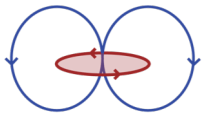
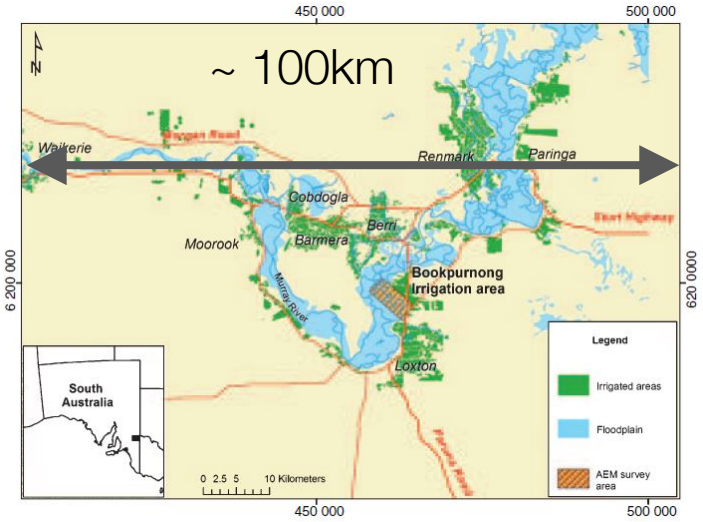
# EM: Inductive Sources

GeoSci
.xyz

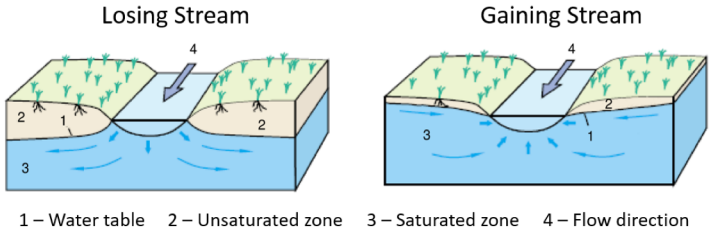


# Motivation

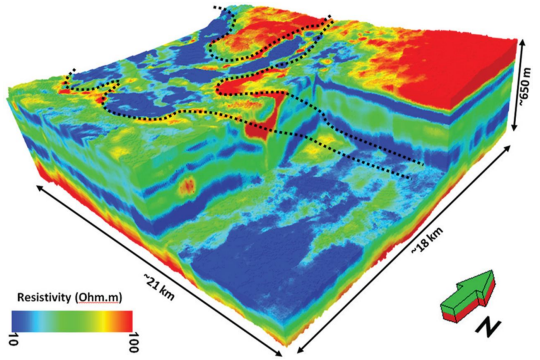
## Large areas to be covered




## Groundwater



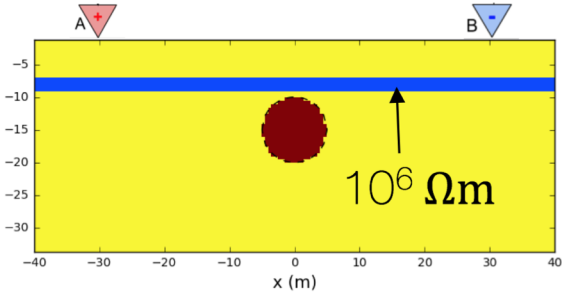

## High resolution near surface




## Rugged terrain

## Minerals

## Shielding problem



# Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

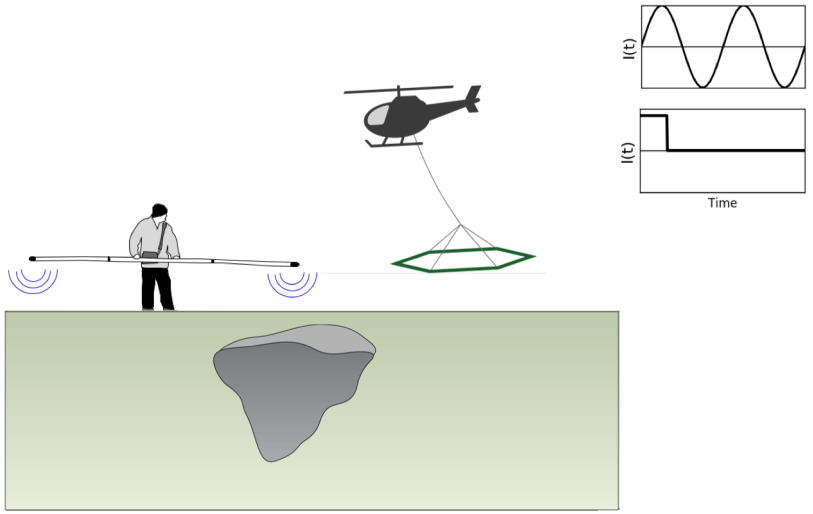
- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Groundwater, Minerals, Hydrocarbons
- Horizontal magnetic dipole

Frequency Domain EM

- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater, Minerals

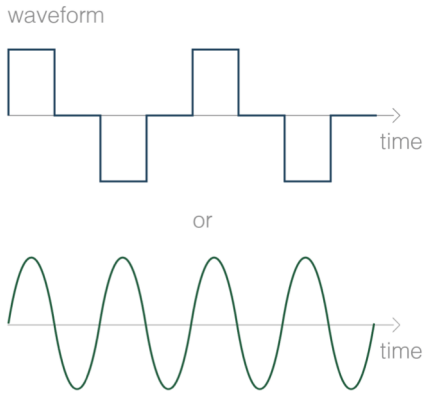
# Important questions

- What is the target?
  - at the surface? At depth?. 1D, 2D, 3D?
- Transmitter
  - Location: surface? in the air?
  - Waveform: frequency or time?
  - "Size" and orientation?
- Exciting the target
  - Conductivity of the target and host
  - Geometry of the target (Coupling)
- Receiver and data
  - What fields to measure?
  - What instrument?

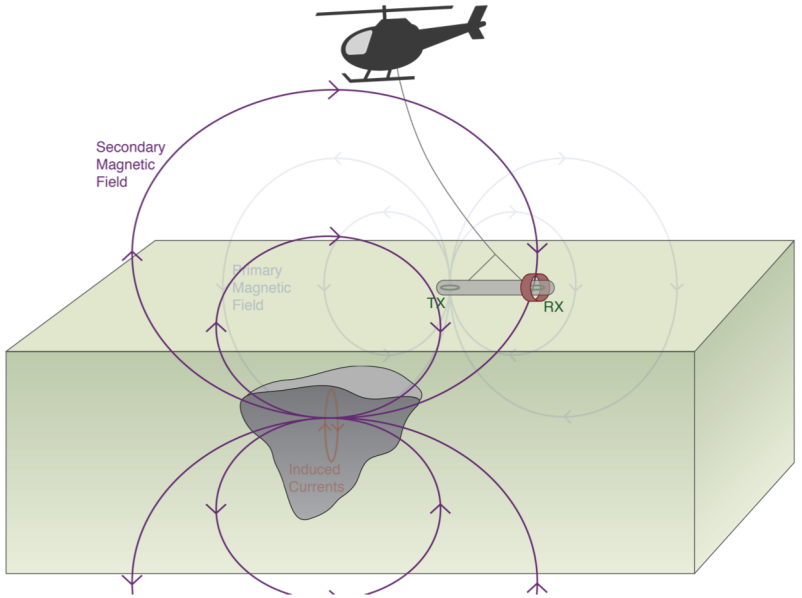



- Where to collect data? How many? How accurate?
- What is depth of investigation?
- What is the "footprint" of the transmitter"
  - These are questions of **SURVEY DESIGN**

# Basic Experiment

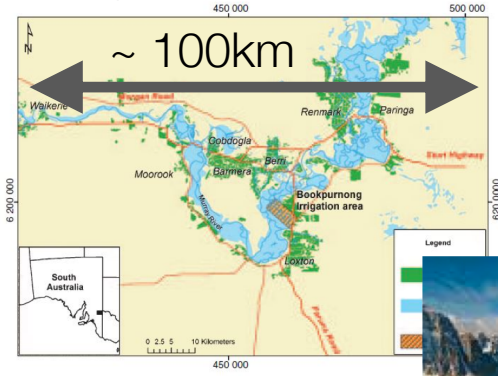



- **Transmitter:**
  - Produces a primary magnetic field
- **Exciting the target:**
  - Time varying magnetic fields generate electric fields everywhere
  - Producing currents in conductors
- **Receiver:**
  - Induced currents produce secondary magnetic fields



# Transmitter

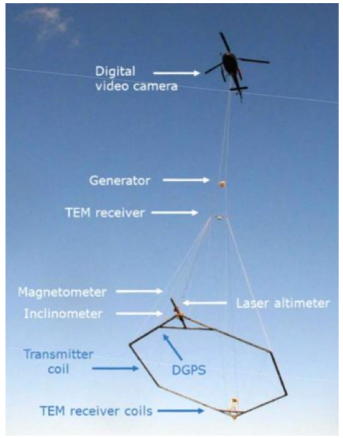
## Large areas




## Rugged terrain

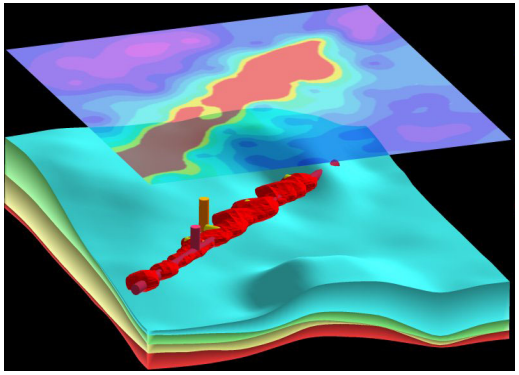
## Airborne Survey

Resolve

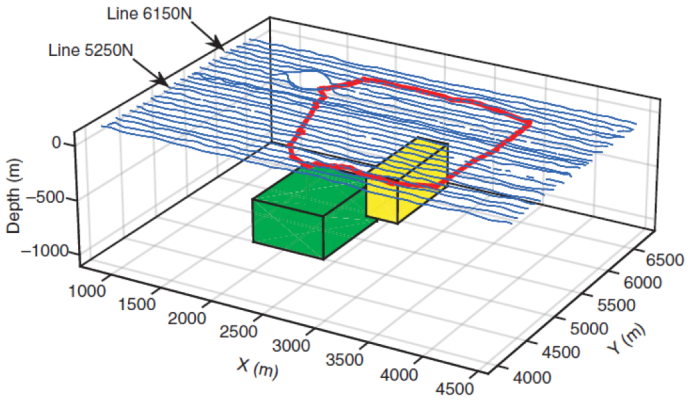



SkyTEM

## Deep Targets

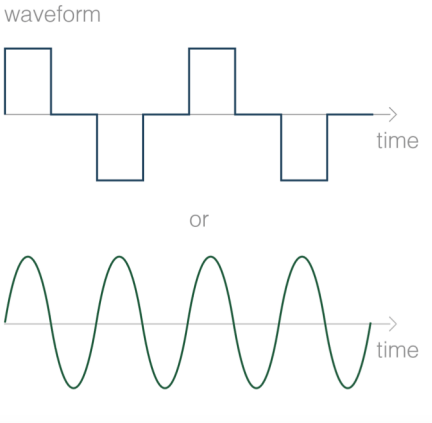


## Large Loop



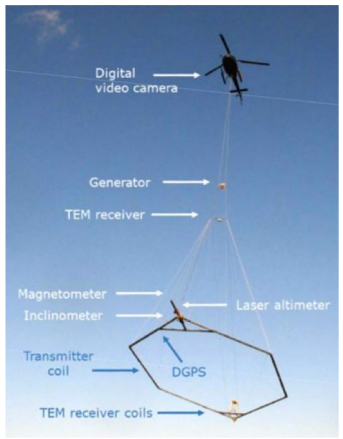
# Transmitter

- Time or frequency?




Airborne Survey

Resolve

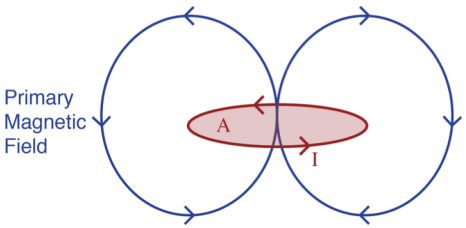



SkyTEM

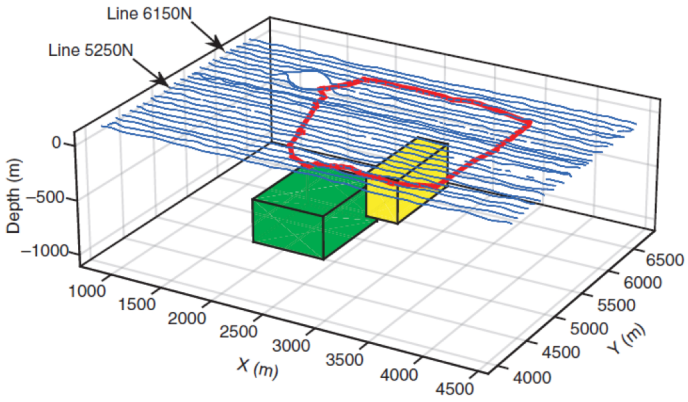
- Key factor is moment

$$m = I\ (\text{current})\ A\ (\text{area})\ N\ (\#\ \text{of turns})$$

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3}\right)$$




Large Loop

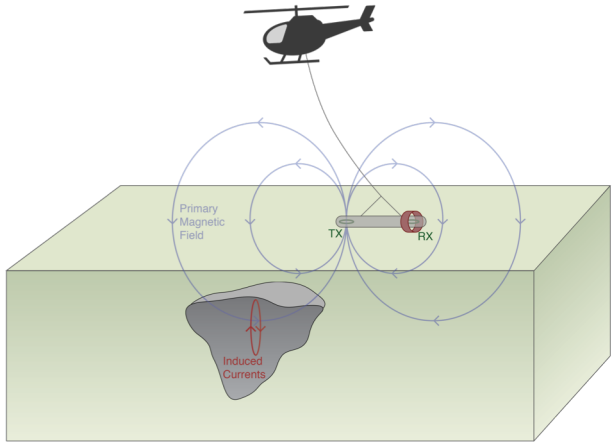


# Exciting the target

- Primary field from a loop

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3}\right)$$

- Fields fall off
  - $1/r^3$ geometric decay
  - Attenuation
- Want to be as close as possible to target
  - Ground based systems
  - Helicopter
  - Fixed wing aircraft
- Always concerned about coupling

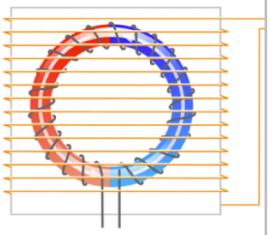


# Receiver and Data

## Magnetometer

- Measures:
  - Magnetic field
  - 3 components
- eg. 3-component fluxgate

$$\mathbf{b}(t)$$

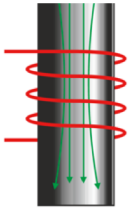


Fluxgate

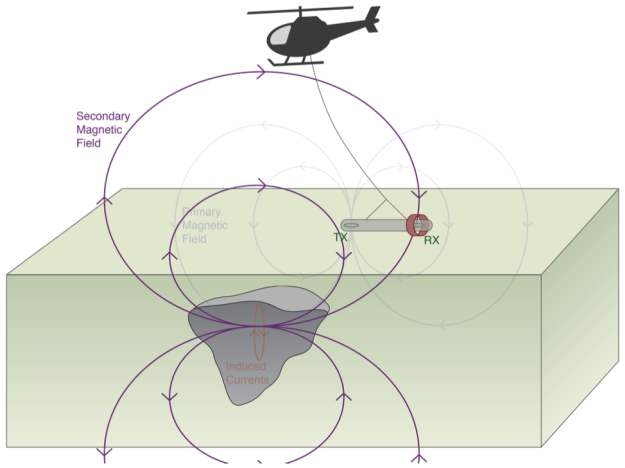
## Coil

- Measures:
  - Voltage
  - Single component that depends on coil orientation
    - Coupling matters
- eg. airborne frequency domain.
  - ratio of Hs/Hp is the same as Vs/Vp

$$\frac{\partial b}{\partial t}$$

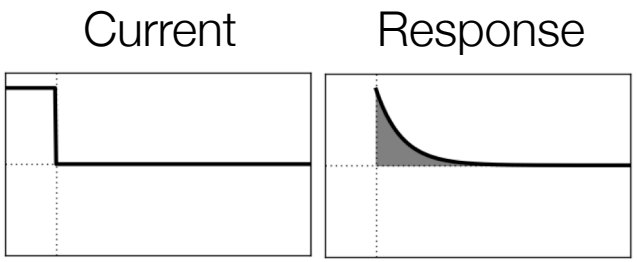


Coil

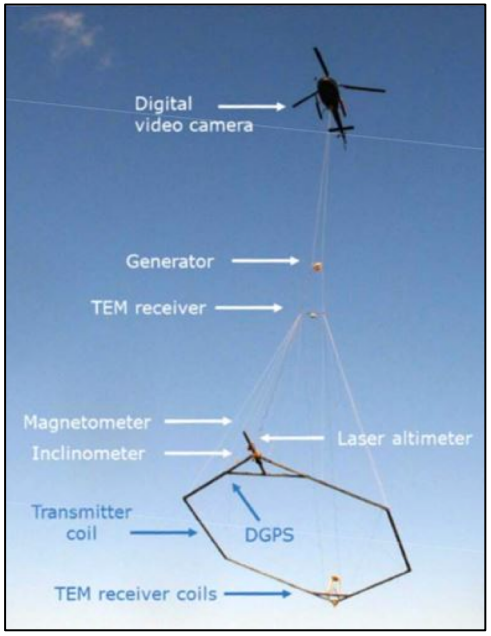


# Receiver: Time Domain

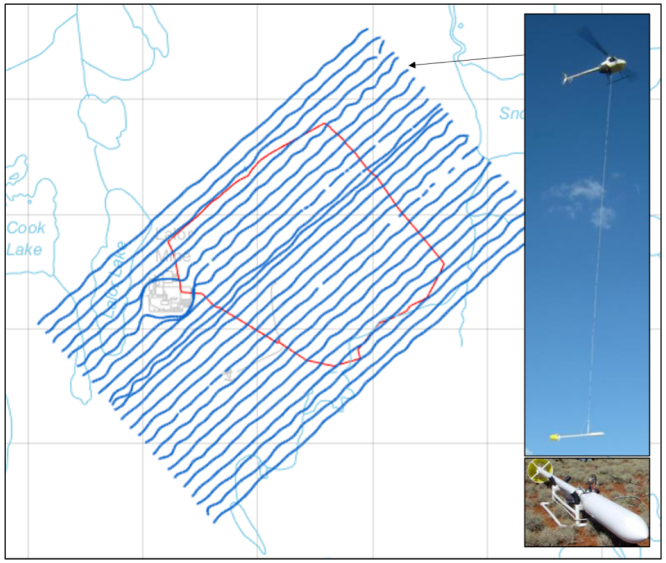
- Primary field has off-time
- Measure secondary fields
- Receivers can be mounted on transmitter loop or above it




SkyTEM

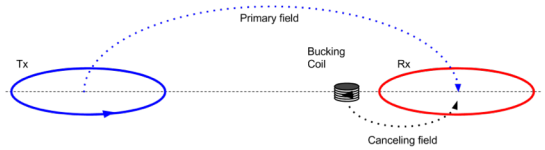



HeliSAM

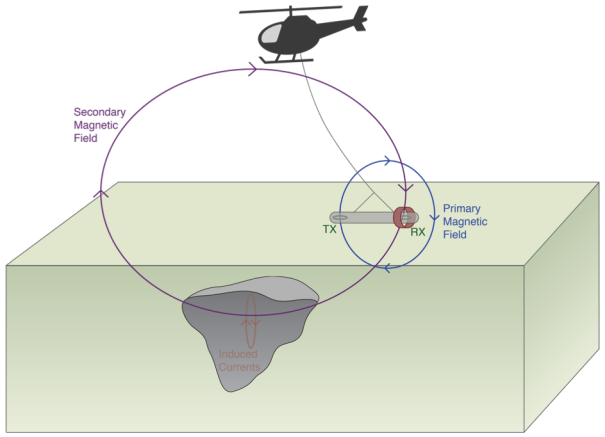


# Receiver: Frequency Domain

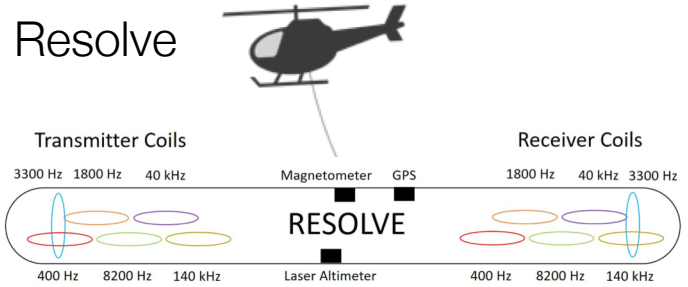
- Primary field
  - always “on”
  - large compared to secondary fields
- Primary removal
  - Compute and subtract
  - Bucking coil



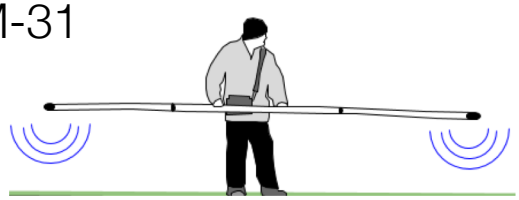

- Main requirement:
  - Know positions of Tx and Rx
  - Keep them in one unit




Resolve

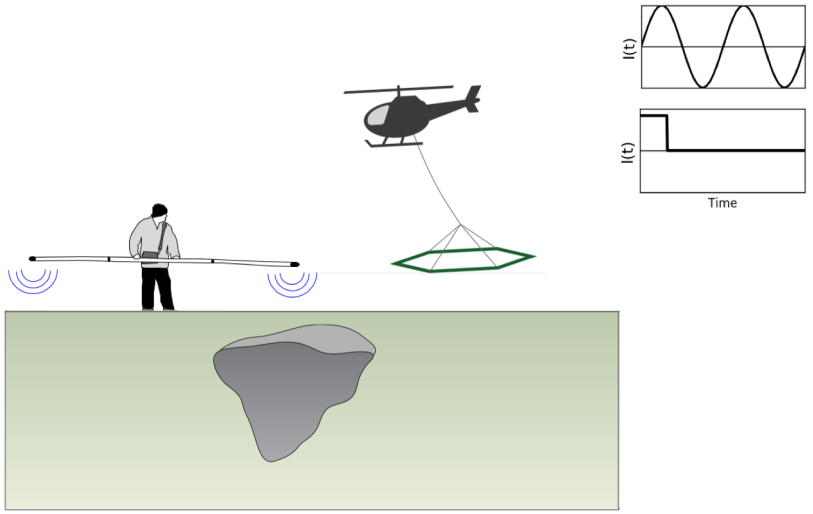



EM-31



# Important questions

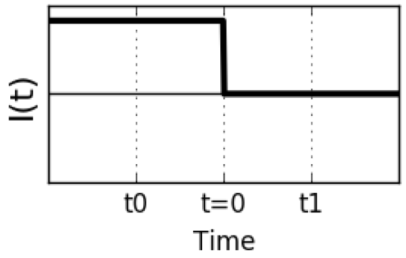
- What is the target?
  - at the surface? At depth?. 1D, 2D, 3D?
- Transmitter
  - Location: surface? in the air?
  - Waveform: frequency or time?
  - "Size" and orientation?
- Exciting the target
  - Conductivity of the target and host
  - Geometry of the target (Coupling)
- Receiver and data
  - What fields to measure?
  - What instrument?

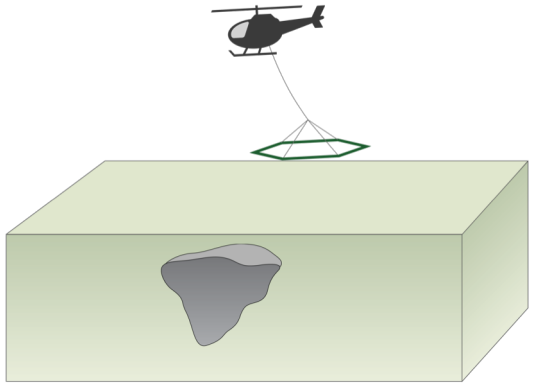



- Where to collect data? How many? How accurate?
- What is depth of investigation?
- What is the "footprint" of the transmitter"
  - These are questions of **SURVEY DESIGN**

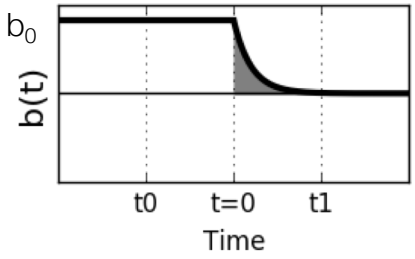
# EM with Inductive Sources: Time Domain

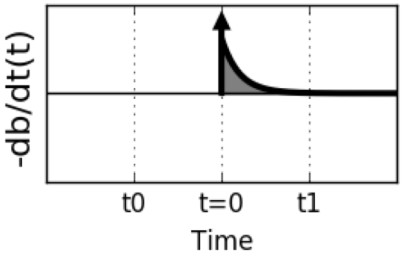
Transmitter current



Receiver




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

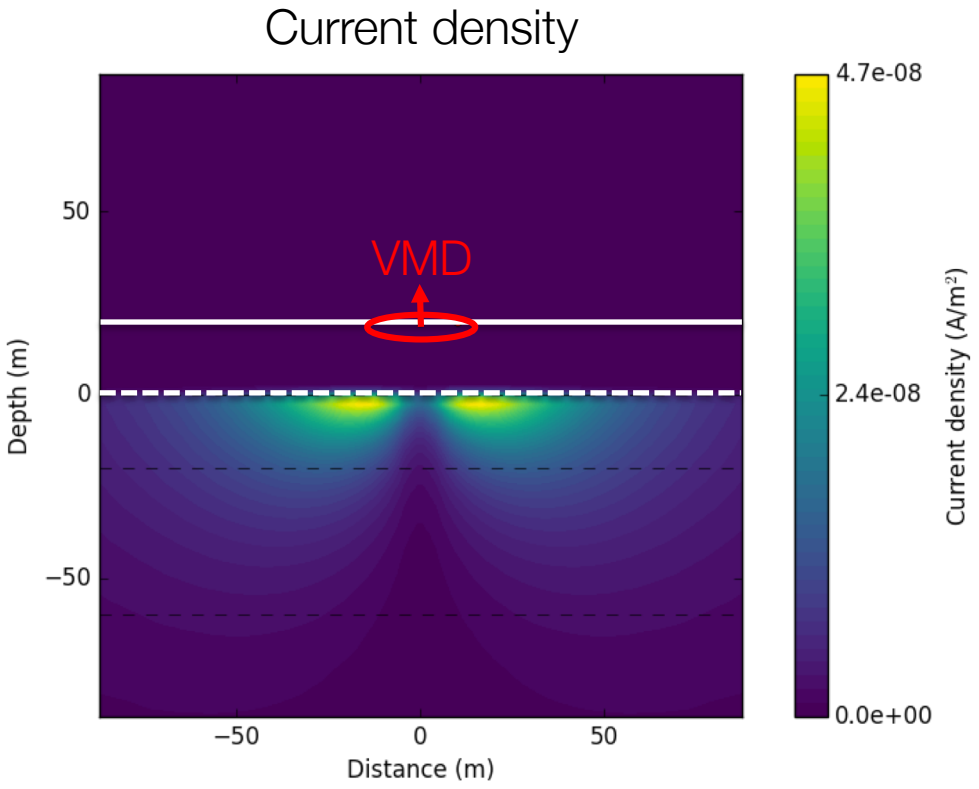
$\delta(t)$: Dirac-delta function

# Footprint of Airborne EM system

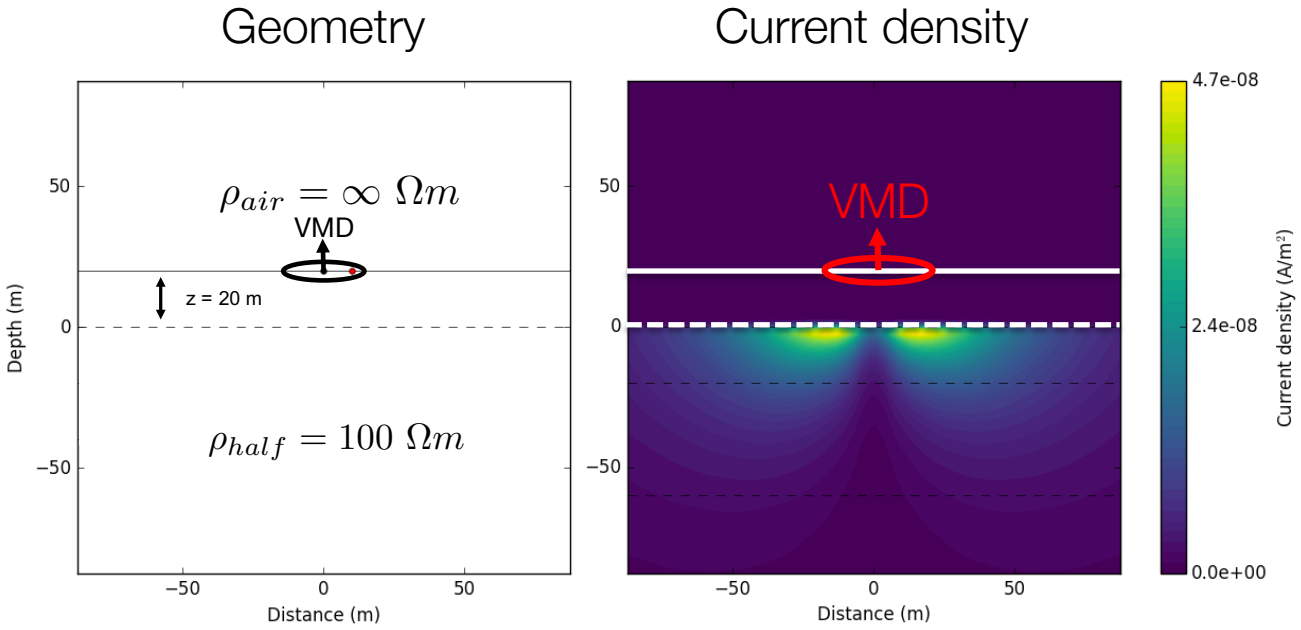
- What volume of earth is “seen” by the airborne system?
  - Where are the currents?

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

- Simple case: loop source over homogeneous earth

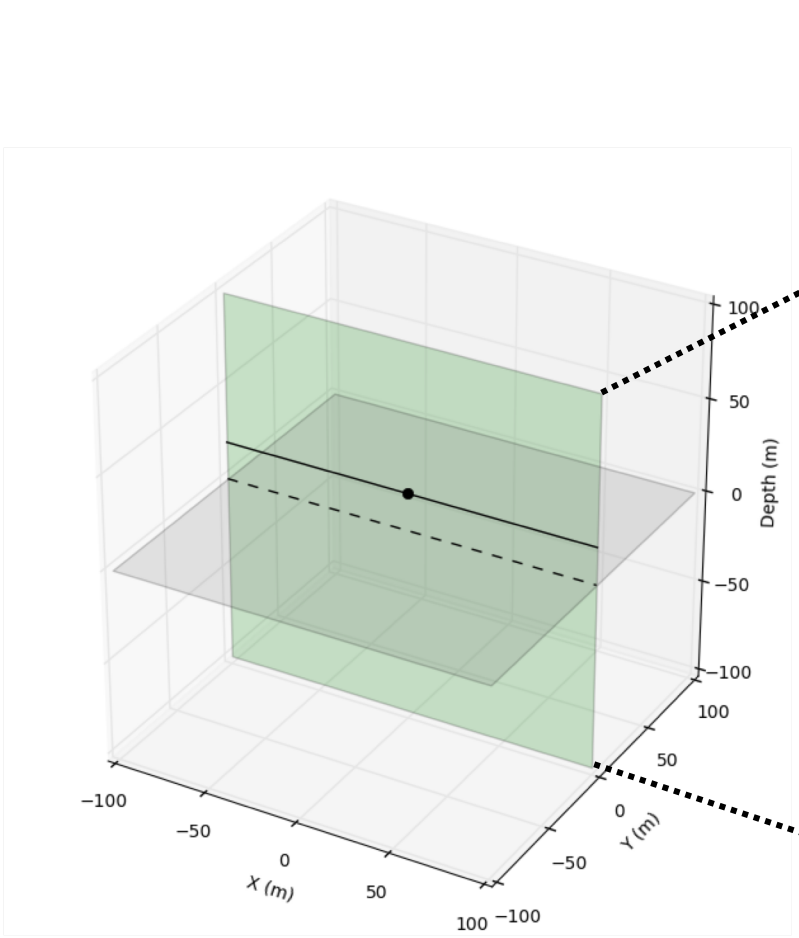


# Vertical Magnetic Dipole (VMD)

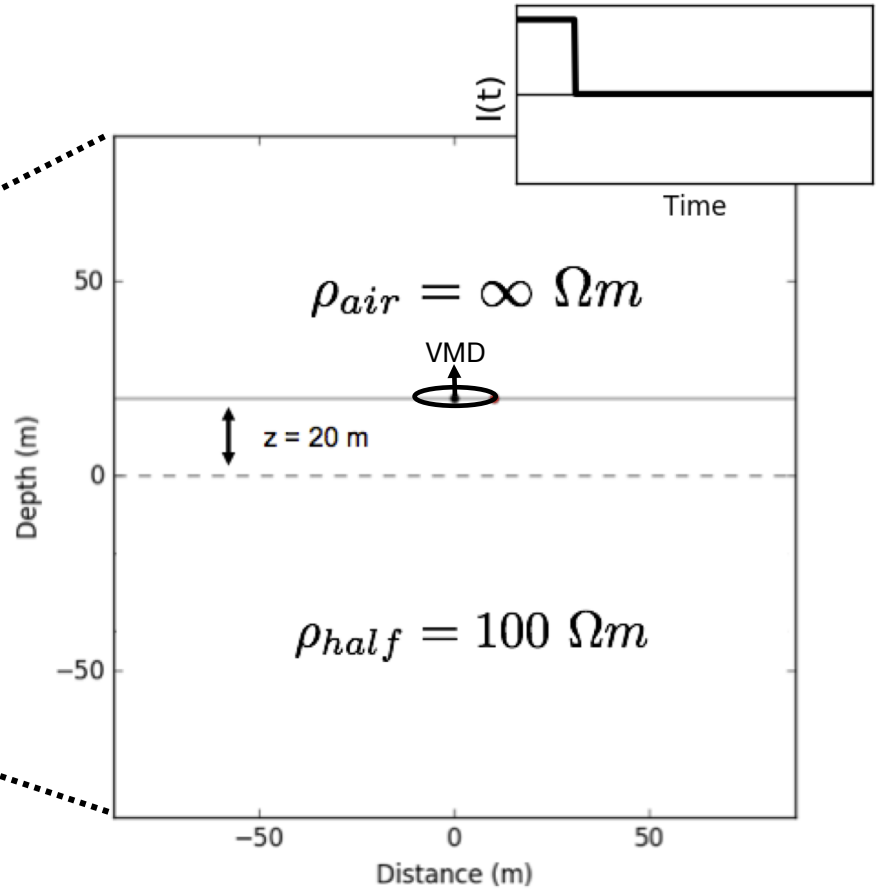



- Some questions
  - Where, and how strong, are the currents?
  - How do they depend upon the conductivity?
  - What do the resulting magnetic fields look like?

