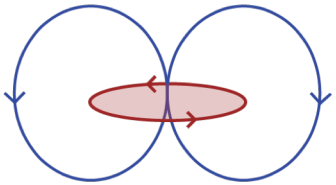
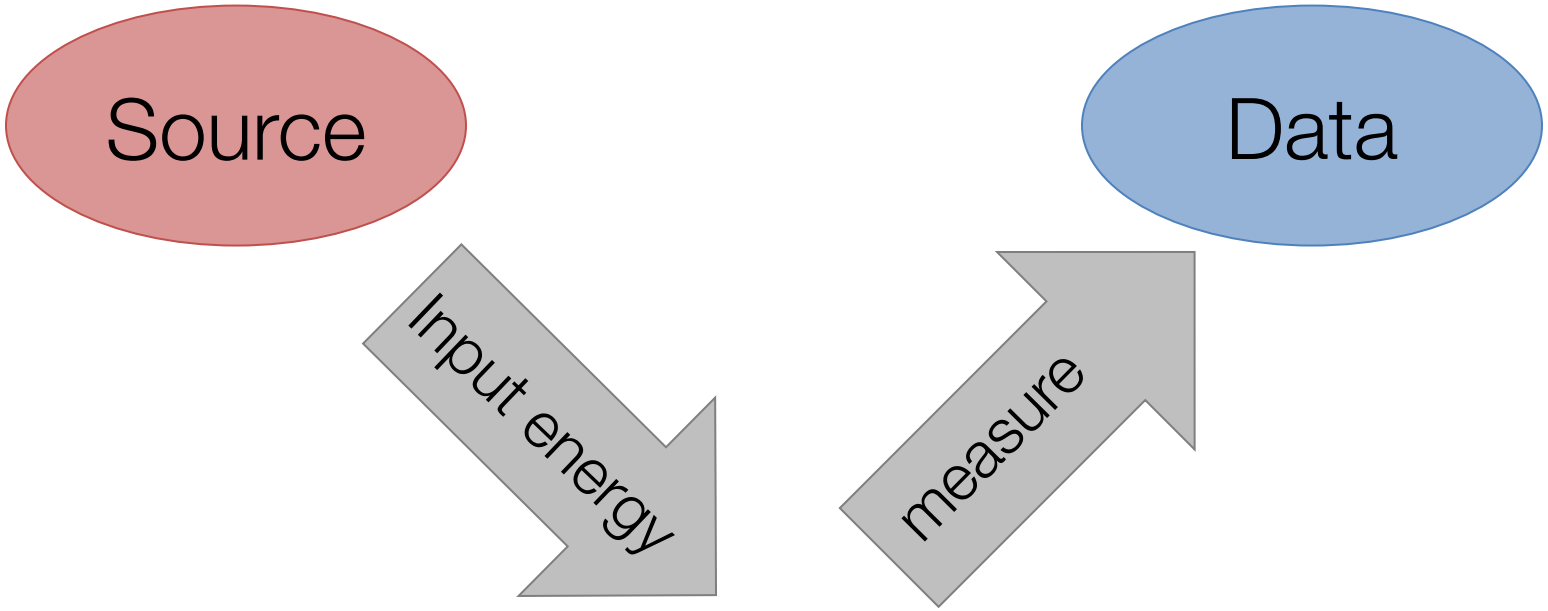
EM Induction



EM Survey & Physical Properties

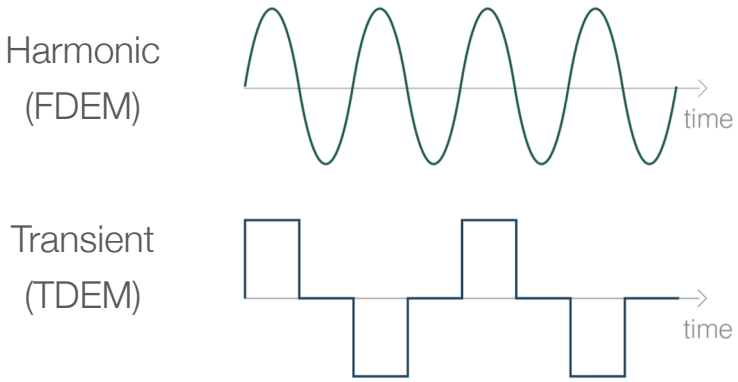


Physical Properties

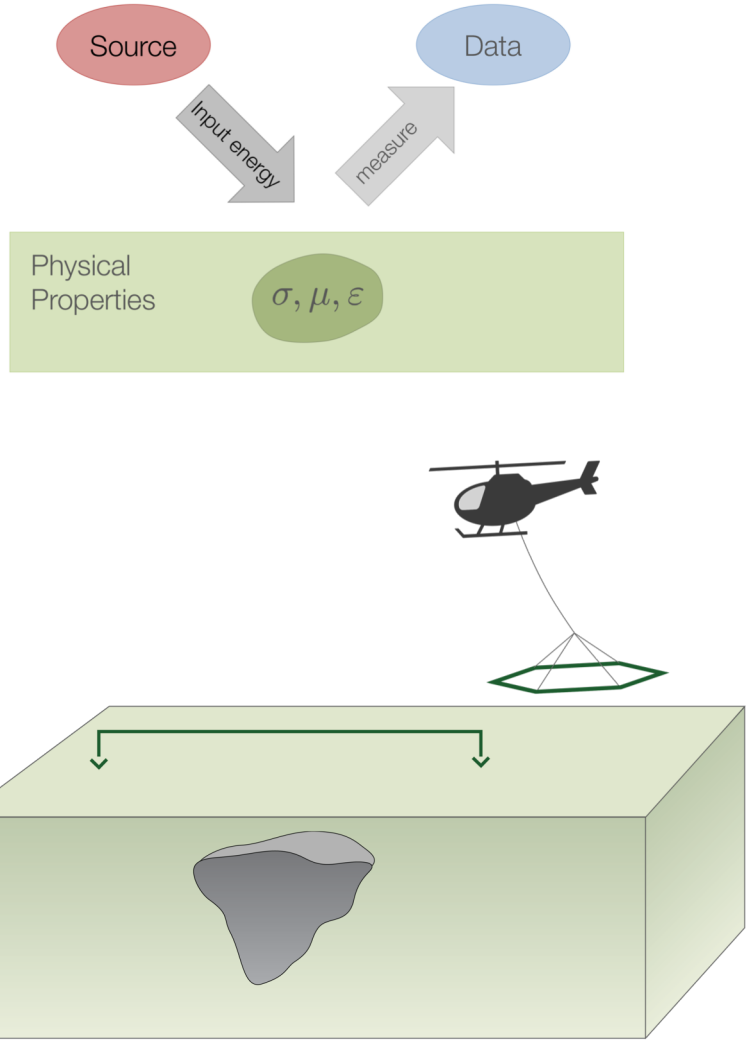
σ, μ, ε

Electromagnetic Survey: Sources

- Type
  - Inductive
  - Grounded
- Waveform

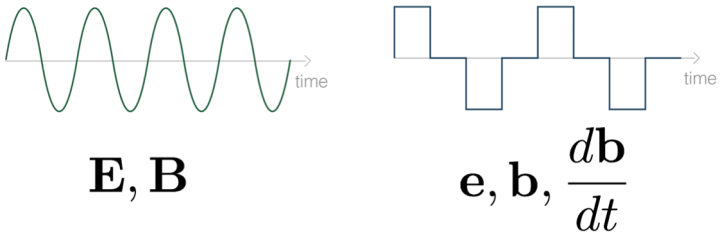


- Location
  - Airborne
  - Ground
  - Borehole



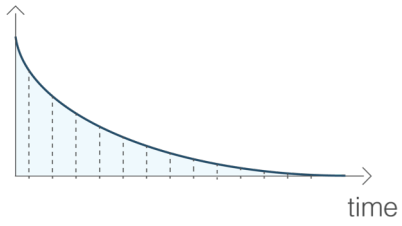
Electromagnetic Survey: Data

- Which field?

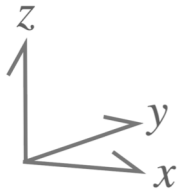


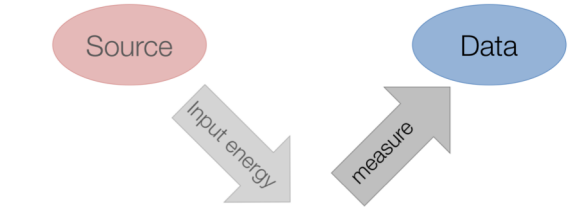
- Which frequencies?

- times?

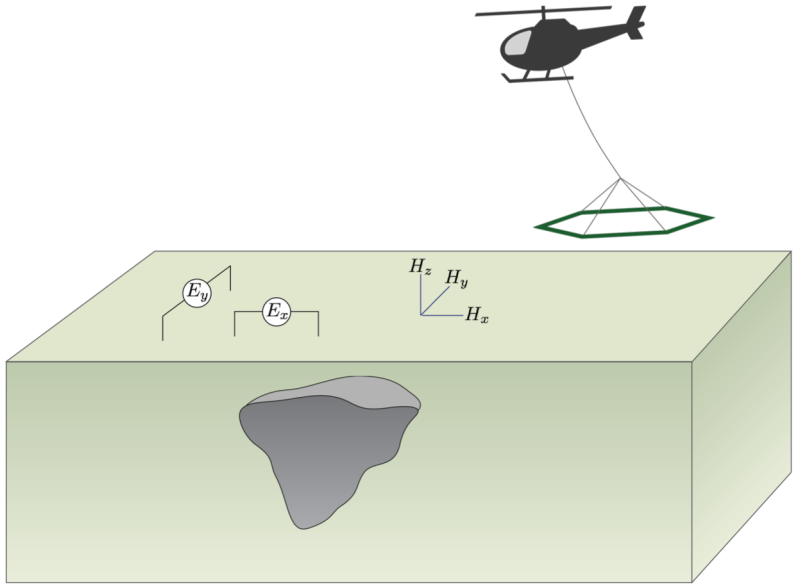


- Components?
- Location?
  - Airborne
  - Ground
  - Borehole

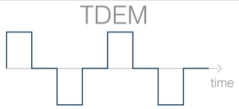
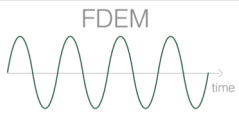




Physical Properties σ, μ, ε

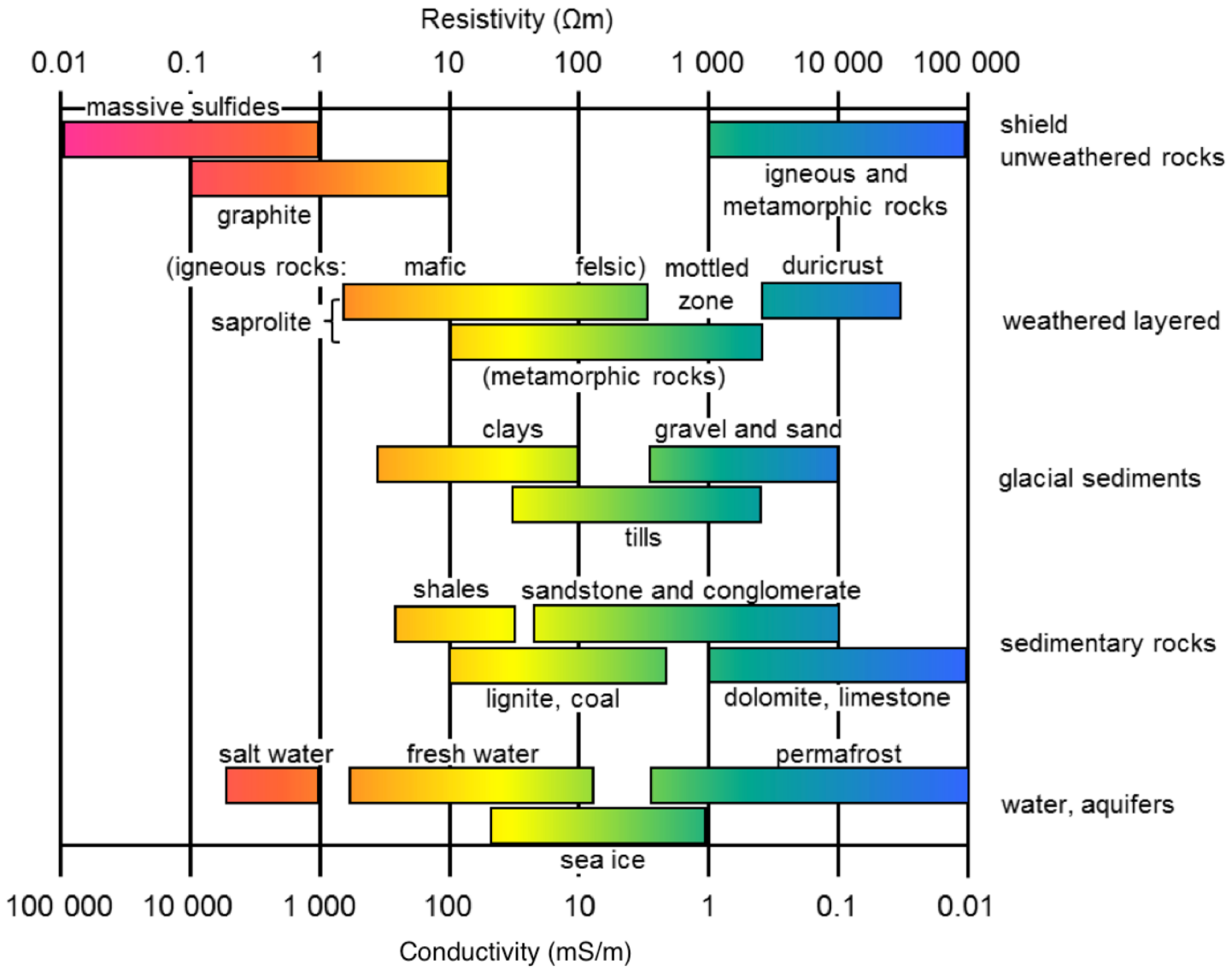


Basic Equations

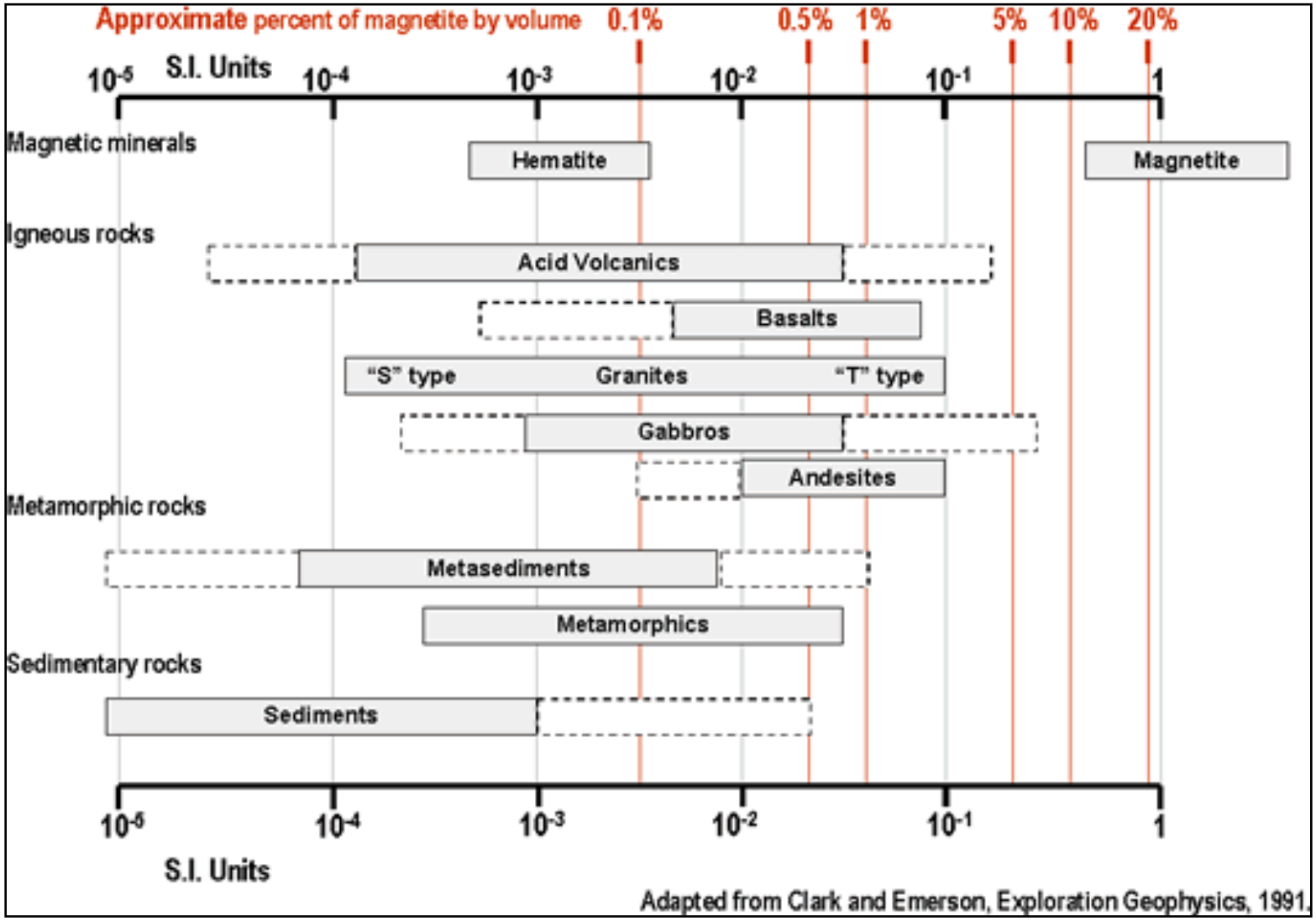
	Time 	Frequency 
Faraday's Law	$\nabla \times \mathbf{e} = -\frac{\partial \mathbf{b}}{\partial t}$	$\nabla \times \mathbf{E} = -i\omega\mathbf{B}$
Ampere's Law	$\nabla \times \mathbf{h} = \mathbf{j} + \frac{\partial \mathbf{d}}{\partial t}$	$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$
No Magnetic Monopoles	$\nabla \cdot \mathbf{b} = 0$	$\nabla \cdot \mathbf{B} = 0$
Constitutive Relationships (non-dispersive)	$\mathbf{j} = \sigma\mathbf{e}$ $\mathbf{b} = \mu\mathbf{h}$ $\mathbf{d} = \varepsilon\mathbf{e}$	$\mathbf{J} = \sigma\mathbf{E}$ $\mathbf{B} = \mu\mathbf{H}$ $\mathbf{D} = \varepsilon\mathbf{E}$

* Solve with sources and boundary conditions

Electrical Resistivity / Conductivity



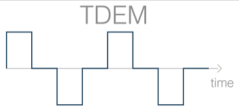
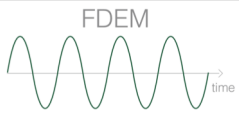
Magnetic Susceptibility



Dielectric constant

Material	Relative Permittivity	Conductivity (mS/m)	Average Velocity (m/ns)
Air	1	0	3
Fresh Water	80	0.5	0.033
Sea Water	80	3000	0.01
Ice	3-4	0.01	0.16
Dry Sand	3-5	0.01	0.15
Saturated Sand	20-30	0.1-1	0.06
Limestone	4-8	0.5-2	0.12
Shales	5-15	1-100	0.09
Silts	5-30	1-100	0.07
Clays	5-40	2-1000	0.06
Granite	4-6	0.01-1	0.13
Anhydrites	3-4	0.01-1	0.13

Quasi-static

	Time 	Frequency 
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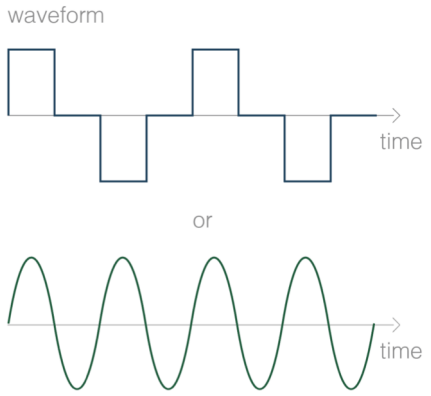
No Magnetic Monopoles	$\nabla \cdot \mathbf{b} = 0$	$\nabla \cdot \mathbf{B} = 0$
Constitutive Relationships (non-dispersive)	$\mathbf{j} = \sigma\mathbf{e}$ $\mathbf{b} = \mu\mathbf{h}$ $\mathbf{d} = \varepsilon\mathbf{e}$	$\mathbf{J} = \sigma\mathbf{E}$ $\mathbf{B} = \mu\mathbf{H}$ $\mathbf{D} = \varepsilon\mathbf{E}$

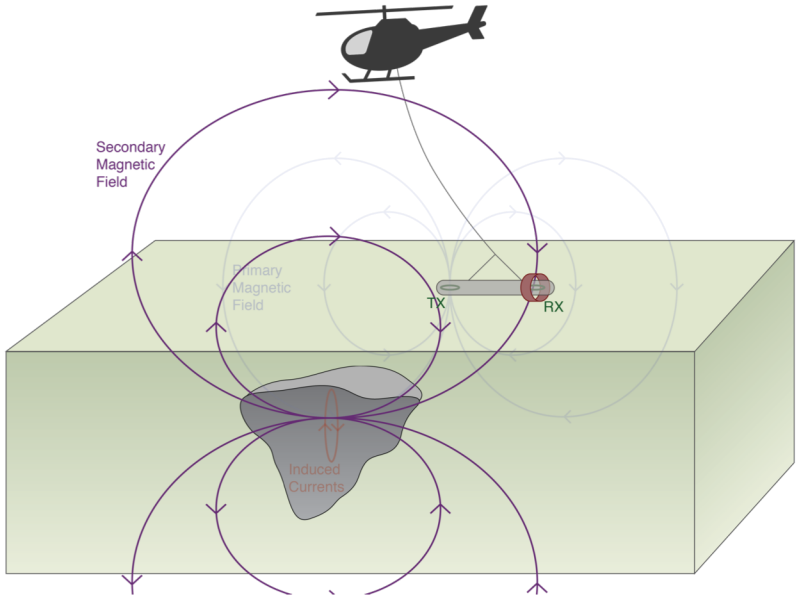
Basic Experiment



- **Transmitter:**
  - Produces a primary magnetic field

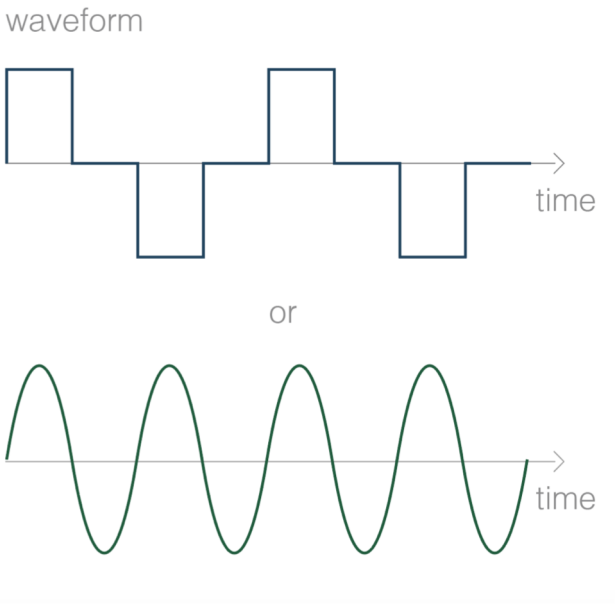
- **Exciting the target:**
  - Time varying magnetic fields generate electric fields everywhere
  - Producing currents in conductors

- **Receiver:**
  - Induced currents produce secondary magnetic fields



Frequency vs time

- Same physics
- Time domain is more intuitive for understanding the physics.

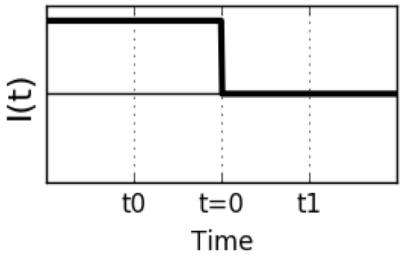


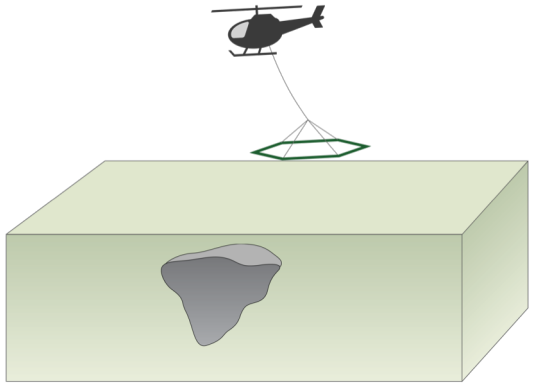
Outline

- TDEM: Currents and sounding curves for 1D earth
- Overview of inverse problem
- 1D inversion using SimPEG
- Effects of a background conductivity
- Conductive sphere in a halfspace
- 1D vs 3D inversions
- Examples where 3D inversion required?
- Frequency domain
- Summary

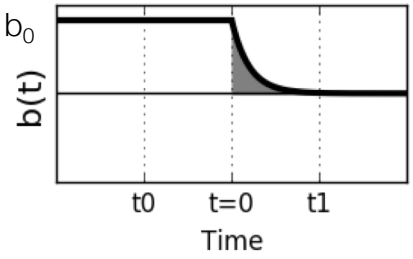
EM with Inductive Sources: Time Domain

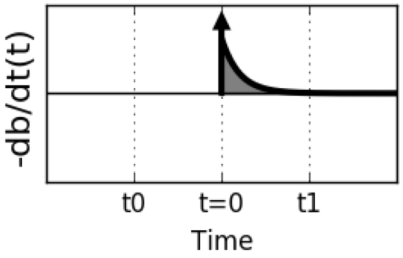
Transmitter current





Receiver





time	**b**	**db/dt**
$t < 0$	b_0	0
$t = 0$	b_0	$-b_0\delta(t)$
$t > 0$	secondary	secondary

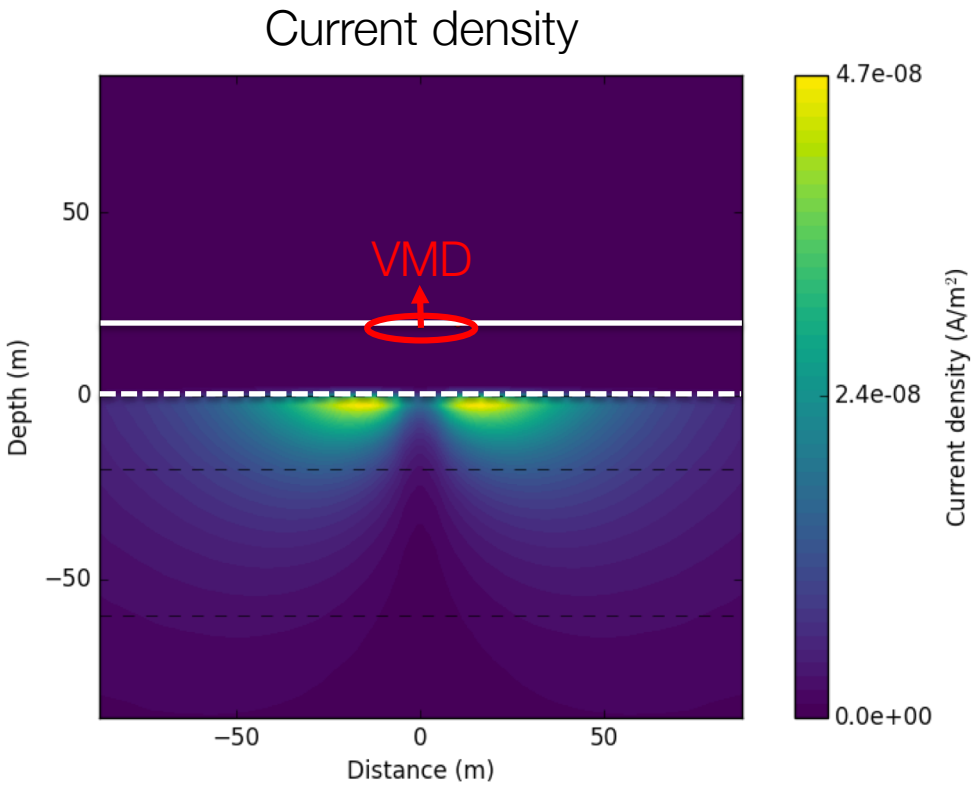
$\delta(t)$: Dirac-delta function

Footprint of Airborne EM system

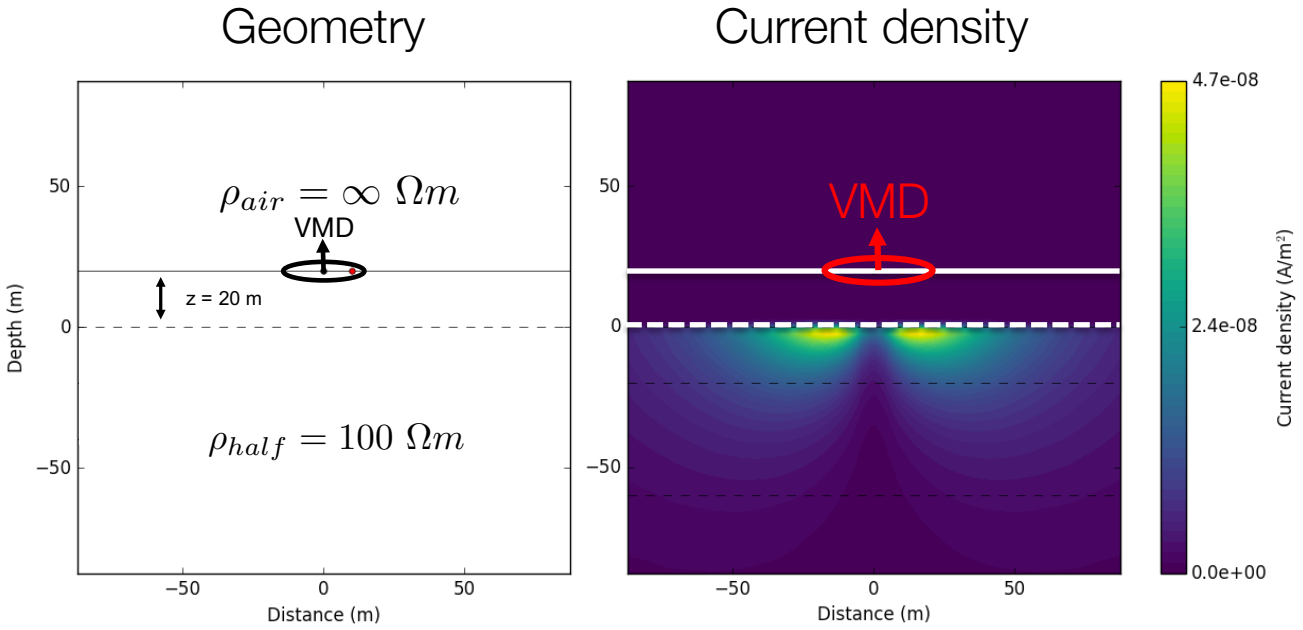
- What volume of earth is “seen” by the airborne system?
  - Where are the currents?

- Currents depend on
  - Transmitter
  - Waveform: time or frequency
  - Background conductivity

- Simple case: loop source over homogeneous earth

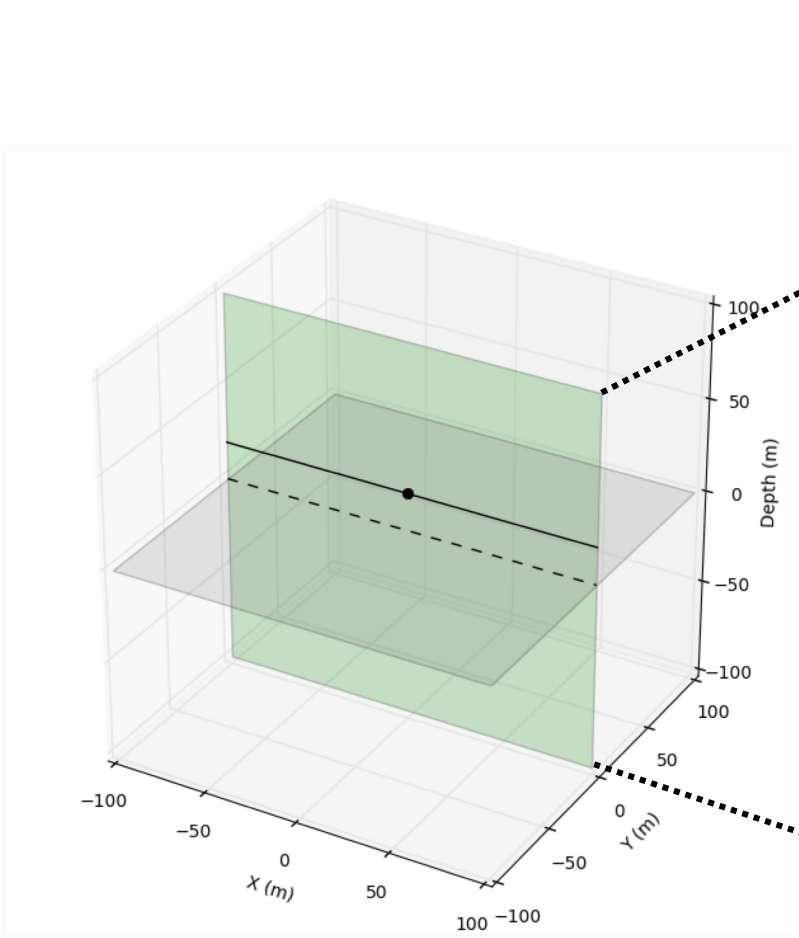


Vertical Magnetic Dipole (VMD)

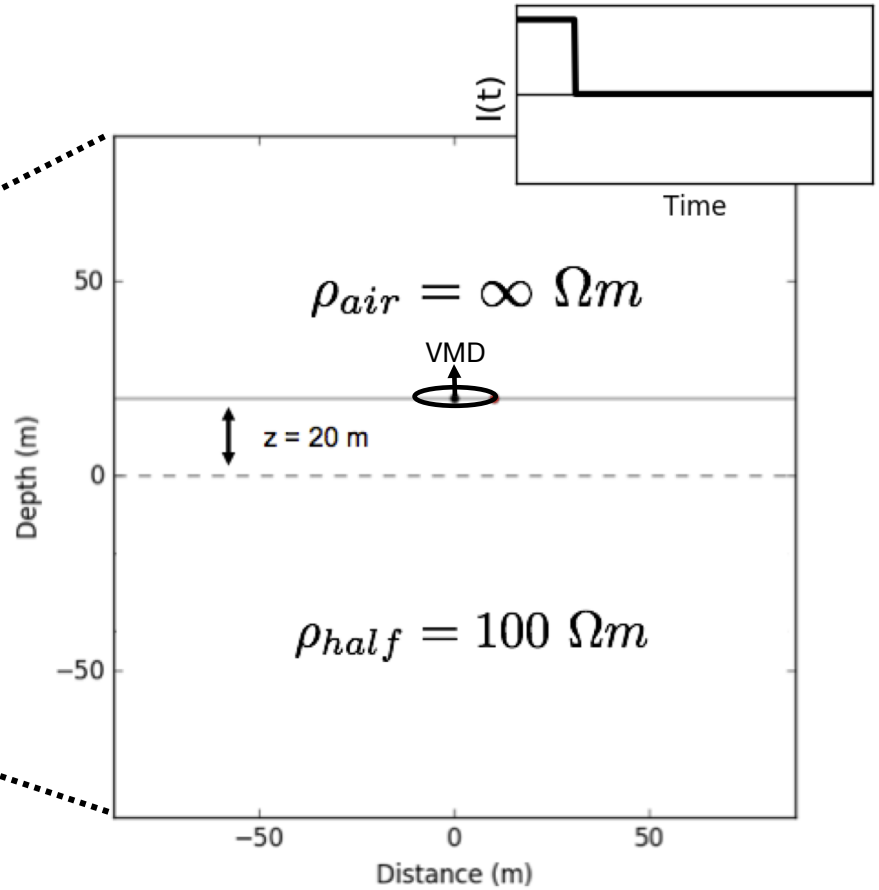


- Some questions
  - Where, and how strong, are the currents?
  - How do they depend upon the conductivity?
  - What do the resulting magnetic fields look like?

Vertical Magnetic Dipole over a halfspace (TDEM)



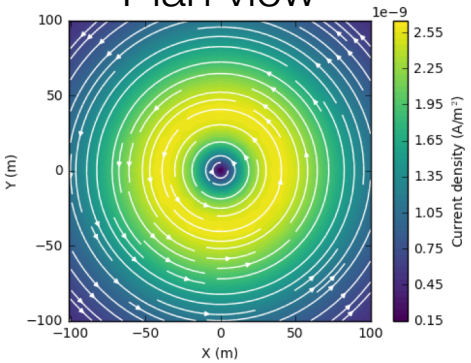
Step-off



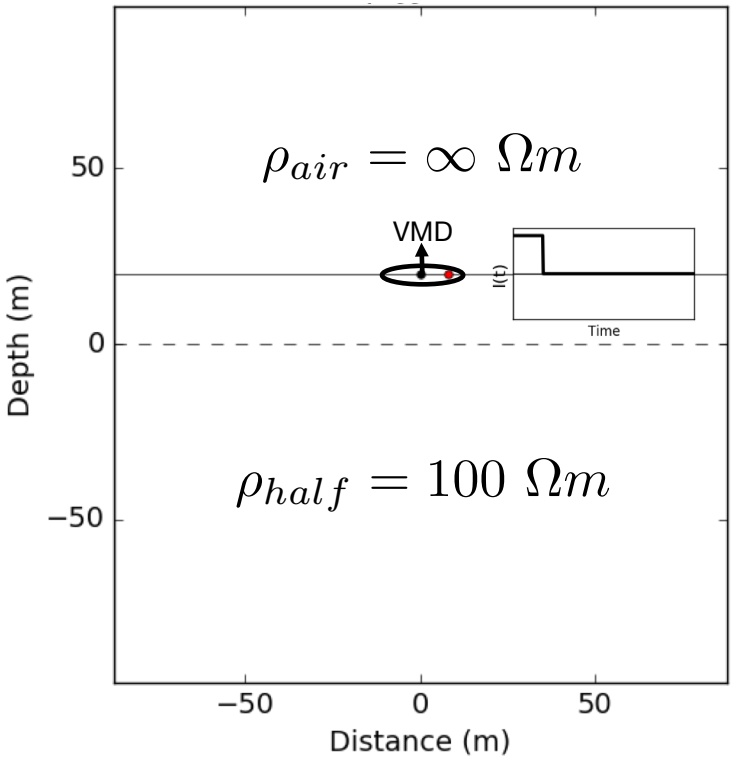
Current Density

- Time: 0.01ms

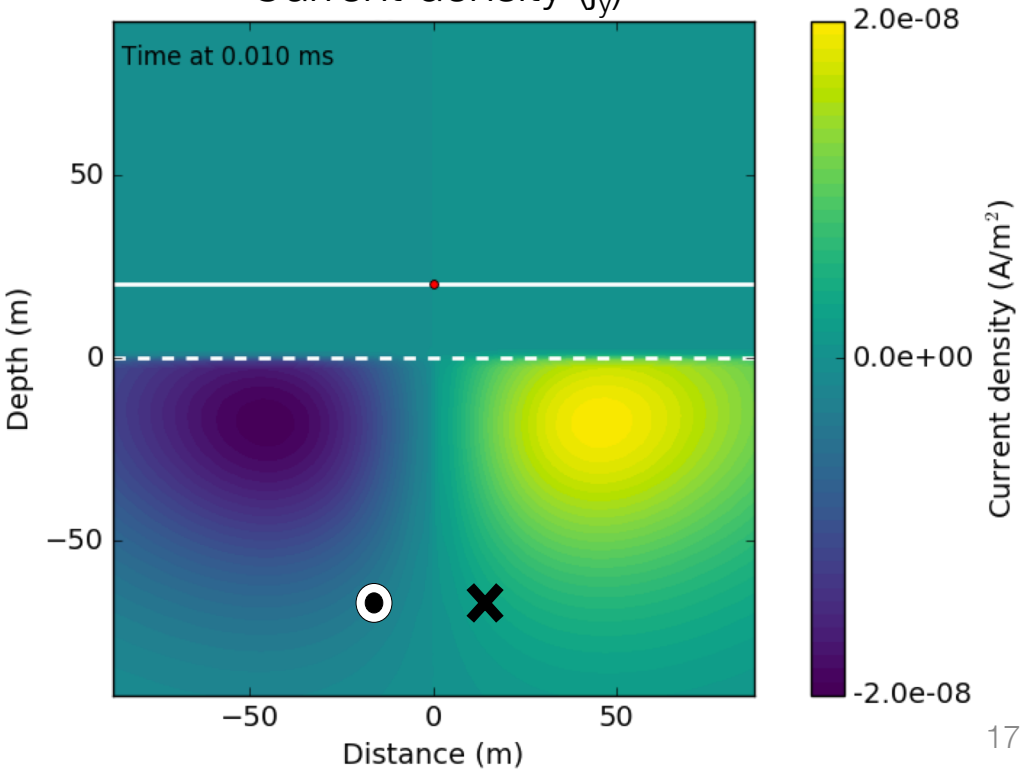
Plan view



Geometry

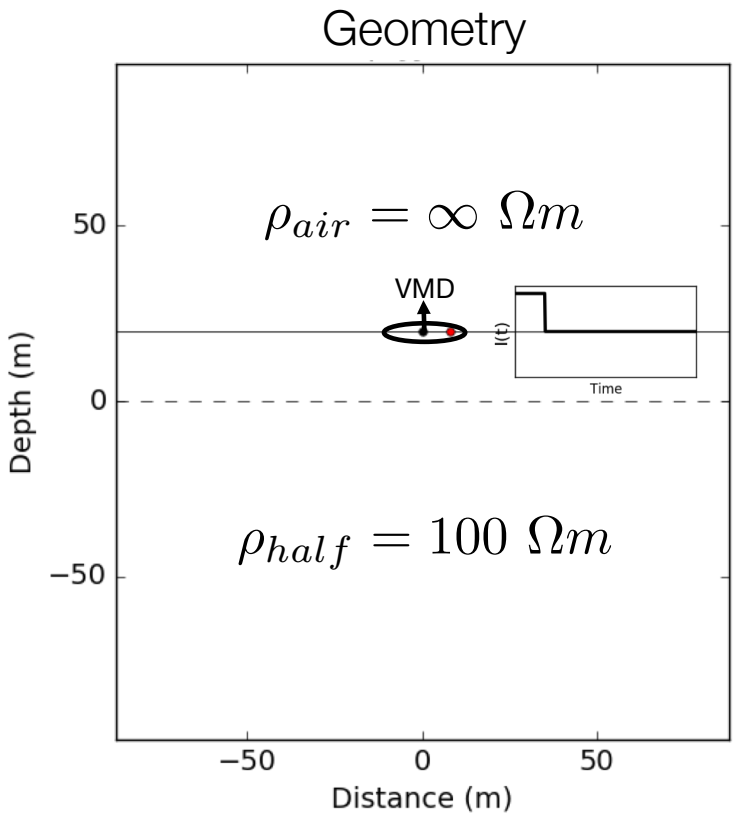


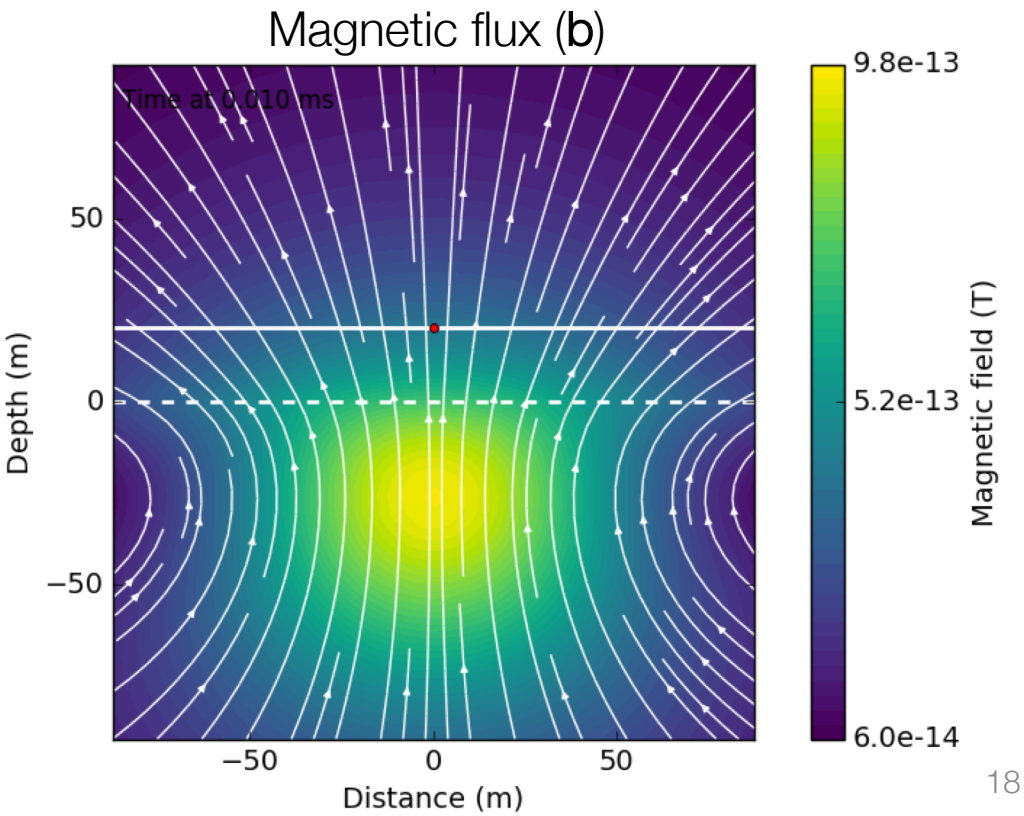
Current density (j_y)



