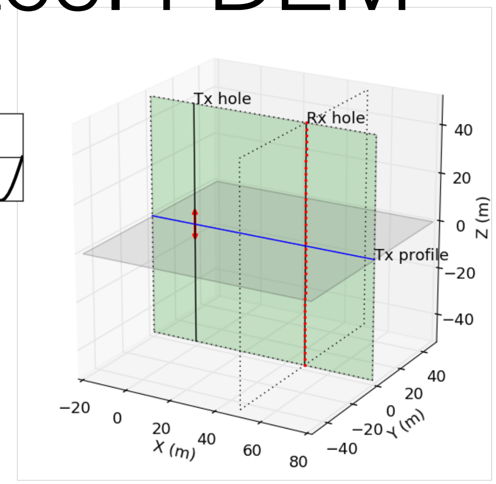
$$\mathbf{J}_{DC}(\mathbf{r}) = \frac{1}{4\pi|\mathbf{r}|^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m}\right)$$

- Geometric decay: $1/r^3$
- Currents path is geometric for homogeneous earth, but electric field is dependent upon σ

Electric Dipole in a whole space: FDEM

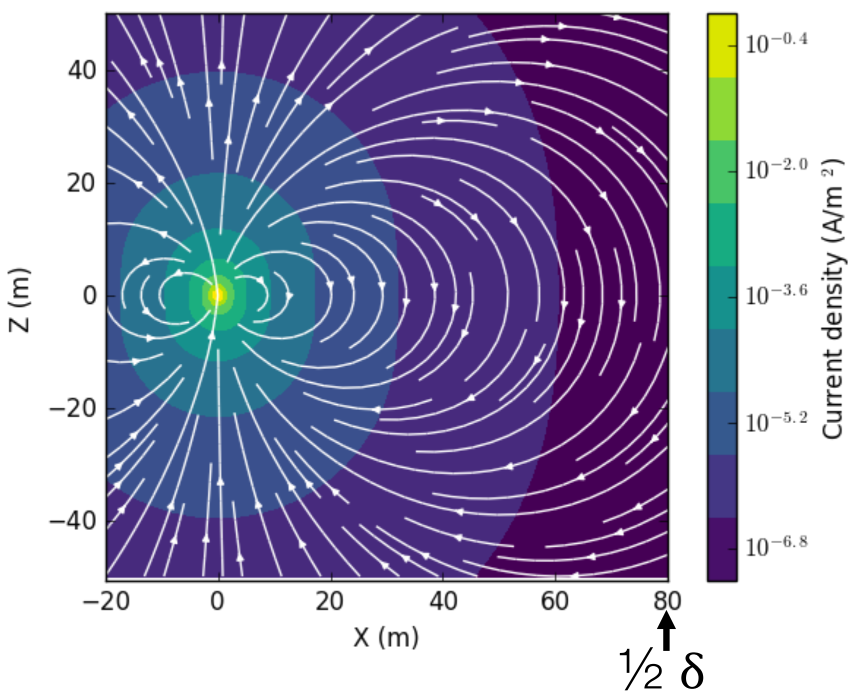
Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\mu\sigma}}.$





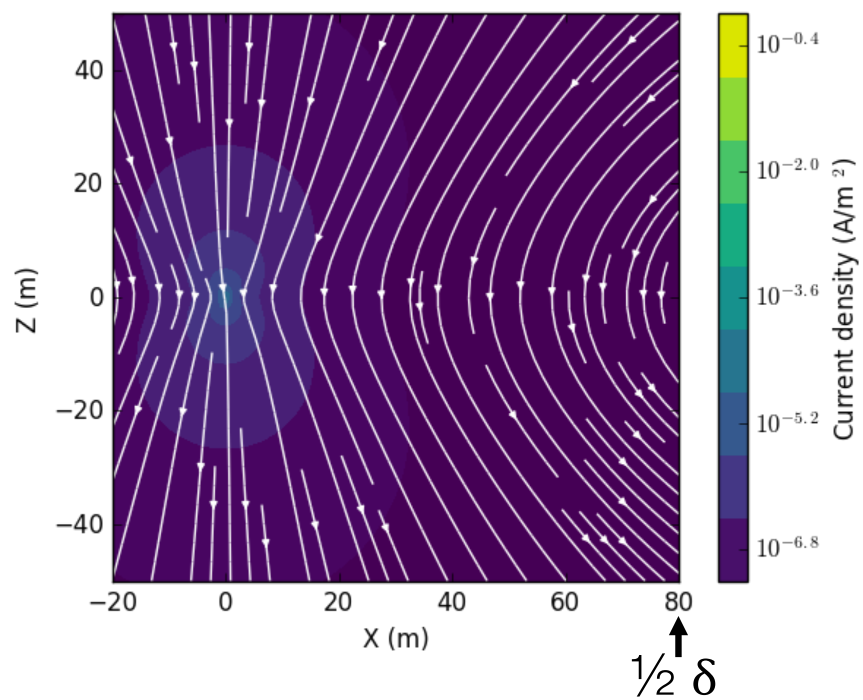
- Electric dipole in a whole space
  - 1000 Hz, 0.01 S/m, δ= 160 m

Current density (Real part)



DC + EM induction

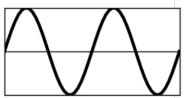
Current density (Imaginary part)

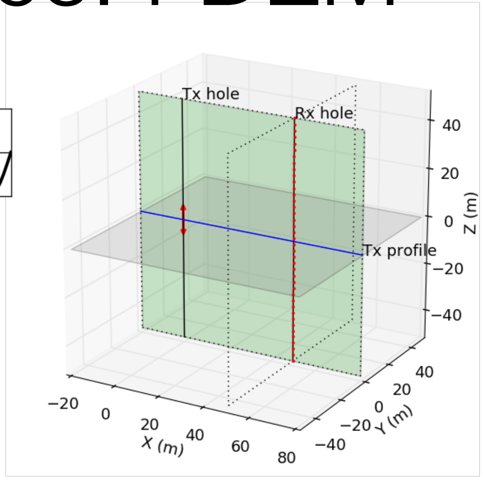


EM induction

Electric Dipole in a whole space: FDEM

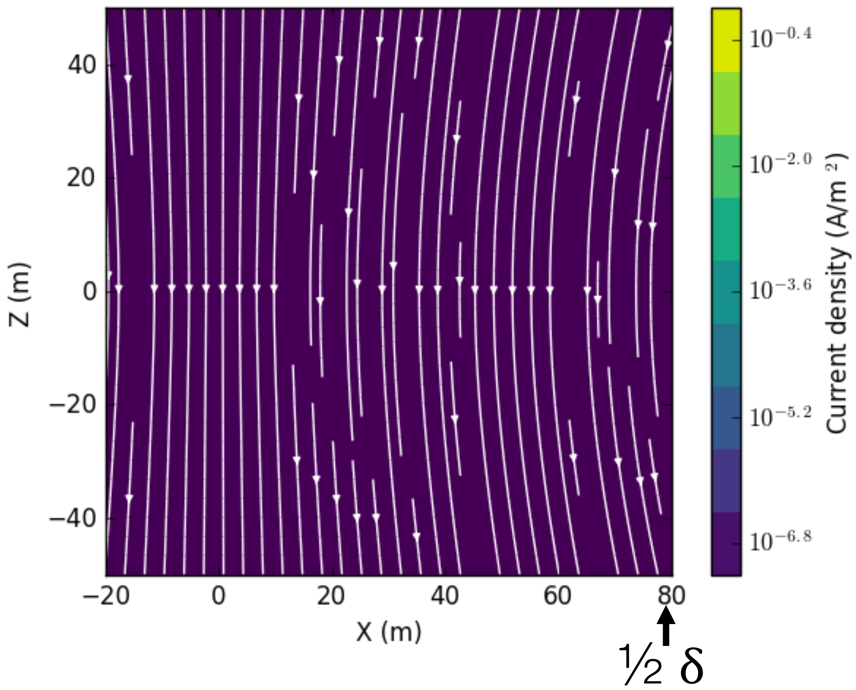
Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\mu\sigma}}.$





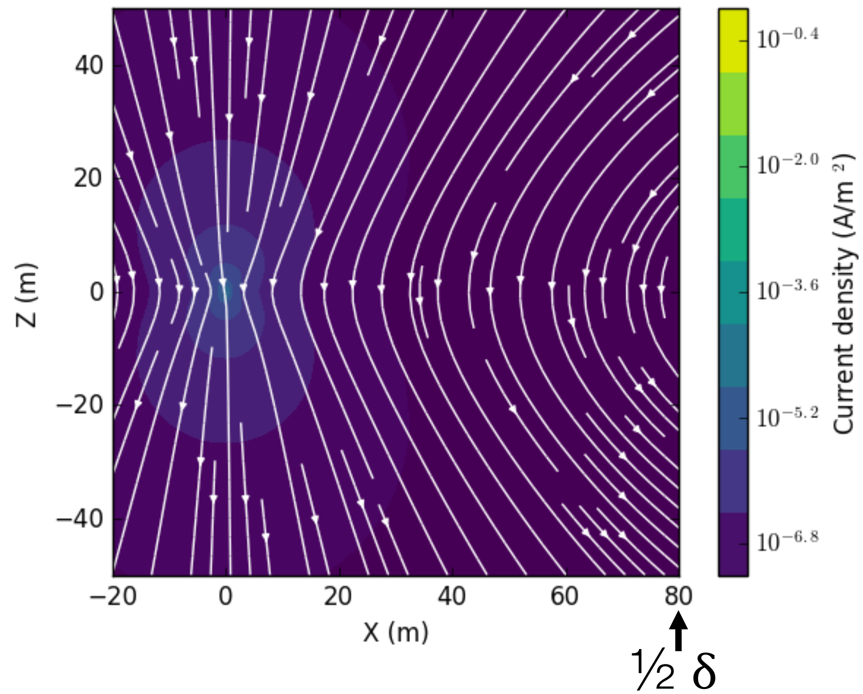
- Electric dipole in a whole space
  - 1 kHz, 0.01 S/m, δ= 160 m

Remove DC part
Re (J) –J^{DC}



EM induction

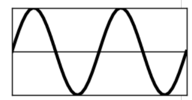
Im (J)

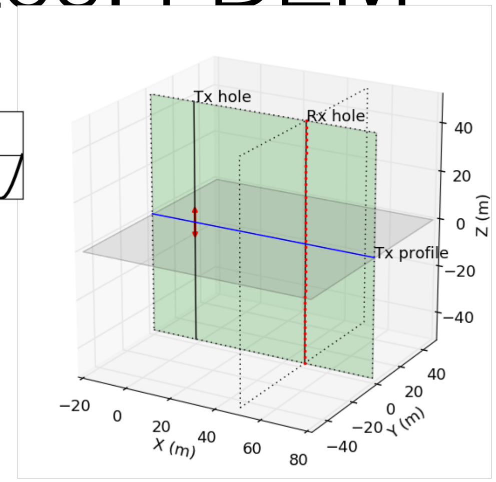


EM induction

Electric Dipole in a whole space: FDEM

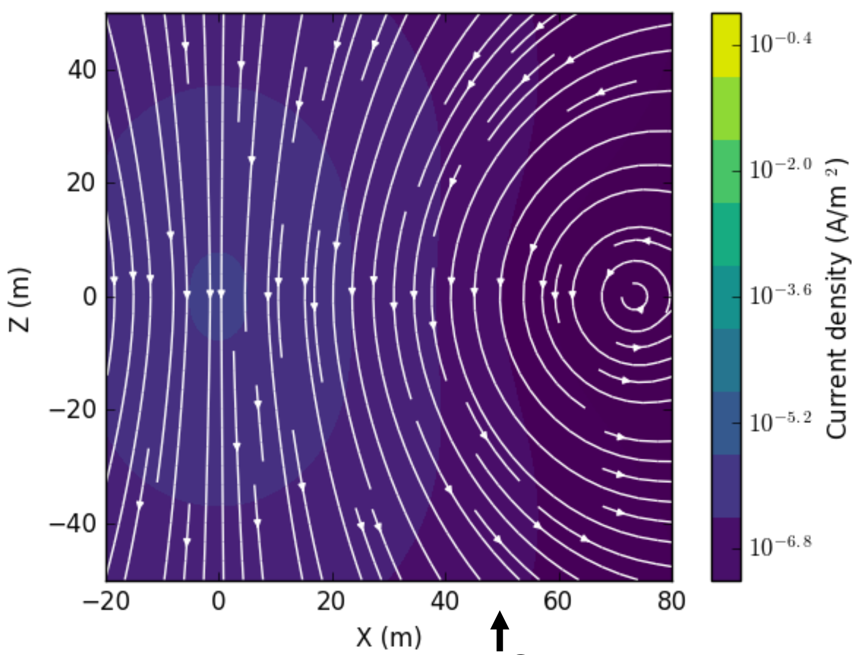
Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\mu\sigma}}.$





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

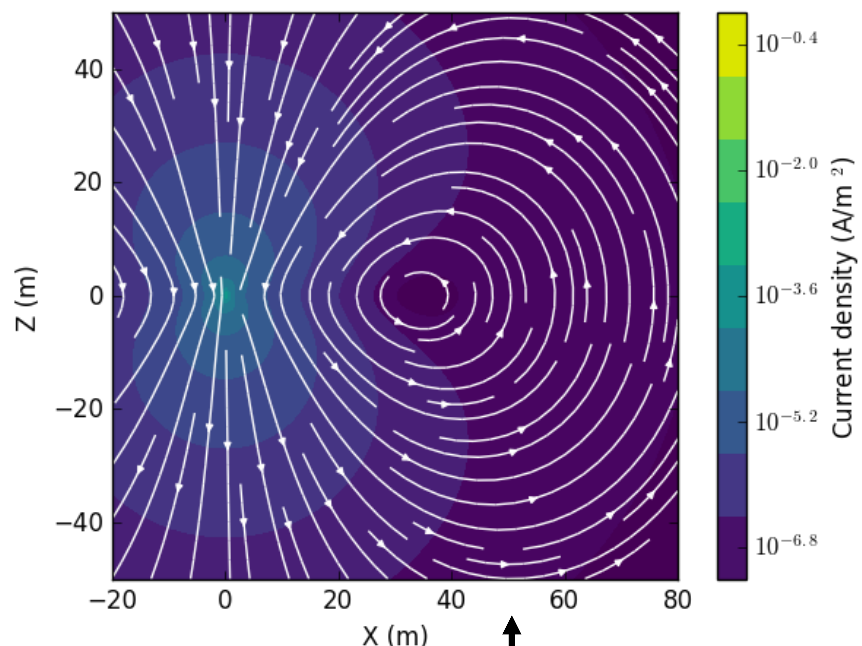
Re (J) –J^DC



1 δ

EM induction

Im (J)

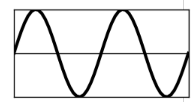


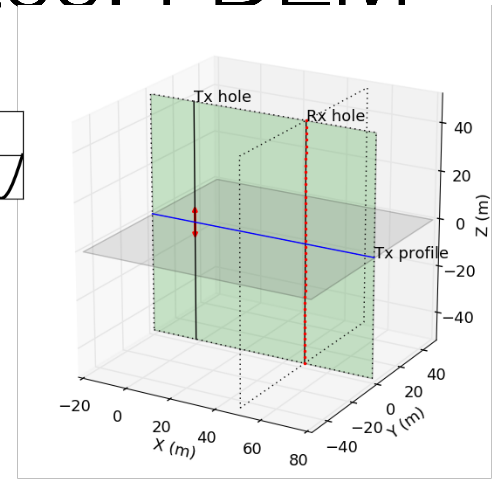
1 δ

EM induction

Electric Dipole in a whole space: FDEM

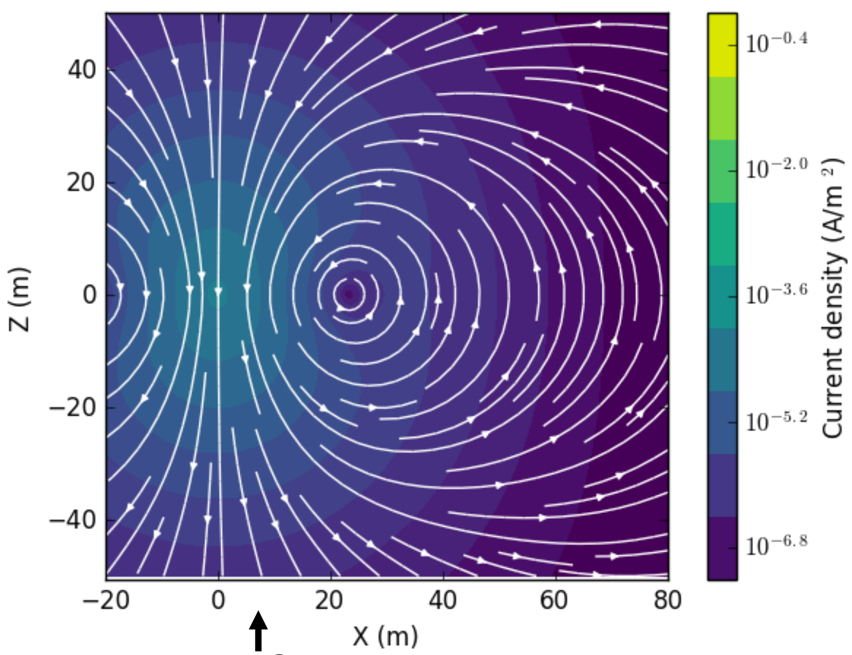
Skin depth: $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}.$





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

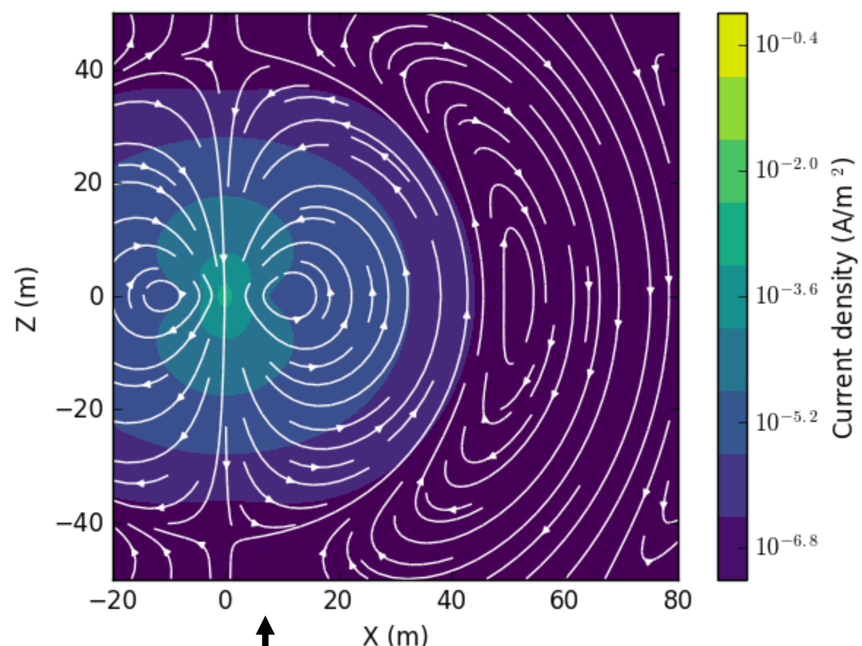
Re (J) –J^DC



1 δ

EM induction

Im (J)

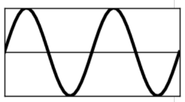


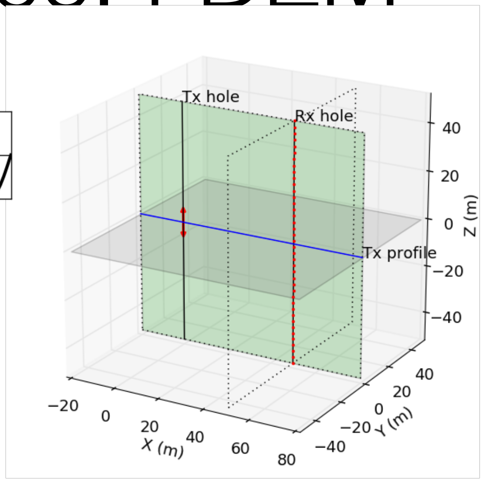
1 δ

EM induction

Electric Dipole in a whole space: FDEM

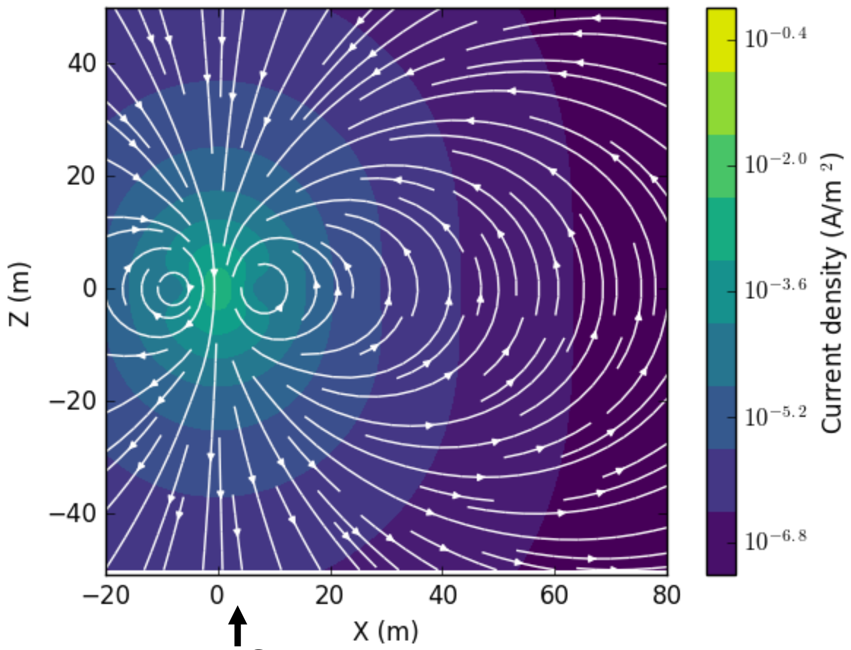
Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\mu\sigma}}.$





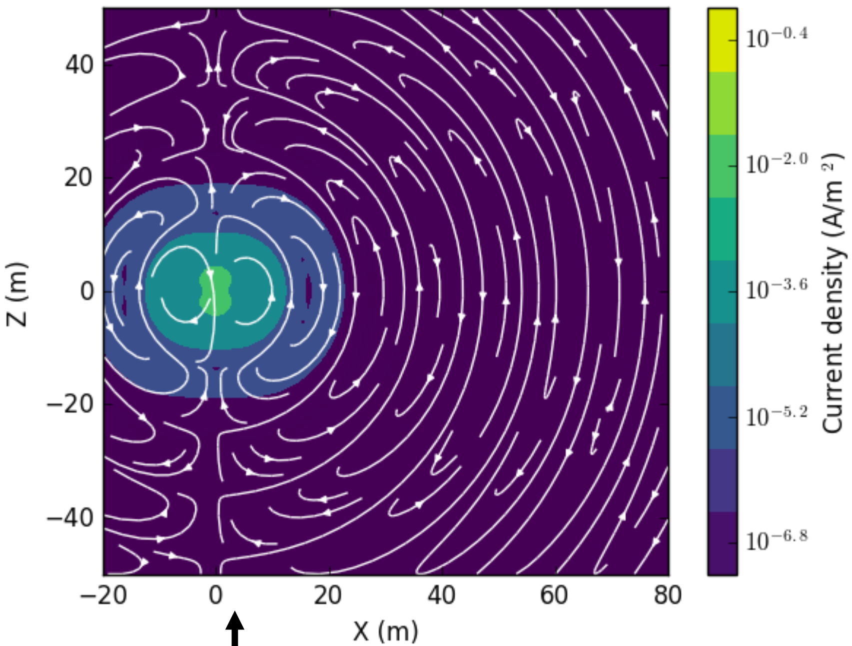
- Electric dipole in a whole space
  - 1000 kHz, 0.01 S/m, δ= 5 m

Re (J) –J^{DC}

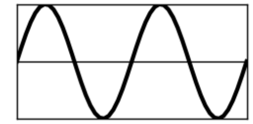


EM induction

Im (J)



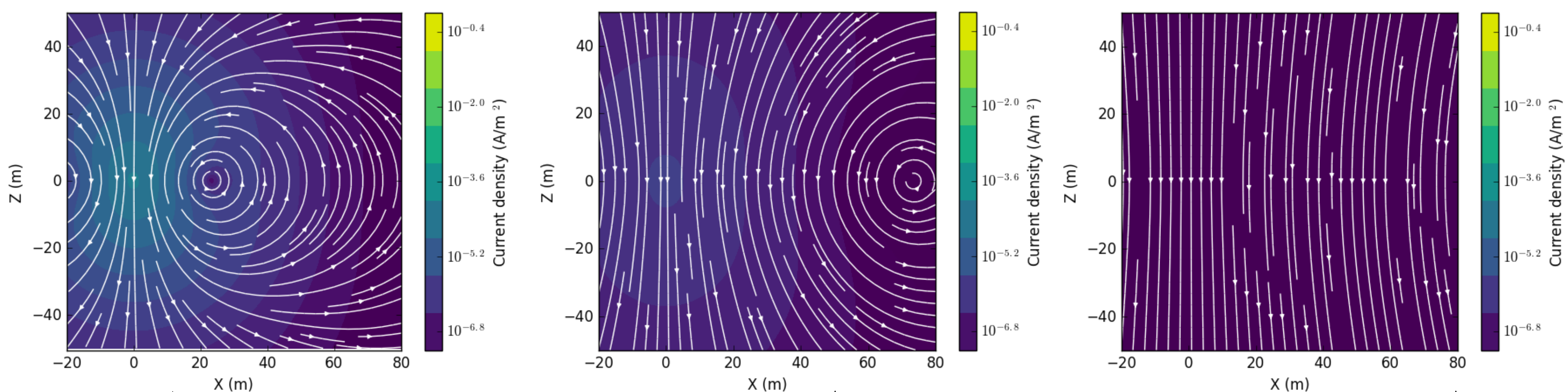
EM induction



Summary:
FDEM Electric Dipole in a whole space

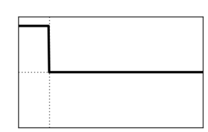
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Re (**J**) –**J**^{DC}



1 δ	1 δ	½ δ
100 kHz	10 kHz	1 kHz

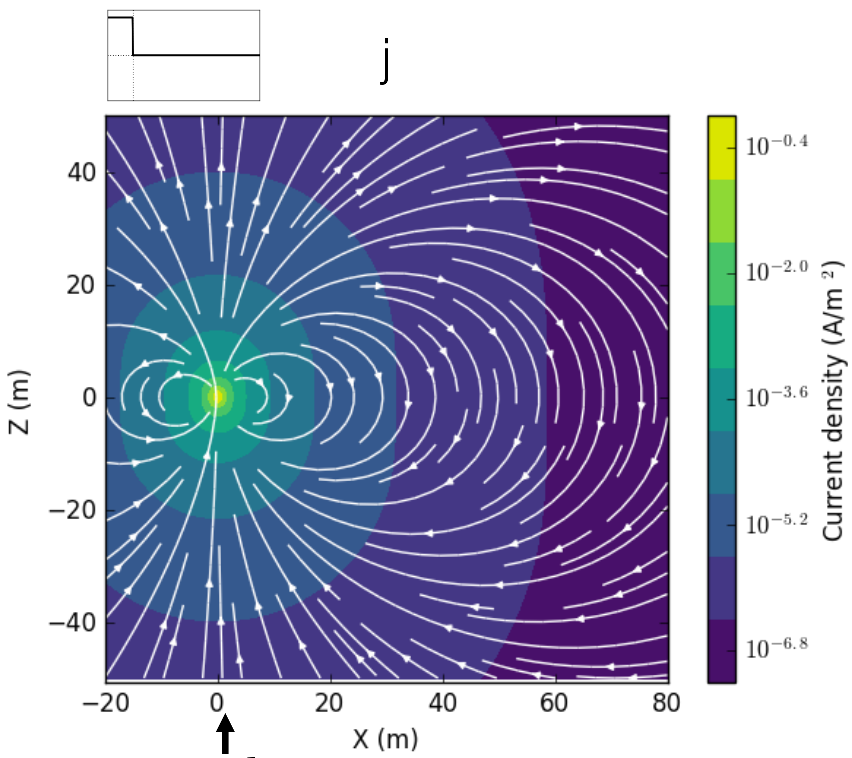
In time…



Electric Dipole in a whole space: TDEM

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

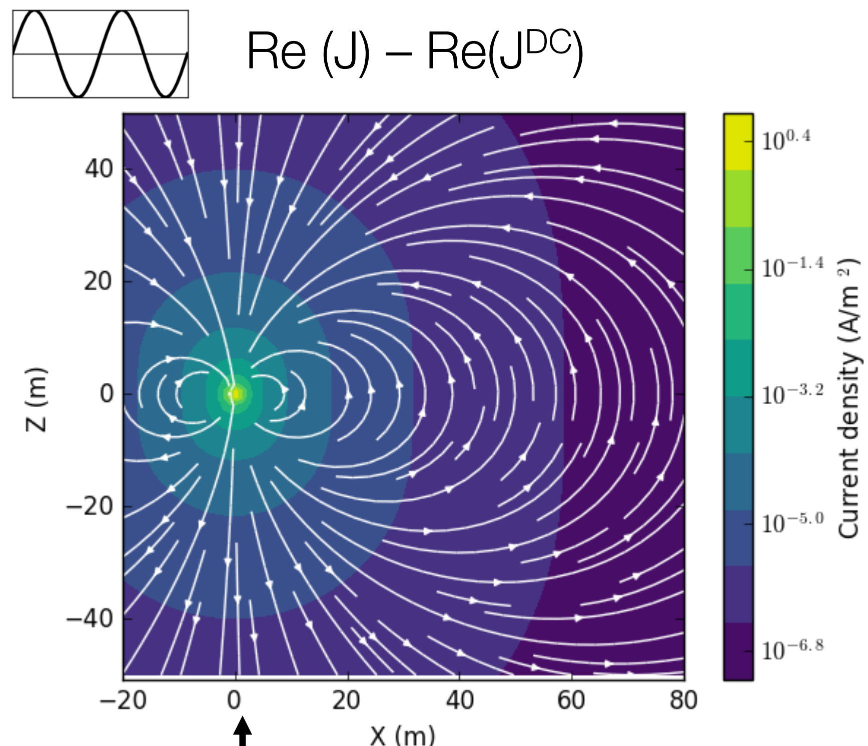
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$