# Vertical Magnetic Dipole over a halfspace (TDEM)



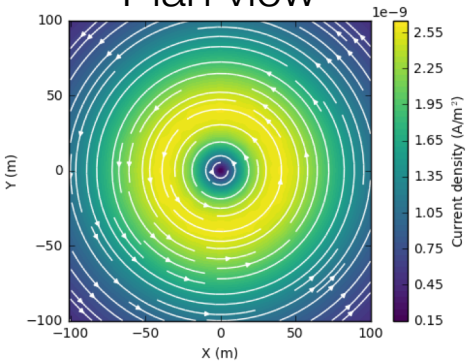

Step-off



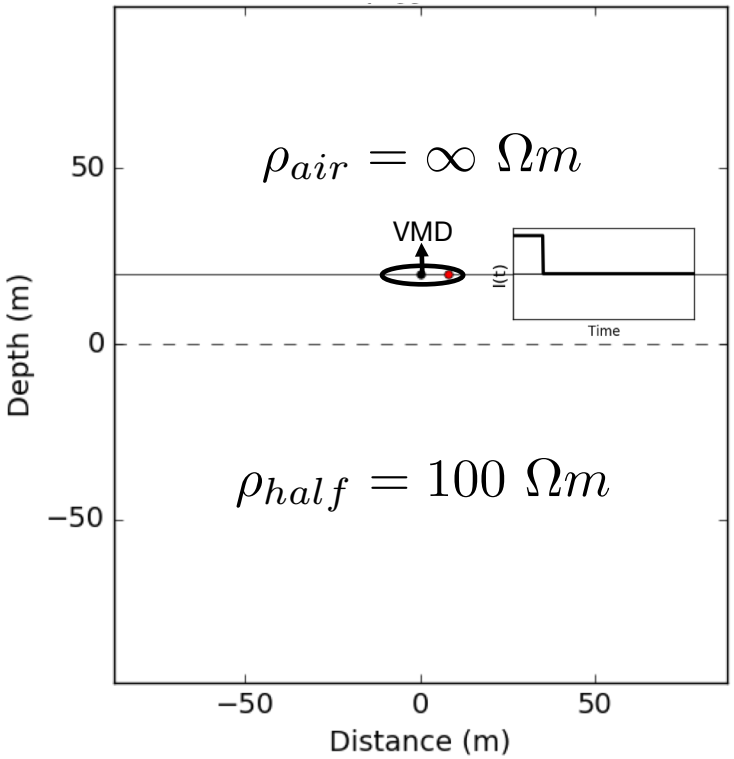
# Current Density

- Time: 0.01ms

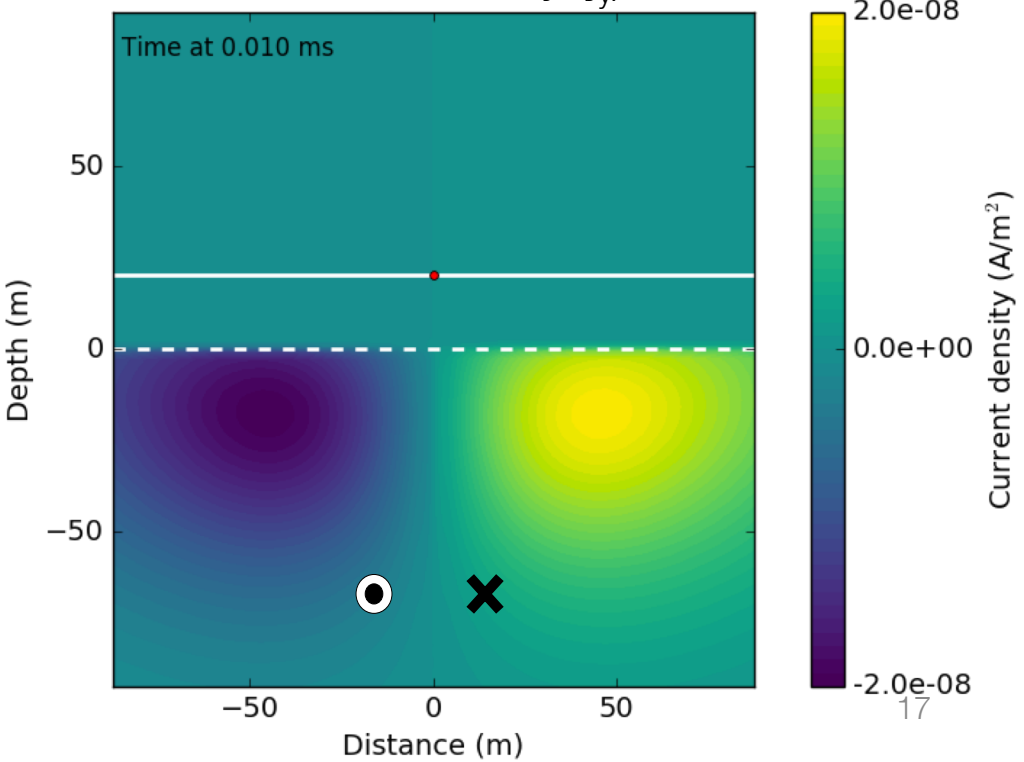
Plan view




Geometry

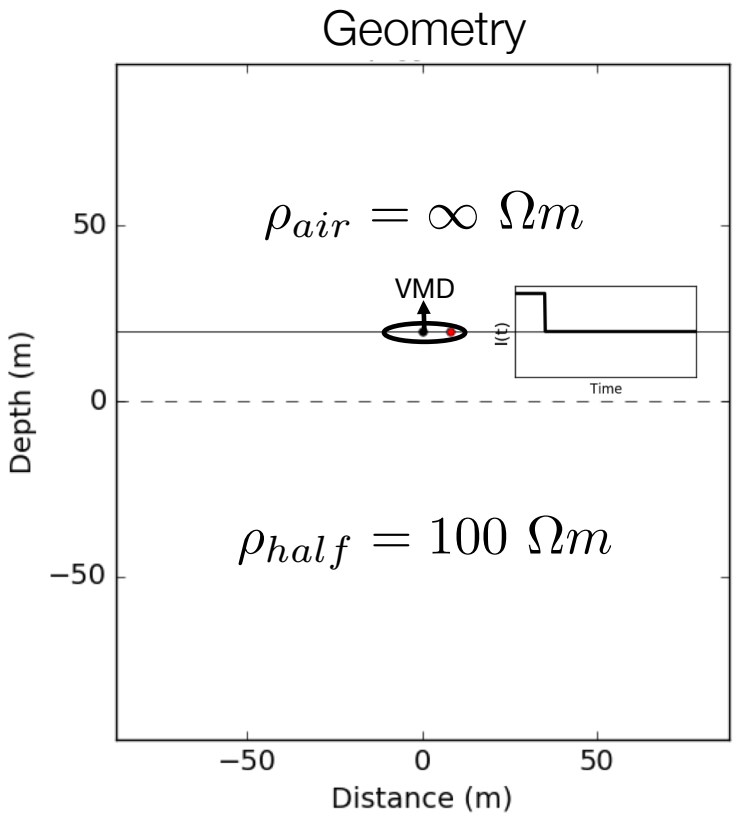


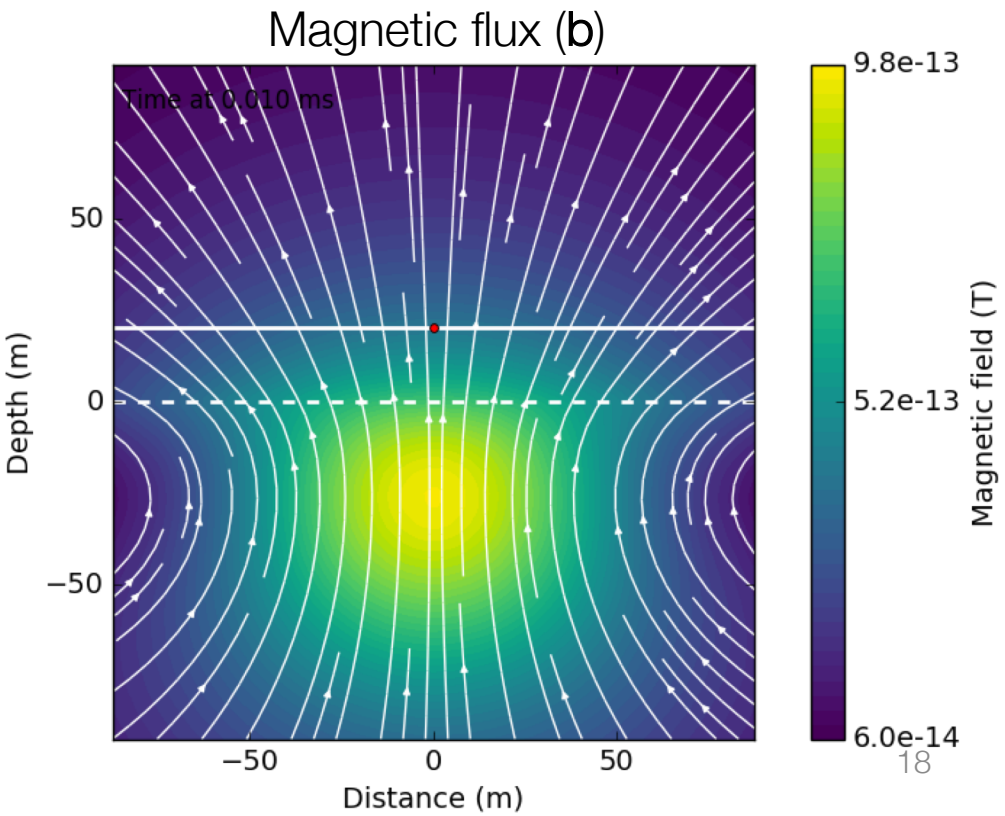

Current density ($j_y$)



# Magnetic flux density

- Time: 0.01ms

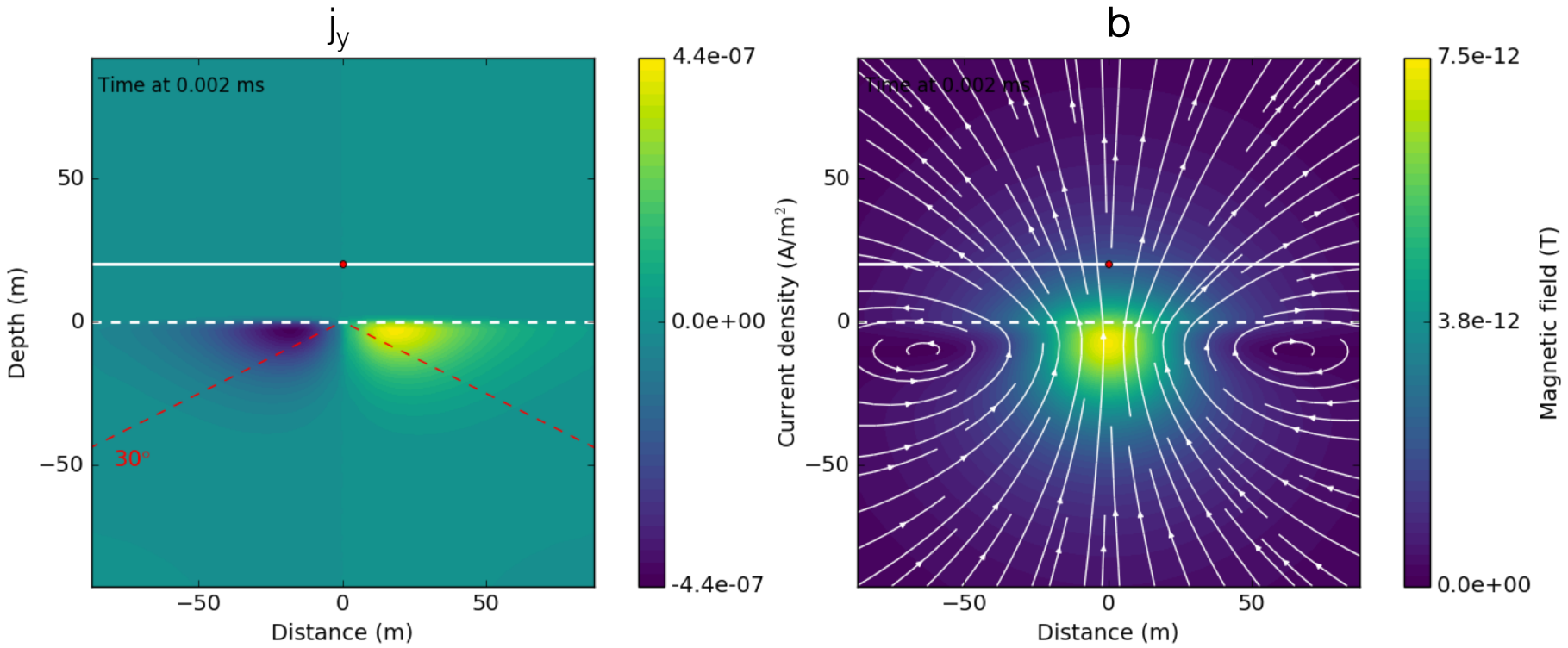


# Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

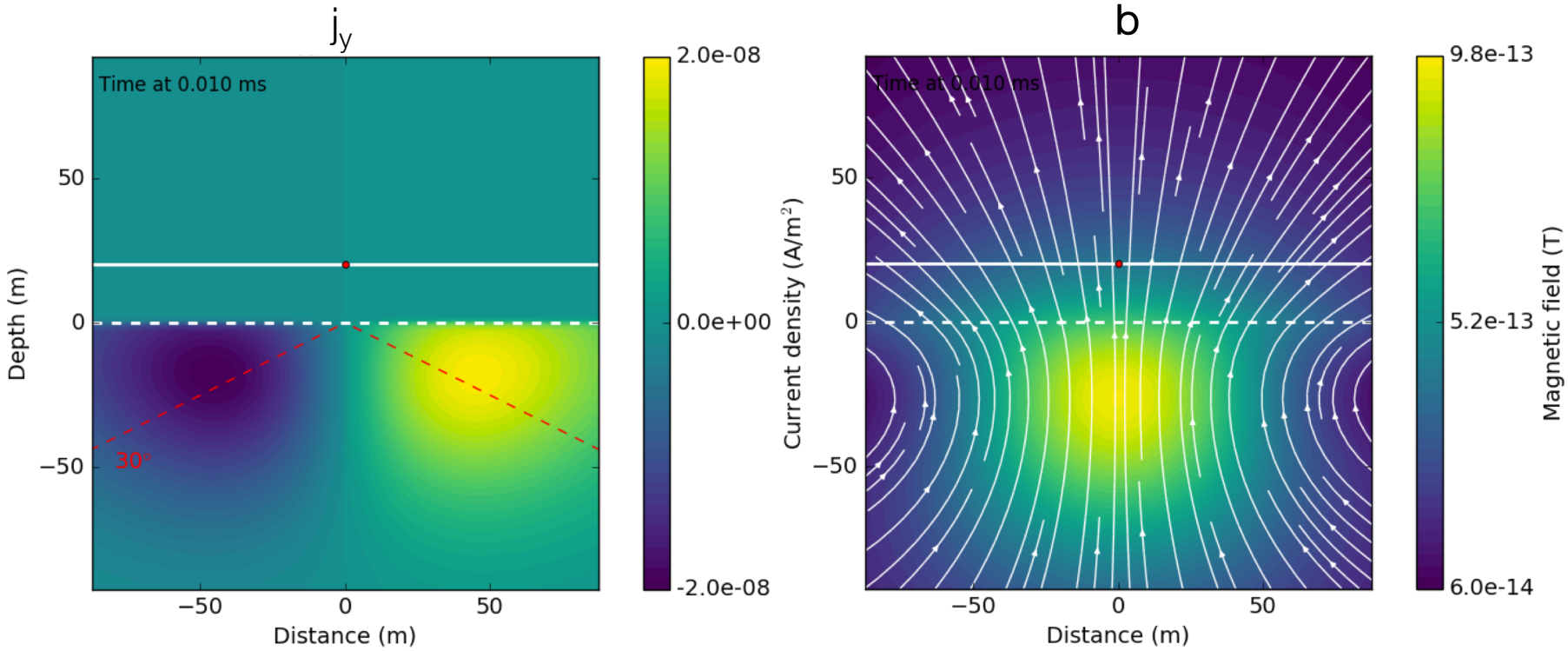
$$d = 1260\sqrt{t\rho}$$



# Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

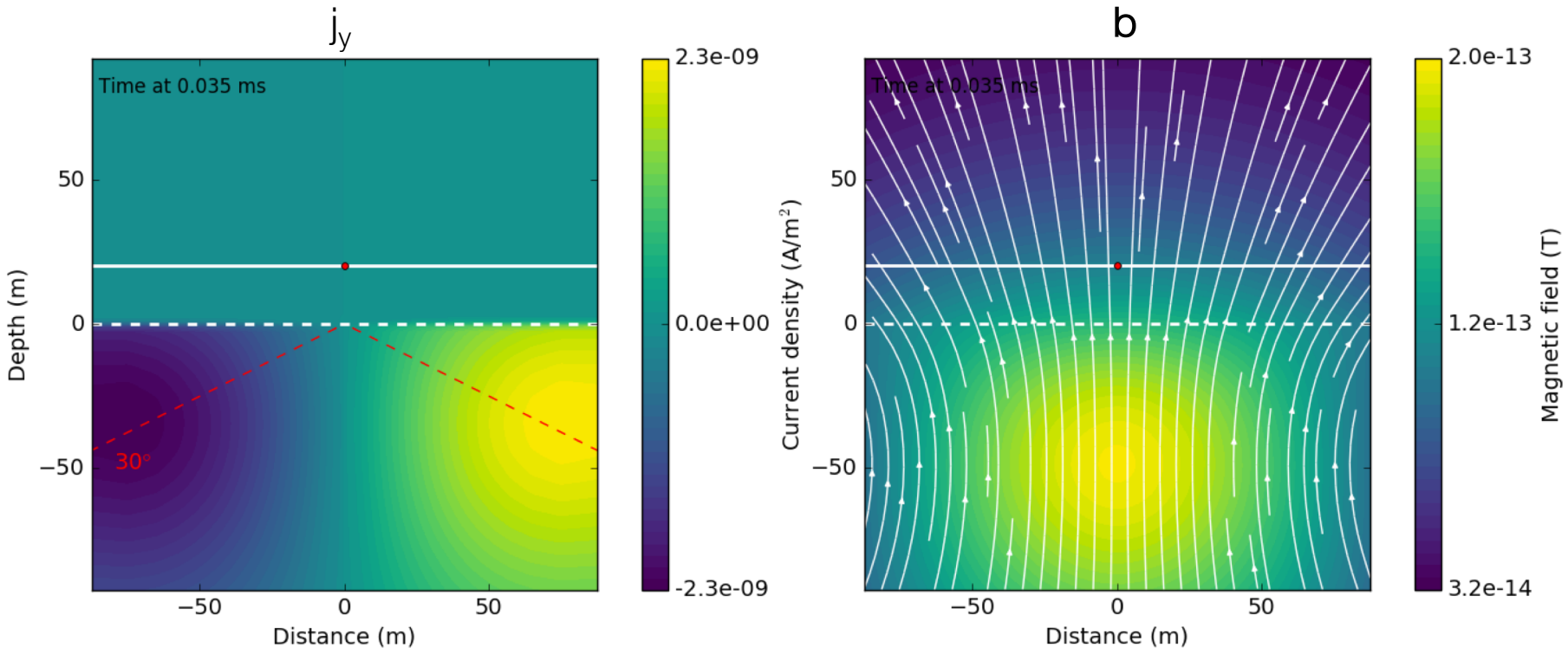
$$d = 1260\sqrt{t\rho}$$



# Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

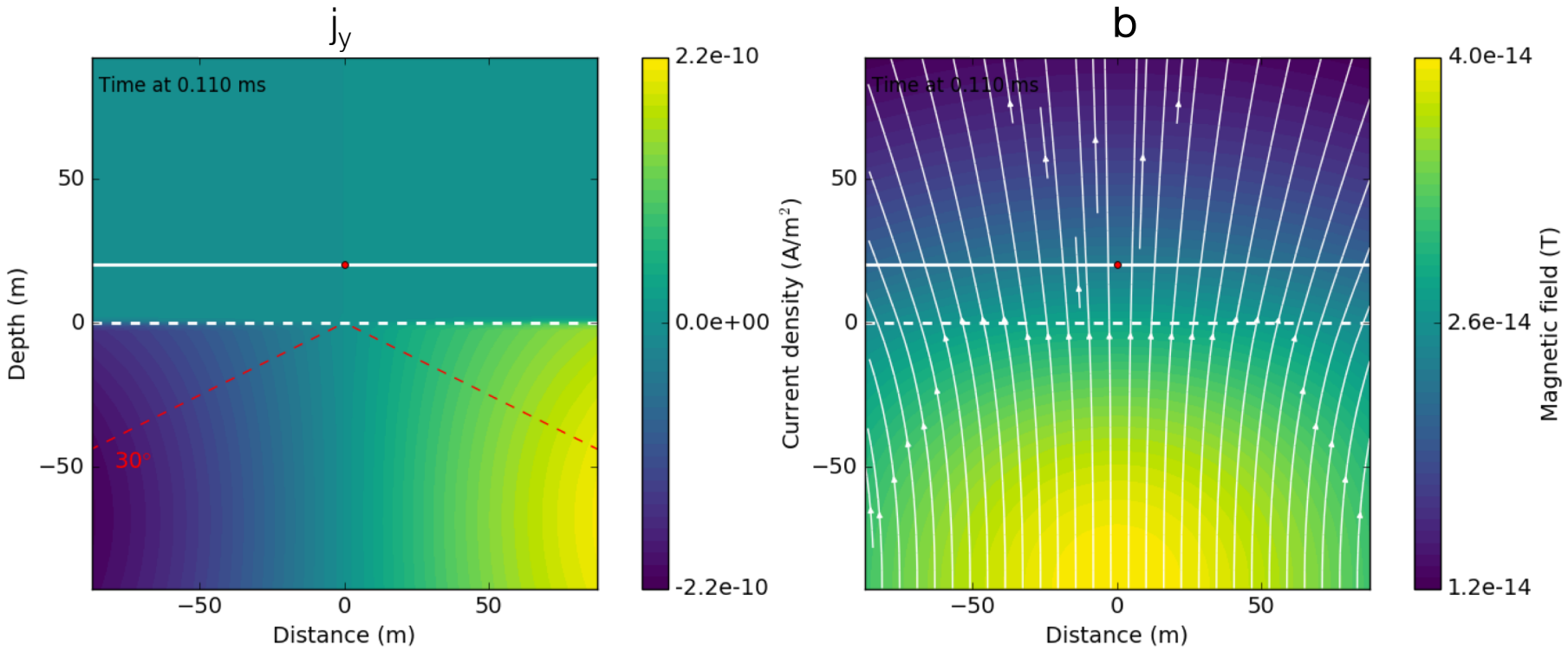
$$d = 1260\sqrt{t\rho}$$



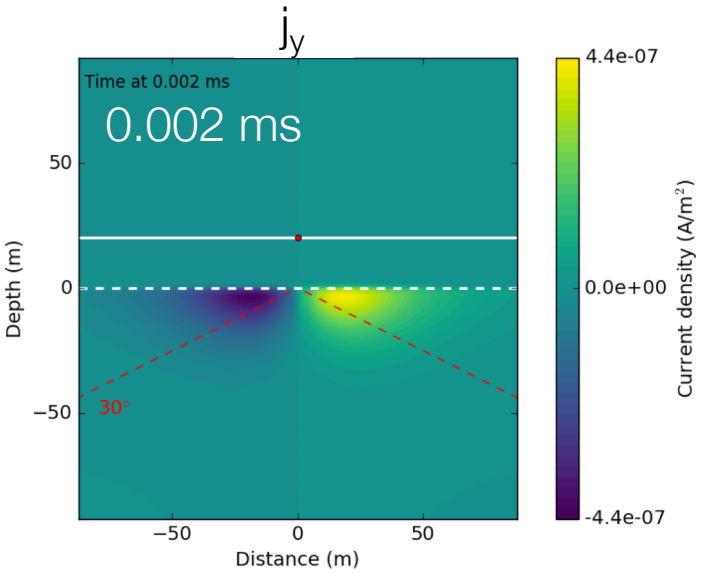
# Propagation through time

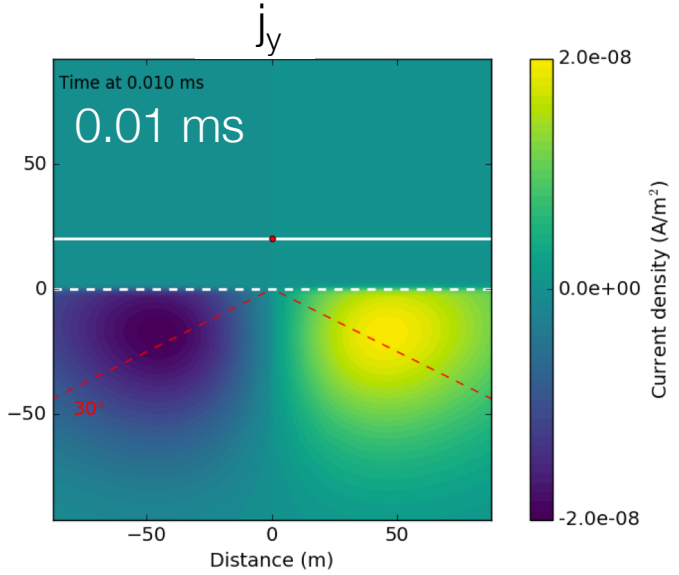
- Time: 0.110ms
- diffusion distance = 132 m

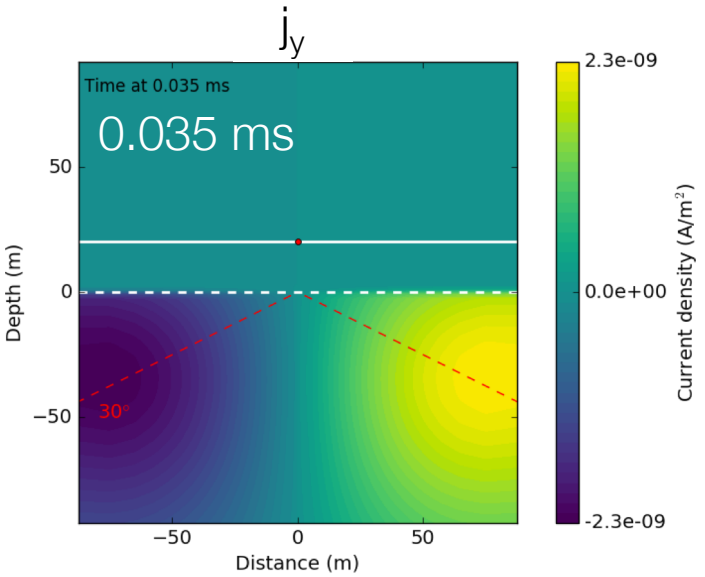
$$d = 1260\sqrt{t\rho}$$



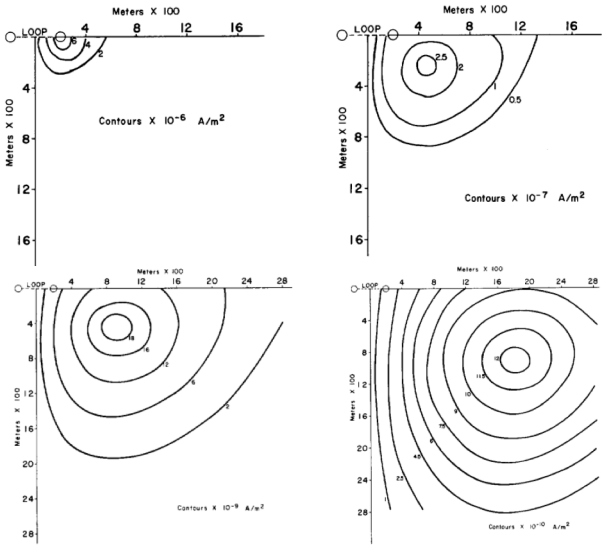
# Summary: propagation through time



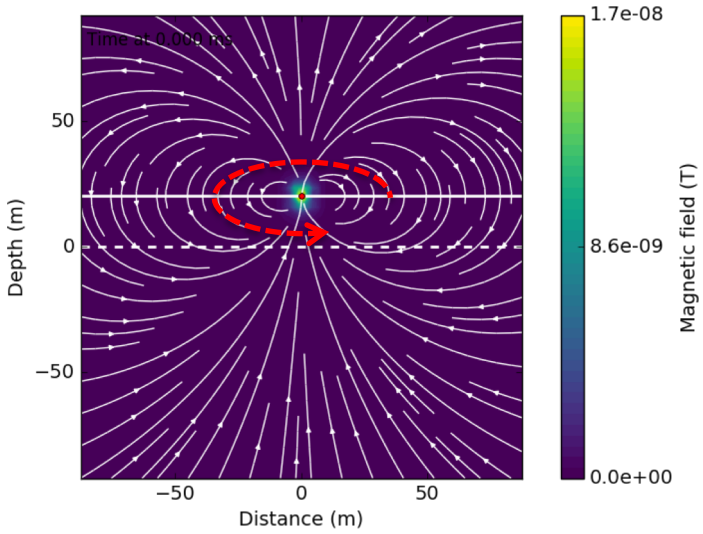

Nabighian (1979)



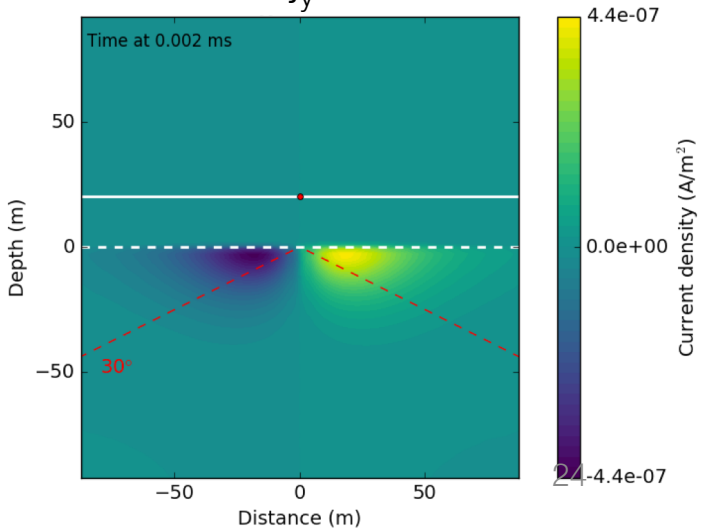
# Important points

- 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)



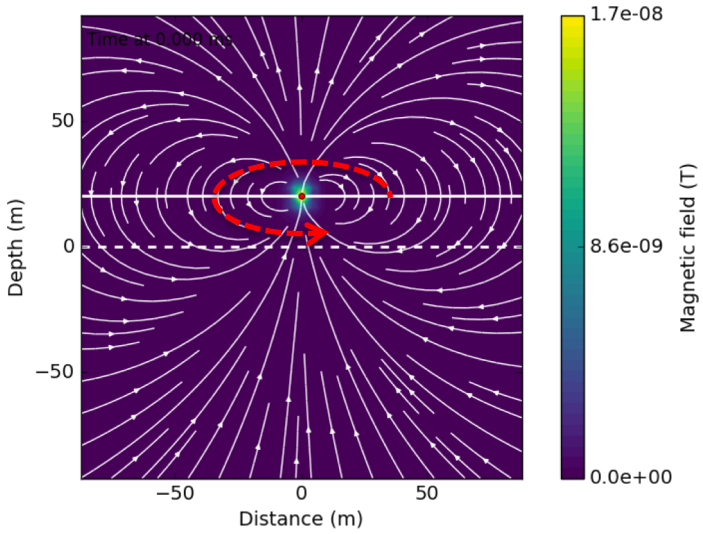

$j_y$



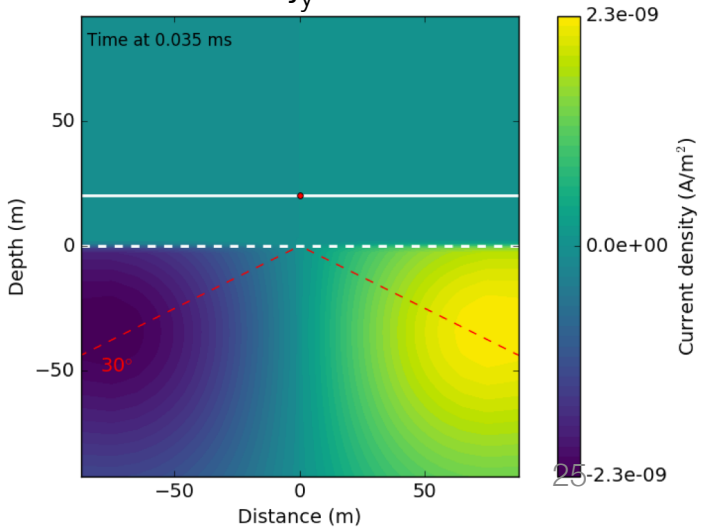
# Important points

- 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)