Magnetic flux density

- Time: 0.01ms

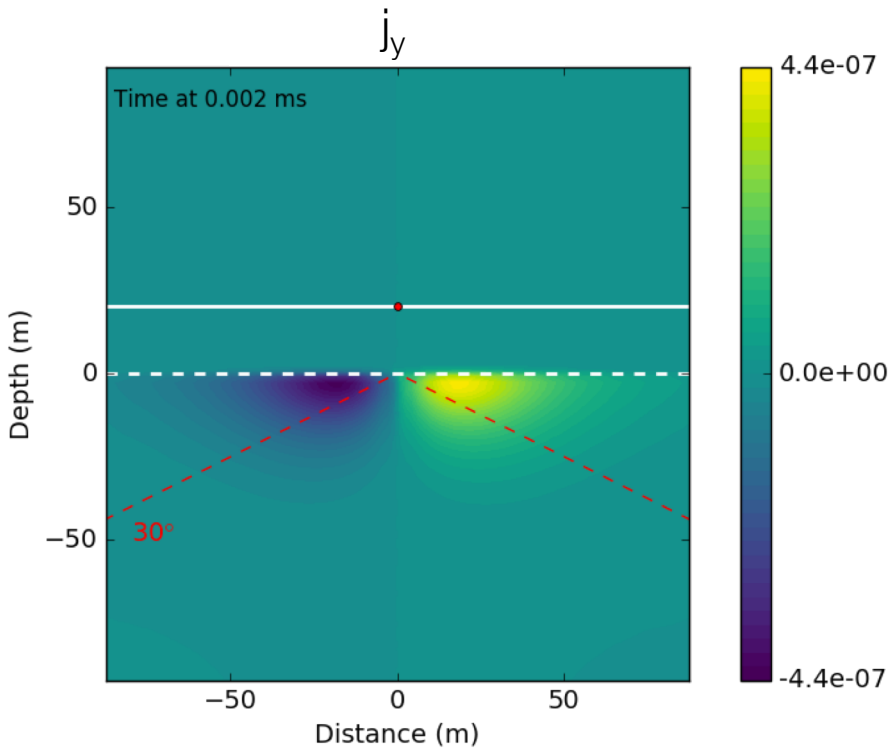


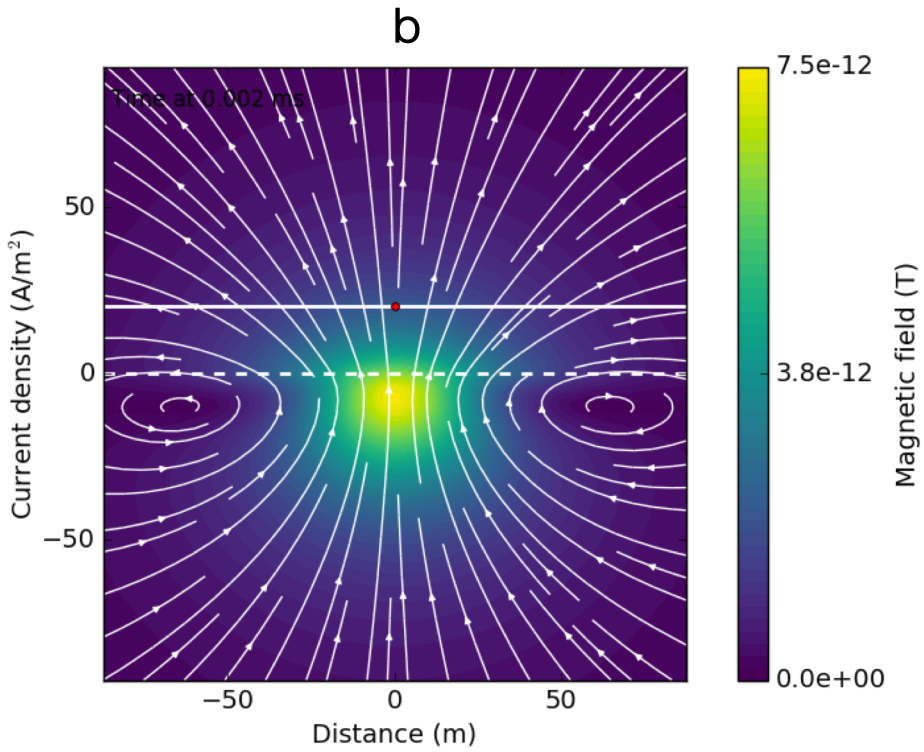


Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

$$d = 1260\sqrt{t\rho}$$

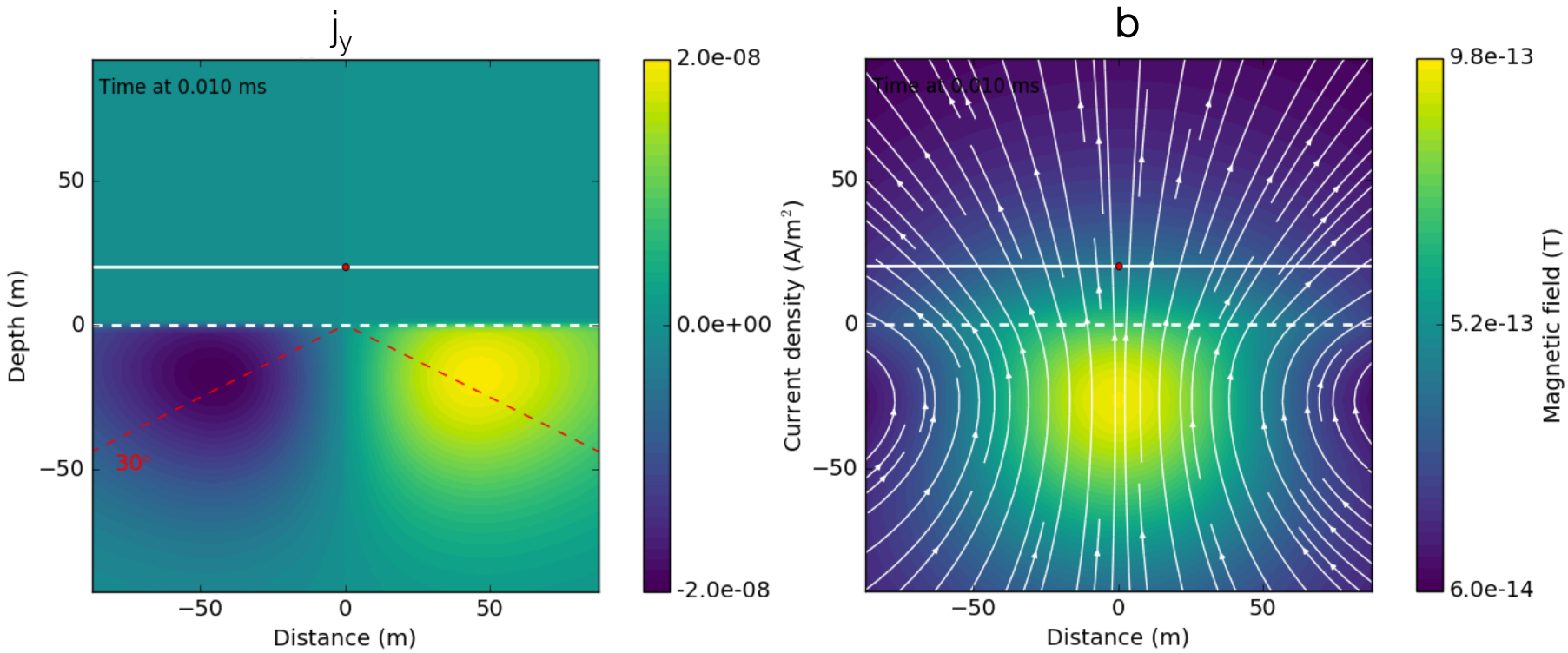




Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

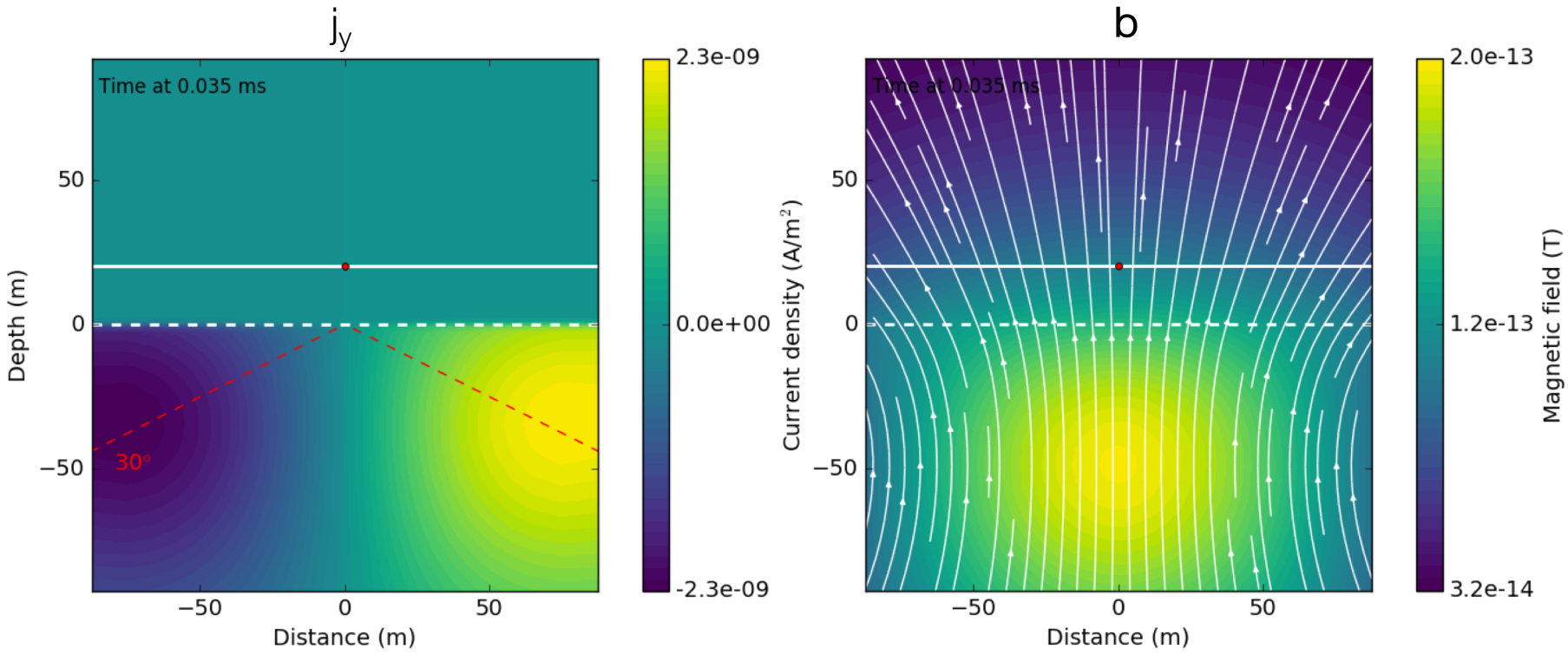
$$d = 1260\sqrt{t\rho}$$



Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

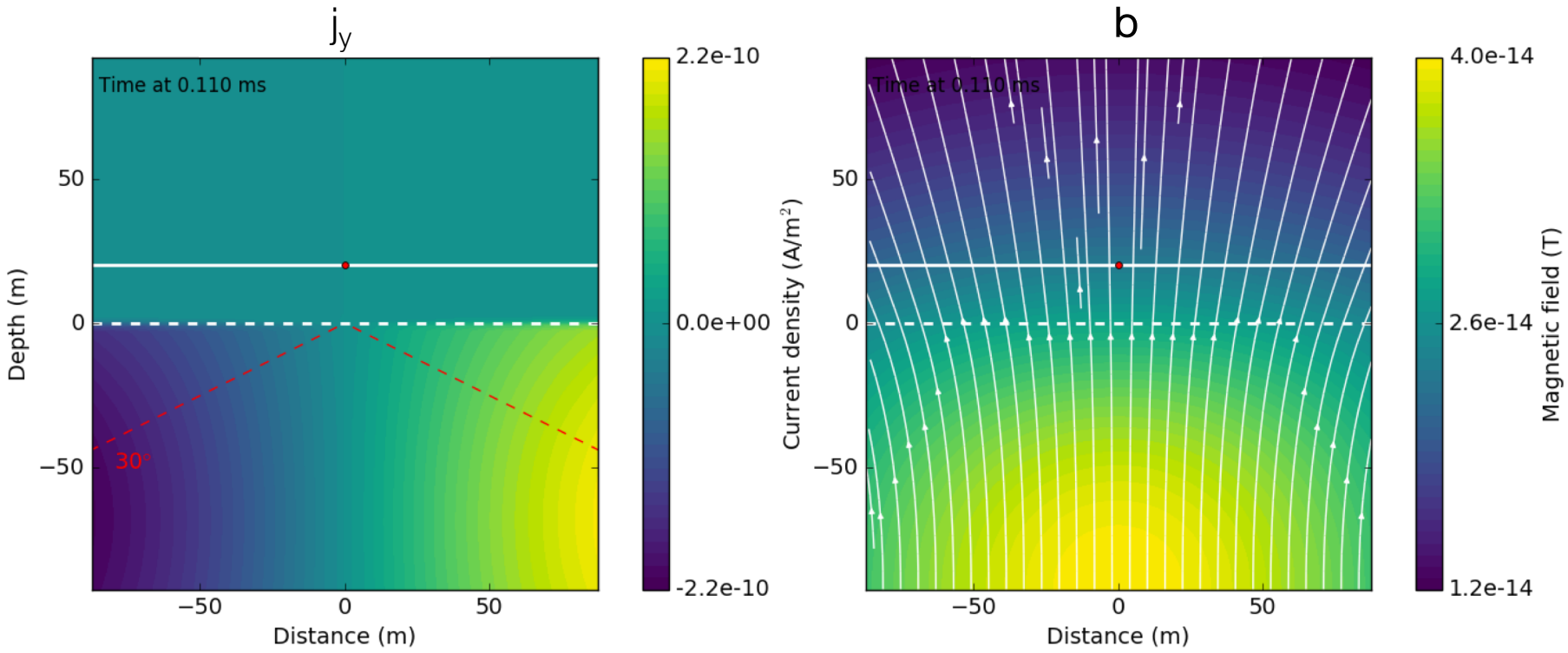
$$d = 1260\sqrt{t\rho}$$



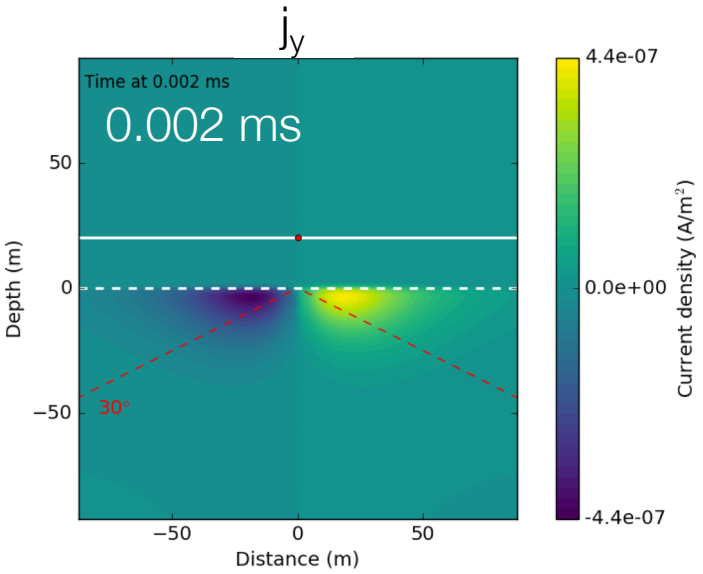
Propagation through time

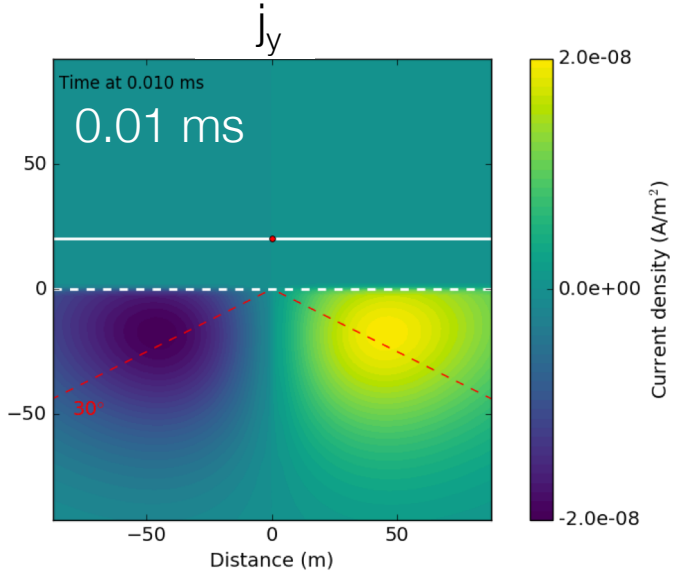
- Time: 0.110ms
- diffusion distance = 132 m

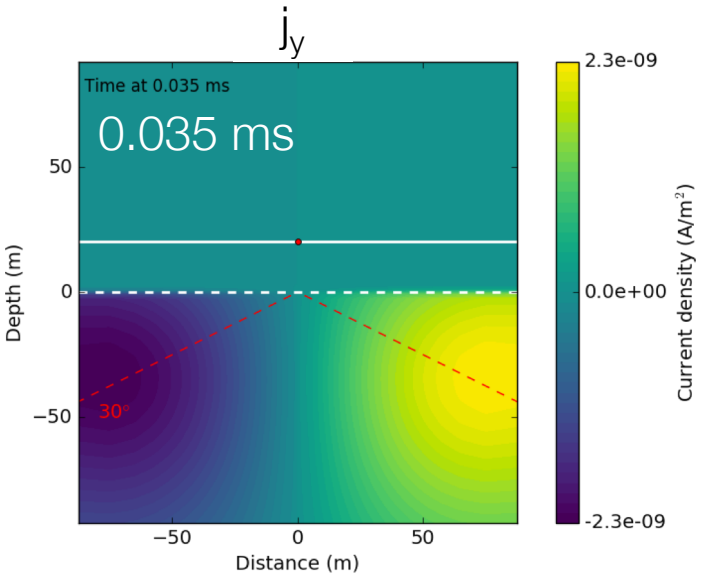
$$d = 1260\sqrt{t\rho}$$



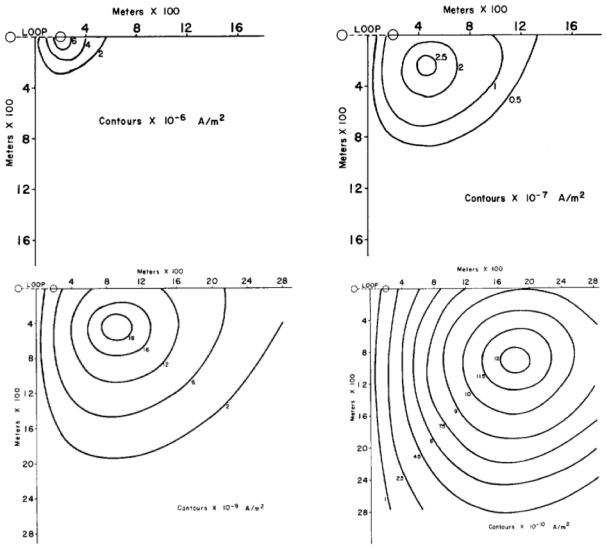
Summary: propagation through time



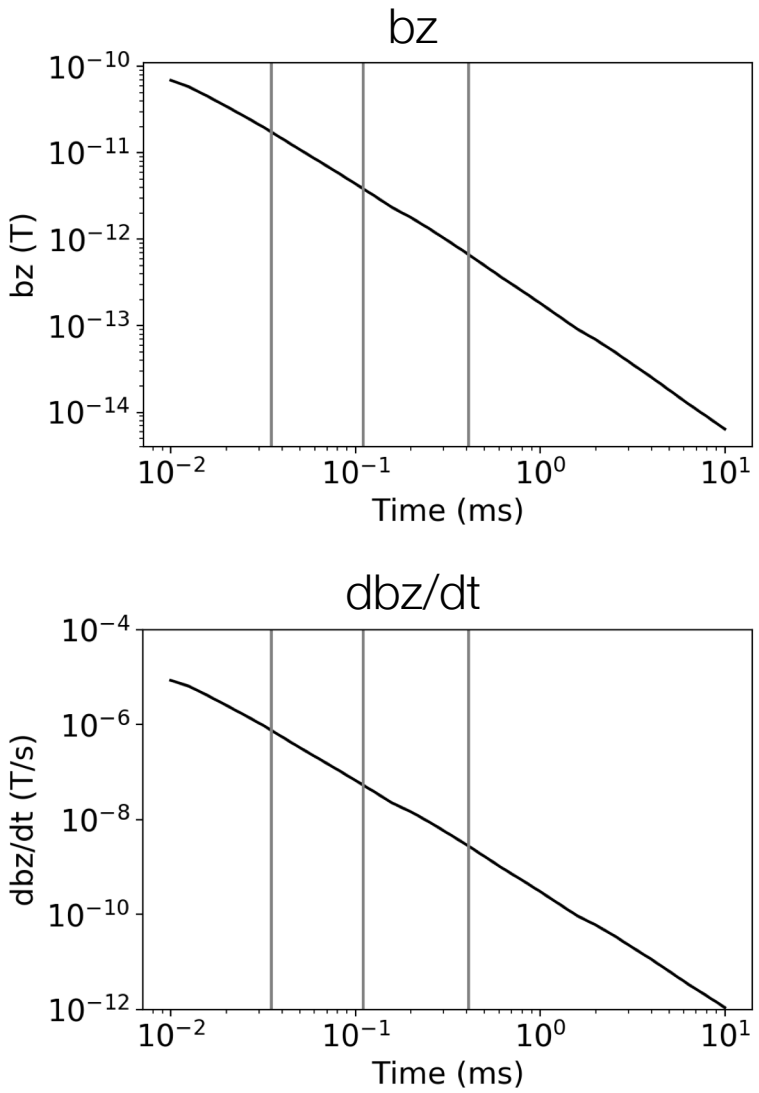


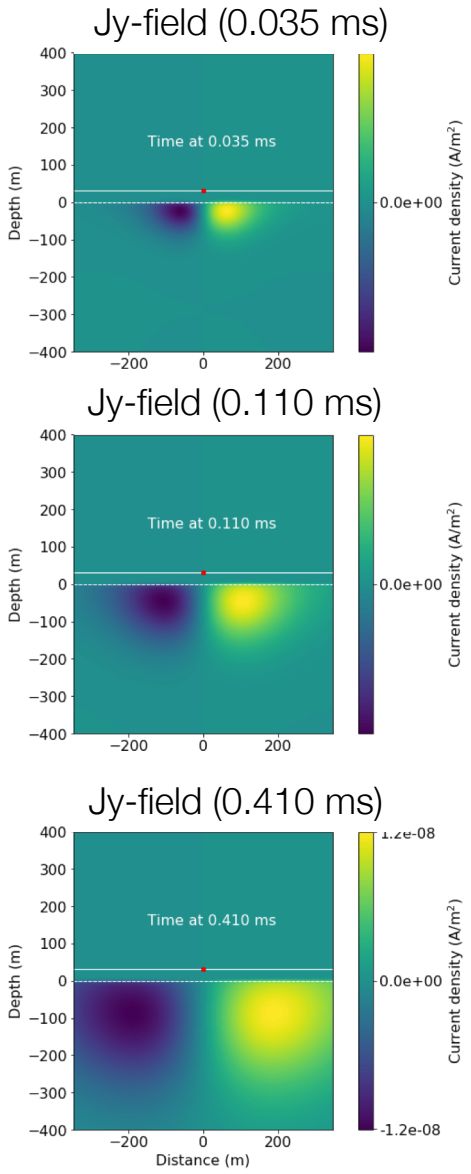


Nabighian (1979)



Sounding curve

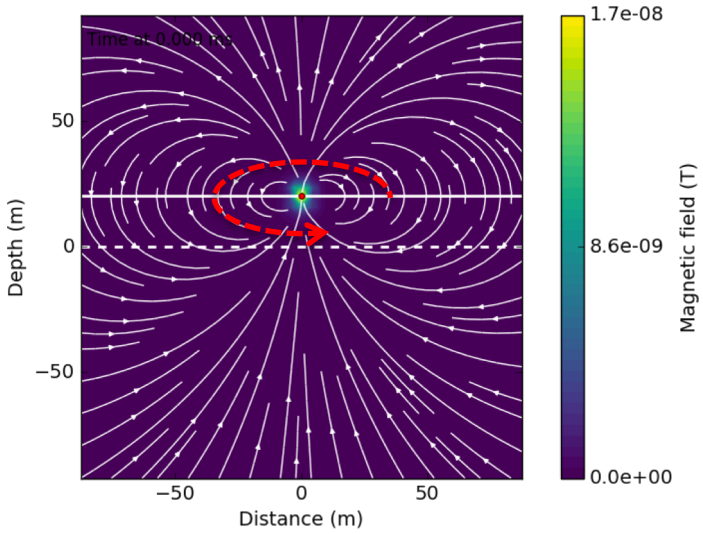




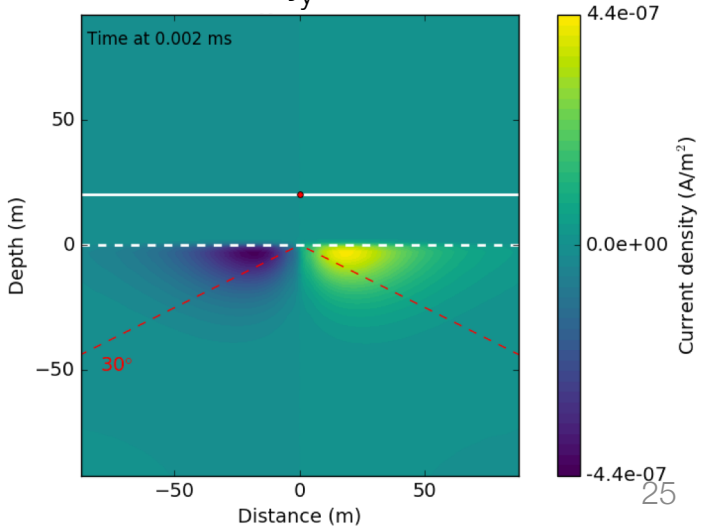
Important points

- Currents flow in same plane as transmitter currents
- Currents diffuse outward downward
- Each transmitter has a “footprint”
- Max resolution controlled by earliest time
- Depth of investigation controlled by latest time

magnetic field (on-time)



j_y



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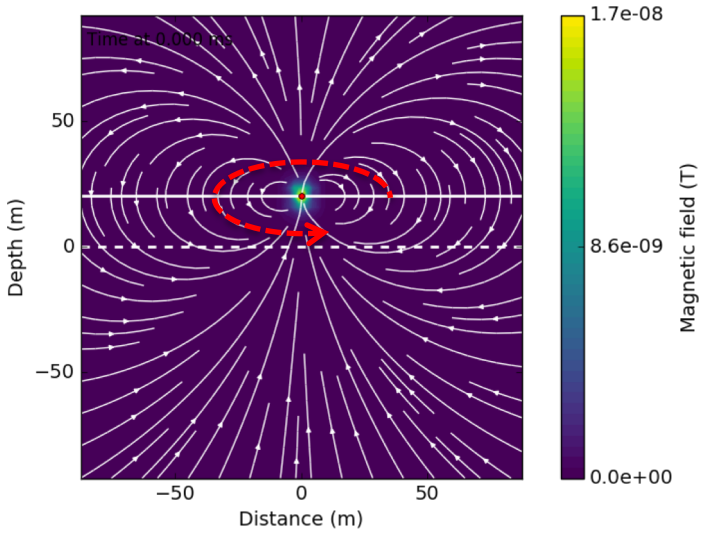
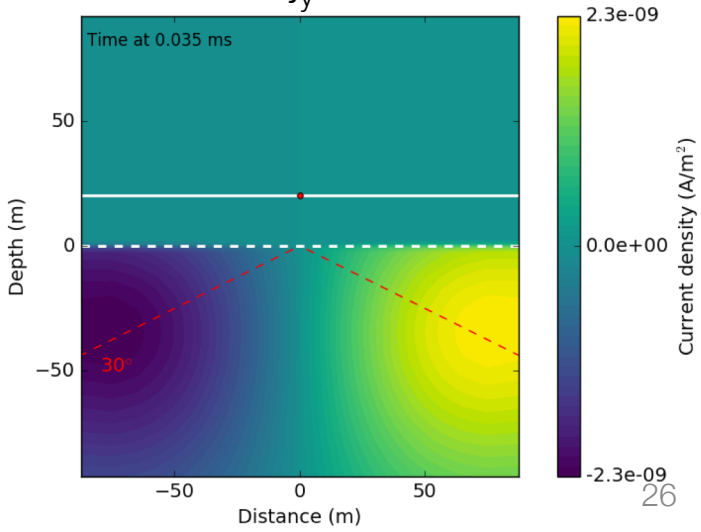
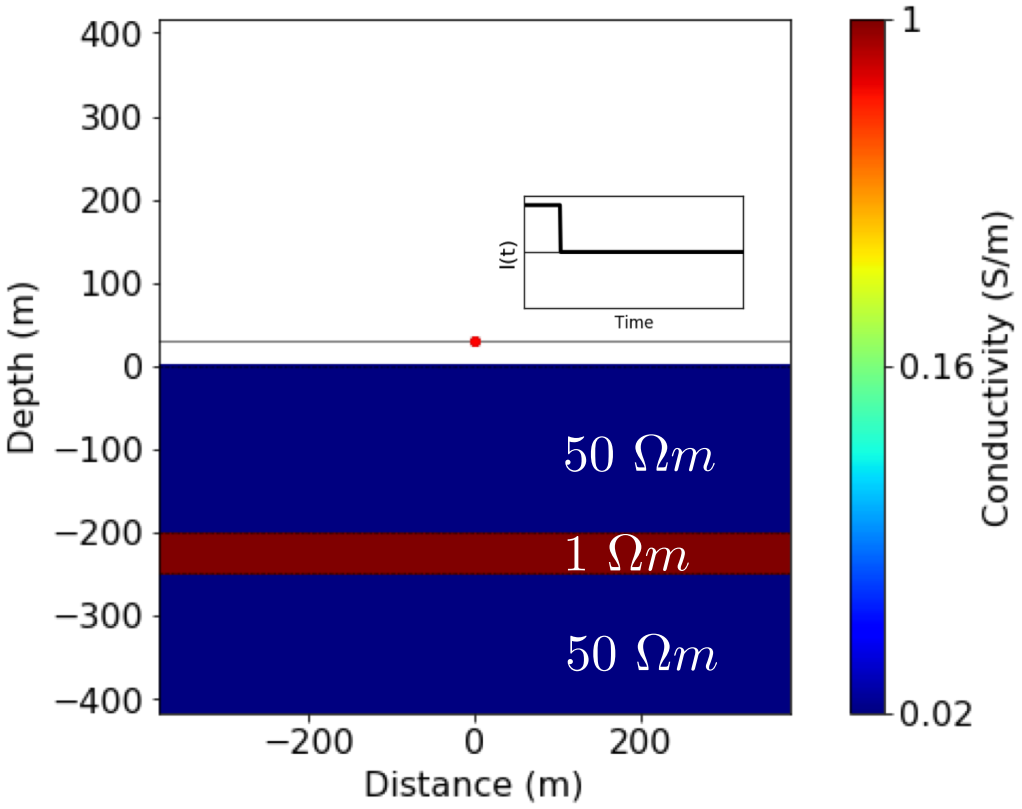


j_y

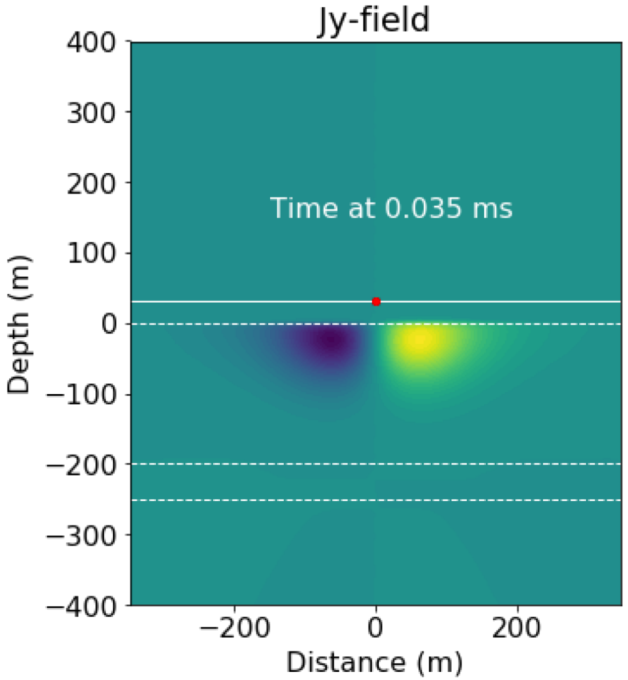


Conductive layer in a halfspace

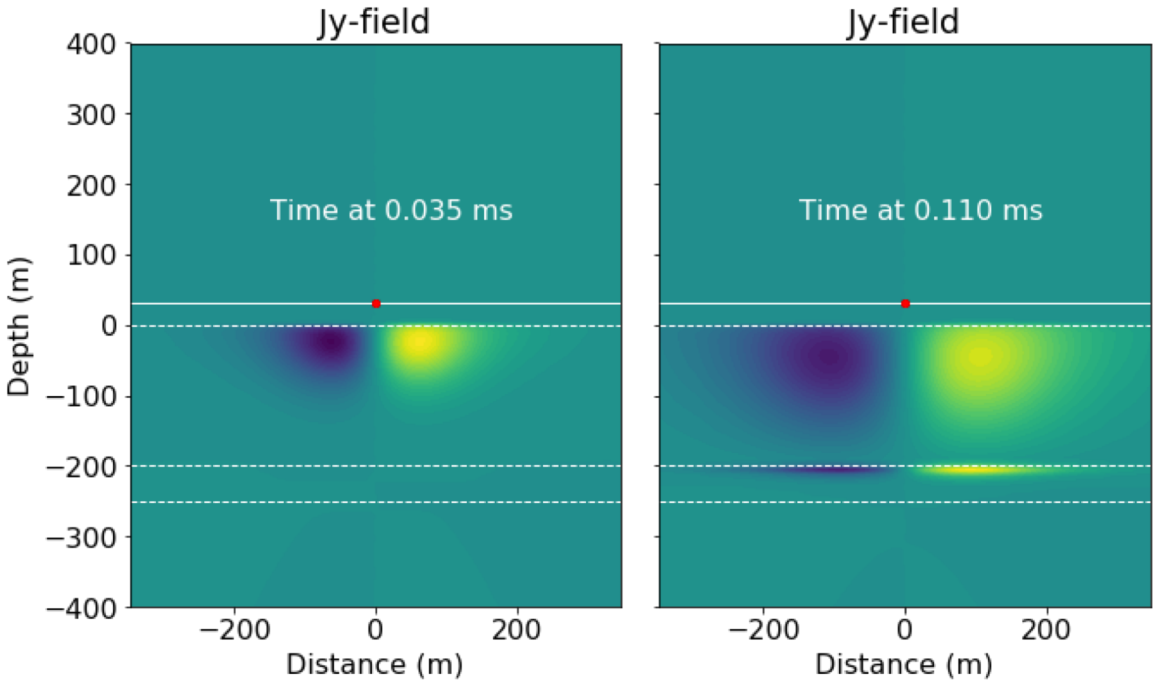


- Loop source
  - 13m radius
- Conductive layer
  - 200 m below
  - 50 m thickness
- Fields
  - j_y off-time

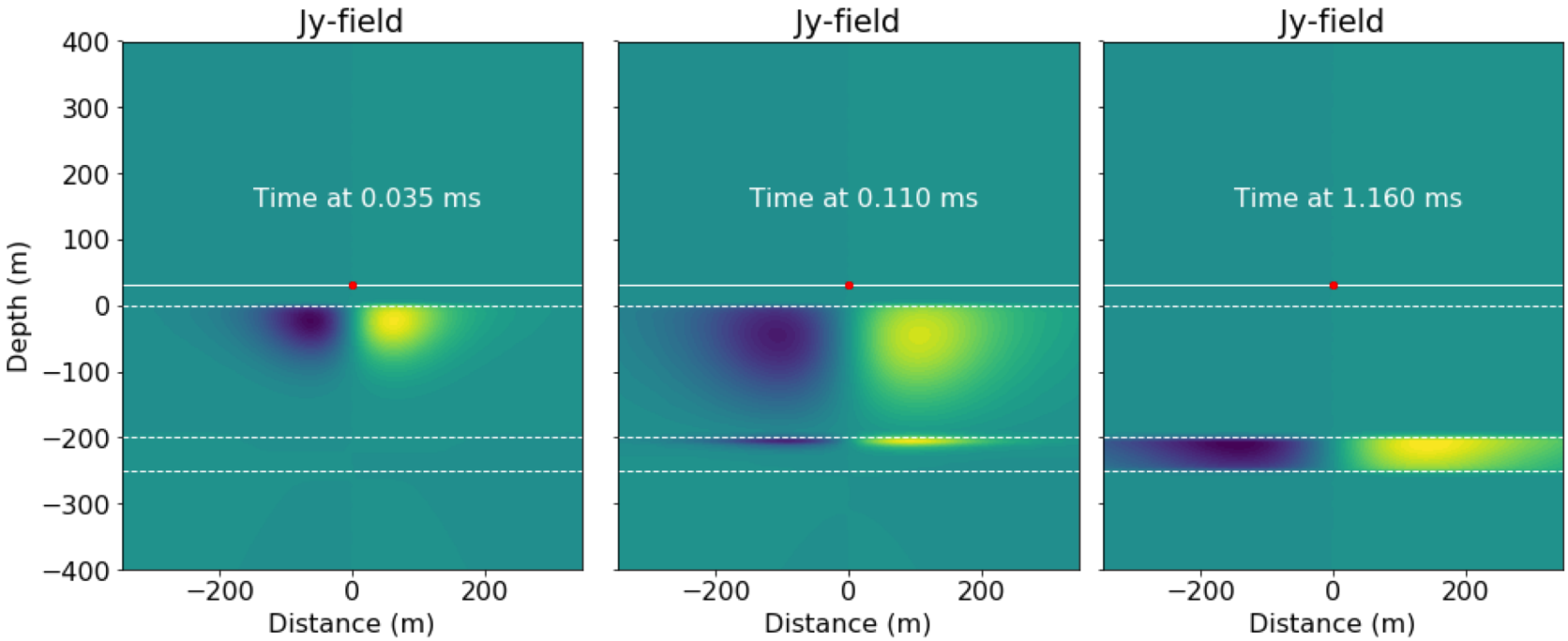
Layered earth currents (j_y)



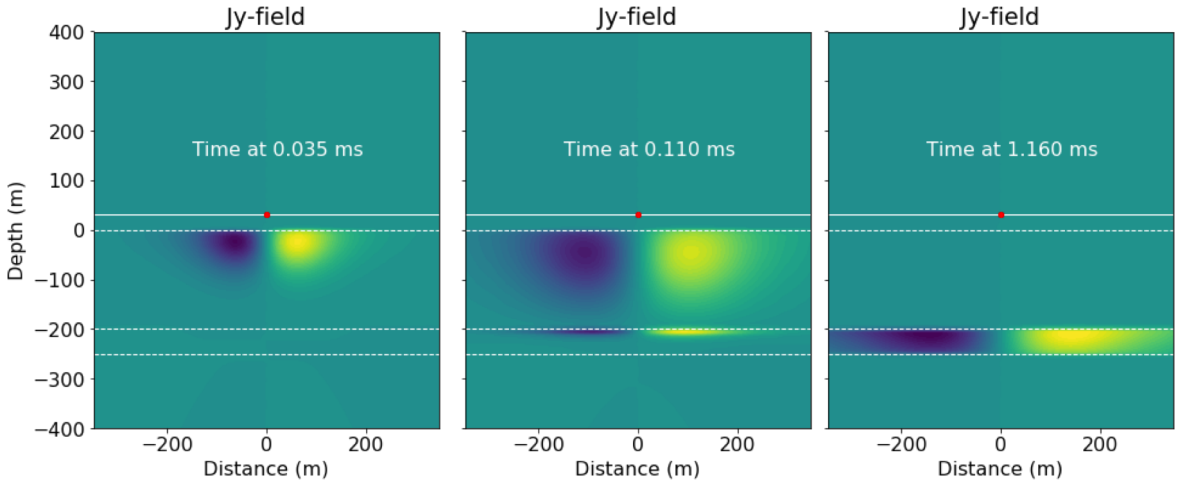
Layered earth currents (j_y)

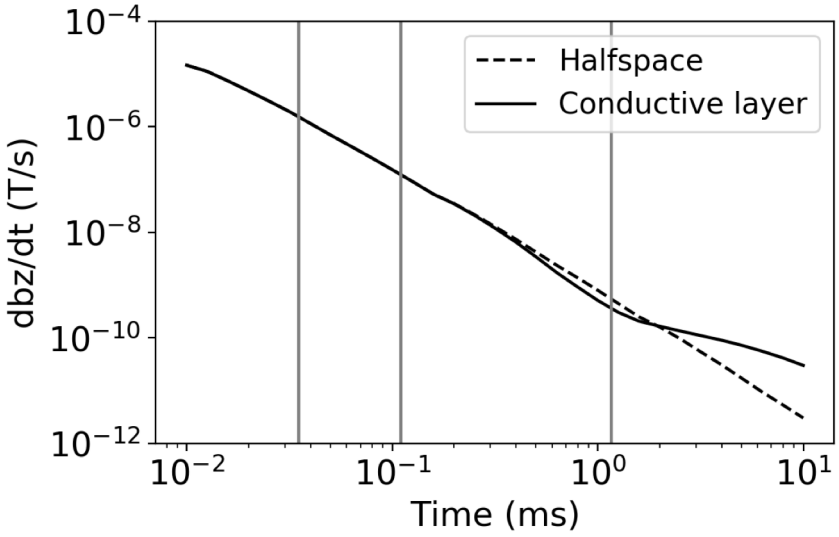


Layered earth currents (j_y)

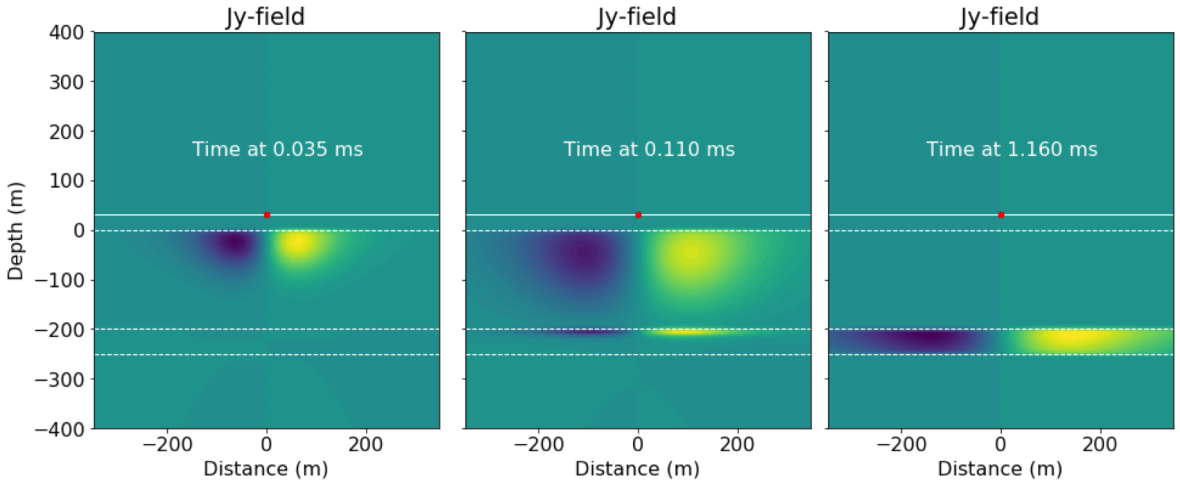


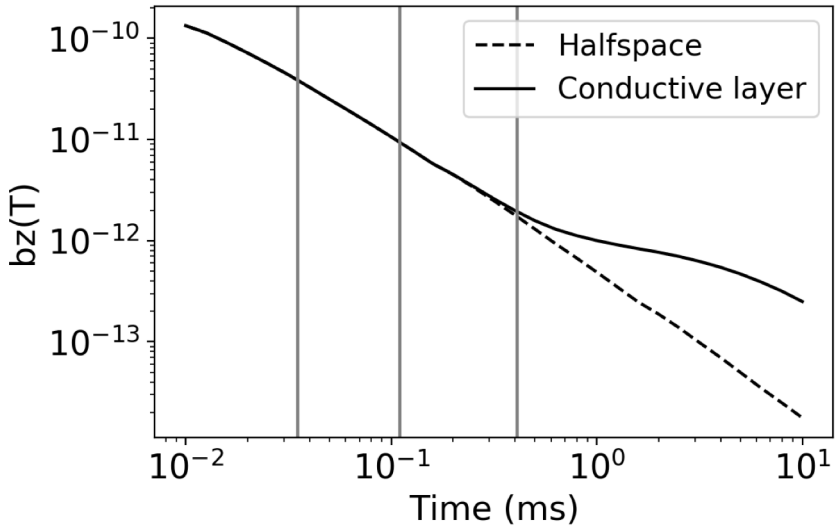
Sounding curve (bz)