1 d

f=10^{4} kHz, δ = 2 m

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

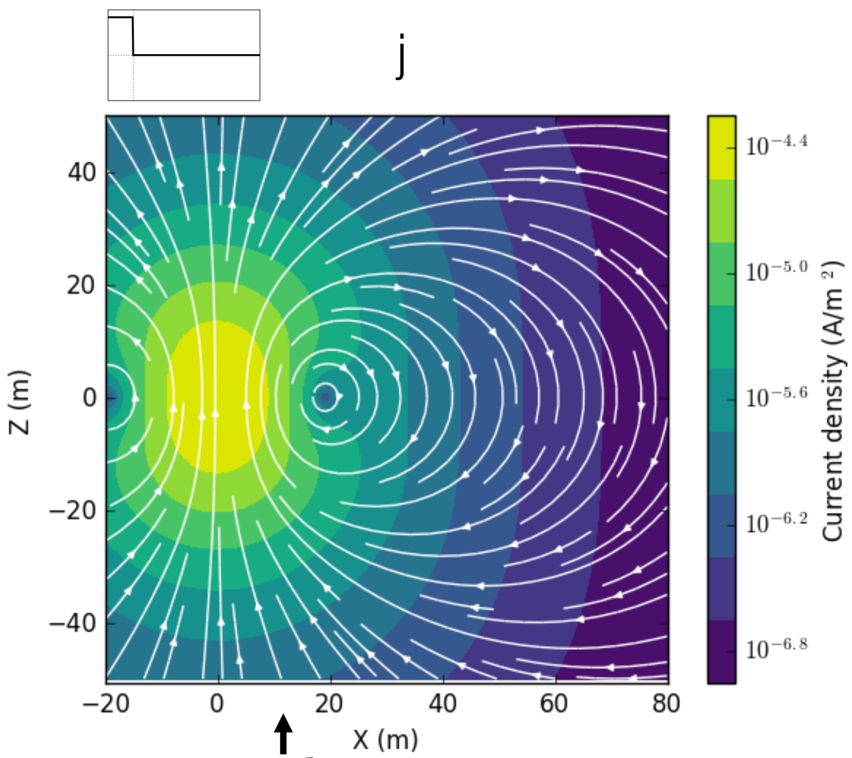


1 δ

Electric Dipole in a whole space: TDEM

t=10^{-3} ms, **d** = 13 m

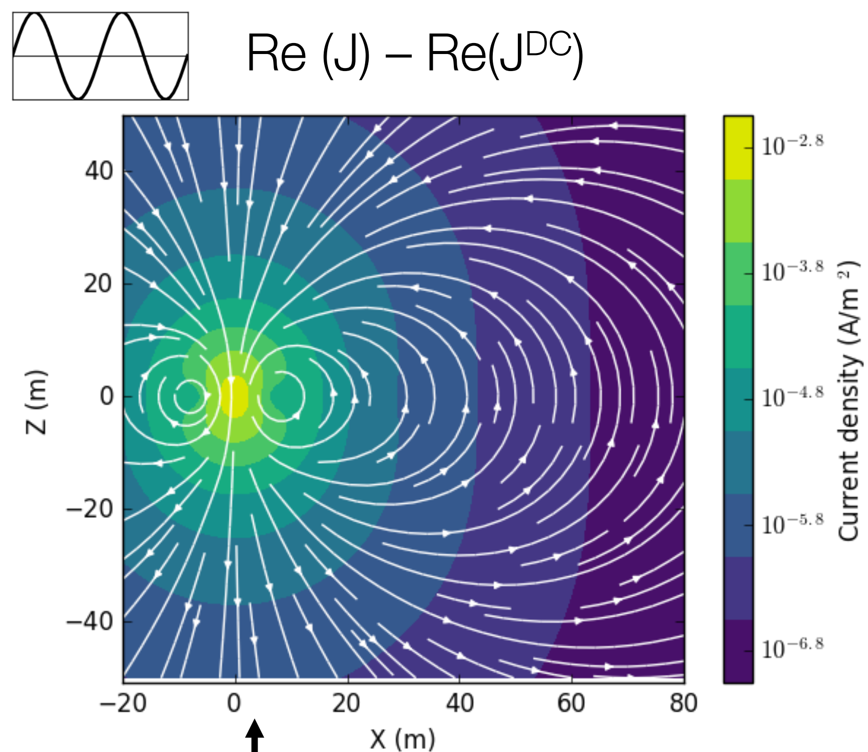
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$



1 d

f=10^3 kHz, δ = 5 m

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



1 δ

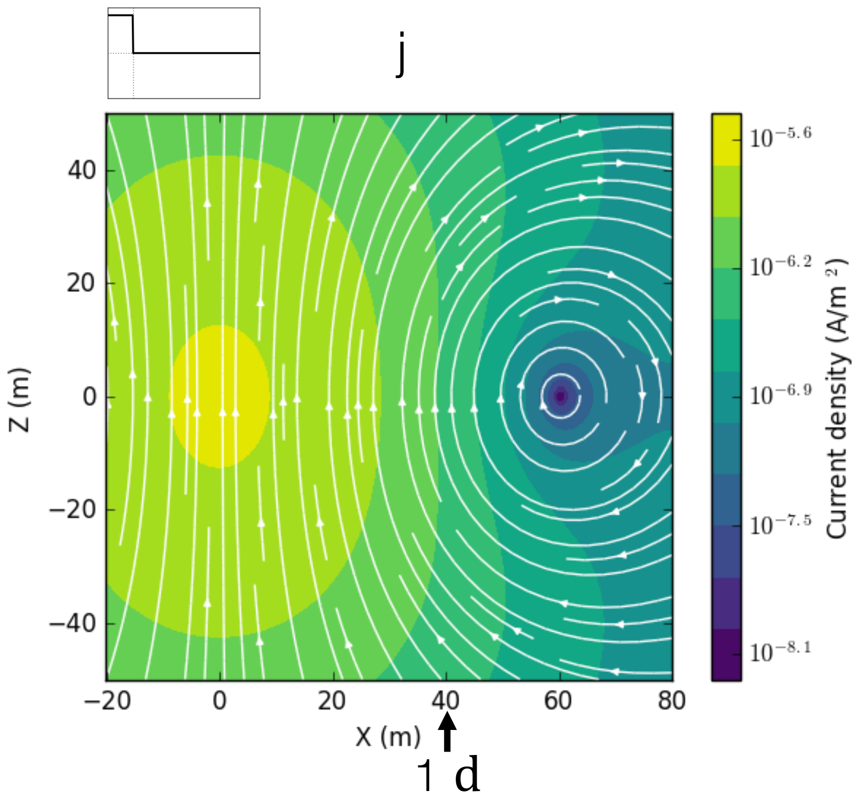
Electric Dipole in a whole space: TDEM

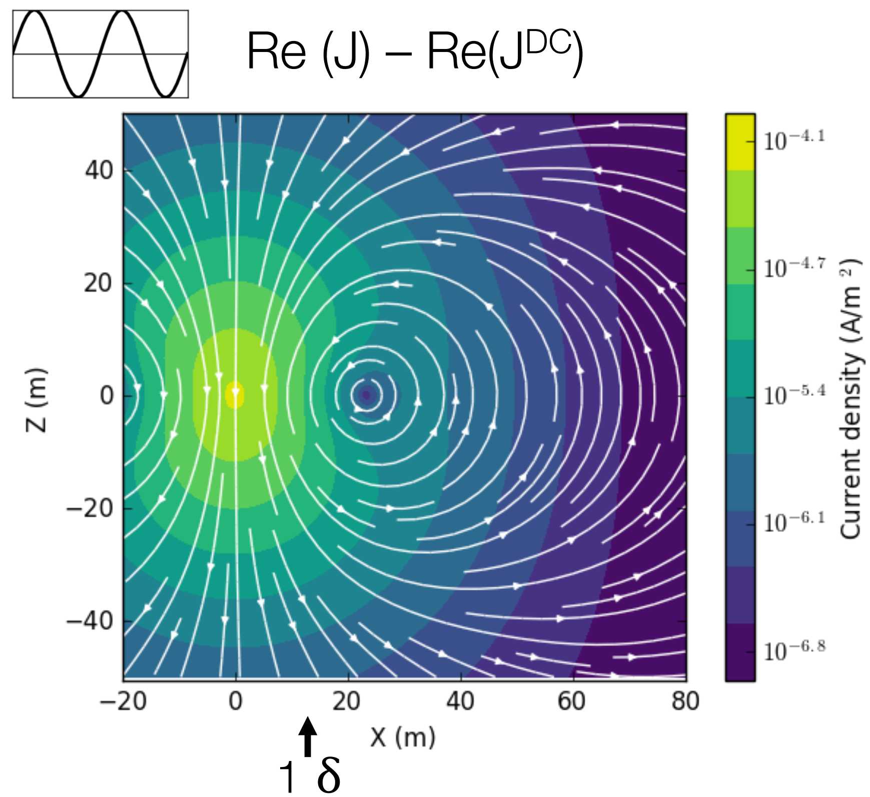
t=10^{-2} ms, **d** = 40m

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

f=10^{2} kHz, δ = 16 m

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





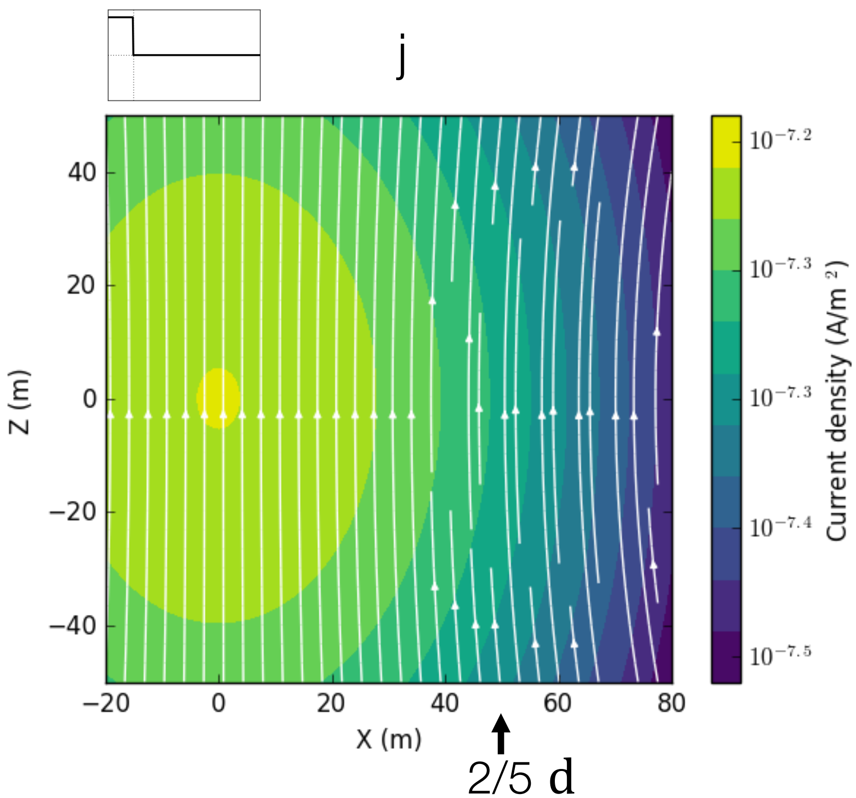
Electric Dipole in a whole space: TDEM

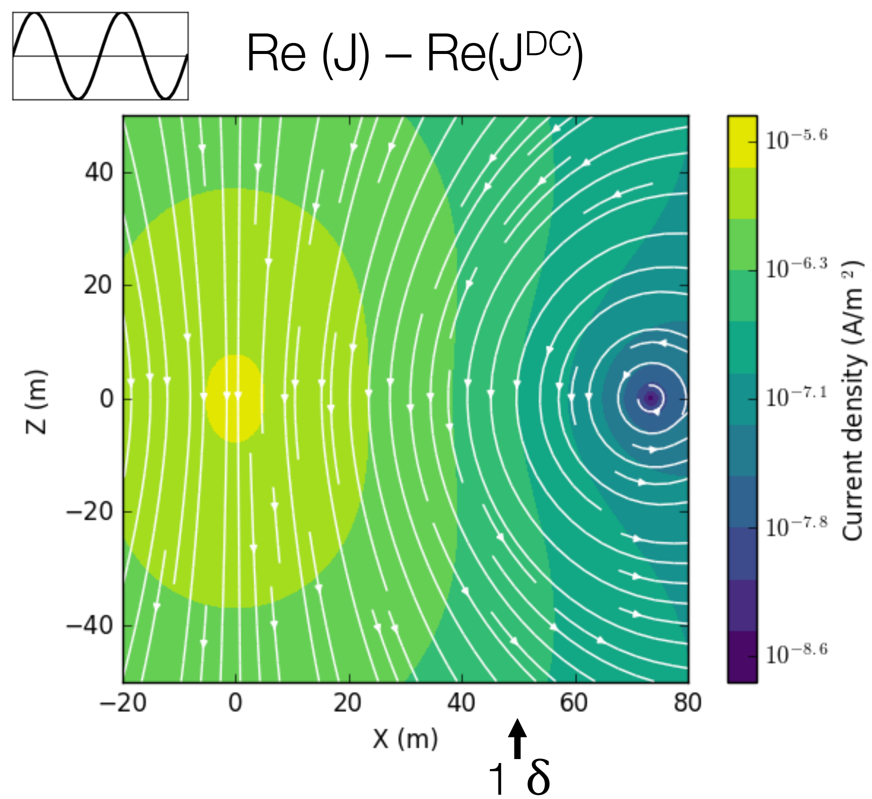
t=10^{-1} ms, $\mathbf{d}$ = 126m

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

f=10^{1} kHz, δ = 50 m

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





Electric Dipole in a whole space: TDEM

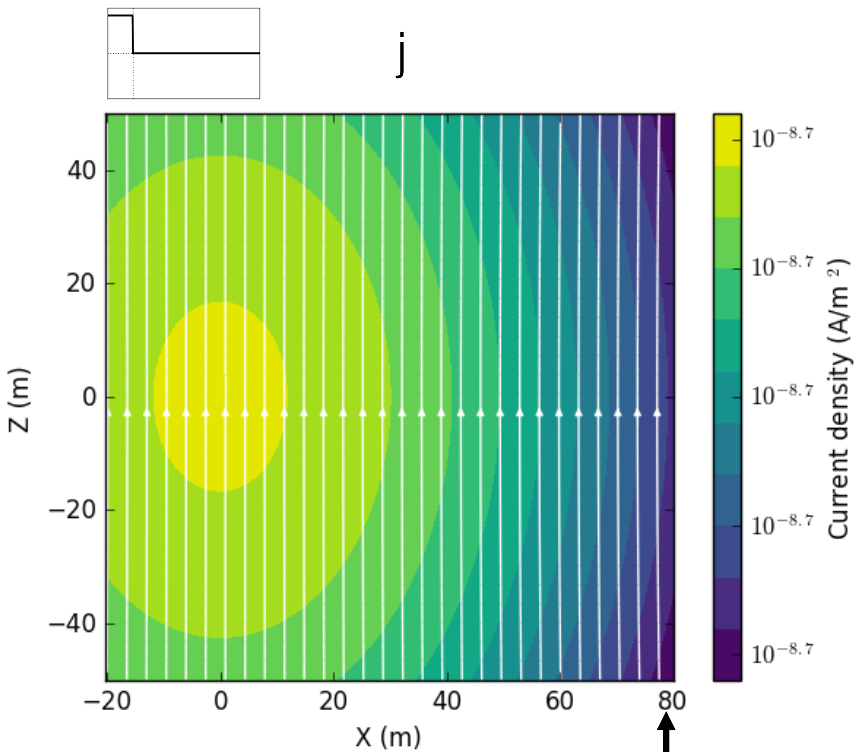
t=1 ms, $\mathbf{d}$ = 400m

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

f=1 kHz, δ = 160 m

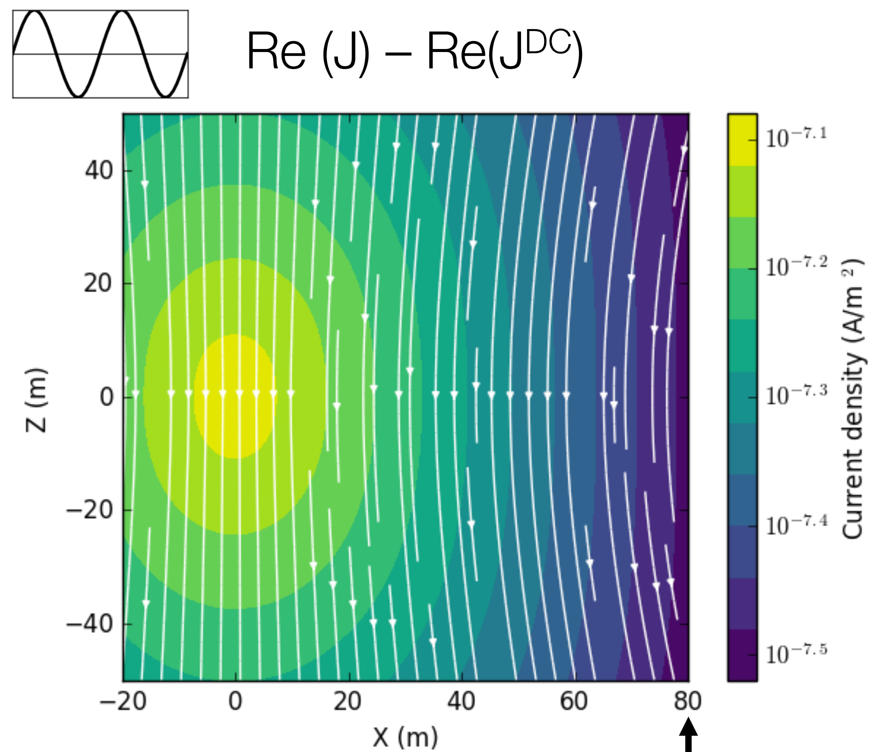
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

j



1/5 d

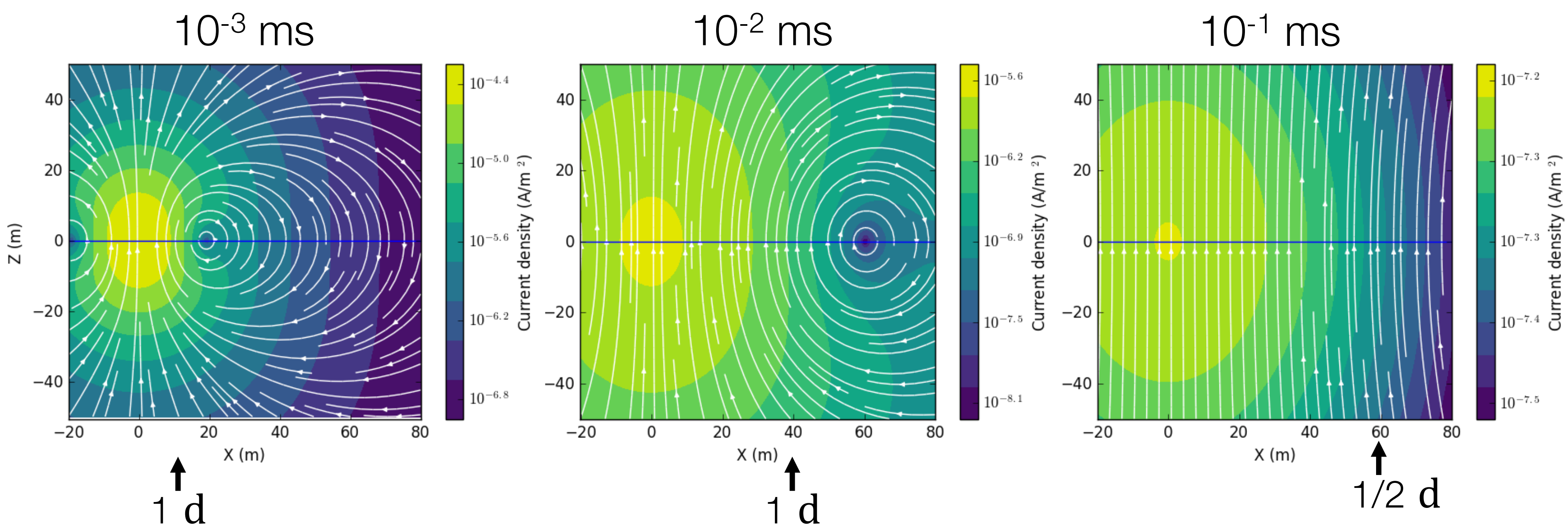
Re (J) – Re(J^{DC})



½ δ

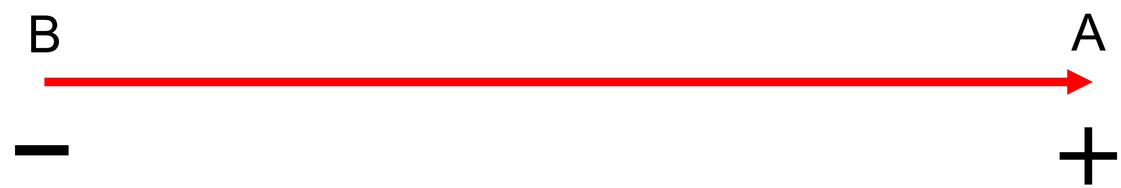
Diffusing currents

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



Bipole Sources

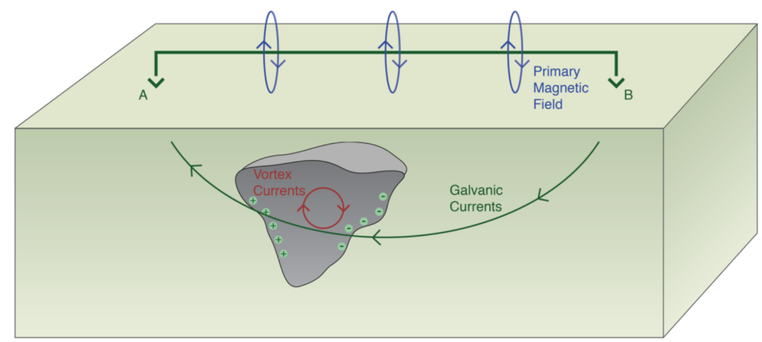
- Extended line sources
  - Grounded term (**galvanic**) + wire path (**inductive**)
  - Straight line



  - Crooked line (horse shoe)

Grounded Sources: On the surface

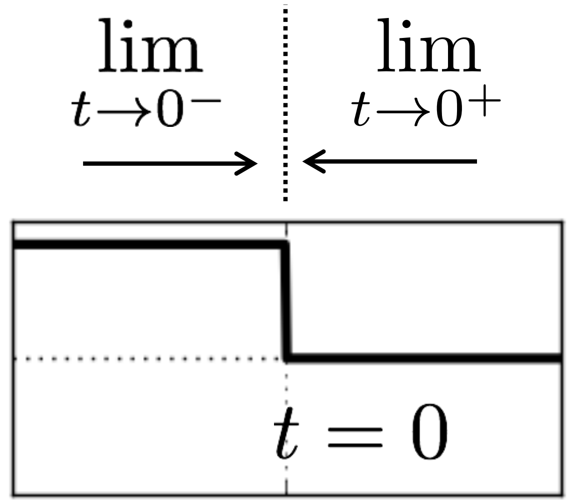
- Ability to detect target depends on
  - Geometry, conductivity of target & host
  - Geometry of TX
  - Frequency or time
  - Fields and components measured
    - e, b, db/dt
  - Location of Tx and Rx with respect to the target

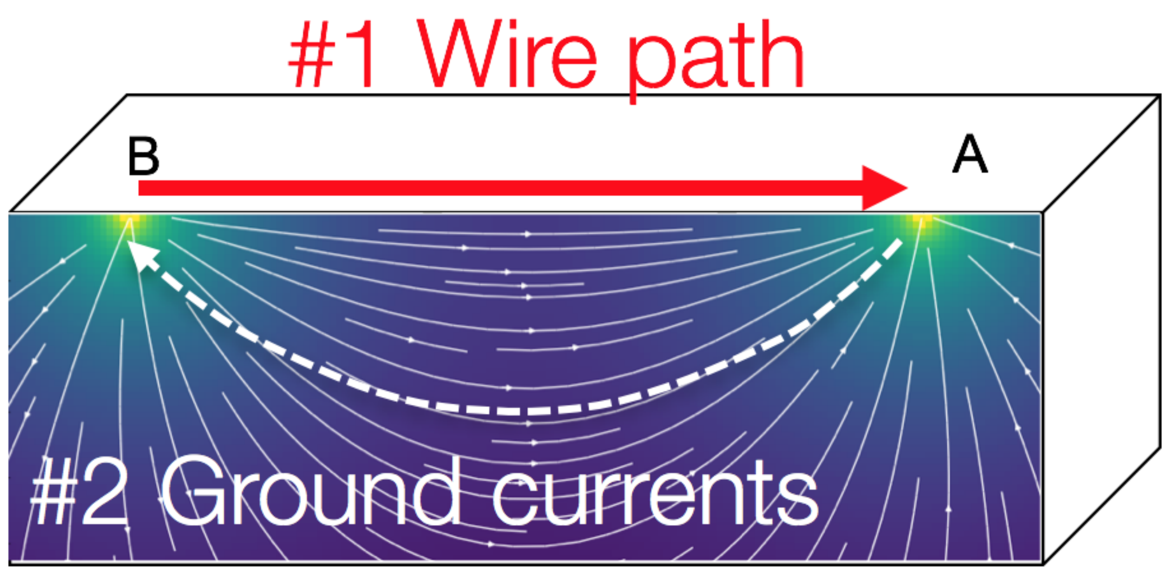


- Lots of variables…
  - Use an example to highlight important concepts

Currents: Grounded System

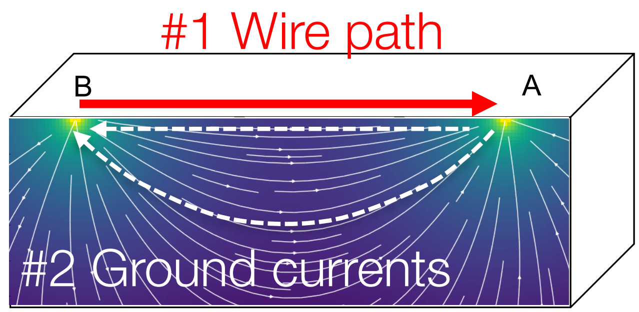
- $t = 0^-$ Steady state
- $t = 0$ Shut off current
- $t = 0^+$ Off-time

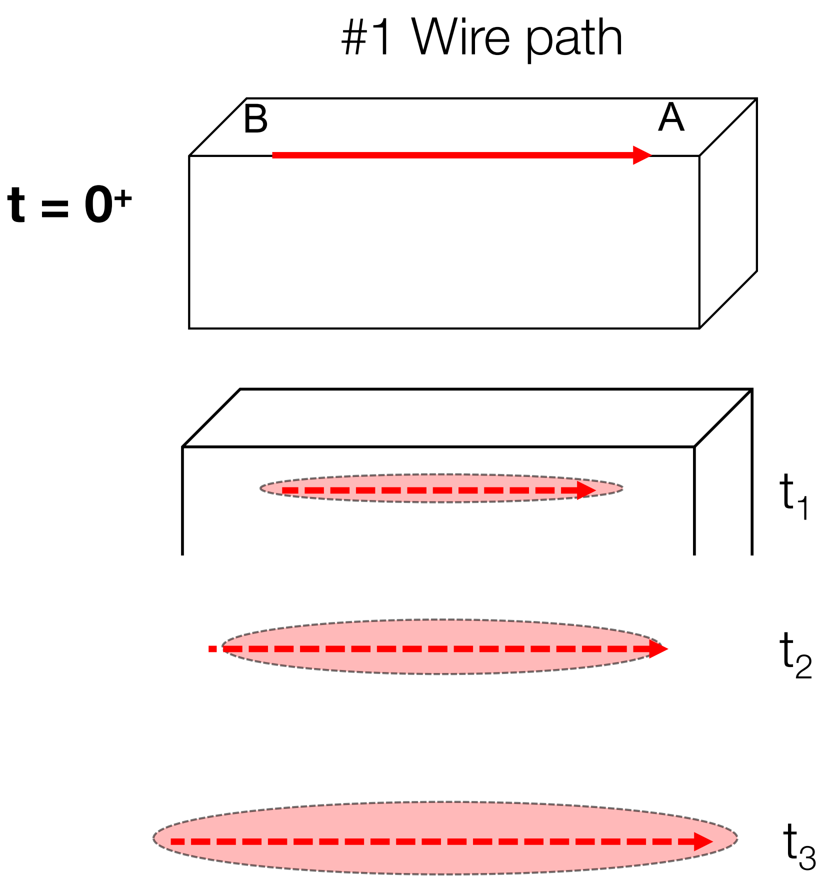




What happens when we shut the system off?