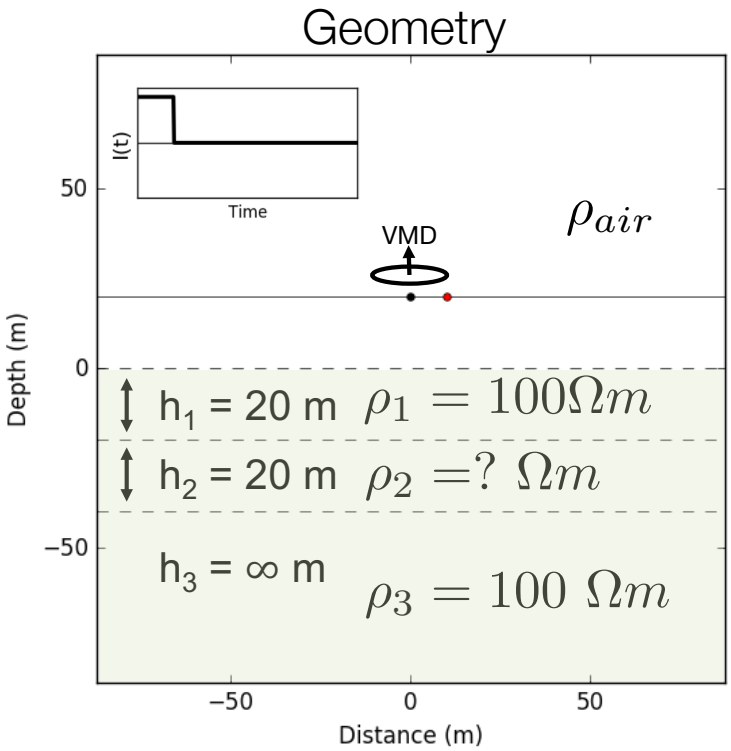



$j_y$



# Layered earth

- 3 layers + air,
- $\rho_2$ varies

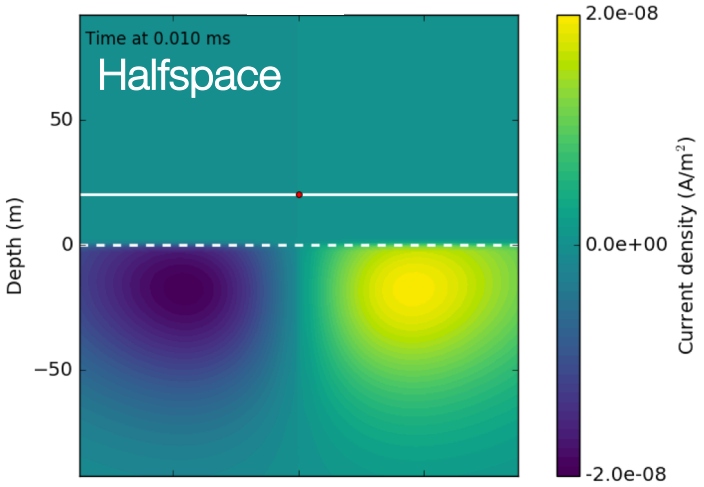



- Four different cases:
  - Halfspace
    $\rho_2 = 100 \ \Omega m$
  - Resistive
    $\rho_2 = 1000 \ \Omega m$
  - Conductive
    $\rho_2 = 10 \ \Omega m$
  - Very conductive
    $\rho_2 = 1 \ \Omega m$

- Fields
  - $j_y$ off-time
  - **b** off-time

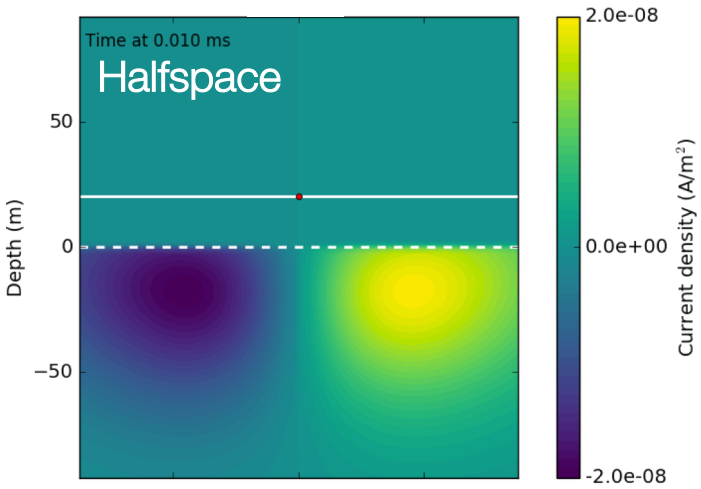
# Layered earth currents ($j_y$)

$\rho_2 = 100\ \Omega m$

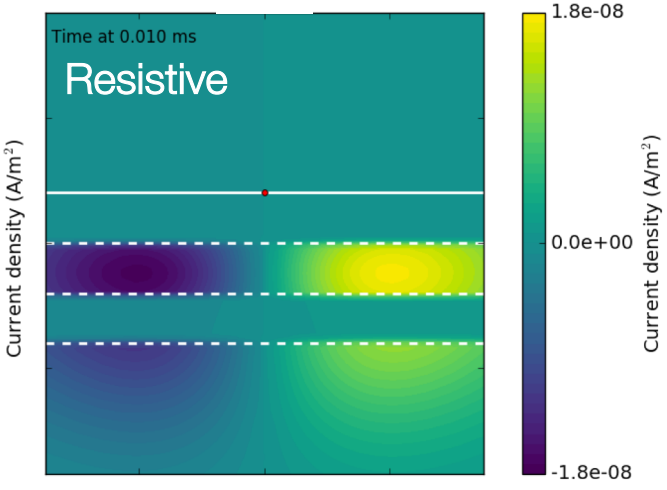


# Layered earth currents ($j_y$)

$\rho_2 = 100\ \Omega m$

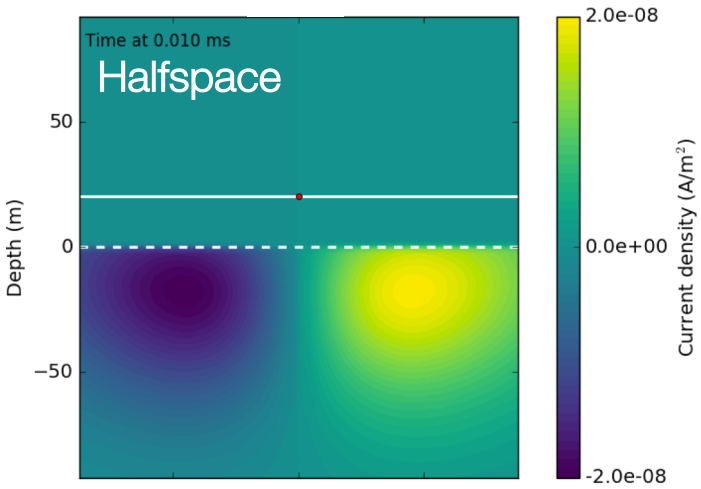



$\rho_2 = 1000\ \Omega m$

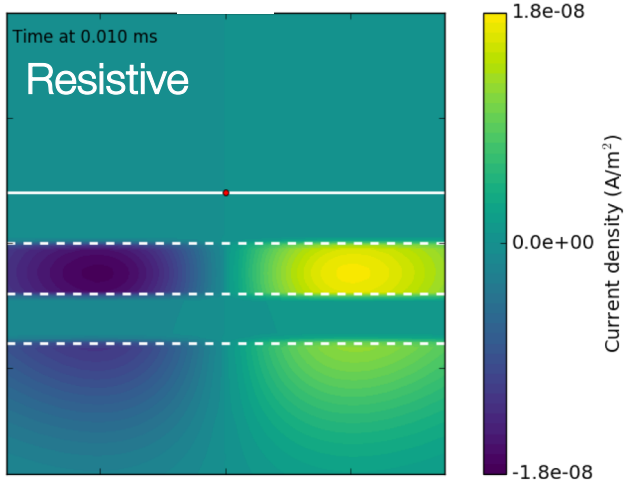


# Layered earth currents ($j_y$)

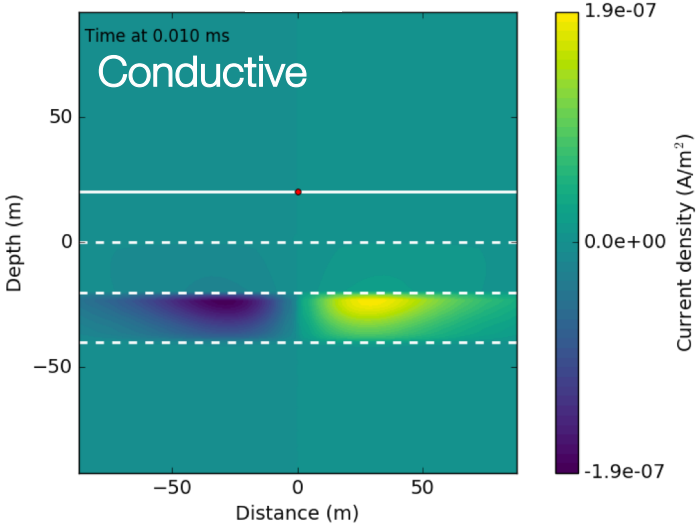
$\rho_2 = 100\ \Omega m$




$\rho_2 = 1000\ \Omega m$

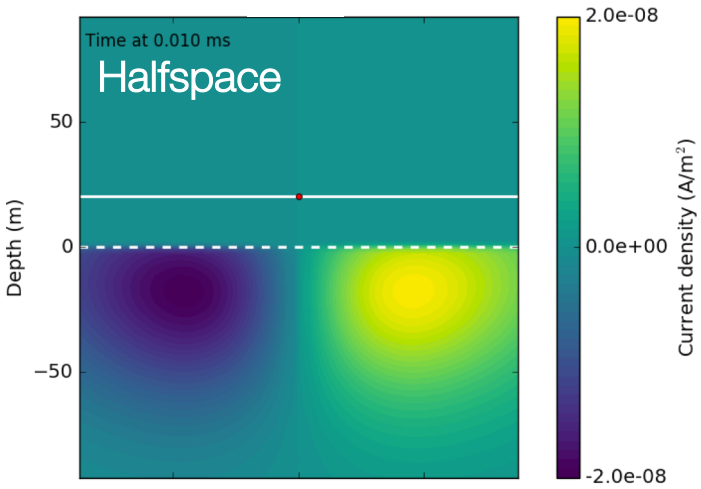



$\rho_2 = 10\ \Omega m$

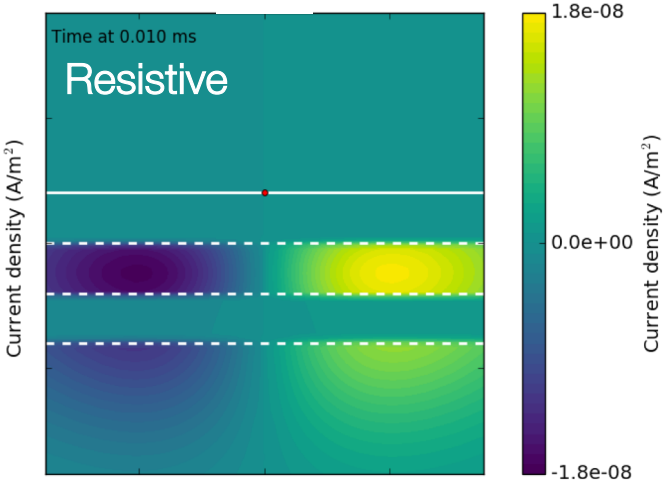


# Layered earth currents ($j_y$)

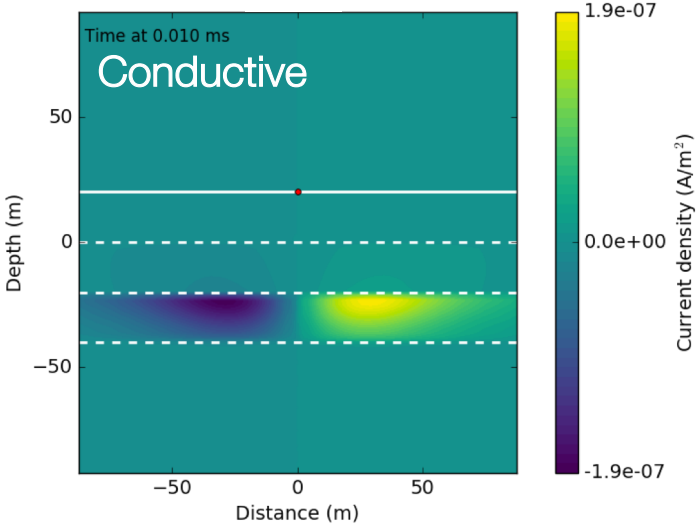
$\rho_2 = 100\ \Omega m$



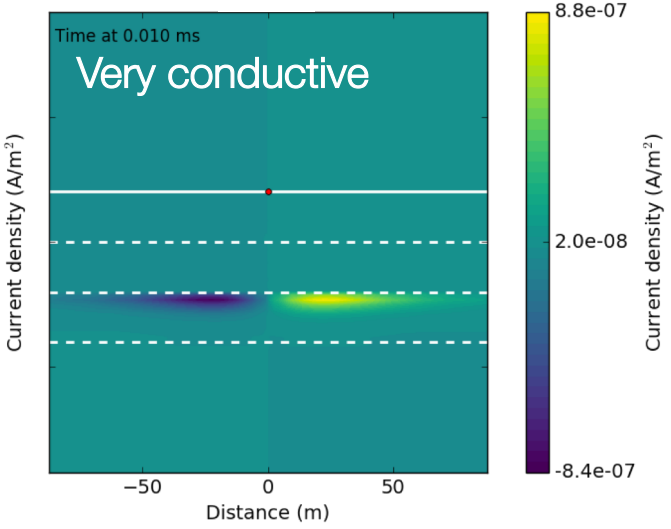

$\rho_2 = 1000\ \Omega m$




$\rho_2 = 10\ \Omega m$

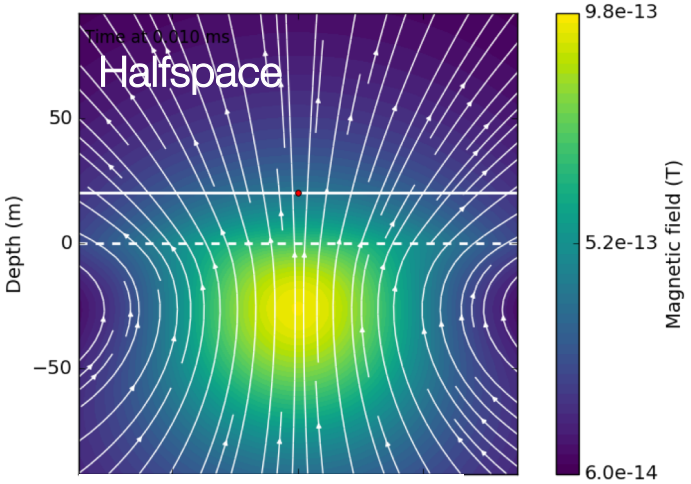



$\rho_2 = 1\ \Omega m$

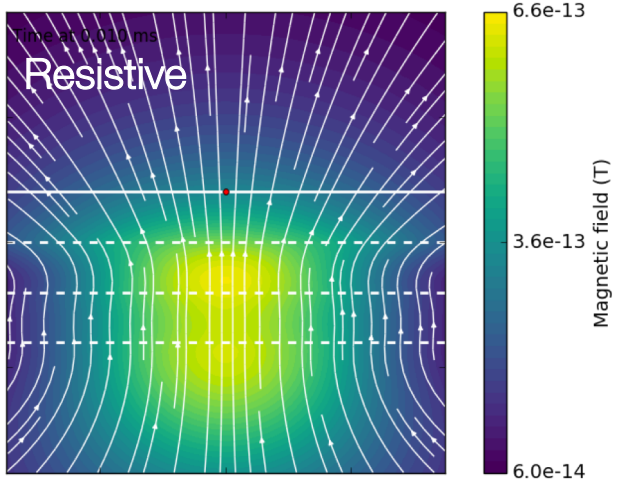


# Layered earth mag. fields (b)

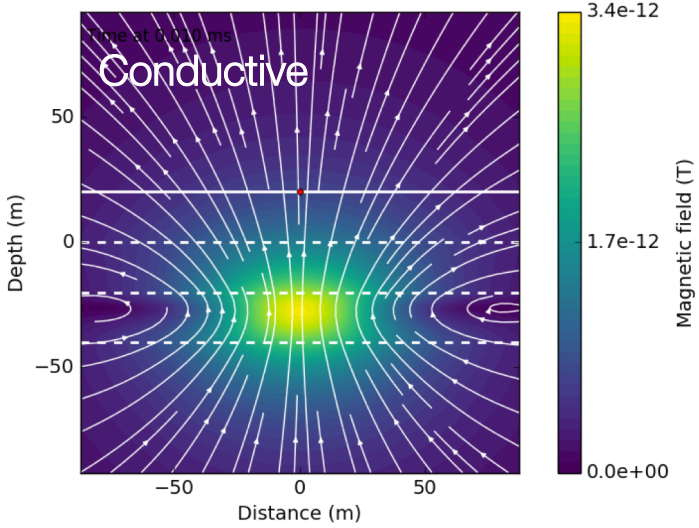
$\rho_2 = 100\ \Omega m$



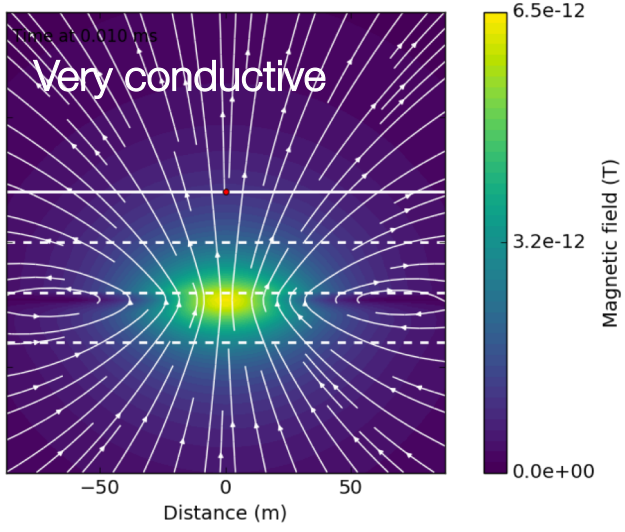

$\rho_2 = 1000\ \Omega m$




$\rho_2 = 10\ \Omega m$

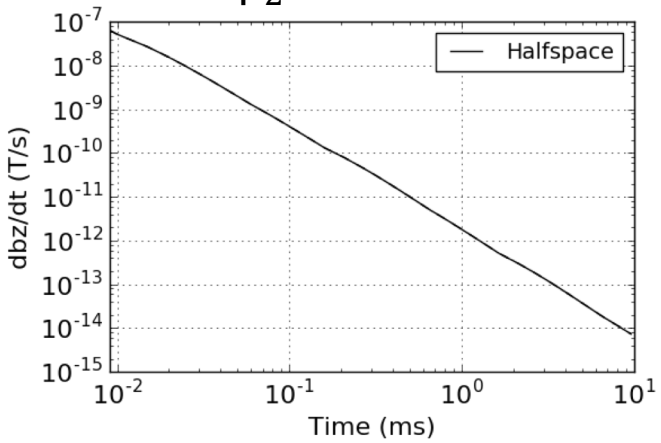


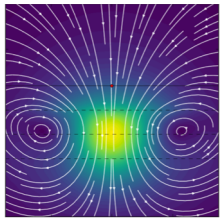

$\rho_2 = 1\ \Omega m$



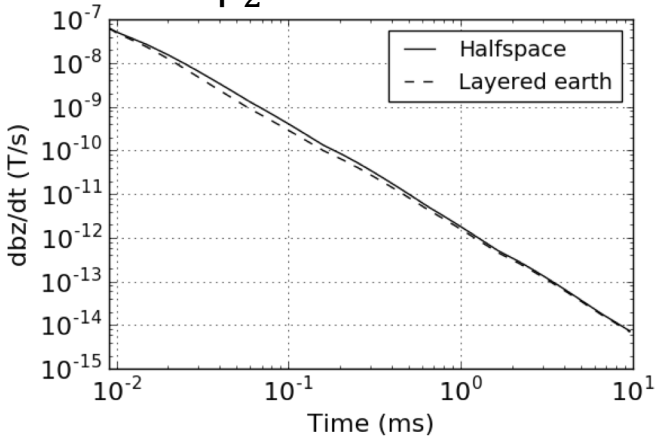
# $db_z/dt$ sounding curves

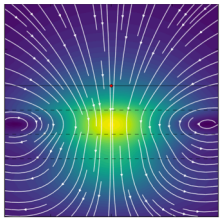
$\rho_2 = 100\ \Omega m$



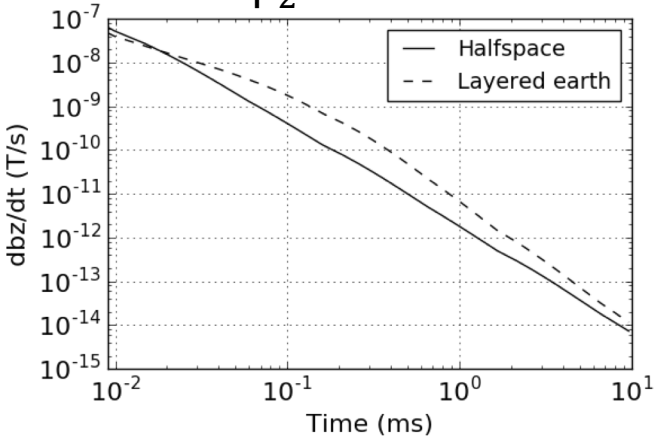



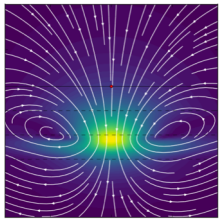
$\rho_2 = 1000\ \Omega m$



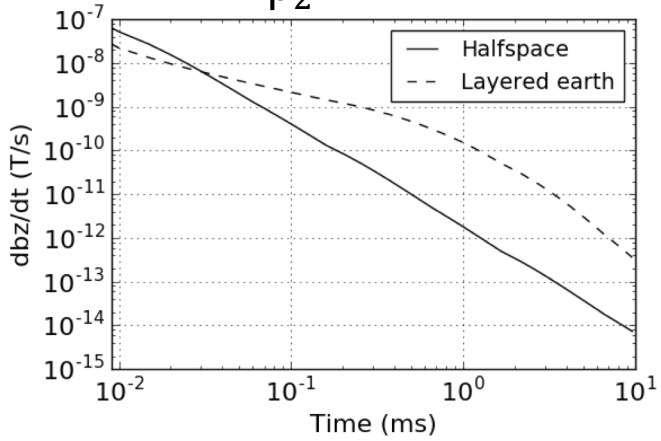



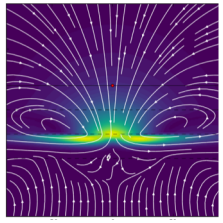
$\rho_2 = 10\ \Omega m$



$\rho_2 = 1\ \Omega m$



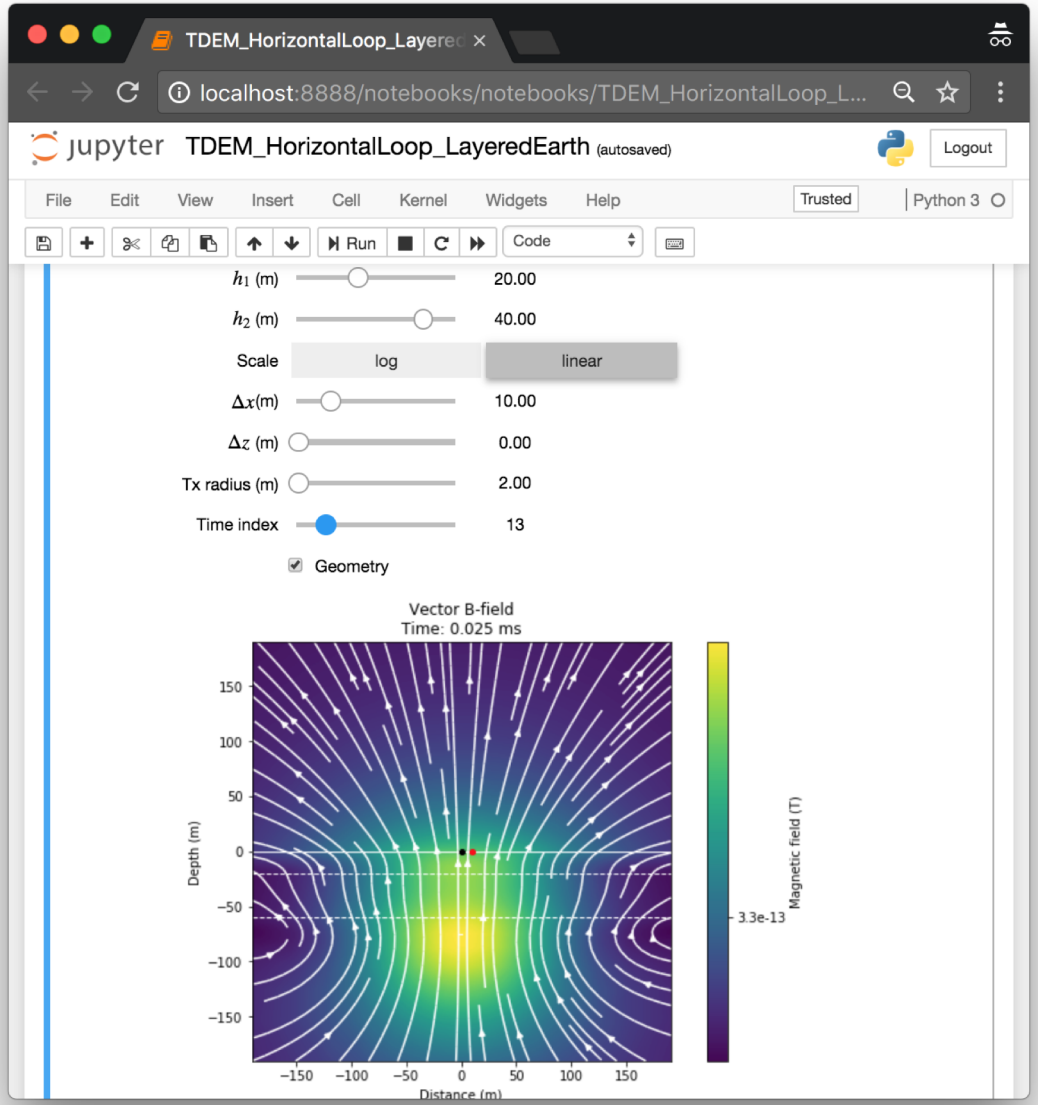



# App: VMD over a layered earth (demo)

- TDEM_HorizontalLoop_Layered Earth

- Parameters:
  - Layer resistivities
  - Layer thicknesses
  - Source height, source receiver separation

- View:
  - Model
  - Electric field, magnetic field, current density through time
  - data