Sounding curve (dbz/dt)

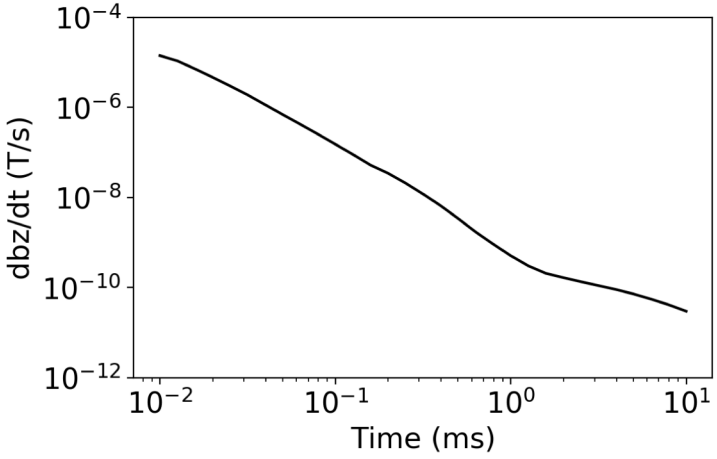


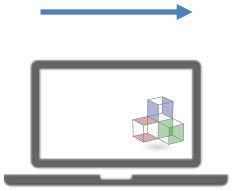


- We have data
- Invert to recover conductivity

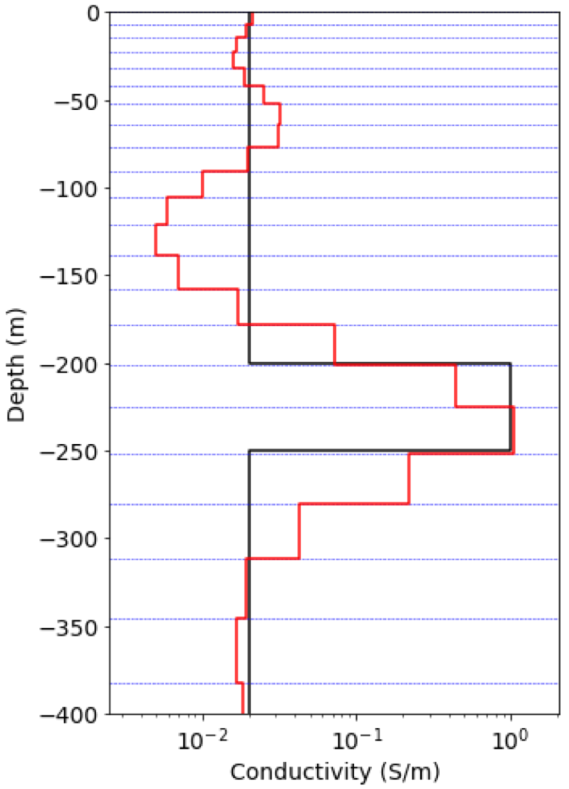
Inversion

Observed data

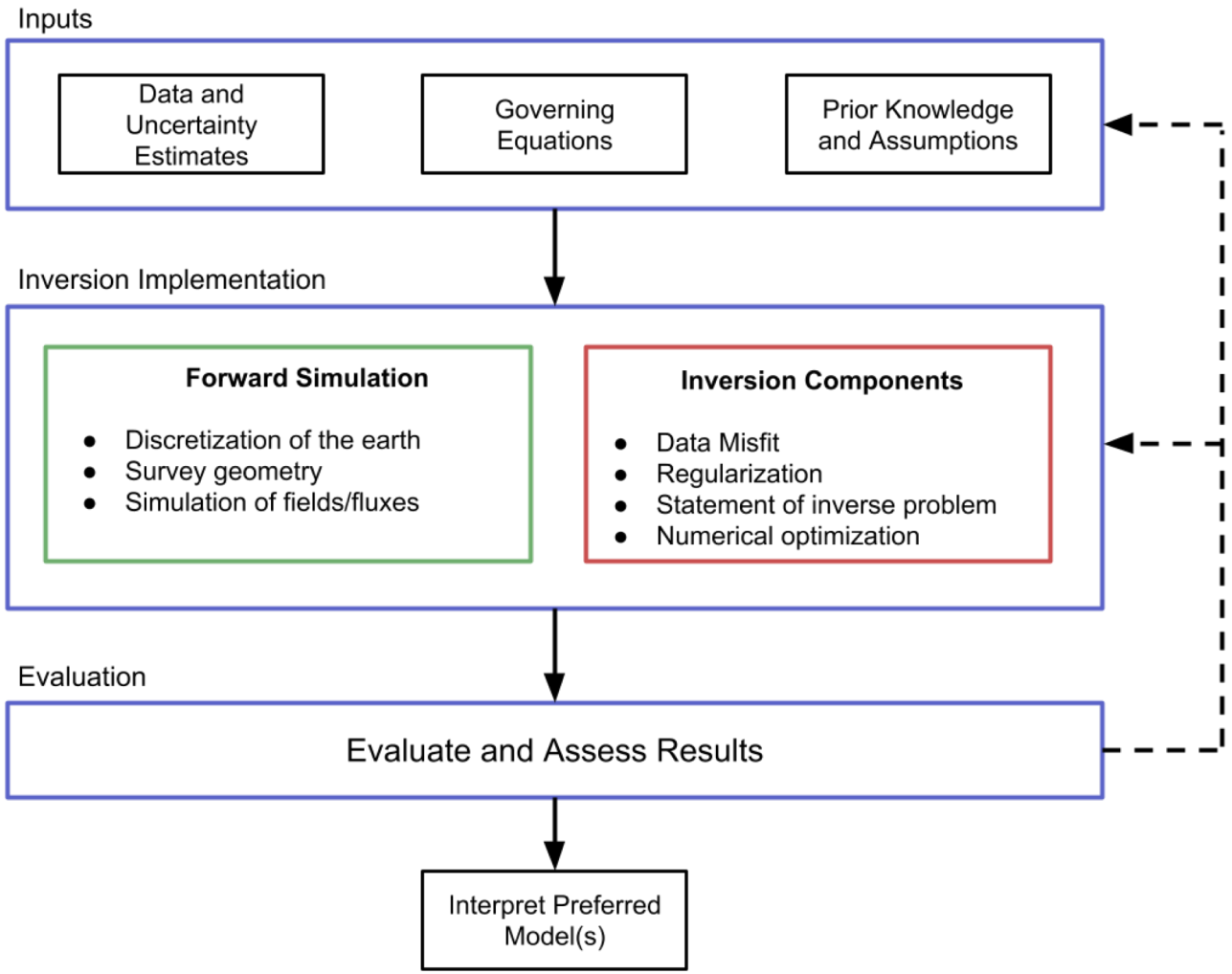




Recovered conductivity



Inversion flow chart



Inverse problem

- Minimize

$$\phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m})$$

$$\text{subject to} \qquad \mathbf{m}_{lower} < \mathbf{m} < \mathbf{m}_{upper}$$

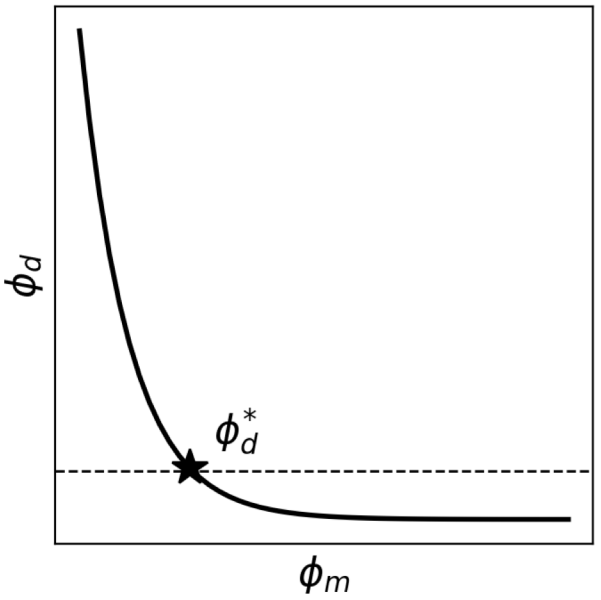
Data misfit

$$\phi_d(\mathbf{m}) = \frac{1}{2}\|\mathbf{W}_\mathrm{d}(F[\mathbf{m}] - \mathbf{d}_\mathrm{obs})\|_2^2.$$

Regularization

$$\phi_m(\mathbf{m}) = \frac{1}{2}\|\mathbf{W}_\mathrm{m}(\mathbf{m} - \mathbf{m}_\mathrm{ref})\|_2^2.$$

Tikhonov curve



Regularization and a-priori information

$$\phi_m(\mathbf{m}) = \frac{1}{2}\|\mathbf{W}_\mathrm{m}(\mathbf{m} - \mathbf{m}_\mathrm{ref})\|_2^2.$$

Inversion Parameters: (model)

- conductivities 1D, 2D, or 3D
- linear or log
- geometrical parameters
- …

- Smallness
- Smoothness
- Cell weight
- Face weight
- ..

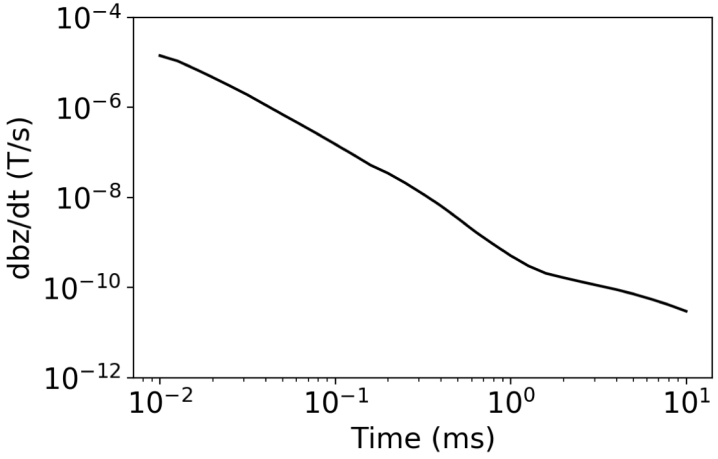
Reference model

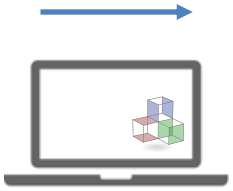
Norms

- L_p: 0<p<2
- L2 (smooth)
- L0 (sparse)

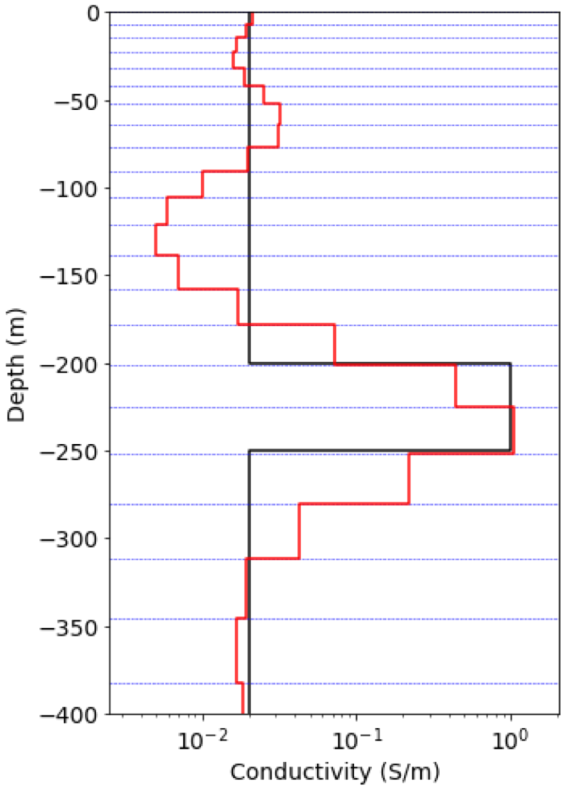
Inversion

Observed data





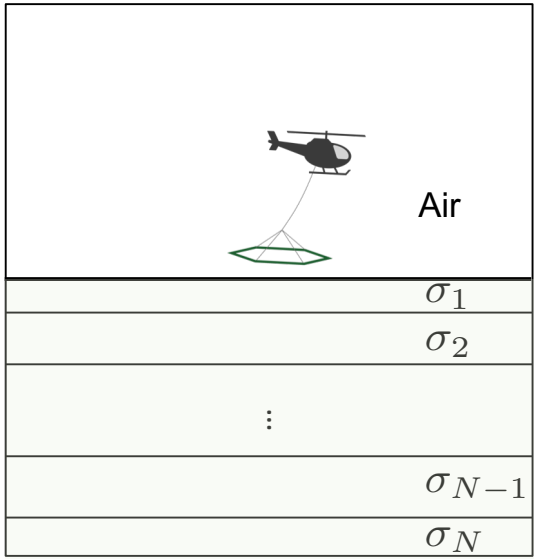
Recovered conductivity



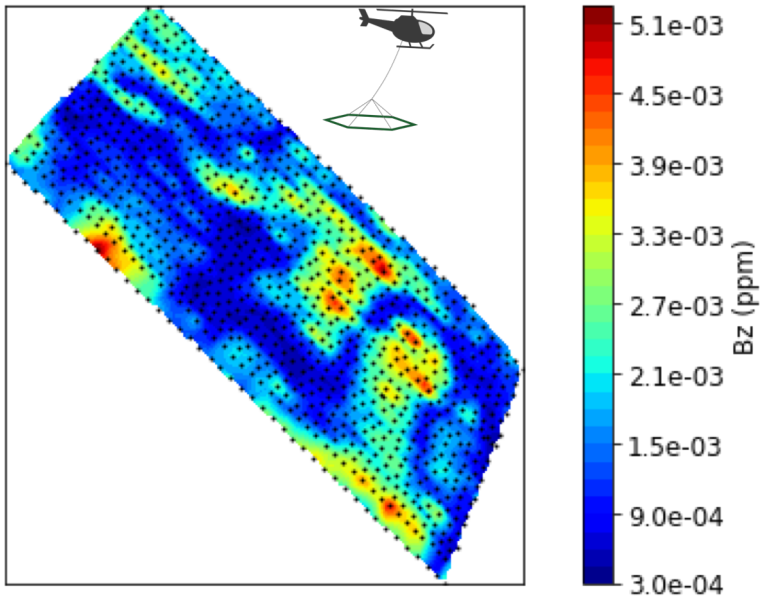
What software algorithm?

SimPEG-EM1D inversion code

Layered conductivity



AEM data

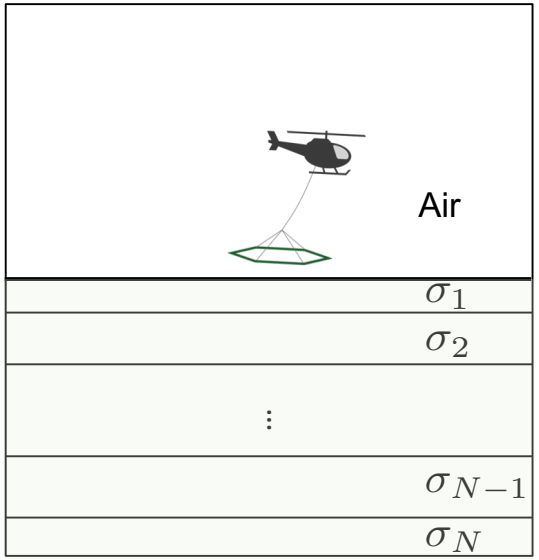


- Pseudo-analytic solution
  - Similar to UBC EM1DFM and EM1DTM
- Multiple sources
  - ~100,000 sources
- 1D inversion for each sounding

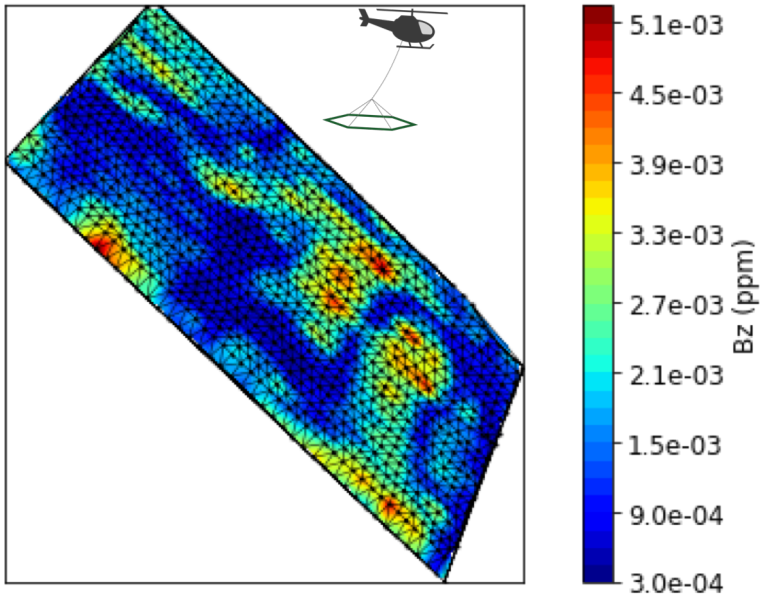
- Spatial constraint
  - Ask for horizontally smooth model
  - Use Delaunay triangulation
  - Similar to AarhusInv
- Effective tool to invert large scale AEM data

SimPEG-EM1D inversion code

Layered conductivity



AEM data



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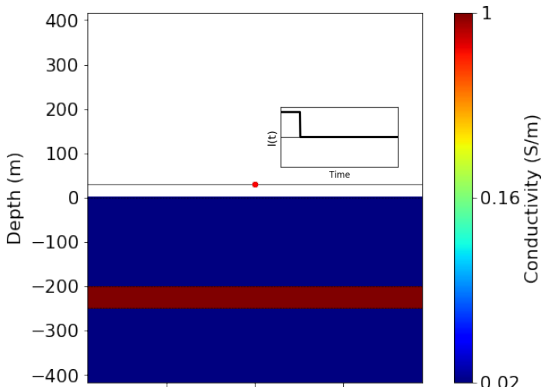
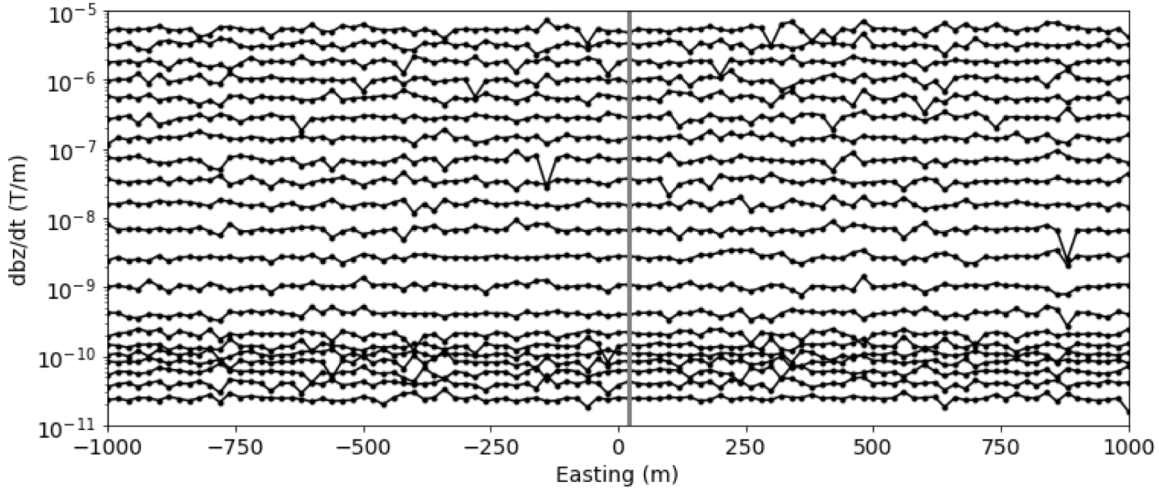
Layered Earth: 1D inversion

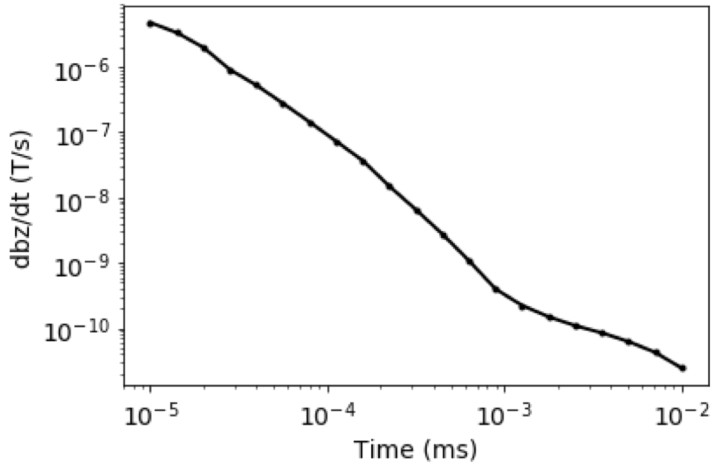
Layered conductivity

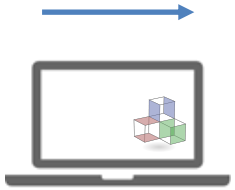


Sounding curves with noise

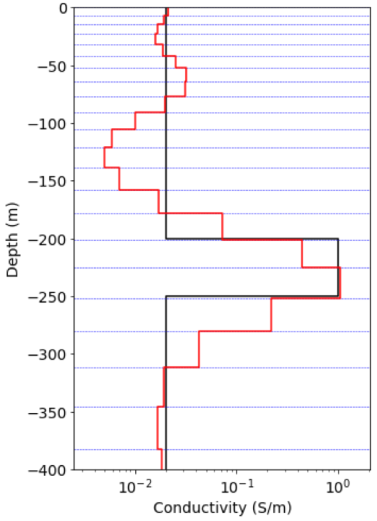


Observed data at a single sounding



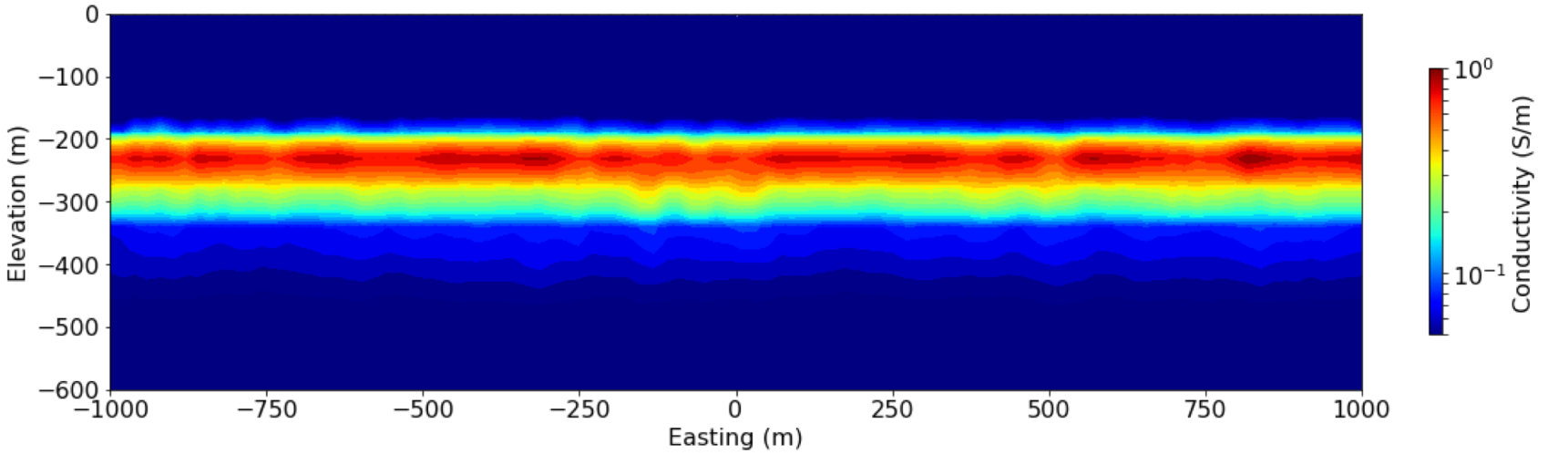


Recovered conductivity

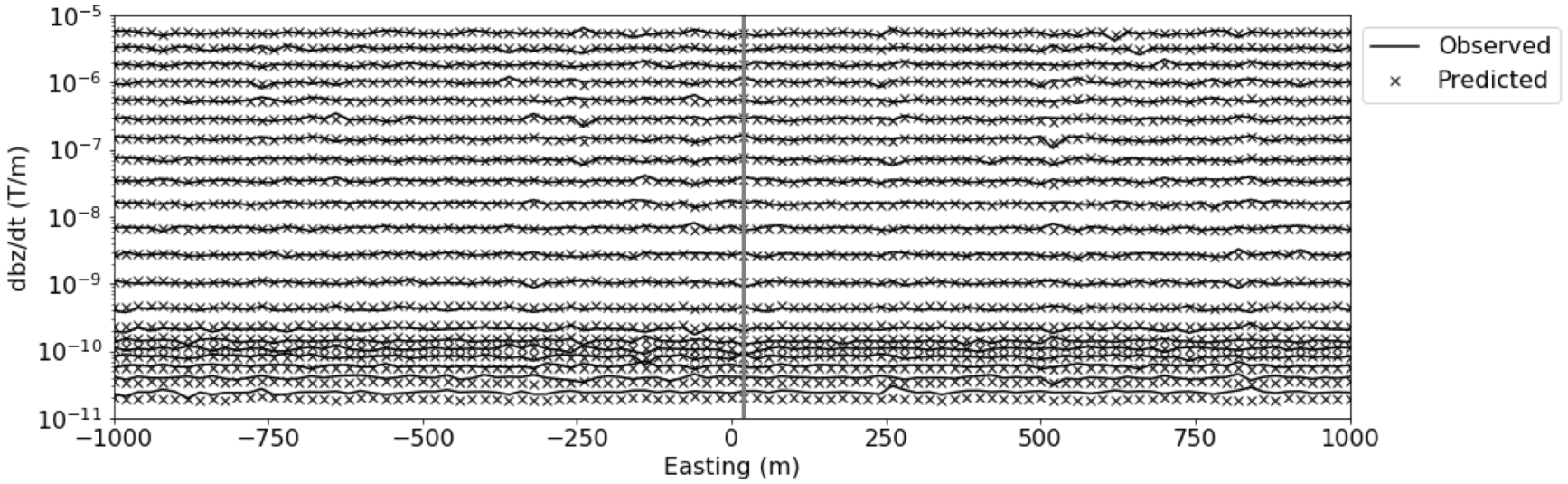


1D inversion

- Recovered conductivity section



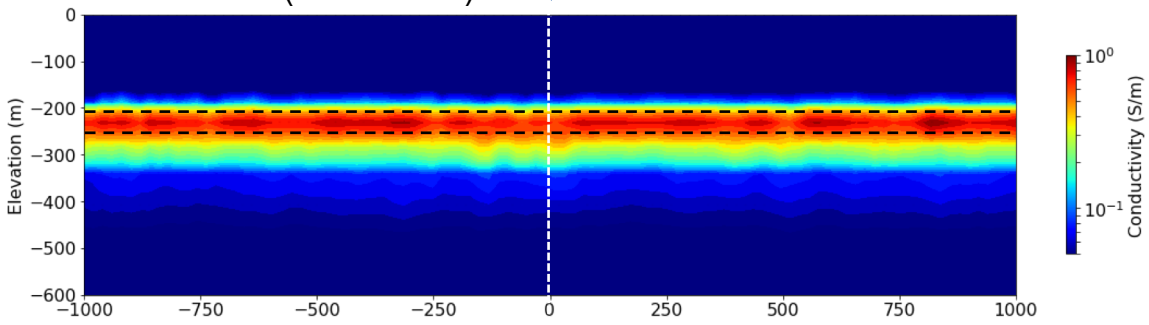
- Observed vs. Predicted

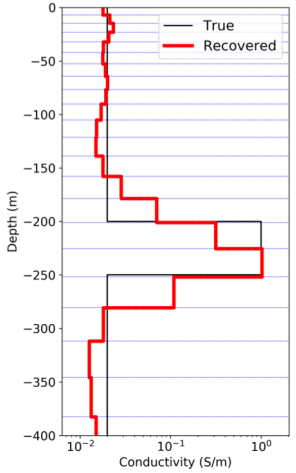


Different regularization function

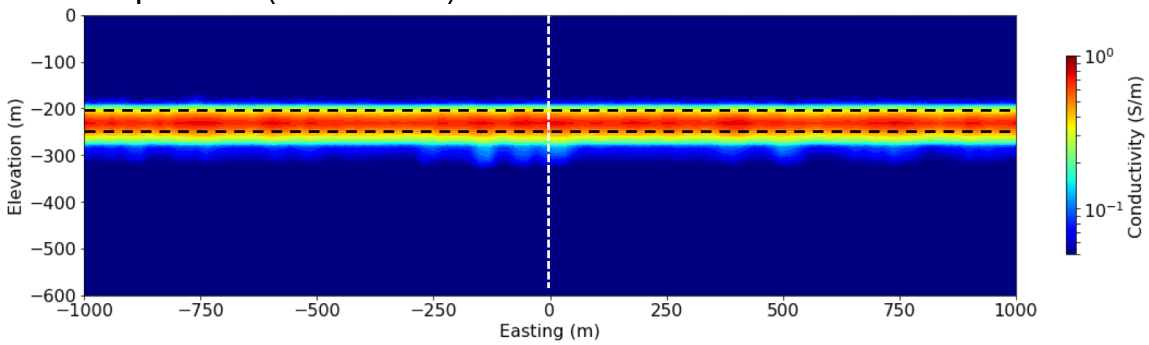
$$\phi_m(\mathbf{m}) = \frac{1}{2}\|\mathbf{W}_\mathrm{m}(\mathbf{m} - \mathbf{m}_\mathrm{ref})\|_2^2$$

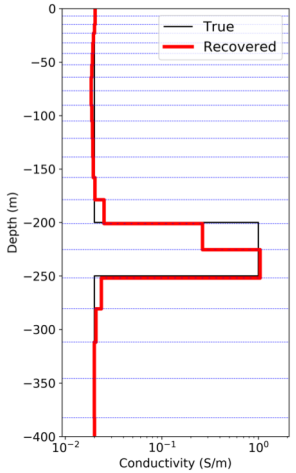
Smooth (L2 norm)



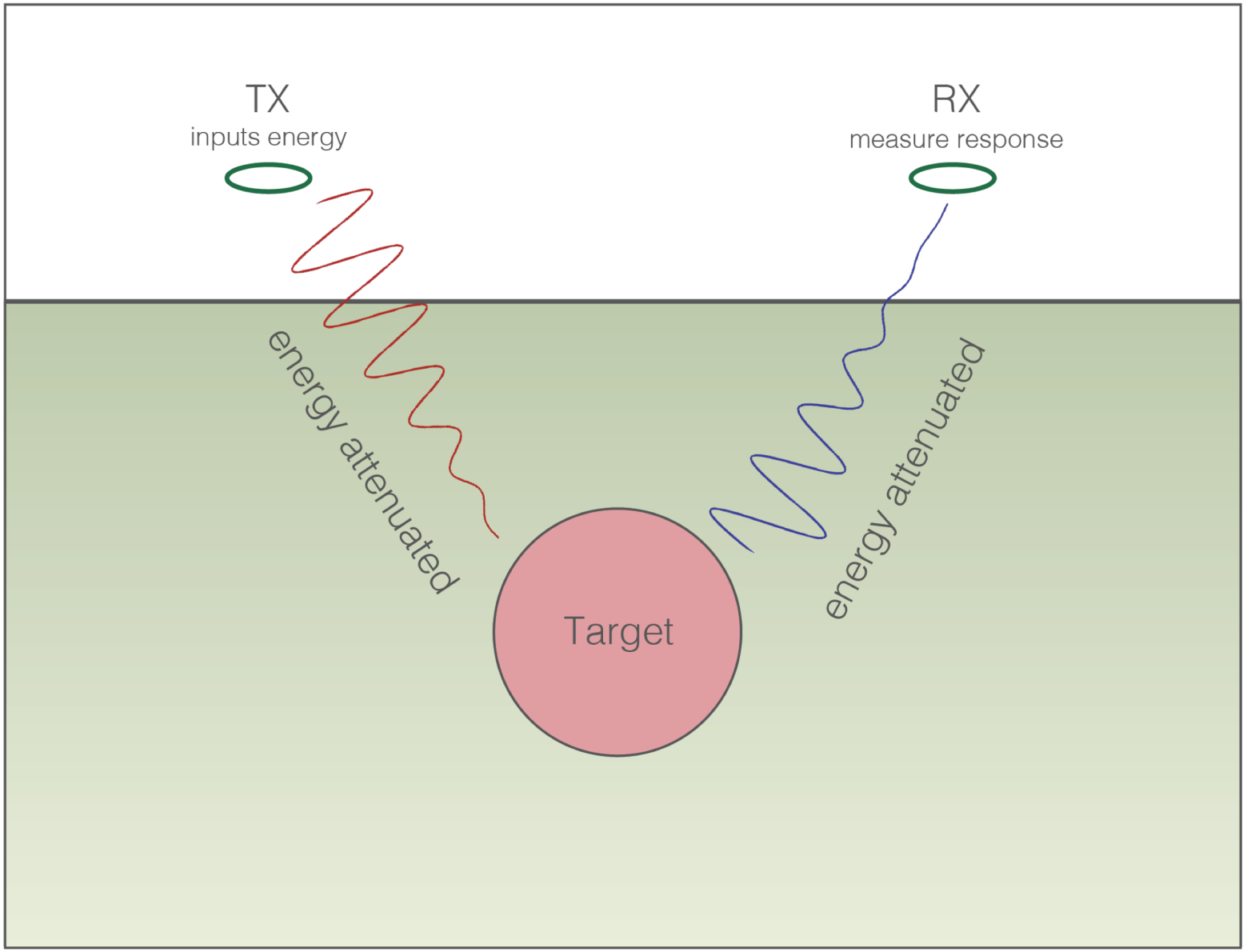


Sparse (L0 norm)



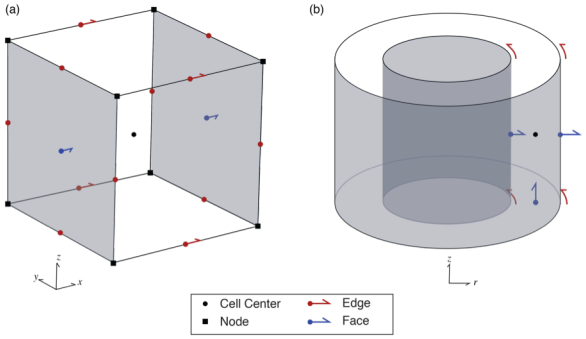


EM effects with 3D structure: Conductive sphere



Cyl Code

- Finite Volume EM
  - Frequency and Time



- Built on SimPEG

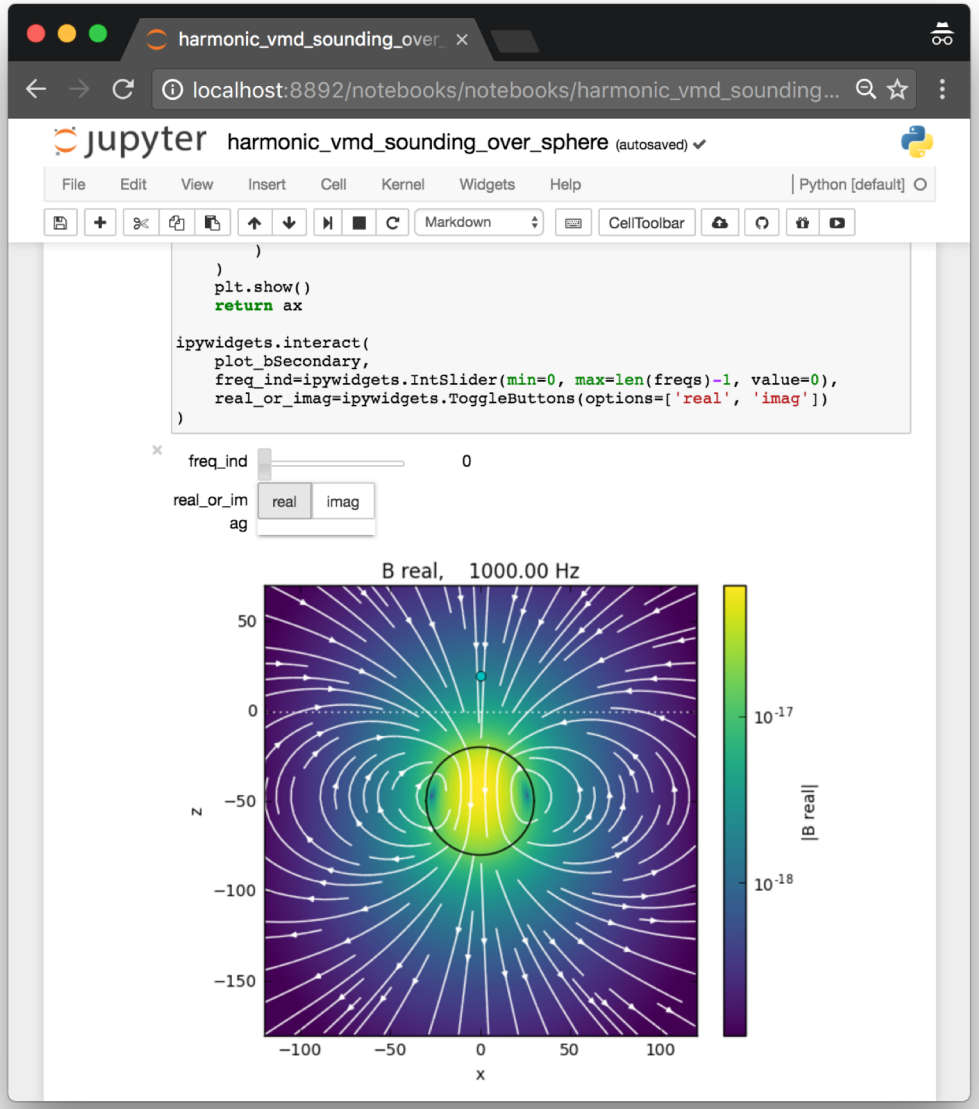
- Open source, available at:

http://em.geosci.xyz/apps.html

- Papers

Cockett et al, 2015

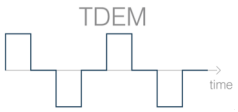
Heagy et al, 2017



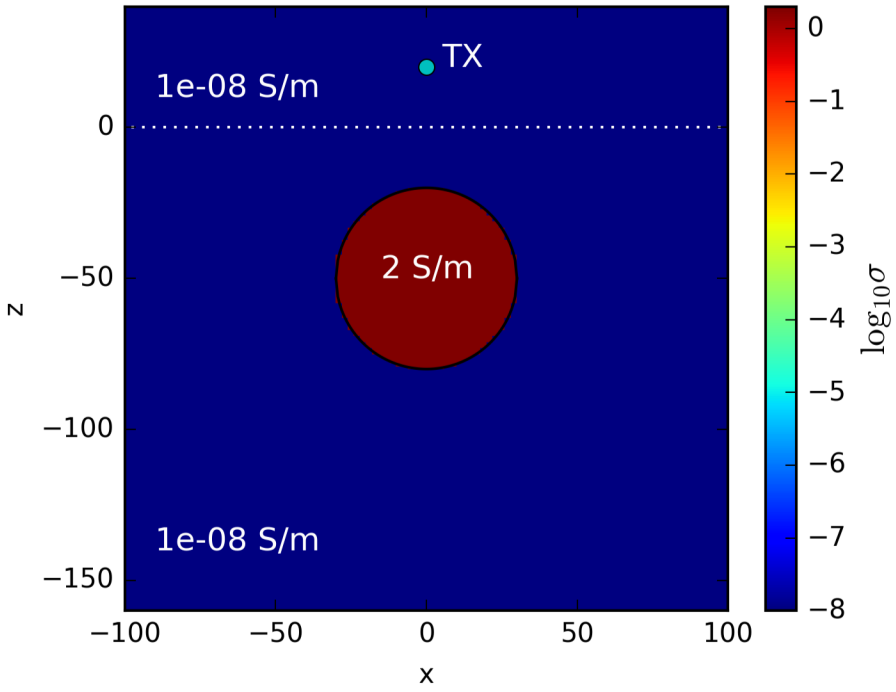
Effects of background resistivity: Time

- Buried, conductive sphere
- Vary background conductivity

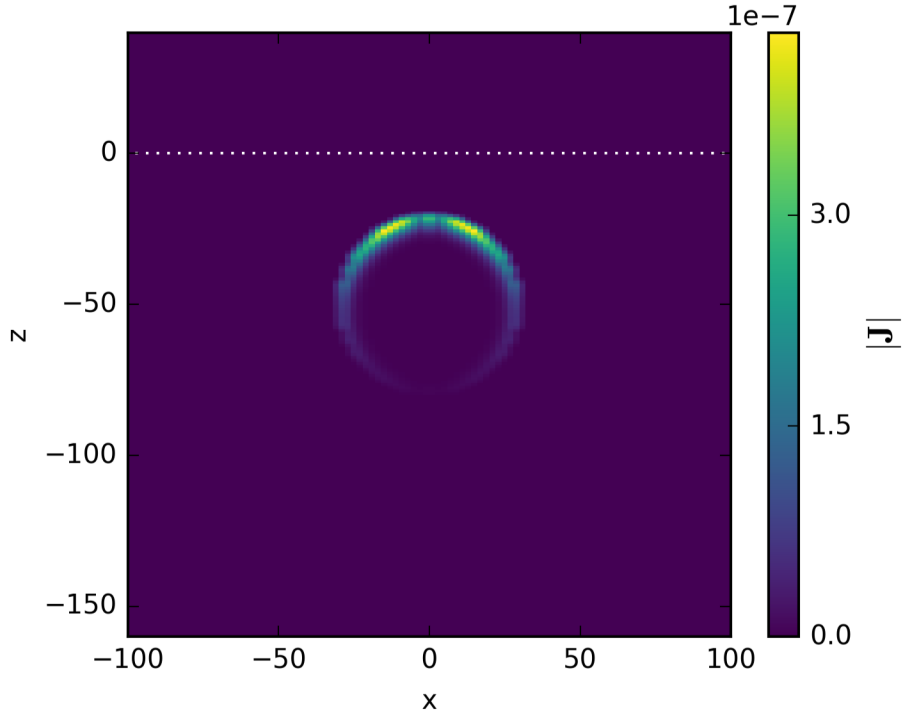
- Time: 10^{-5} s



10^{-8} S/m background



Current Density



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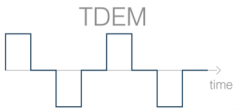
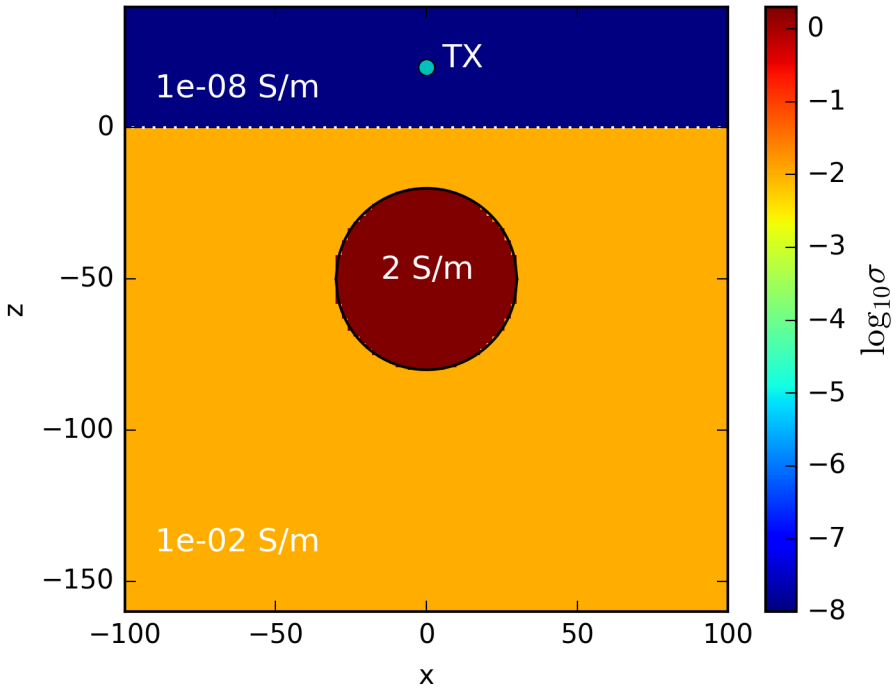
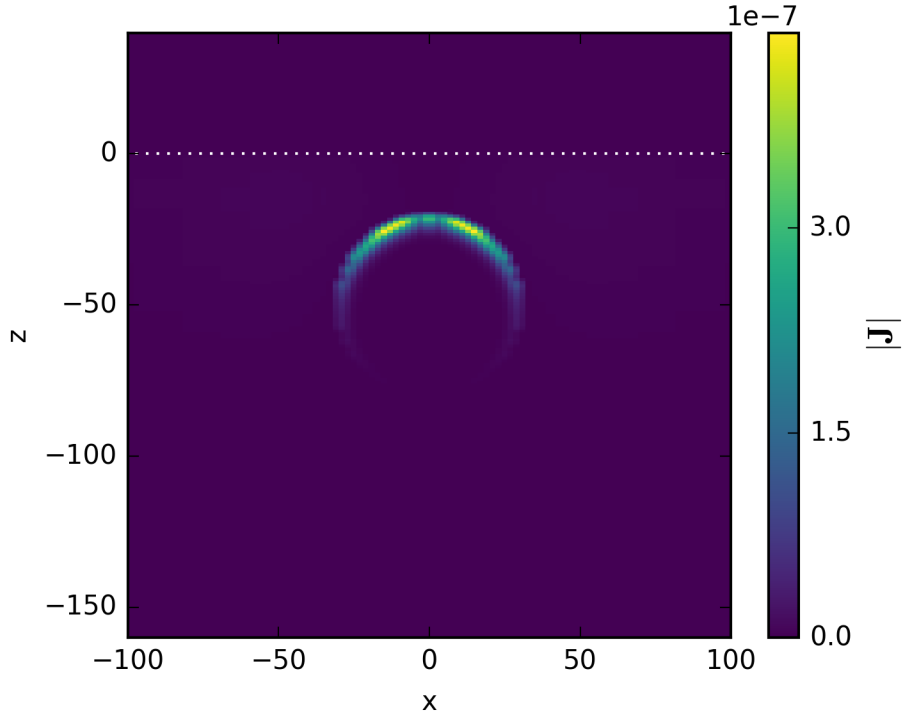