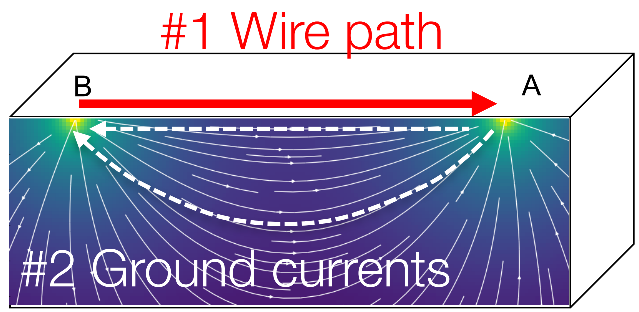
Currents: Grounded System





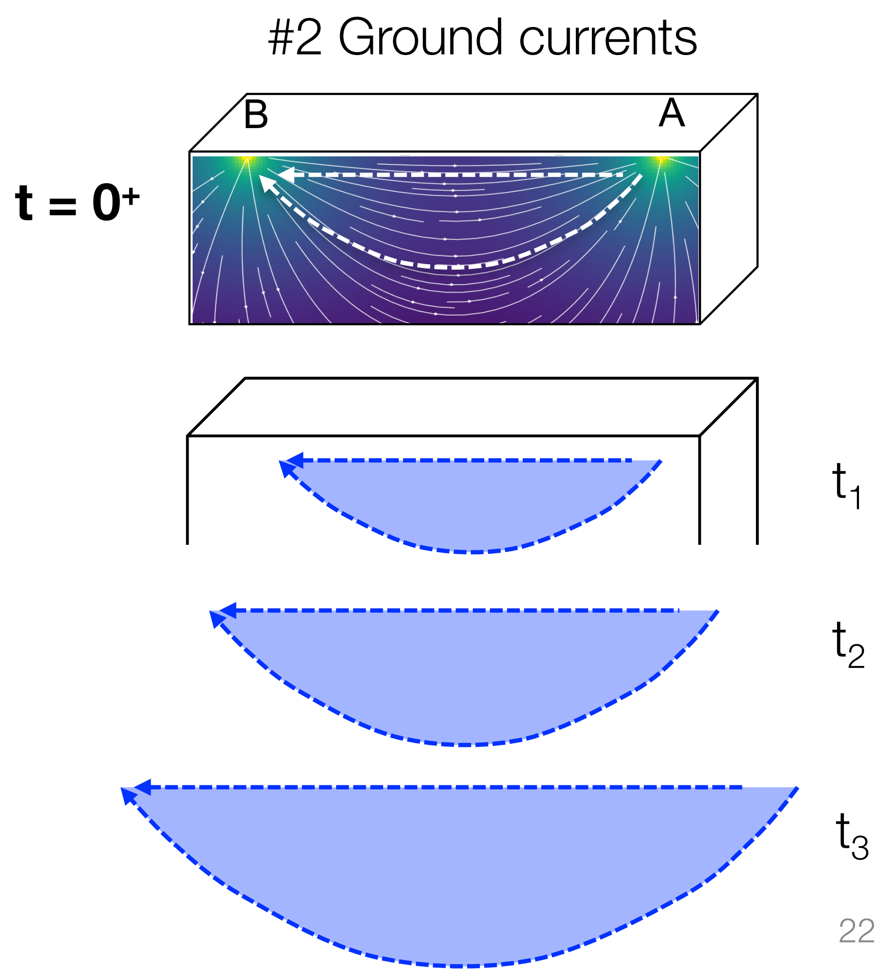
- Immediately after shut off: image current at the surface
- Successive time: currents diffuse downwards and outwards

Currents: Grounded System

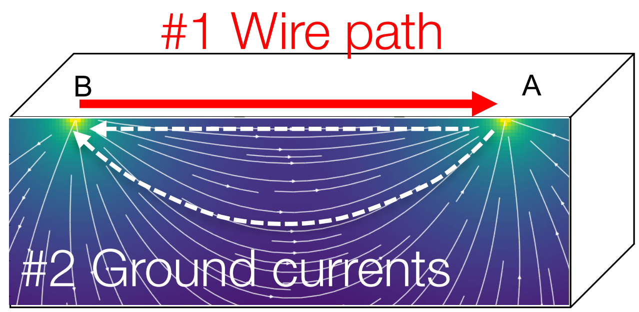


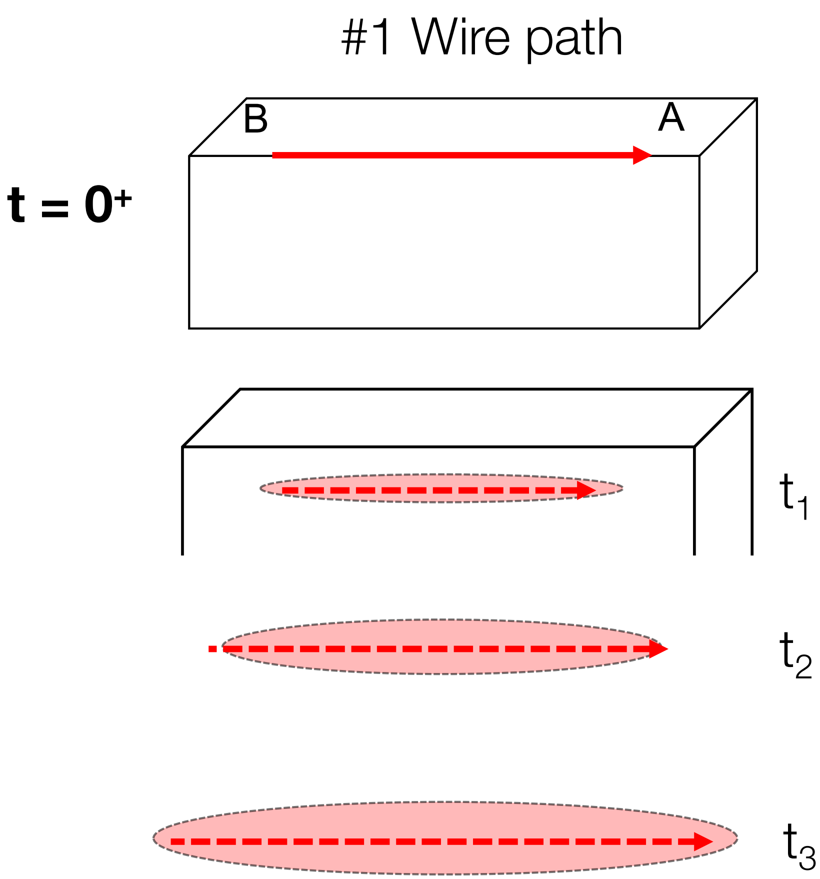
- Immediately after shut off: ground currents are still there

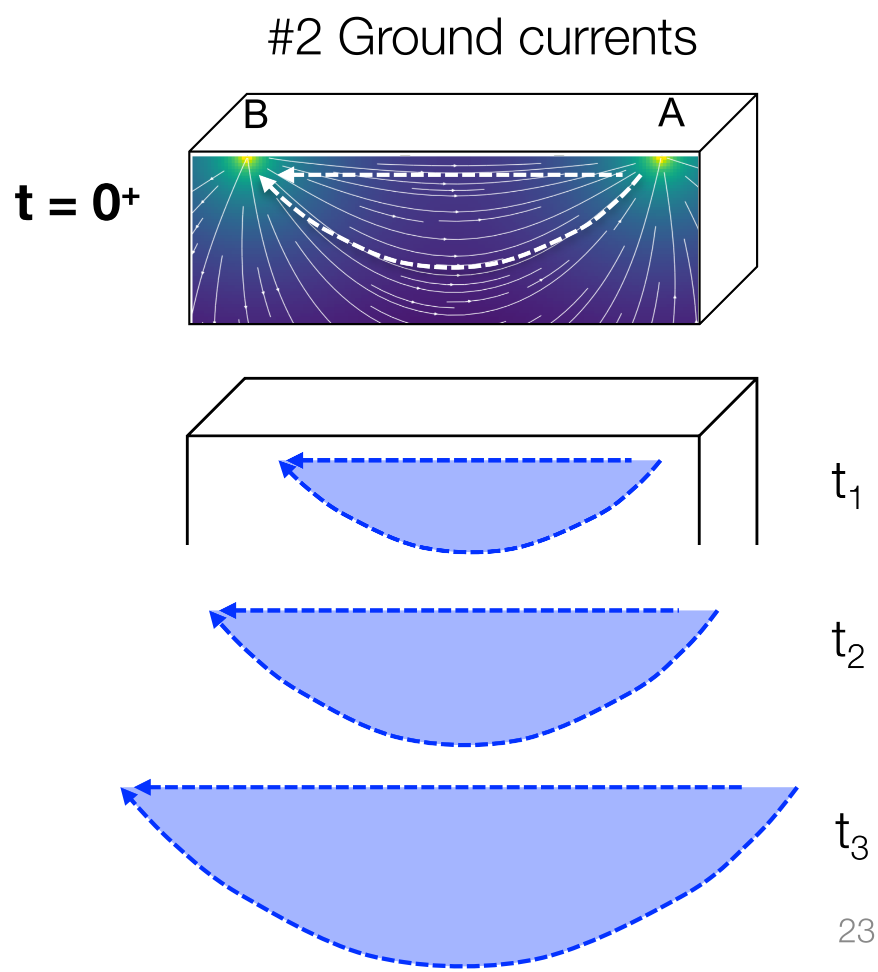
- Successive time: currents diffuse downwards and outwards



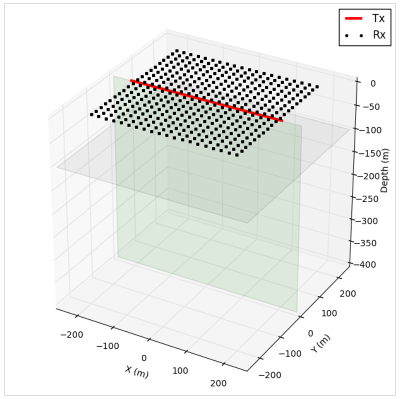
Currents: Grounded System





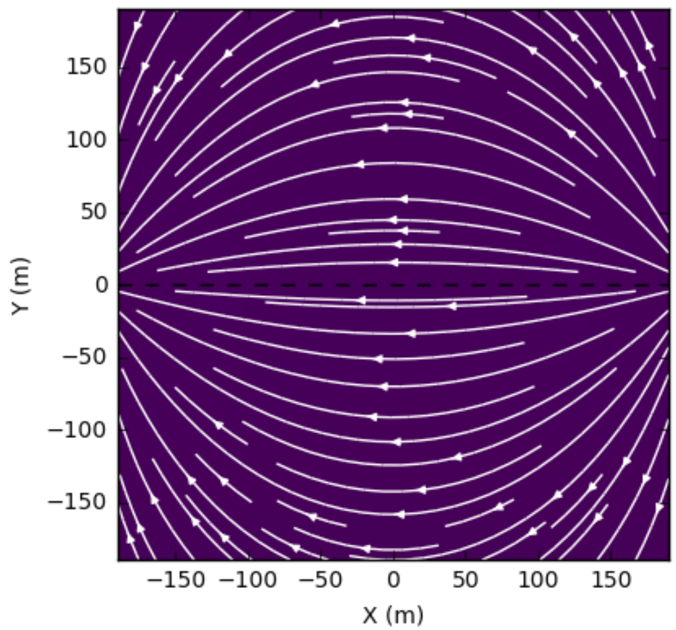


Grounded Source: Halfspace Currents

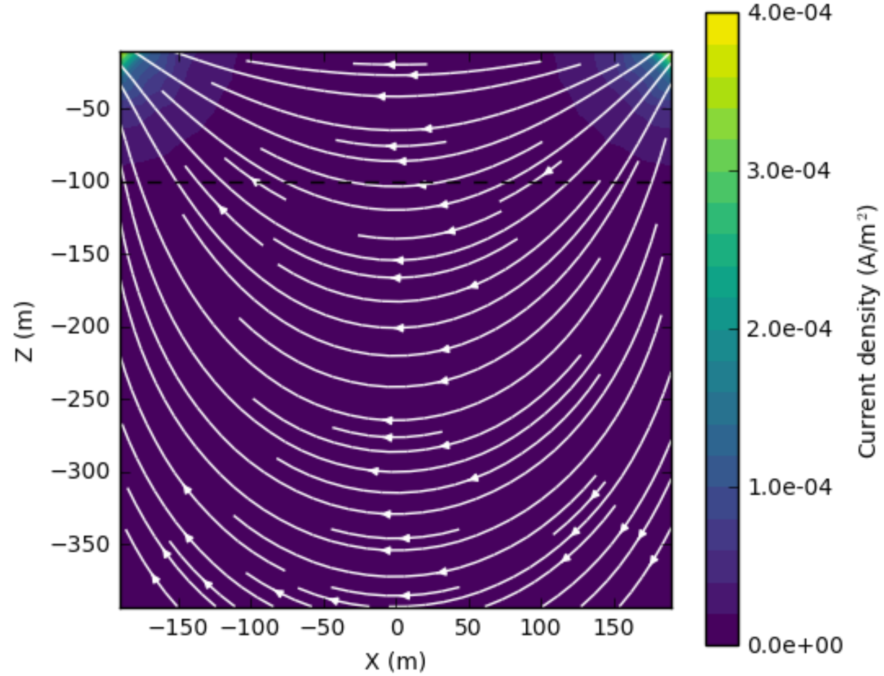


- Parameters:
  - halfspace (0.01 S/m)
  - **t=0$^-$**, steady state

XY plane at Z=-100 m

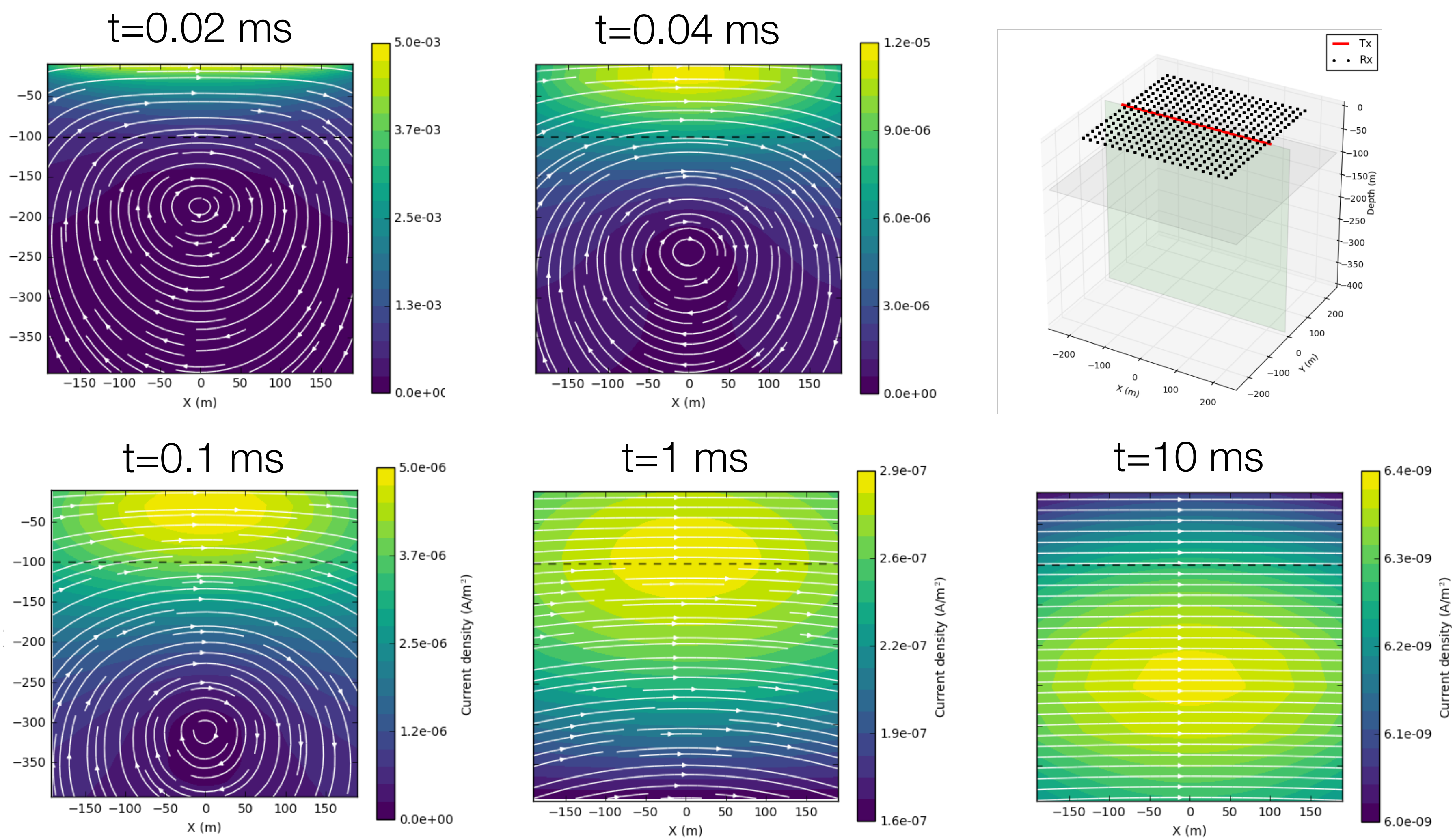


XZ plane at Y=0 m



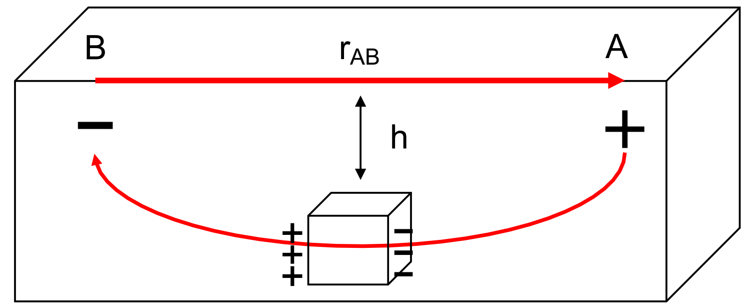
Grounded Source: Halfspace currents

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

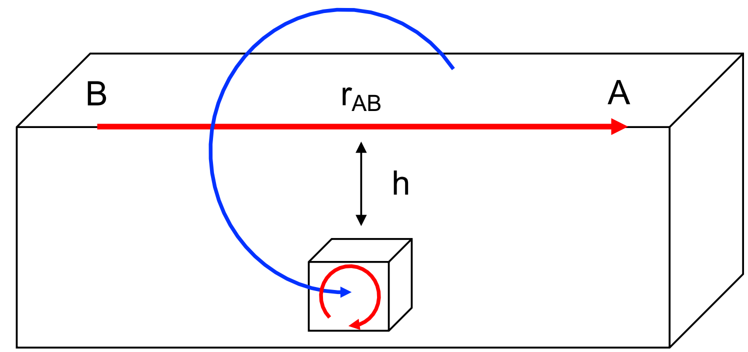


Grounded sources: with a target

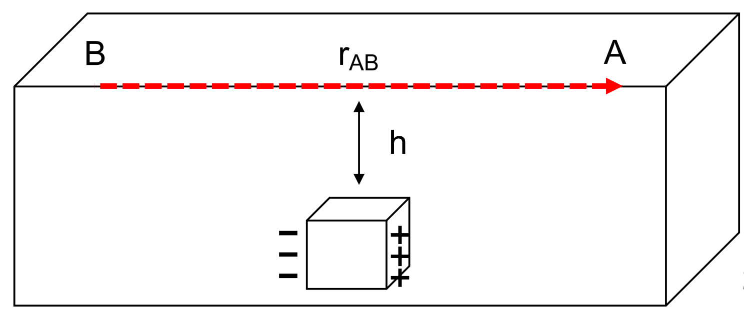
- Block in a halfspace
  - DC
    - Good coupling if h < r_{AB}



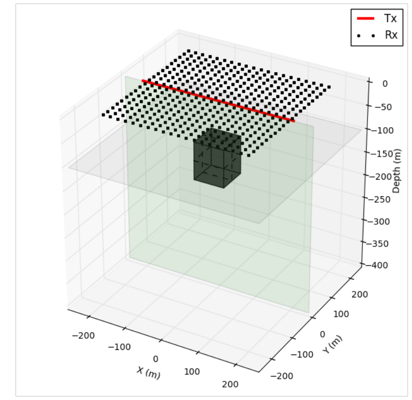
  - Vortex currents
    - Good coupling (magnetic fields)
    - Good signal for conductor
    - Resistor more difficult