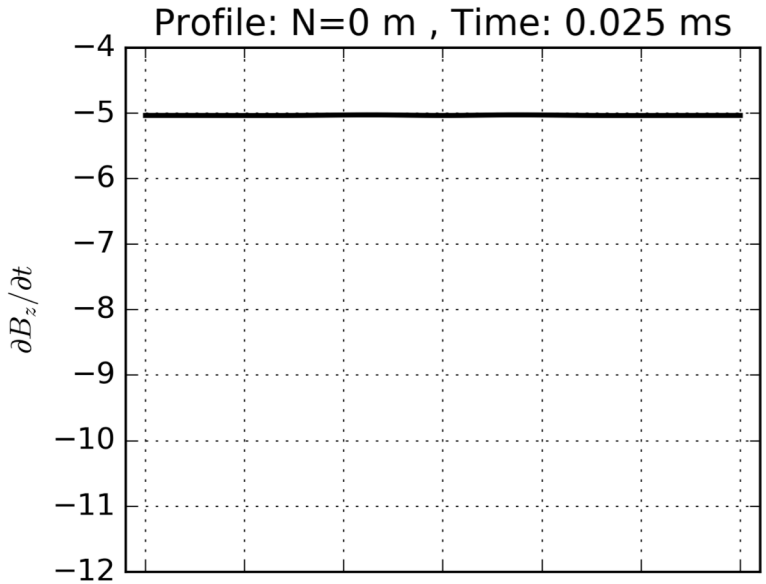




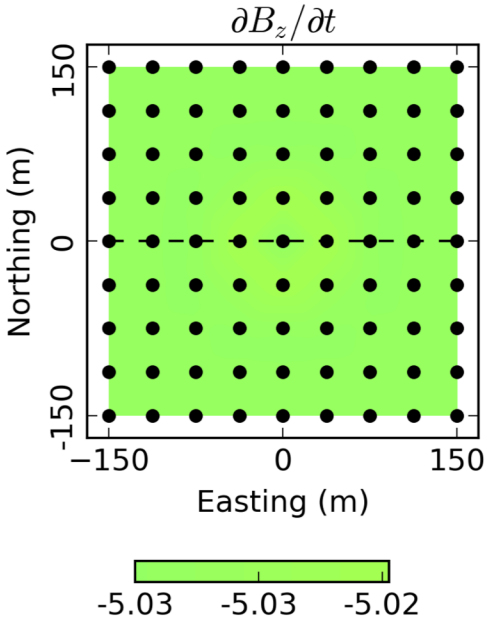

http://em.geosci.xyz/apps.html

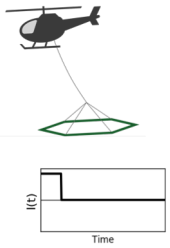
# Airborne example: conductive sphere

Data profile

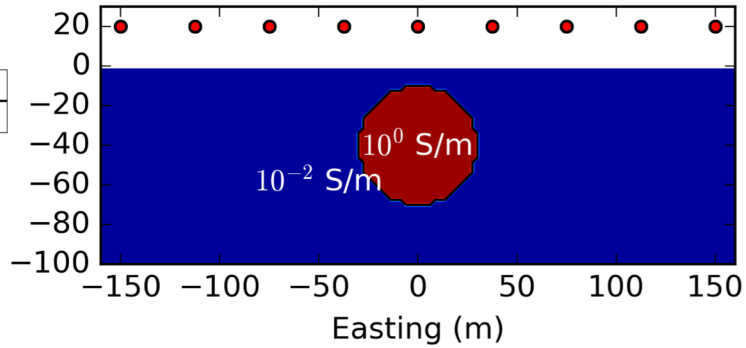



Data map



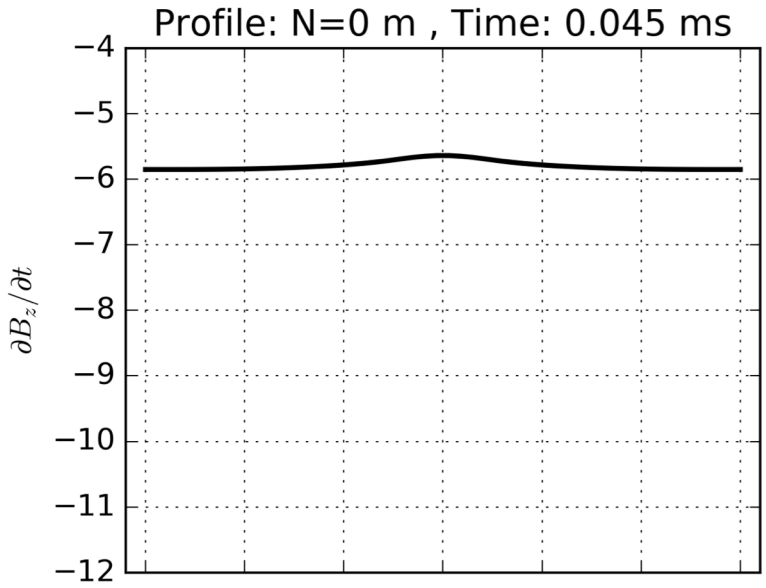




Conductivity

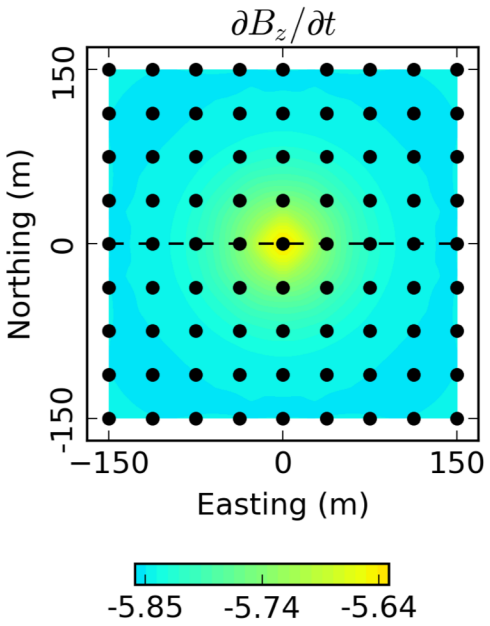


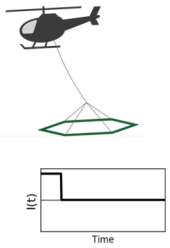
# Airborne example: conductive sphere

Data profile

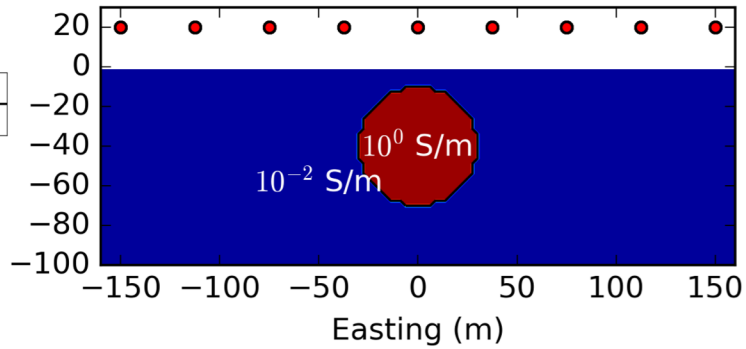



Data map



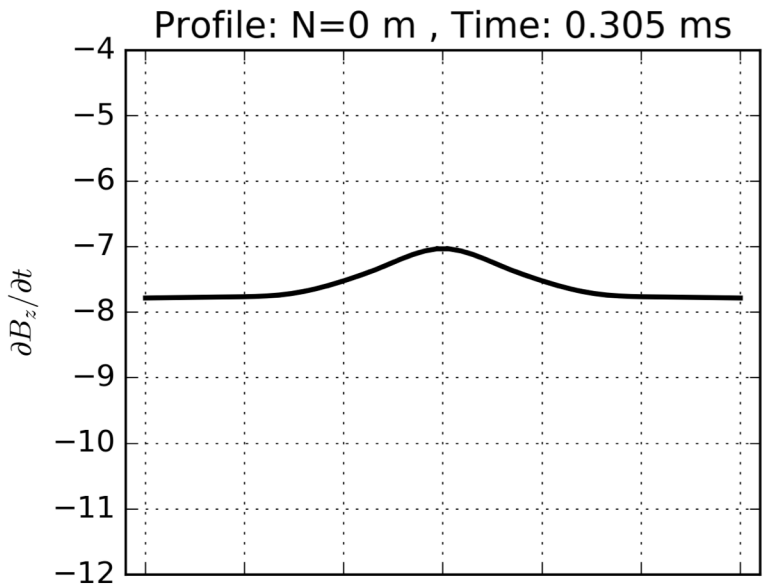




Conductivity

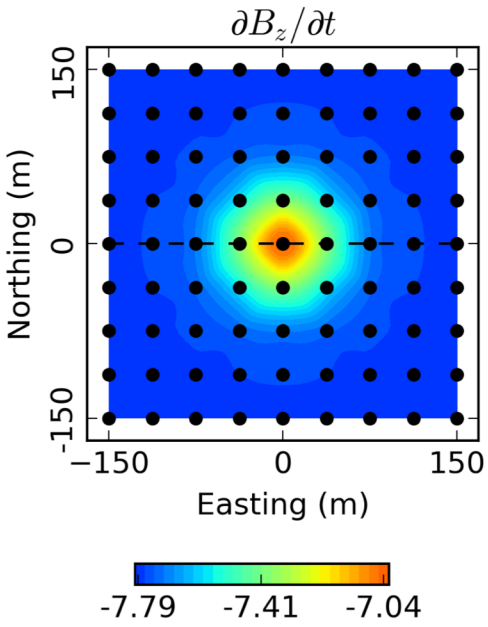


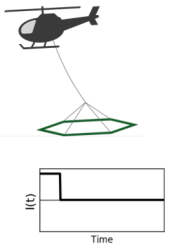
# Airborne example: conductive sphere

Data profile

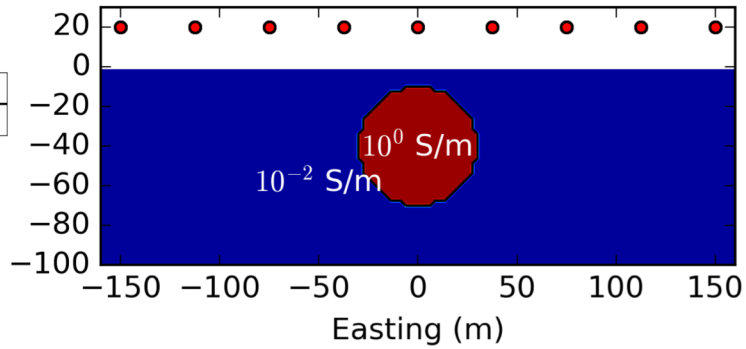



Data map



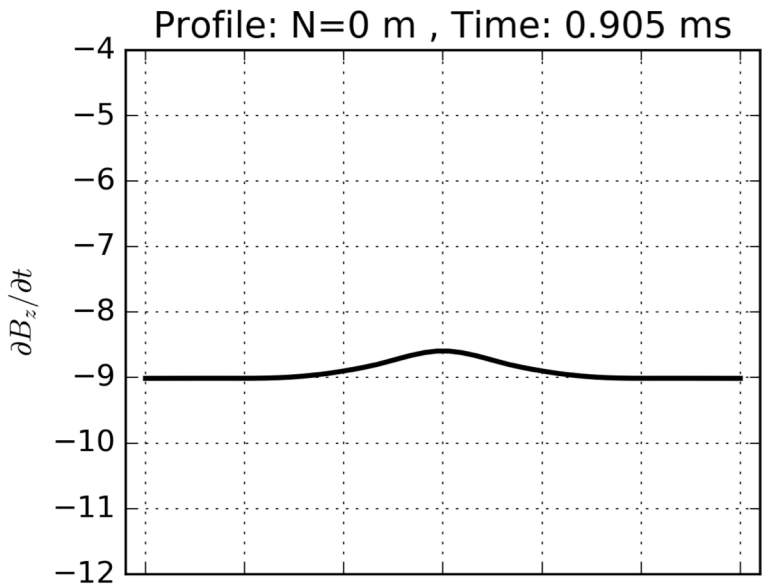




Conductivity

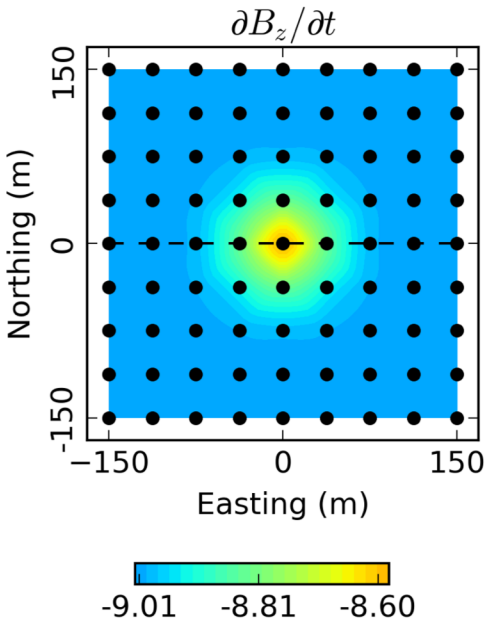


# Airborne example: conductive sphere

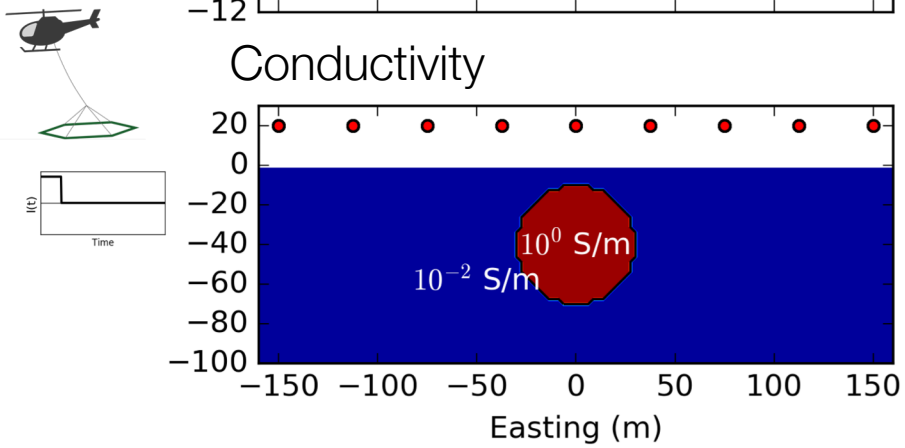
Data profile




Data map

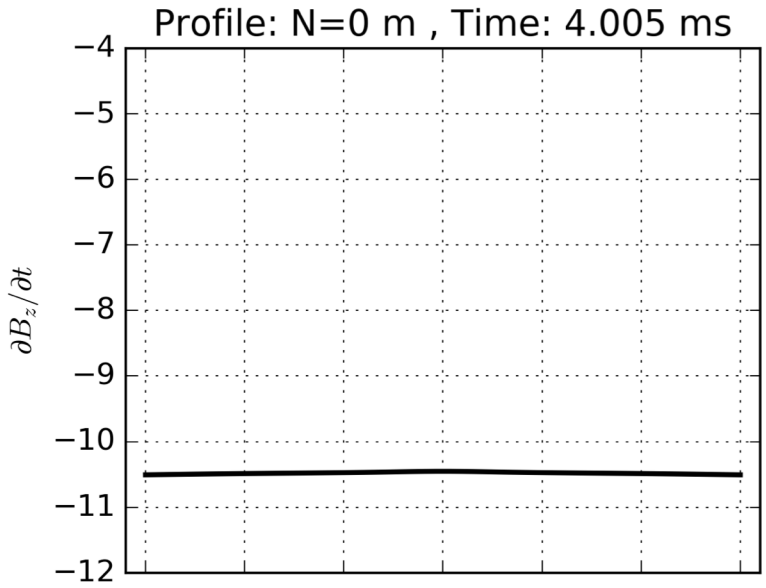



Conductivity

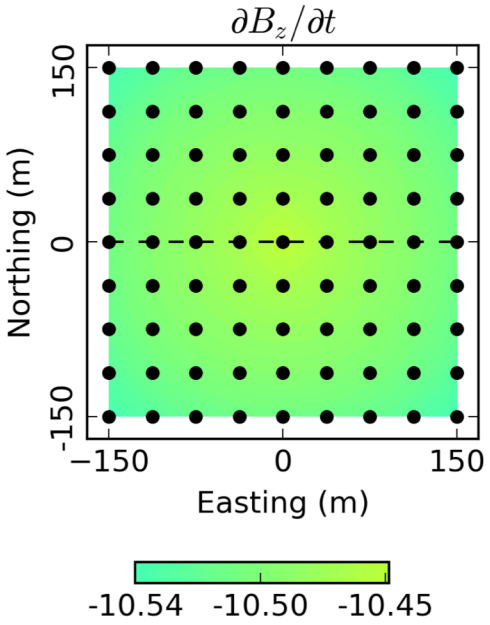


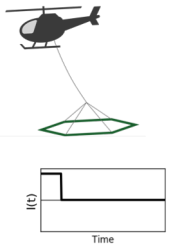
# Airborne example: conductive sphere

Data profile

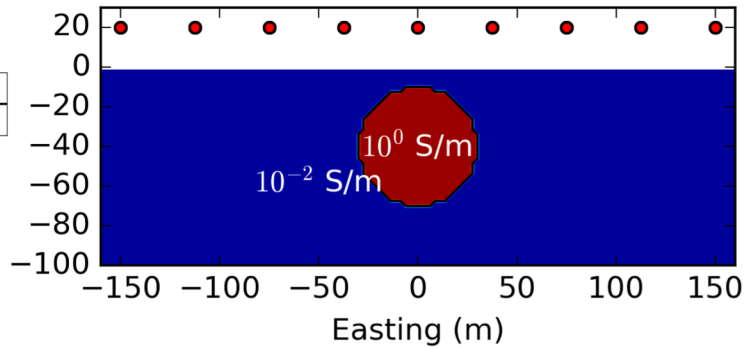



Data map



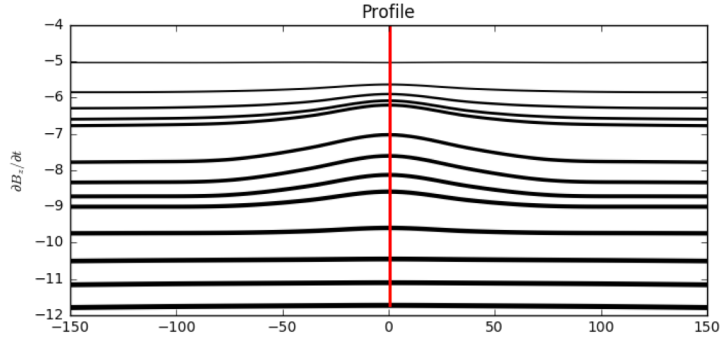



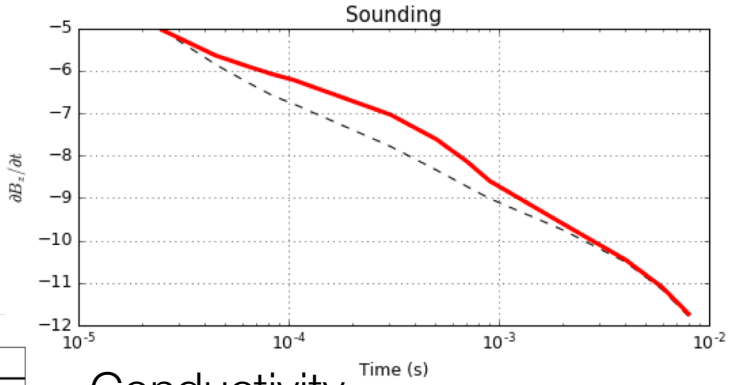

Conductivity

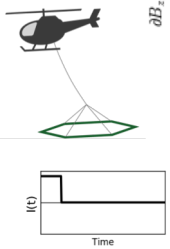


# Summary: airborne example

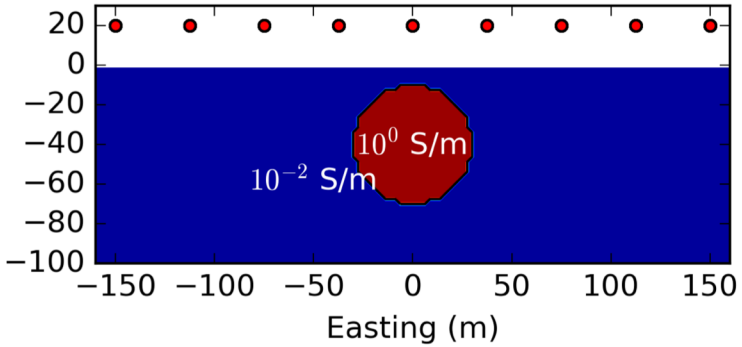
Data profile



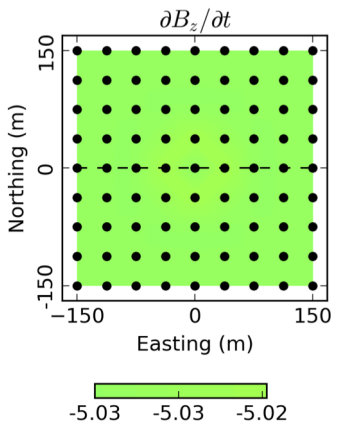



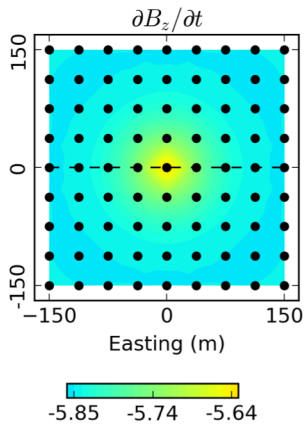

Conductivity



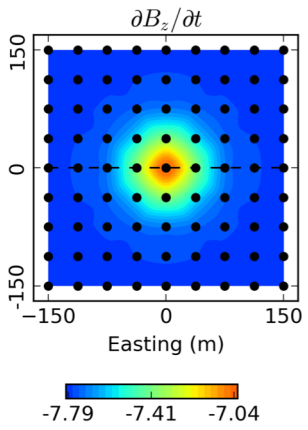

0.025 ms



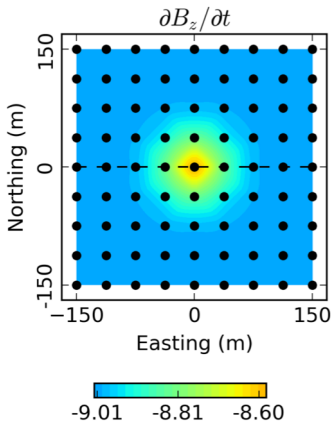

0.045 ms



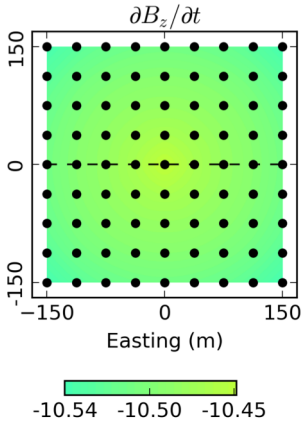

0.305 ms




0.905 ms

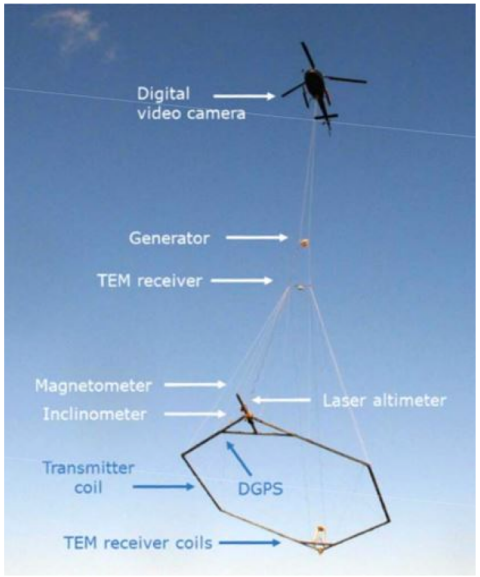



4.005 ms



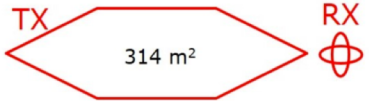
# Some Airborne TDEM Systems

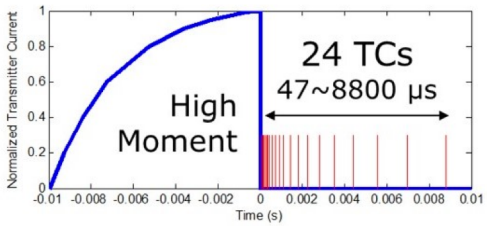
## SkyTEM (2006)



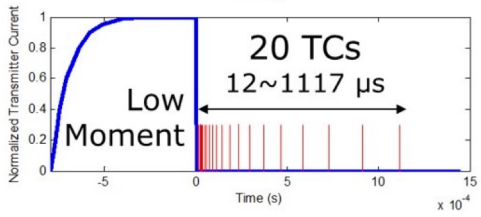

Area = 314 $m^2$

Peak dipole moment:
- HM: 113040 NIA
- LM: 12560 NIA



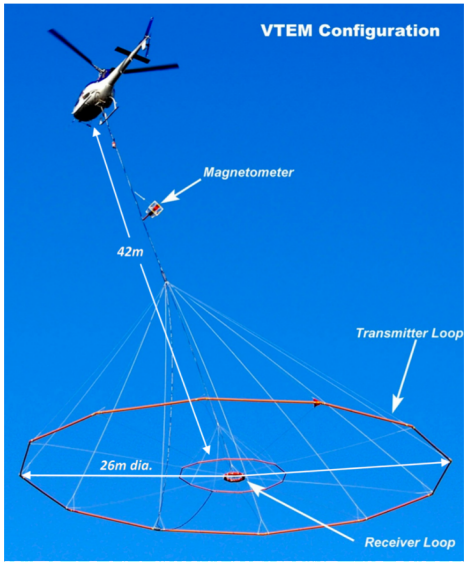




Peak current: 90 A
Turns: 4
On-time: 10 ms
Off-time: 10 ms



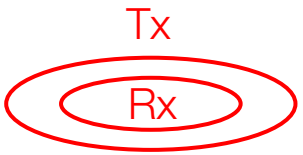

Peak current: 40 A
Turns: 1
On-time: 0.8 ms
Off-time: 1.45 ms

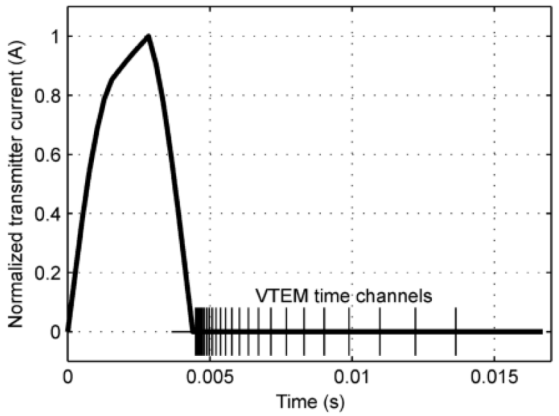
## VTEM (2007)




Area = 535 $m^2$

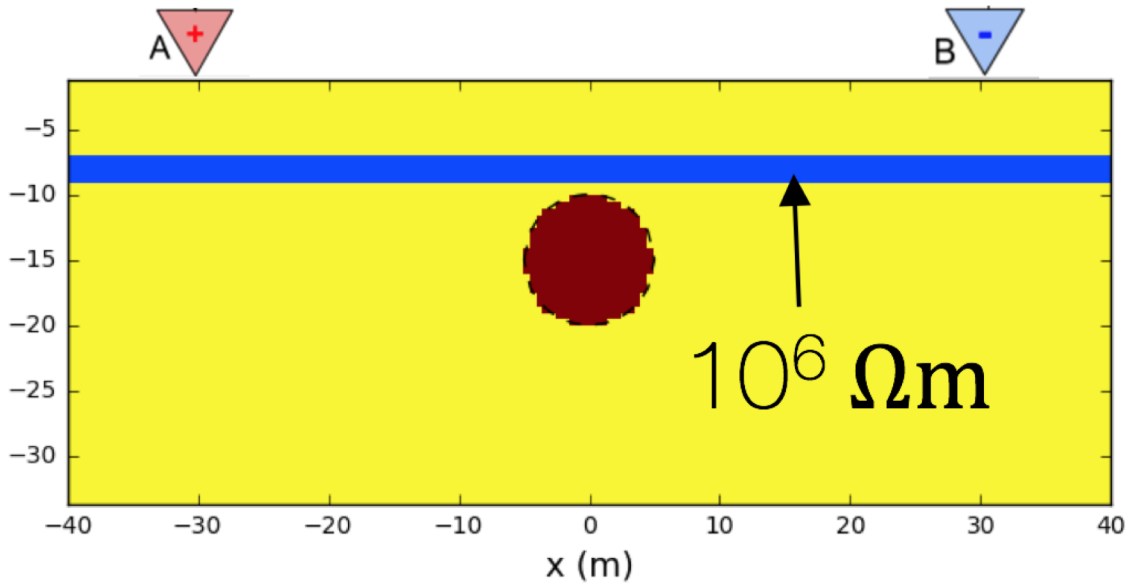
Peak dipole moment:
- 503,100 NIA



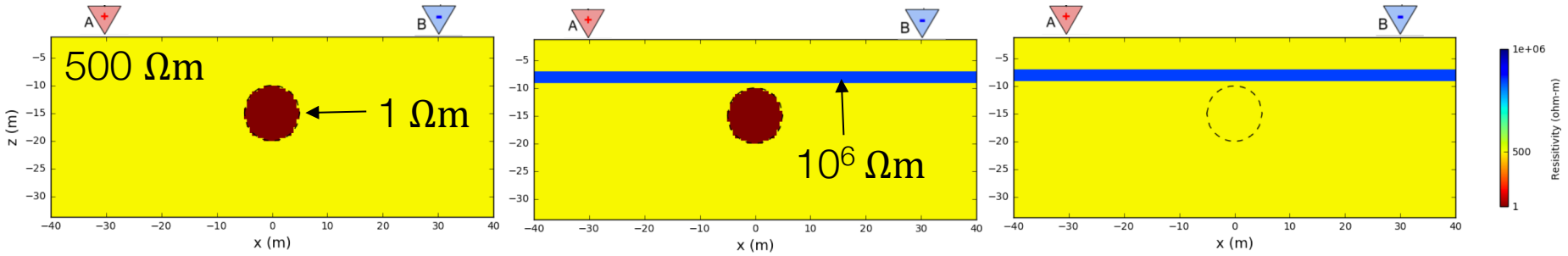

Peak current: 235 A
Turns: 4
On-time: 4.5 ms
Off-time: 9.1 ms

# Back to the “shielding” problem

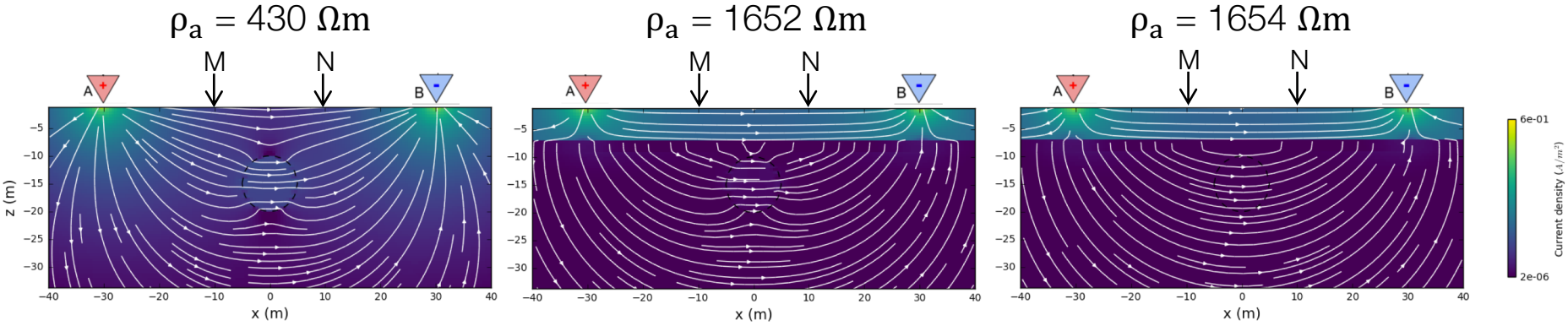


# Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)

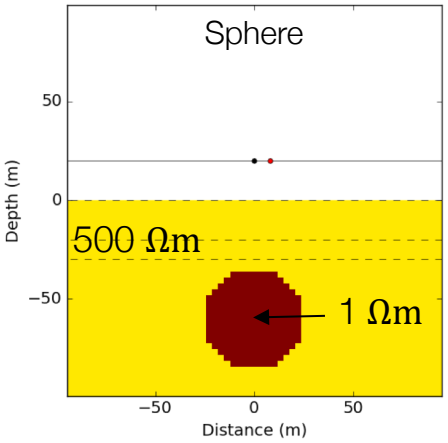



Currents and measured data at MN

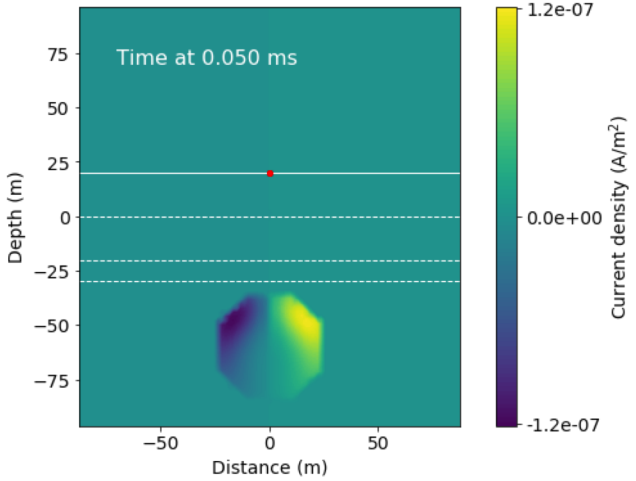


# Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

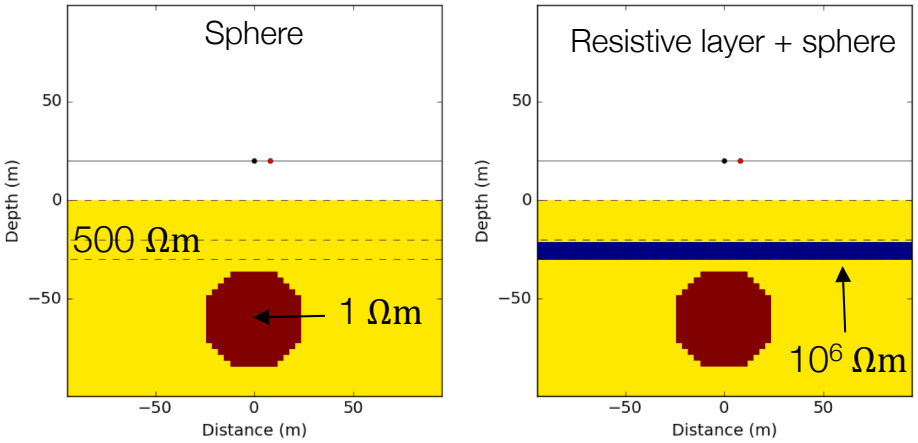



Currents ($J_y$)

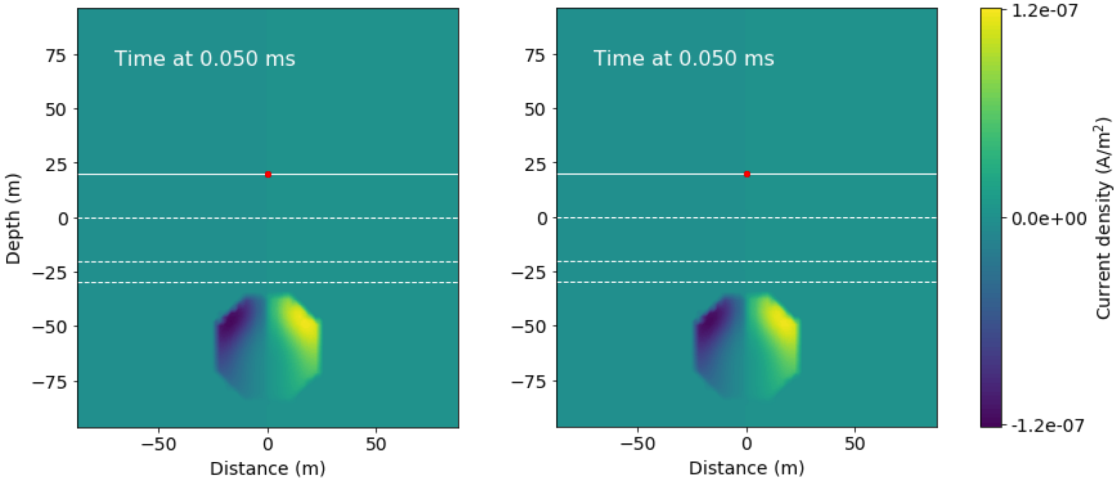


# Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

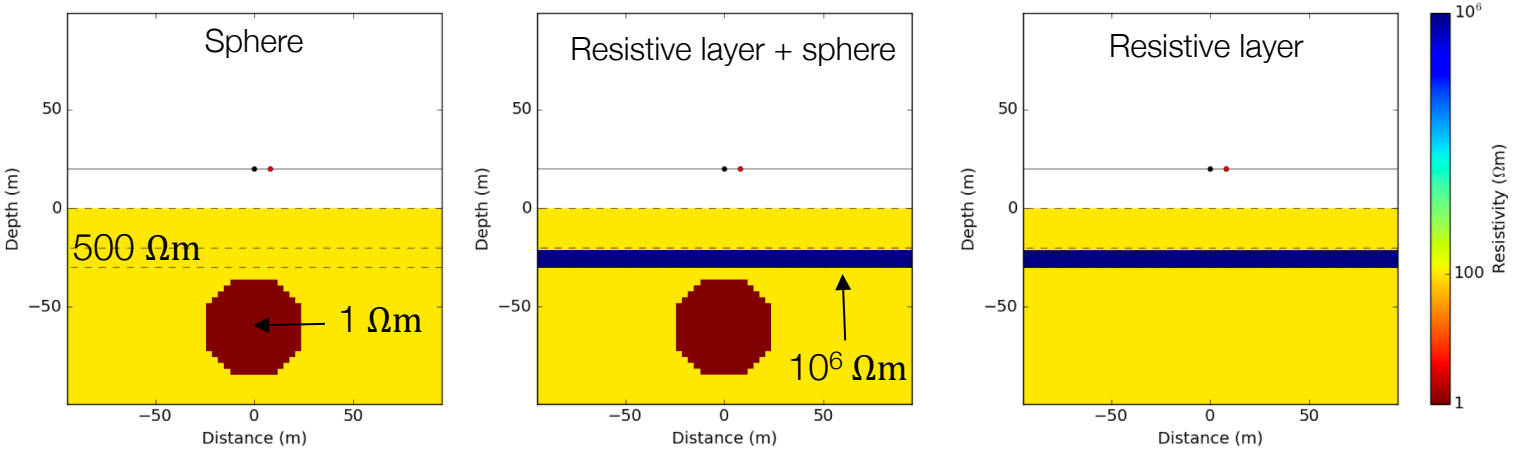



Currents ($J_y$)