10^{-2} S/m background



Current Density



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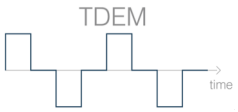
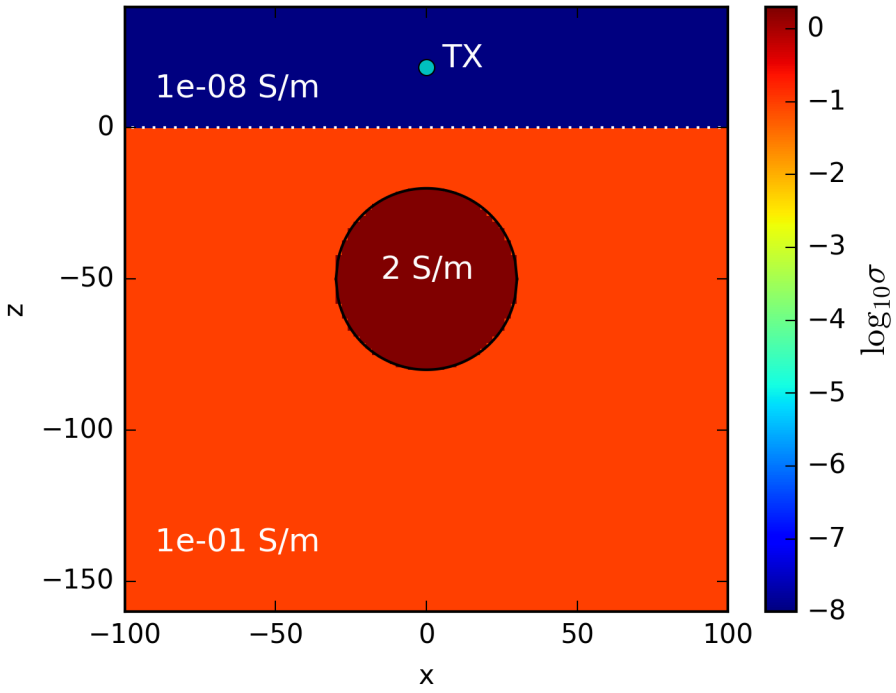
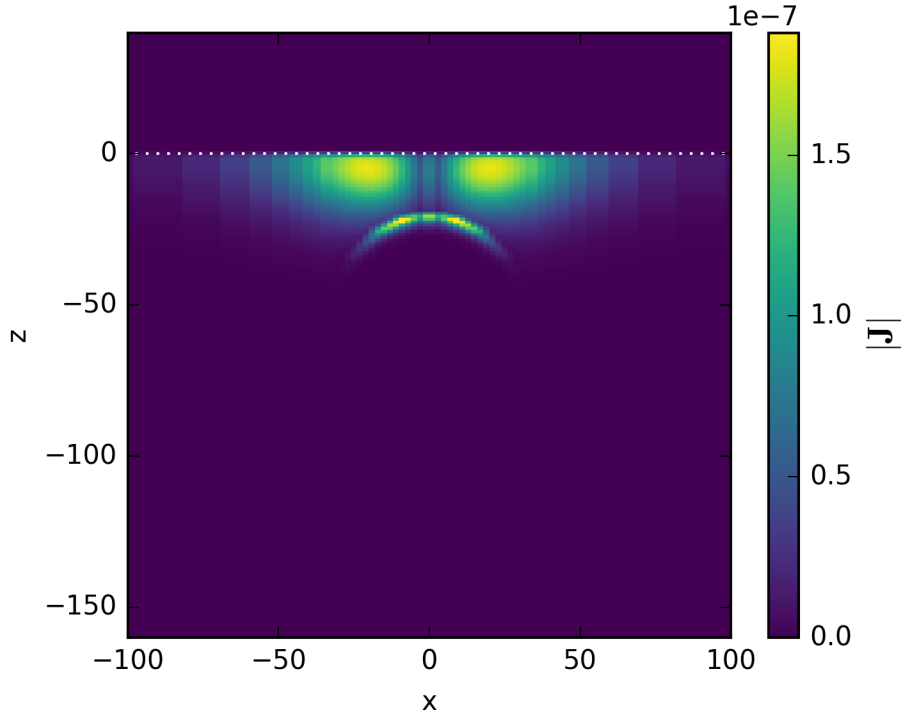


10^{-1} S/m background



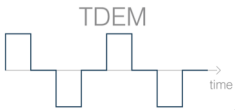
Current Density



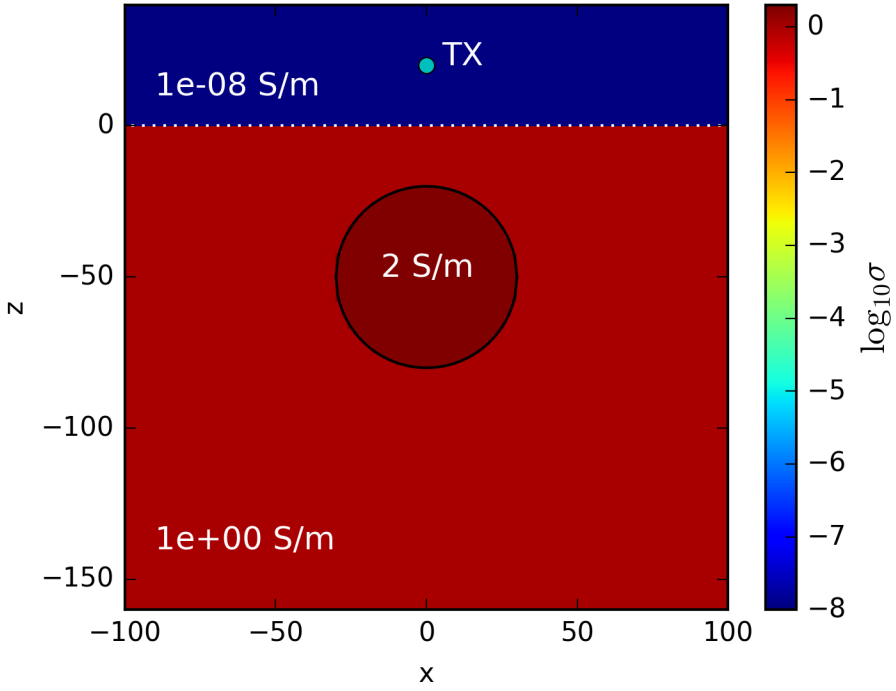
Effects of background resistivity: Time

- Buried, conductive sphere
- Vary background conductivity

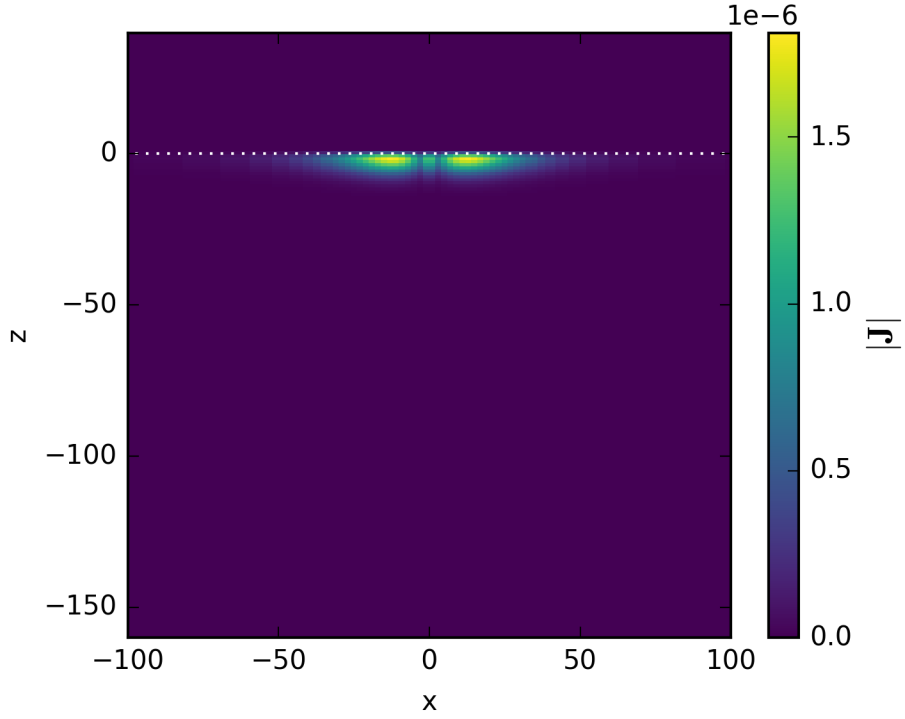
- Time: 10^{-5} s



1 S/m background



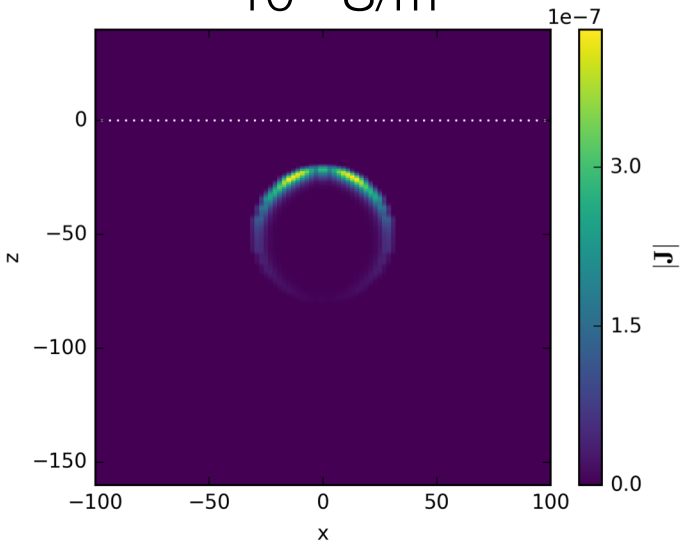
Current Density



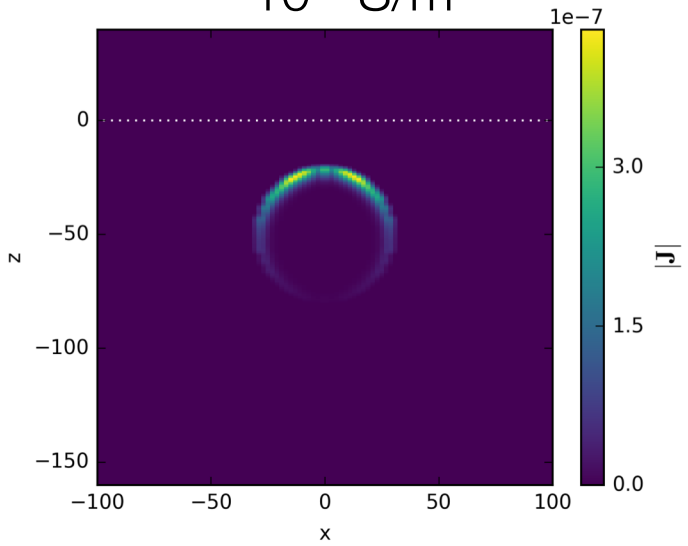
10^{-5} s

Effects of background resistivity: Time

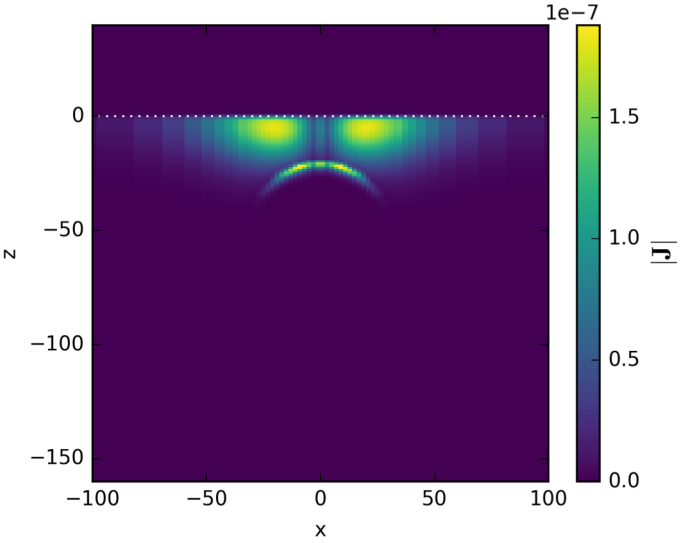
10^{-8} S/m



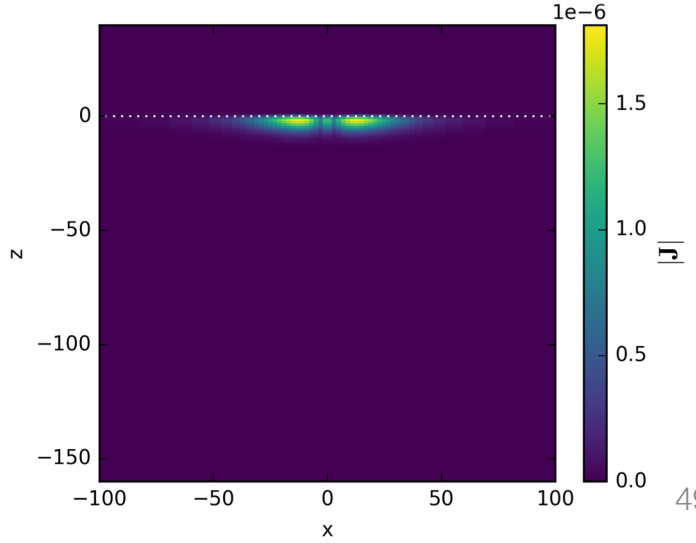
10^{-2} S/m



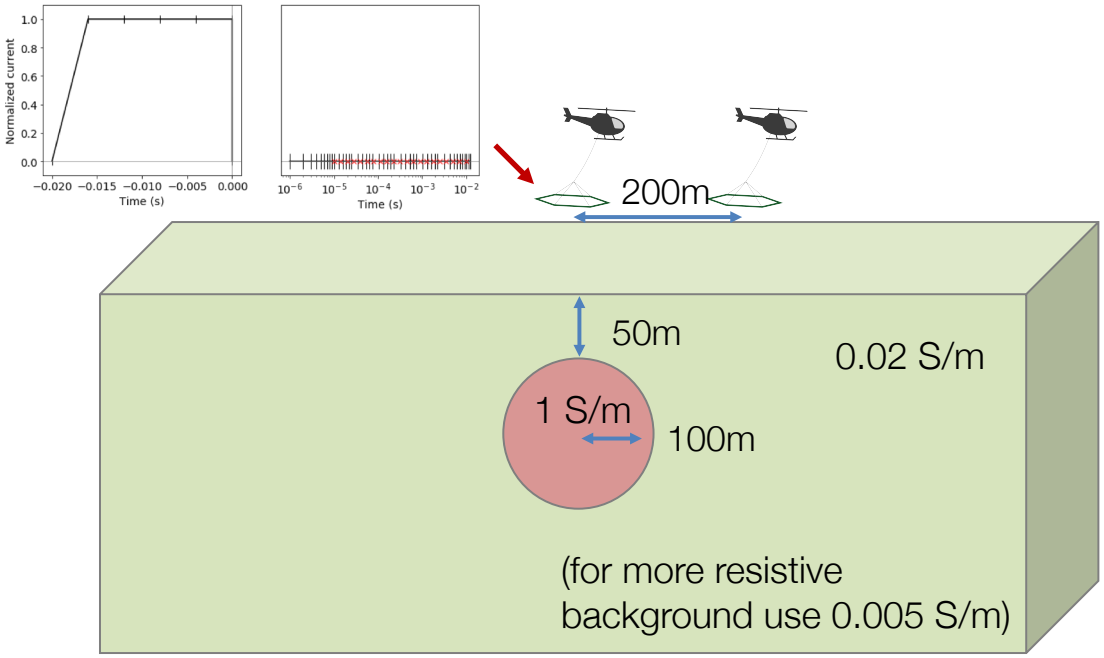
10^{-1} S/m



1 S/m

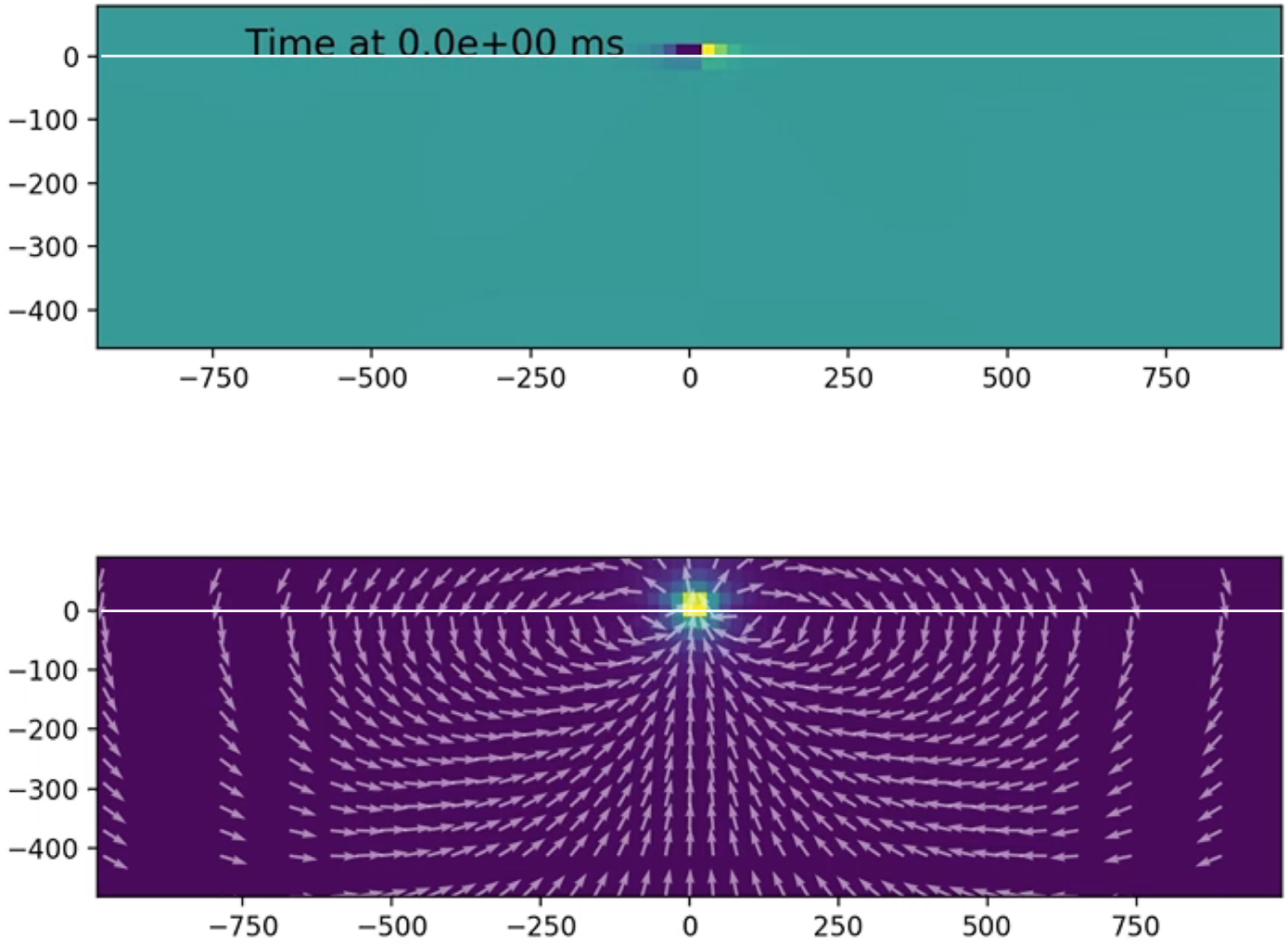


Conductive sphere in a halfspace

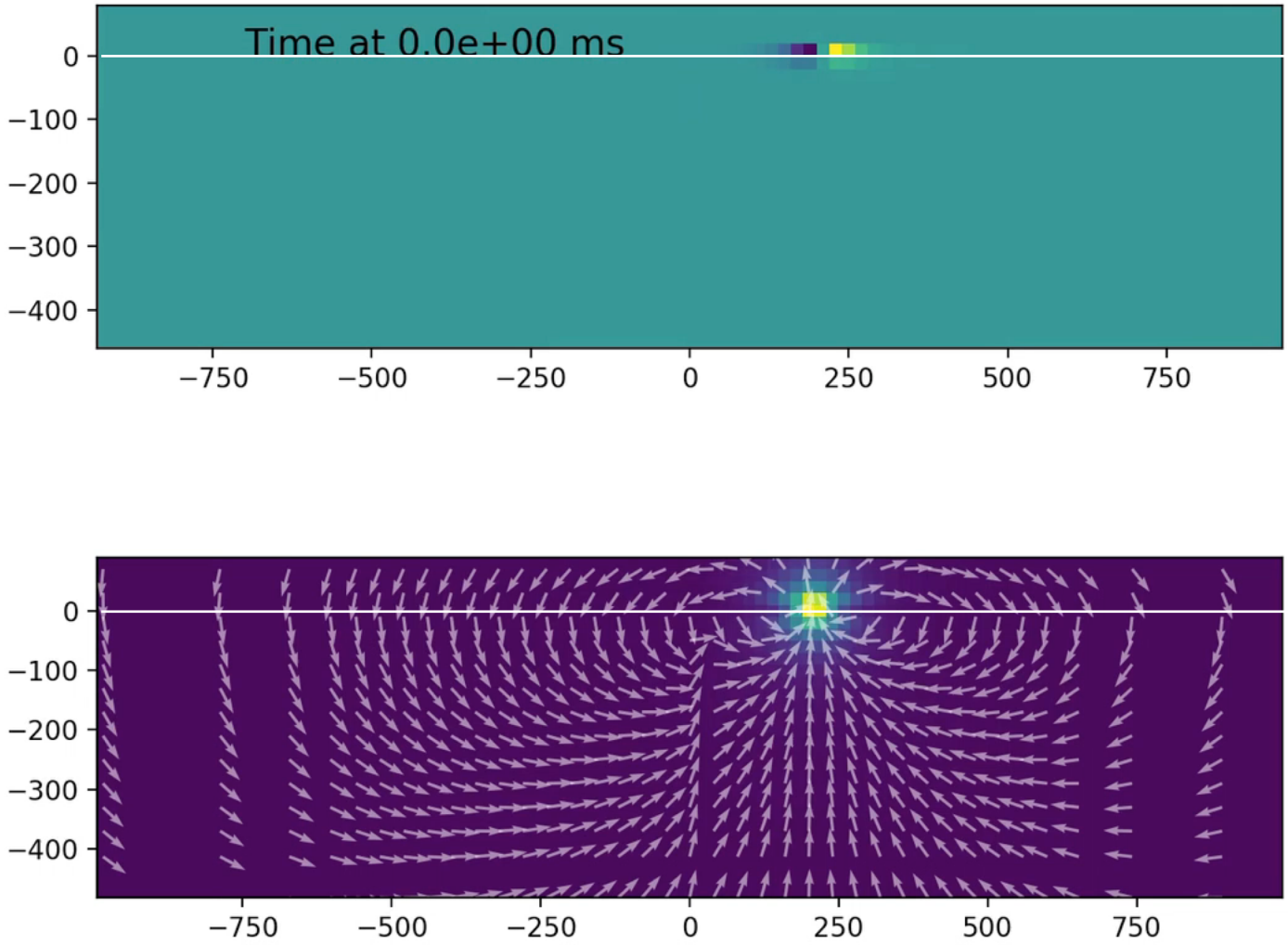


- Explore fields
- Generate synthetic data (3D simulation)
- Invert in 1D (artefacts?)
- Invert in 3D

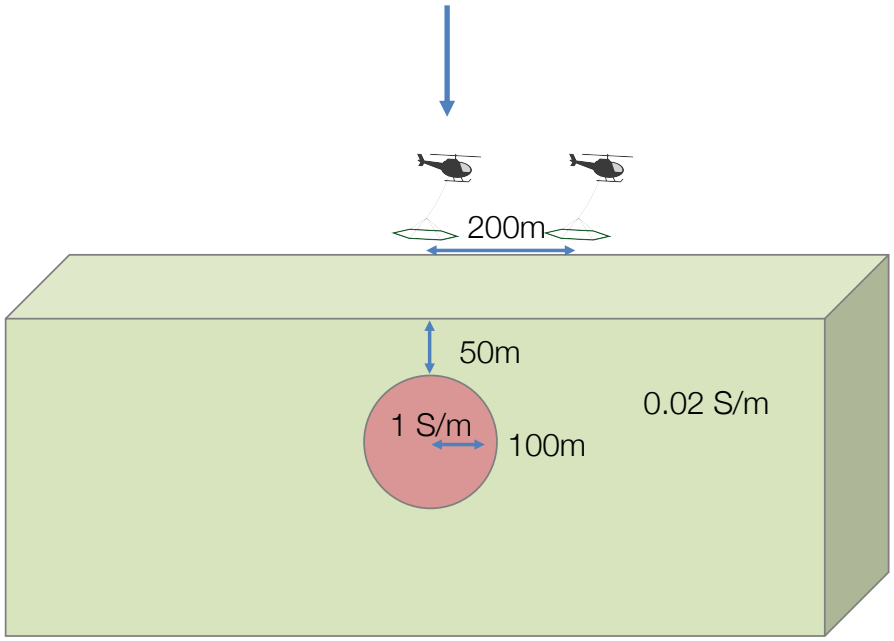
Currents and Magnetic Field (x=0m)



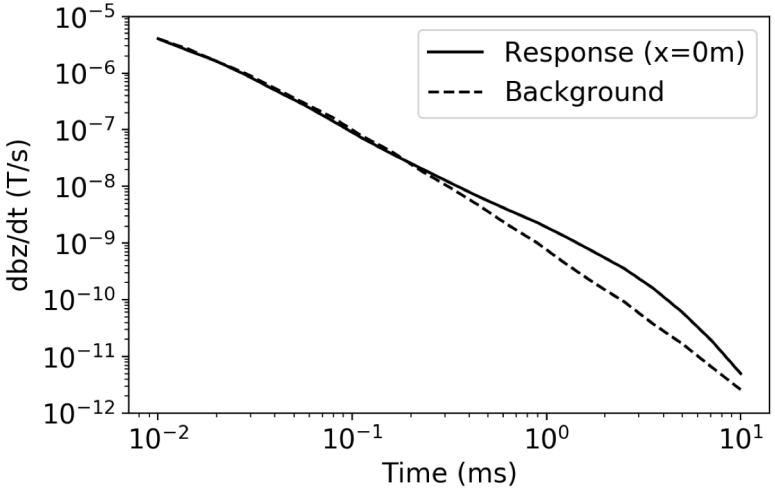
Currents and Magnetic Field (x=200m)



Soundings



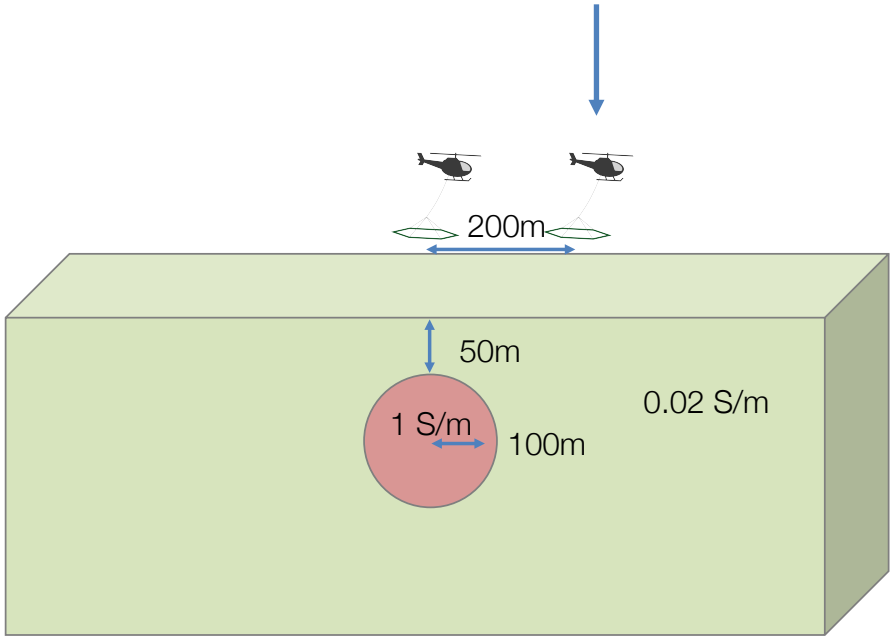
x=0m



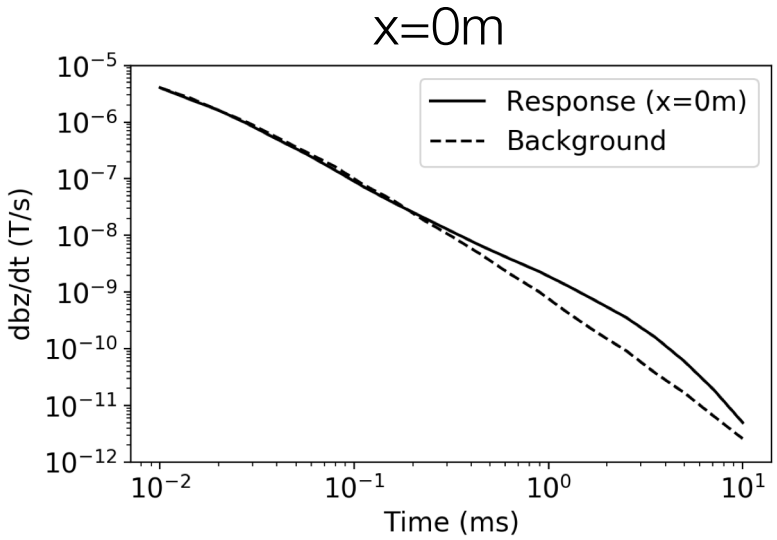
x=200m

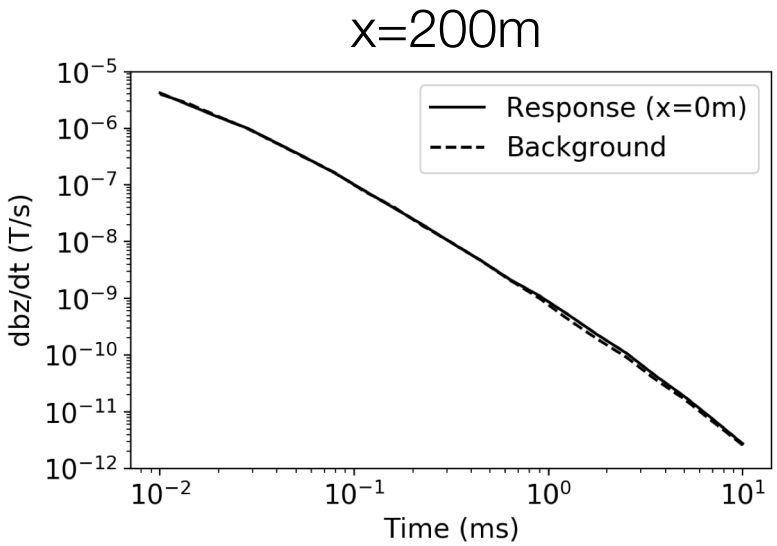
Responses are differ due to conductive sphere

Soundings

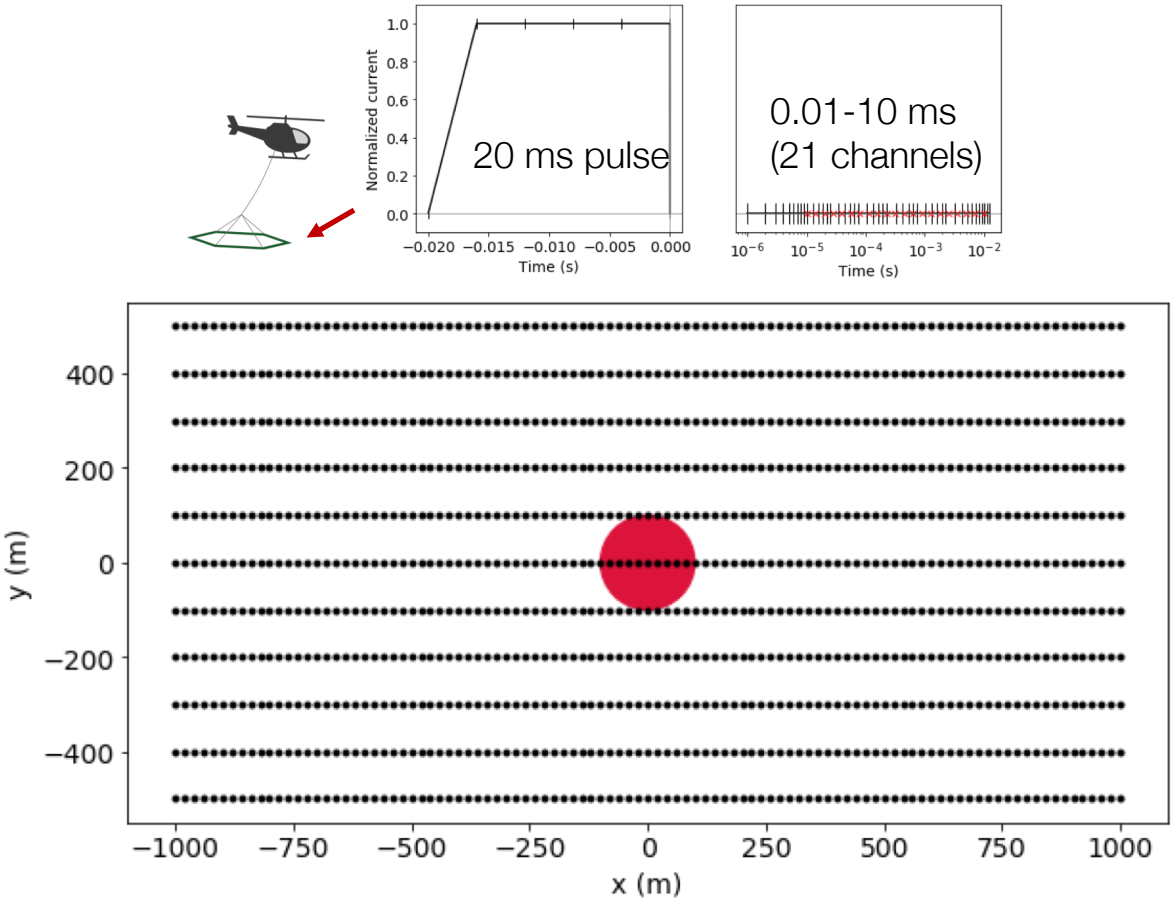


Responses are differ due to conductive sphere





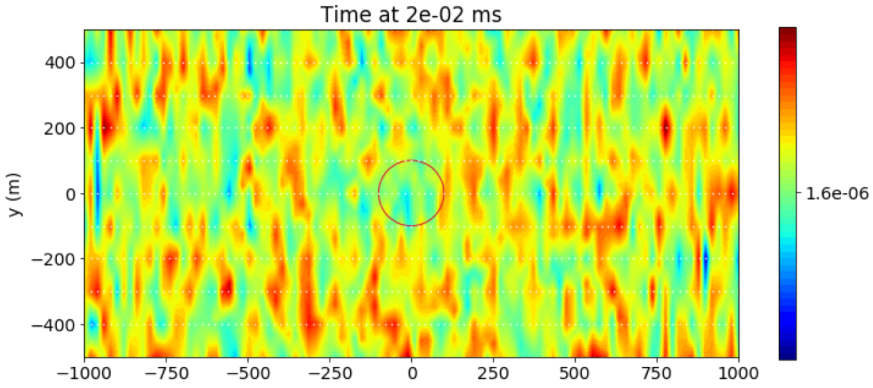
AEM survey over a sphere

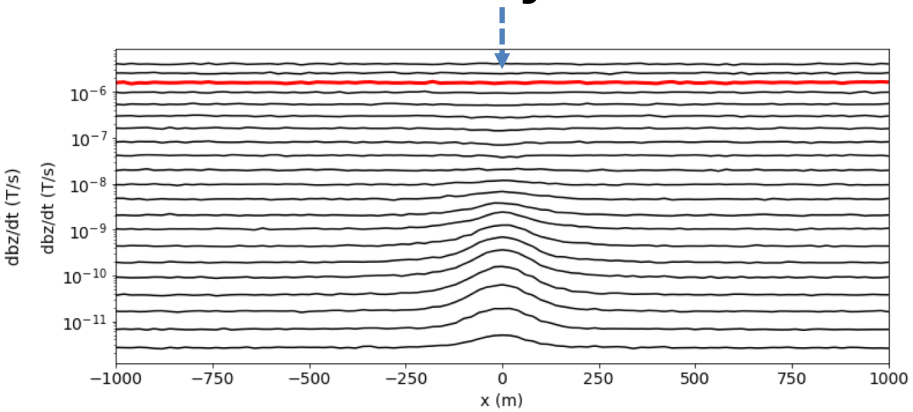


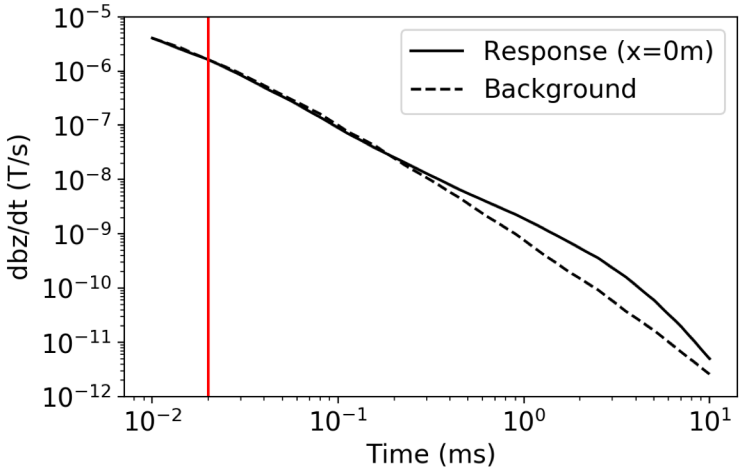
- Loop source
  - 13m radius
  - 30 m height
- Survey geometry
  - 11 lines
  - 100 line spacing
  - # of sounding: 1111
- Data
  - dbz/dt
  - 2% noise