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

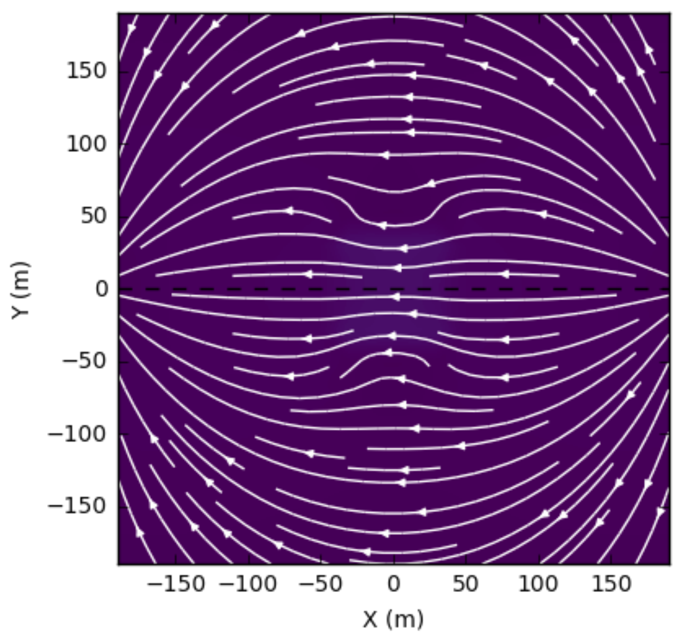


Conductor: currents

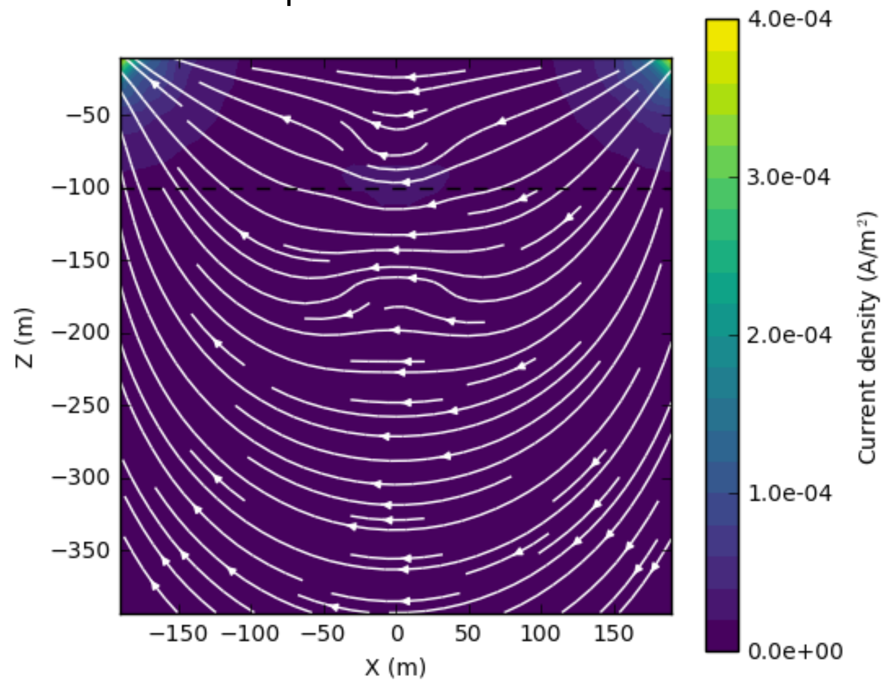


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **t=0⁻**, steady state

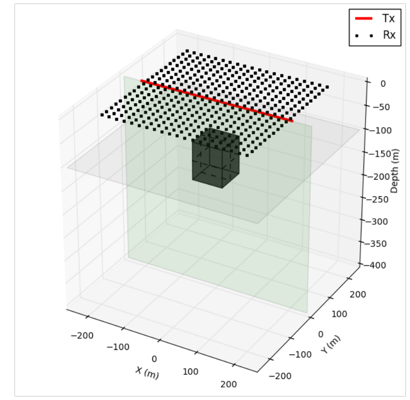
XY plane at Z=-100 m



XZ plane at Y=0 m

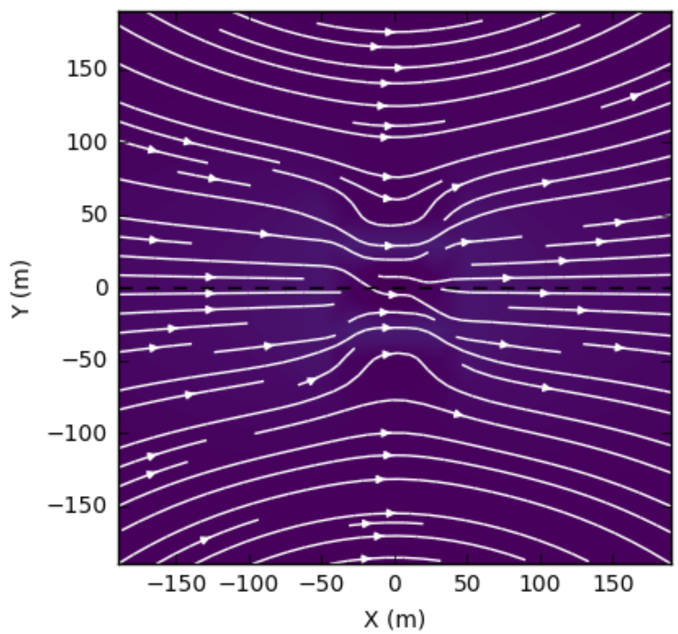


Conductor: currents

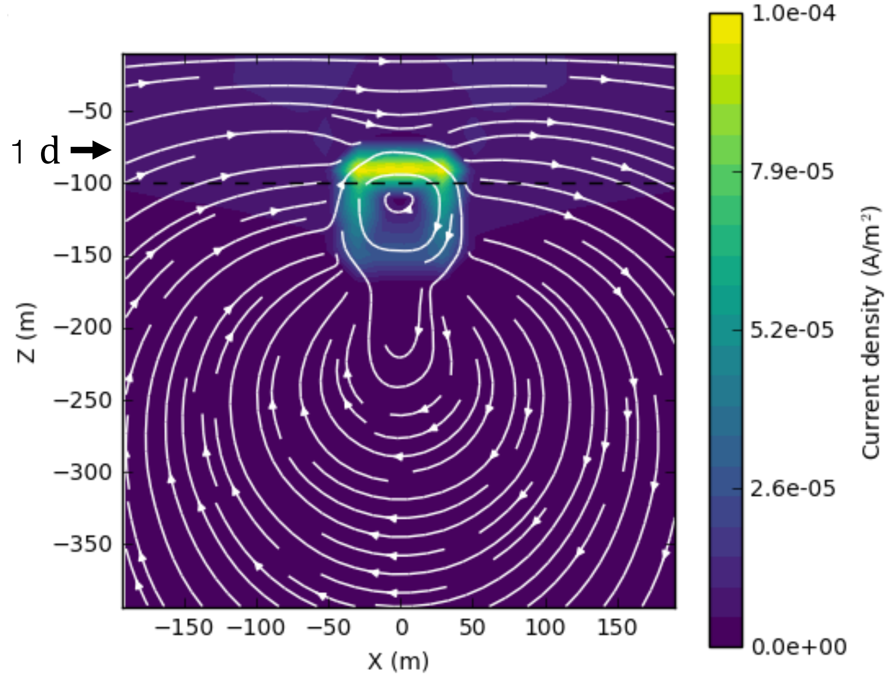


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

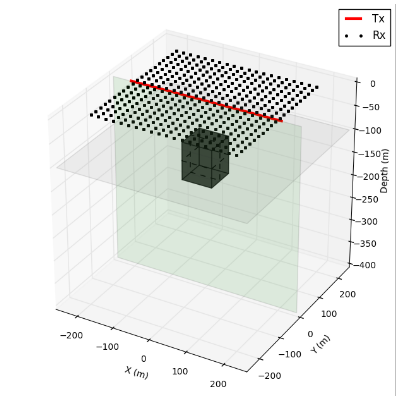
XY plane at Z=-100 m



XZ plane at Y=0 m

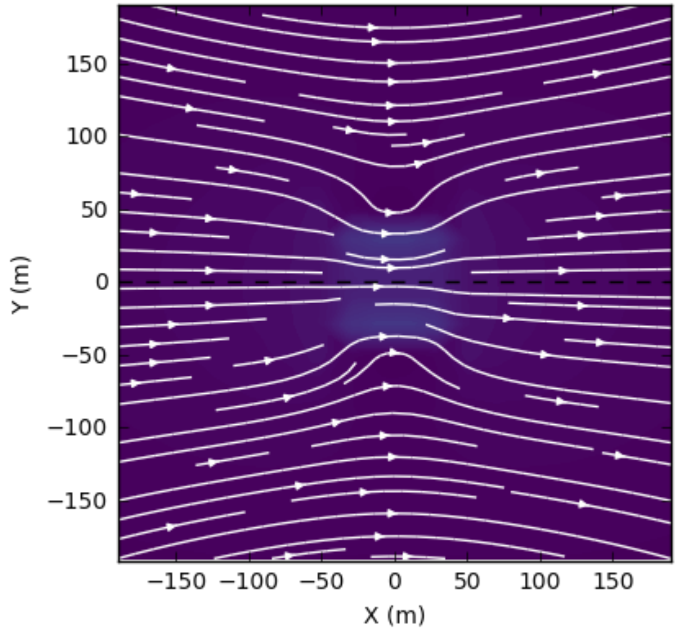


Conductor: currents

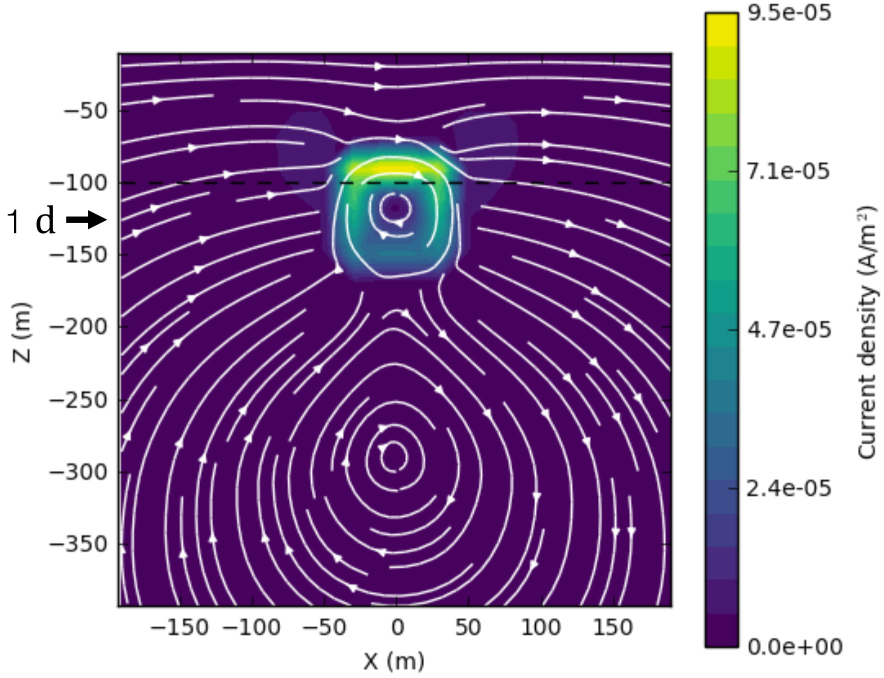


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m

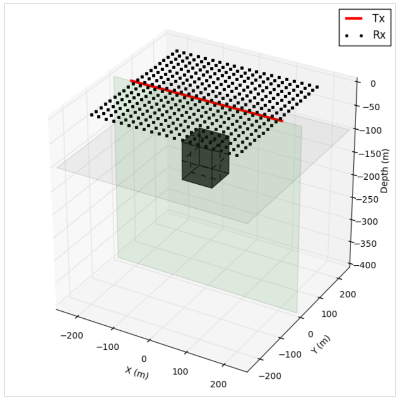
XY plane at Z=-100 m



XZ plane at Y=0 m

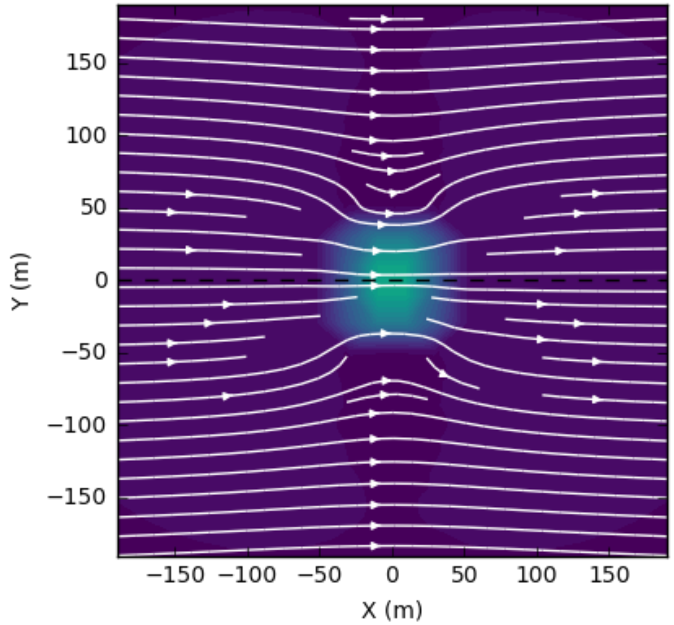


Conductor: currents

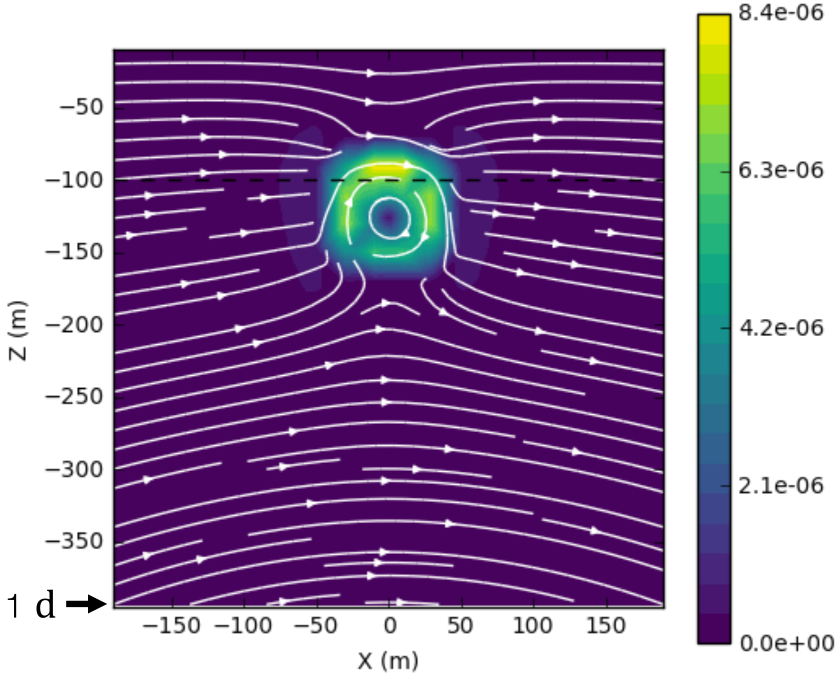


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - 1 ms, d = 400 m

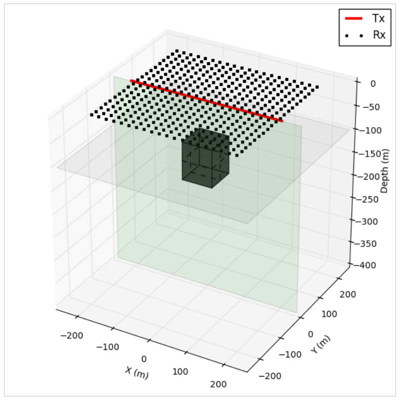
XY plane at Z=-100 m



XZ plane at Y=0 m

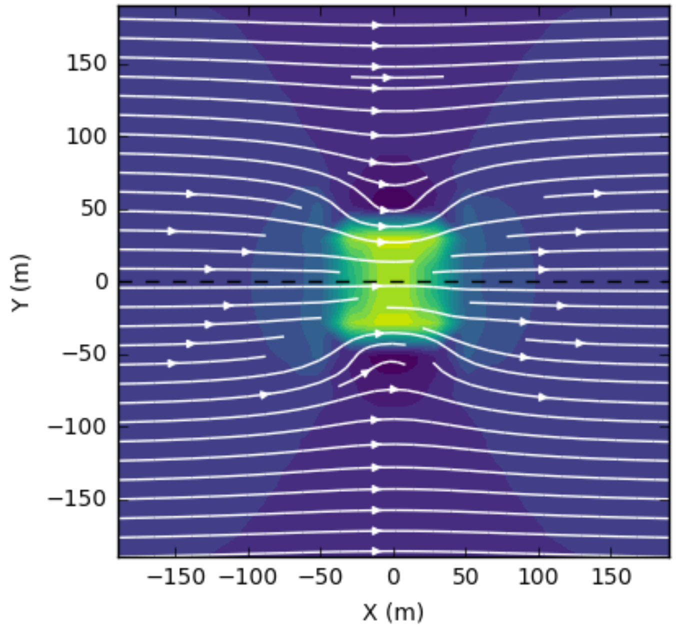


Conductor: currents

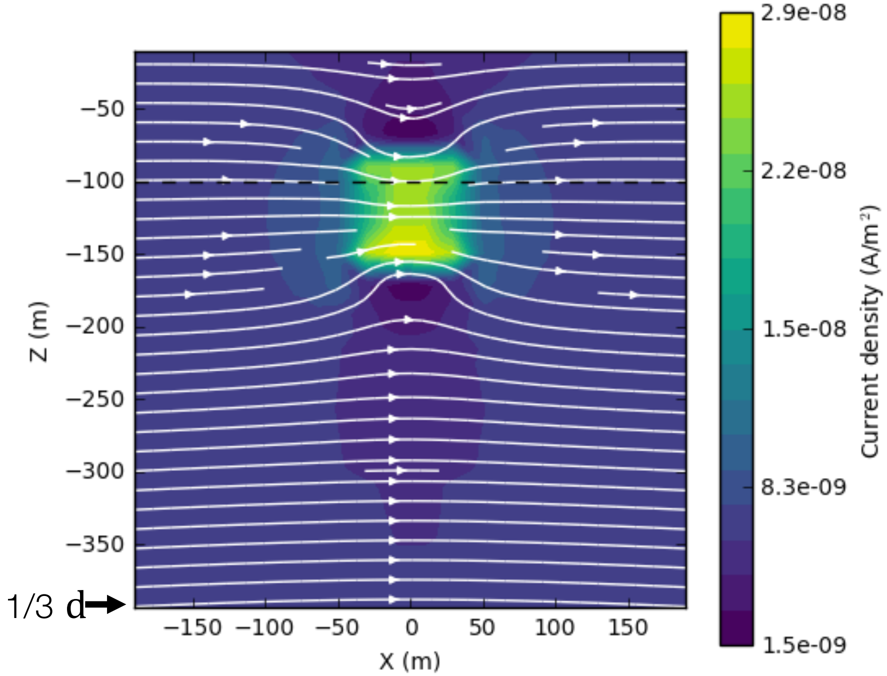


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m

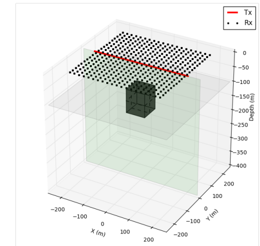
XY plane at Z=-100 m



XZ plane at Y=0 m

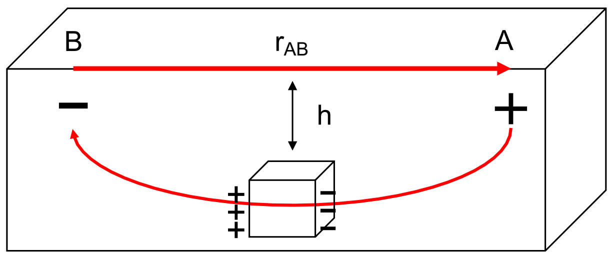


Conductor: currents

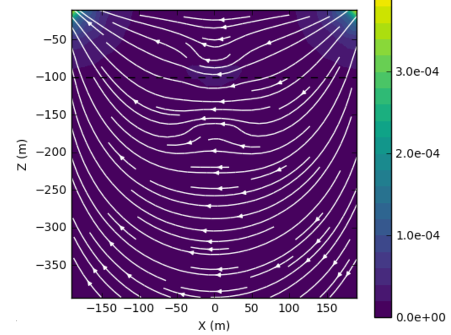


Cross section

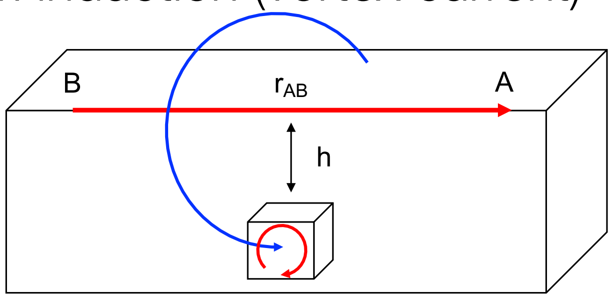
Steady State (galvanic current)



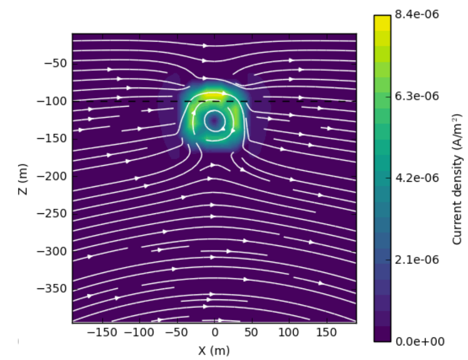
Galvanic current
t = 0⁻



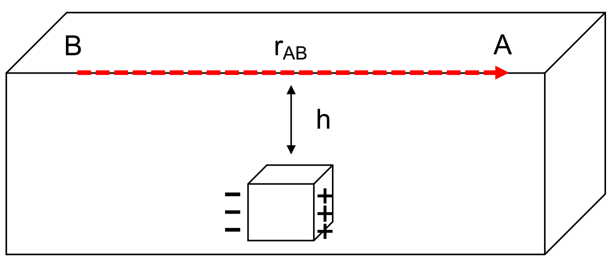
EM induction (vortex current)



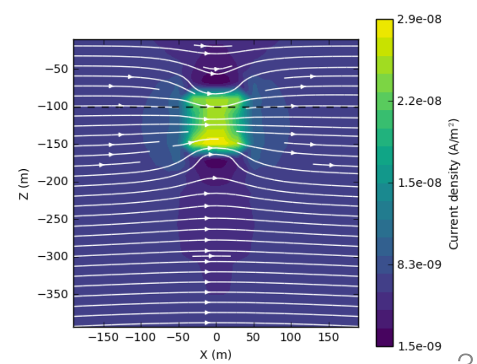
Vortex current
t = 1 ms



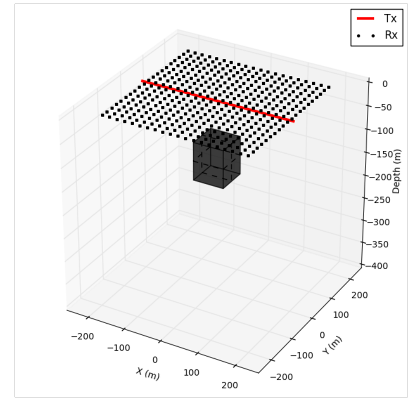
EM induction (galvanic current)