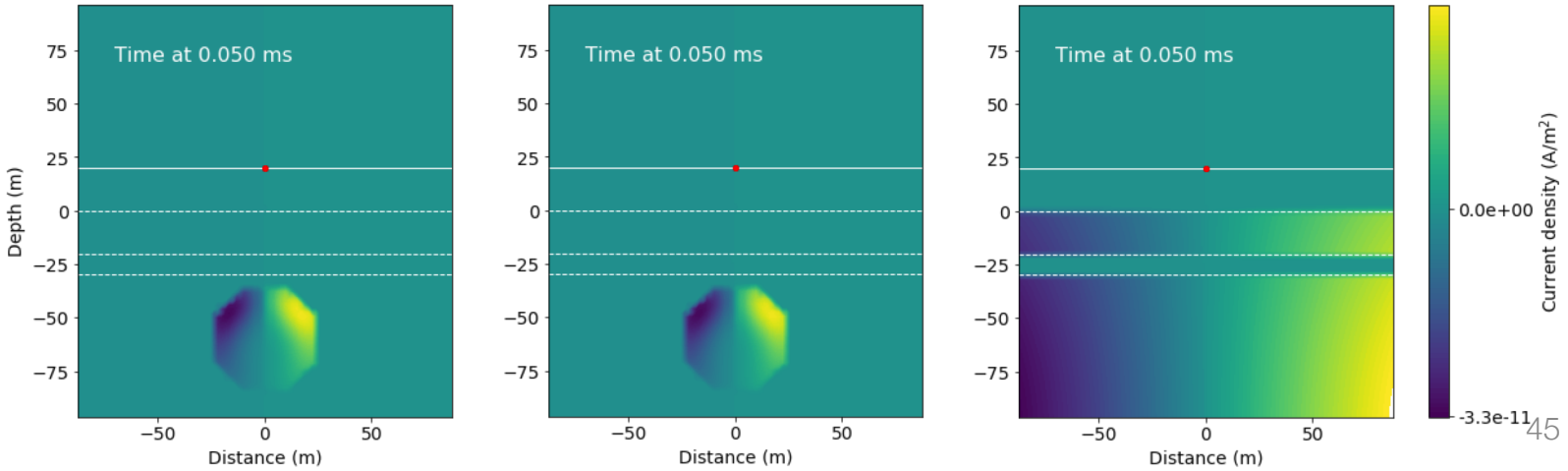


# Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

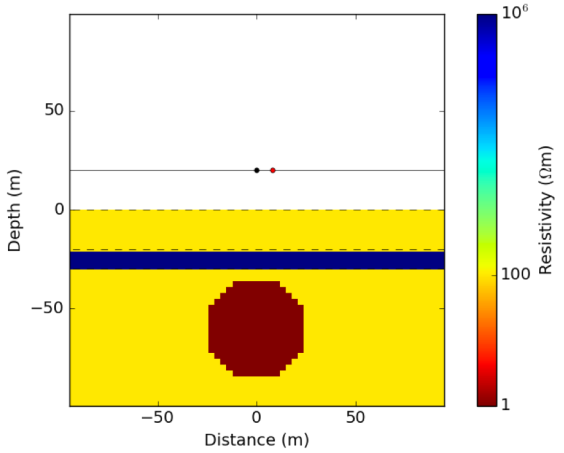



Currents ($J_y$)

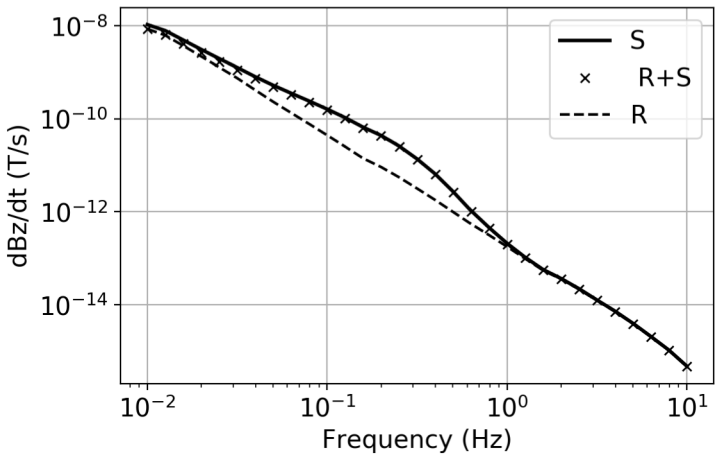


# Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

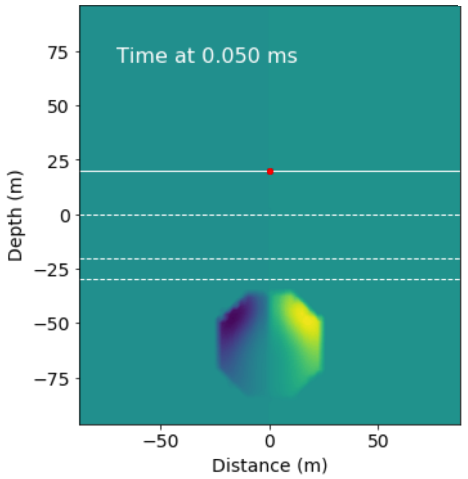



$db_z/dt$ sounding curves

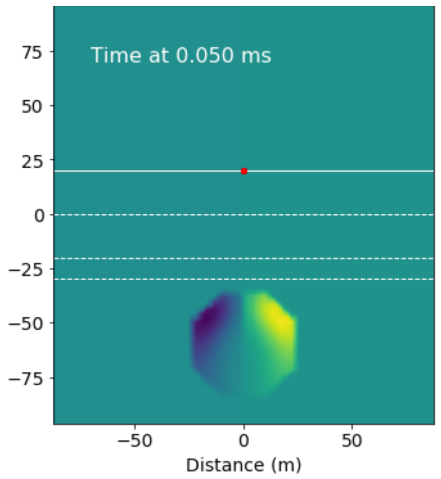



Currents ($J_y$)

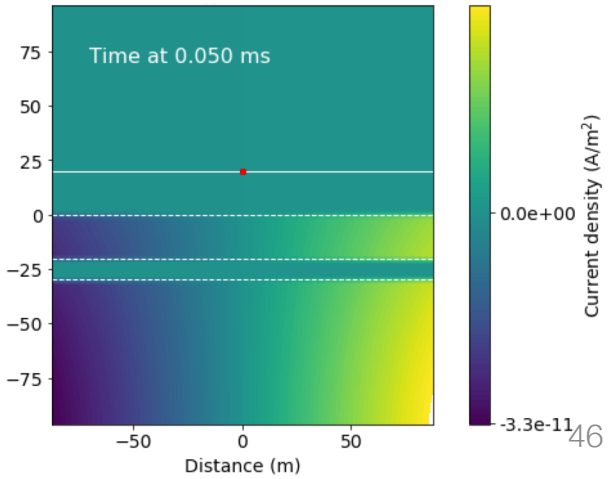
Sphere




Resistive layer + sphere

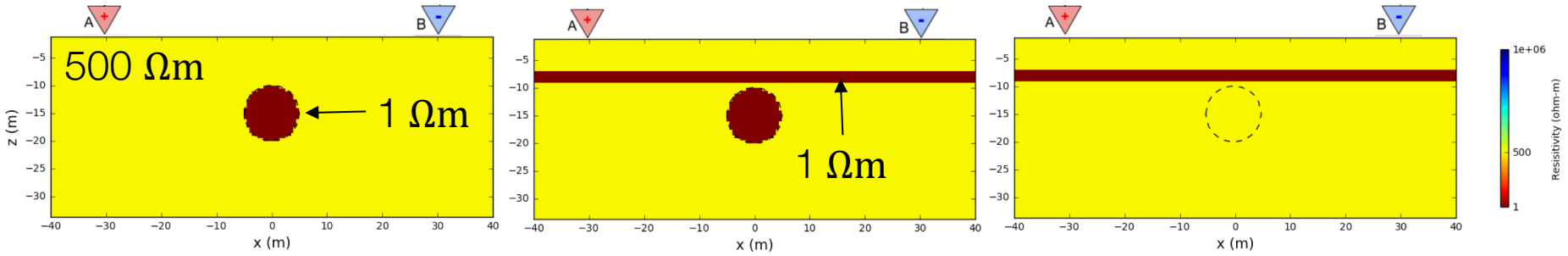



Resistive layer

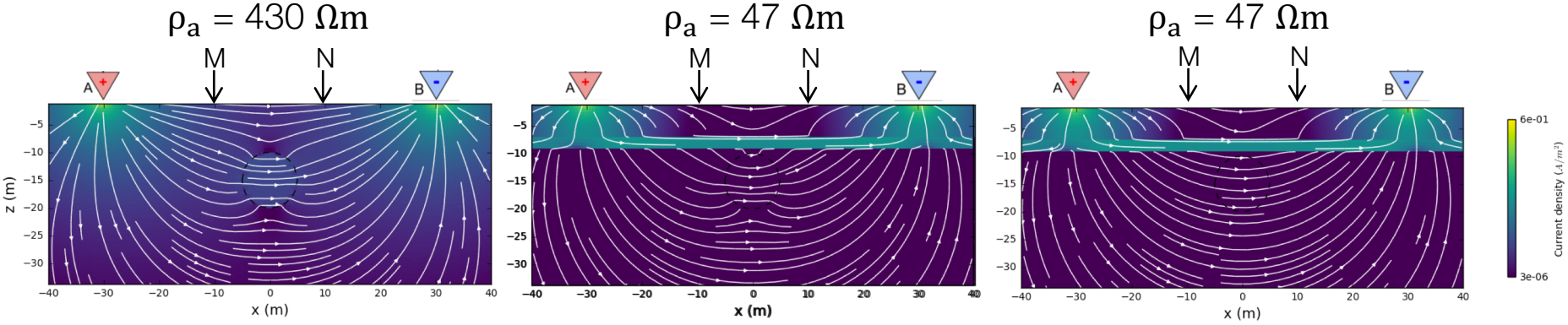


# Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)

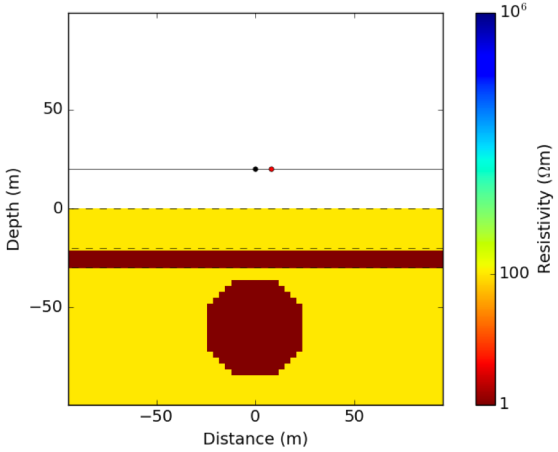



Currents and measured data at MN

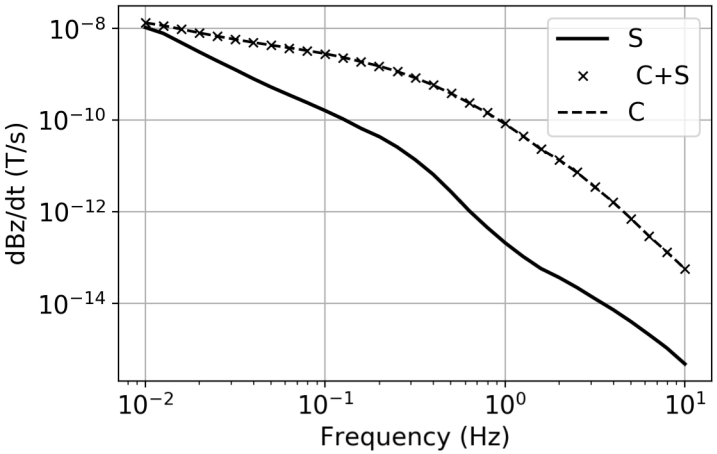


# Shielding: EM with conductive layer

Resistivity models (thin **conductive** layer)

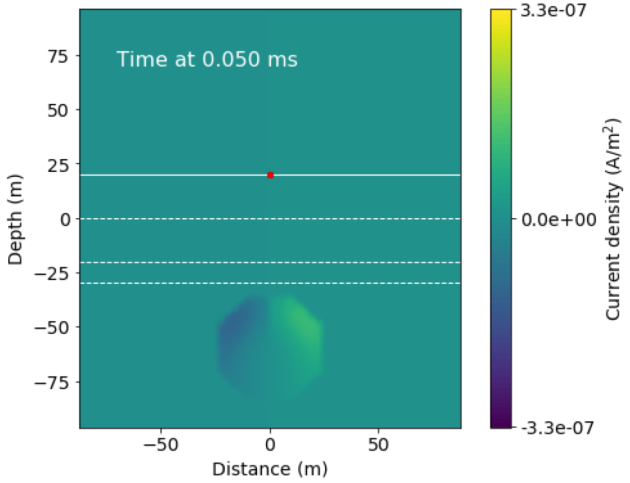



$db_z/dt$ sounding curves



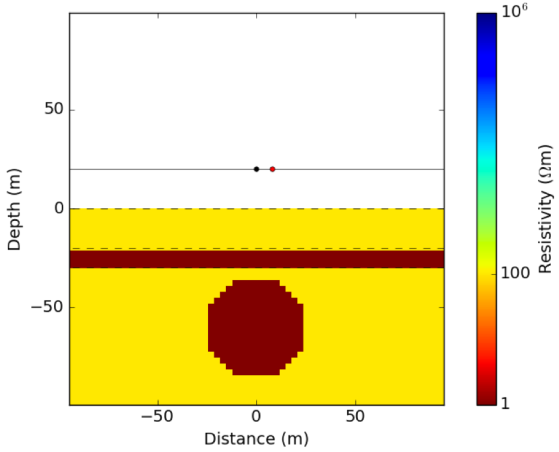

Currents ($J_y$)

Sphere

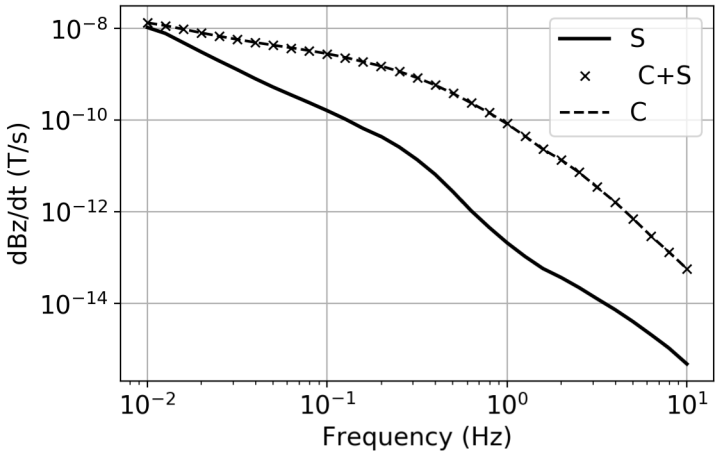


# Shielding: EM with conductive layer

Resistivity models (thin **conductive** layer)

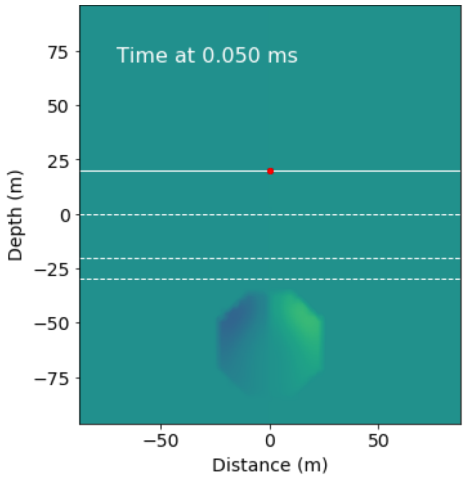



$db_z/dt$ sounding curves

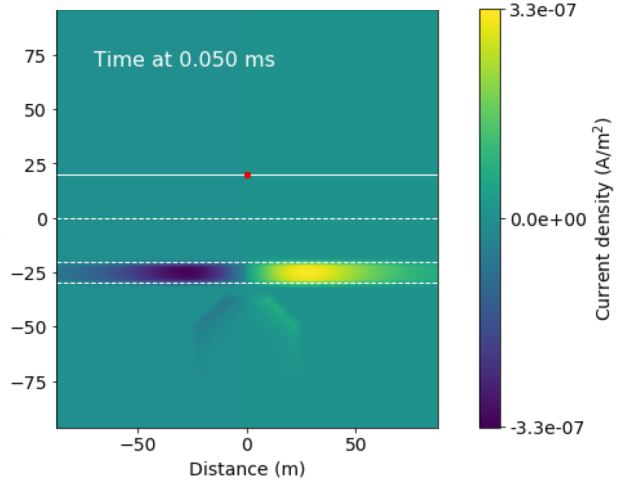



Currents ($J_y$)

Sphere

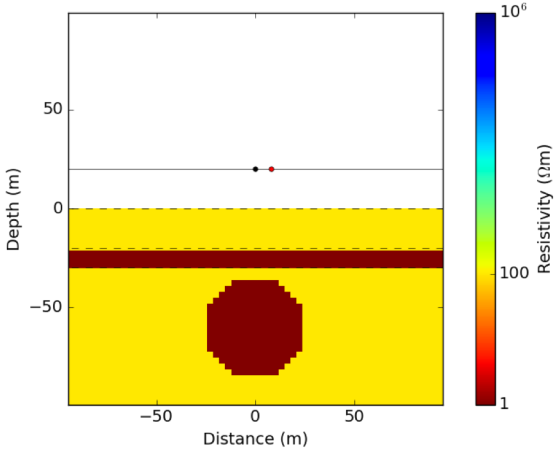



Conductive layer + sphere

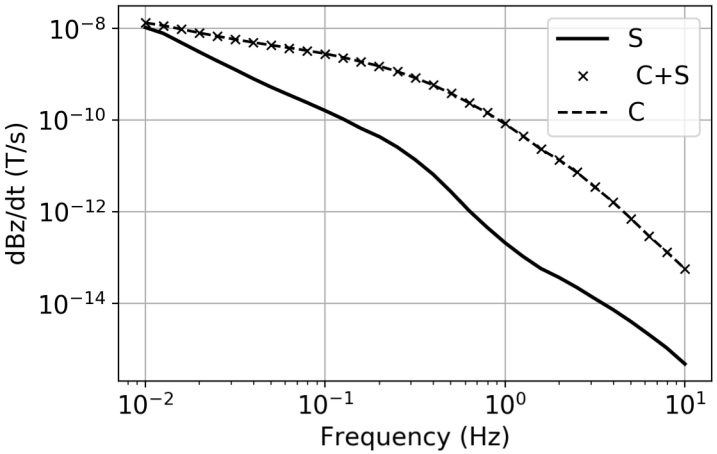


# Shielding: EM with conductive layer

Resistivity models (thin **conductive** layer)

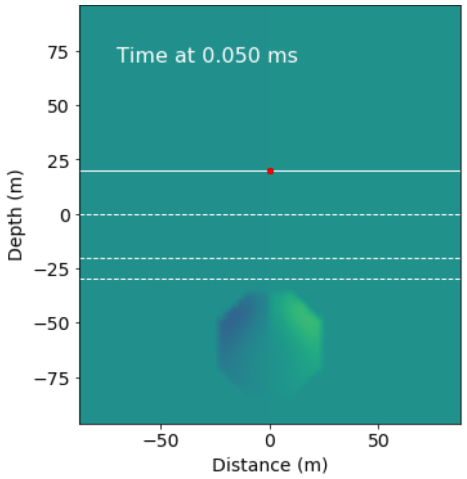



$db_z/dt$ sounding curves

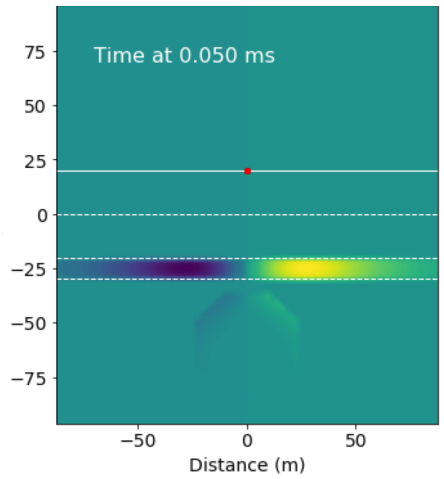



Currents ($J_y$)

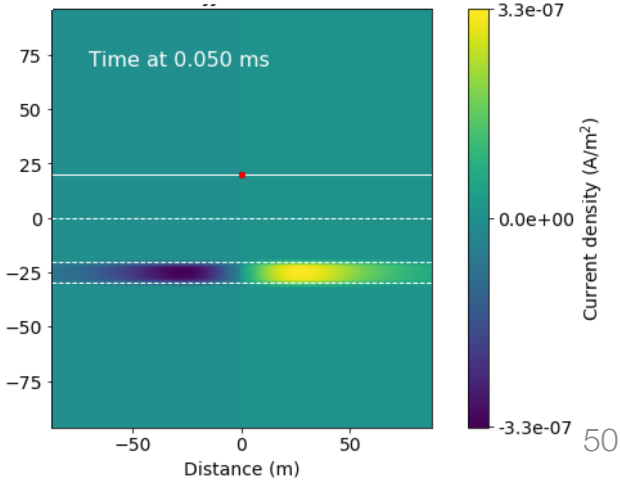
Sphere




Conductive layer + sphere

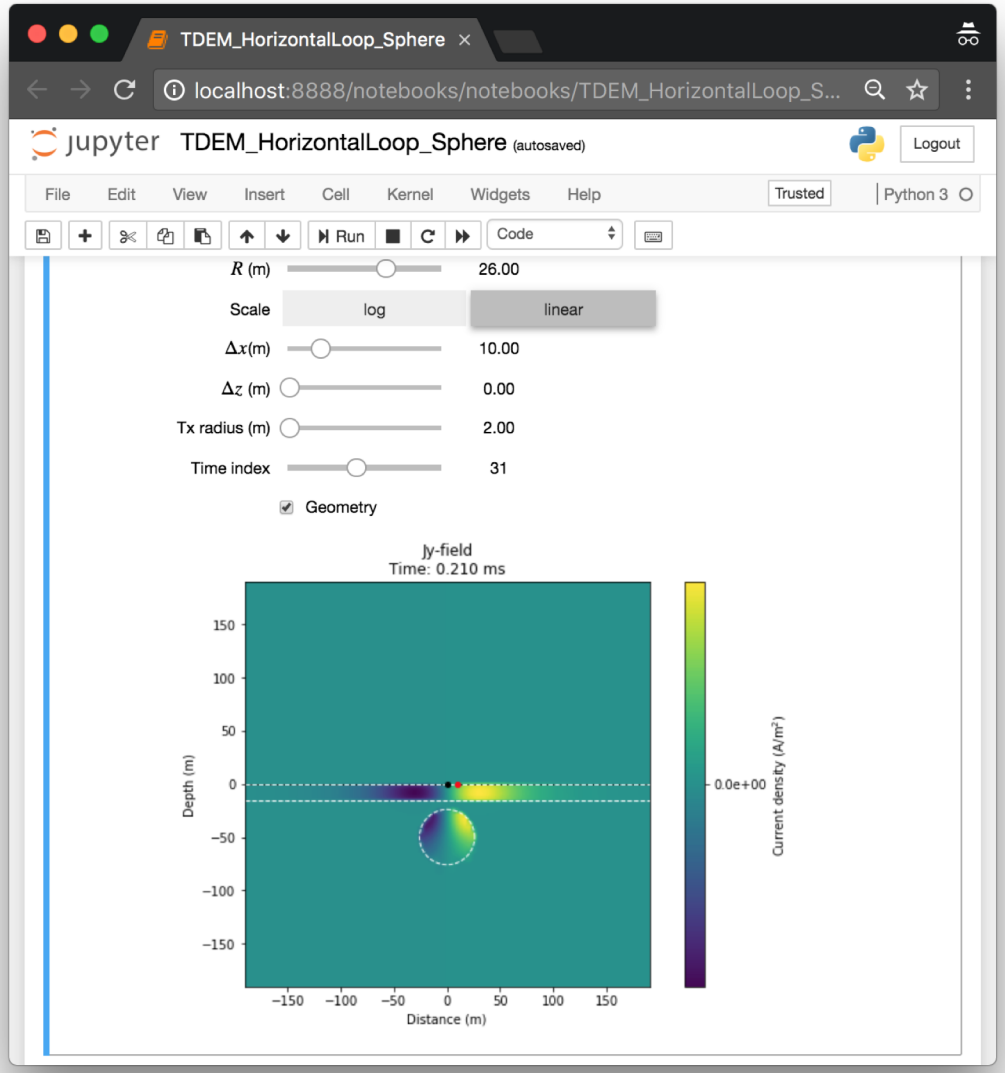



Conductive layer



# App: VMD over sphere with overburden

- TDEM_HorizontalLoop_Sphere
- Parameters:
  - Resistivities of layer, background sphere
  - Geometry of sphere, layer
  - Source height, source receiver separation
- View:
  - Model
  - Electric field, magnetic field, current density through time
  - data




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

# Outline

Setup

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Effects of Background Conductivity
- Transmitters and receivers
- Decay Curves
- Case History: Groundwater, Minerals, Hydrocarbons
- Horizontal magnetic Dipole

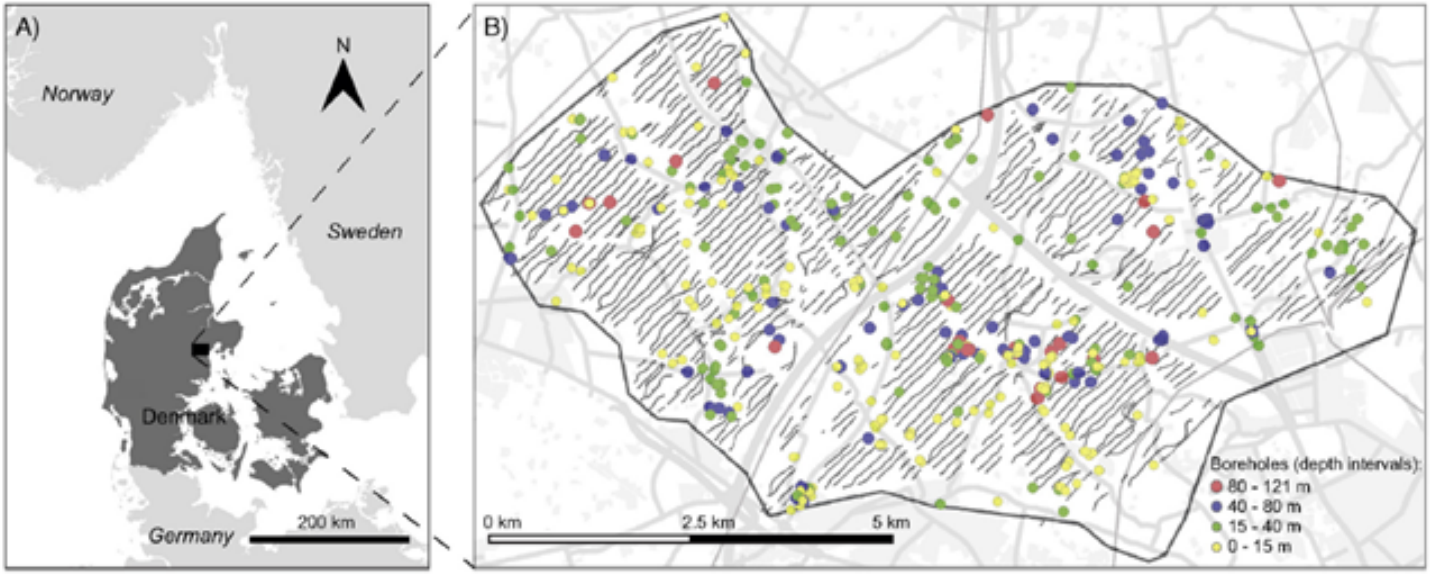
# Case History: Kasted

Vilhelmsen et al. (2016)

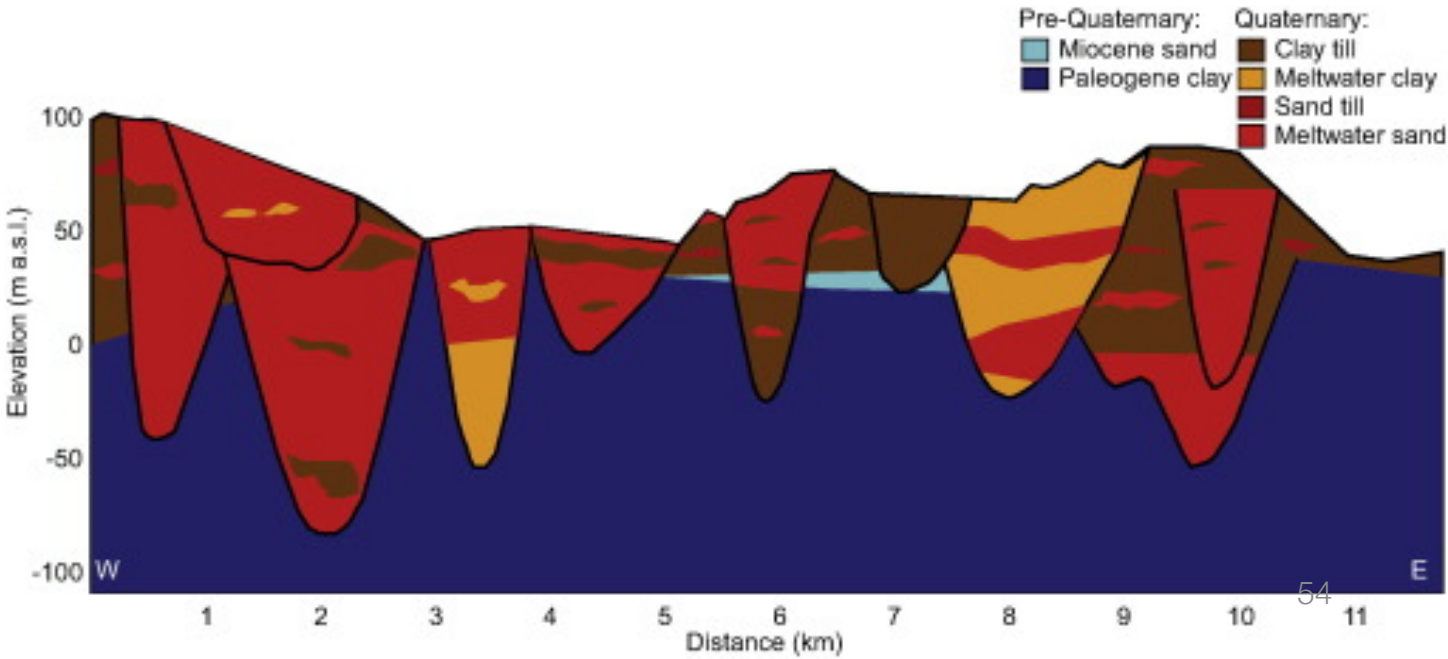
# Setup

A) Survey Area: Kasted, Demark

B) Borehole locations

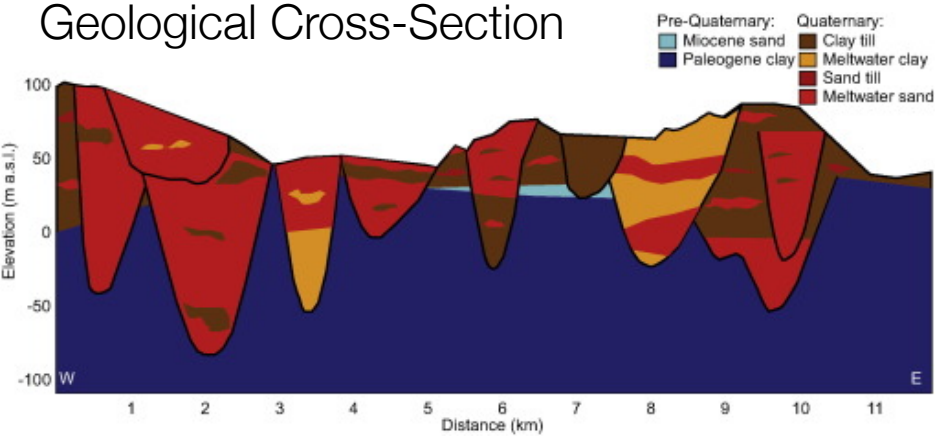



Local Geology: W-E cross-section



# Properties

Geological Cross-Section

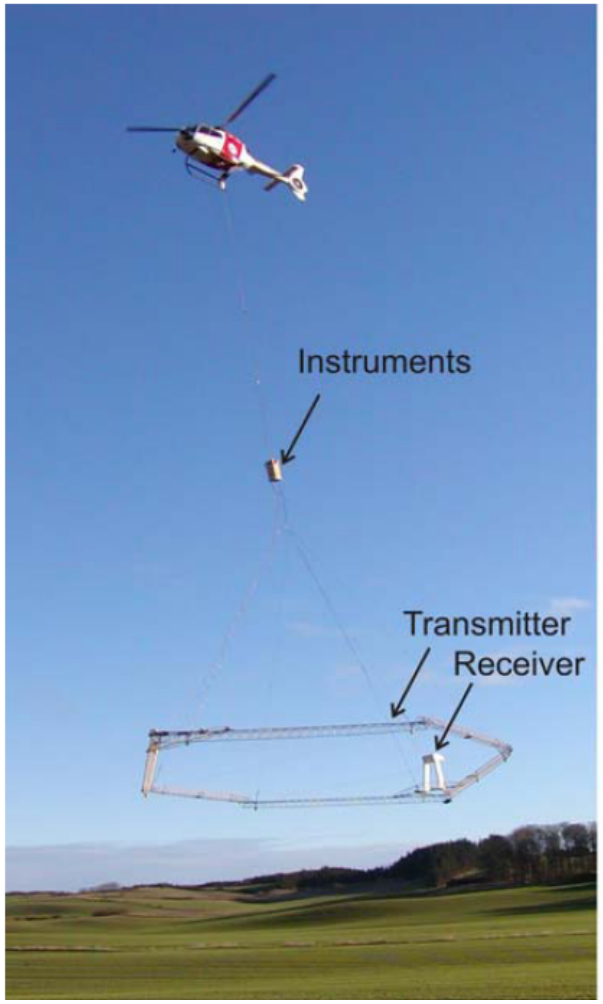



| Geological Units | Resistivity ($\Omega m$) |
|---|---|
| Palaeogene Clay | 1-10 |
| Clay Till | 25-60 |
| Sand Till | >50 |
| Meltwater Sand and Gravel | >60 |
| Glaciolacustrine Clay | 10-40 |
| Miocene Silt and Sand | >40 |
| Miocene Clay | 10-40 |
| Sand | >40 |
| Clay | 1-60 |