UBC-TDOctree code

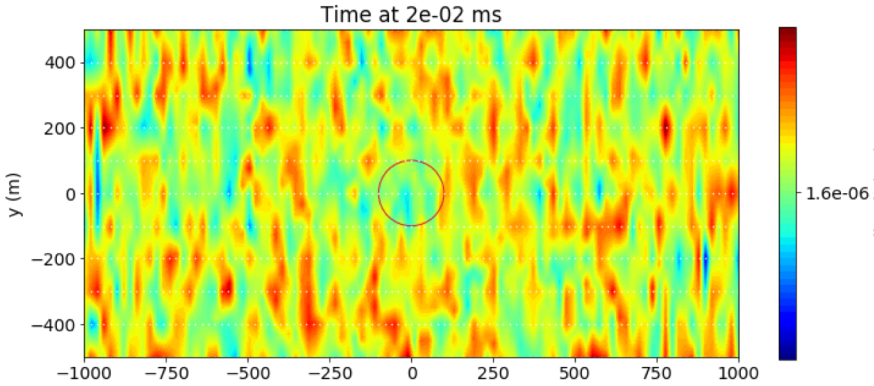
Data map, profile, and decay

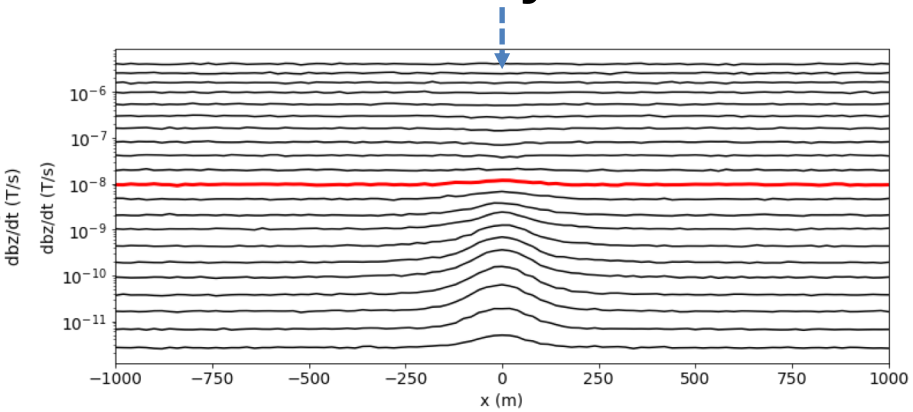


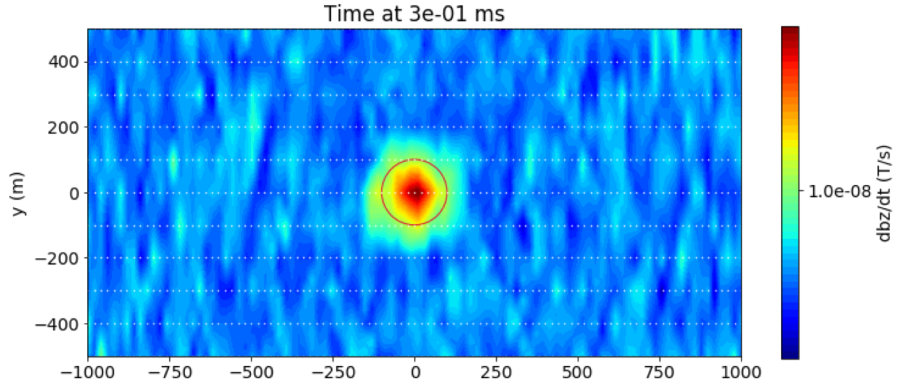


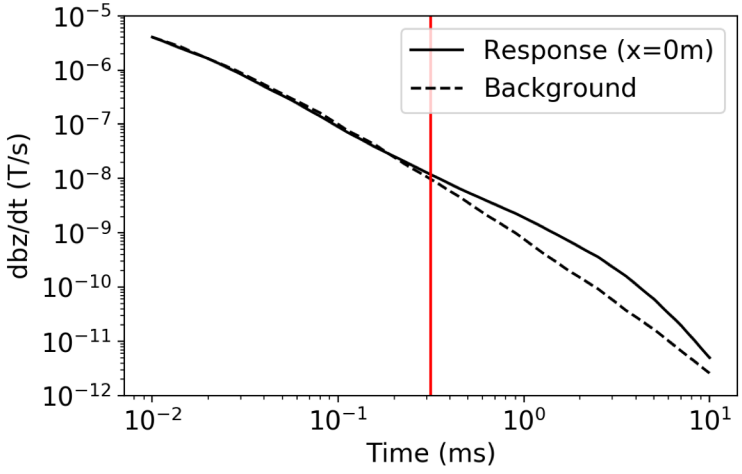


Data map, profile, and decay

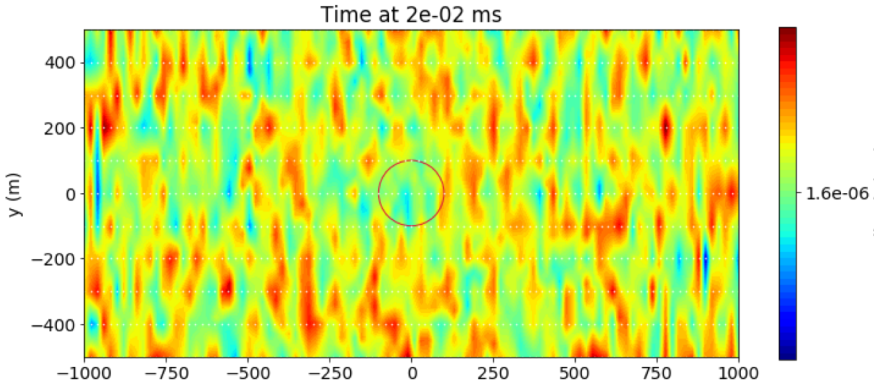


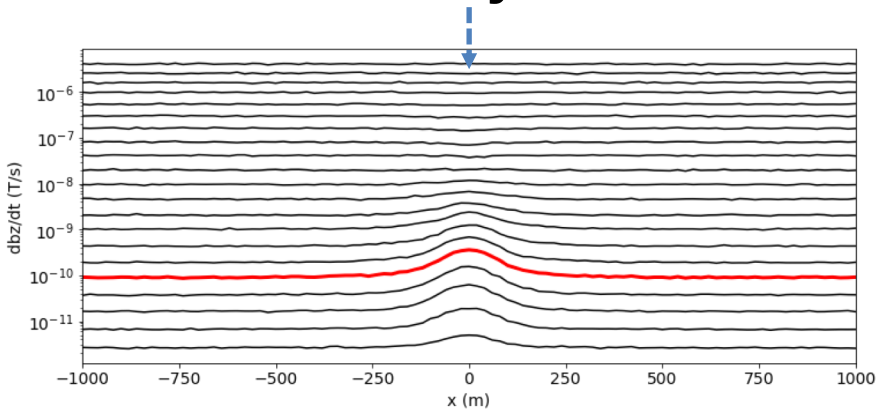


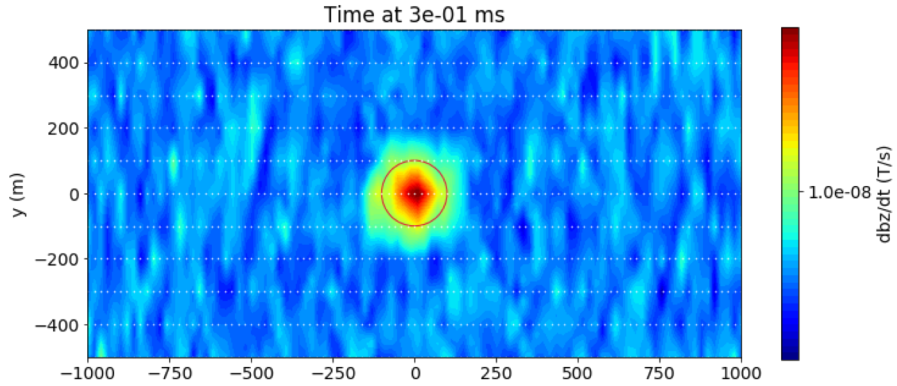


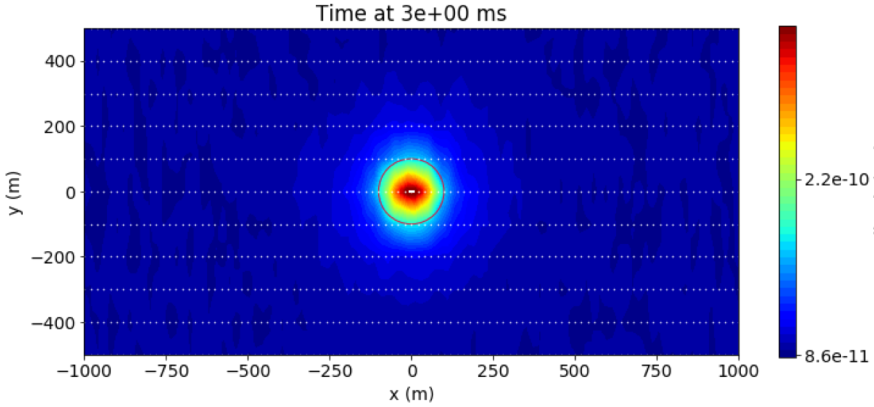


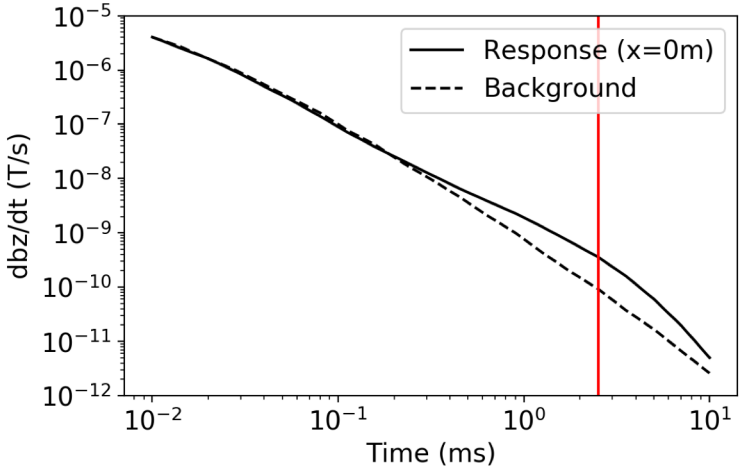
Data map, profile, and decay



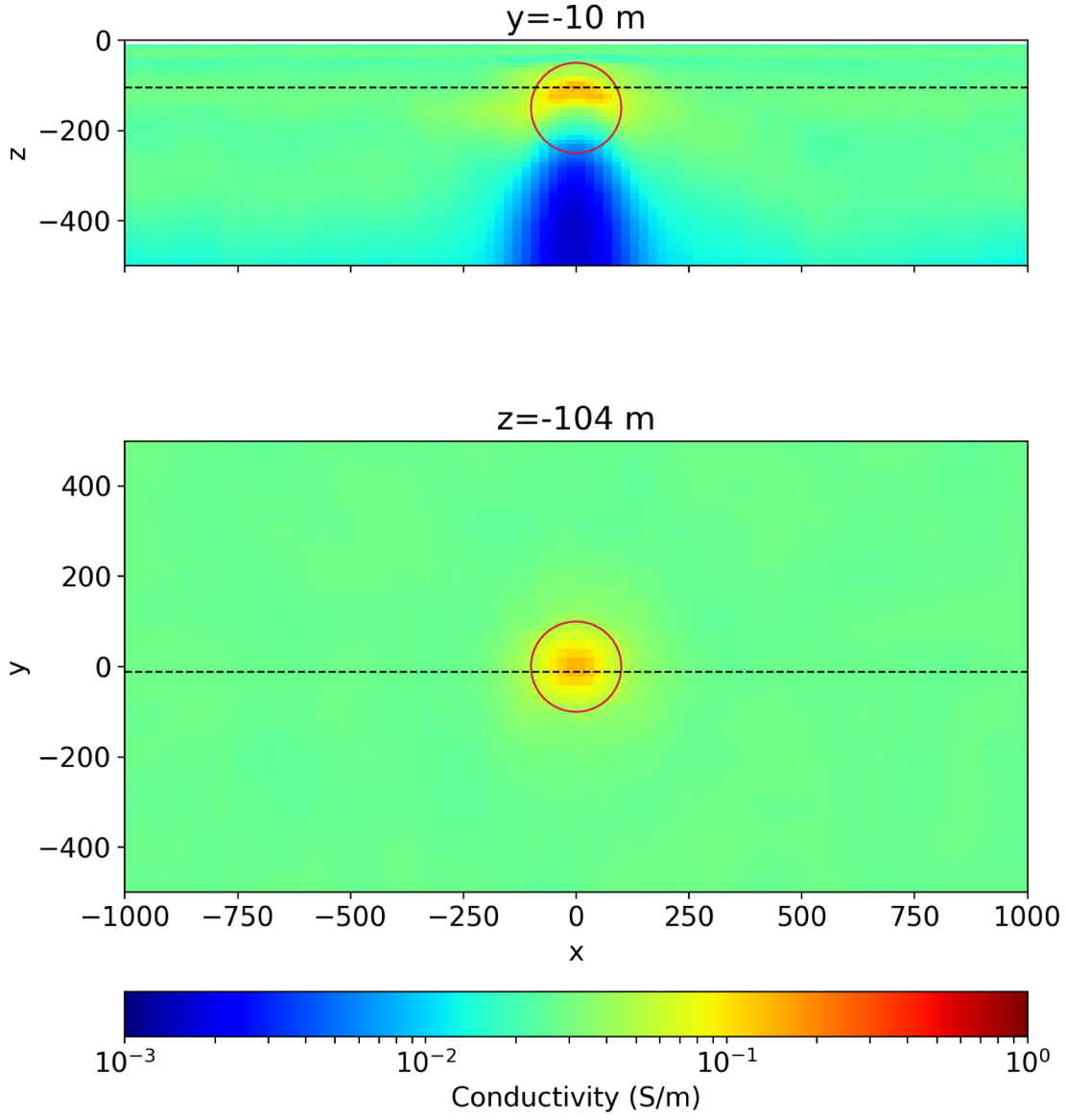








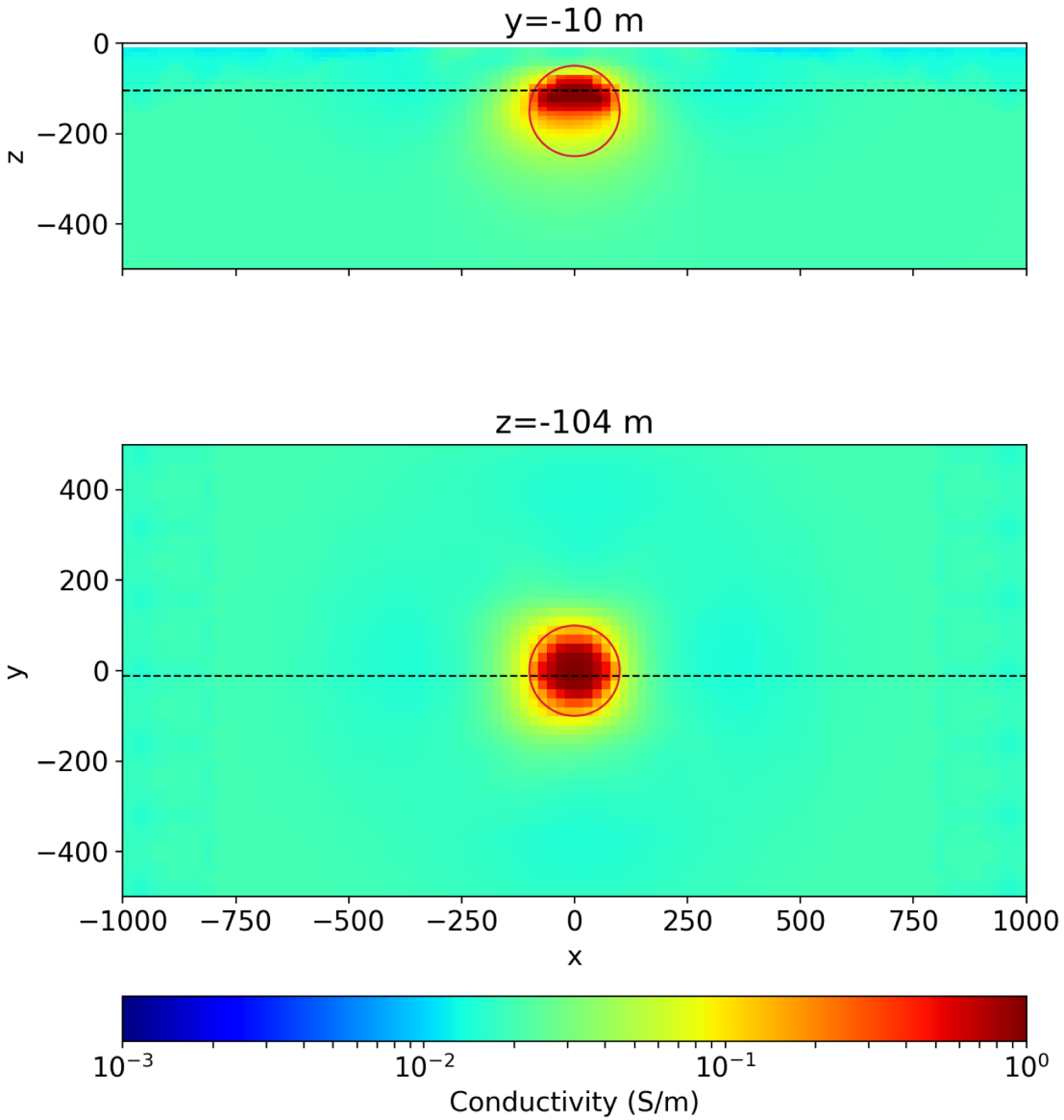
1D inversion



- Start: 0.02 S/m
- Reach target misfit (rms=1)
- Conductor at correct depth
- Underestimate conductivity value (max = 0.15 S/m)
- Resistive artifact below

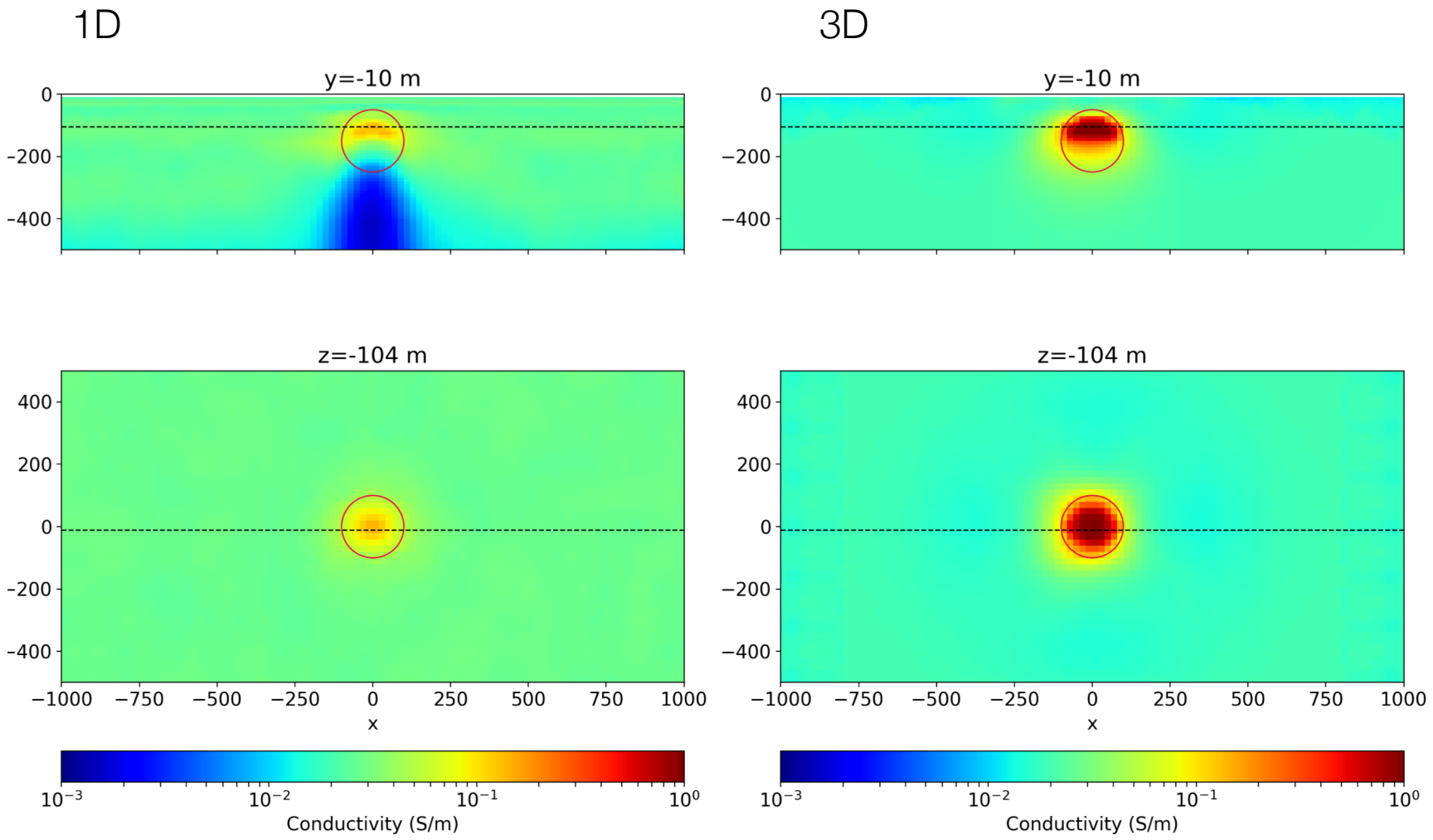
Can 3D make it better?

3D inversion

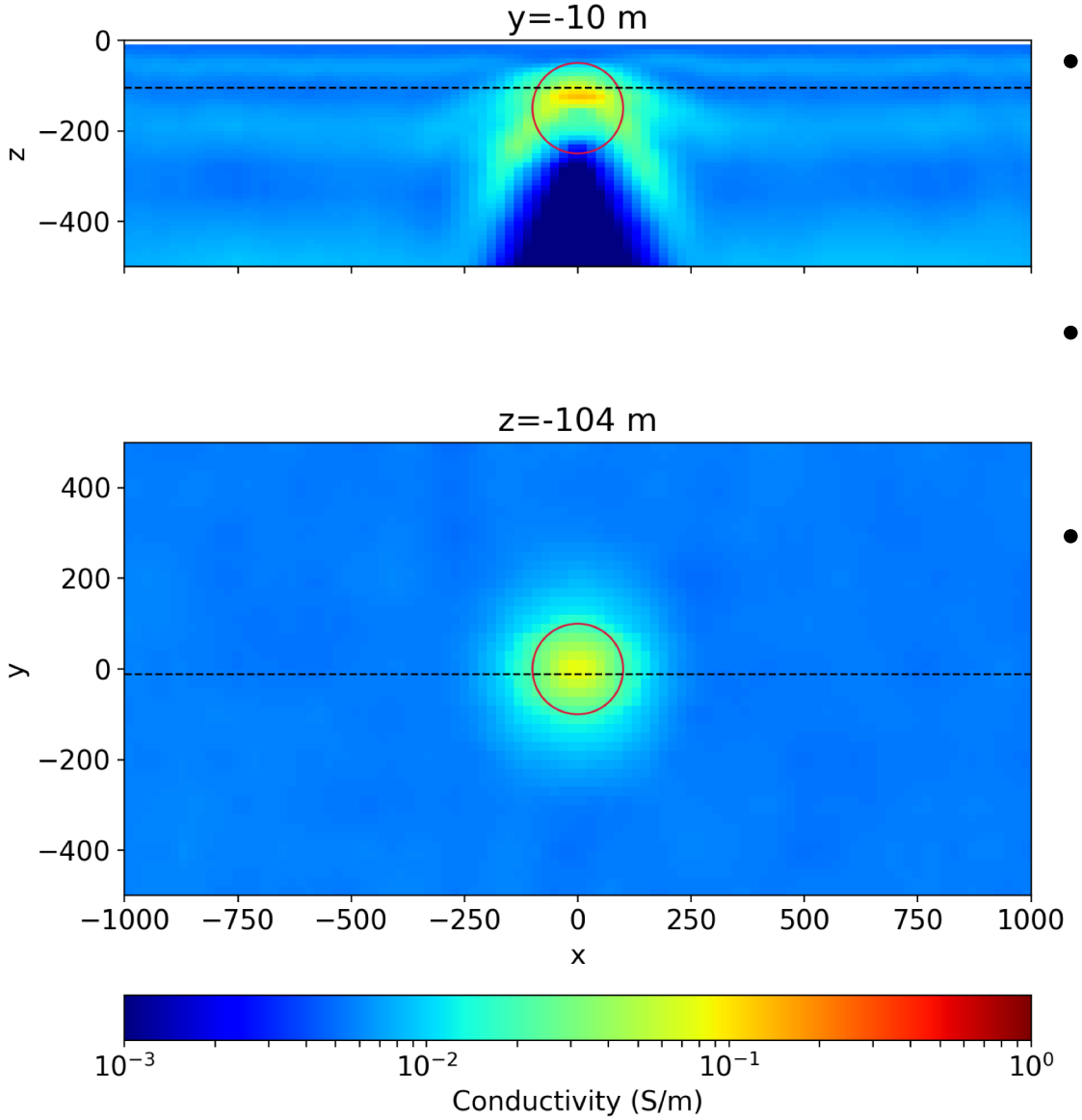


- Use 1D conductivity as an initial model
- Closer to the true conductivity (1S/m)
- No resistive artifact

Comparison 1D and 3D

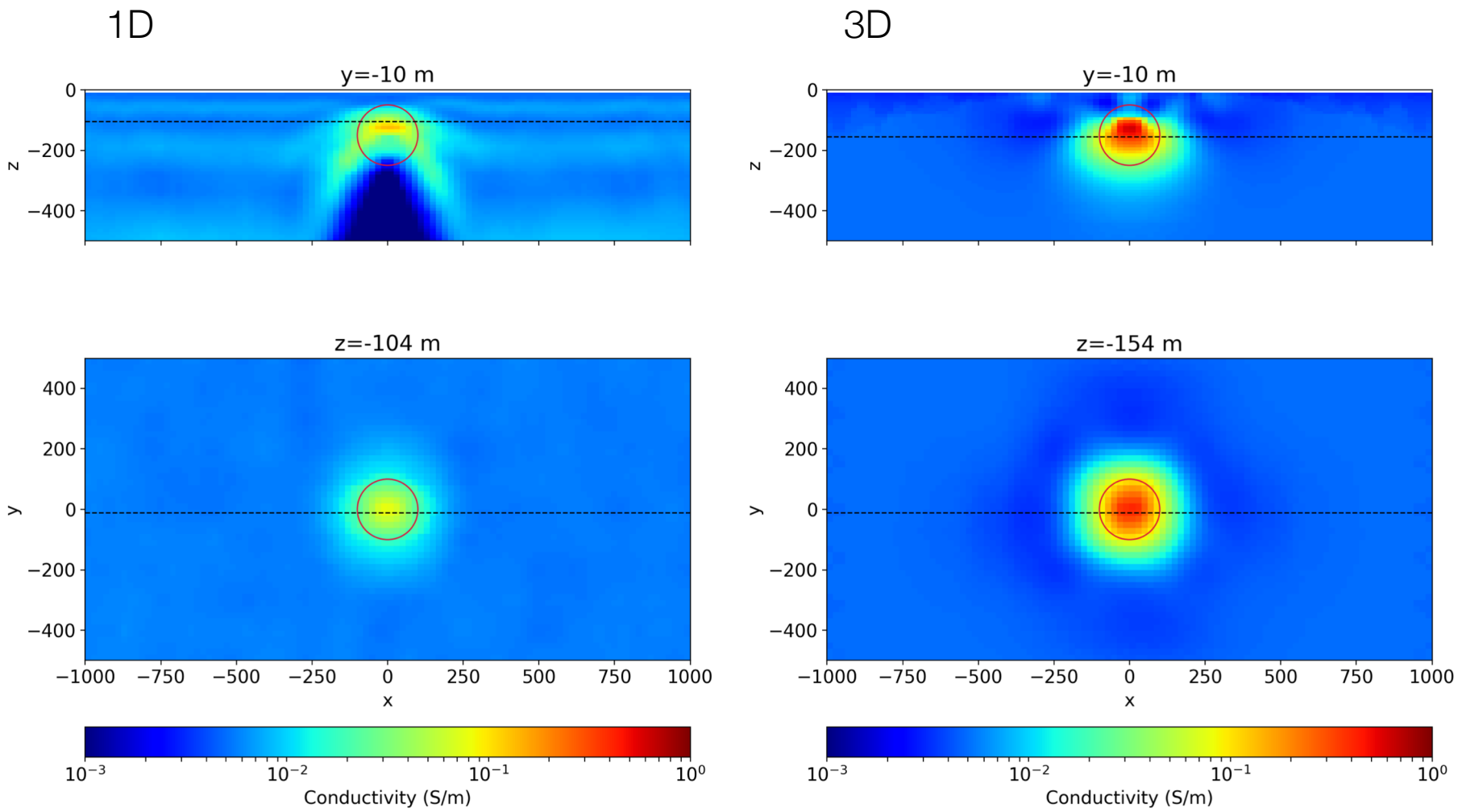


More resistive background.



- Decrease background conductivity
  - 0.02 → 0.005 S/m
- Pronounced pant-legs (larger foot-print)
- Resistive artefact beneath conductor.

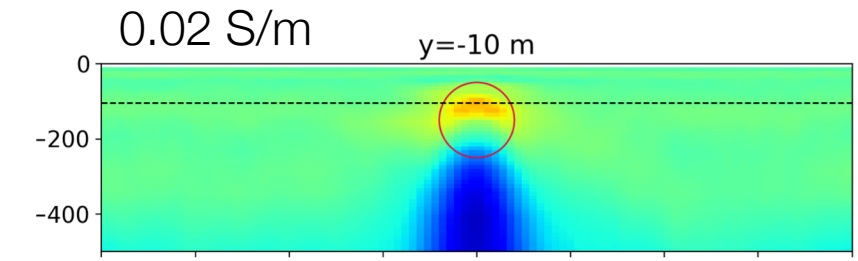
Comparison 1D and 3D

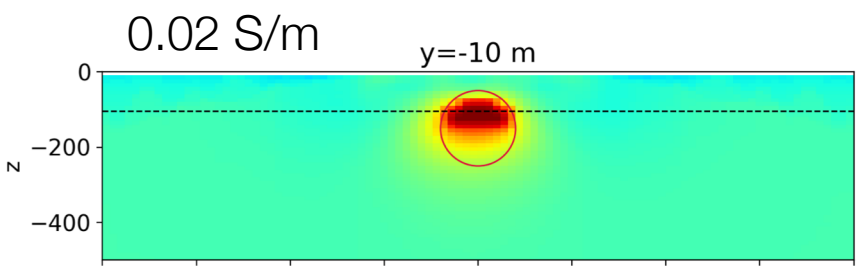


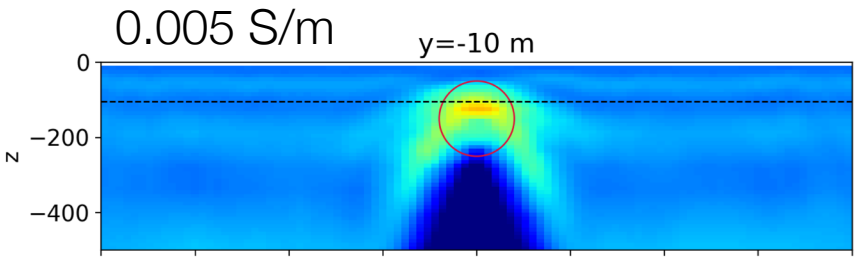
Inversion with different backgrounds

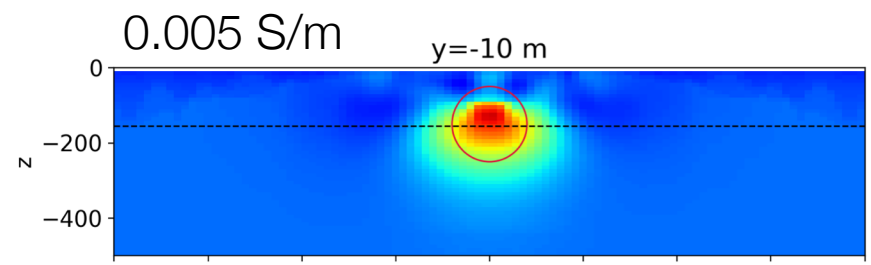
1D

3D



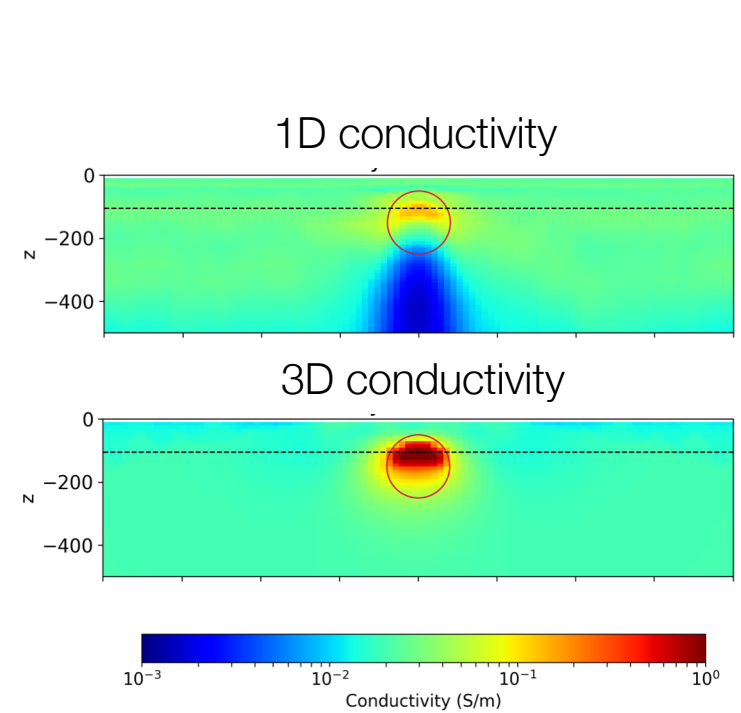






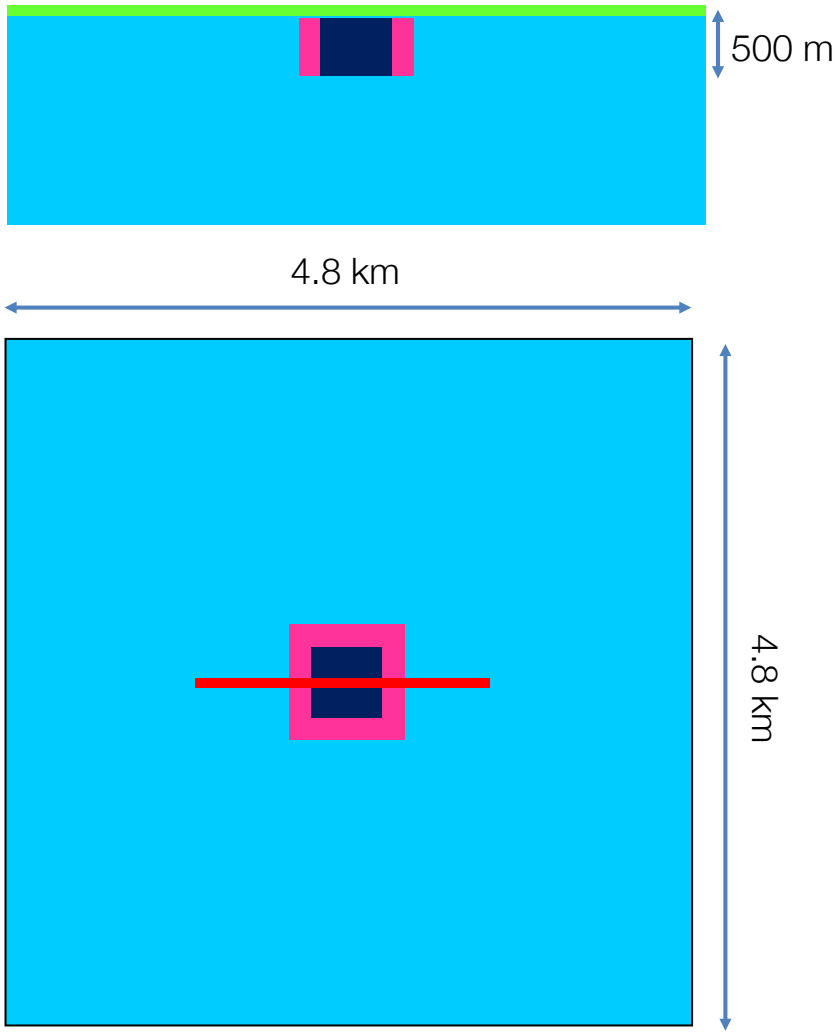
When is 3D inversion required?

- Depends upon the goal:
  - target detection?
  - detailed structure/
  - What resolution scale is needed?



- Some other generic cases:
  - compact resistor
  - topography
  - general 3D structure with different scale lengths

Compact resistor in porphyry deposit



Resistive stock surrounded by conductive alteration halo

overburden 100 Ωm
thickness 60m

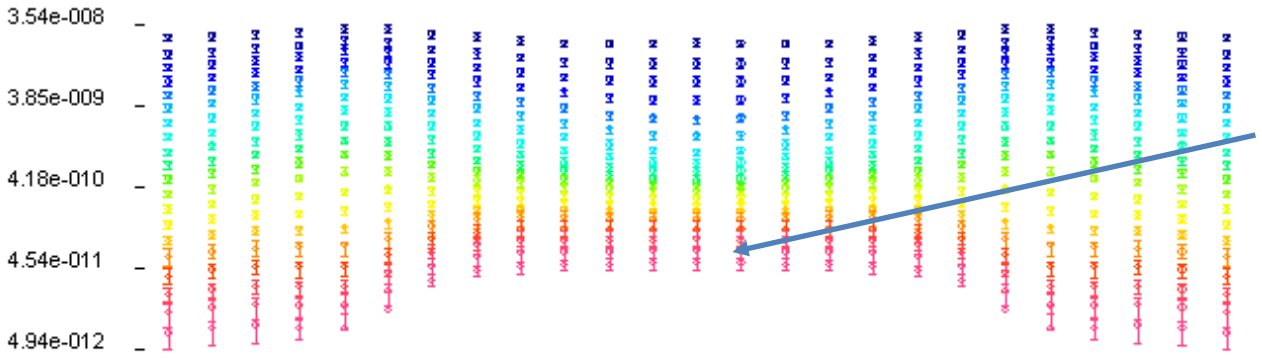
resistive stock 2000 Ωm
depth 60m ~ 400m
width 600m

conductive alteration 10 Ωm
thickness 150m

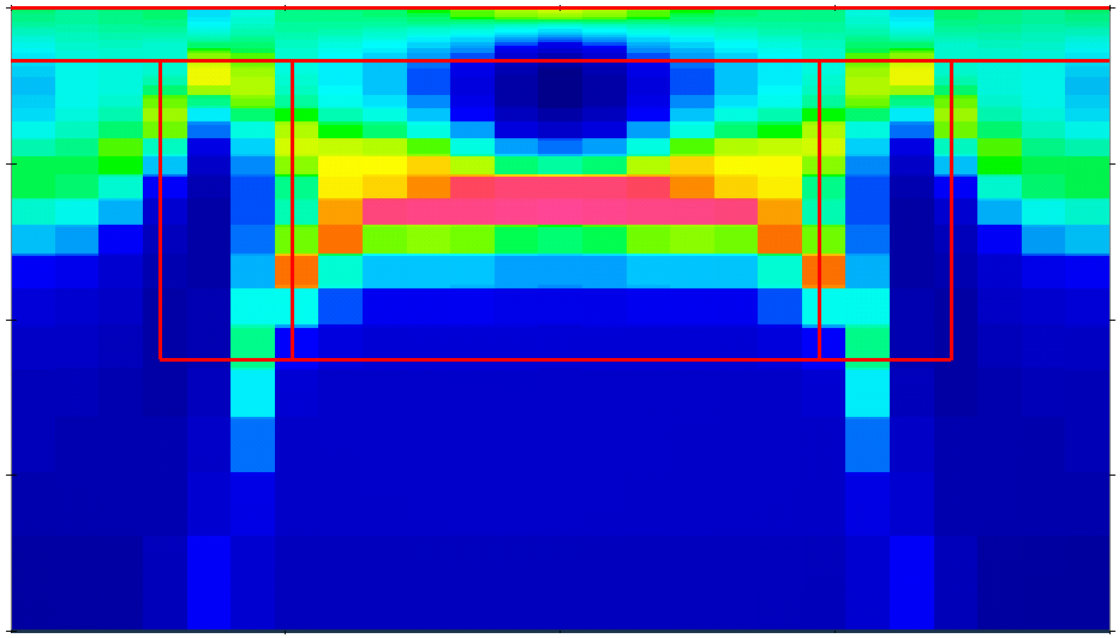
host rock 500 Ωm

VTEM sounding
flight height 50m

1D Inversion of 3D Synthetic Data

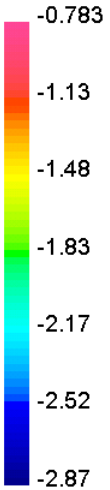


high late-time data over the stock



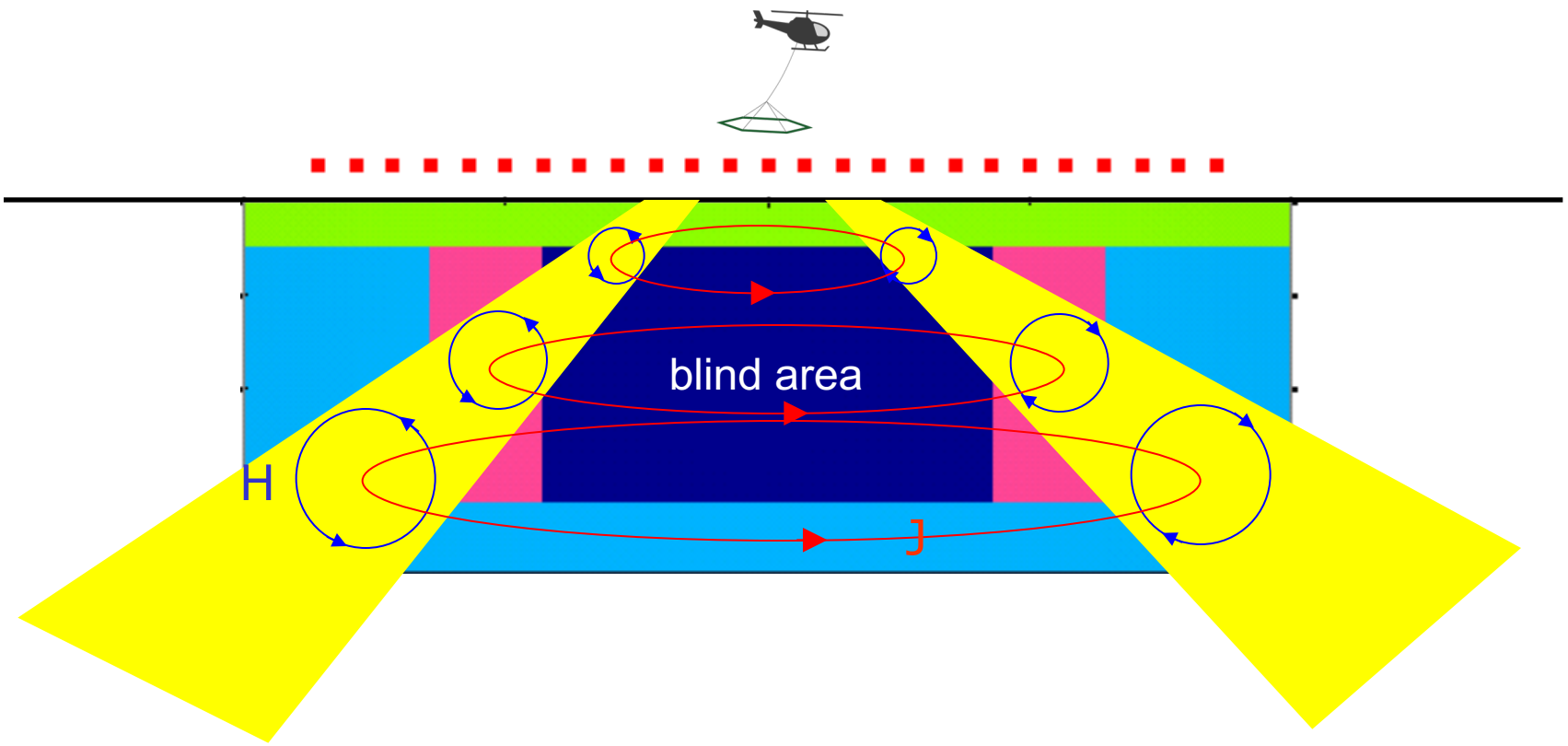
800 m

1.2 km



Log 10 conductivity

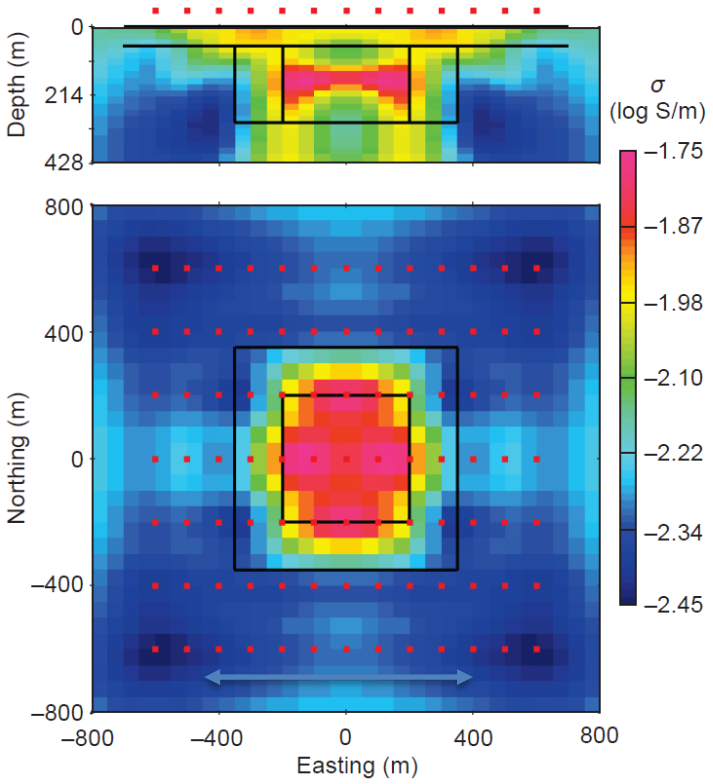
What is wrong with 1D inversion?