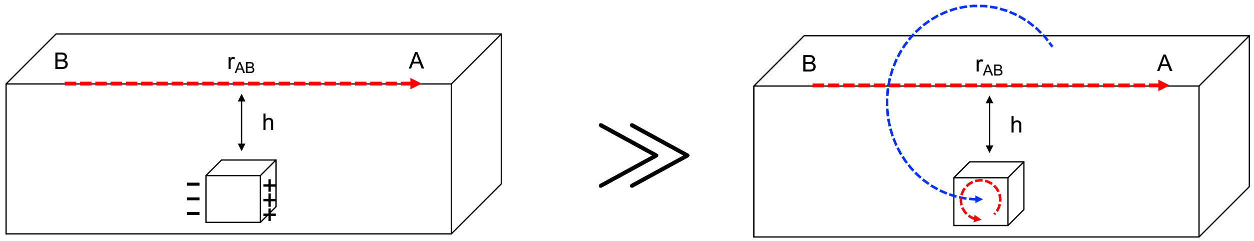


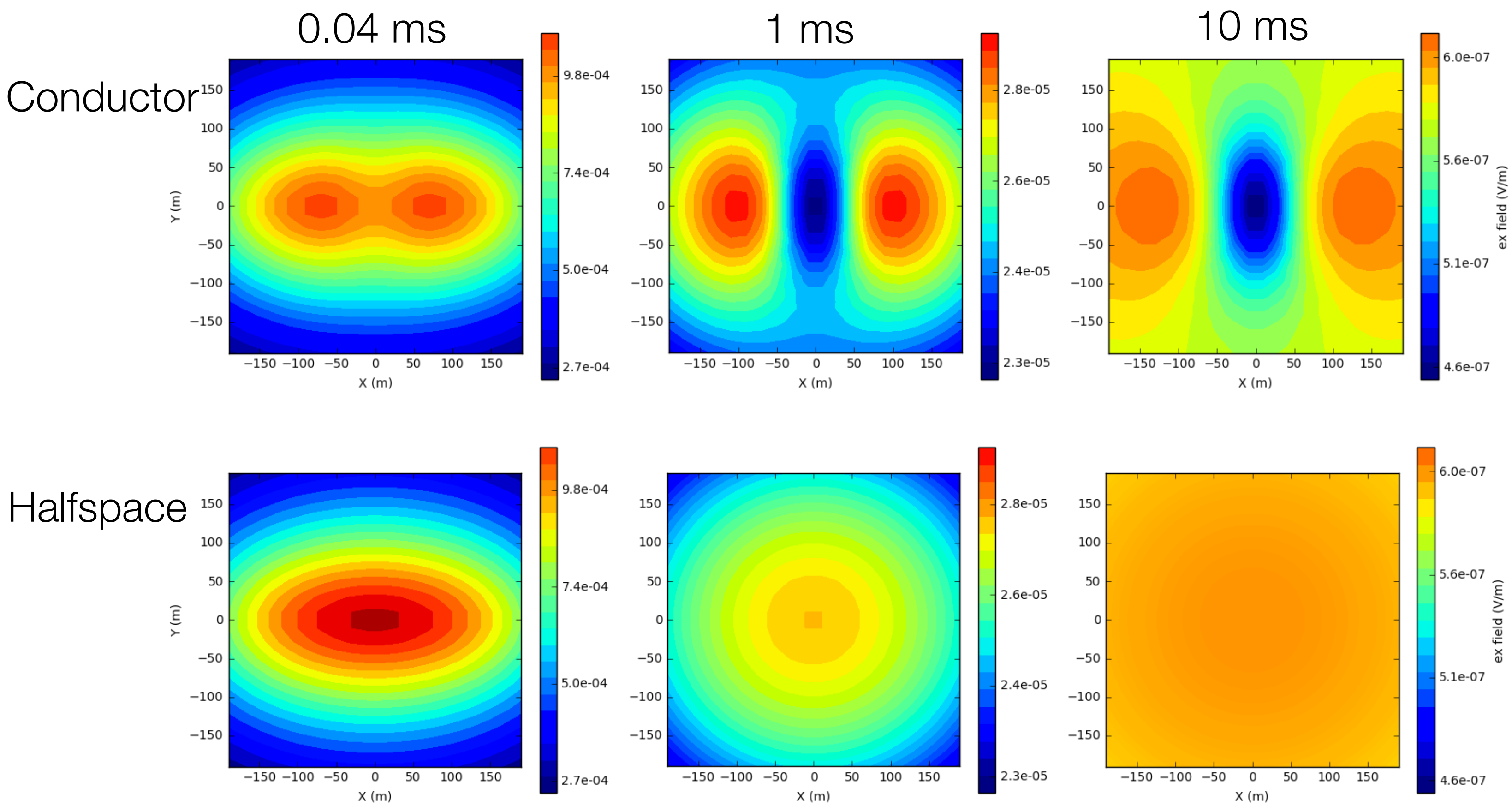
Galvanic current
t = 10 ms



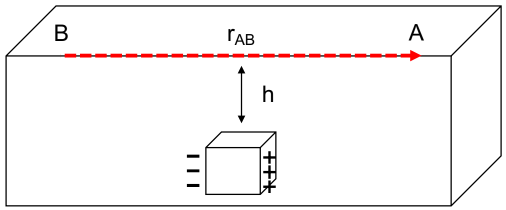
Data: e_x field



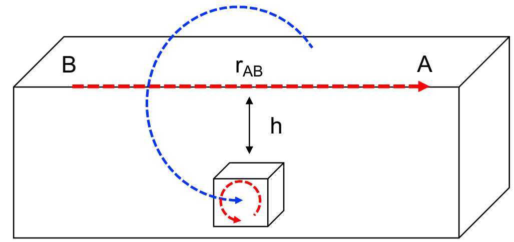


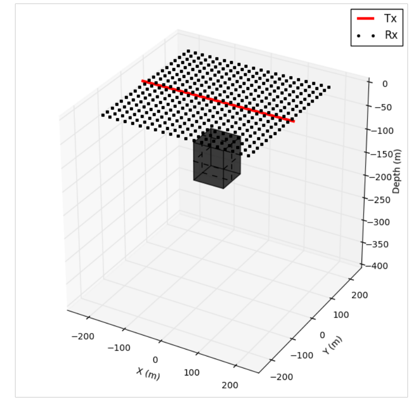


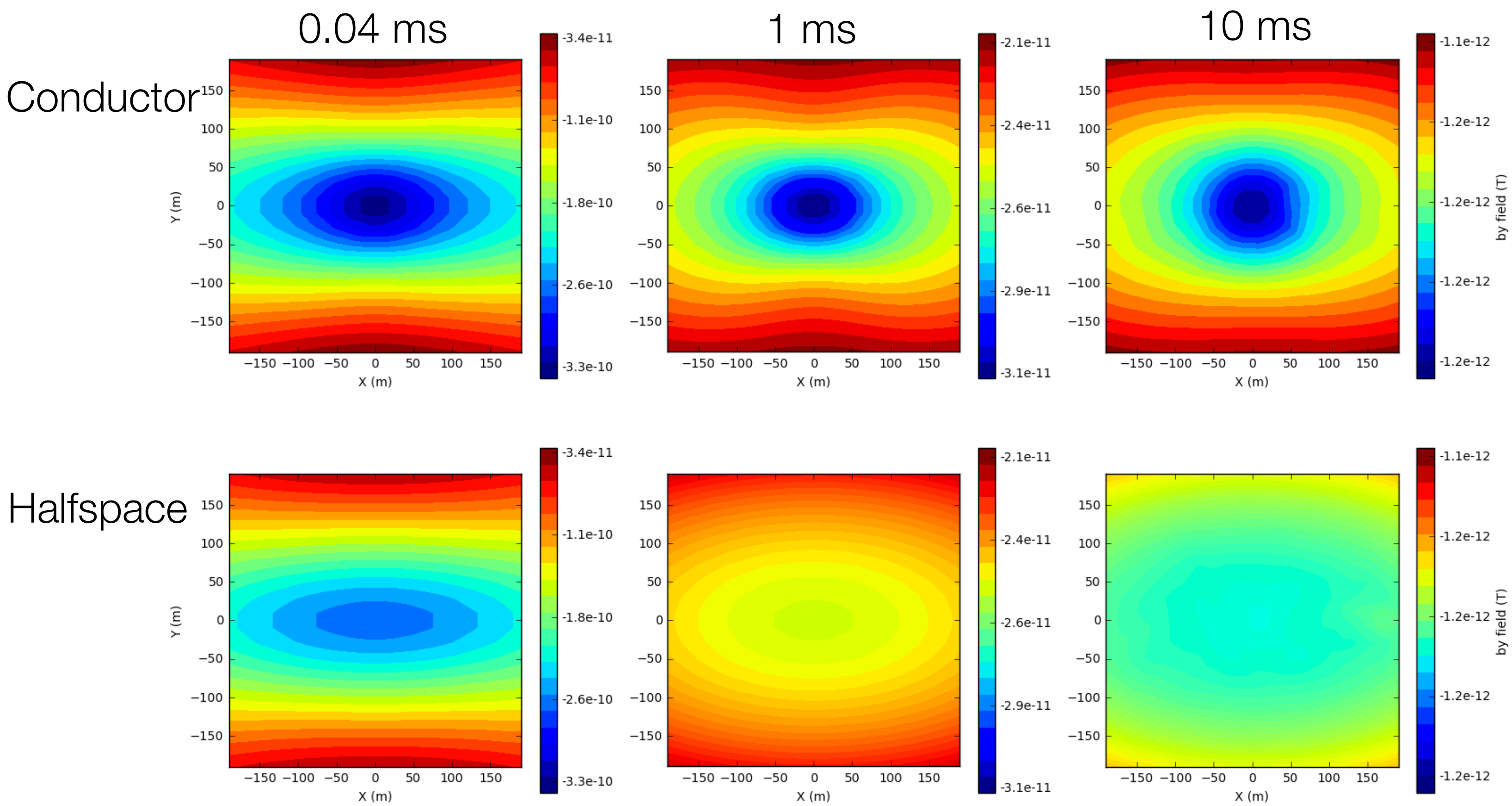
Data: b_y field



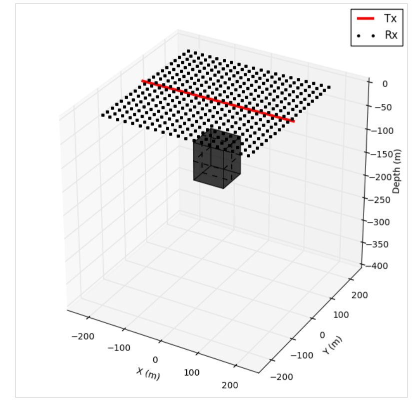
$\ll$

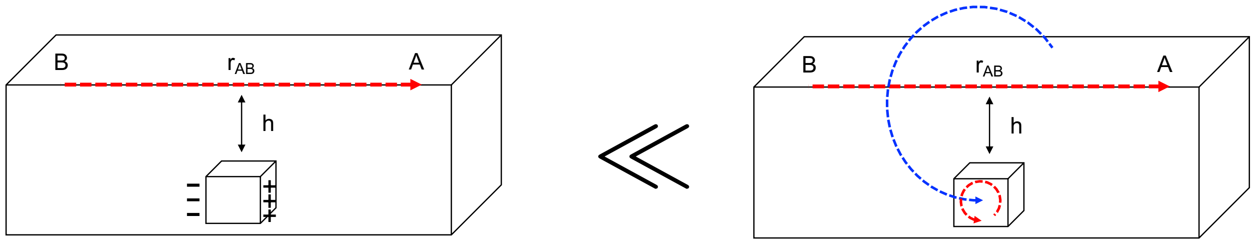


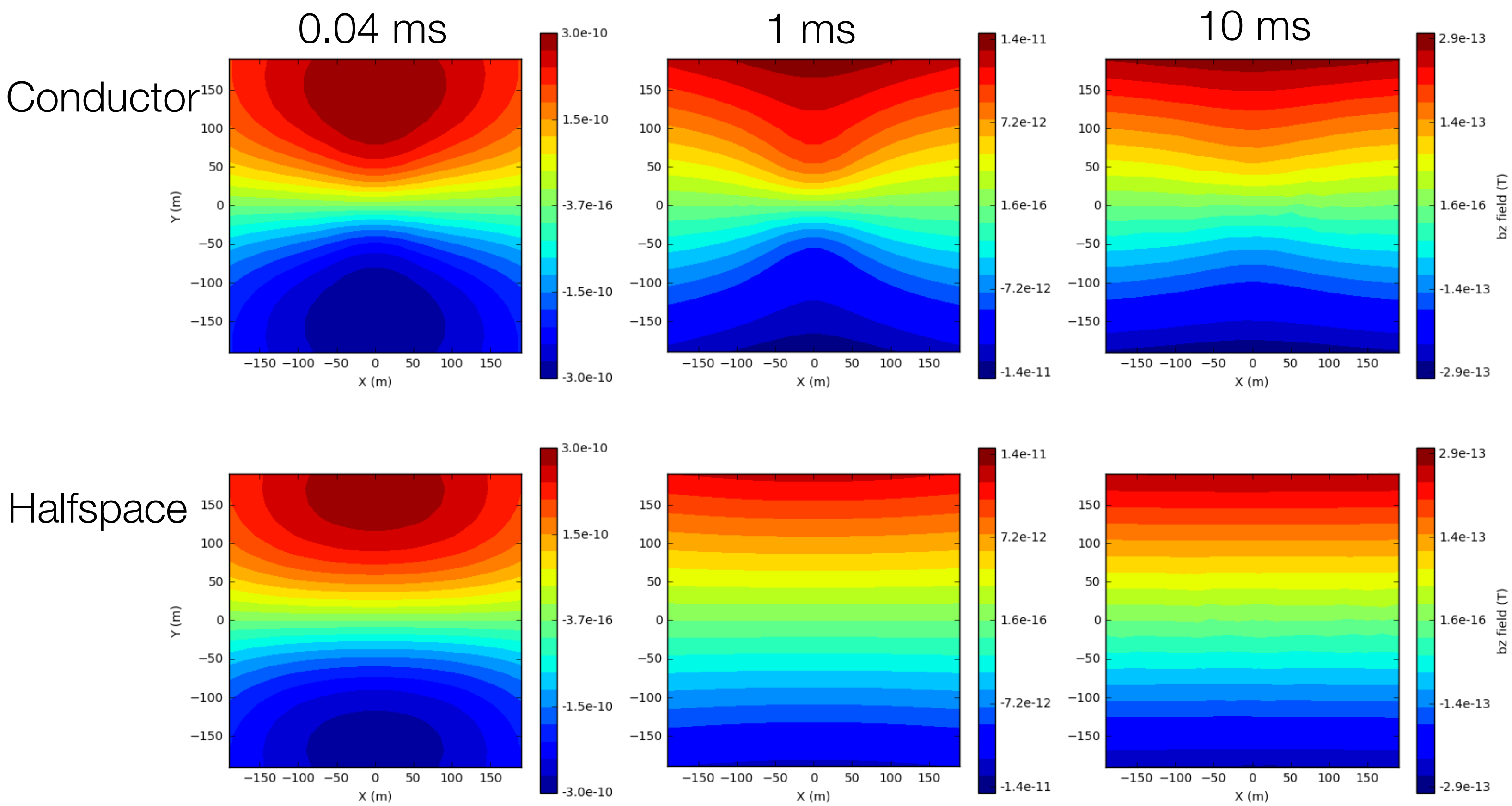




Data: b_z field

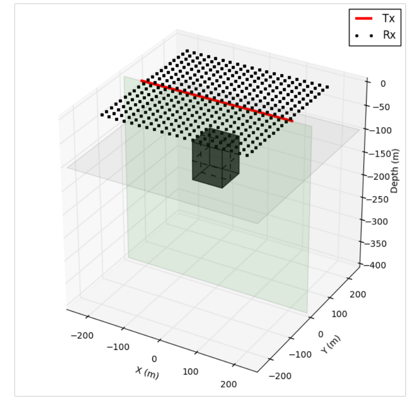






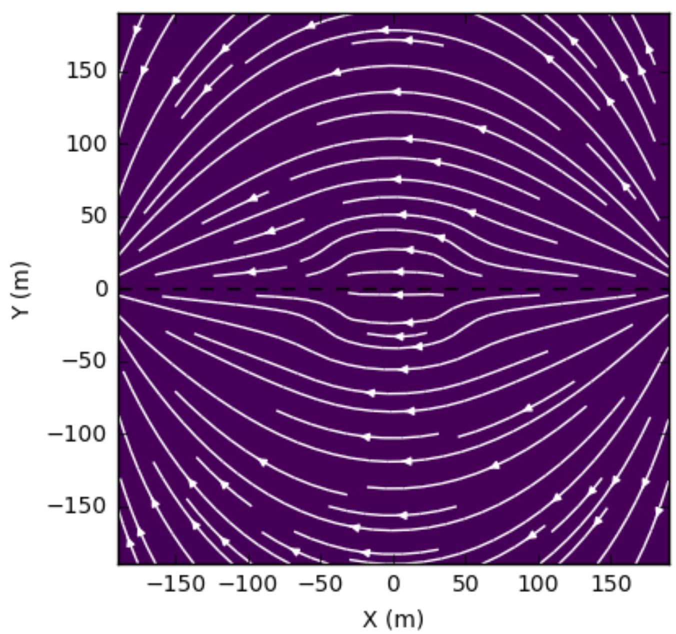
Anomaly: not always bulls-eye

Resistor: currents

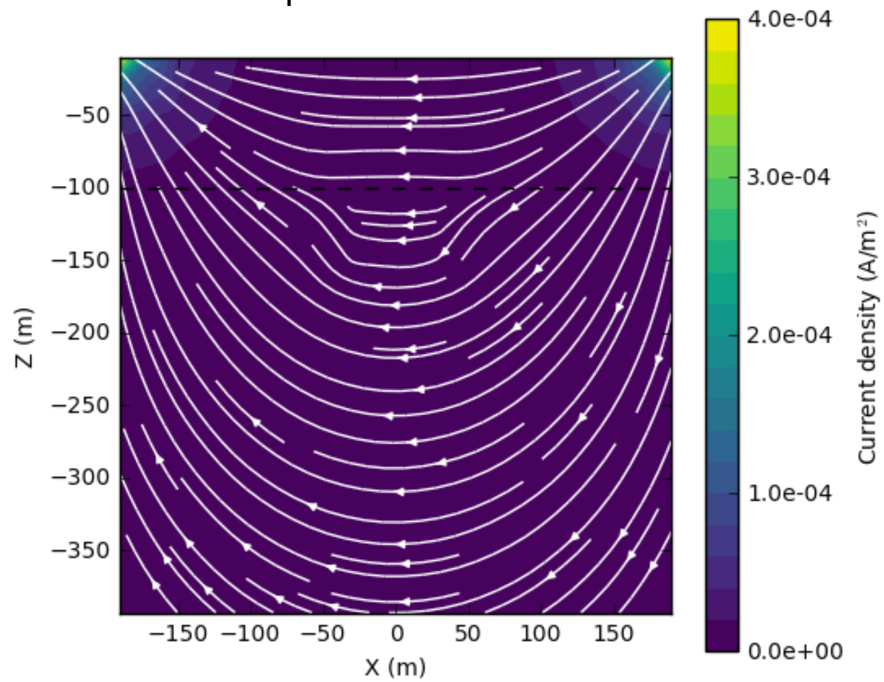


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **t=0$^-$**, steady state

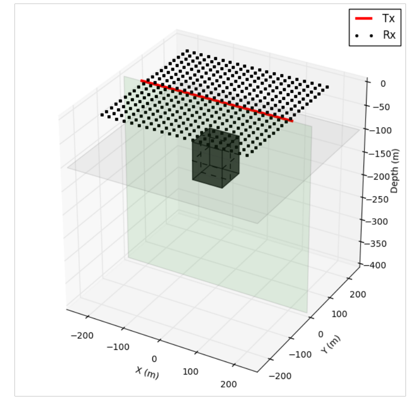
XY plane at Z=-100 m



XZ plane at Y=0 m

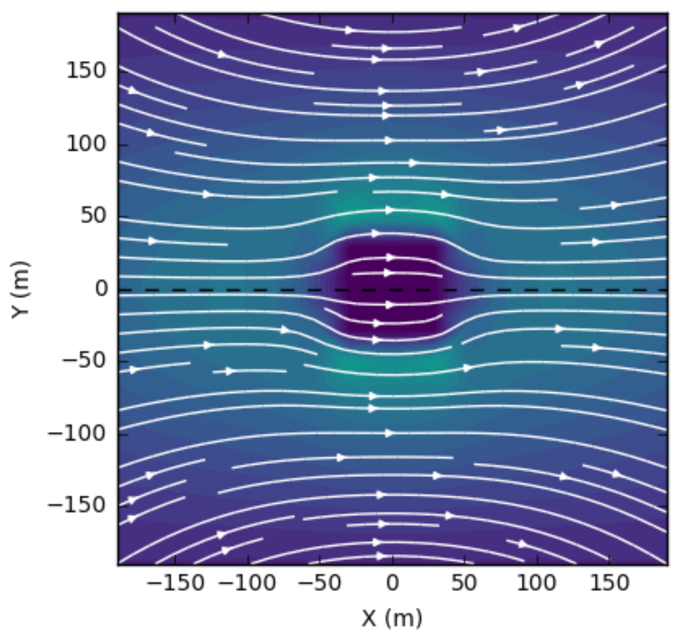


Resistor: currents

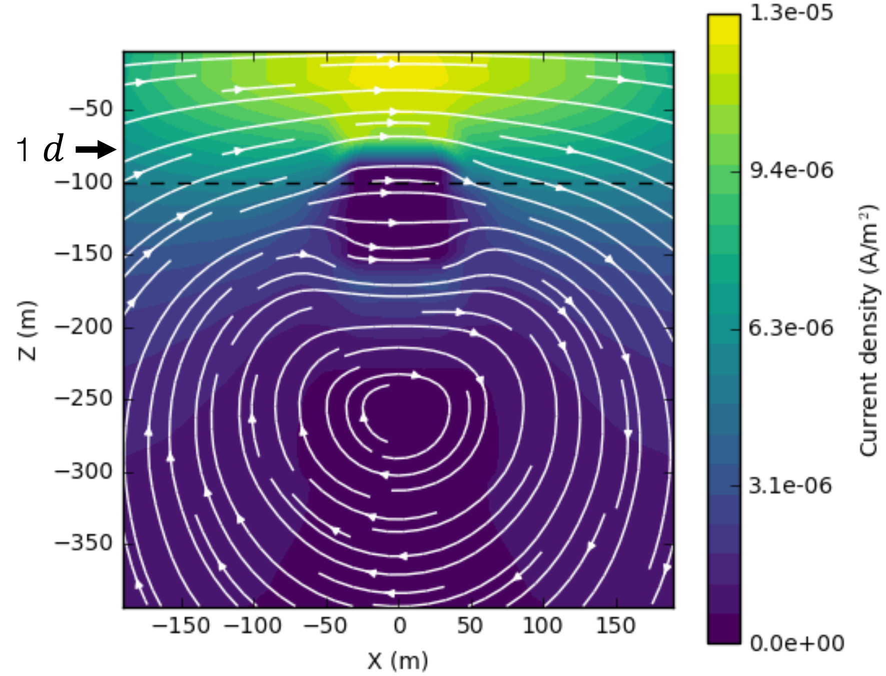


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

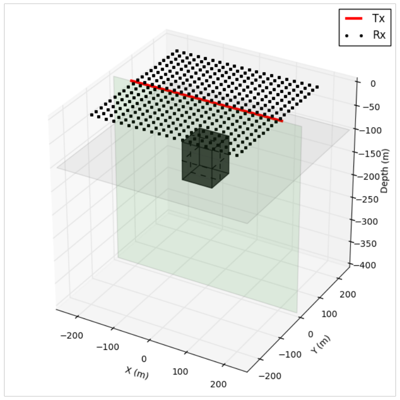
XY plane at Z=-100 m



XZ plane at Y=0 m

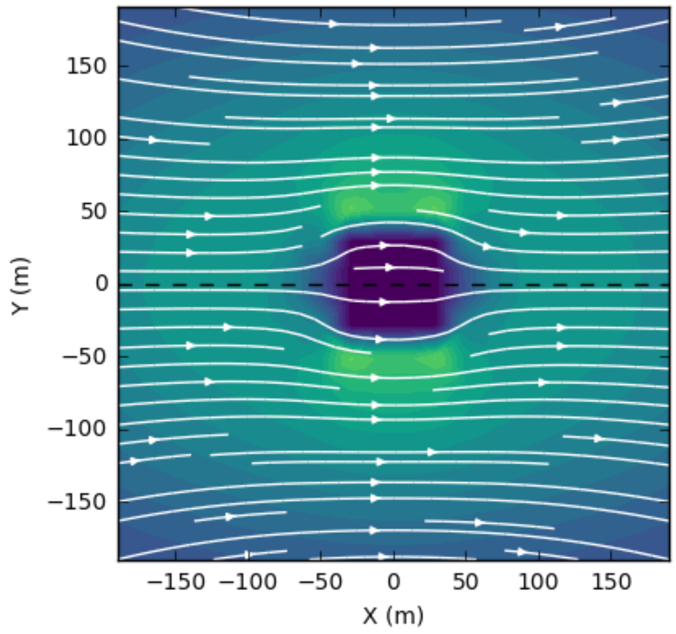


Resistor: currents

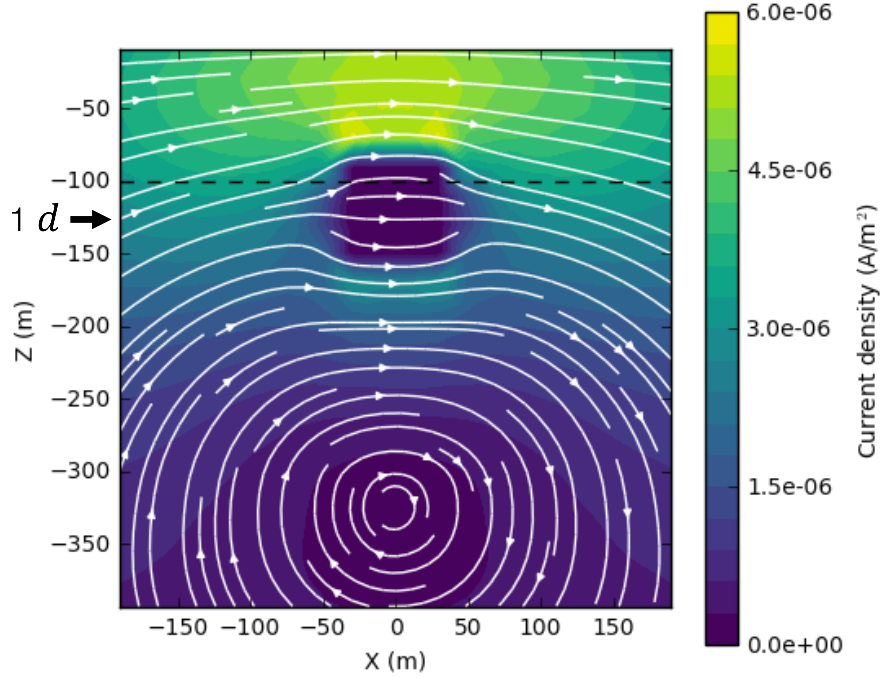


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m

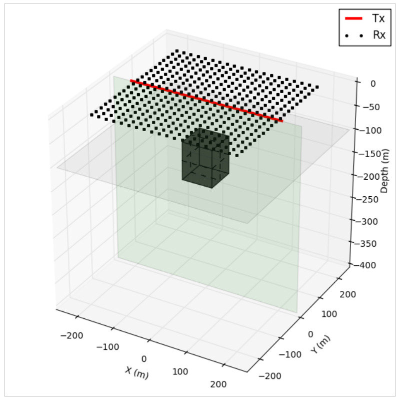
XY plane at Z=-100 m



XZ plane at Y=0 m

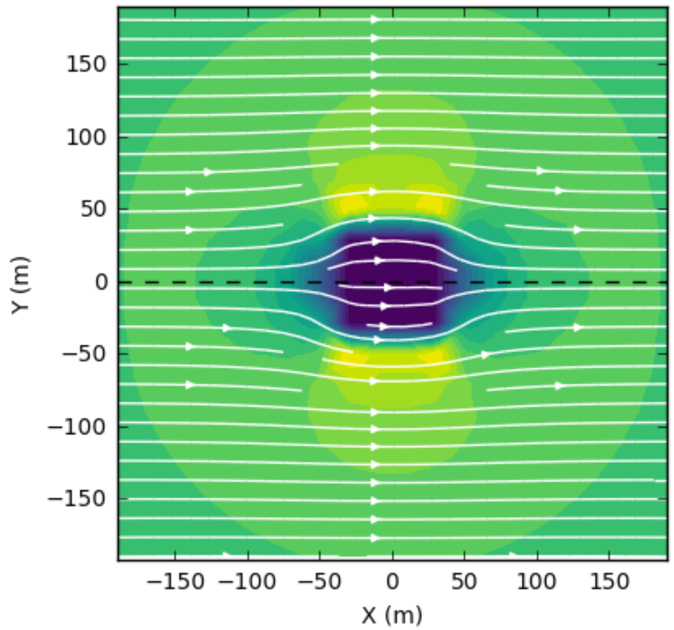


Resistor: currents

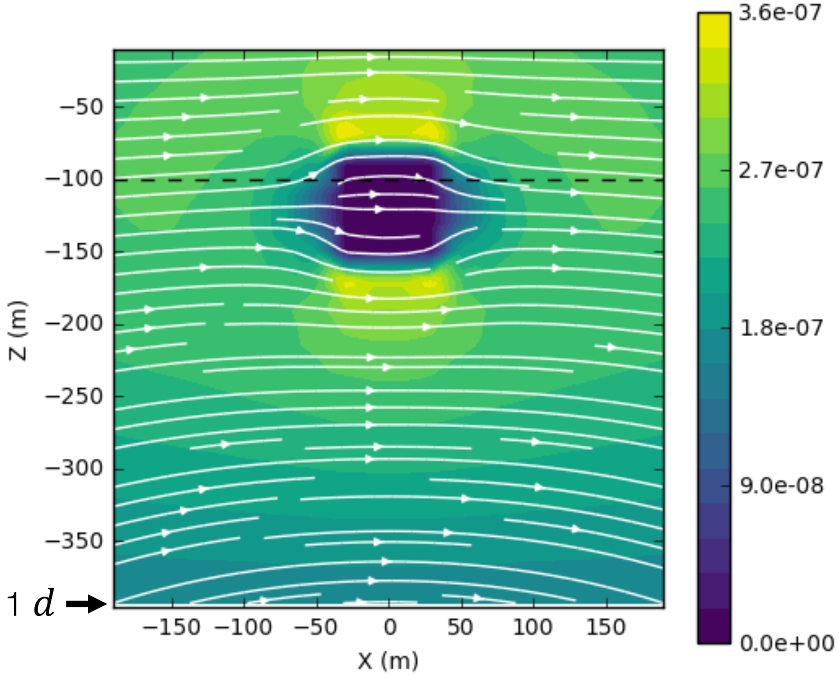


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **1** ms, d = 400 m

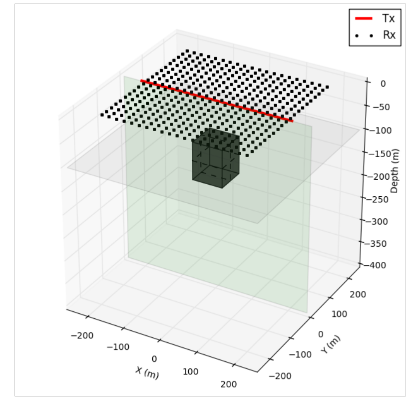
XY plane at Z=-100 m



XZ plane at Y=0 m



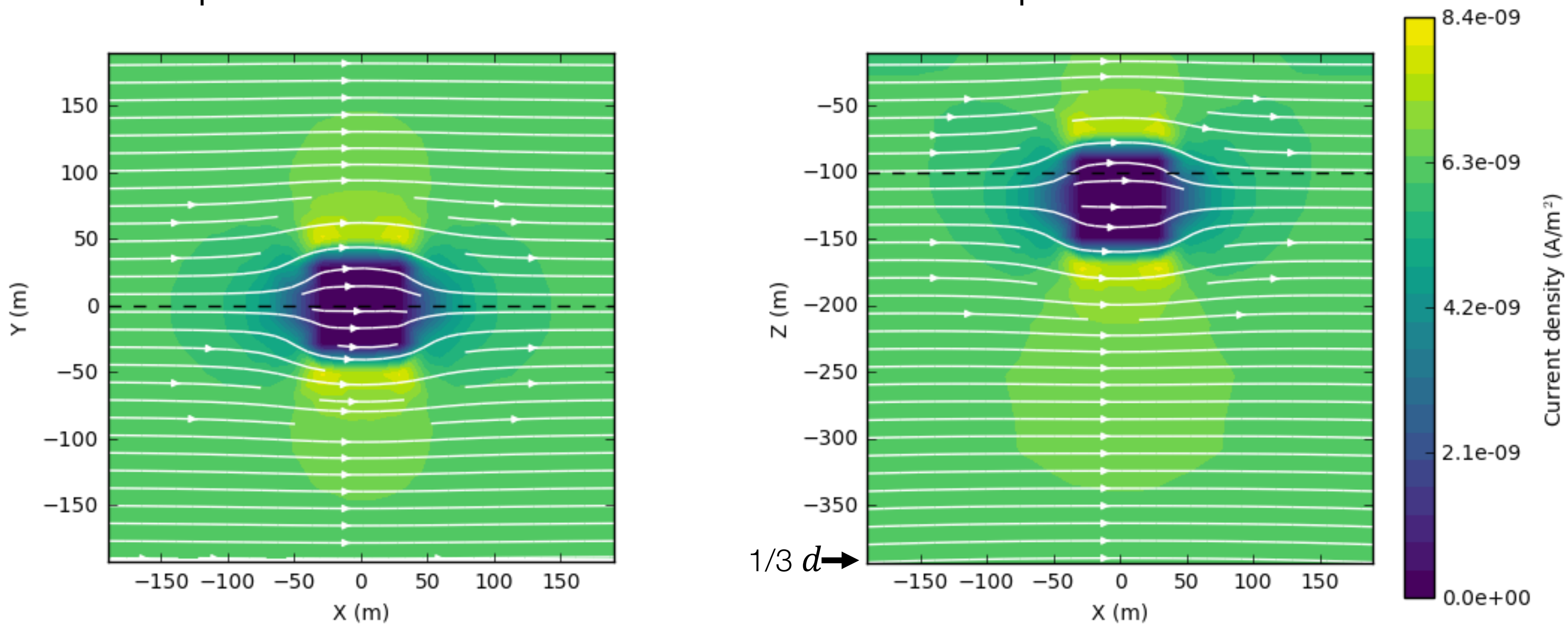
Resistor: currents

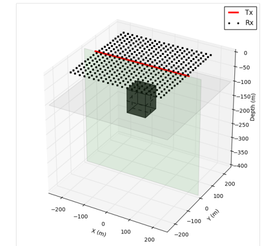


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m

XY plane at Z=-100 m

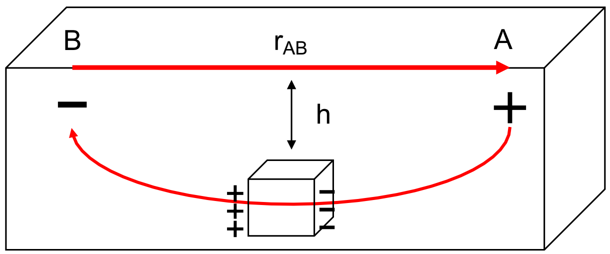
XZ plane at Y=0 m





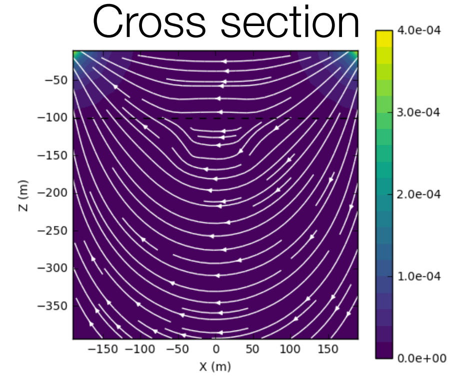
Resistor: currents

DC (galvanic current)

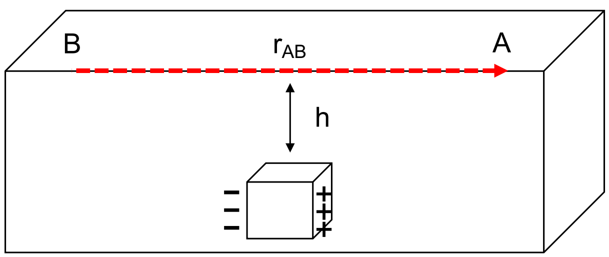


Galvanic current
t = 0^-

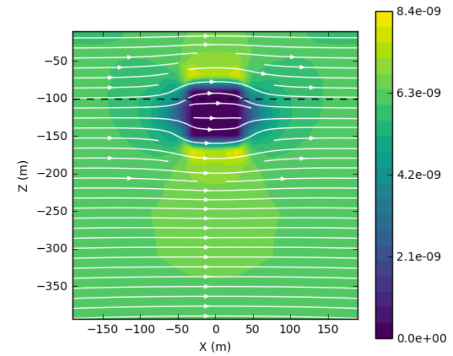
Cross section



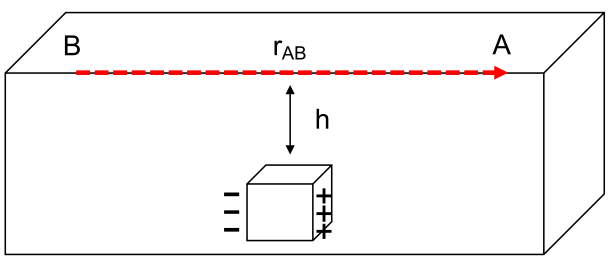
EM induction (galvanic current)



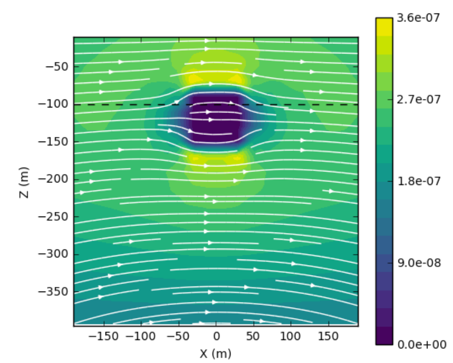
Galvanic current
t = 1 ms



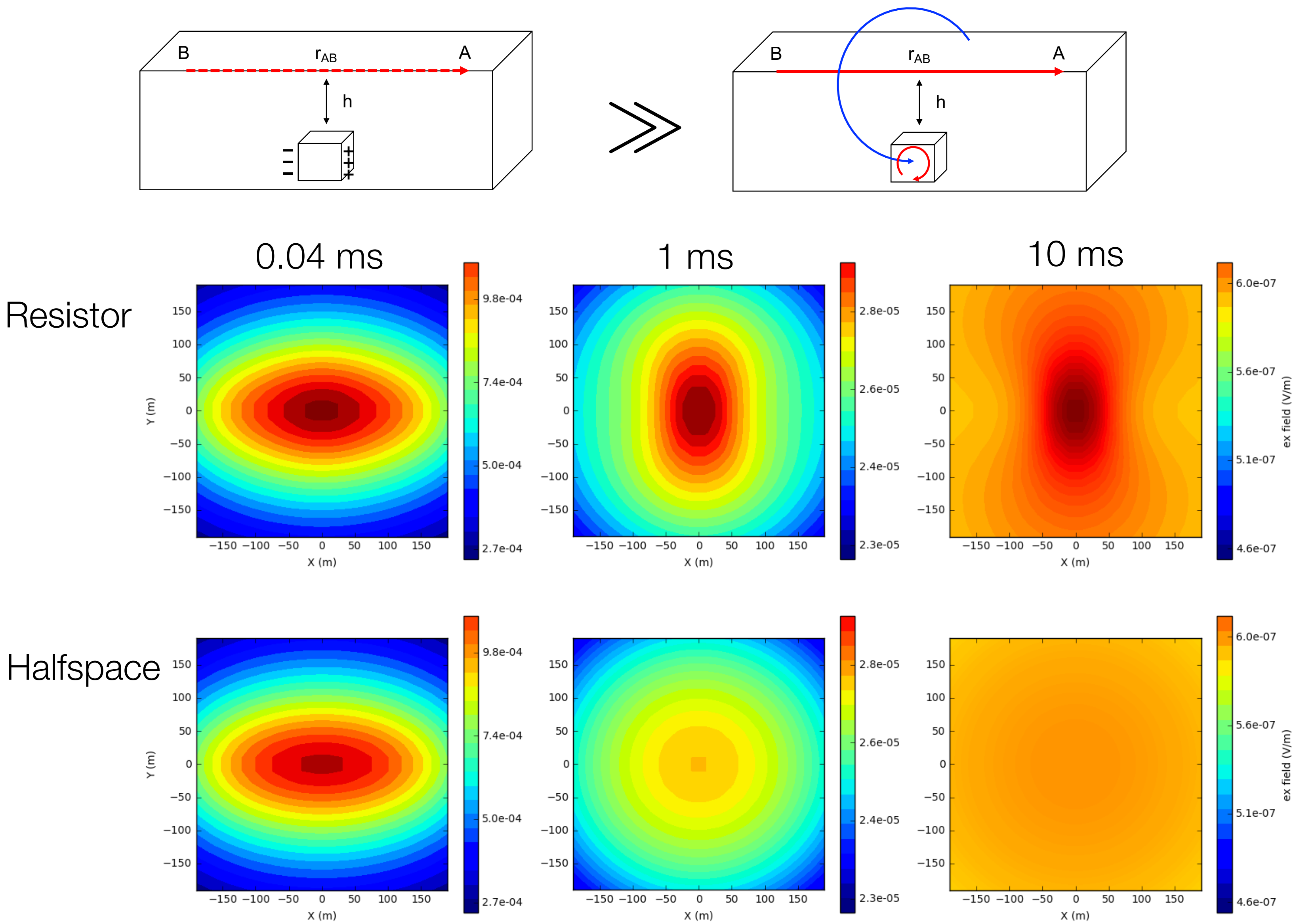
EM induction (galvanic current)