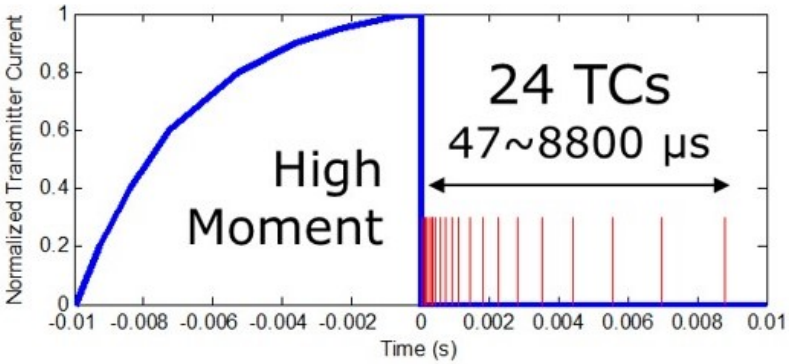
- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40 Ωm)
- Water-bearing sands and gravels are more resistive (>40 Ωm)

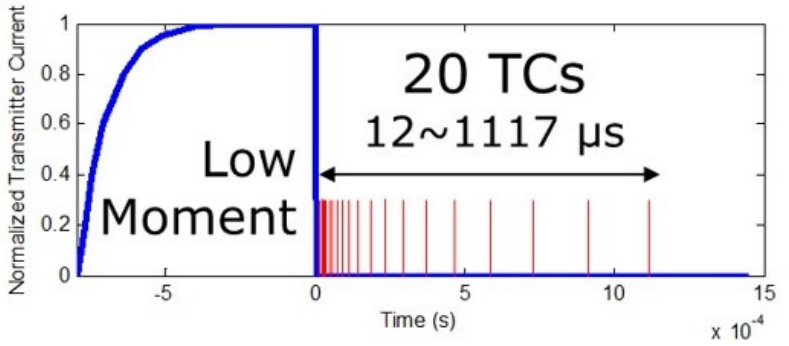
# Survey

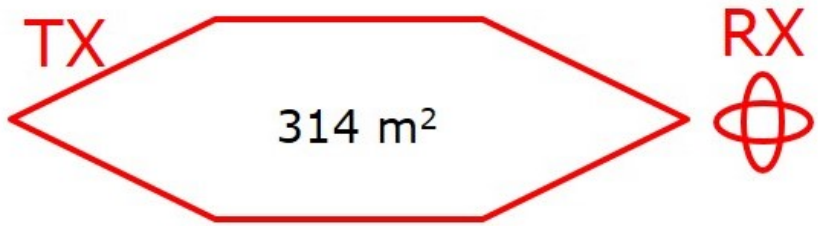
SkyTEM System




System Configuration



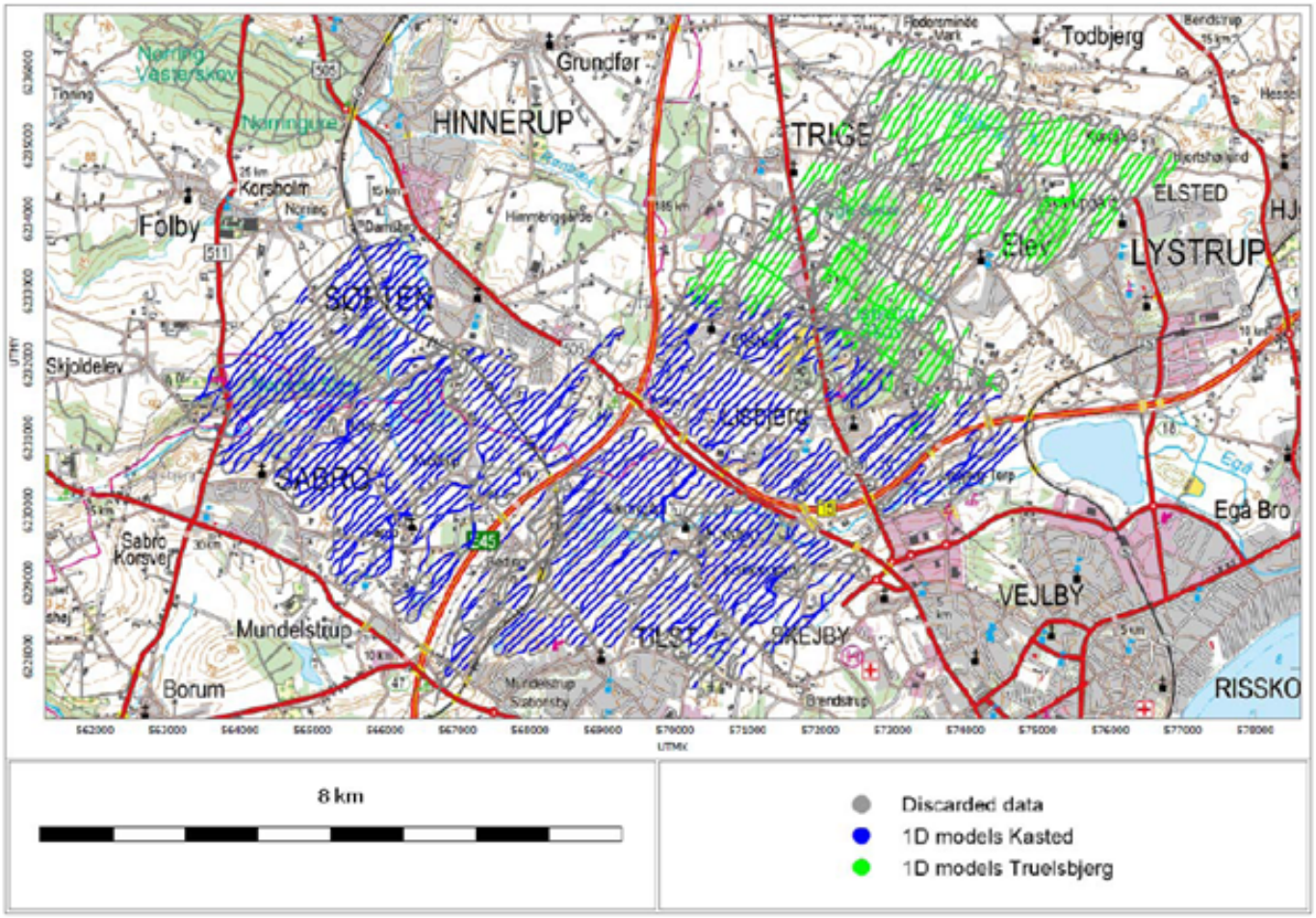




- Low moment (LM) used to image near surface structures
- High moment (HM) used to image deeper structures

# Data

Blue: data used for Kasted study

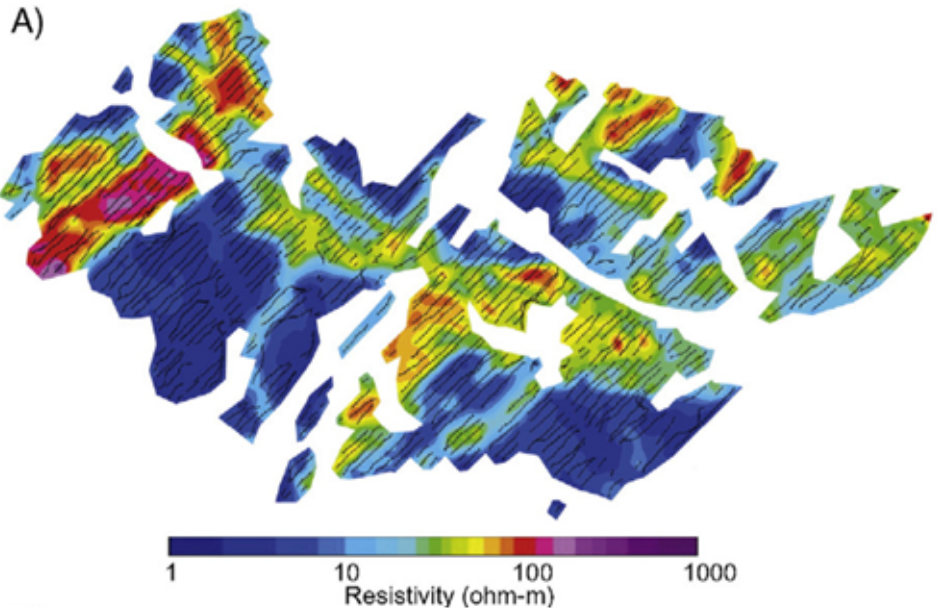



- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

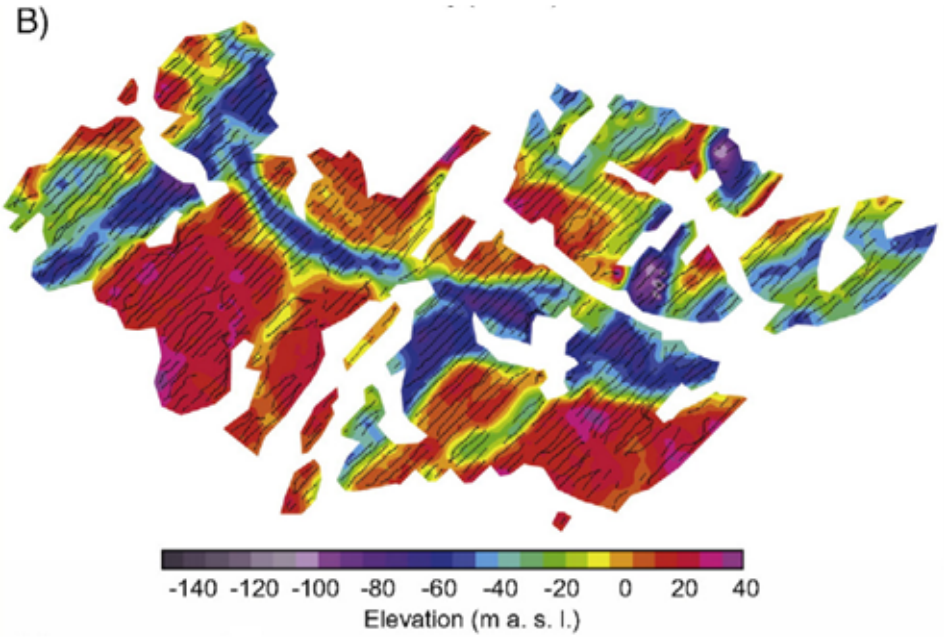
# Processing (inversion)

- Spatially constrained 1D inversion → quasi-3D approach
- 9,500 soundings were inverted using 25 layers

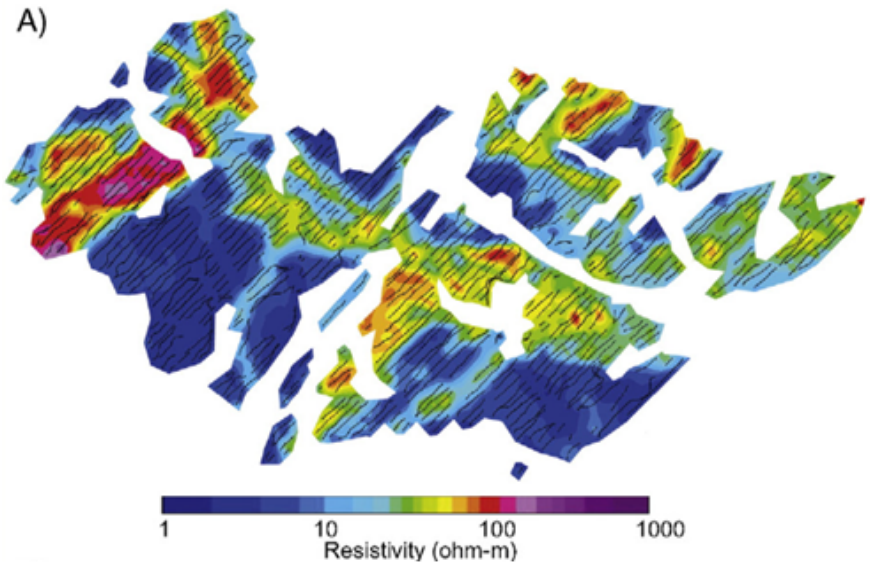
Depth slice 5 m above sea-level

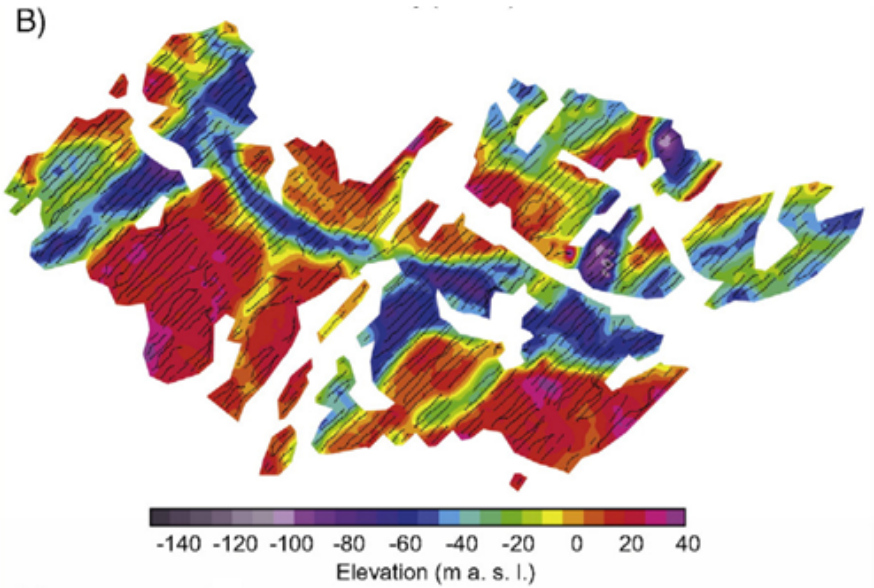



Approximate depth to the top of Paleogene clay layer

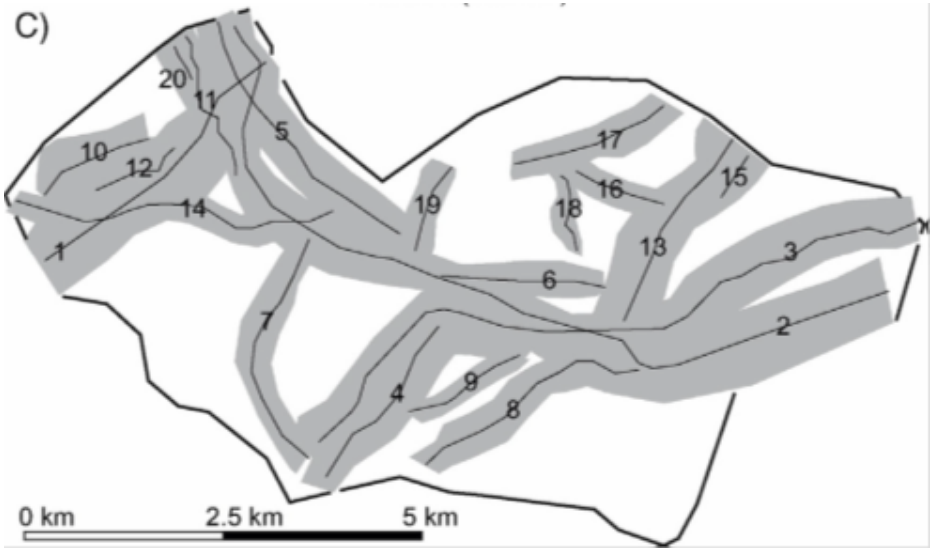


# Interpretation



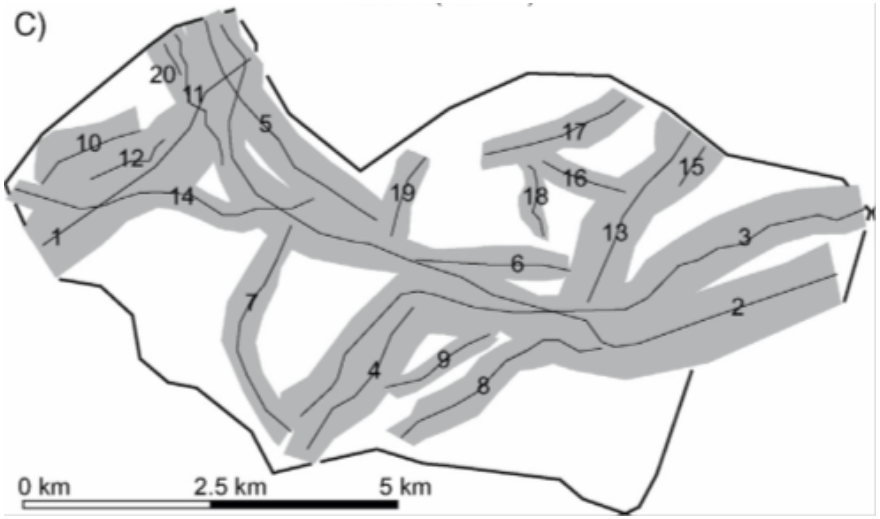




Delineation of valley structures

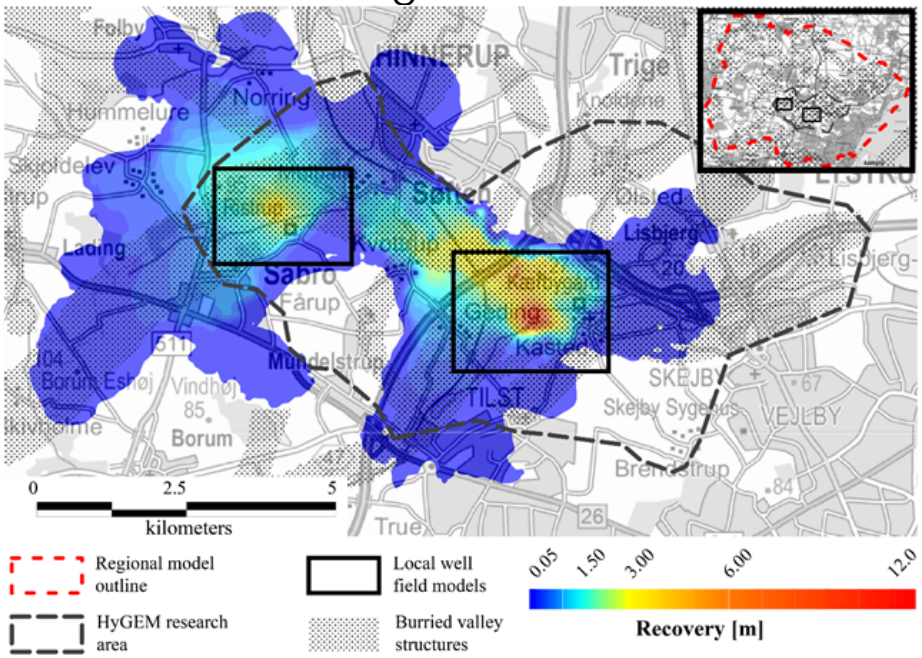



- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

# Synthesis




MODFLOW-USG groundwater model




- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool
- Extracted water from 2 wells.
- Downdraw between the two wells correlated with the resistive valley structures

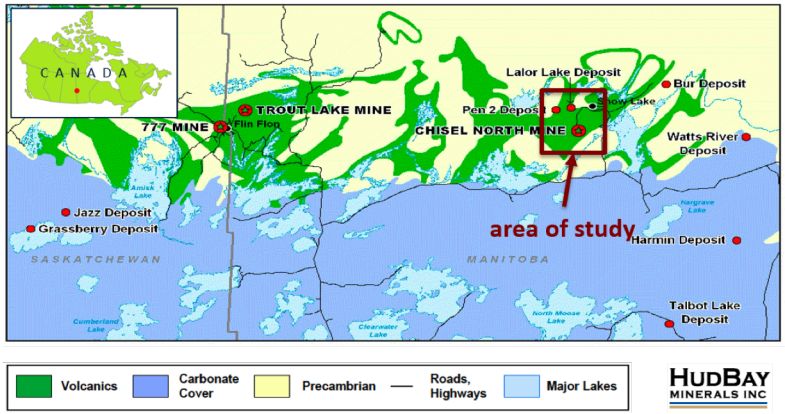
# Case History: HeliSAM at Lalore

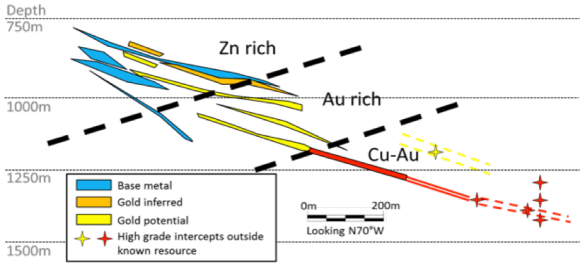
Yang & Oldenburg, 2016

# Setup

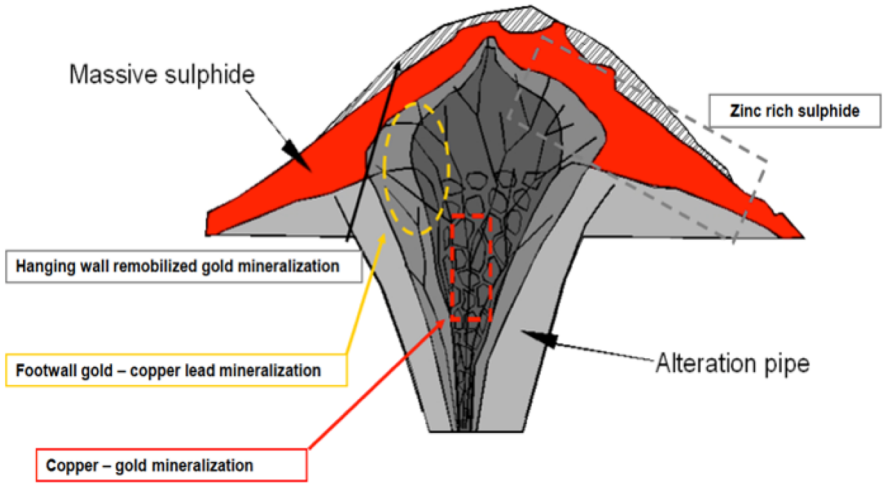
Geological framework

- Zinc-rich massive sulfides (Cap)
- Cu-Au sulfides: (stringers) within pipe
- Disseminated sulfides around deposit




Typical cross-section

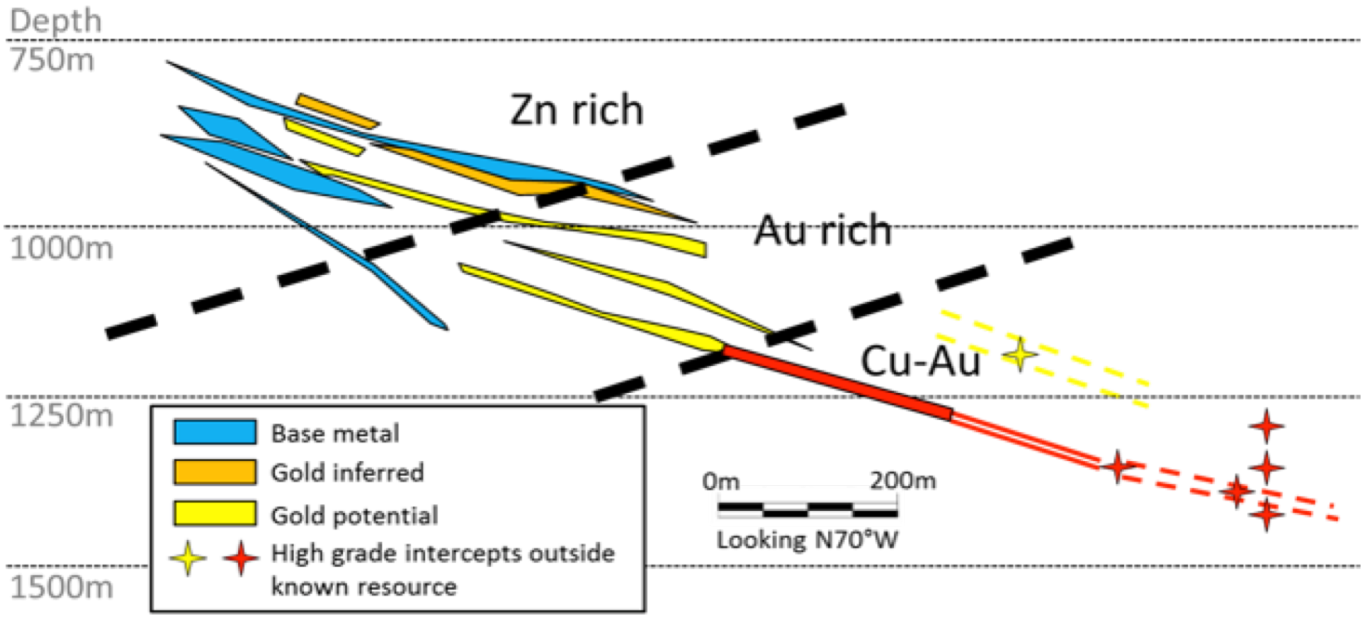



Goal:

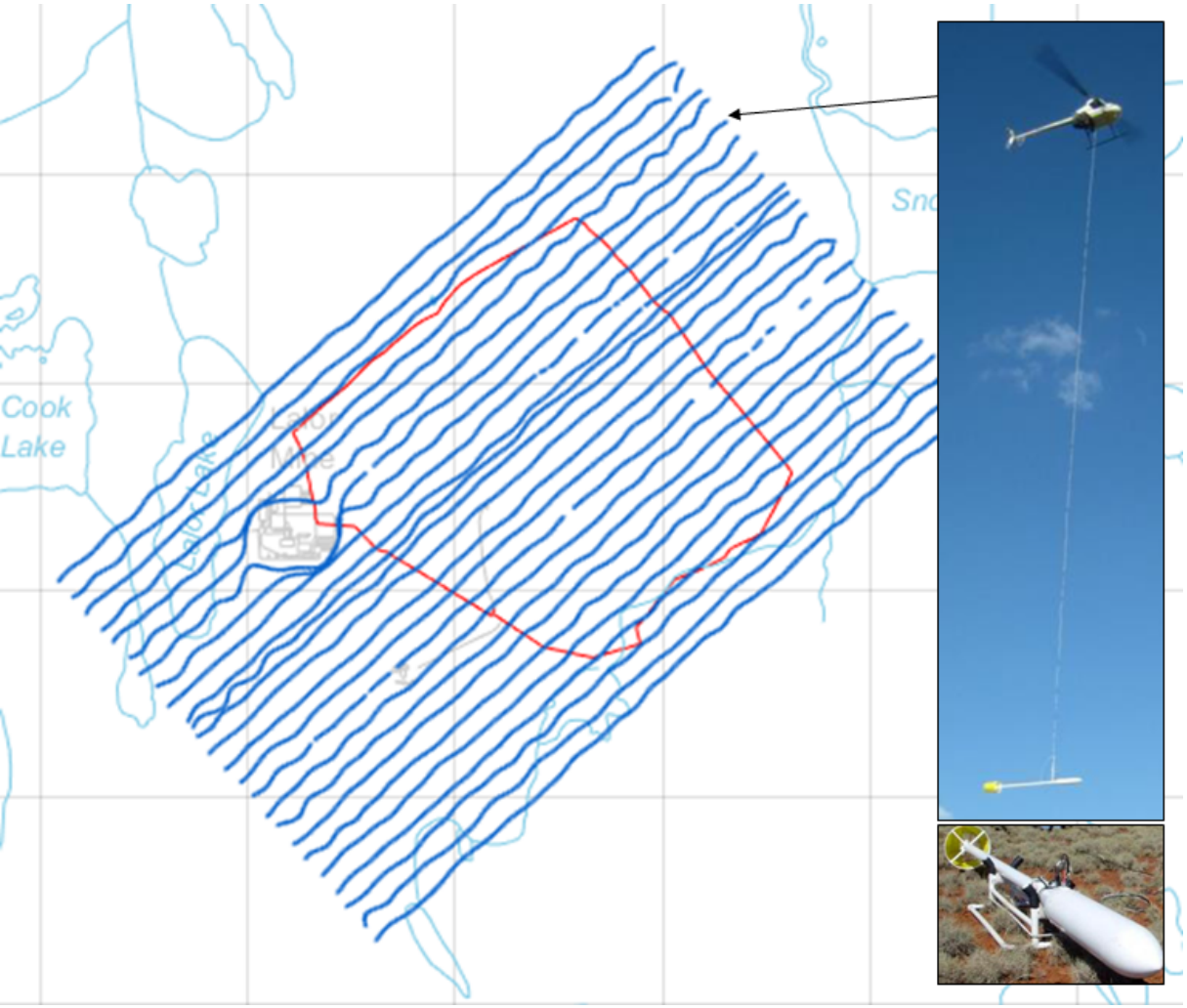
- Find deposits
- TDEM to find deeper off-hole targets

# Properties

| Rocks/minerals | Resistivity |
|---|---|
| volcanics | ~1000 Ωm |
| sulfides | ~ 1 Ωm |



# Survey: HeliSAM








Transmitter: (Red)

- Ground loop (~2km)
- Waveform: 7.5 Hz, 50%
- Ramp turn-off 0.4ms

Receiver:

- Cesium Vapor Mag
- 16 Time Ch: 0.42-27 ms

Flight lines: (Blue)

- 100 m spacing,
- Data every 5 m

# Data

- Measure total field

$$\mathbf{B} = \mathbf{B_0} + \mathbf{B_a} + \mathbf{B_{em}}$$

earth's magnetic field

anomalous earth's field

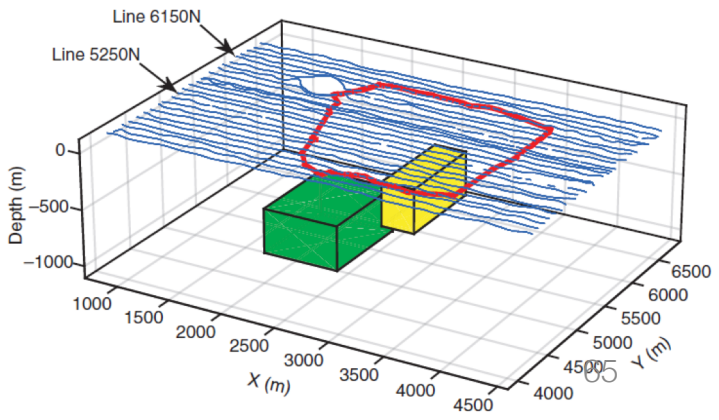
induced EM field

- Project secondary fields onto $\hat{\mathbf{B}}_0$

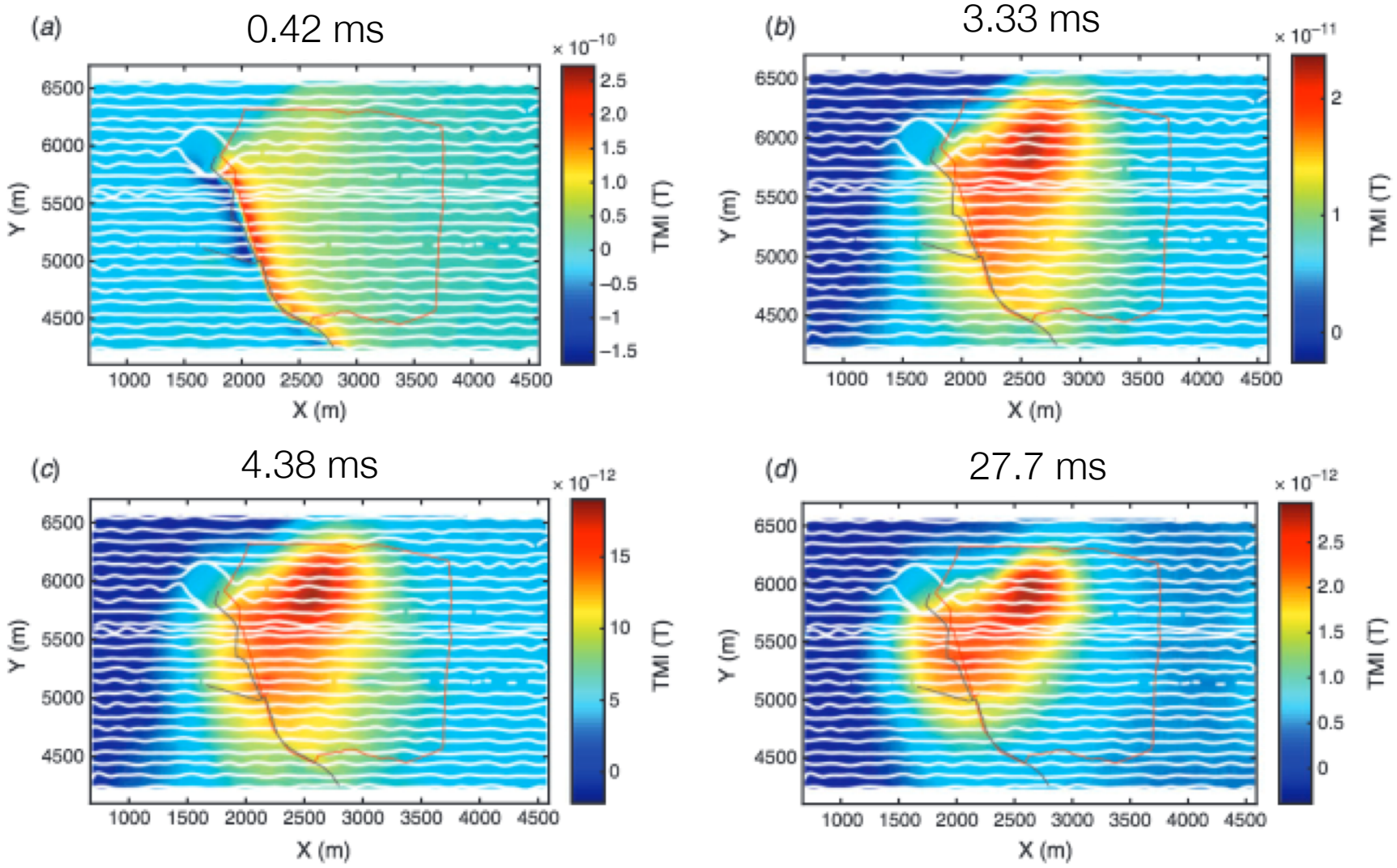
$$\Delta|\mathbf{B}| = |\mathbf{B_0} + \mathbf{B_a} + \mathbf{B_{em}}| - |\mathbf{B_0}|$$
$$\approx (\mathbf{B_a} + \mathbf{B_{em}}) \cdot \hat{\mathbf{B}}_0$$