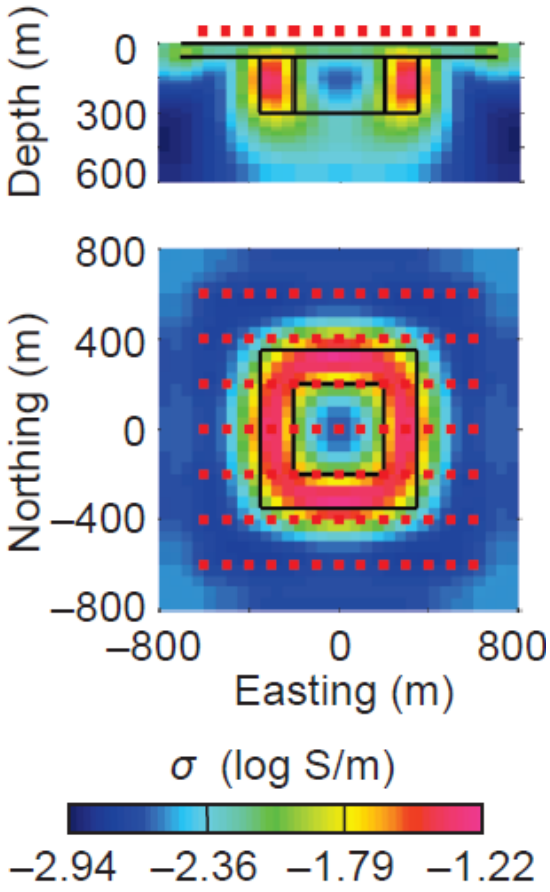
Footprint sensitive to conducting halo around the stock

1D VS 3D: Mt. Milligan Synthetic Model

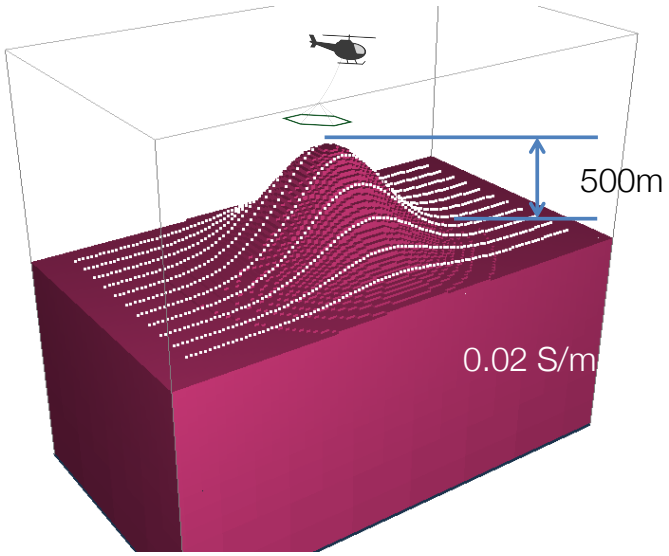
1D Inversion Model



3D Inversion Model

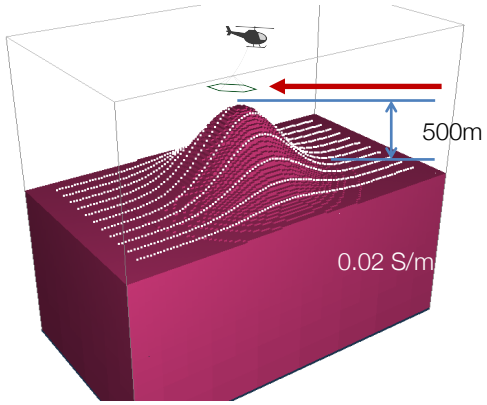


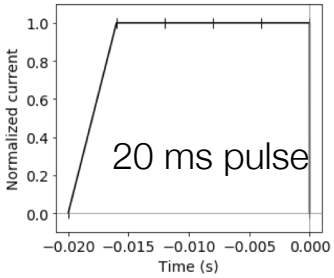
Topography

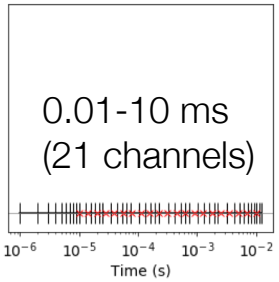


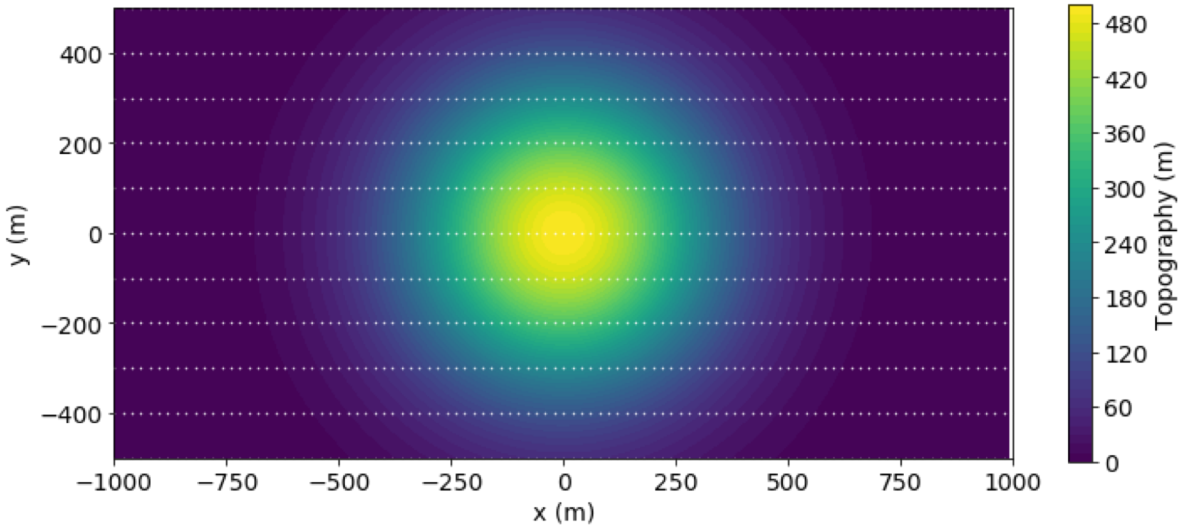
- Explore fields
- Generate synthetic data (3D simulation)
- Invert in 1D (artefacts?)
- Invert in 3D

AEM surveys over topography





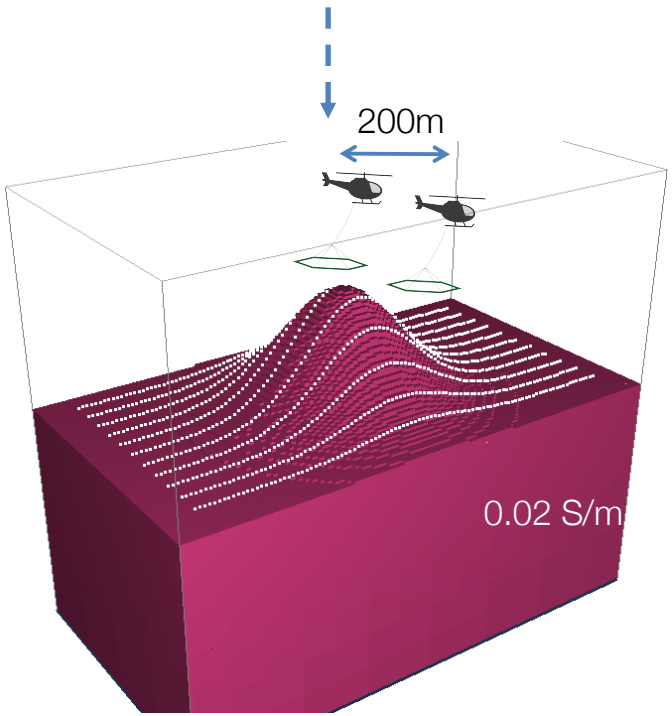


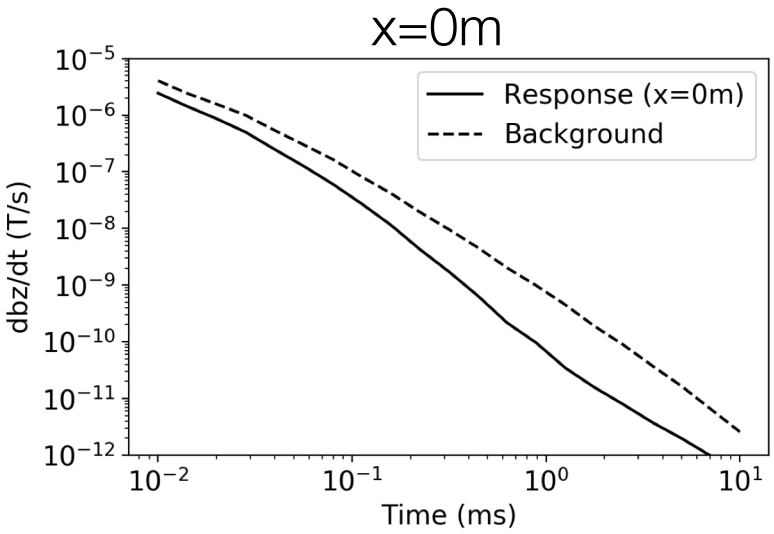


- Loop source
  - 13m radius
  - 30 m height
- Survey geometry
  - 11 lines
  - 100 line spacing
  - # of sounding: 1111
- Data
  - dbz/dt
  - 2% noise

UBC-TDOctree code

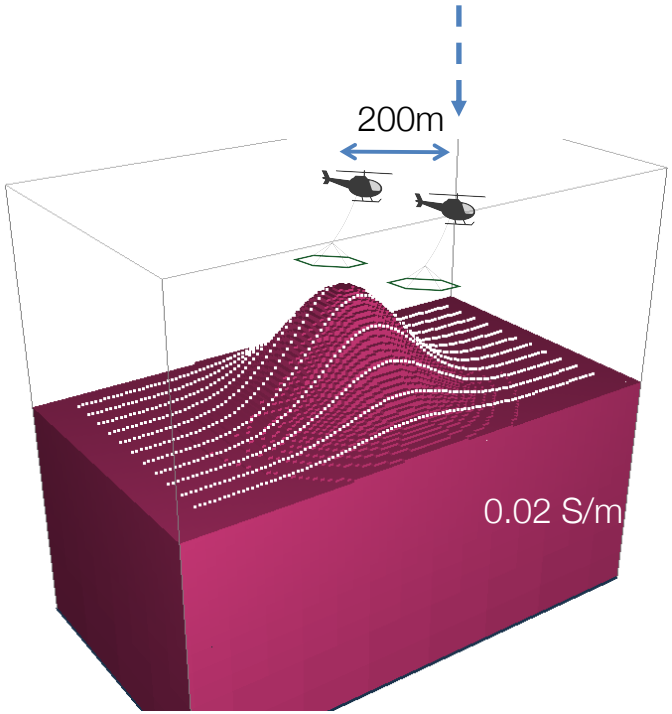
Soundings



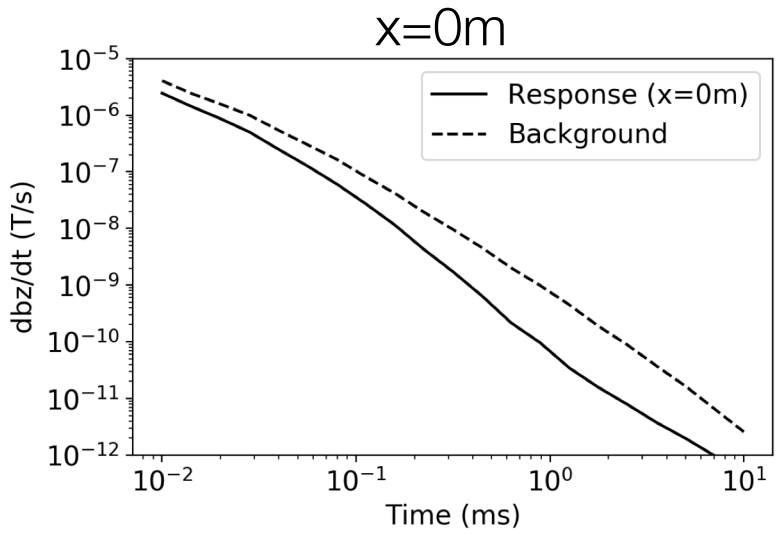


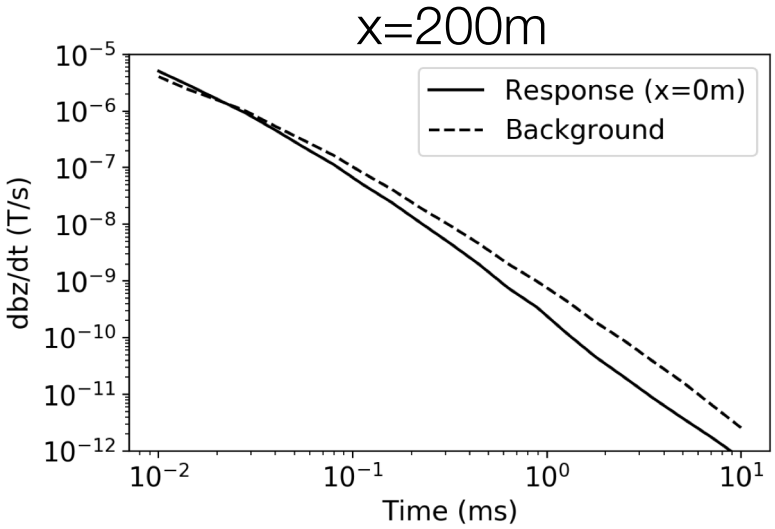
Responses are differ due to conductive sphere

Soundings

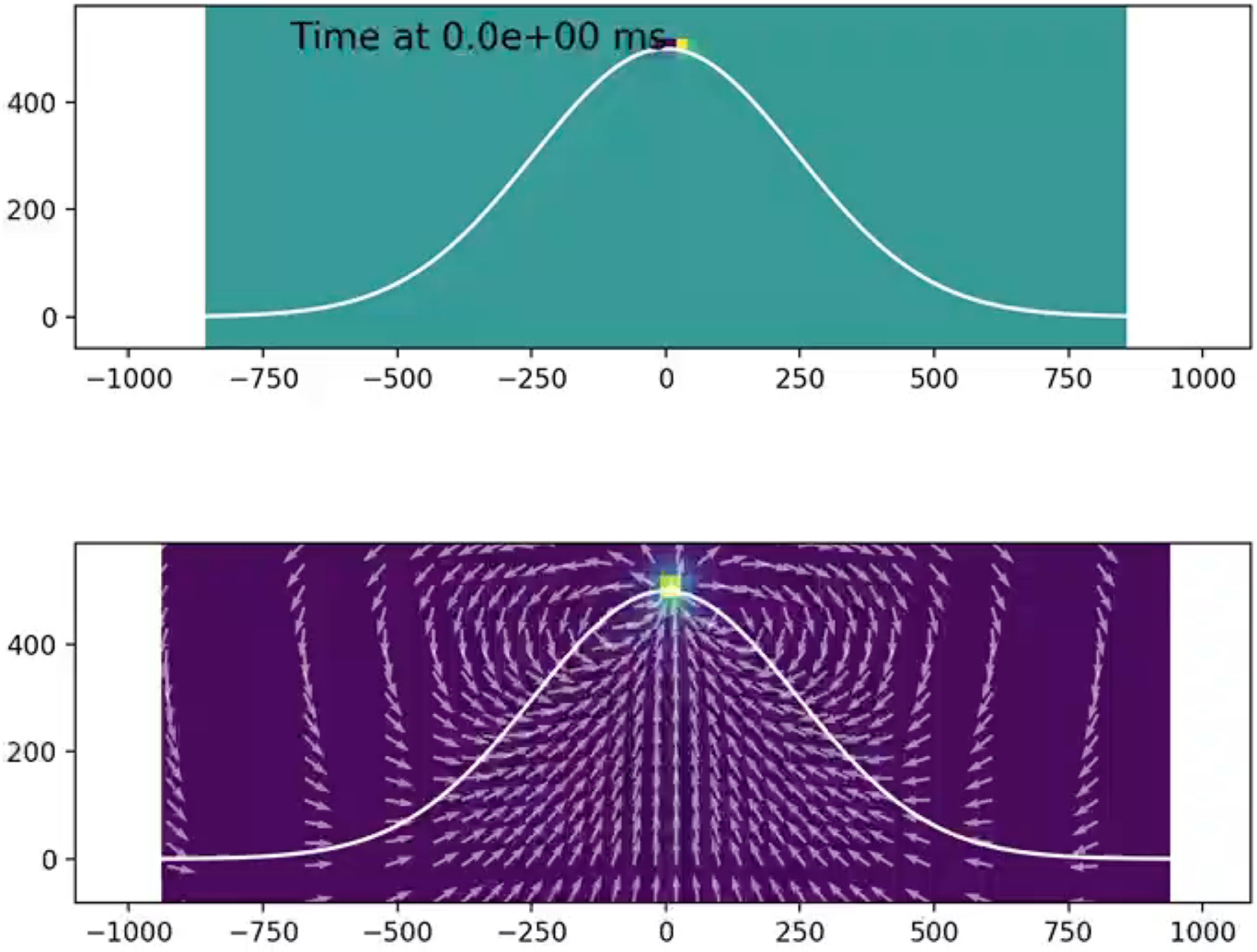


Responses are differ due to conductive sphere

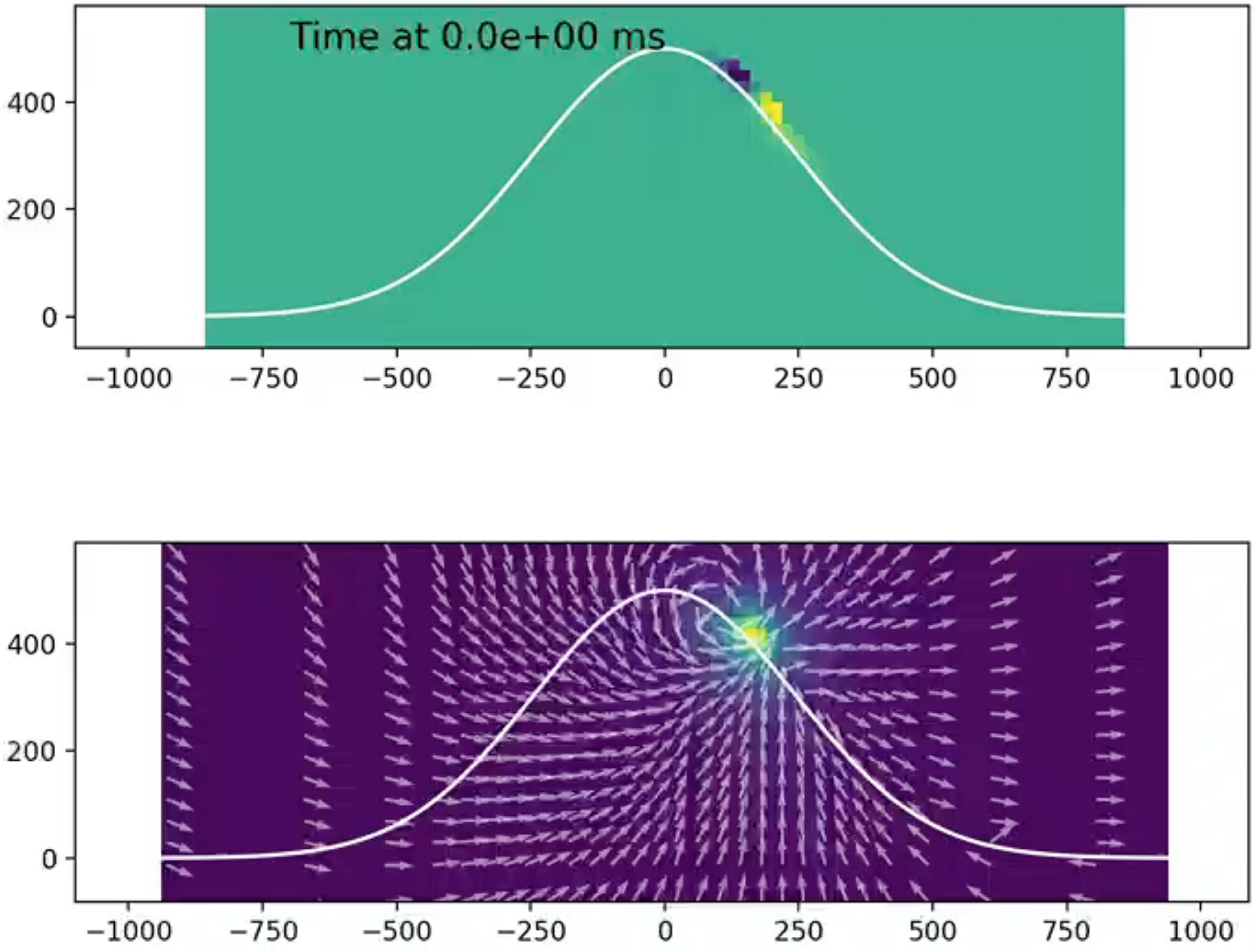




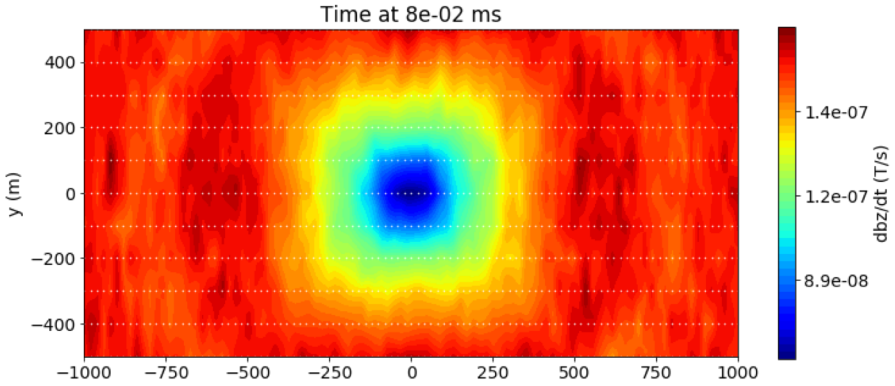
Currents and Magnetic Fields (x=0m)

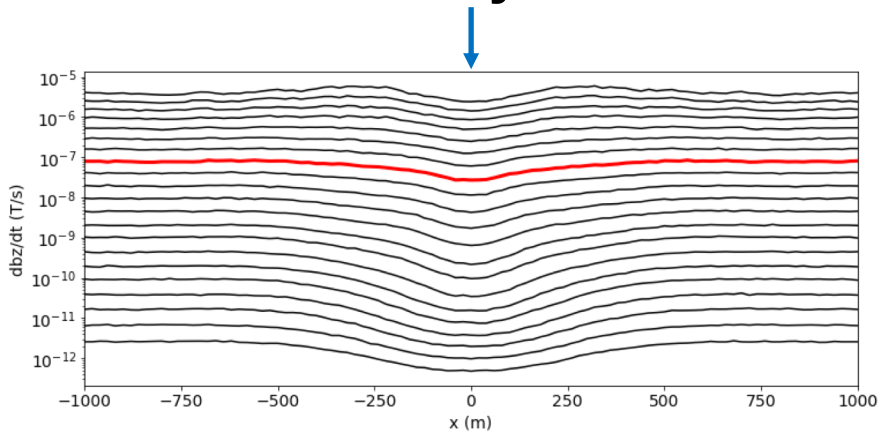


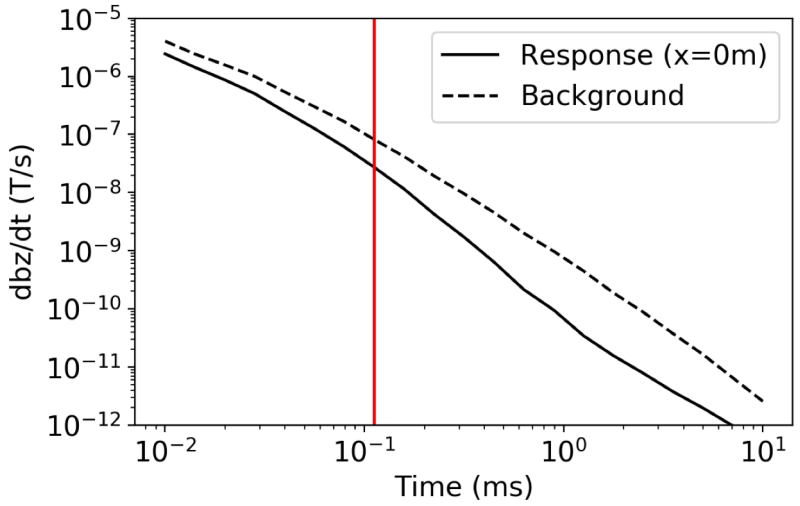
Currents and Magnetic Fields (x=200m)



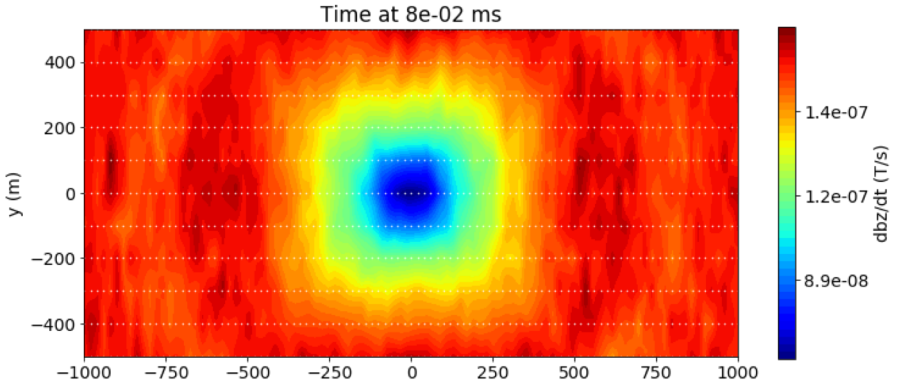
Data map, profile, and decay

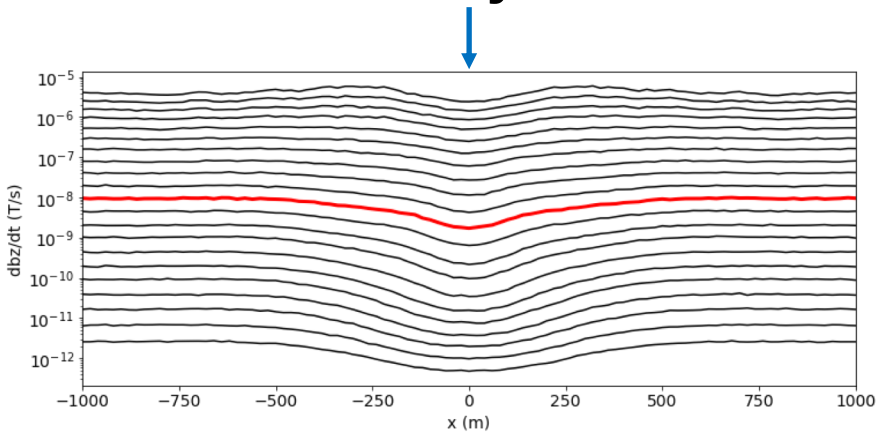


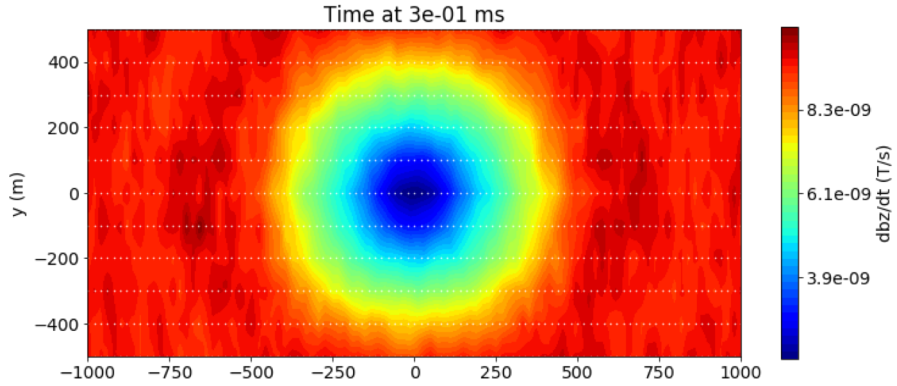


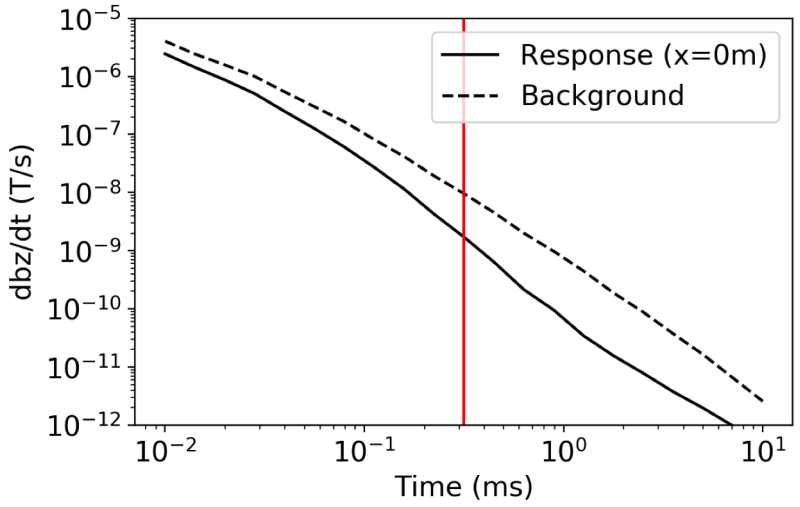


Data map, profile, and decay

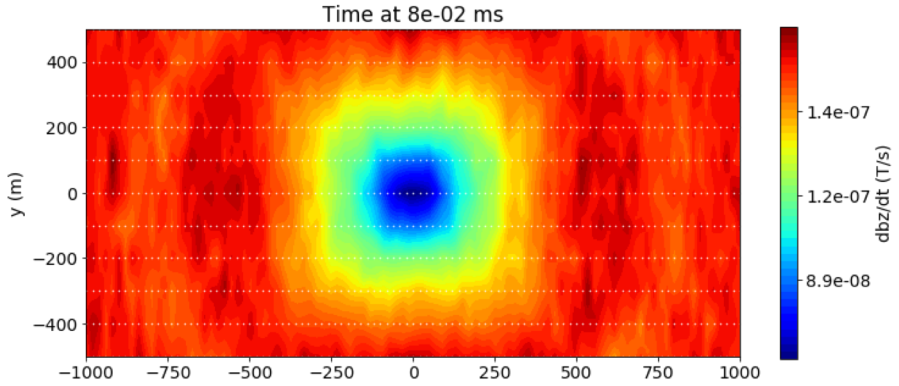


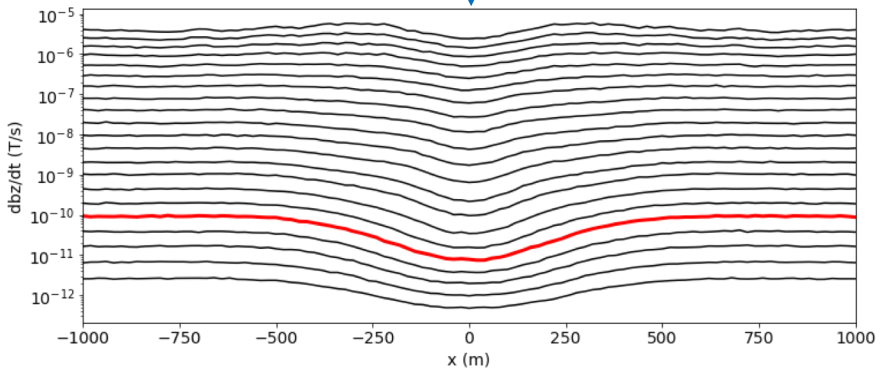


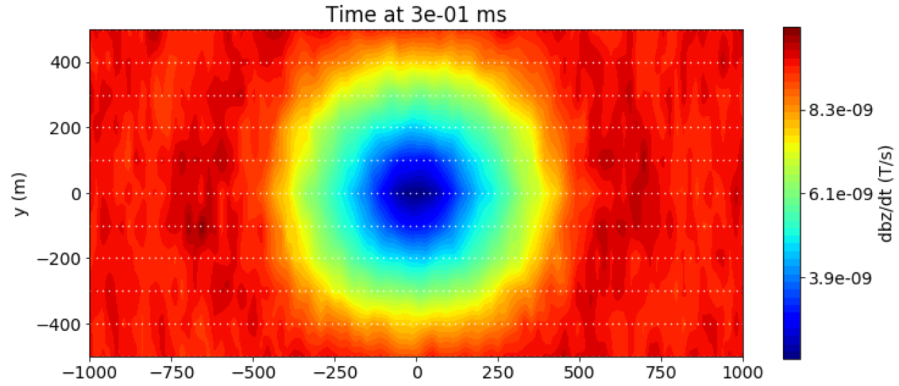


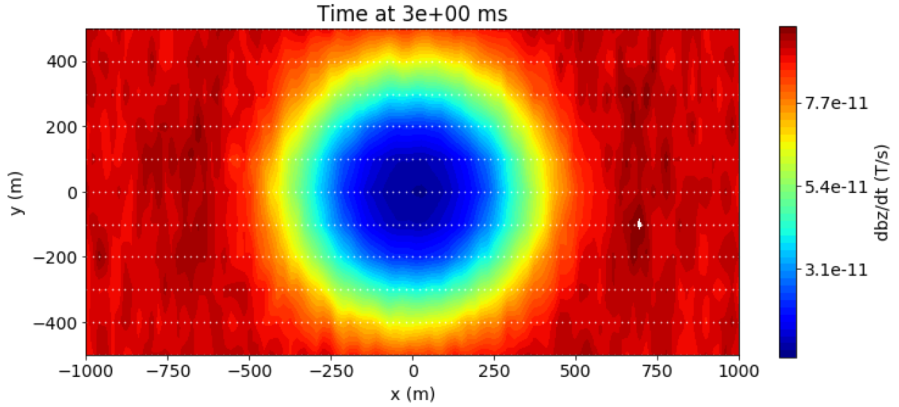


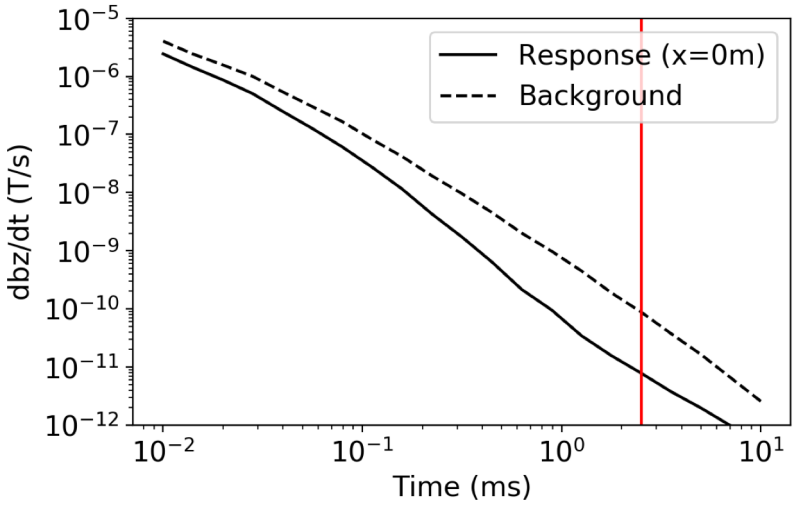
Data map, profiles, and sounding curves



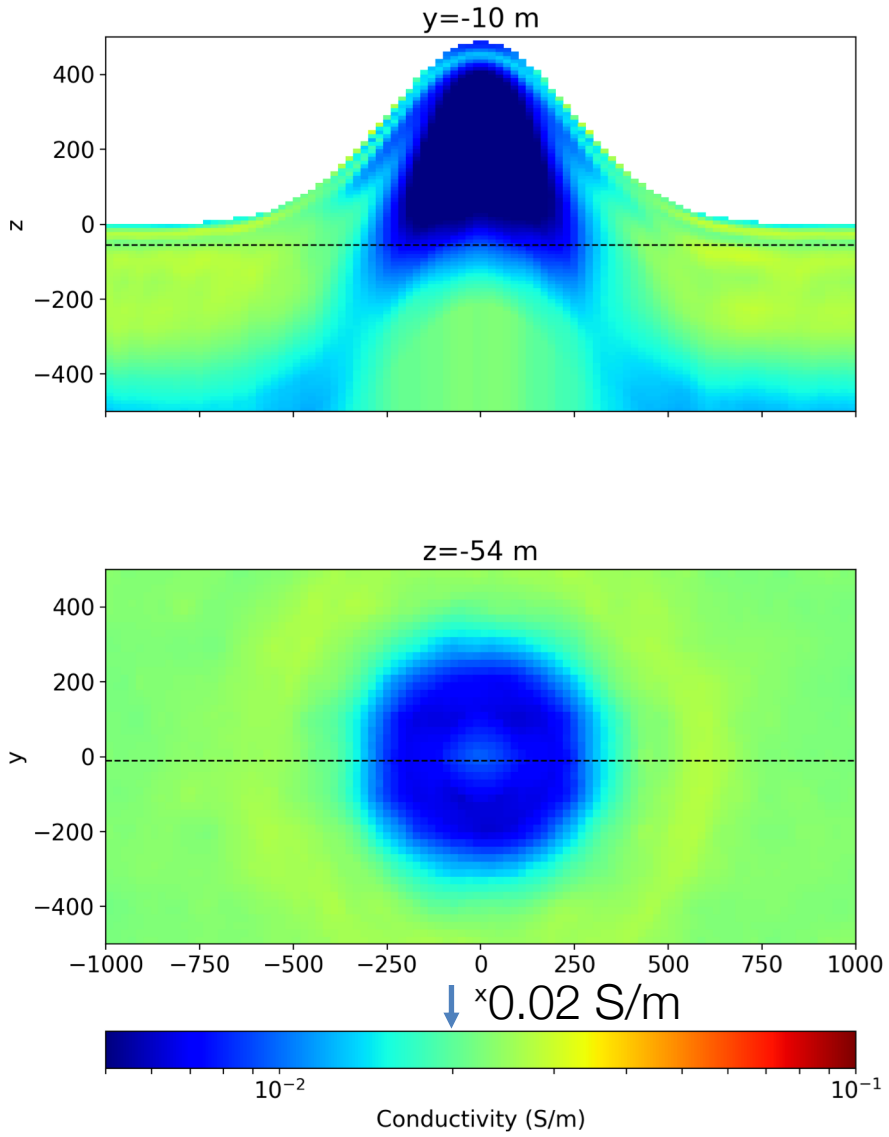








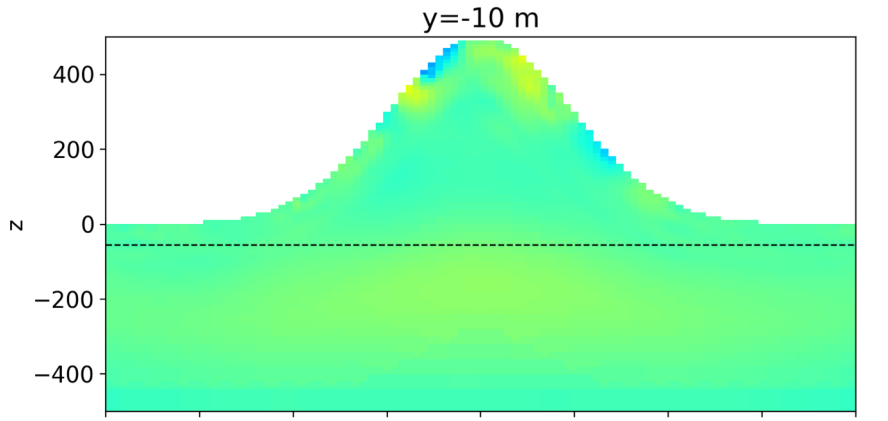
1D inversion

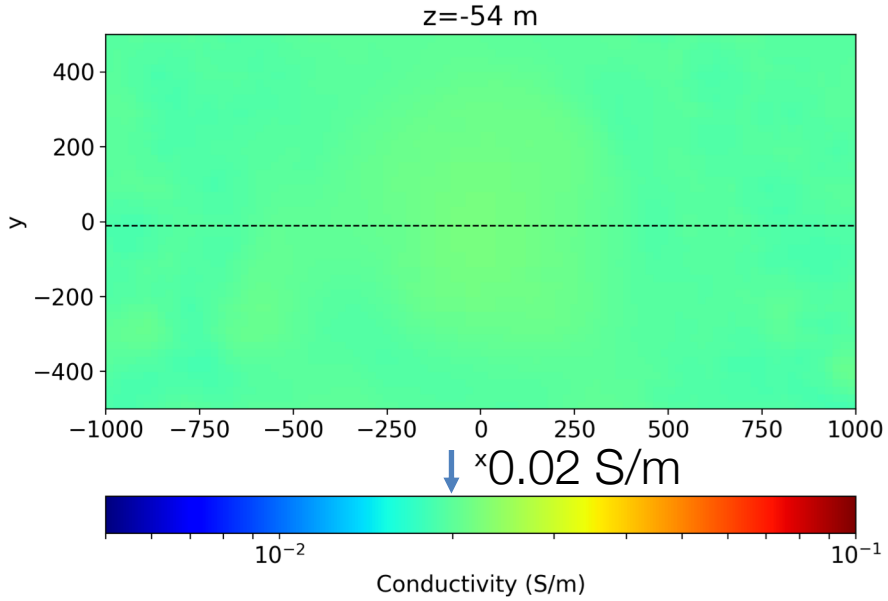


- Start from 0.02 S/m background
- Reached target misfit (rms=1)
- Large resistor below topography

Need to invert in 3D!

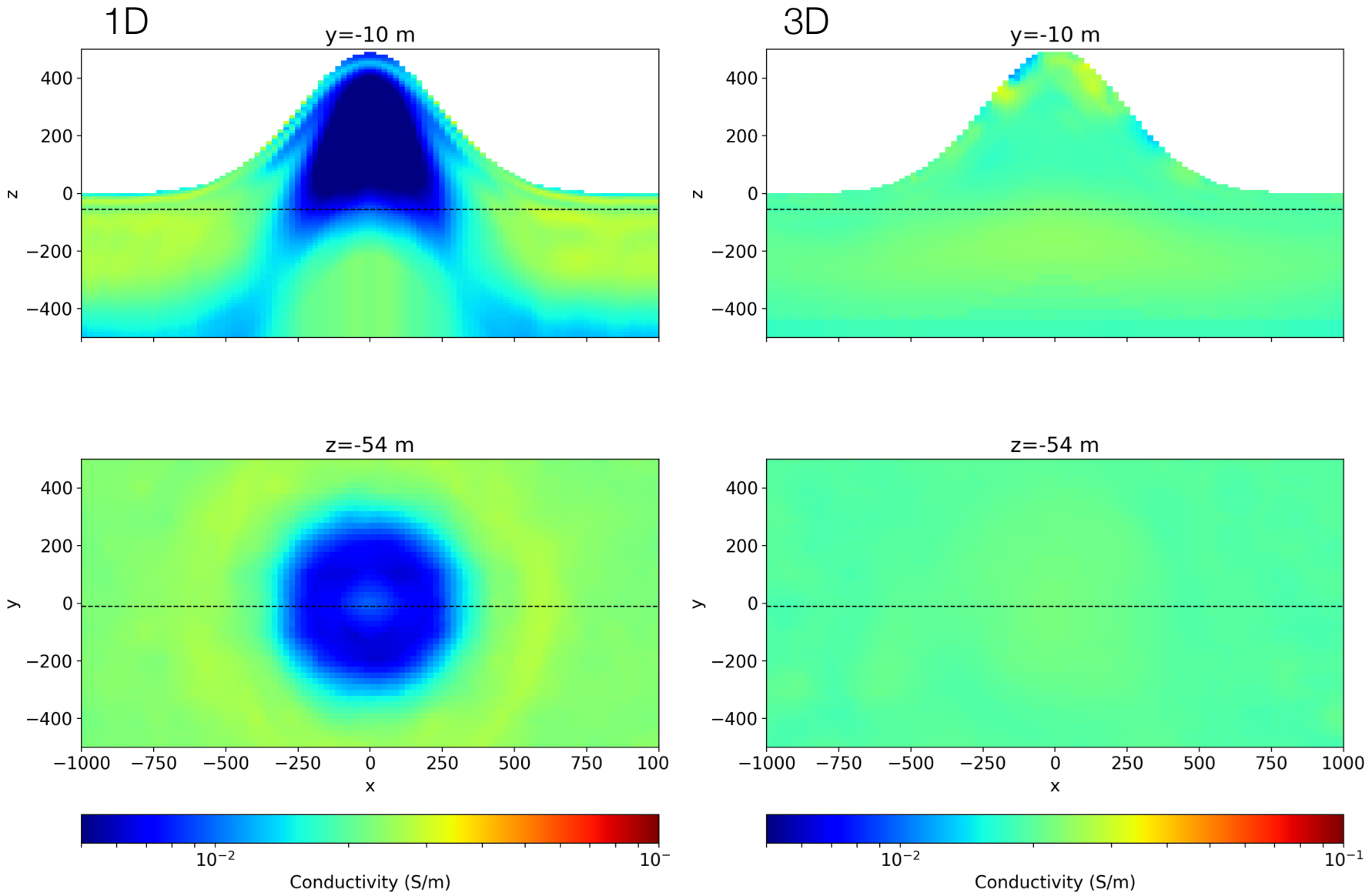
3D inversion



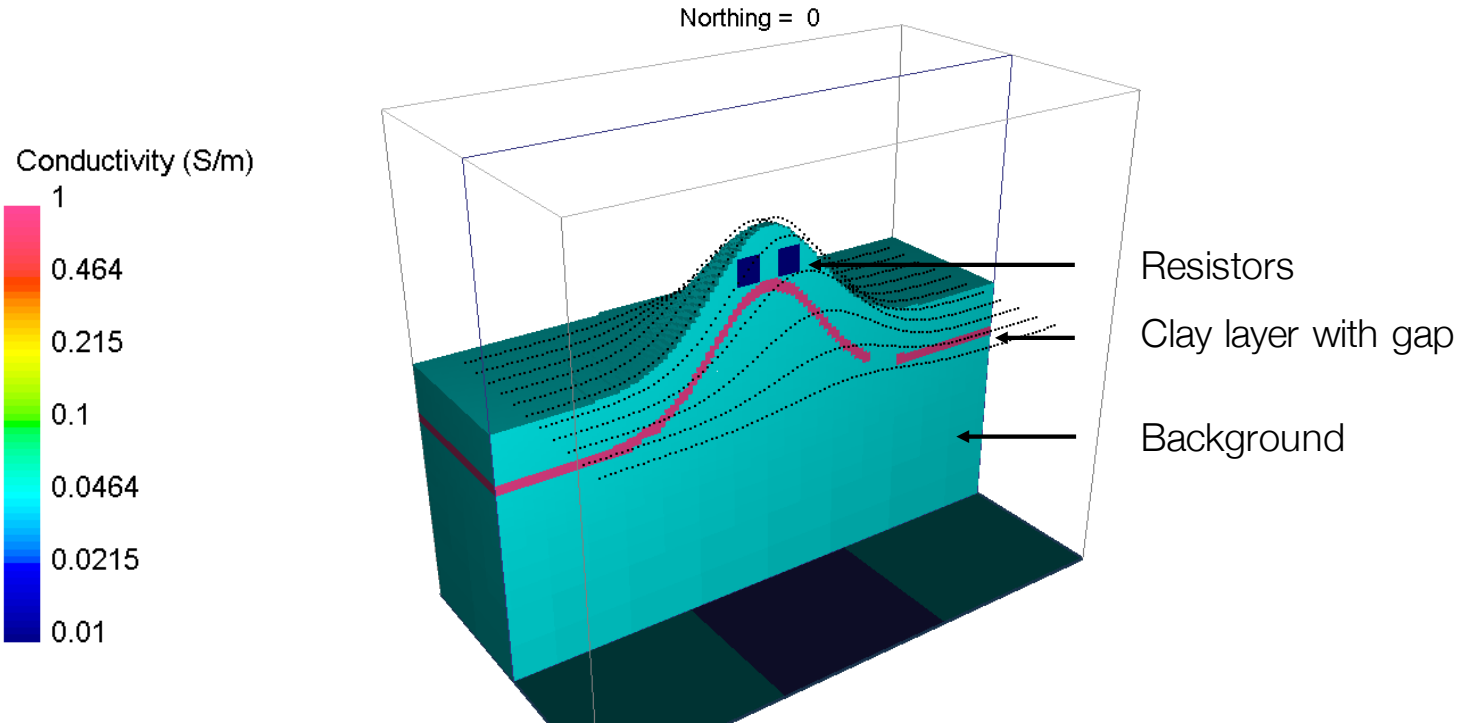


- Start from 0.01 S/m background
- Reached target misfit (rms=1)