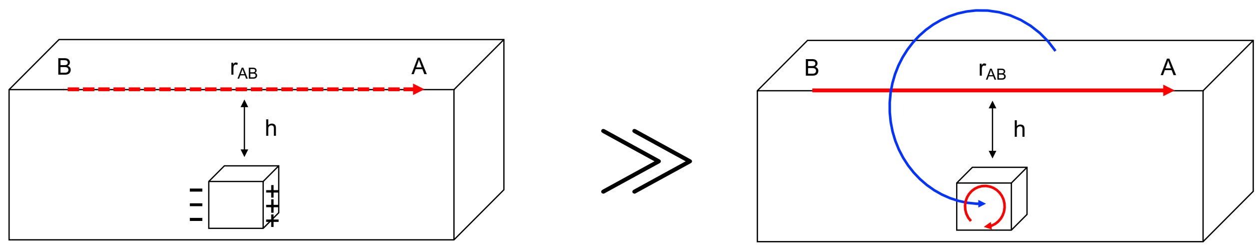
Galvanic current
t = 10 ms

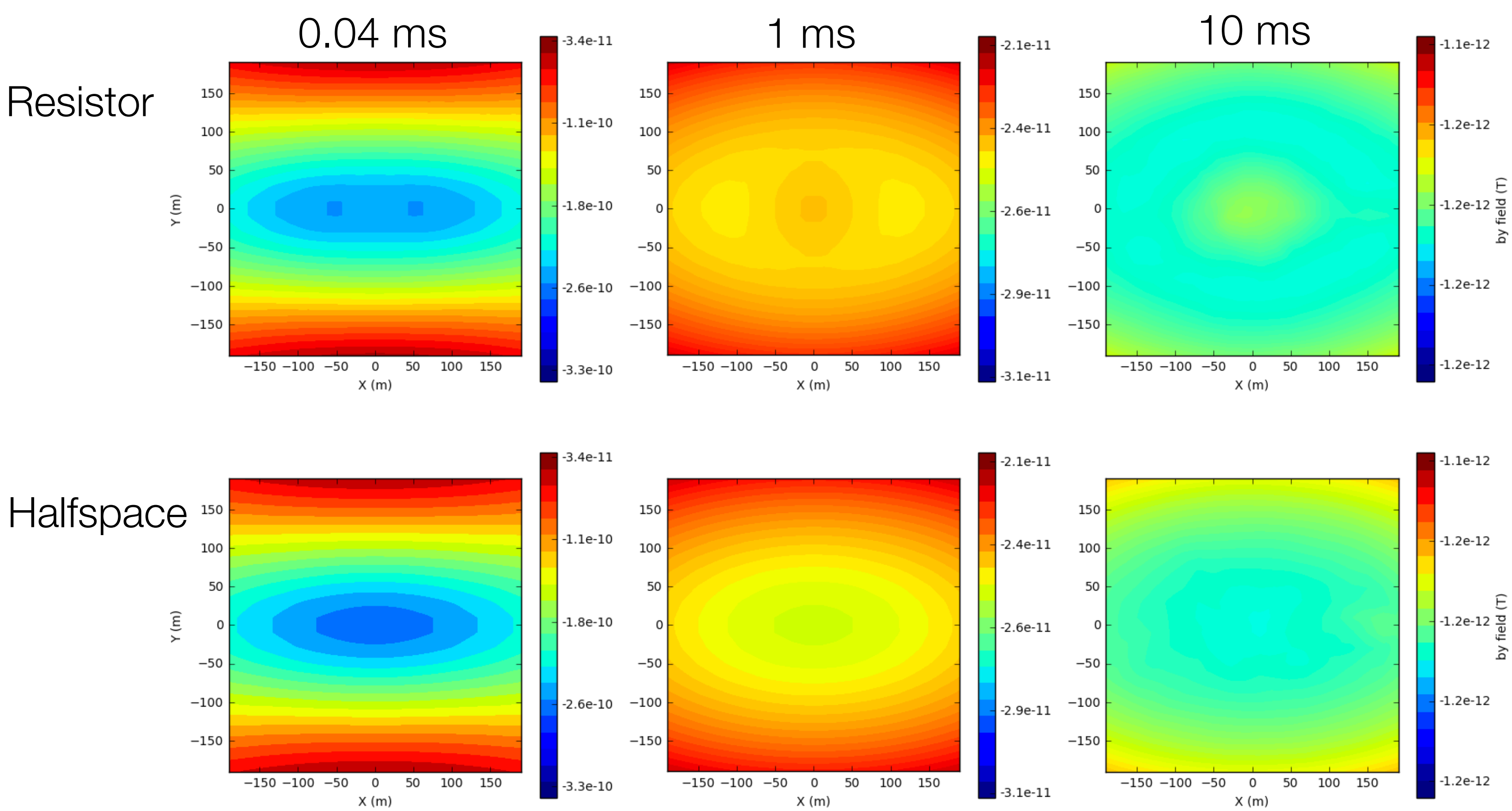


Data: e_x field

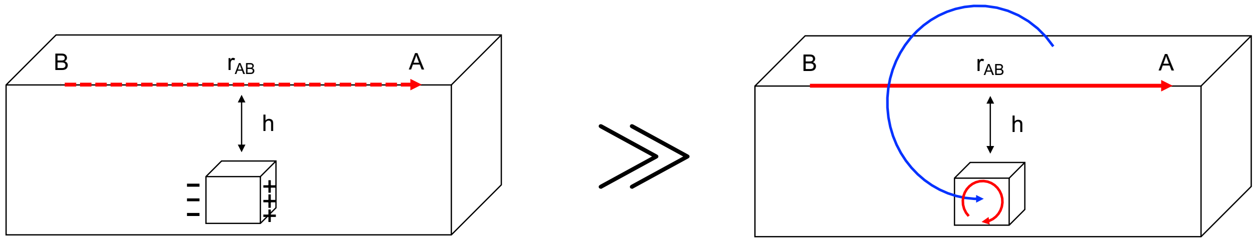


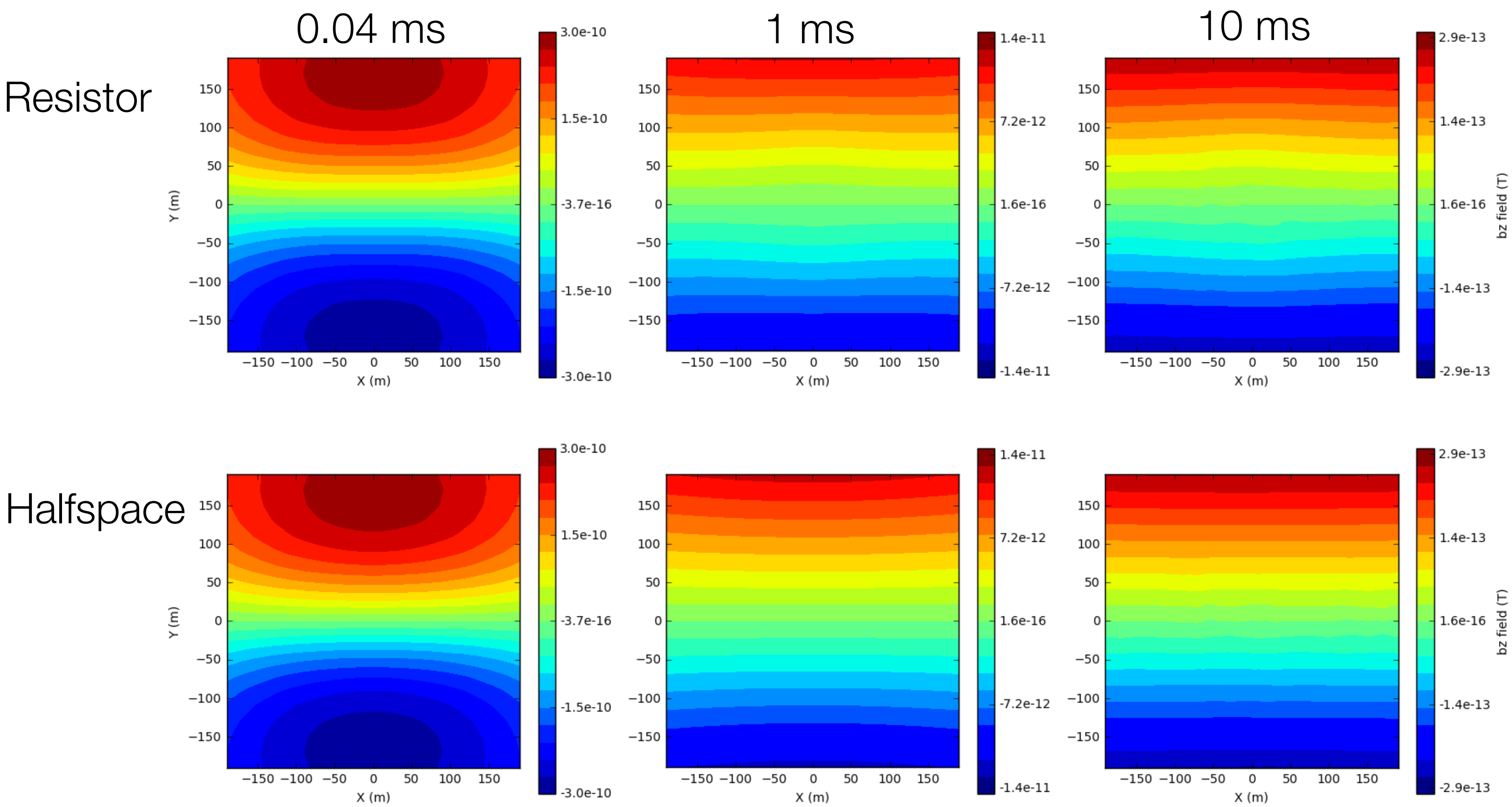
Data: b_y field





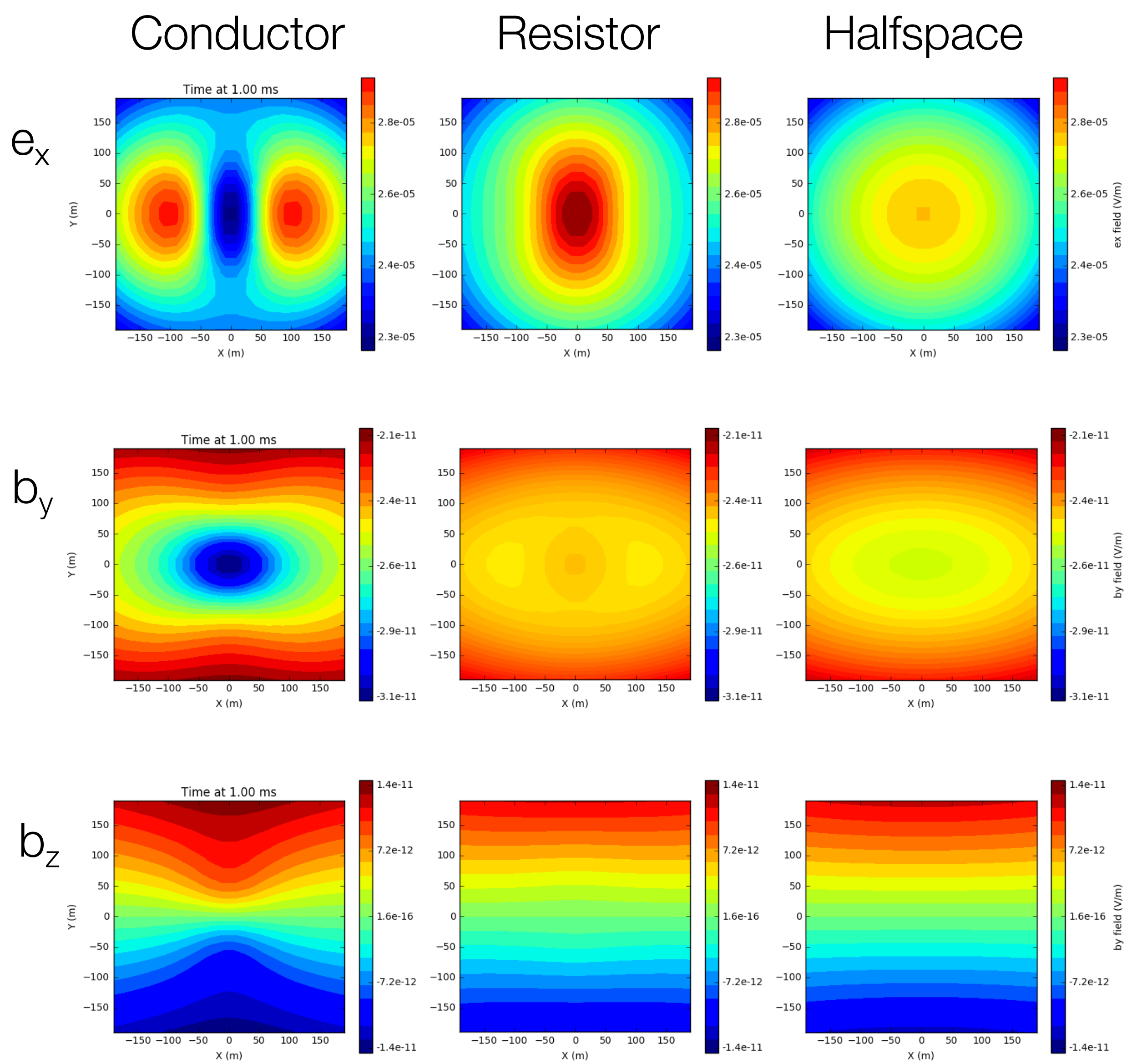
Data: b_z field





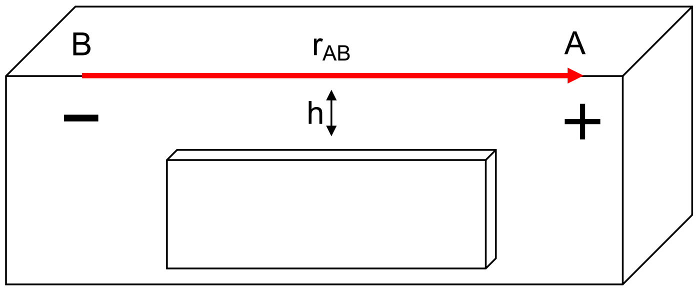
Data summary

t = 1ms

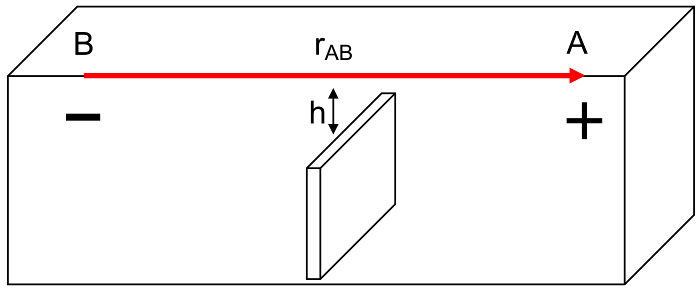


Geometric Complexities

- 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

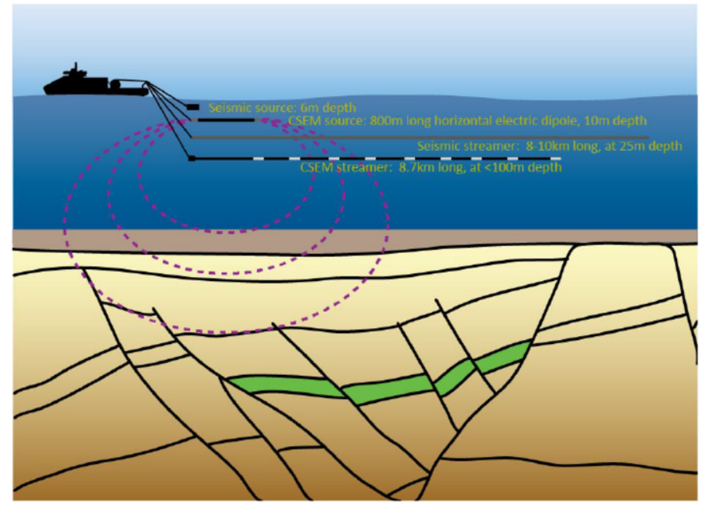
Grounded Sources: Summary

- 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

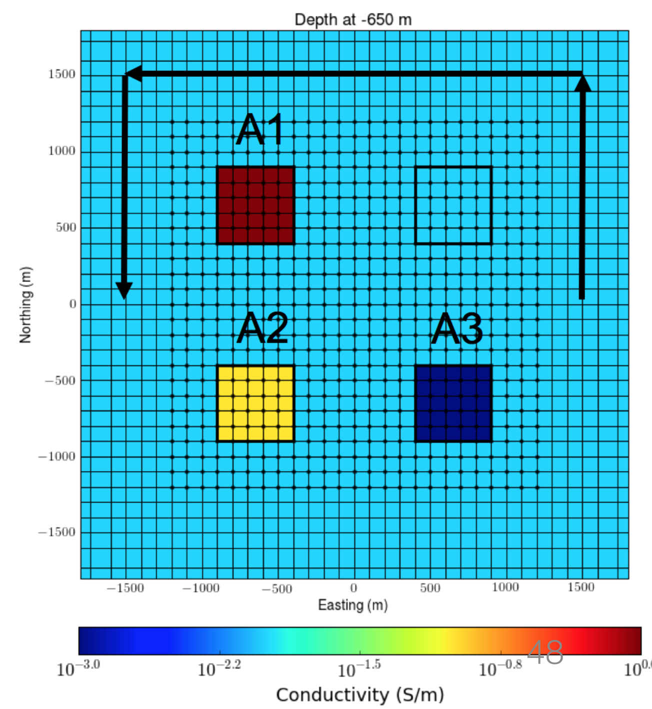
- Questions
- Case History: Barents Sea
- DC/EM Inversion

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…

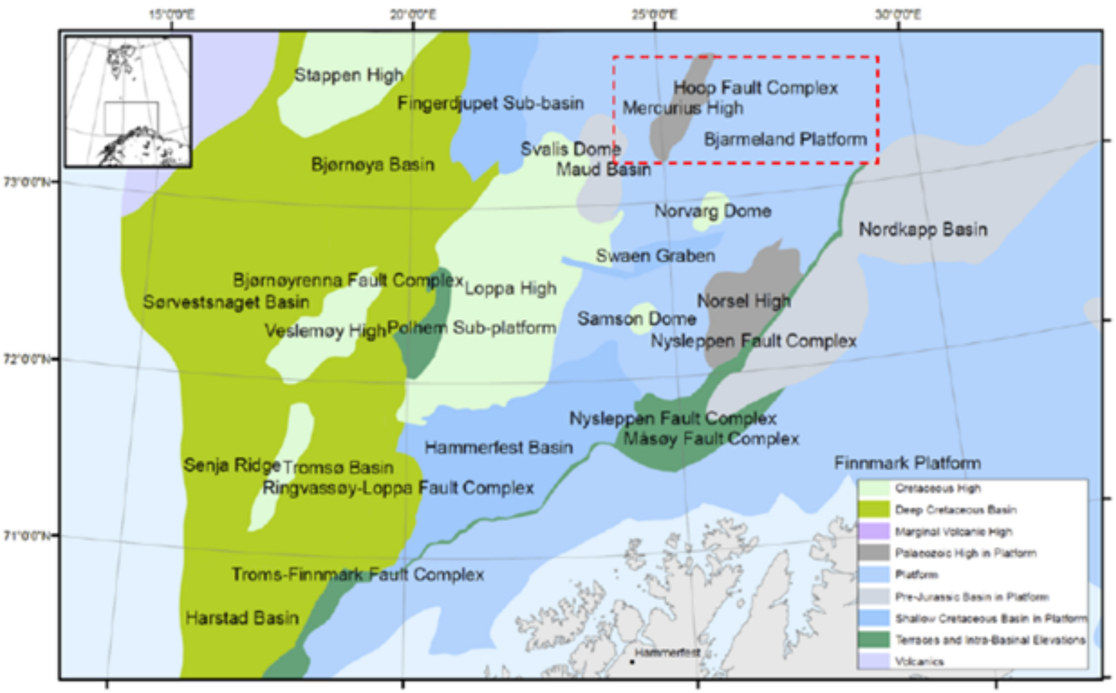


Case History: Barents Sea

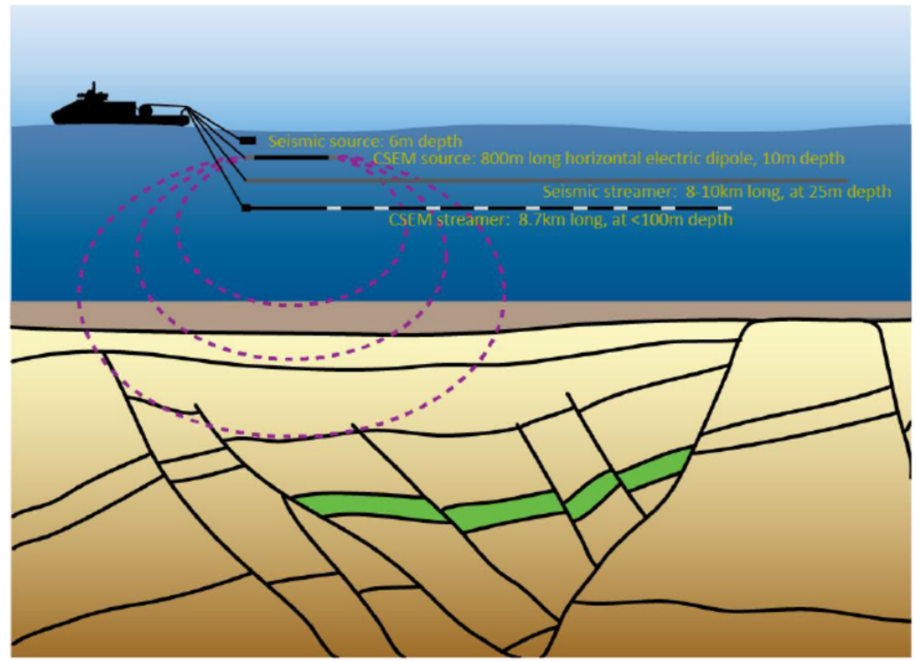
Alvarez et al., 2016. Rock Solid Images

Setup

Hoop Fault Complex, Barents Sea

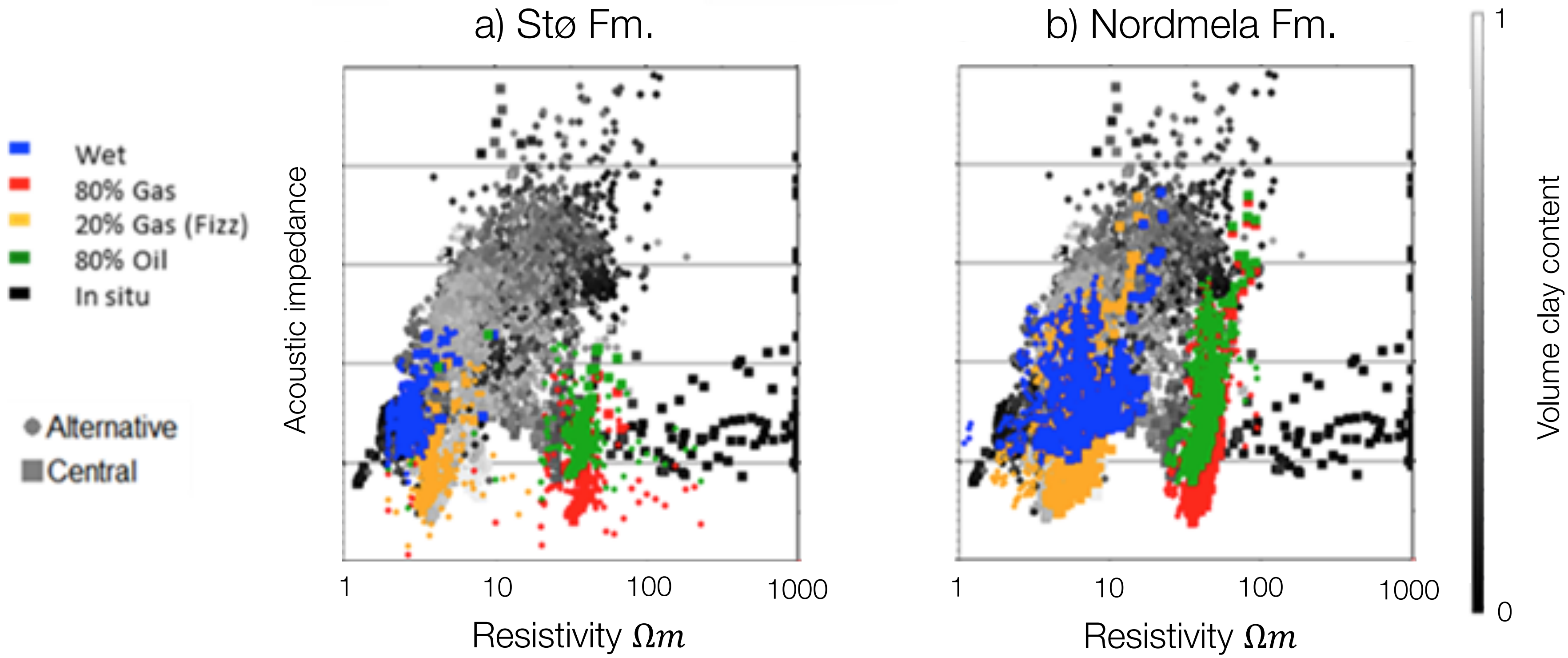


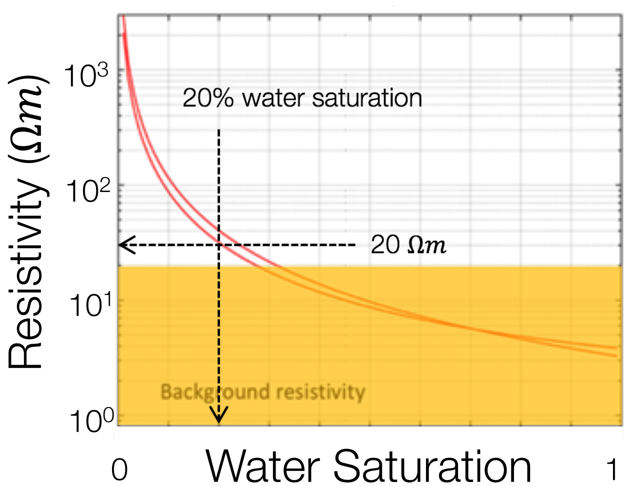
Marine CSEM



- 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

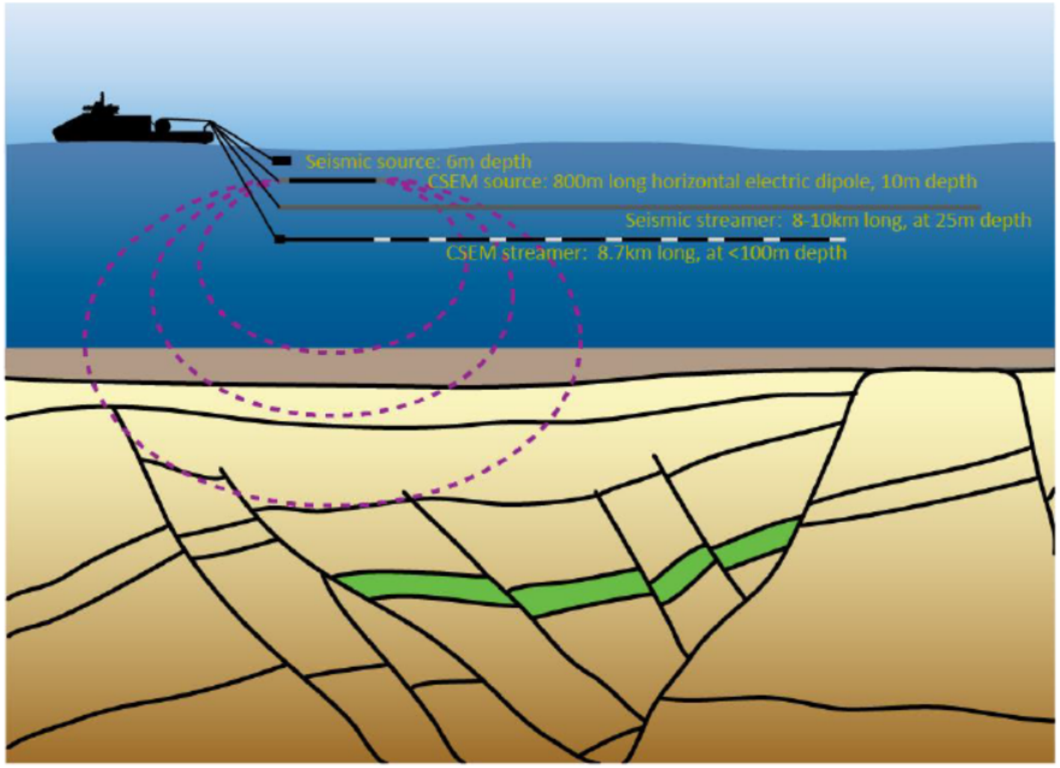




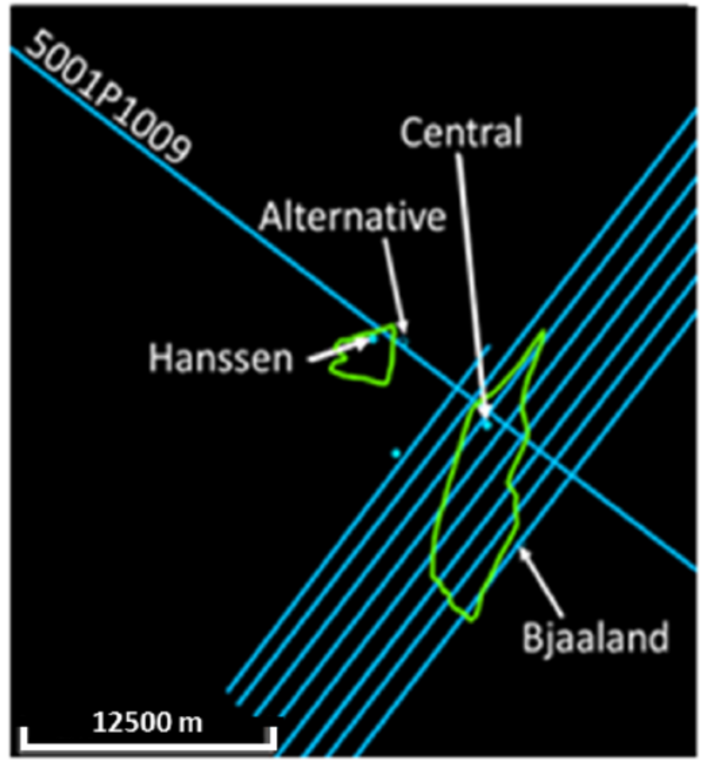
- Highly hydrocarbon-saturated reservoir (< 20% water-wet) significant resistivity
- CSEM can differentiate high from low quality reservoirs

Survey

Towed CSEM and 2D seismic



Survey lines

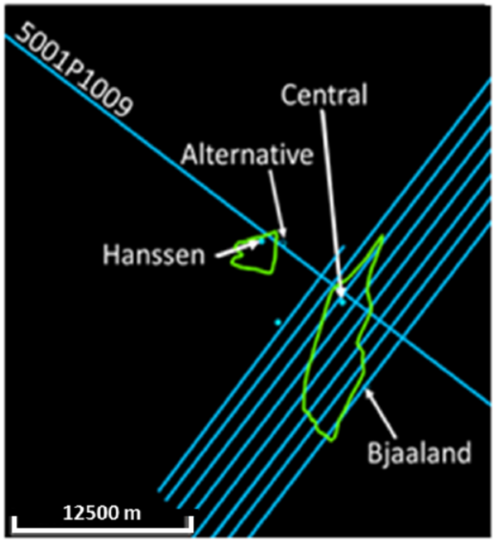


- 6 lines of 2D seismic and towed streamer CSEM data.
- 72 receivers collected CSEM data
    - offsets from 31m to 7.8 km
- CSEM frequencies: 0.2 Hz to 3 Hz.

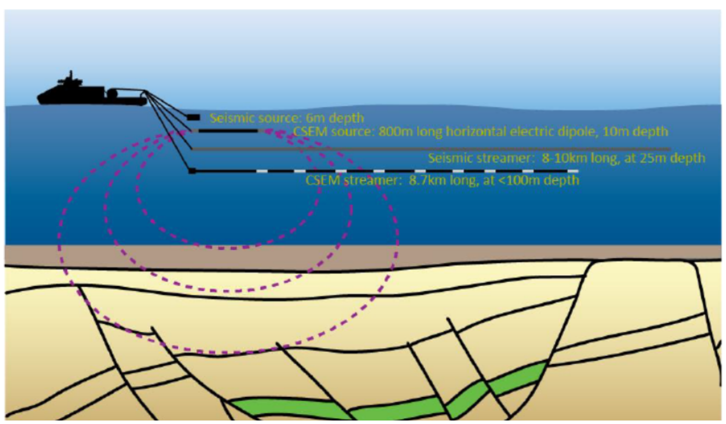
Alternative	Control well, productive
Central	Control well, dry
Hanssen	Validation well
Bjaaland	Validation well

CSEM Data

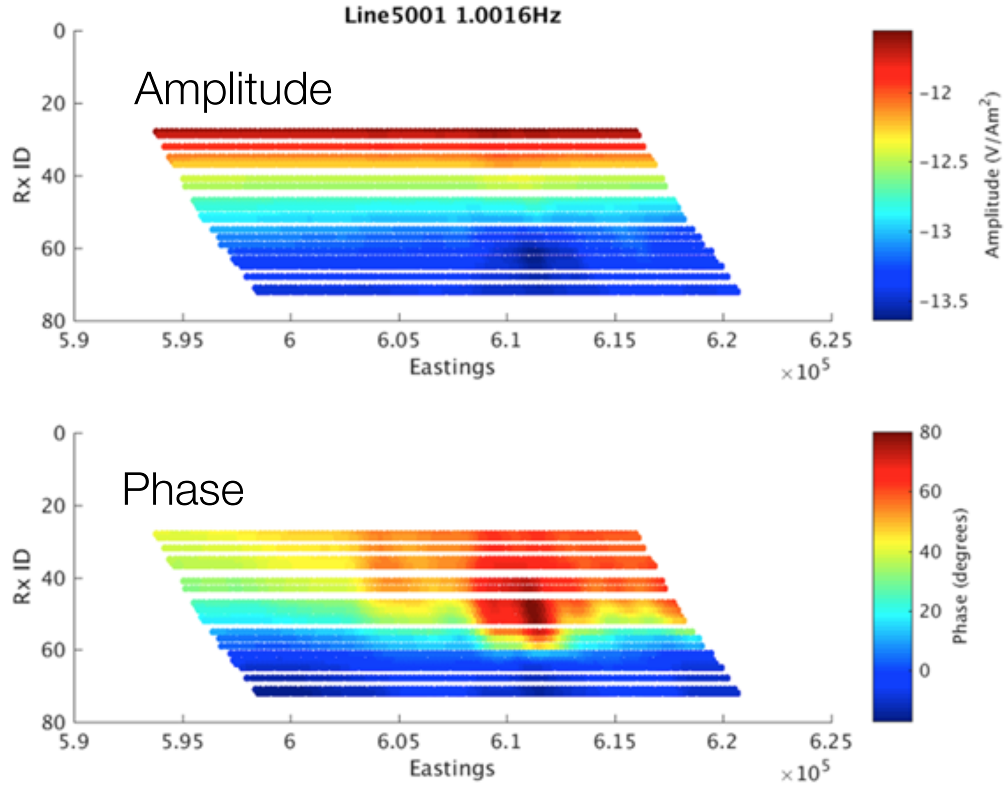
Survey lines



Towed-streamer EM



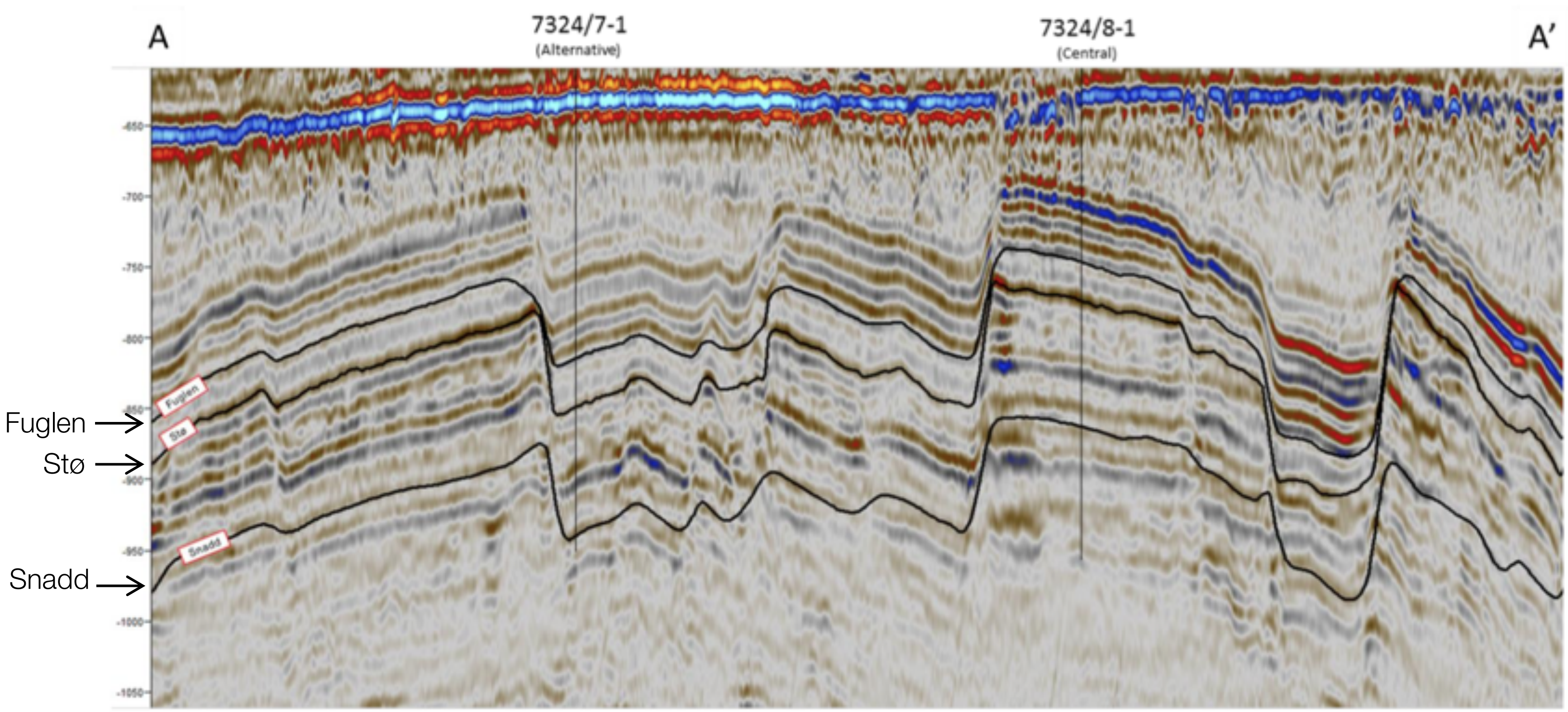
CSEM data over central reservoir (1 Hz)

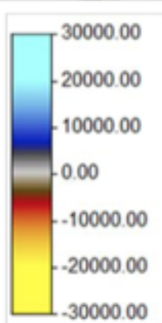


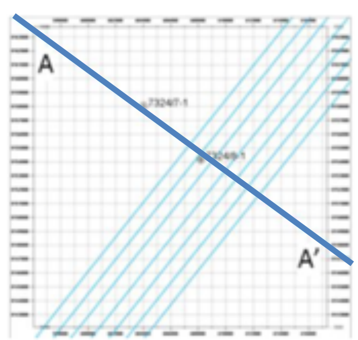
- Significant phase response over Central reservoir