- Change polarity on TX
- Subtract to obtain HeliSAM data

$$\Delta|\mathbf{B}| \approx \mathbf{B_{em}} \cdot \hat{\mathbf{B}}_0$$

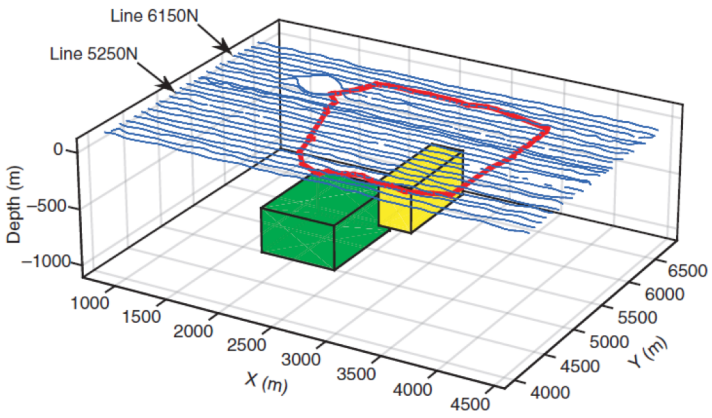


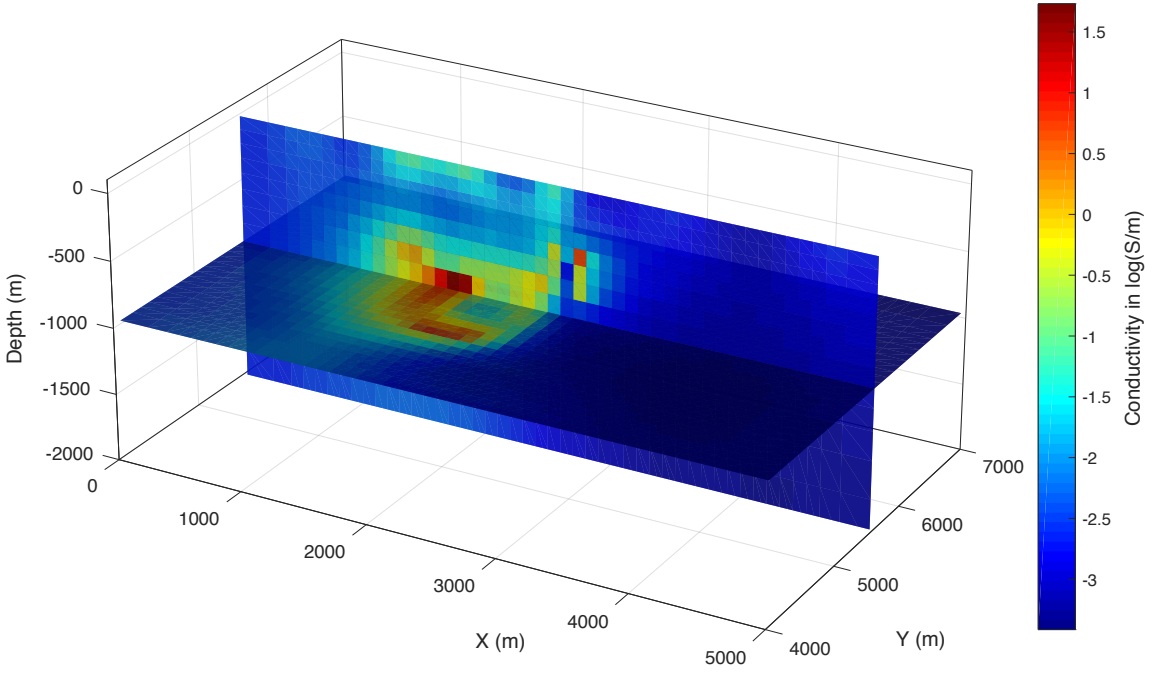
# Data


(a)
0.42 ms
× 10−10
2.5
2.0
1.5
1.0
0.5
0
−0.5
−1
−1.5
TMI (T)
Y (m)
6500
6000
5500
5000
4500
1000 1500 2000 2500 3000 3500 4000 4500
X (m)
(b)
3.33 ms
× 10−11
2
1
0
TMI (T)
Y (m)
6500
6000
5500
5000
4500
1000 1500 2000 2500 3000 3500 4000 4500
X (m)
(c)
4.38 ms
× 10−12
15
10
5
0
TMI (T)
Y (m)
6500
6000
5500
5000
4500
1000 1500 2000 2500 3000 3500 4000 4500
X (m)
(d)
27.7 ms
× 10−12
2.5
2.0
1.5
1.0
0.5
0
TMI (T)
Y (m)
6500
6000
5500
5000
4500
1000 1500 2000 2500 3000 3500 4000 4500
X (m)

# Processing: Inversion of Late Time Data

- Discard early time data
  - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a “warm start”
  - Maxwell used to generate 2 prisms

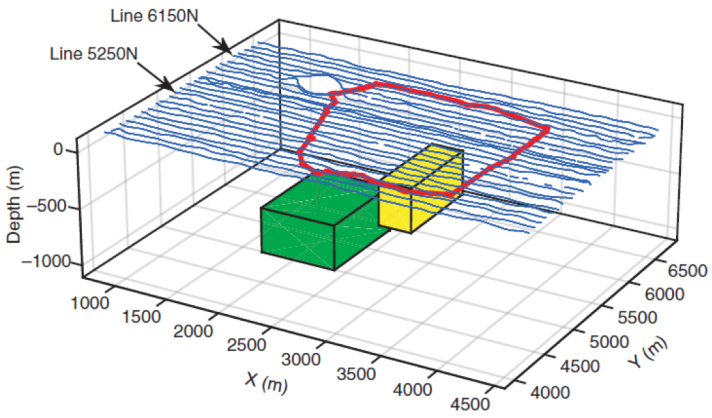


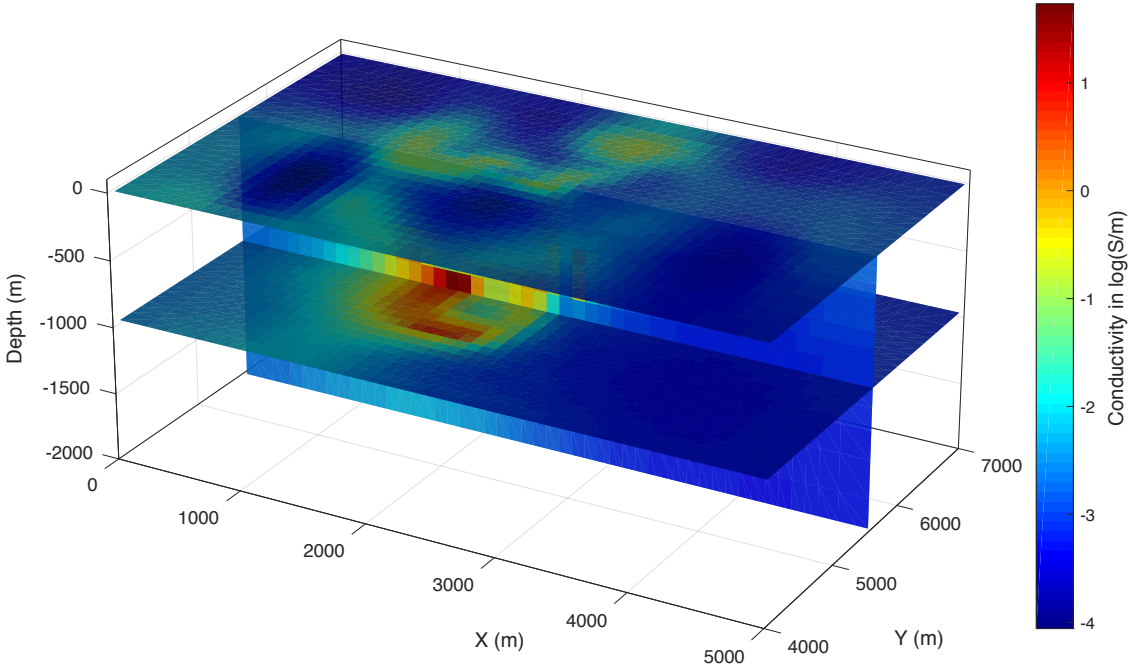




- Image deep structure

# Processing: Inversion of Late Time Data

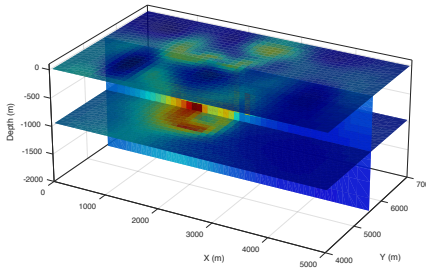
- Discard early time data
  - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a “warm start”
  - Maxwell used to generate 2 prisms



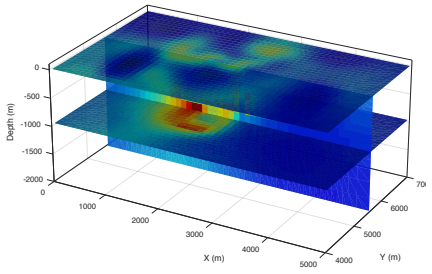

- Image deep structure
- See near surface conductive features

# Processing: Inversion of Early Time Data




- Late-time inversion sees deep structure
- Some conductive features near surface
- What is the effect of throwing away the early time data?

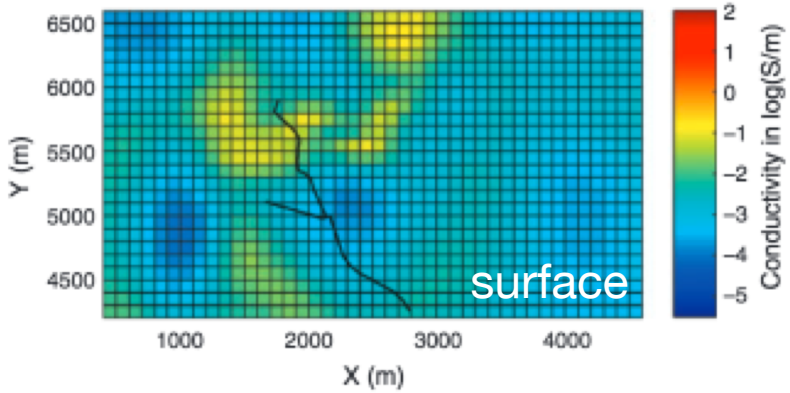
# Processing: Inversion of Early Time Data




- Late-time inversion sees deep structure
- Some conductive features near surface
- What is the effect of throwing away the early time data?

Inverting late time data

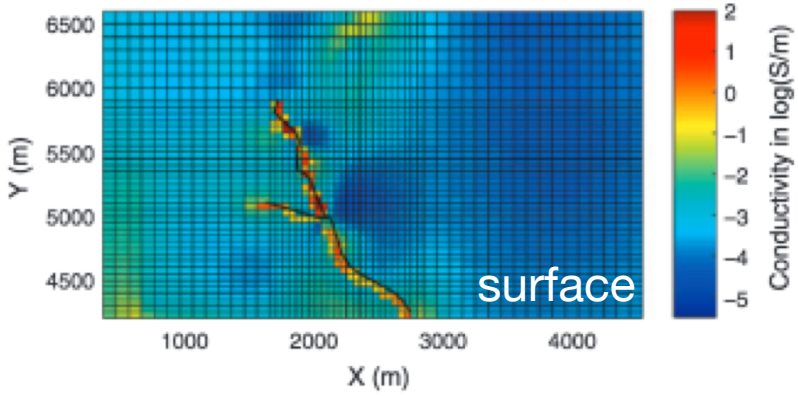
TC 8 – 15 [4.4 – 28 ms]




- erroneous near surface structure

Inverting early time data

TC 1-7 [0.4 – 3.3 ms]

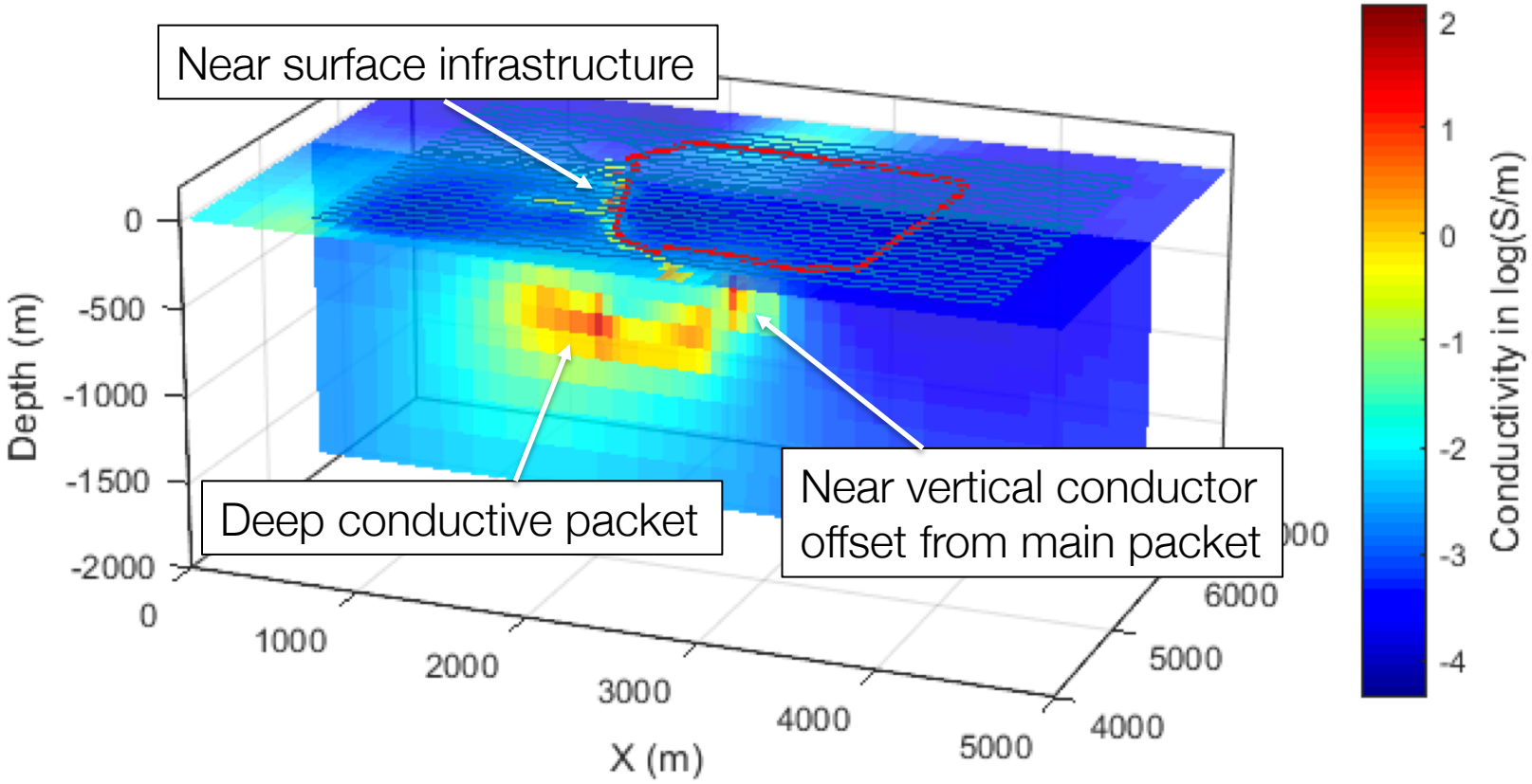



- information about infrastructure and near-surface conductivity

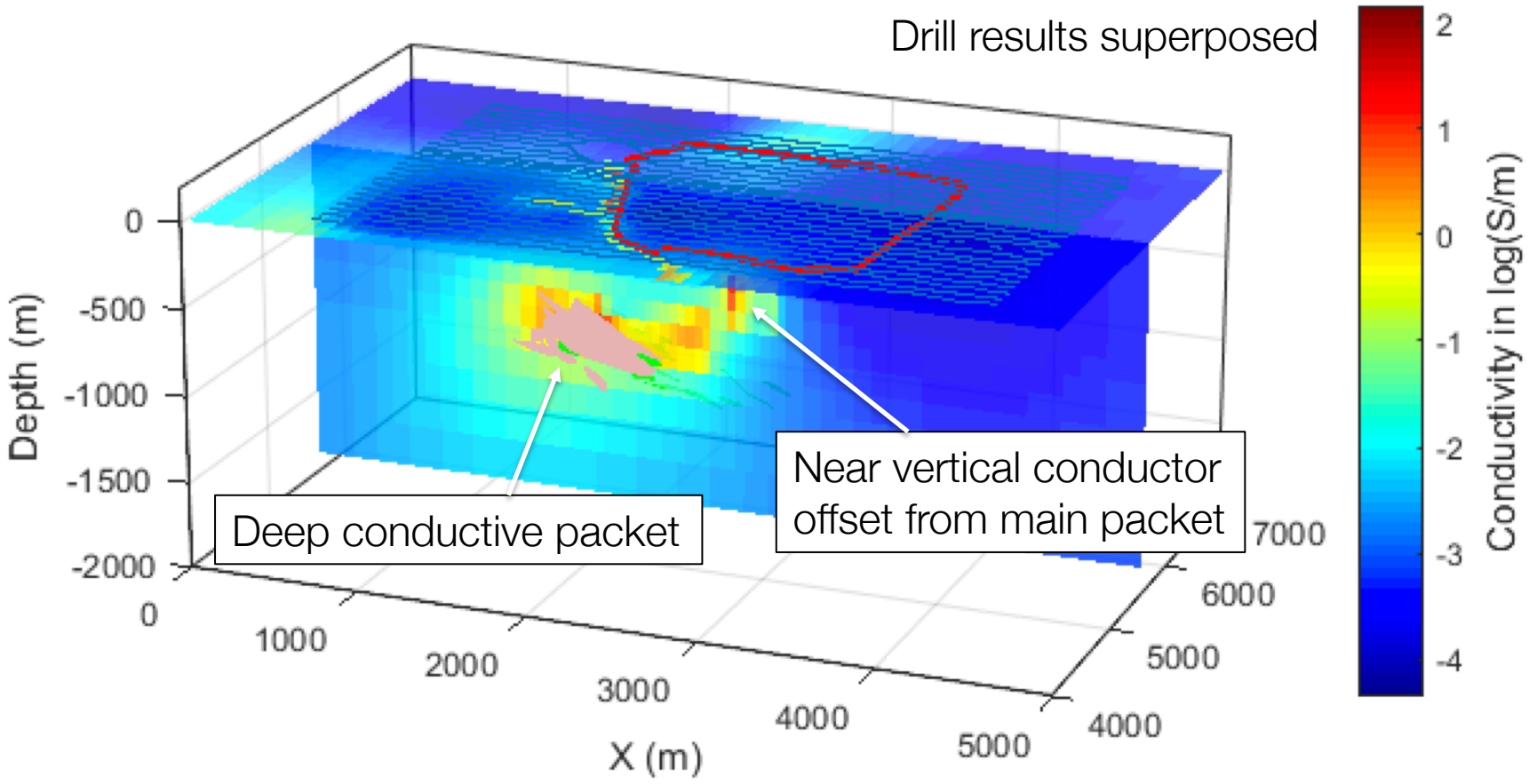
# Processing: Inversion of all time channels

Starting and reference model:

- High conductivity from early time inversion
- Two conductive blocks

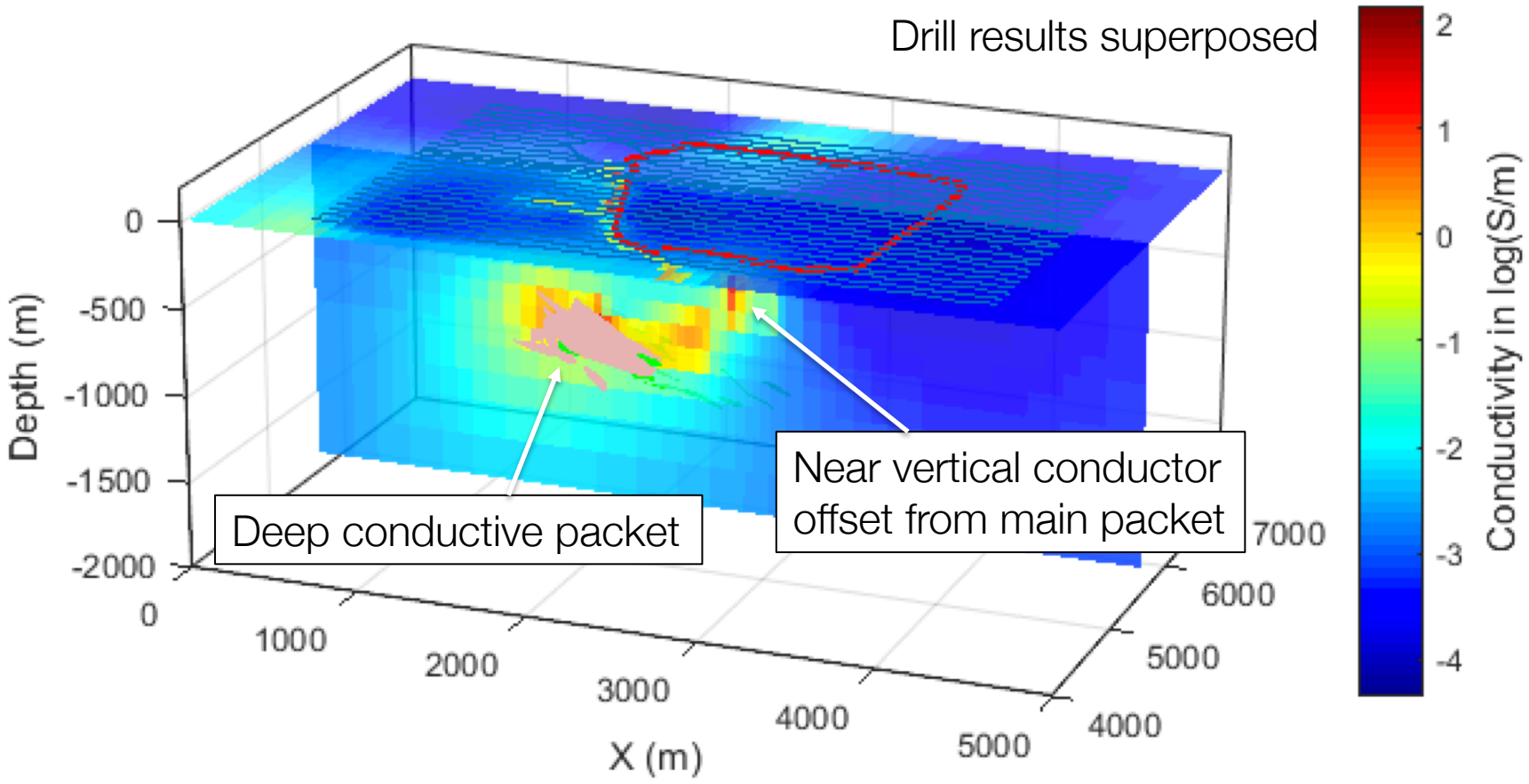


# Synthesis




- Imaged main known conductive bodies
- Second conductor: recently drilled and contained sulfides (argillite)

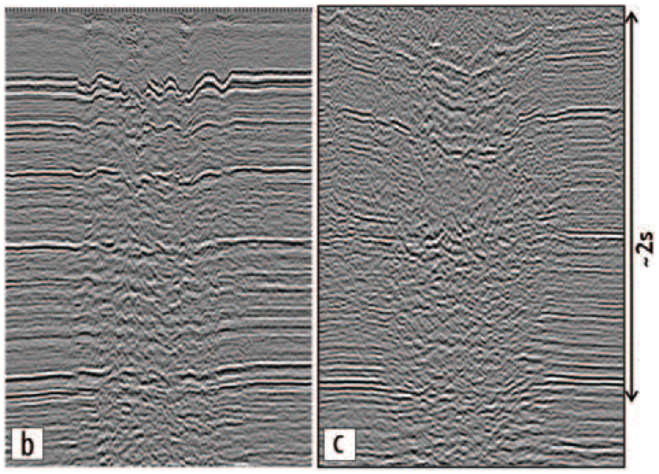
# Takeaways

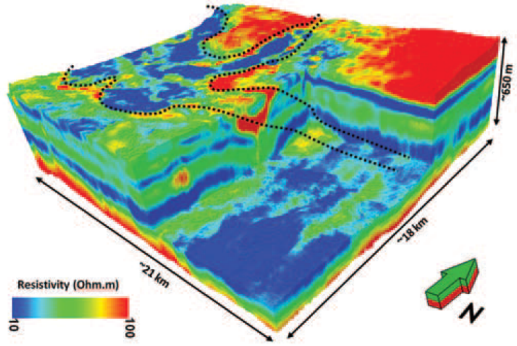



- Early time data:
  - constrain near surface structure infrastructure
  - Improved inversion for late time
- Warm start of inversion was necessary for deep conductors

# Case History: Wadi Sahba

Colombo et al. 2016

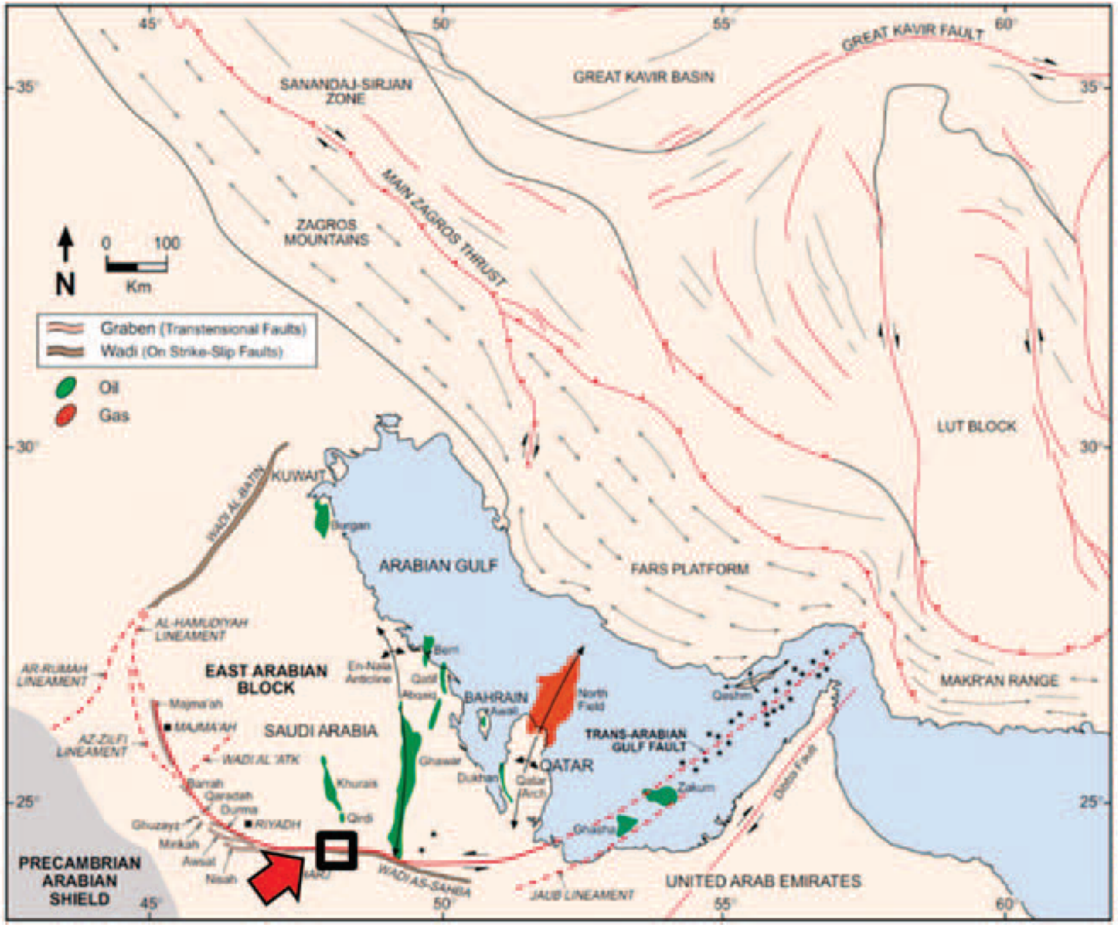


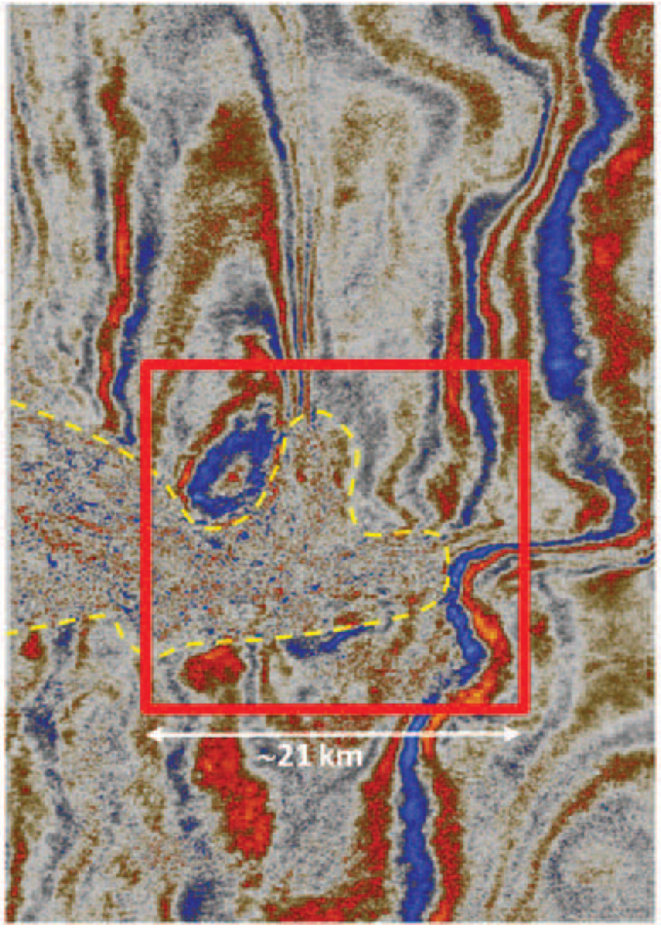

?