Comparison 1D and 3D

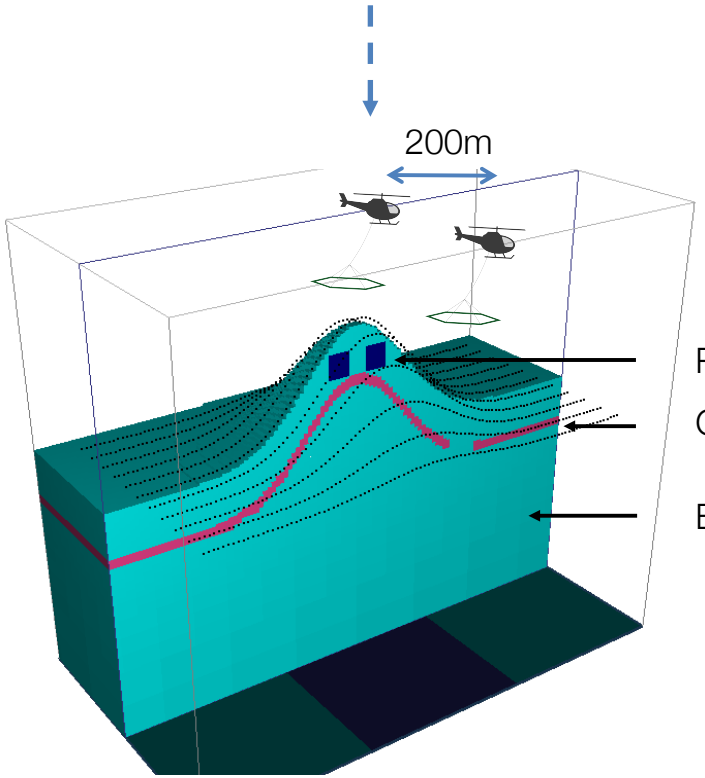


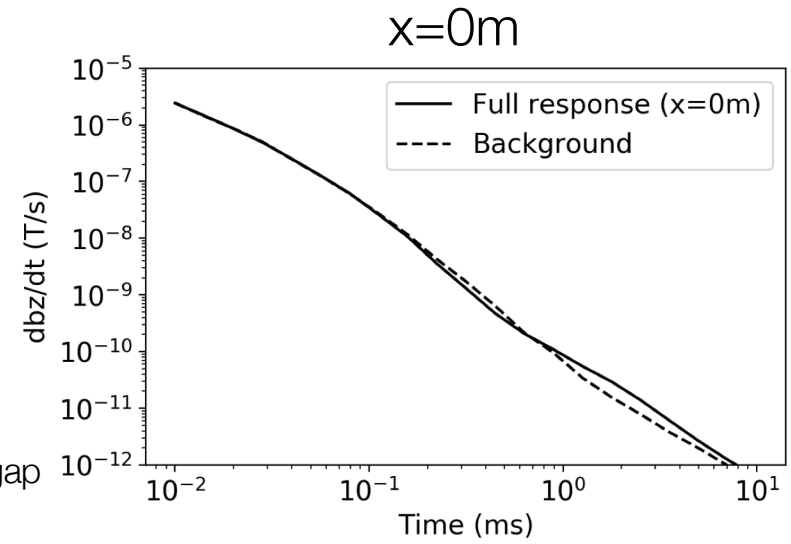
Geologic structures below topography



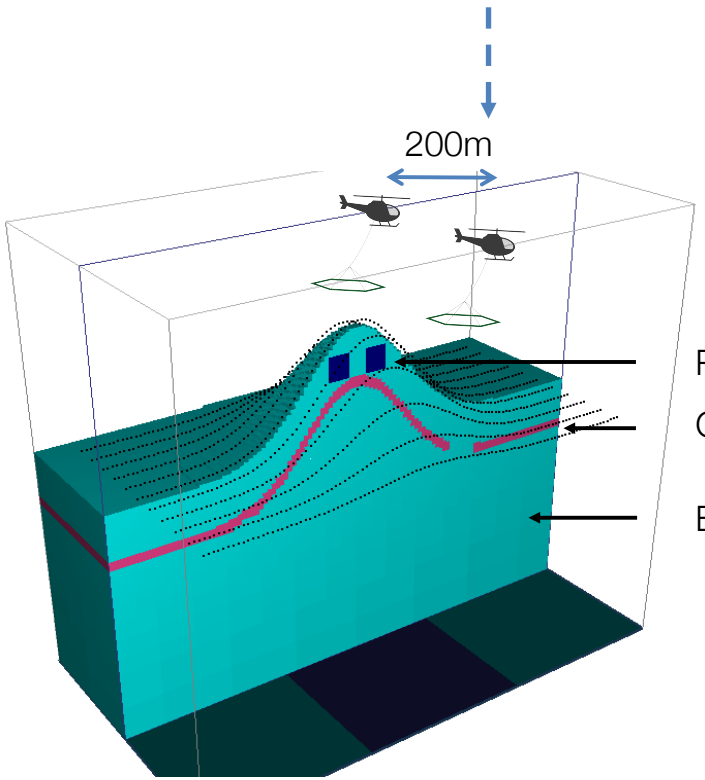
- Generate synthetic data (3D simulation)
- Invert in 1D
- Invert in 3D

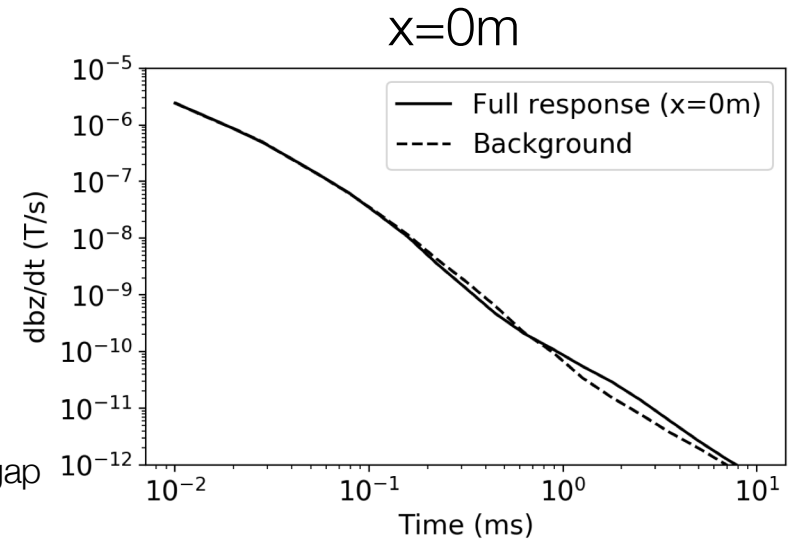
Sounding curves

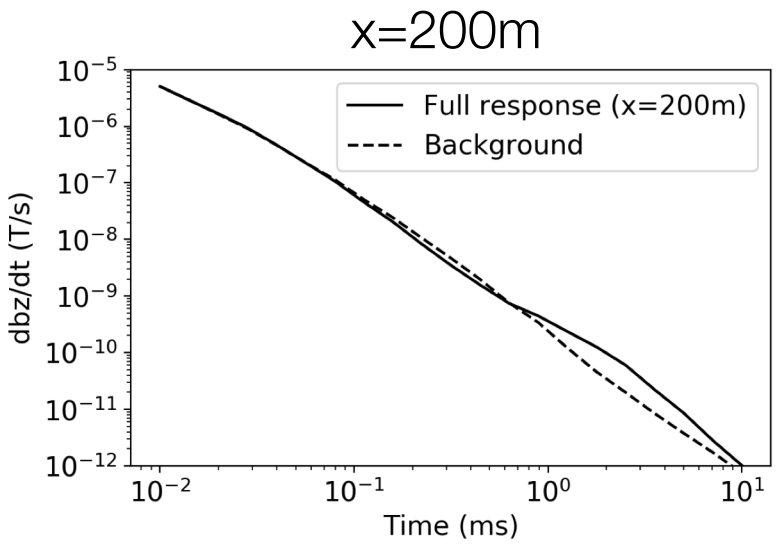




Sounding curves





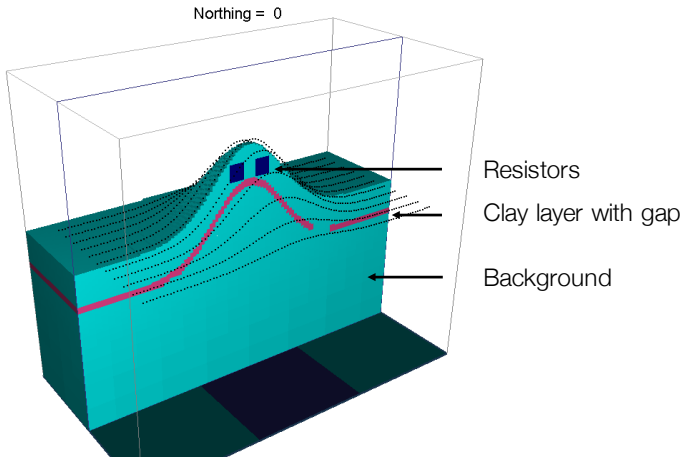


Questions

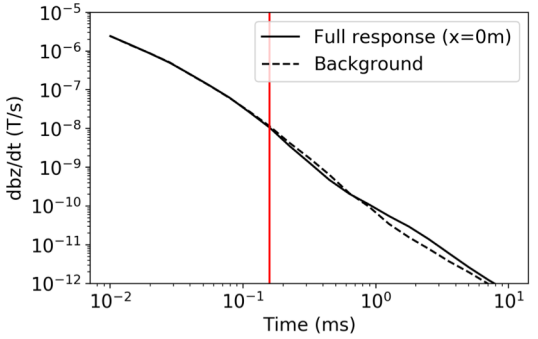
- Can we detect signals from:
  - Conductive clay layer
  - Resistors

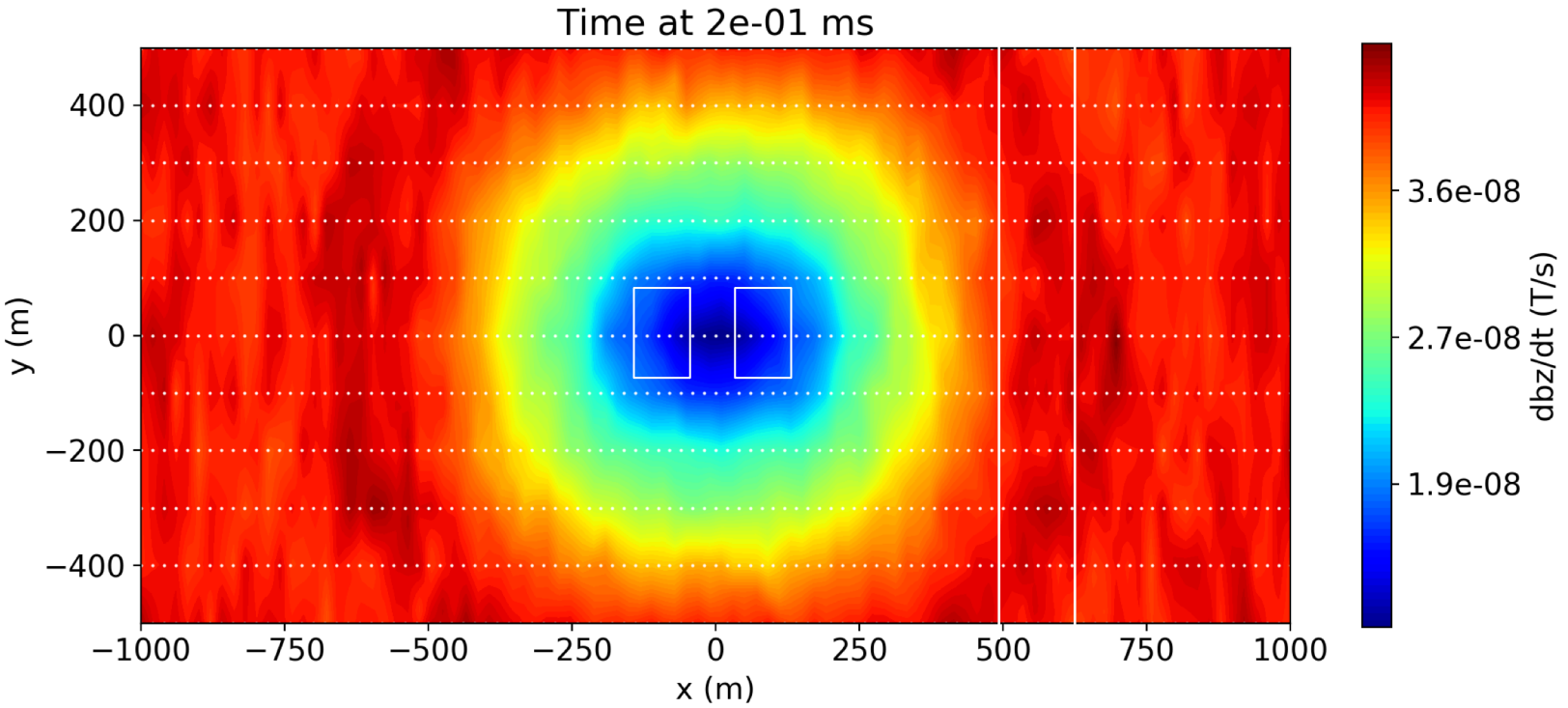
- Can we see the gap in the clay layer?

- How do we invert these data?
  - Is 1D inversion effective?
  - Do we need 3D inversion?
  - How much information can we extract?

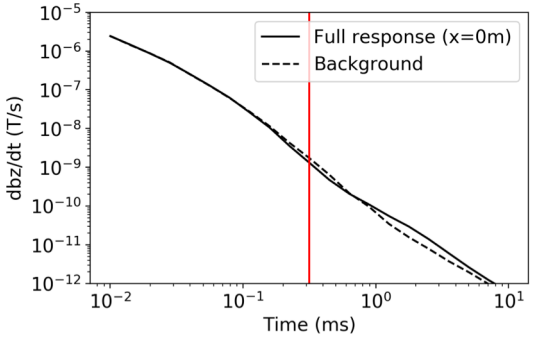


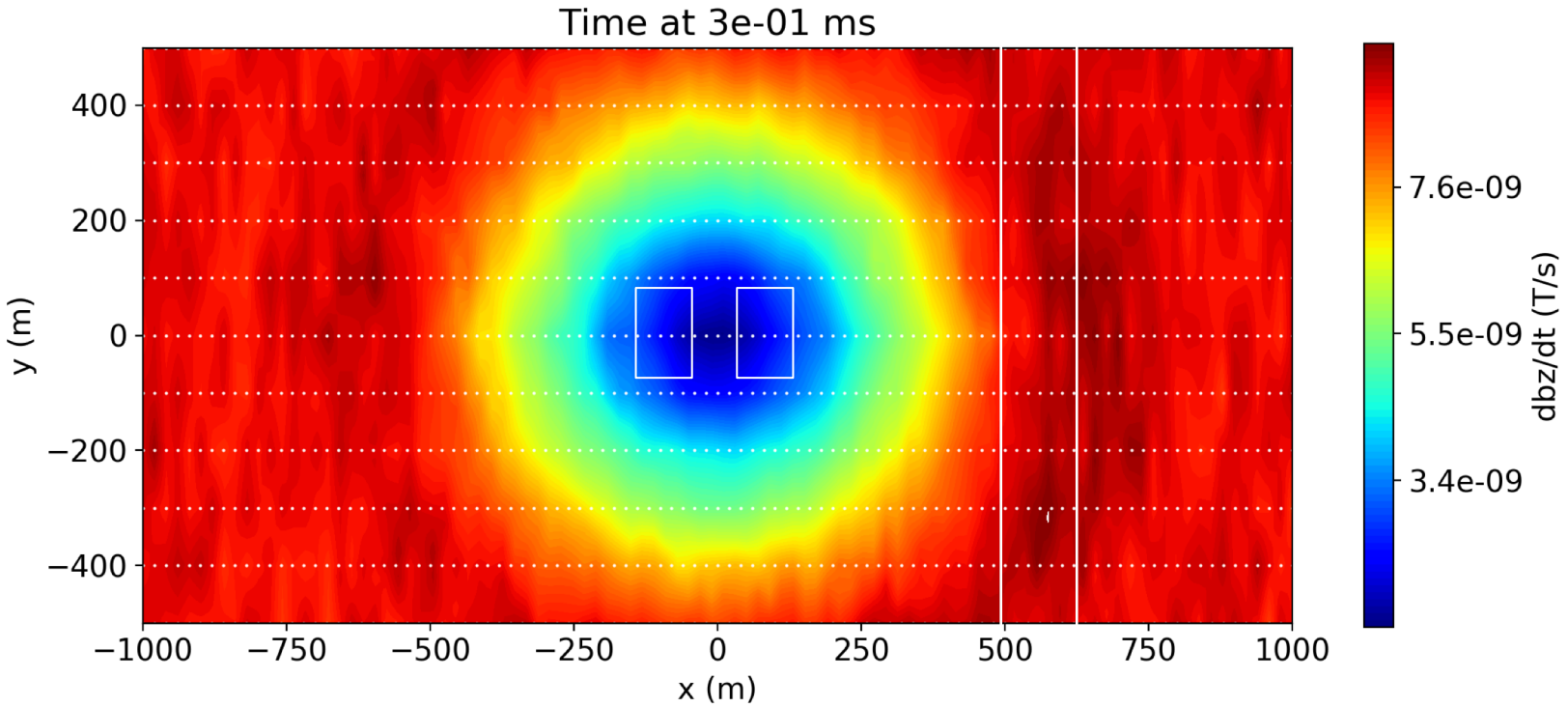
Data: t=0.2ms


Full response (x=0m)
Background
dbz/dt (T/s)
Time (ms)

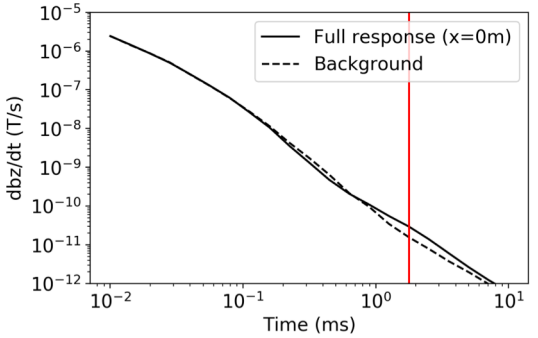

Time at 2e-01 ms
y (m)
x (m)
dbz/dt (T/s)
3.6e-08
2.7e-08
1.9e-08

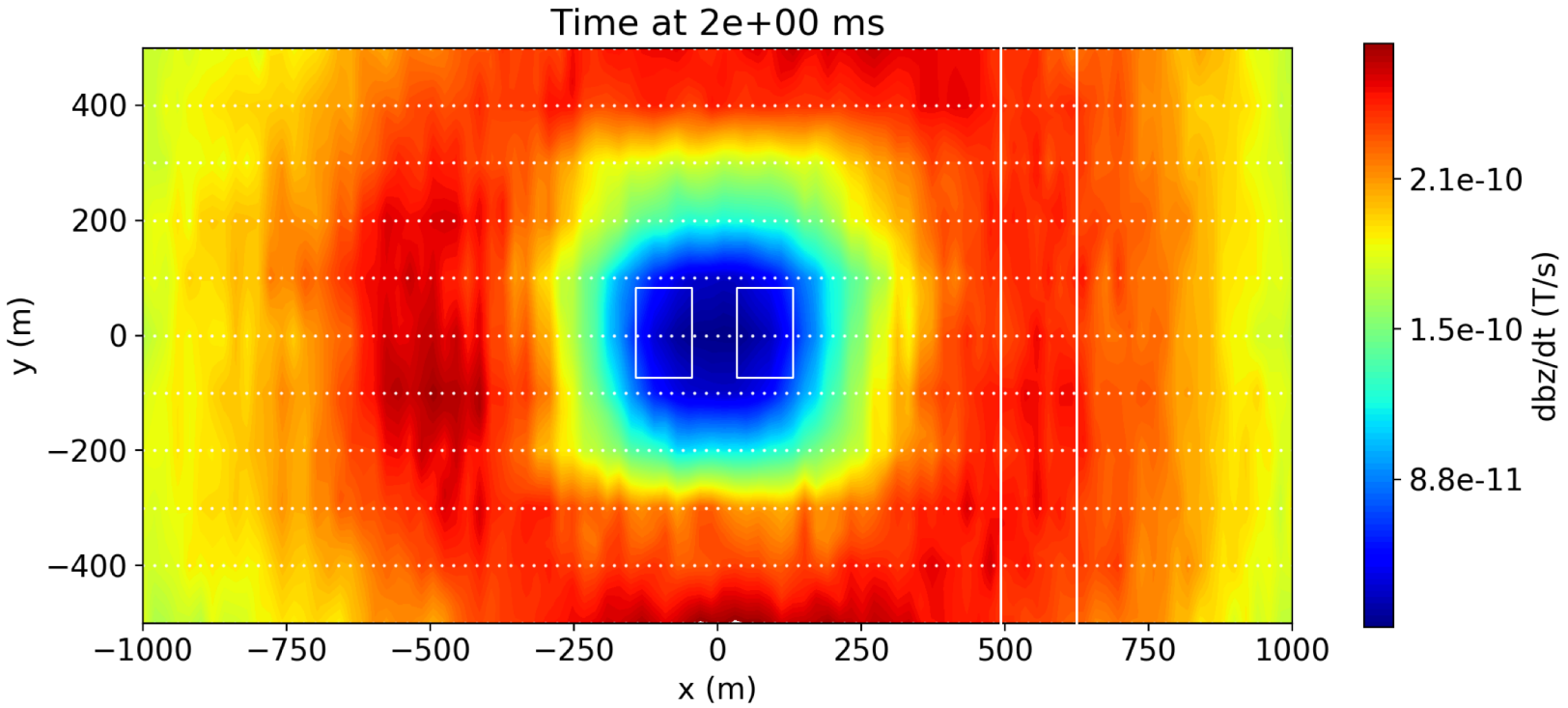
Data: t=0.3ms


Full response (x=0m)
Background
dbz/dt (T/s)
Time (ms)

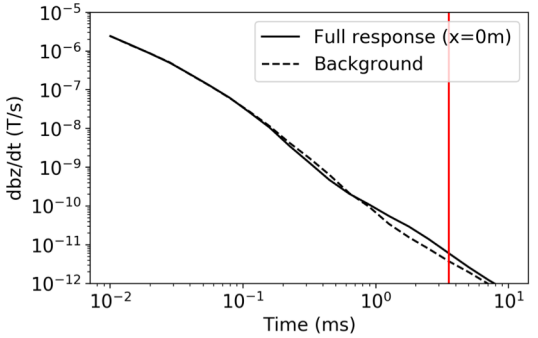

Time at 3e-01 ms
y (m)
x (m)
dbz/dt (T/s)
7.6e-09
5.5e-09
3.4e-09

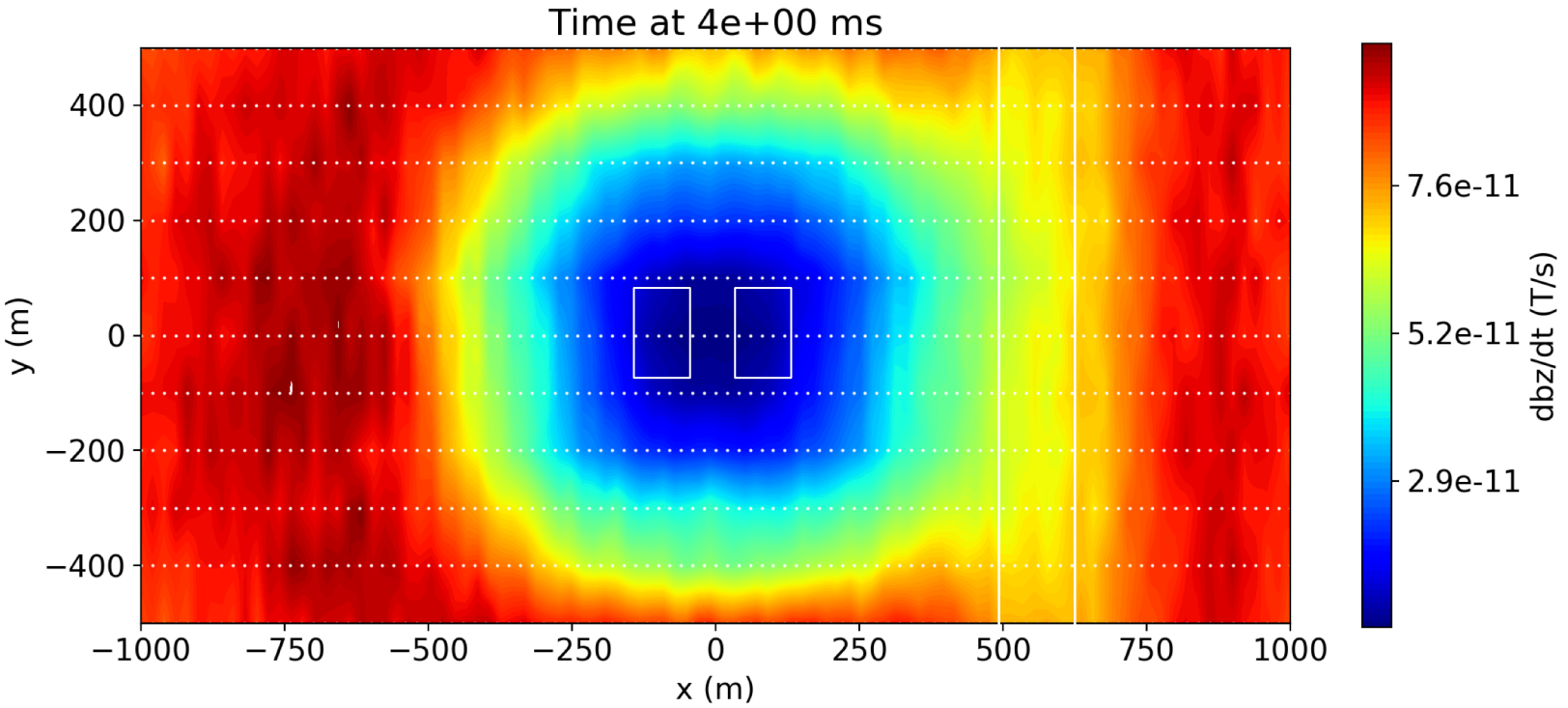
Data: t=2ms


Full response (x=0m)
Background
dbz/dt (T/s)
Time (ms)

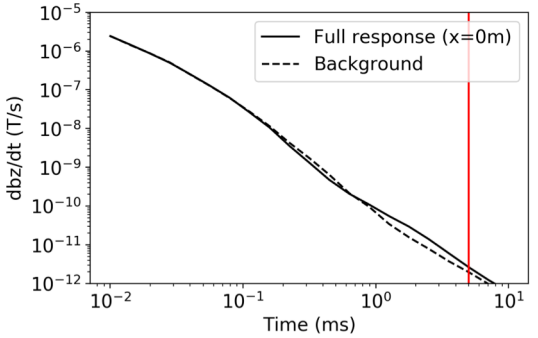

Time at 2e+00 ms
y (m)
x (m)
dbz/dt (T/s)
2.1e-10
1.5e-10
8.8e-11

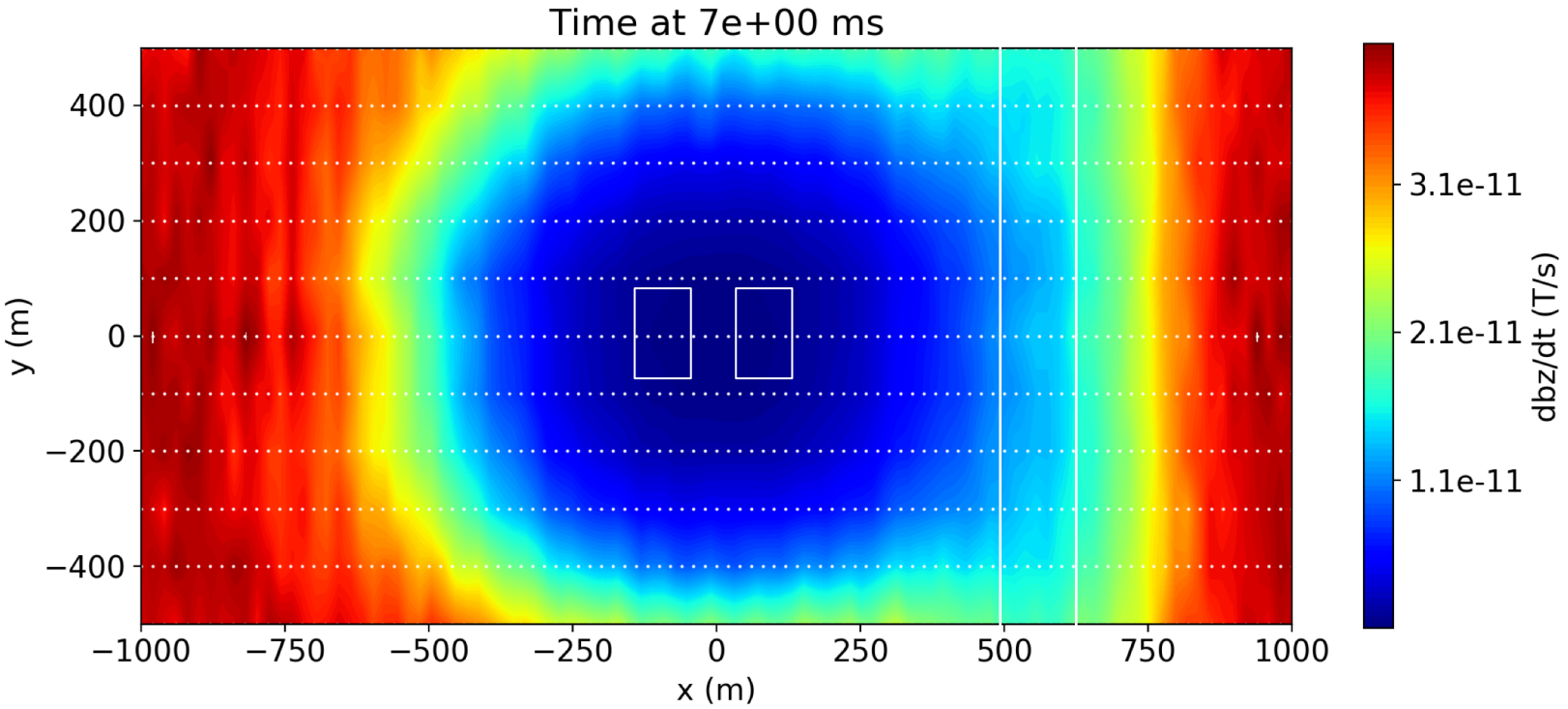
Data: t=4ms


Full response (x=0m)
Background
dbz/dt (T/s)
Time (ms)


Time at 4e+00 ms
y (m)
x (m)
dbz/dt (T/s)
7.6e-11
5.2e-11
2.9e-11

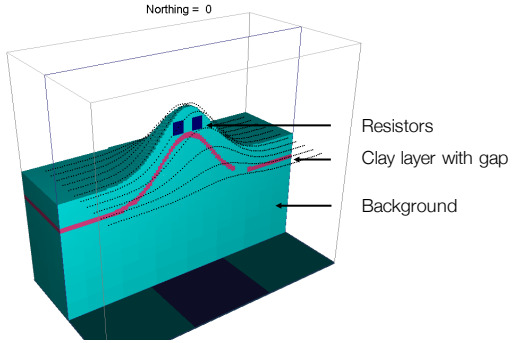
Data: t=7ms

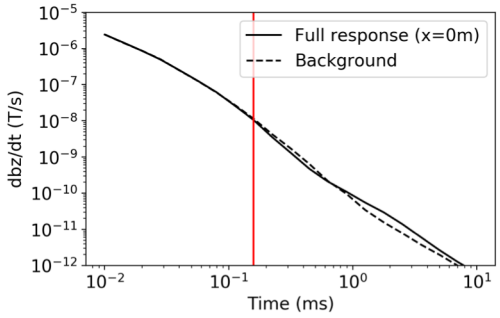

Full response (x=0m)
Background
dbz/dt (T/s)
Time (ms)


Time at 7e+00 ms
y (m)
x (m)
dbz/dt (T/s)
3.1e-11
2.1e-11
1.1e-11

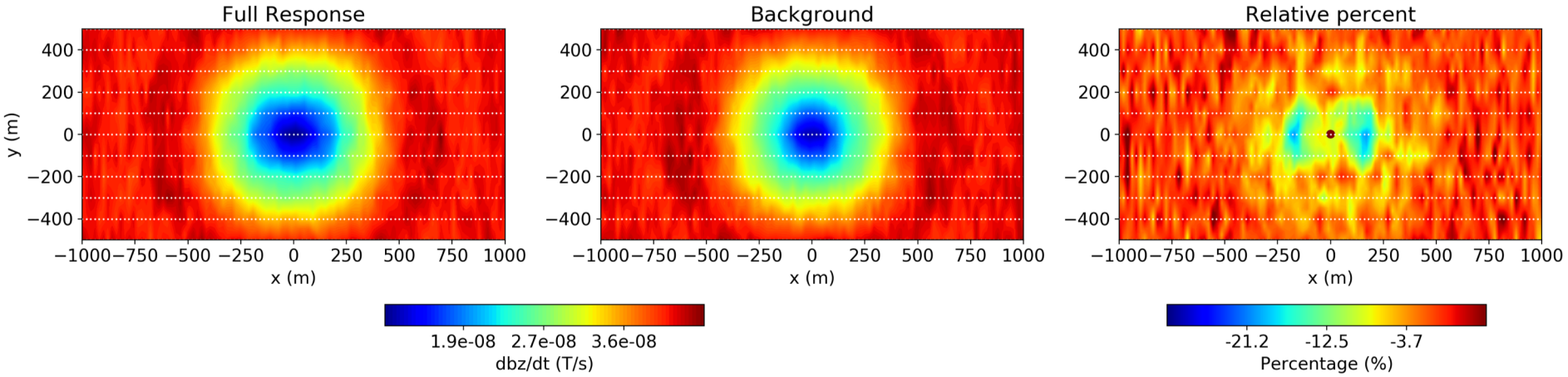
Can we see resistors and clay layer?

Time at 0.2ms



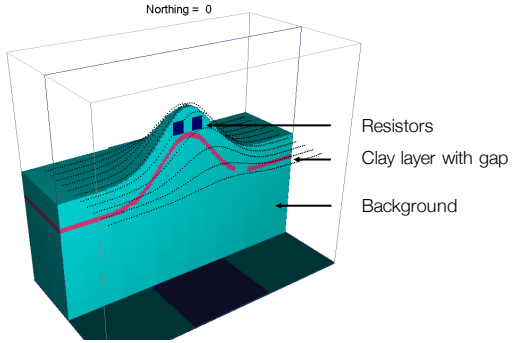


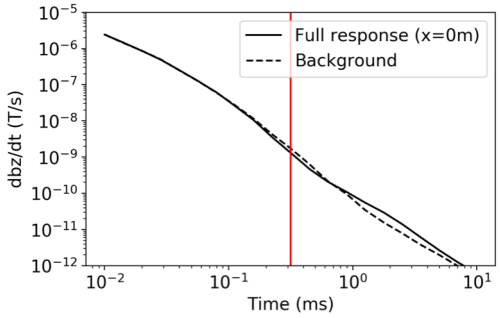
Relative percent (%) = (Full response-Background)/Background x 100



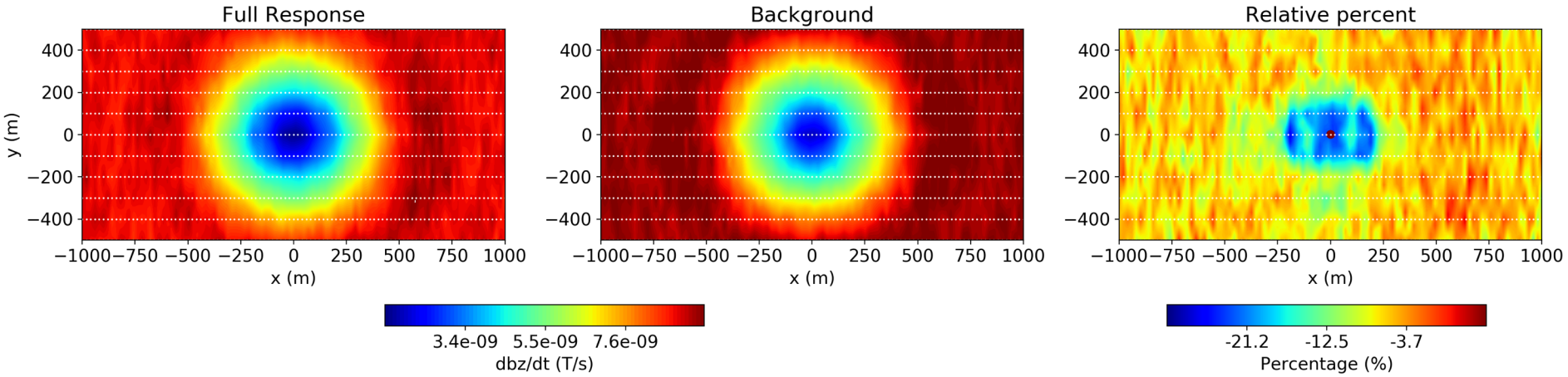
Can we see resistors and clay layer?

Time at 0.3ms



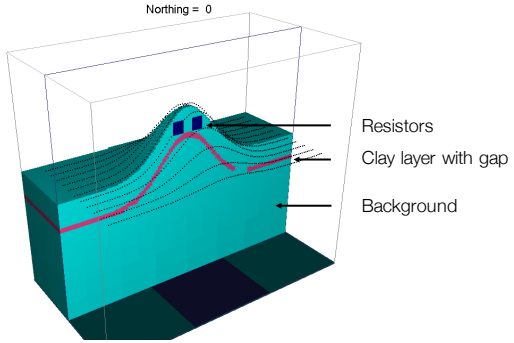


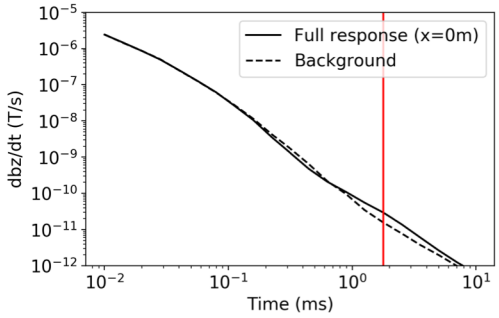
Relative percent (%) = (Full response-Background)/Background x 100



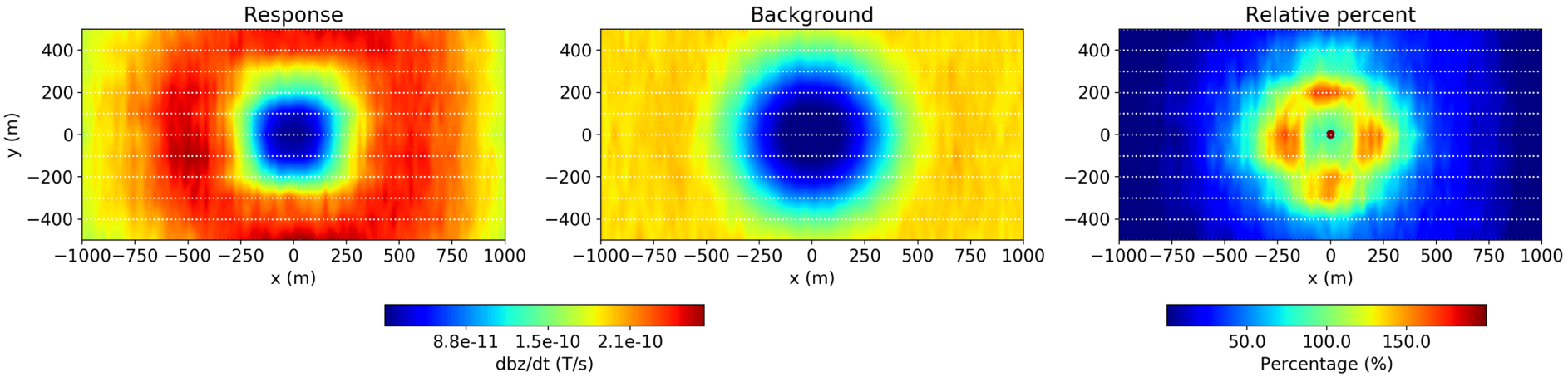
Can we see resistors and clay layer?

Time at 2ms



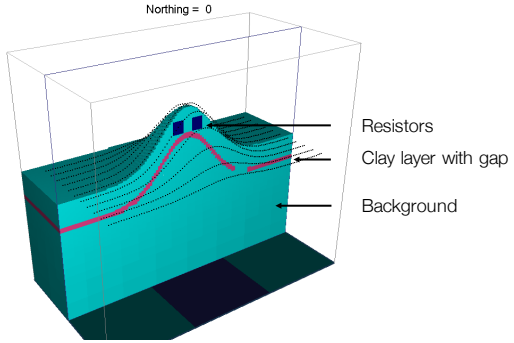


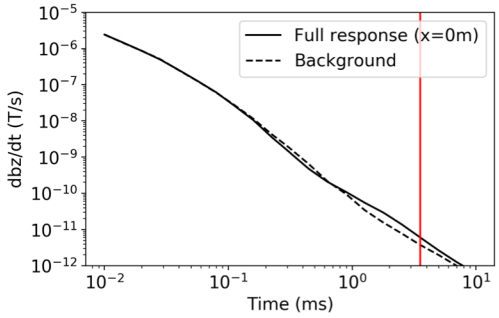
Relative percent (%) = (Full response-Background)/Background x 100



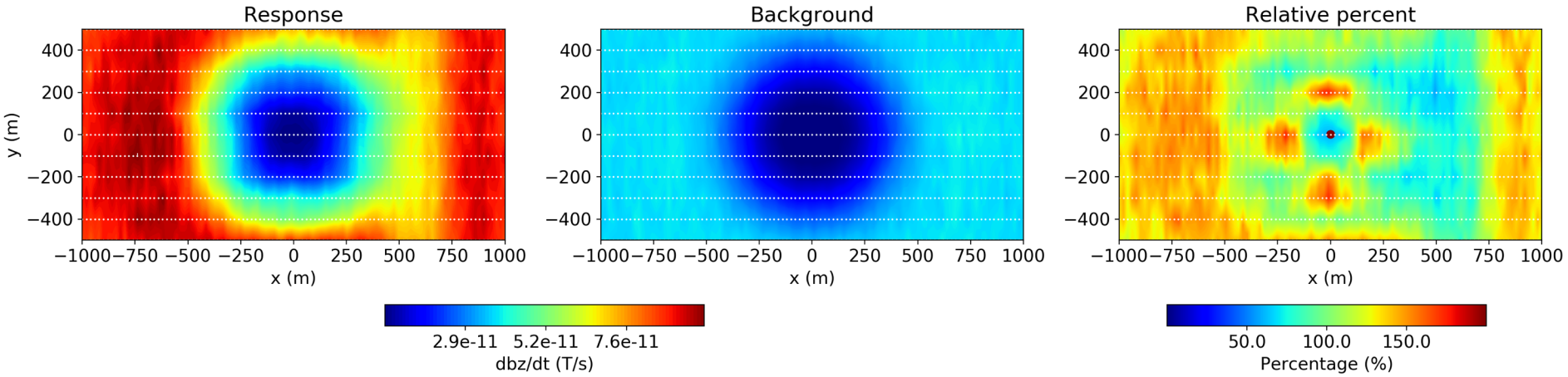
Can we see resistors and clay layer?

Time at 4ms



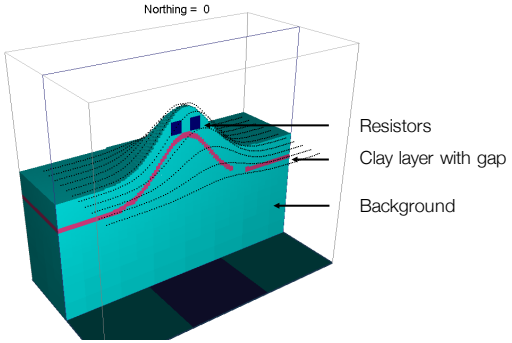


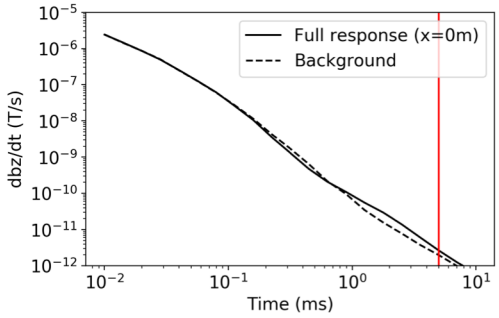
Relative percent (%) = (Full response-Background)/Background x 100



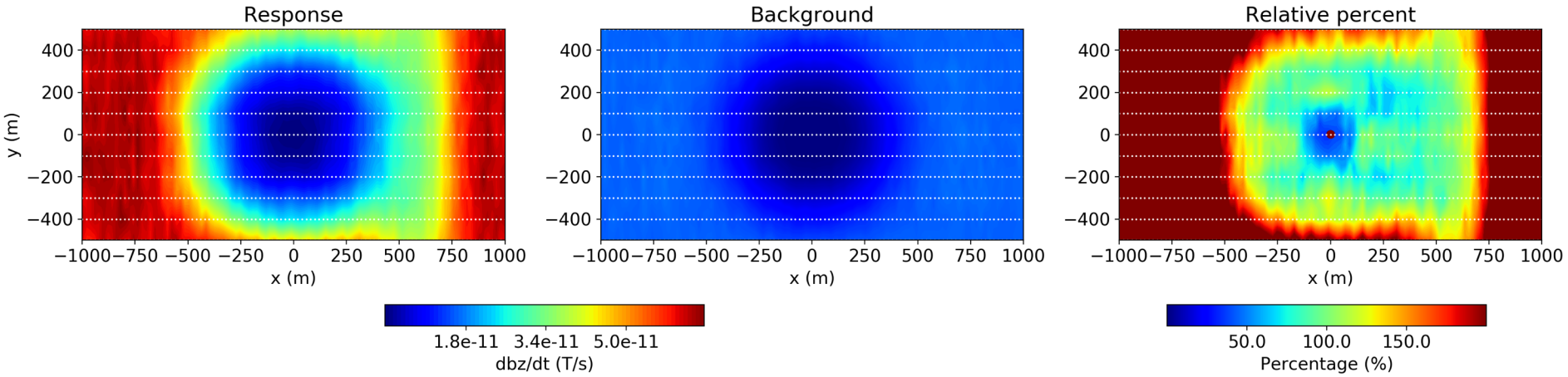
Can we see resistors and clay layer?