Seismic data

Seismic section: Line 5001





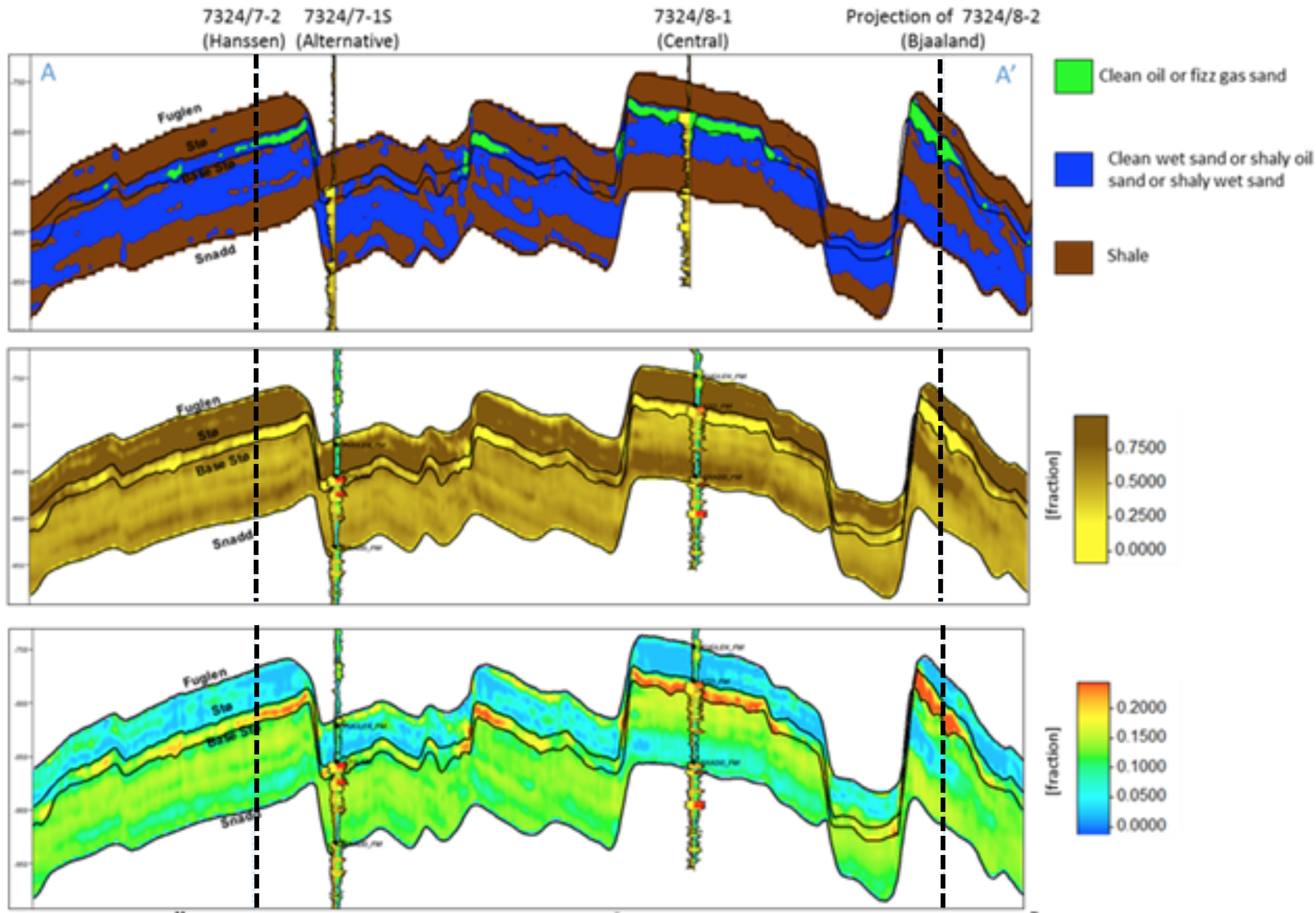


Well-Log and Seismic Inversion

Litho-fluid Facies

Clay Content

Total Porosity



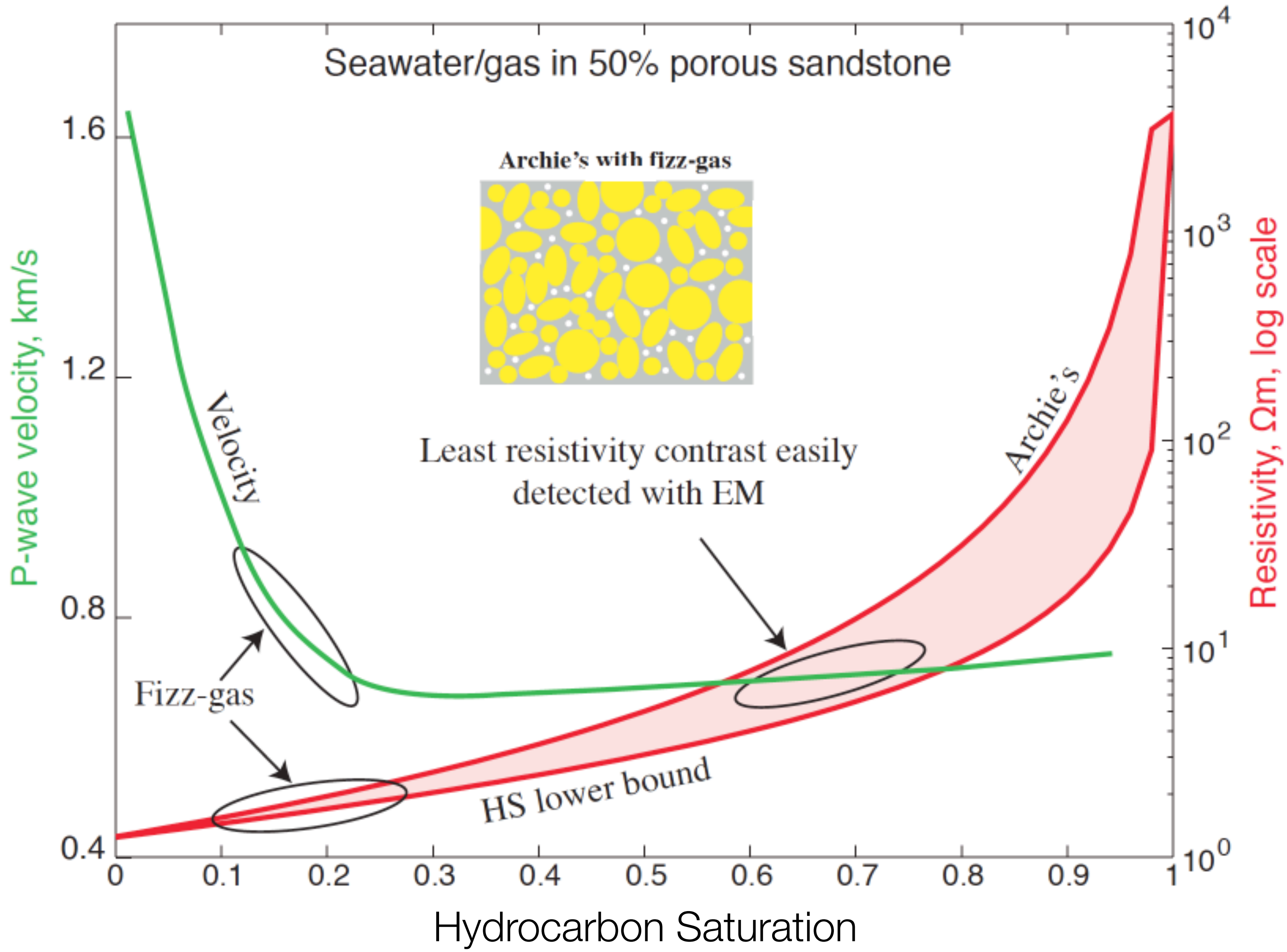
Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

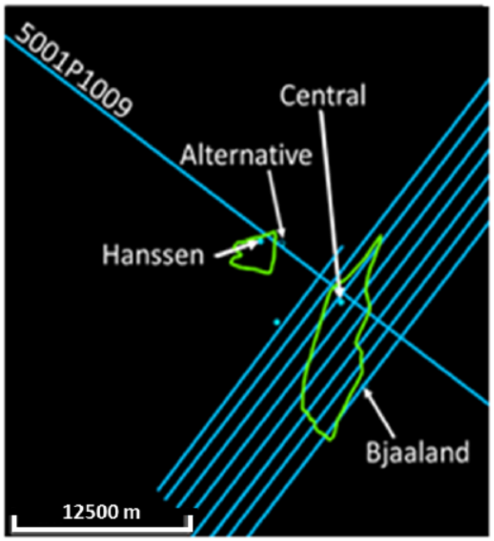
Bjaaland
Validation well

Revisiting physical properties

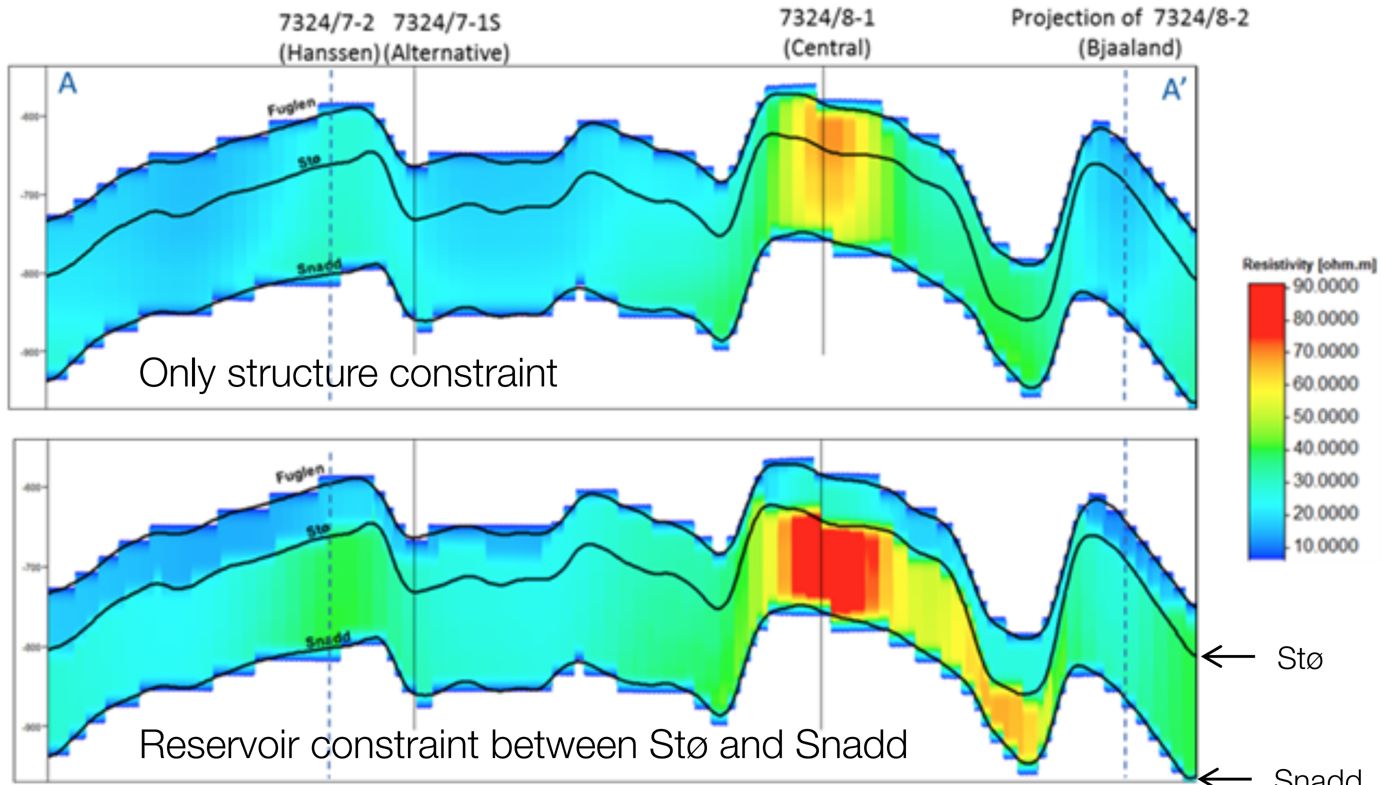


Processing: CSEM Inversion

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'.

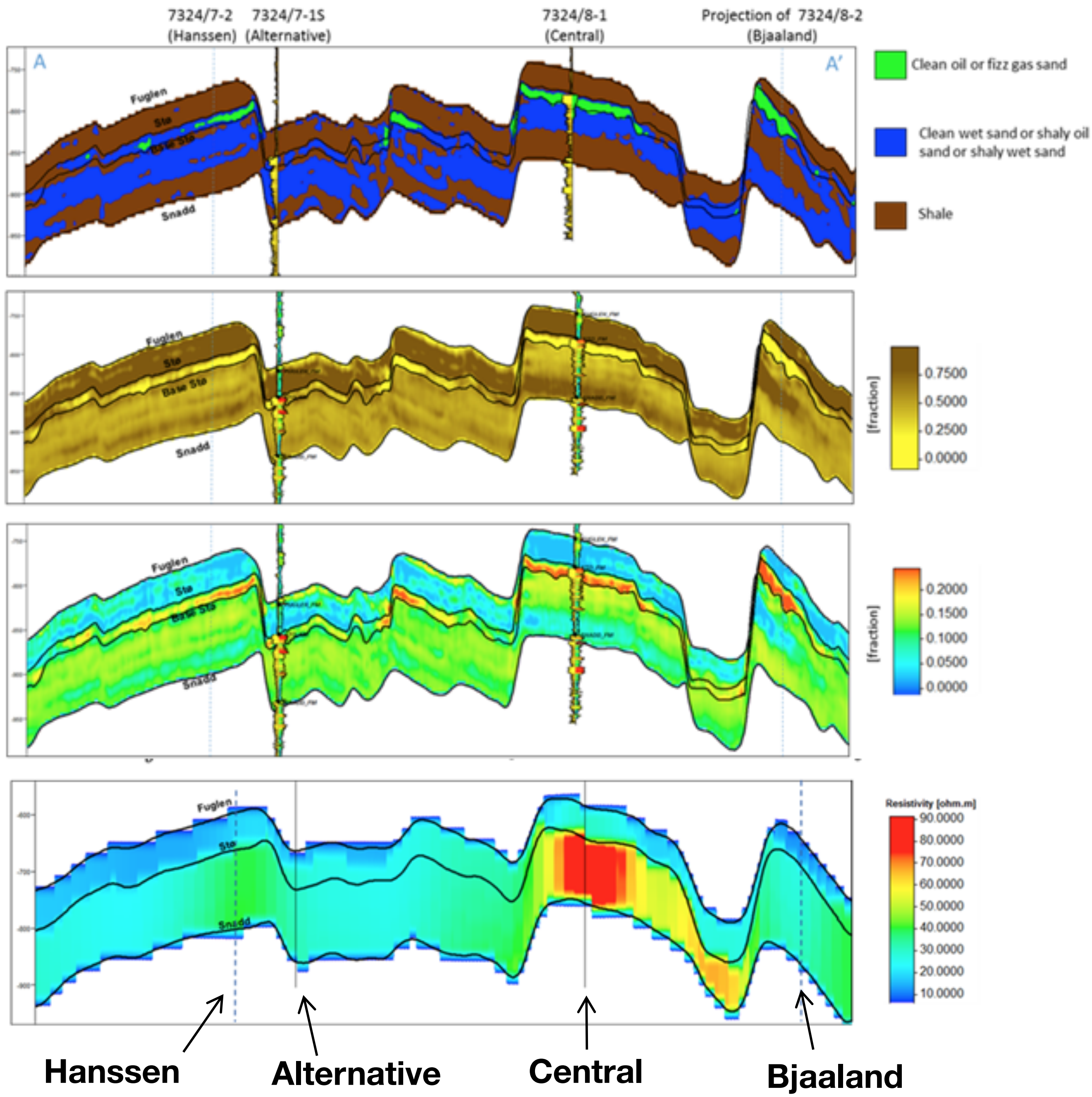
Processing: Multi-physics Approach

Litho-fluid Facies

Clay Content

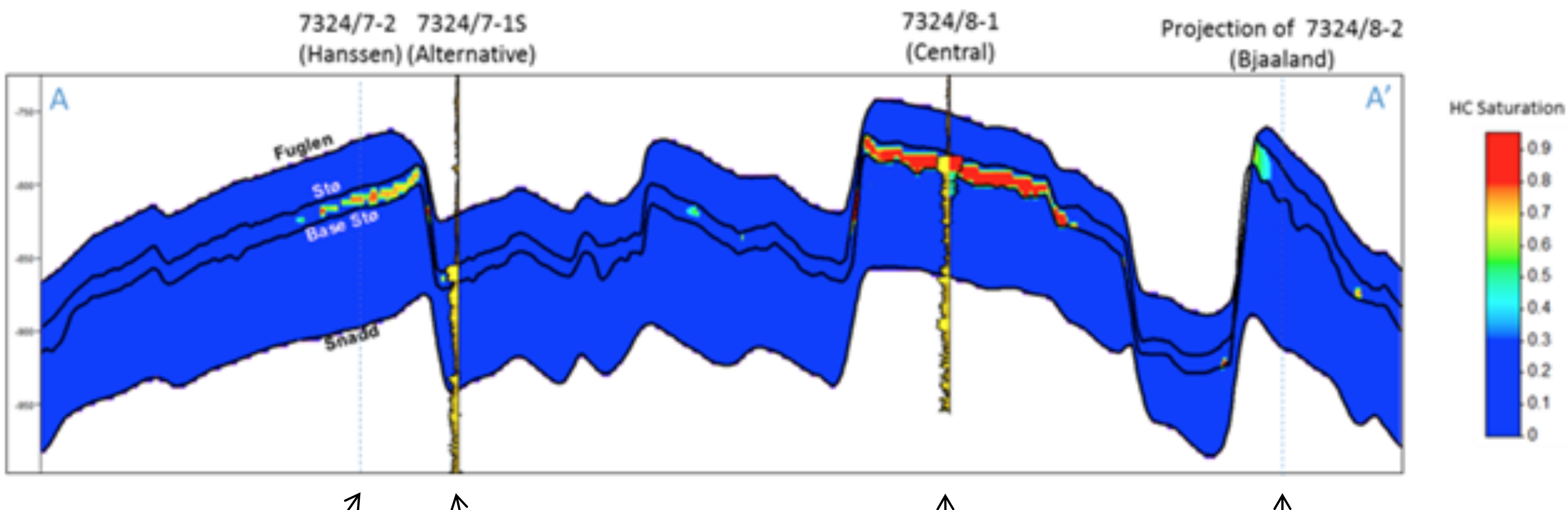
Total Porosity

Resistivity



Interpretation

Final hydrocarbon saturation model



Hanssen
Validation well
productive

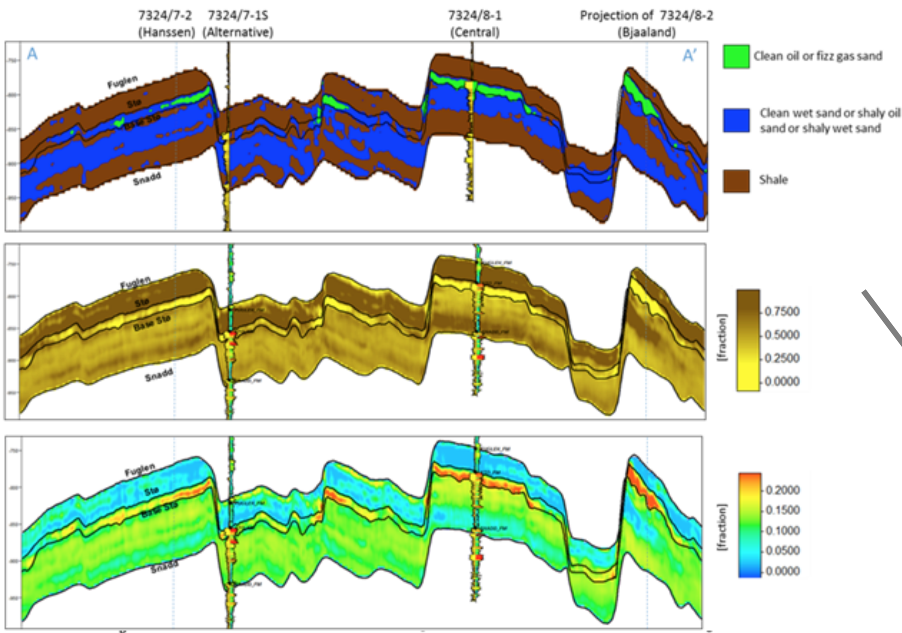
Alternative
Control, dry

Central
Control, productive

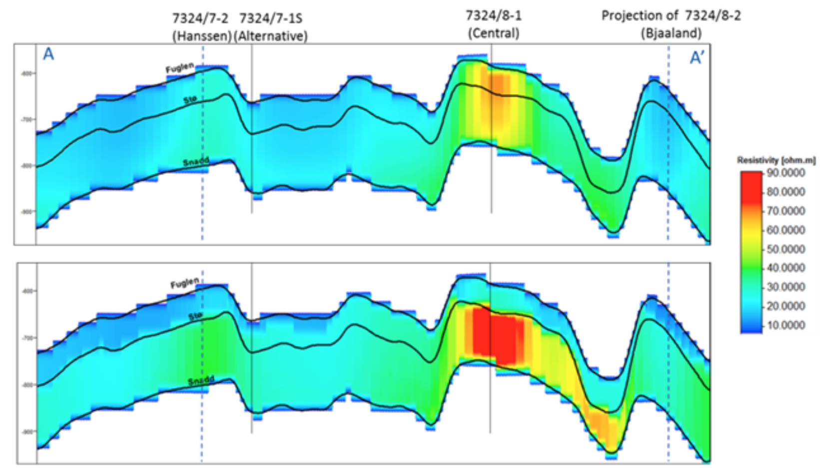
Bjaaland
Validation well
dry

Synthesis

Seismic

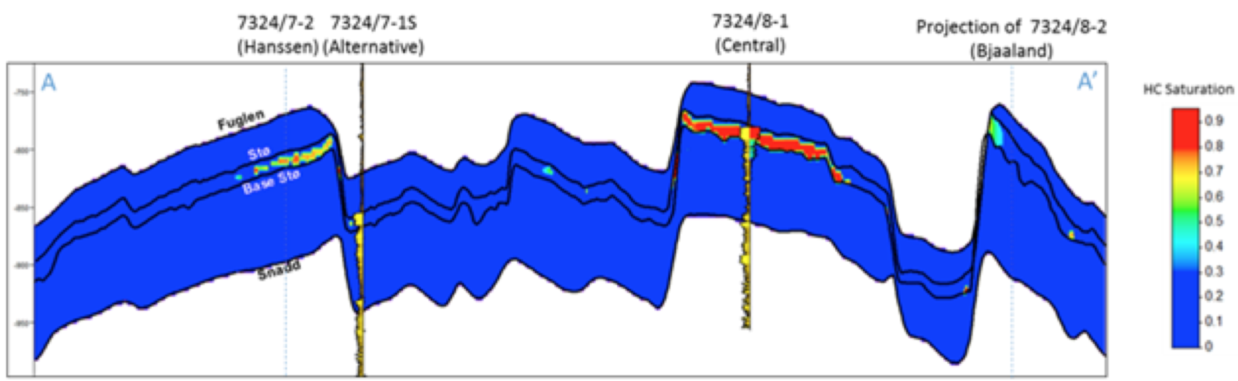


EM



+

Hydrocarbon saturation



Hanssen
Validation well
productive

Alternative
Control, dry

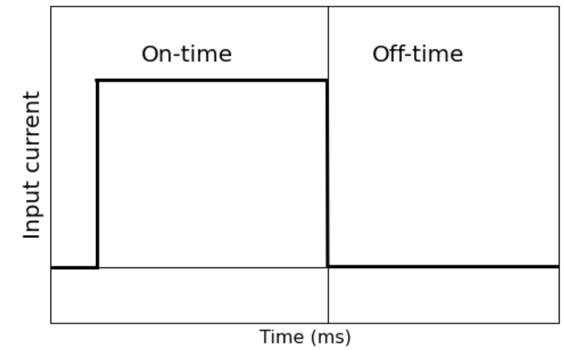
Central
Control, productive

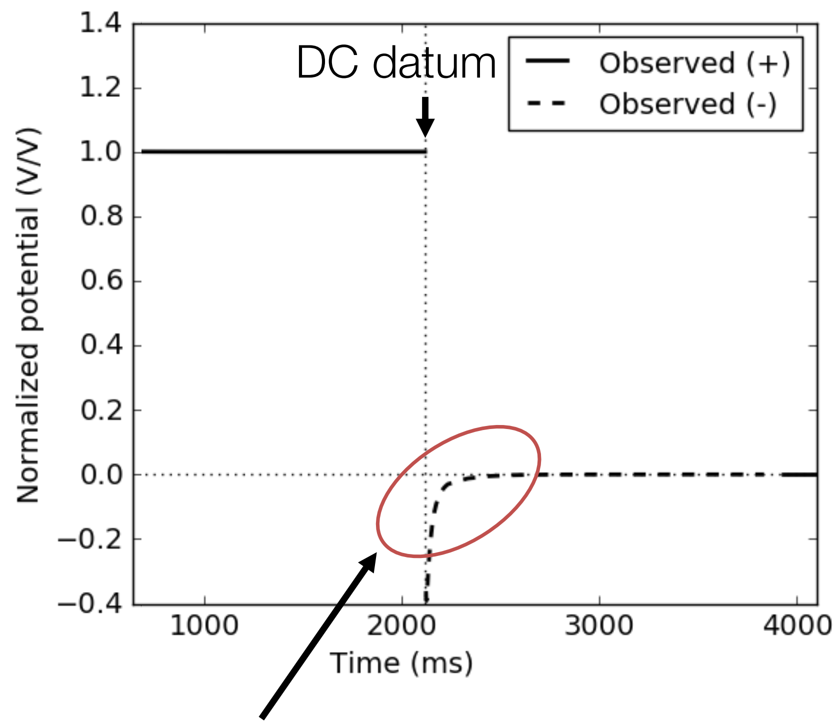
Bjaaland
Validation well
dry

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

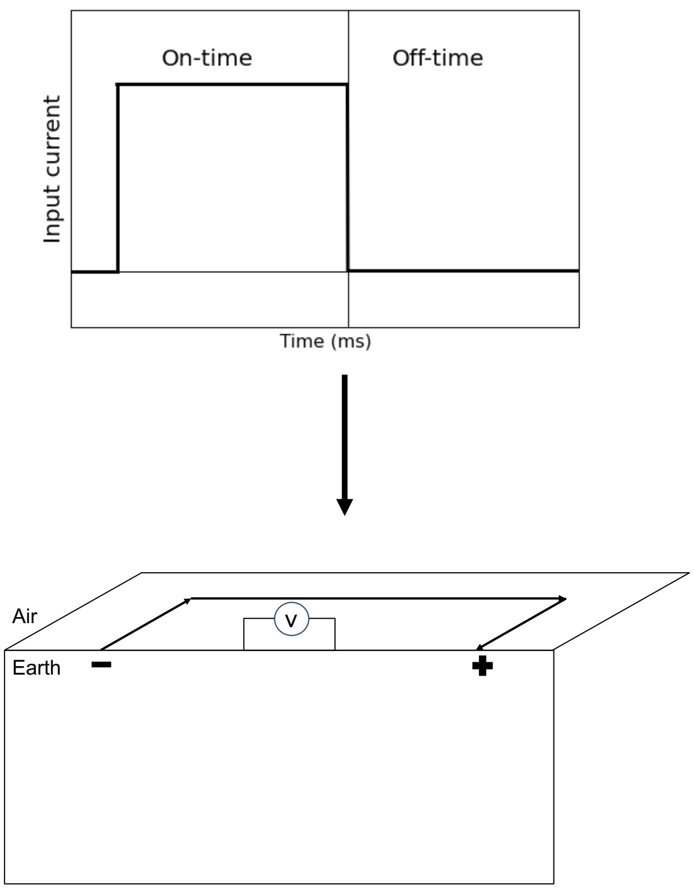




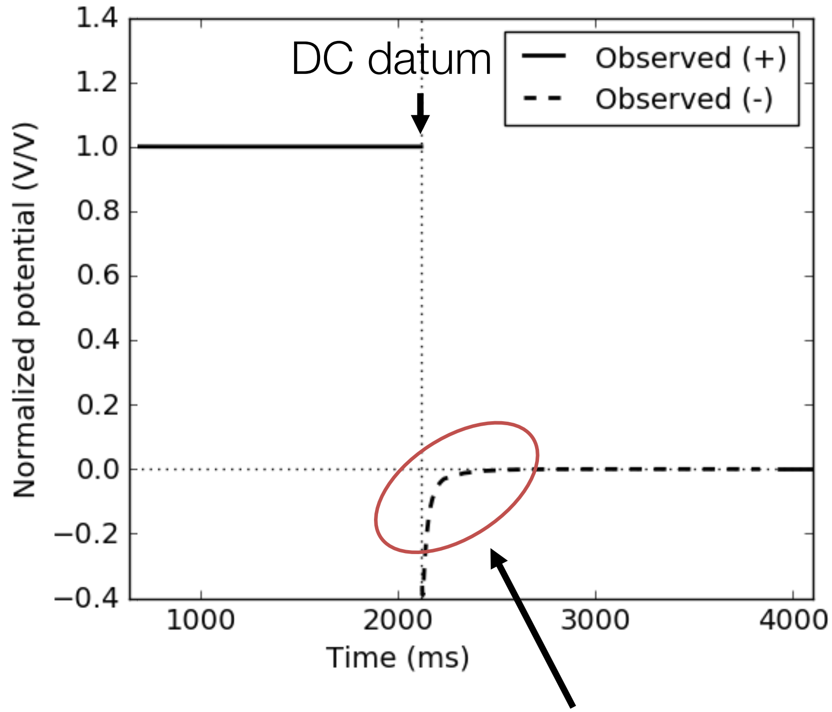
EM portion
Generally considered noise

Survey and Data

Transmitter



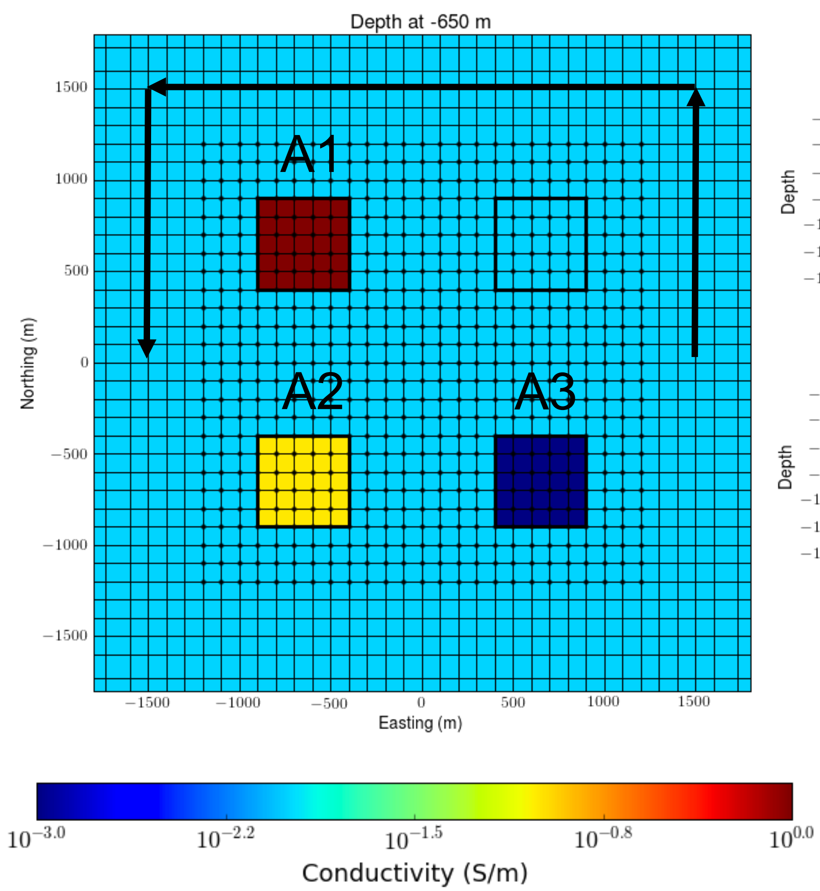
Measured Voltage

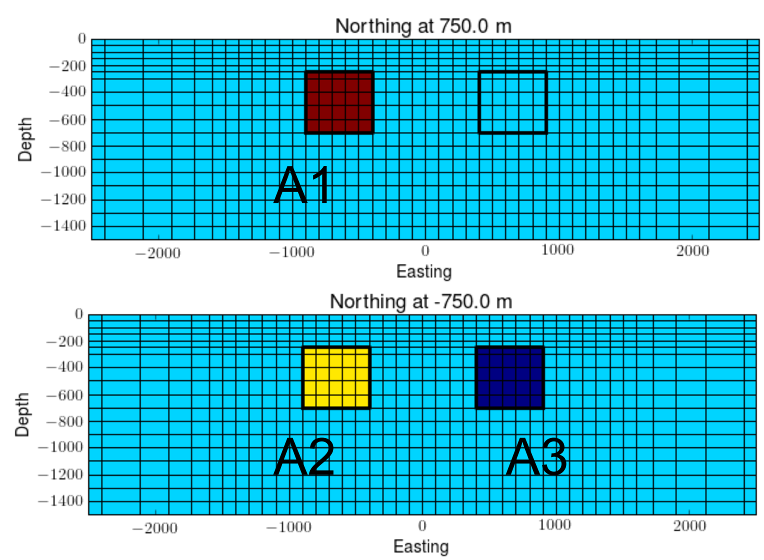


EM portion
Generally considered noise

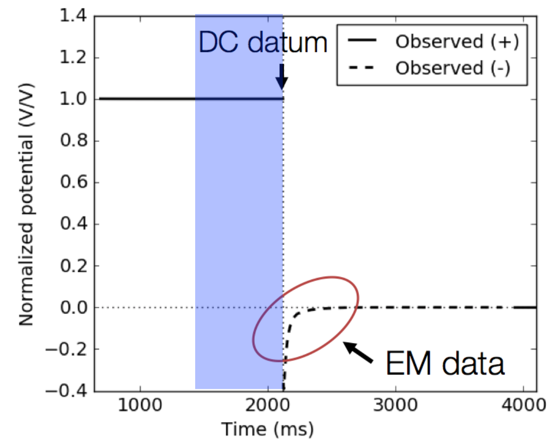
Gradient array

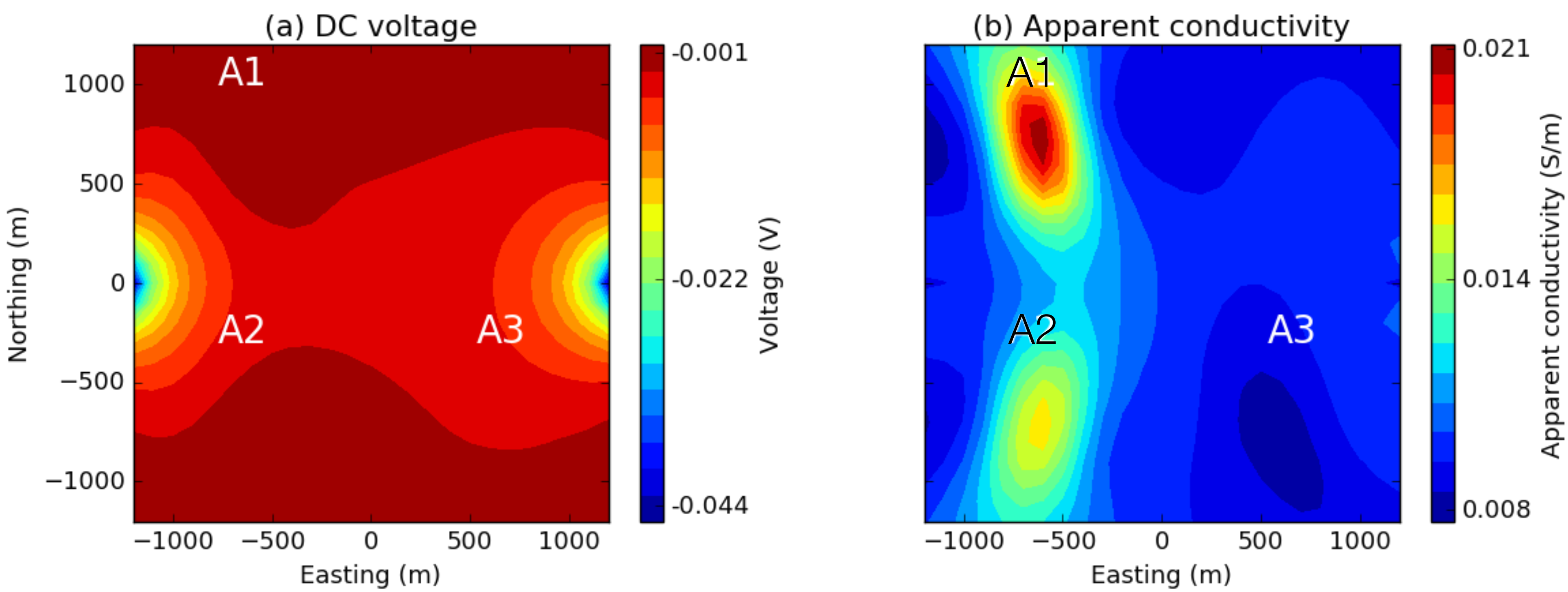
- Model
  - A1: high conductivity
  - A2: moderate conductivity
  - A3: resistive
- Survey
  - 200m bi-pole (625 data)
  - times: 1-600ms



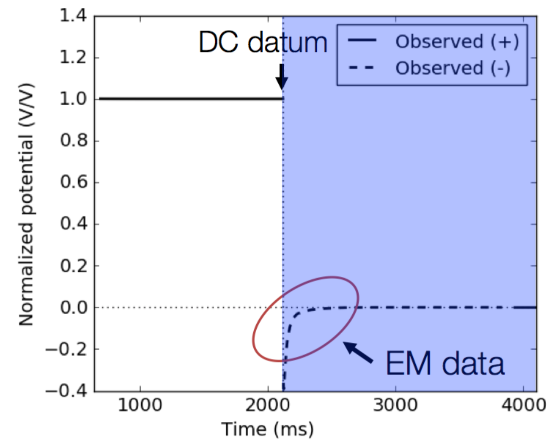


DC data

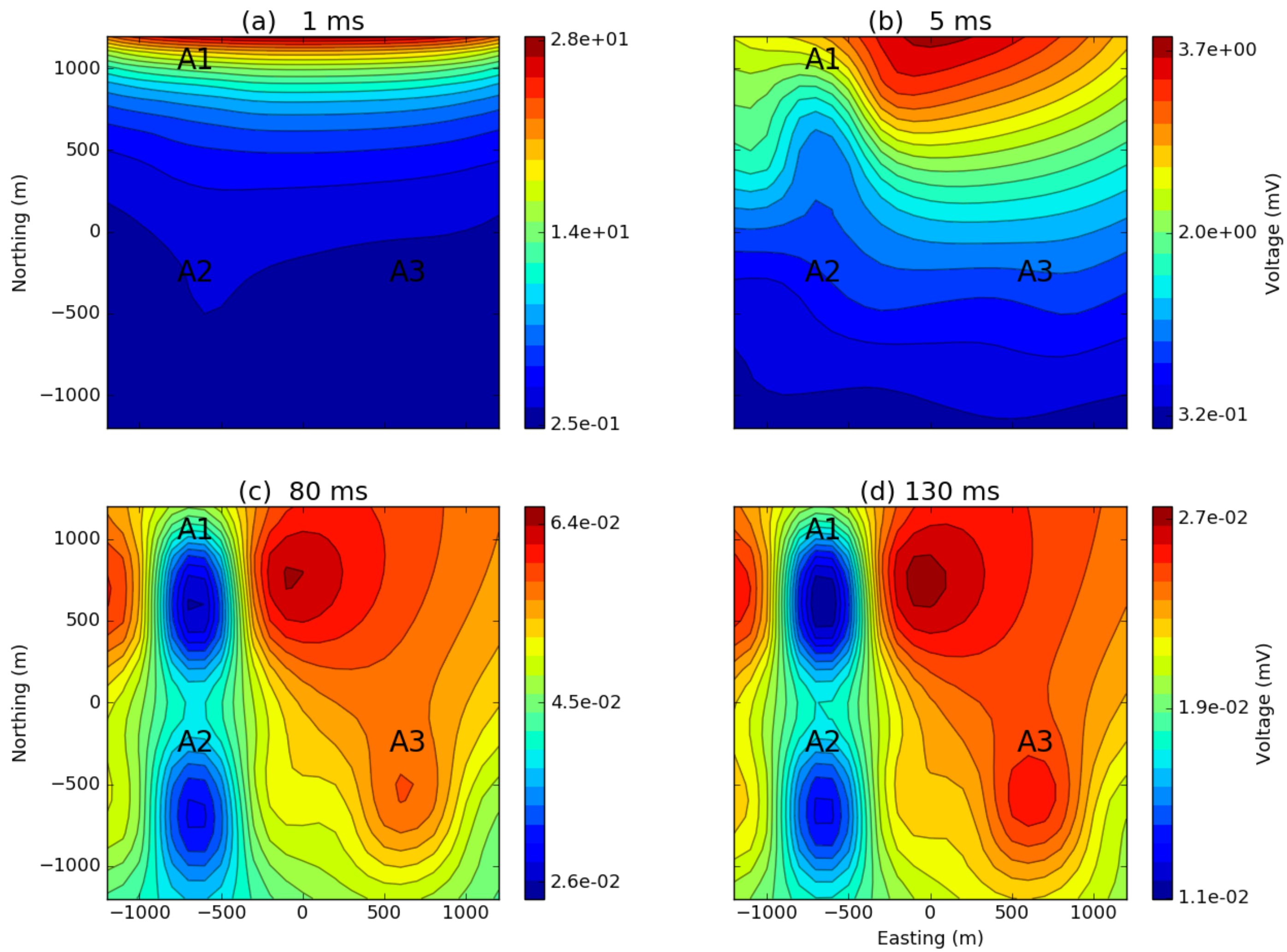

DC datum
Observed (+)
Observed (-)
EM data
Normalized potential (V/V)
Time (ms)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
1000
2000
3000
4000


(a) DC voltage
A1
A2
A3
Northing (m)
Easting (m)
Voltage (V)
-0.001
-0.022
-0.044
1000
500
0
−500
−1000
(b) Apparent conductivity
A1
A2
A3
Apparent conductivity (S/m)
0.021
0.014
0.008

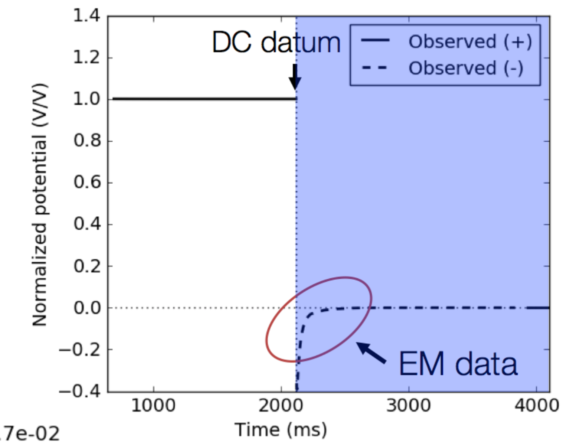
Off-time data



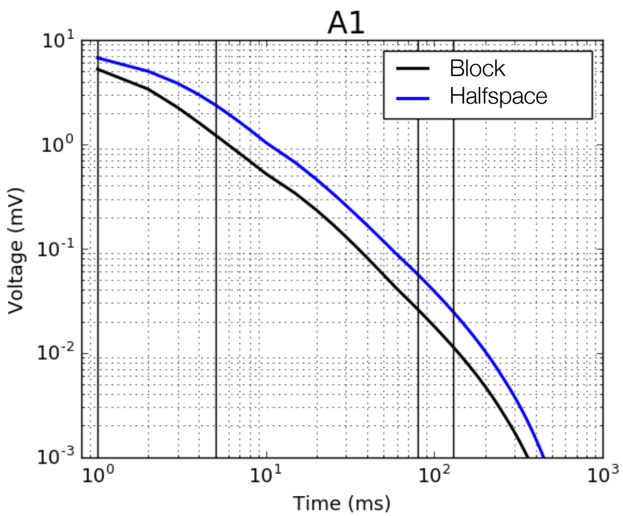
- TDEM data

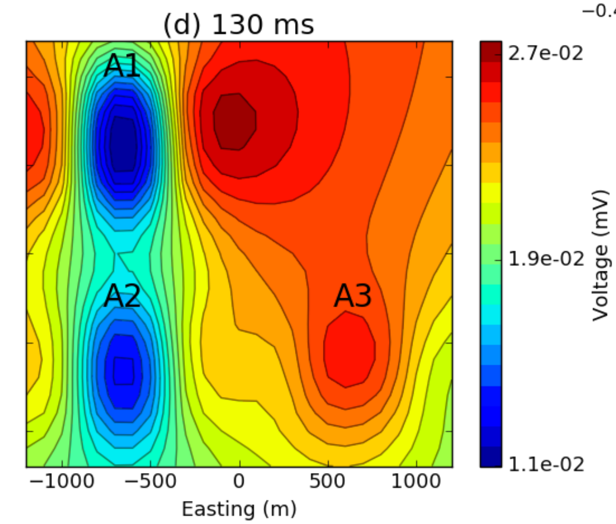


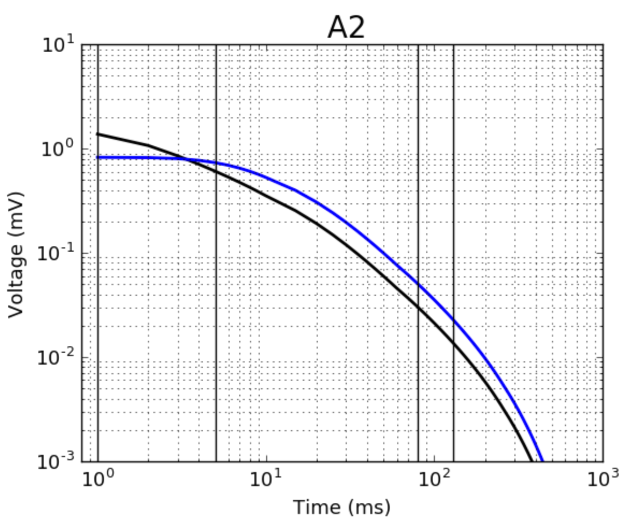
Off-time data

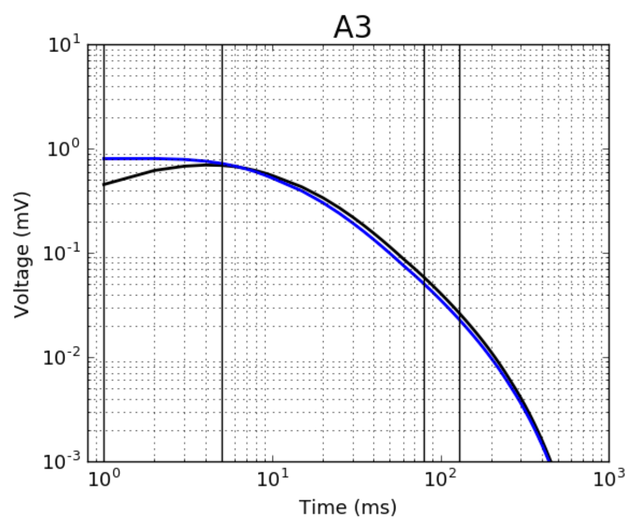


- E_x Decay curves at A1-A3





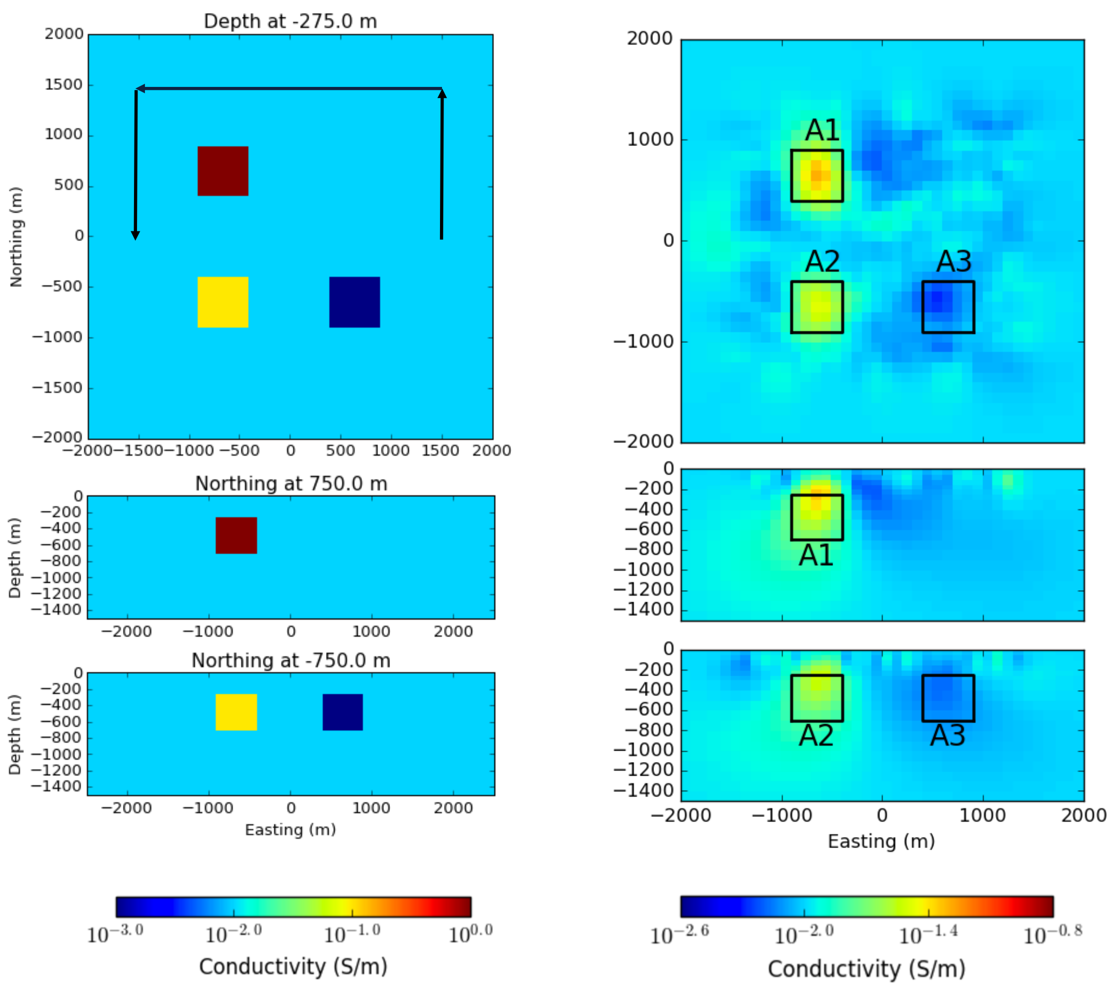




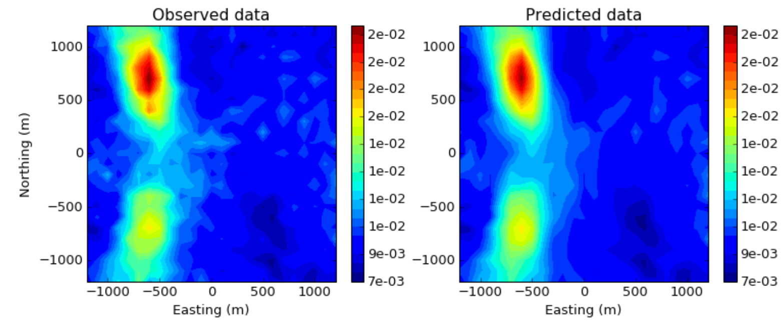
DC inversion

- Recovered 3D conductivity

True | Recovered



Apparent conductivity

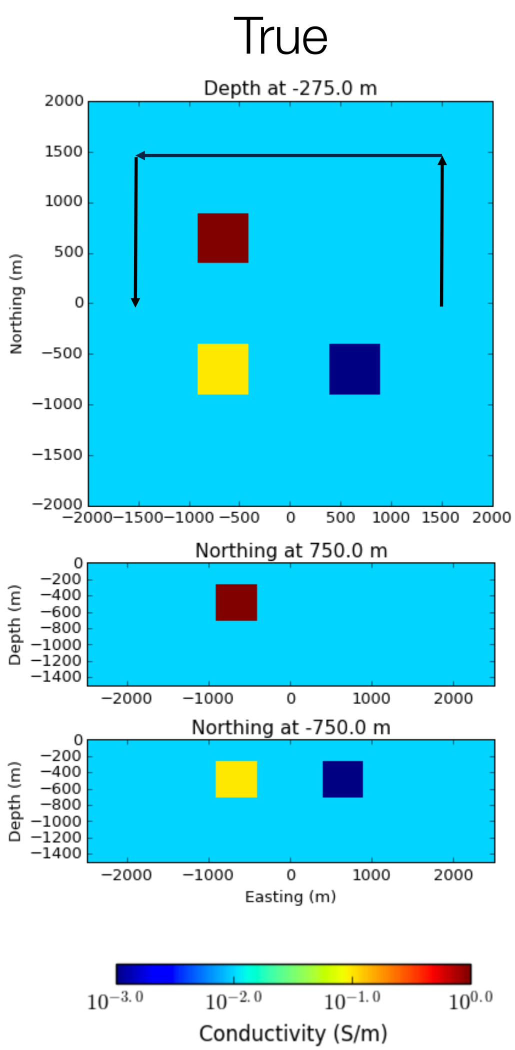


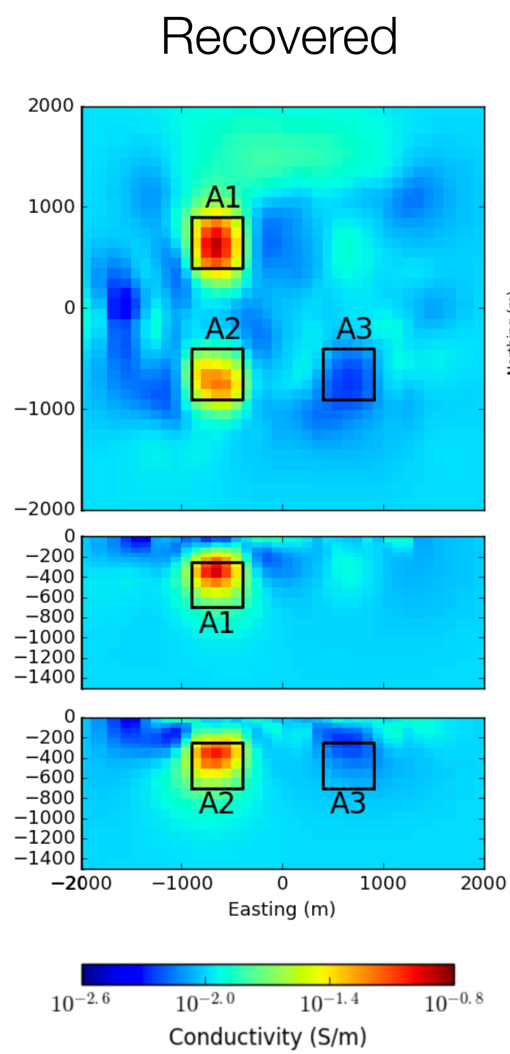
- Depth weighting
  - Compensate for high sensitivity near surface (similar to mag.)

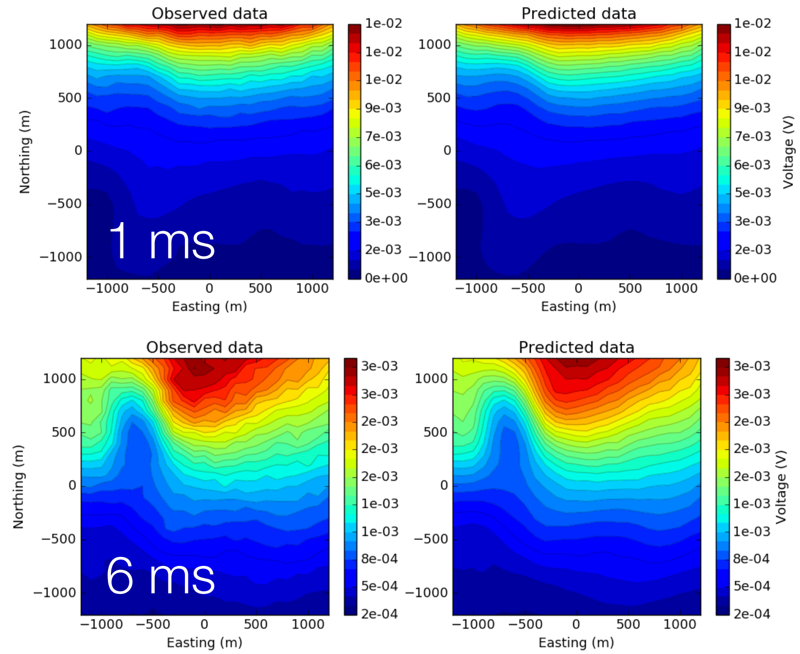
$$\frac{1}{(z - z_0)^3}$$

EM inversion

- Recovered 3D conductivity

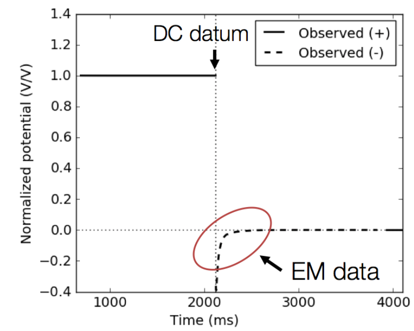




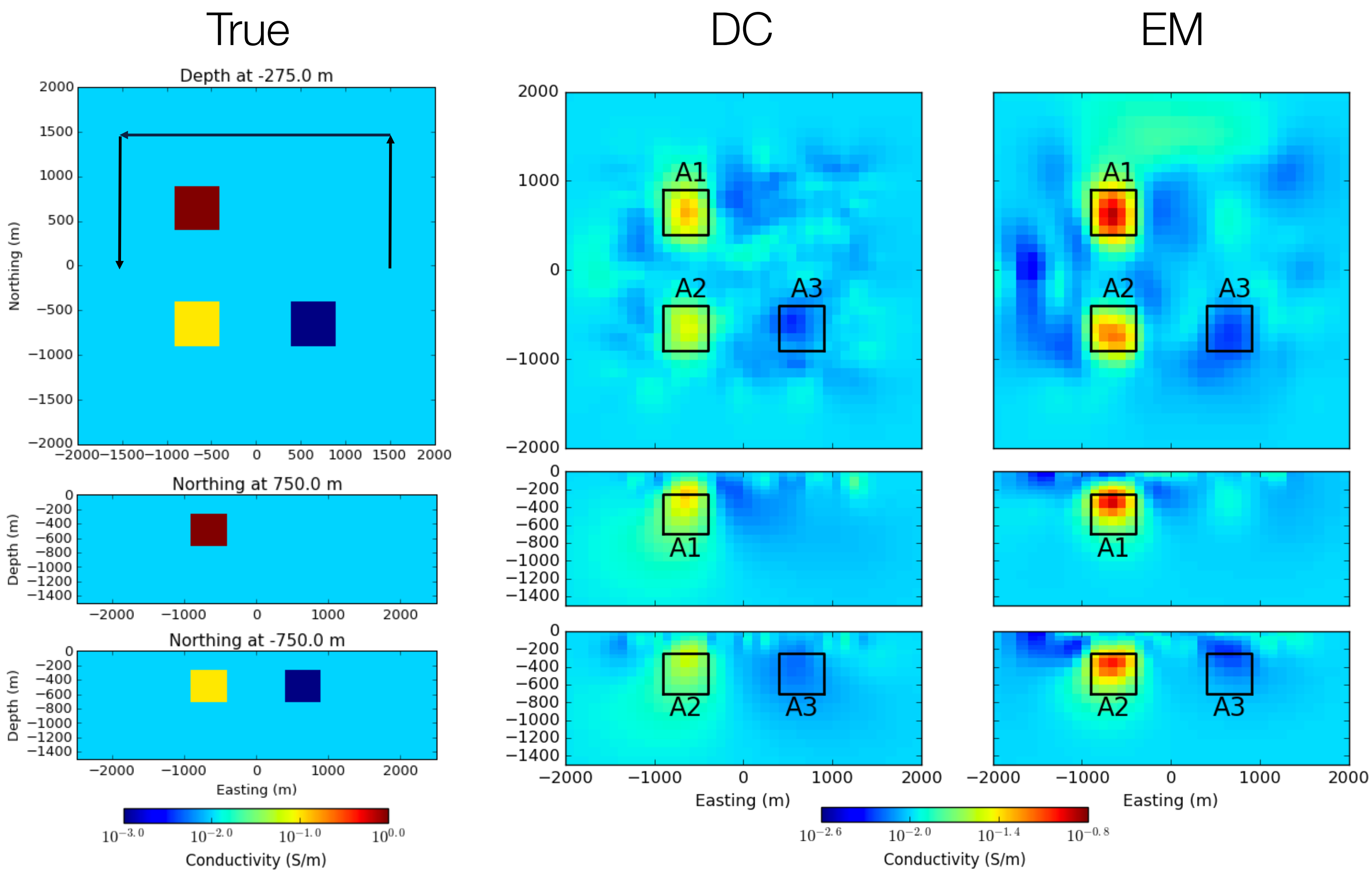


- No depth weighting

Conductivity models



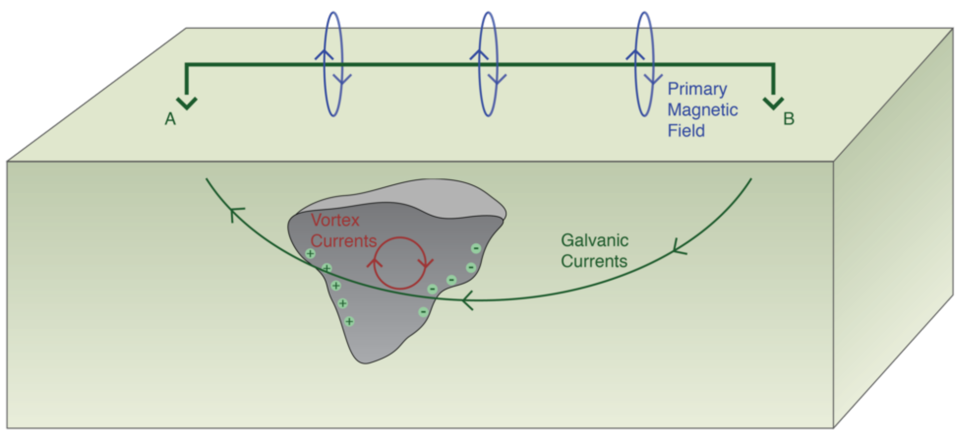
- True, DC, and TEM conductivities



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

- Introduction to EM
- DCR
- EM Fundamentals
- Inductive sources
    - Lunch: Play with apps
- Grounded sources
- Natural sources
- GPR
- Induced polarization
- The Future

Next up → Natural sources

End of Grounded Sources

Next up... Natural Sources