Time at 7ms

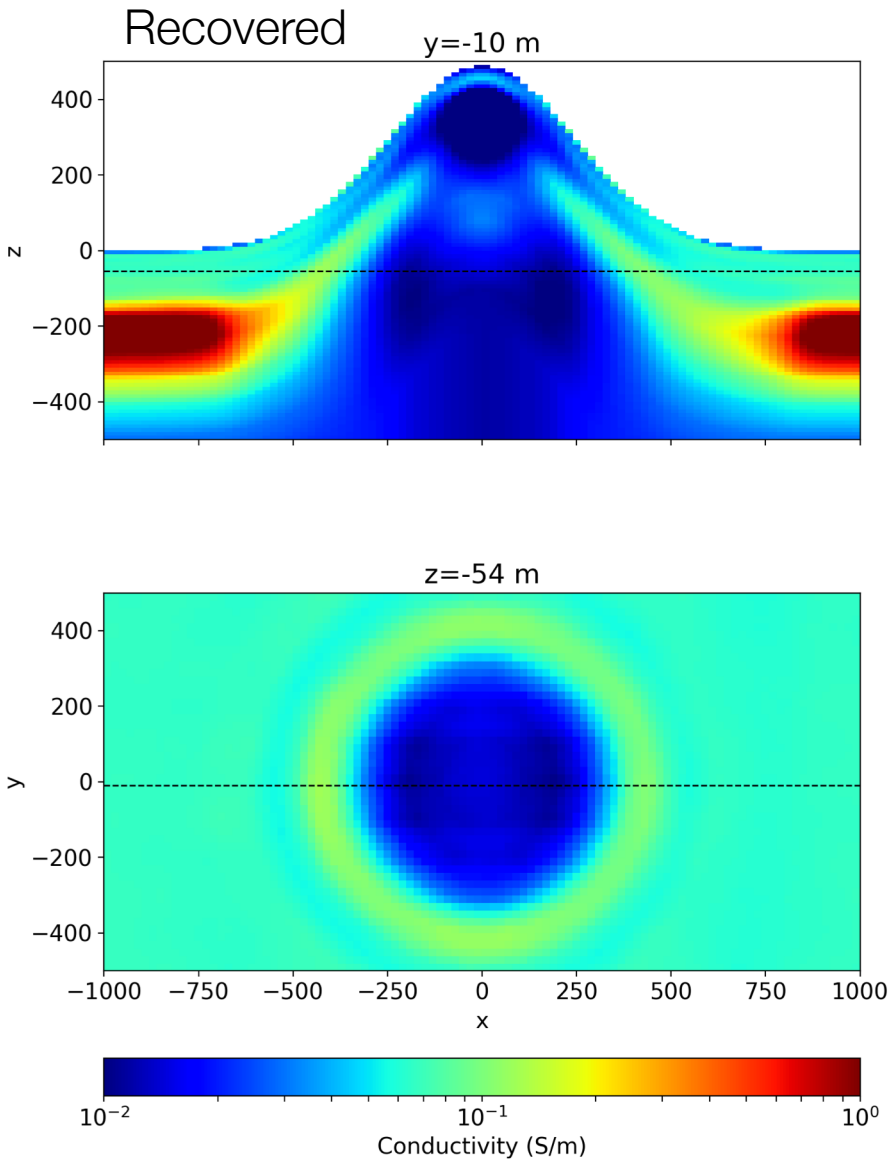




Relative percent (%) = (Full response-Background)/Background x 100



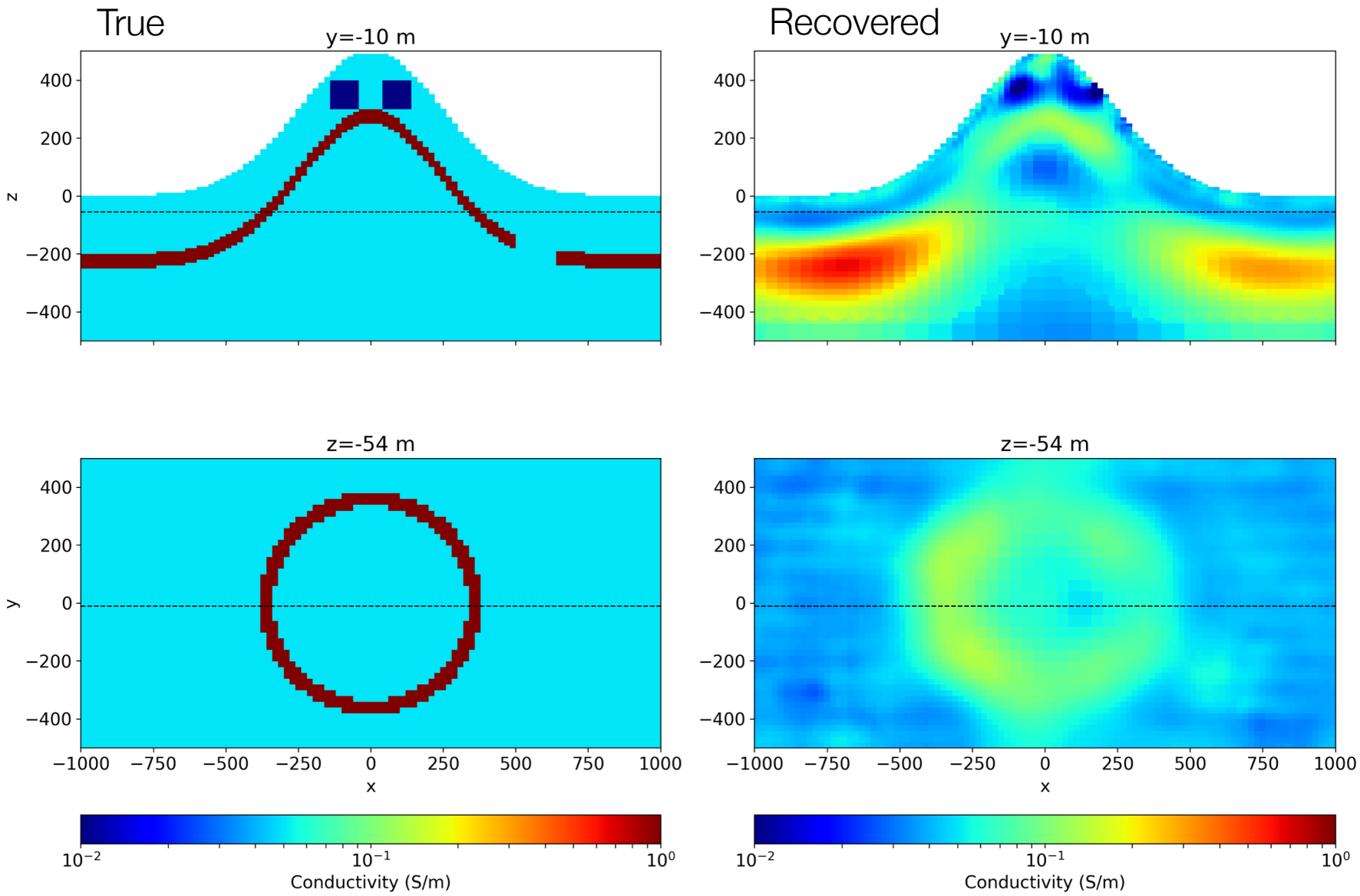
1D inversion



- Background: 0.02 S/m
- Reached target misfit (rms=1)
- Large resistor below topography
- Clay layers away from topography.

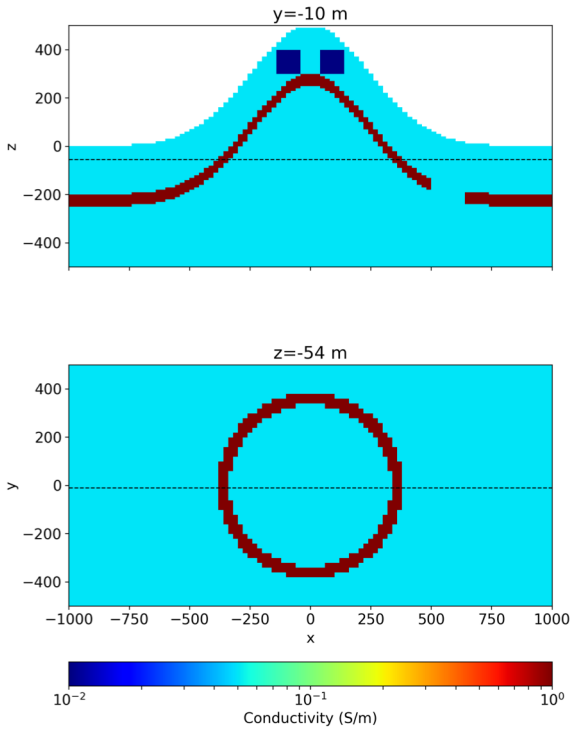
Need to invert in 3D

3D inversion

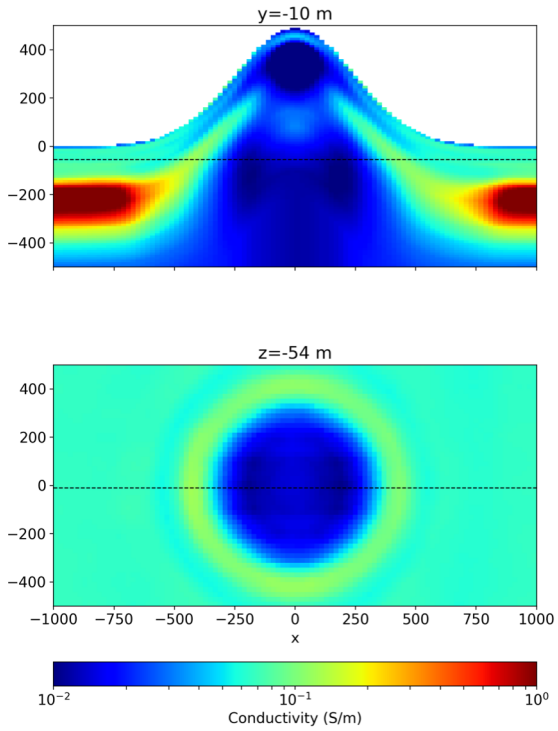


Comparison 3D and 1D

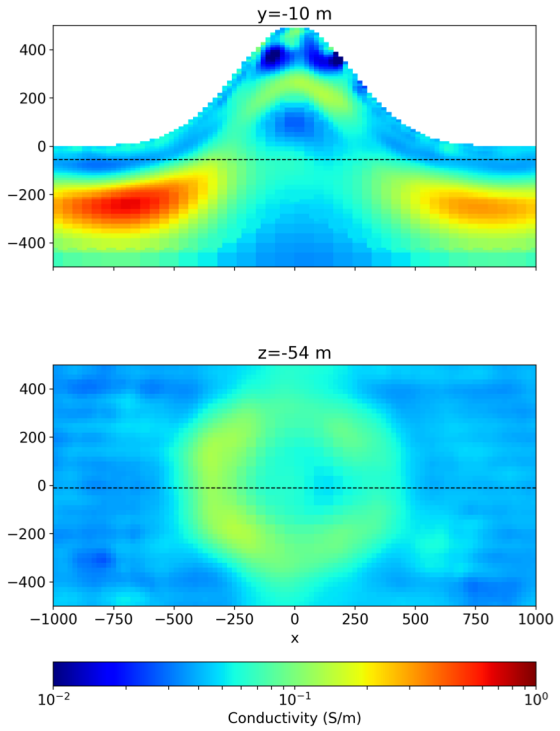
True



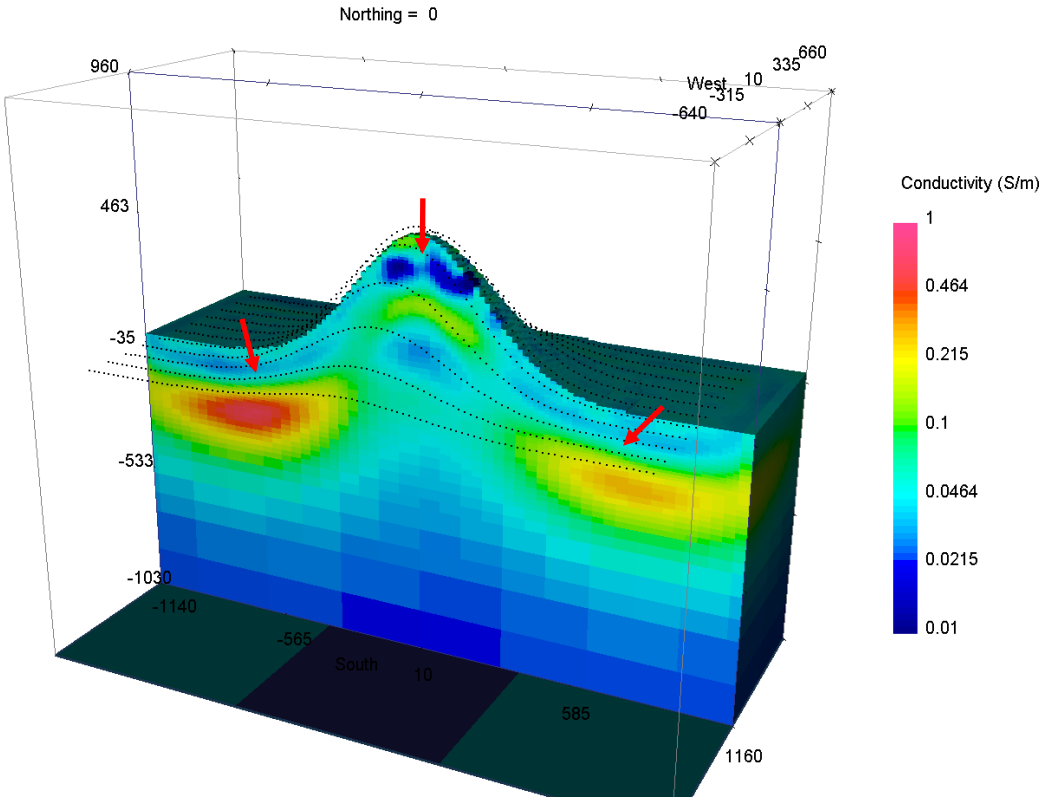
1D



3D

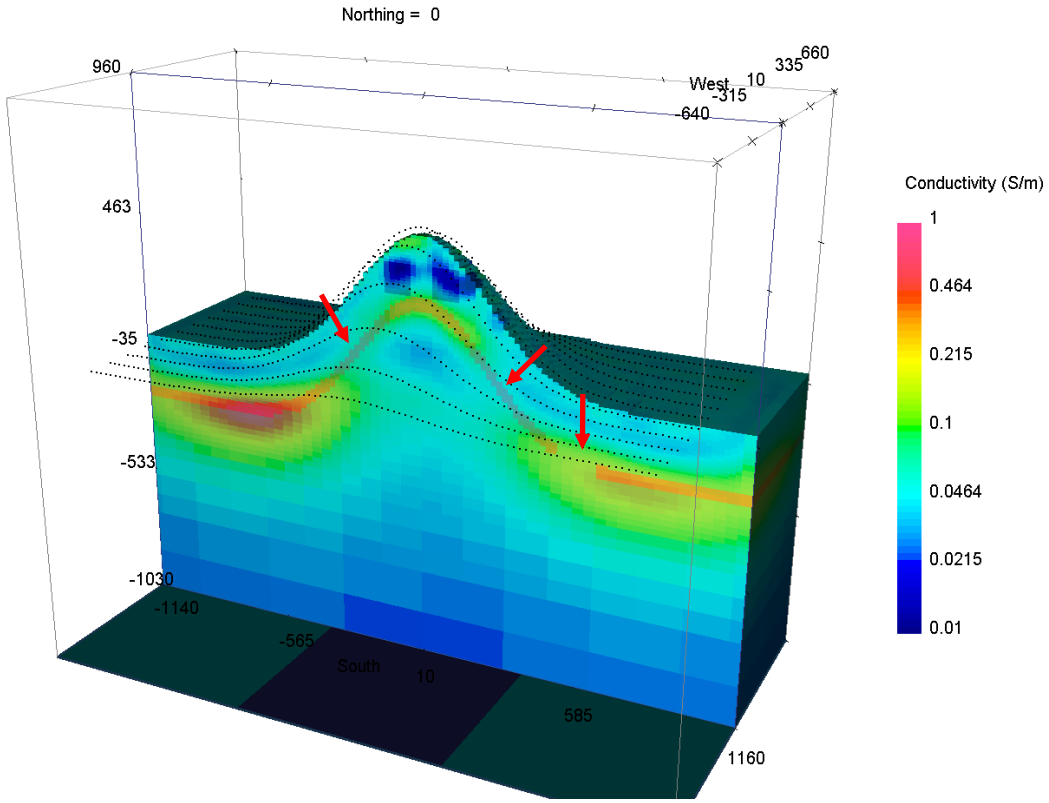


3D view



- Imaged main features in 3D
  - Deep clay layer
  - Resistors

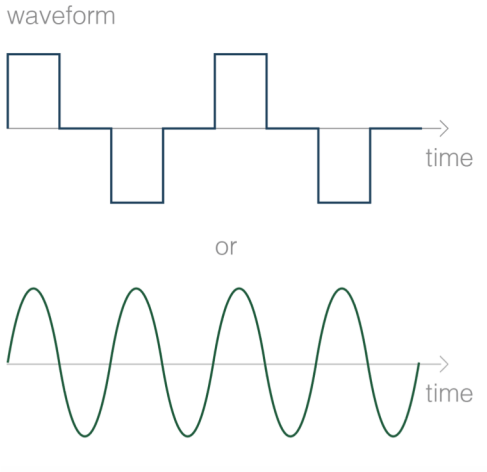
3D view



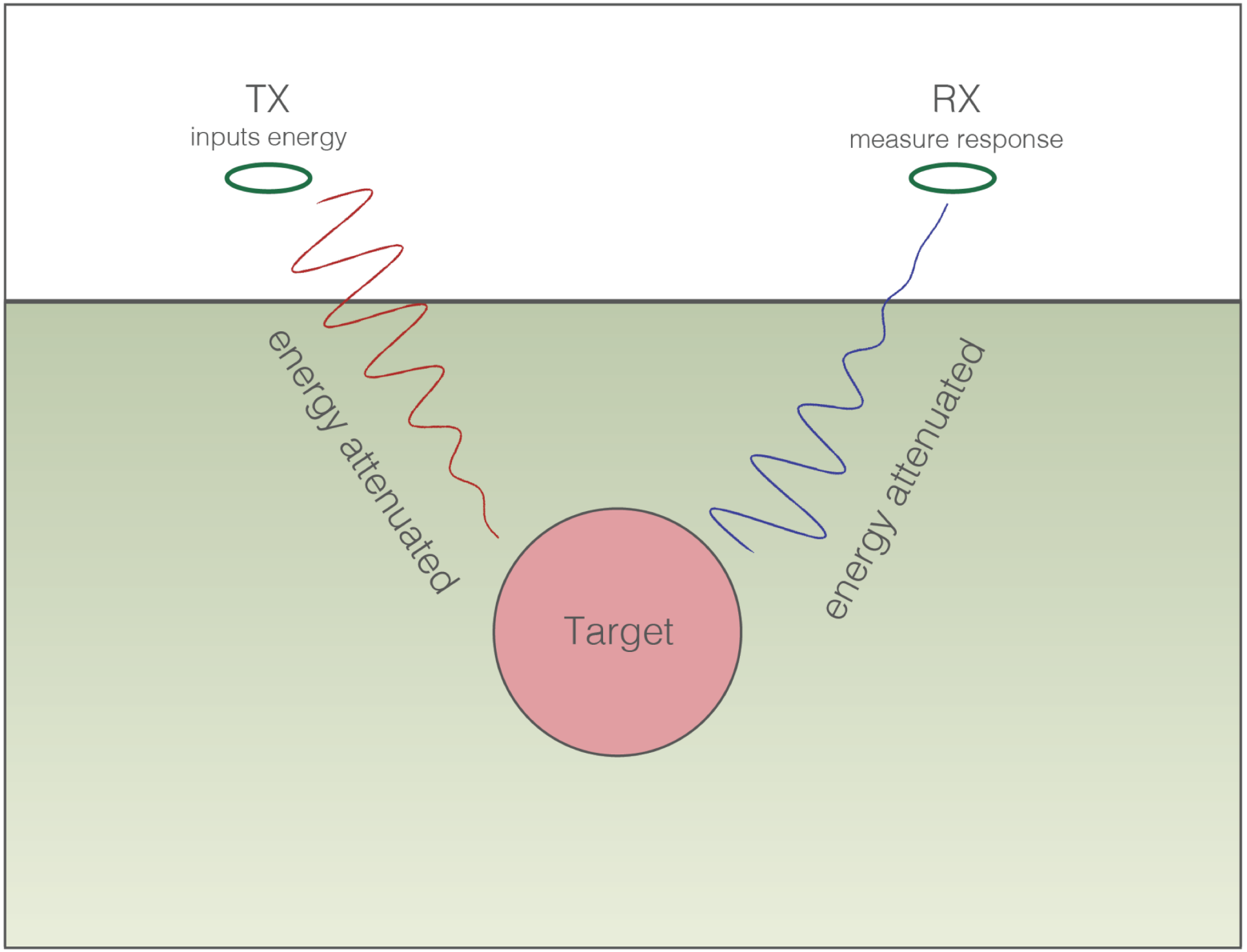
- Imaged
  - Deep clay layer
  - Resistors
- Less sensitive to clay layer on the slopes of the mountain
  - Poor coupling
- Gap in the clay
  - slight indication
  - Requires some a priori information to resolve

Frequency Domain

- Same physics as time domain
- Challenging because primary field is always on
- Currents are partitioned into in-phase and quadrature portions.
- Consider a sphere in a buried background



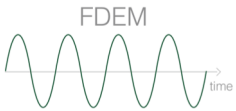
Conductive sphere in a uniform background



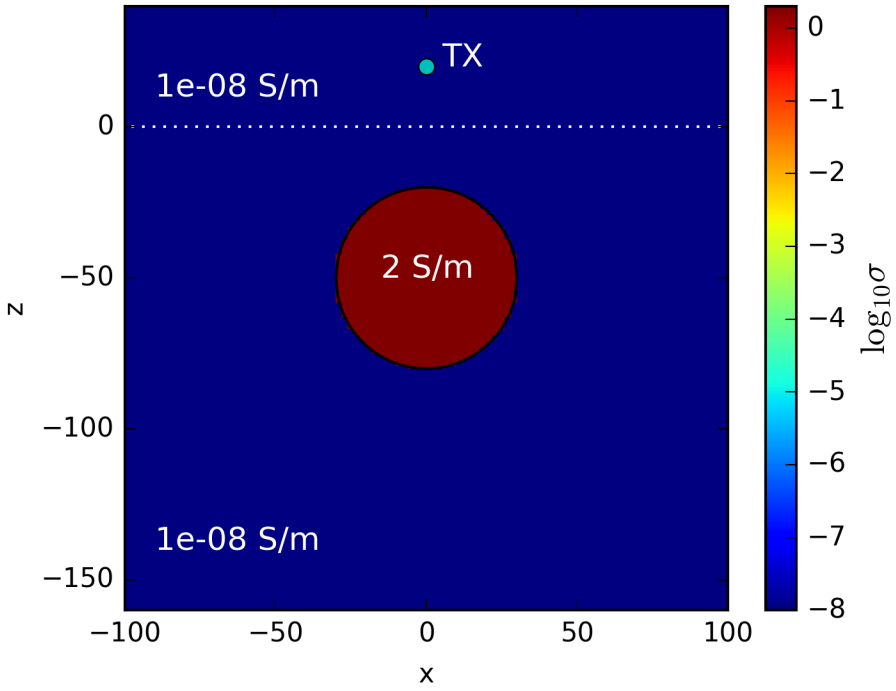
Effects of background resistivity: Frequency

- Buried, conductive sphere
- Vary background conductivity

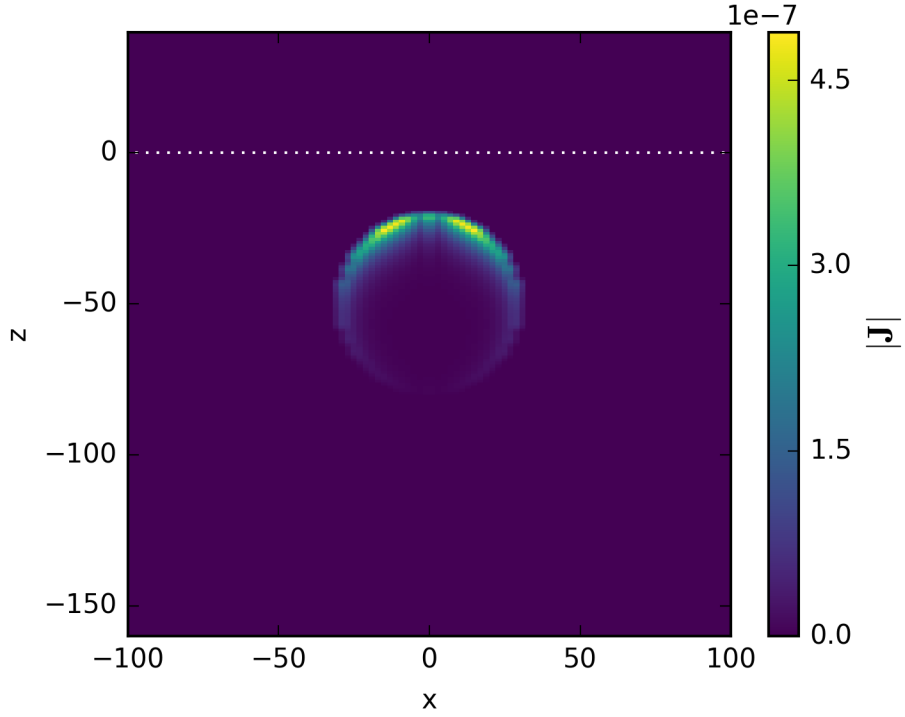
- Frequency: 10^4 Hz



10^{-8} S/m background



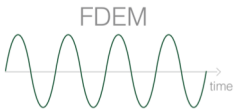
Current Density



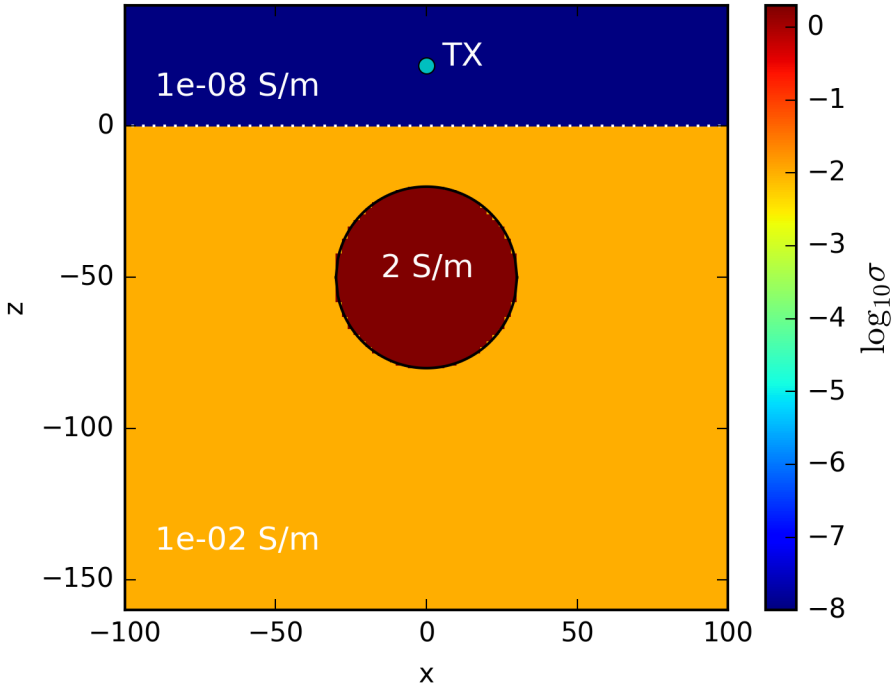
Effects of background resistivity: Frequency

- Buried, conductive sphere
- Vary background conductivity

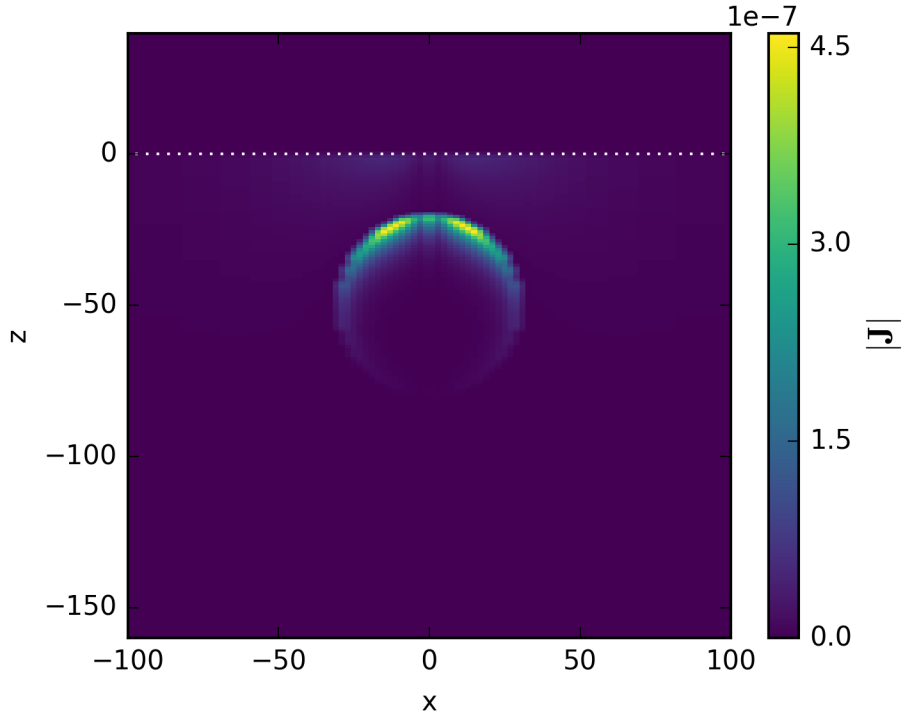
- Frequency: 10^4 Hz



10^{-2} S/m background



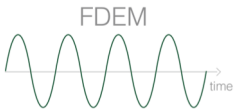
Current Density



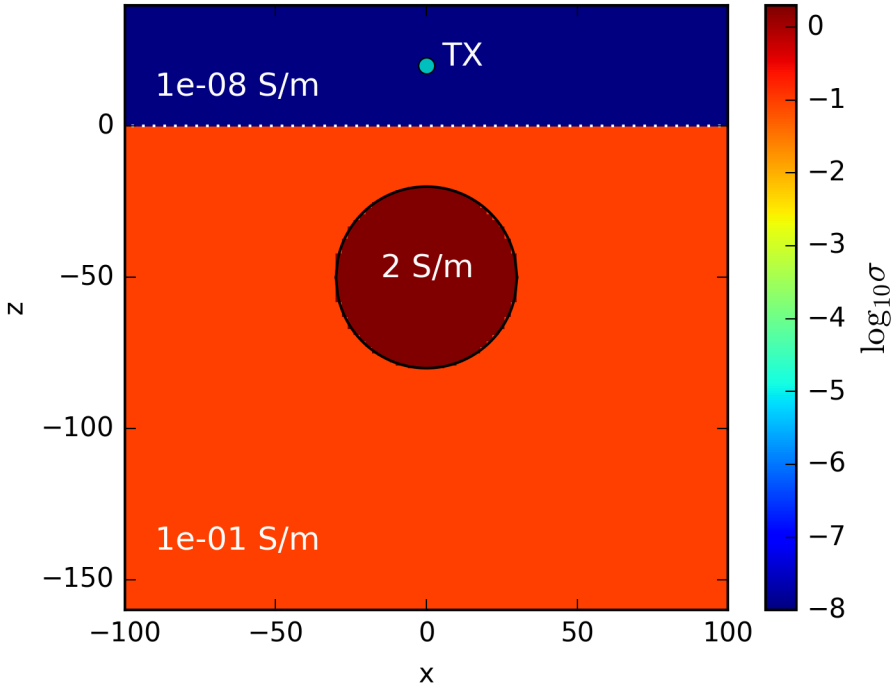
Effects of background resistivity: Frequency

- Buried, conductive sphere
- Vary background conductivity

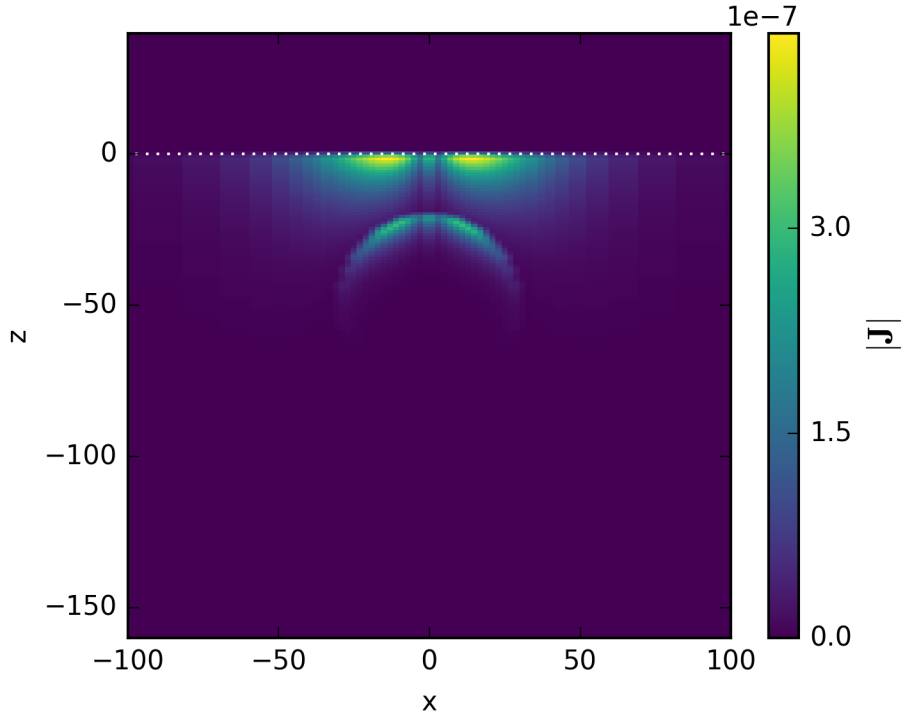
- Frequency: 10^4 Hz



10^{-1} S/m background



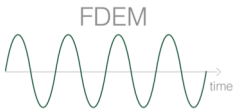
Current Density



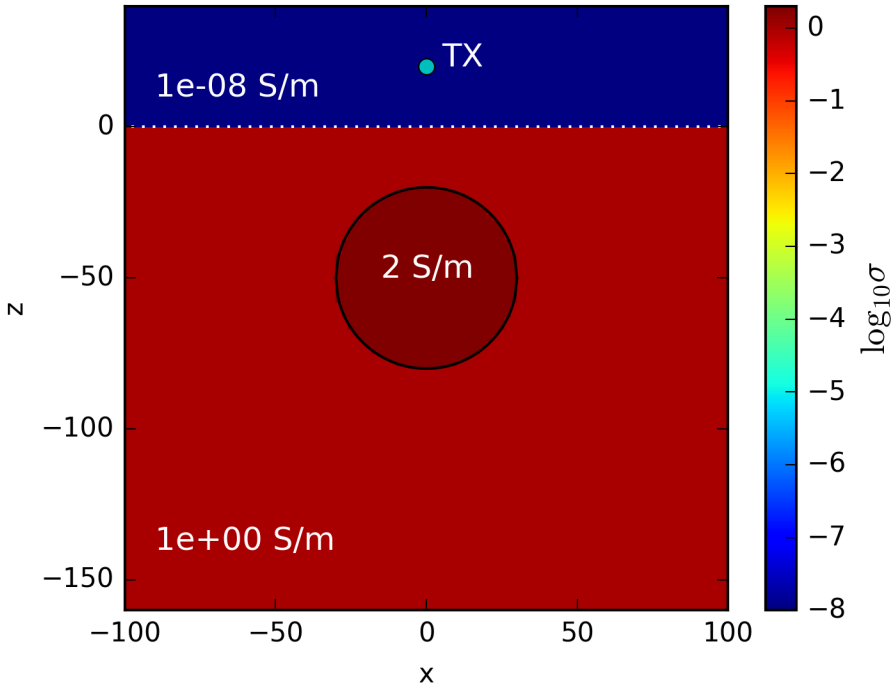
Effects of background resistivity: Frequency

- Buried, conductive sphere
- Vary background conductivity

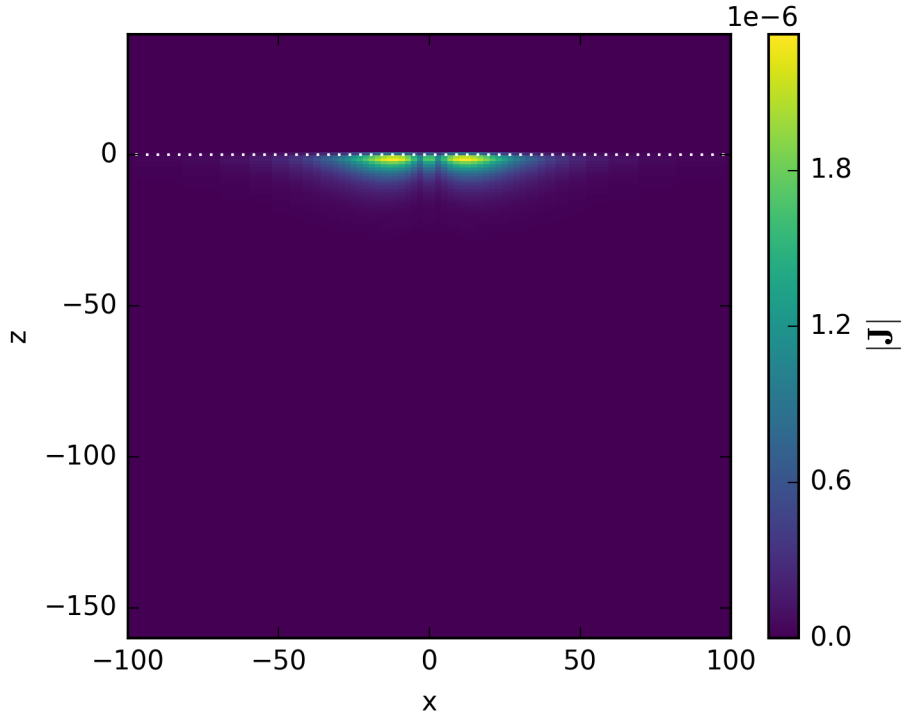
- Frequency: 10^4 Hz



1 S/m background



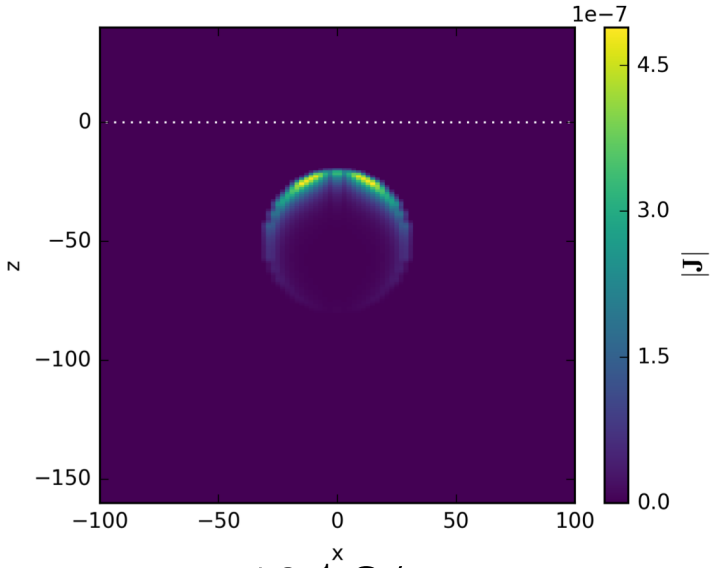
Current Density



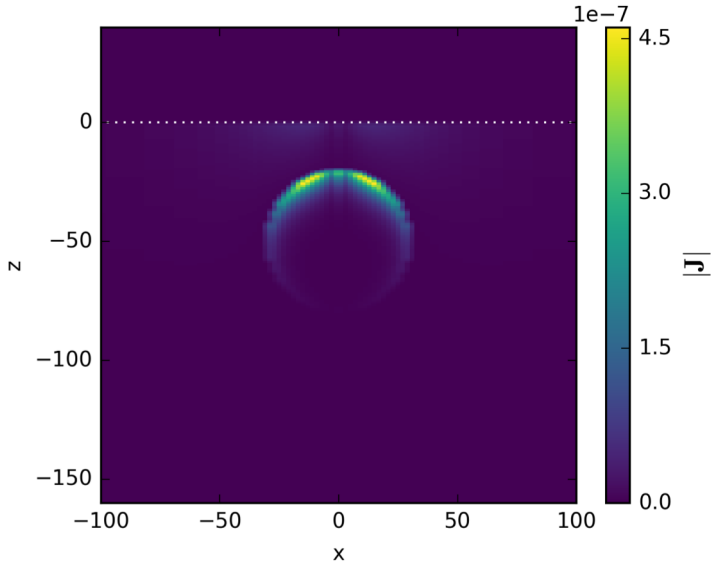
10^4 Hz

Effects of background resistivity: Frequency

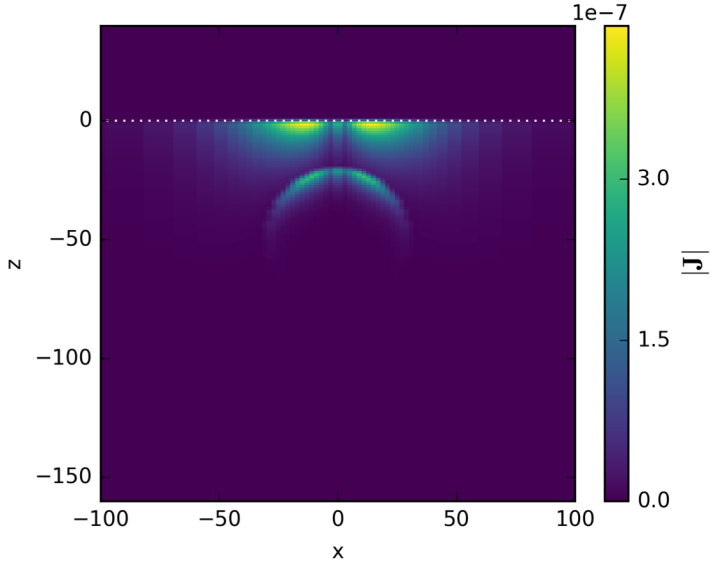
10^{-8} S/m



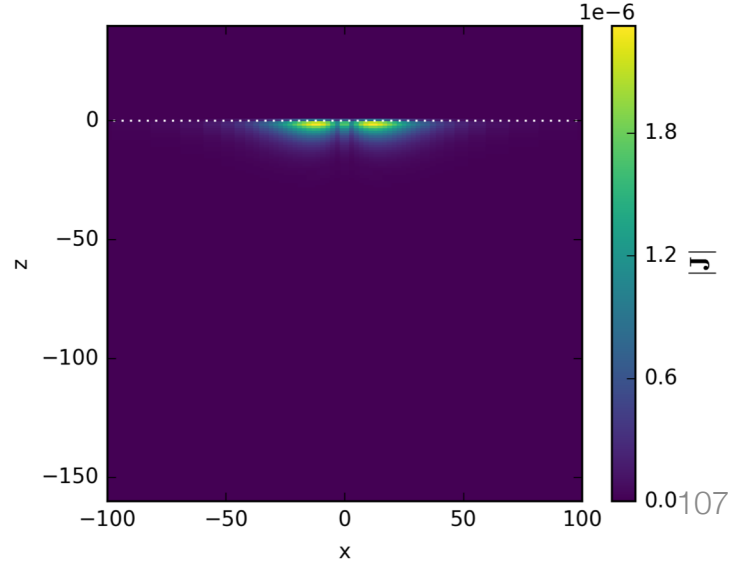
10^{-2} S/m



10^{-1} S/m



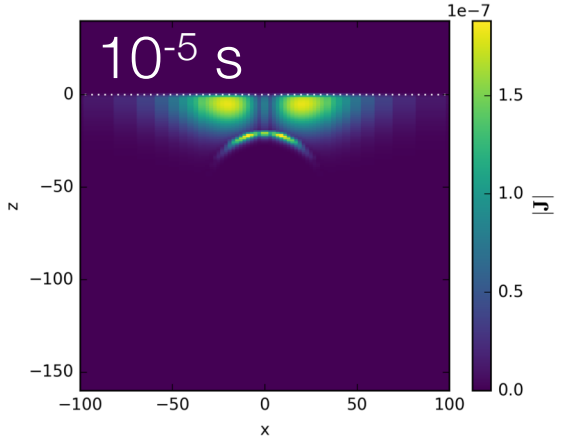
1 S/m



Summary: frequency vs. time

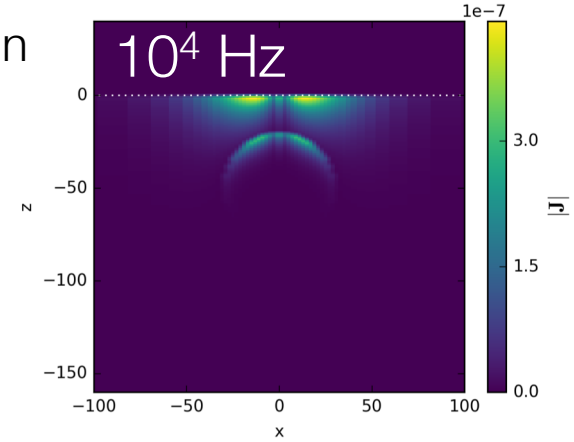
Physics is same, but looking field in time domain is more intuitive in general

Time domain



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

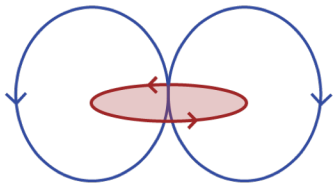
Frequency domain



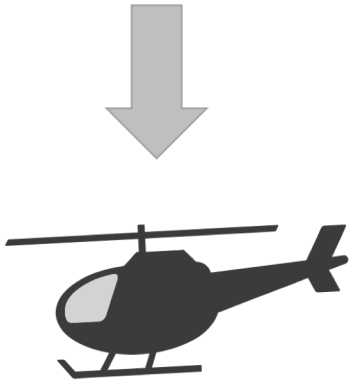
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Summary

- Fundamentals of EM induction
- Fields and fluxes in 3D to aid understanding
- Generic examples where 3D can be important
  - buried conductor
  - buried resistor
  - topography
  - complex structure
- Frequency vs time domain



EM Induction



Field Examples

Computation

Open Source Software