# Setup

Location of Wadi area, Saudi Arabia



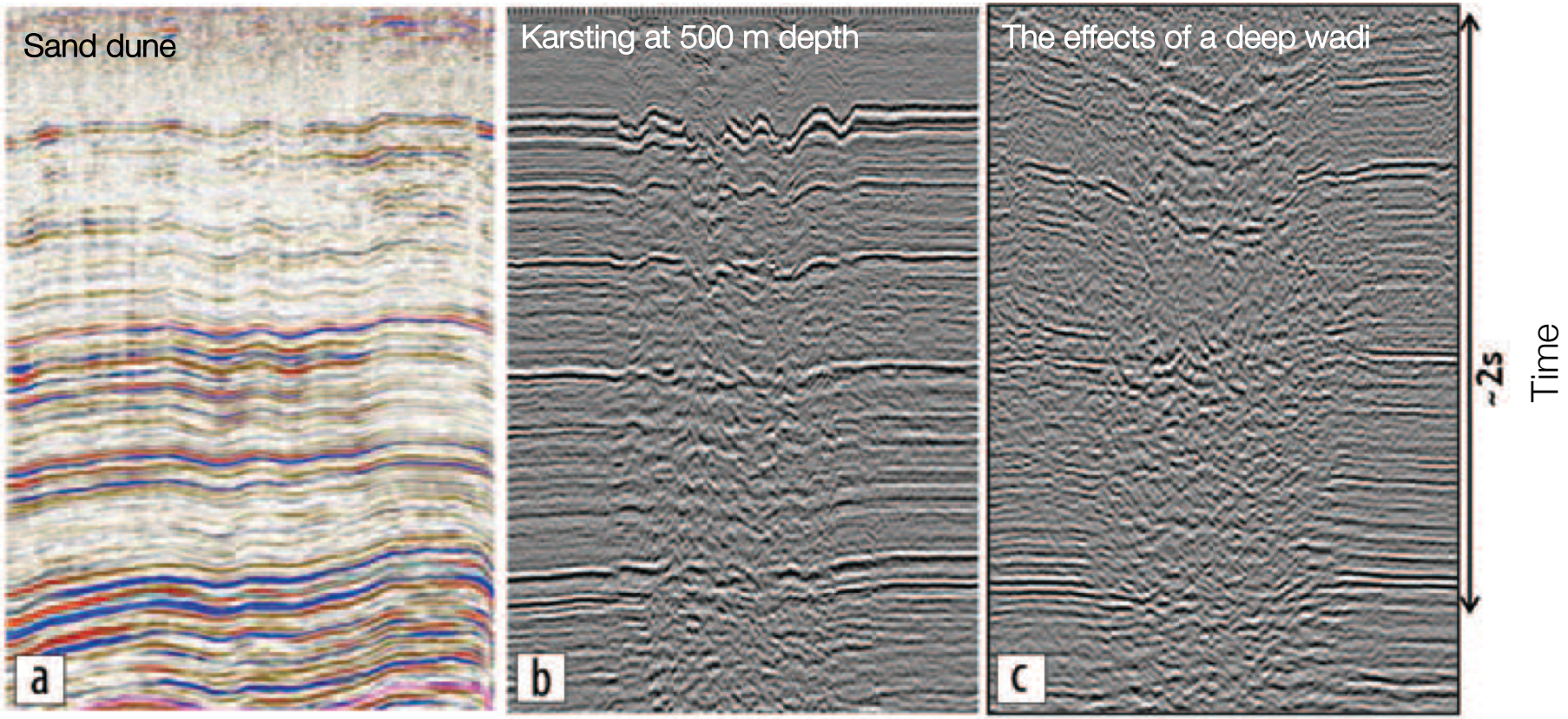

Seismic slice




- Oil and gas exploration in the Middle East: Focus is now stratigraphic traps and low relief structures

# Challenges for processing seismic data

Example seismic sections




- Strong effects from near surface anomalies even after static corrections

# Properties

- P-velocity and conductivity:

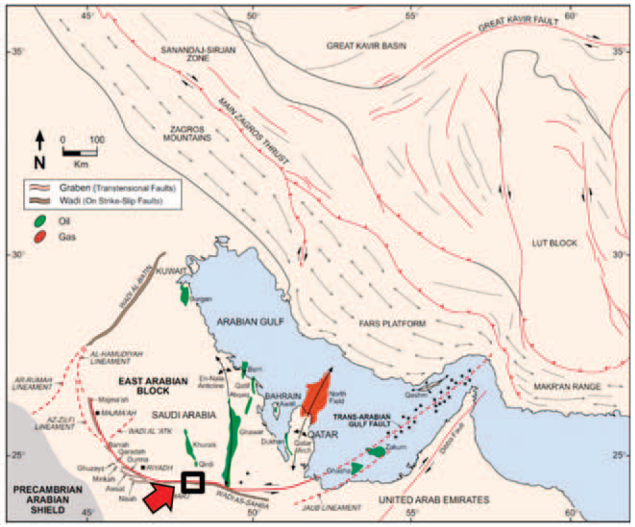
$$v_p = g(\phi)$$
$$\sigma = f(\phi)$$

$v_p$: P-velocity
$\phi$: porosity

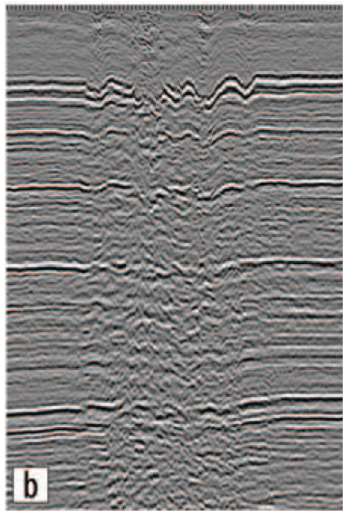
- Poor seismic data:
  - strong scattering effects probably caused by flower faults
  - velocity inversions (high to low $v_p$)

- From previous multi-physics analyses:
  - strong structural similarity between the inverted resistivity, and the existing seismic results

Geologic map



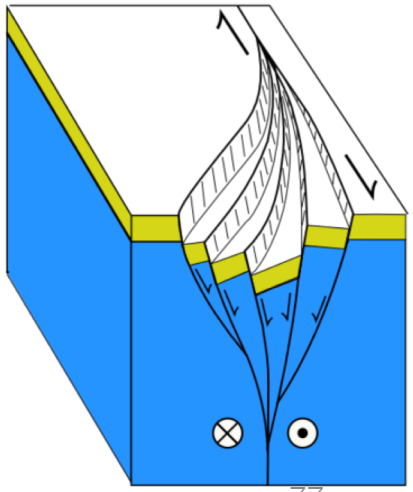

Seismic section




Distance

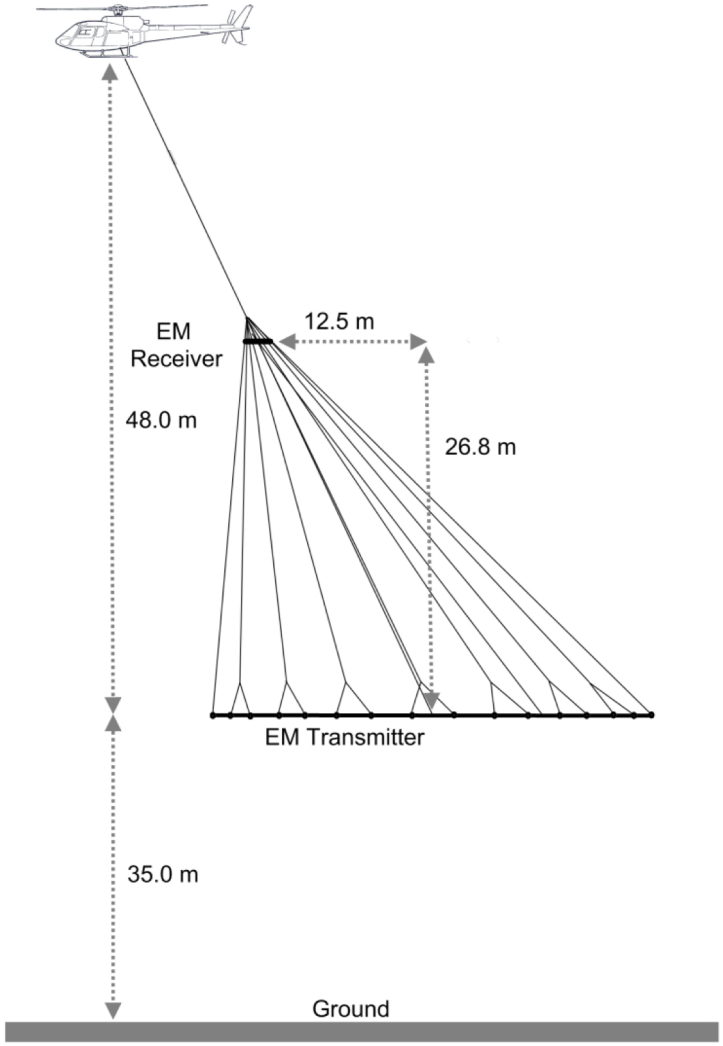
Time

Flower faults

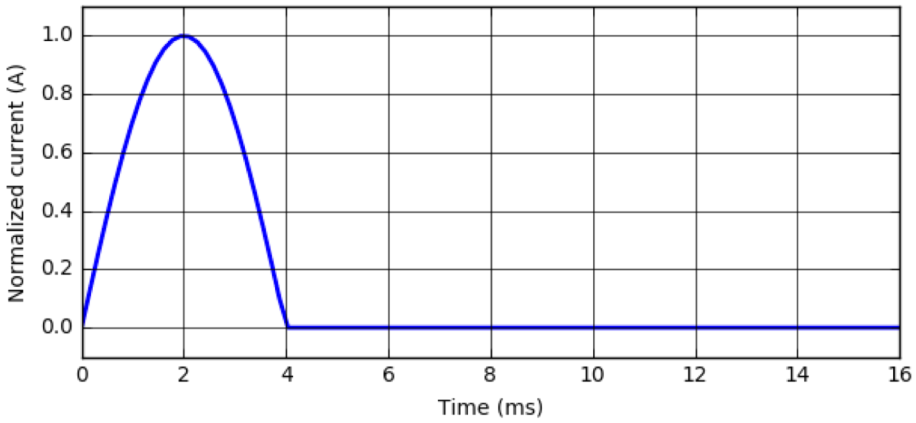


# Survey

## HELITEM

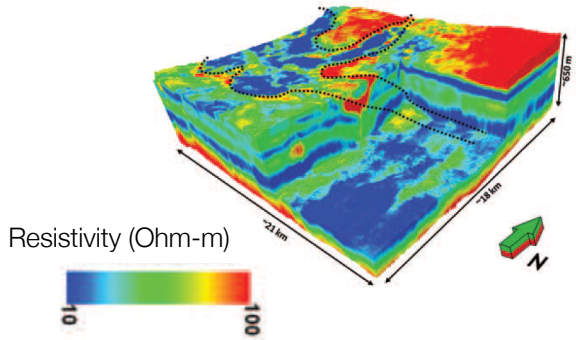



## System Configuration

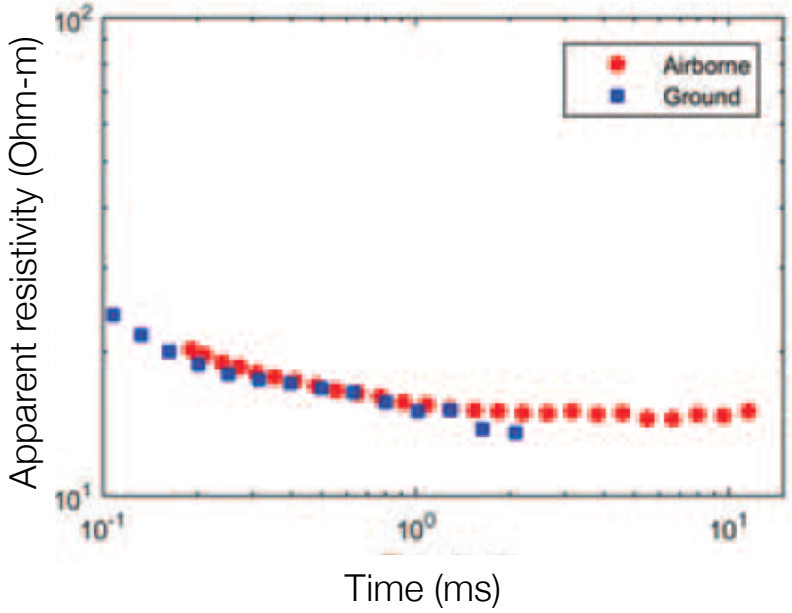



- Peak Tx current: 1200 A
- Dipole moment: $1.7 \times 10^6$ A-m$^2$
- Stacked TEM curve spacing: ~2.7 m
- Total soundings: ~1.6 million

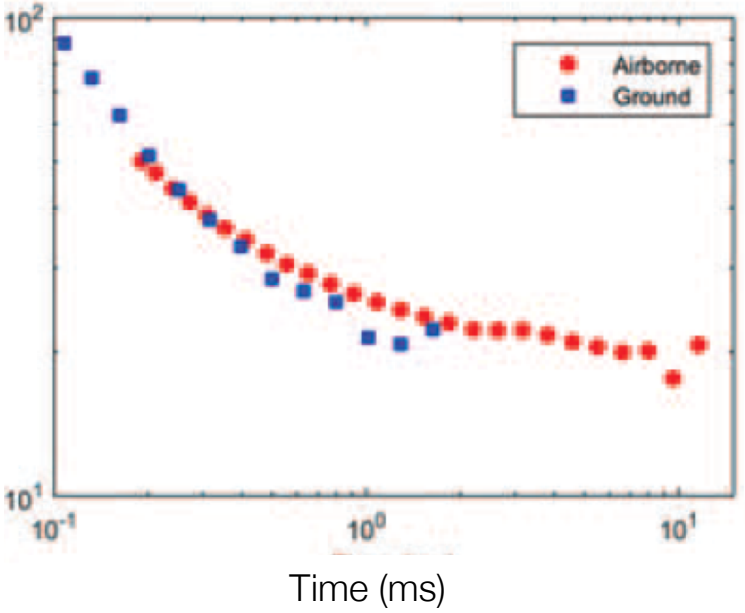
# Comparisons: airborne and ground EM




Conductive area

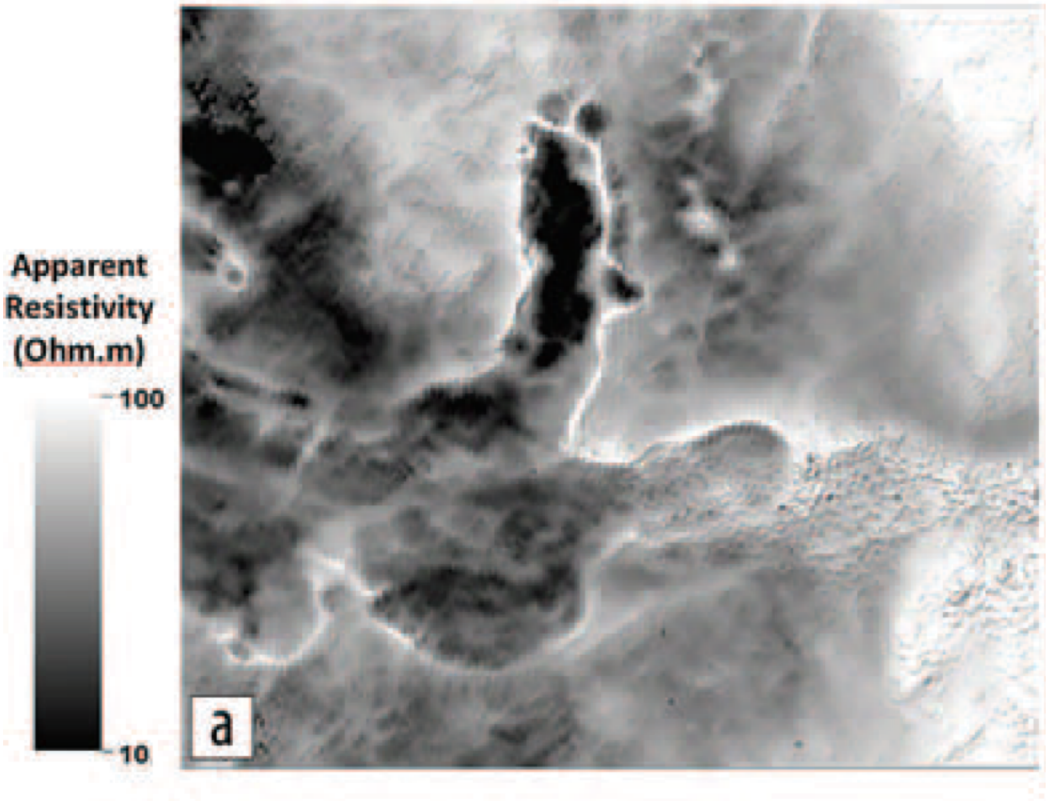



Resistive area

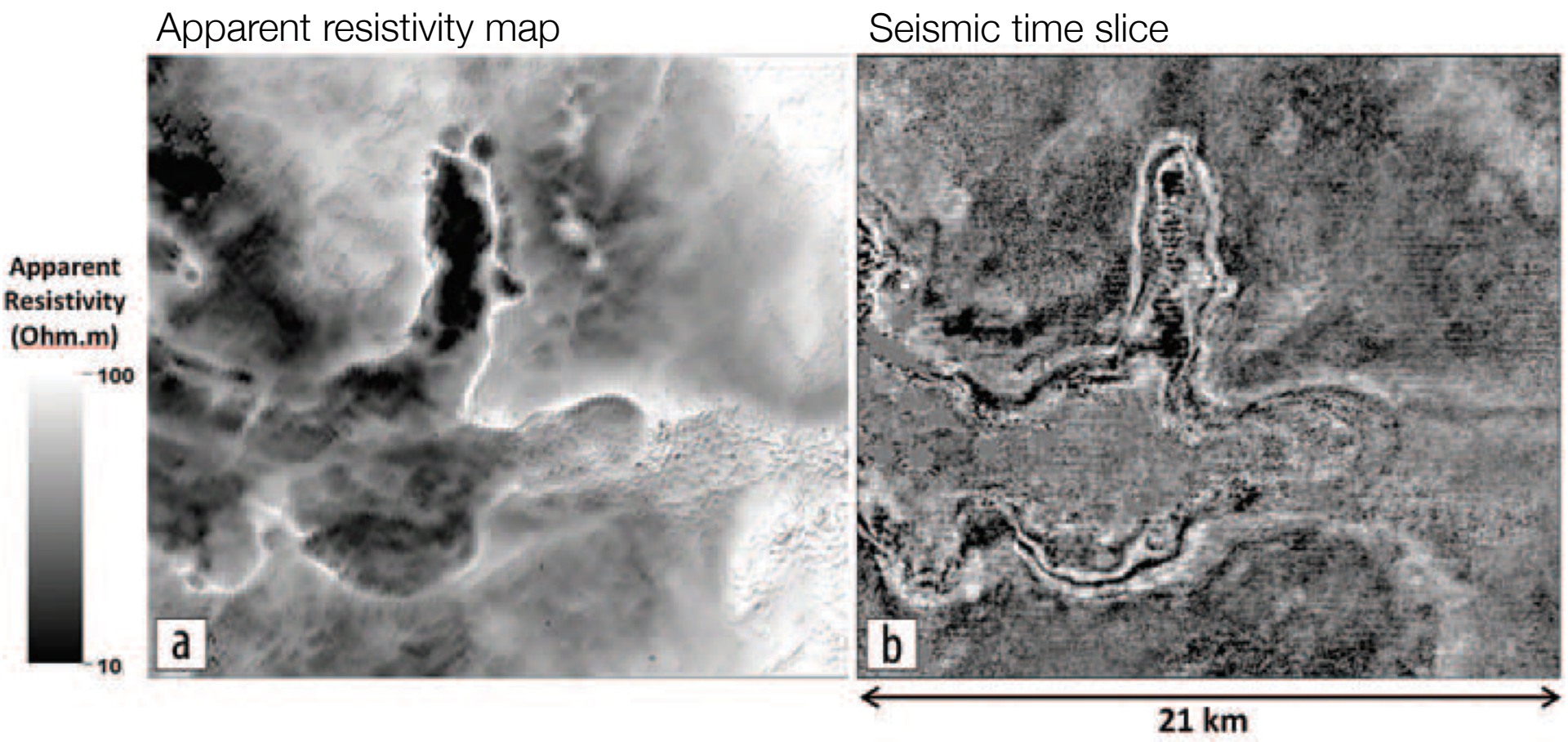


# EM data

Apparent resistivity map

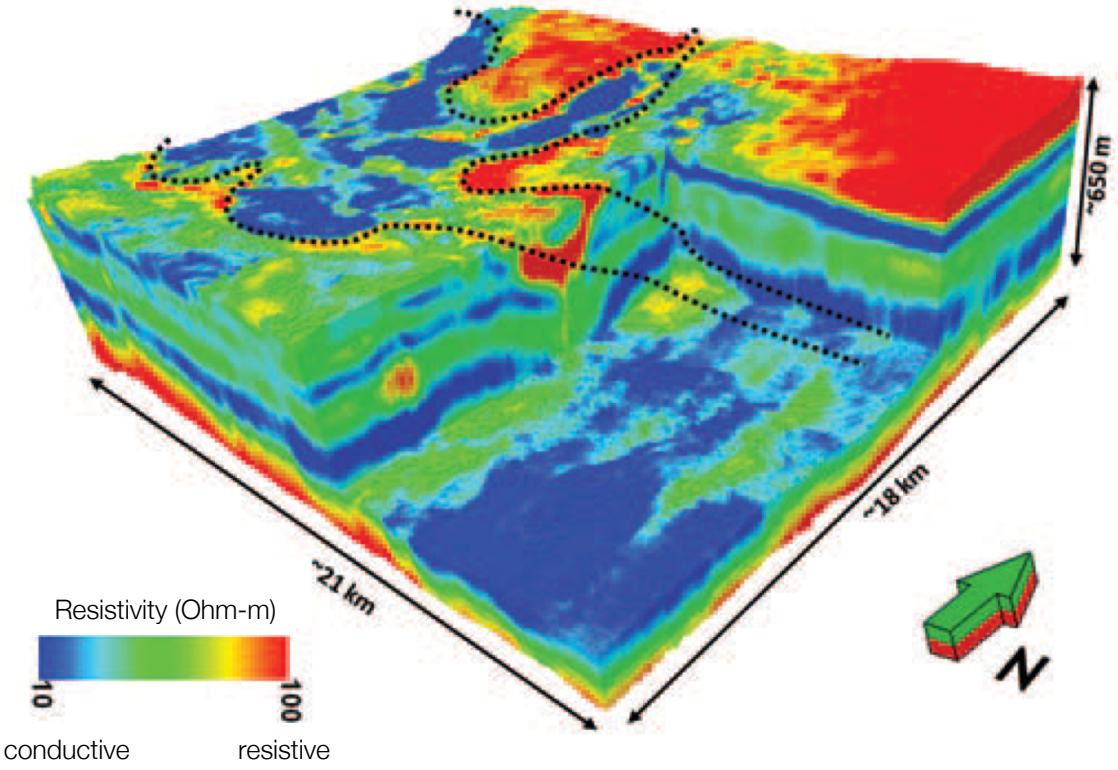


# Comparison: EM and Seismic data



# Processing: EM inversion

Conductivity model




- 1D inversion for each sounding location
- Lateral constraint is used

# Cooperative inversion: Seismic + EM

- How **EM** can help seismic tomography inversion?

Velocity ($v_p$): high to low (significant challenge)

Conductivity (**σ**): high to low

$$v_p = g(\phi)$$
$$\sigma = f(\phi)$$

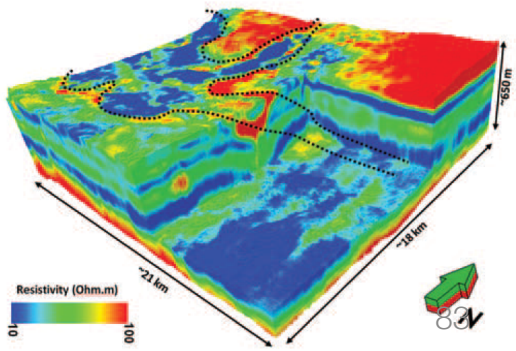
$\phi$: porosity

$\mathbf{m}_s$: Slowness
$\mathbf{m}_\sigma$: Conductivity

$$\psi(\mathbf{m_s}, \mathbf{m}_\sigma) = \psi_m(\mathbf{m}_s) + \frac{1}{\lambda_1}\psi_d(\mathbf{m}_s) + \frac{1}{\lambda_2}\psi_x(\mathbf{m}_s, \mathbf{m}_\sigma) + \frac{1}{\lambda_3}\psi_{rp}(\mathbf{m}_s, \mathbf{m}_\sigma)$$

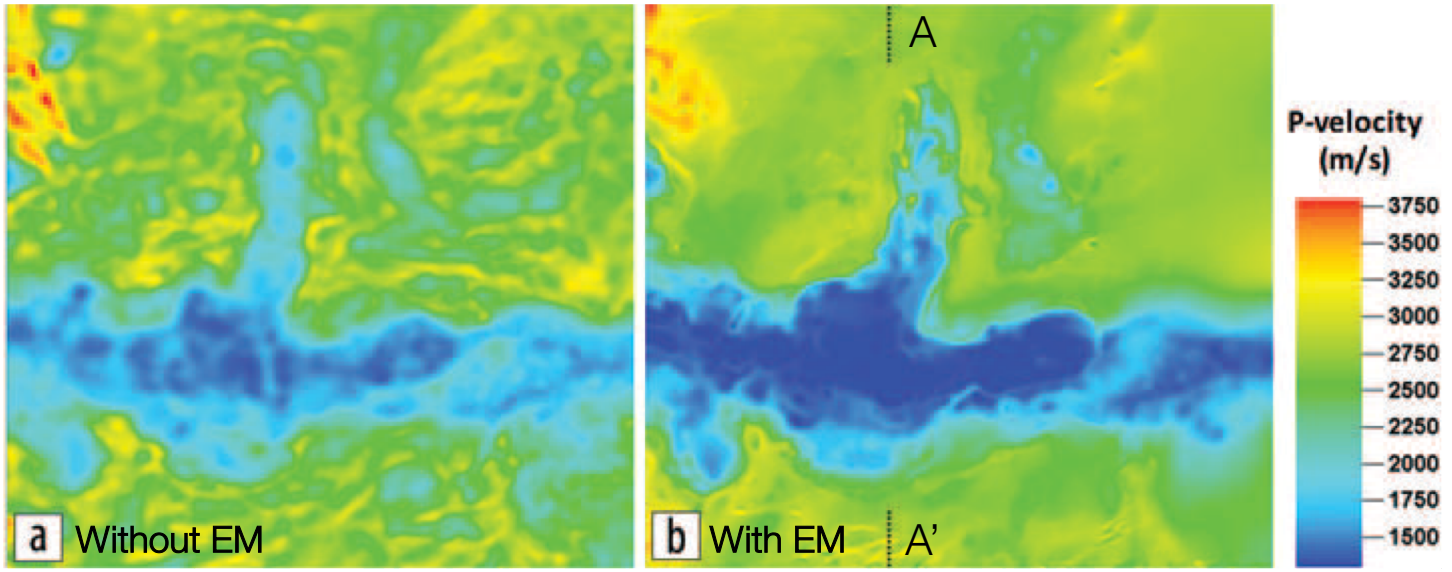
$$\|\nabla \mathbf{m_s} \times \nabla \mathbf{m}_\sigma\|_2^2$$

Gallardo and Meju, 2004



# Cooperative inversion: Seismic + EM

$V_p$ depth slices at 340 m below sea level

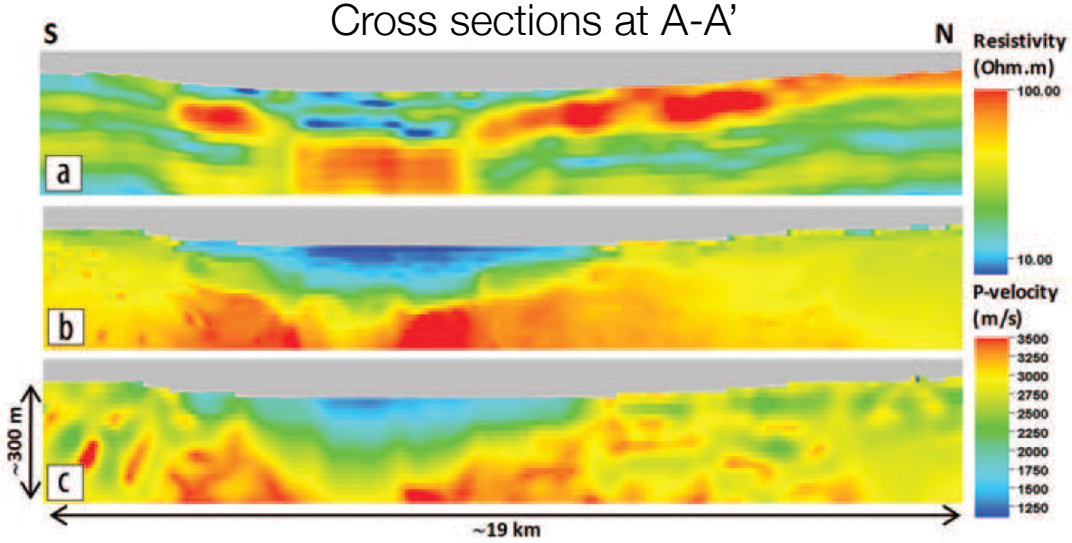



Cross sections at A-A'

Conductivity

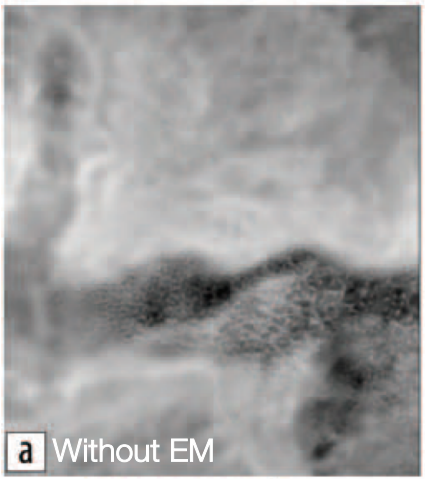
$v_p$ with EM

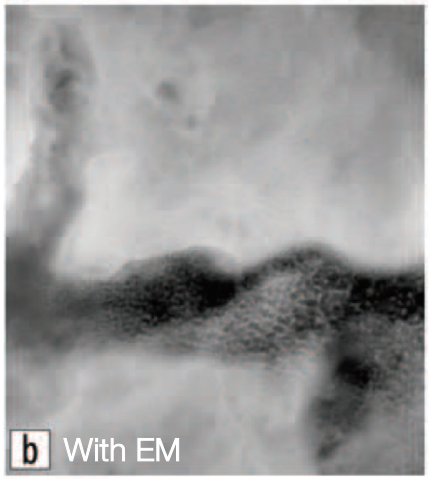
$v_p$ without EM



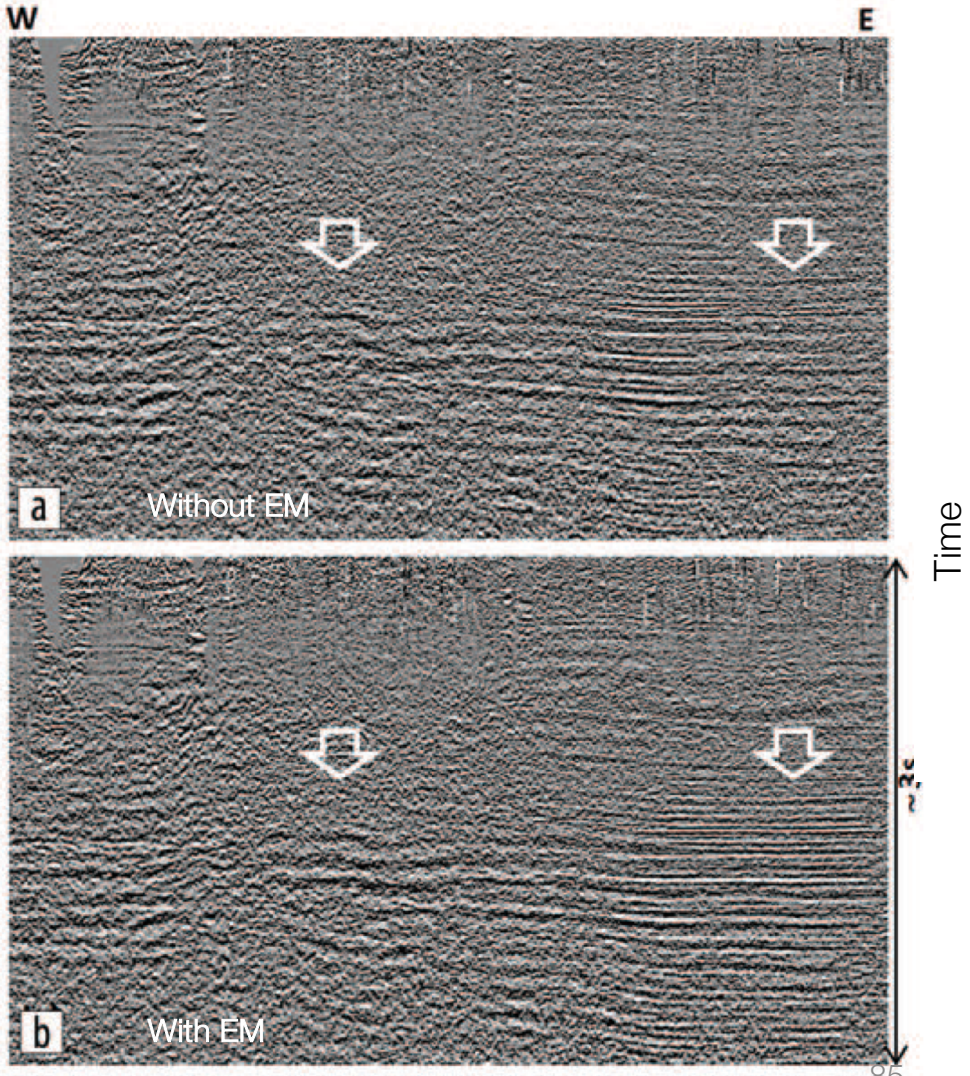
# Static correction

Estimated statics on plan map



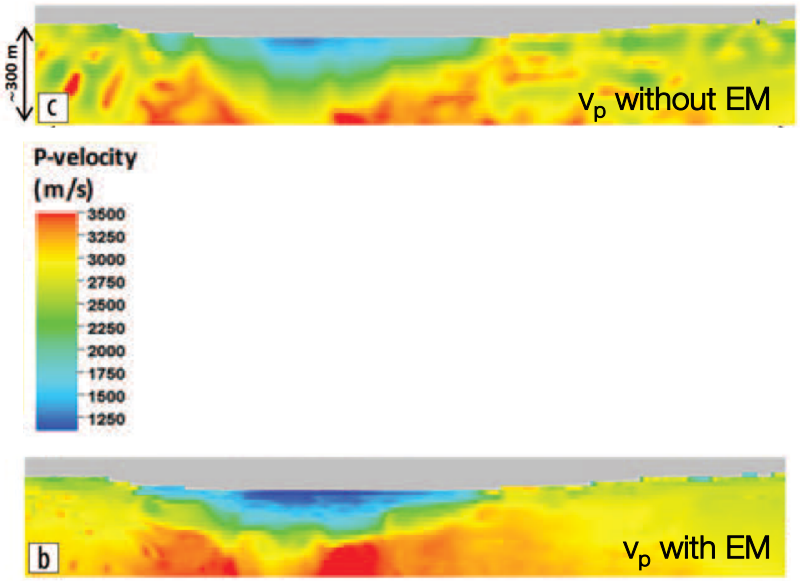

Static corrected sections



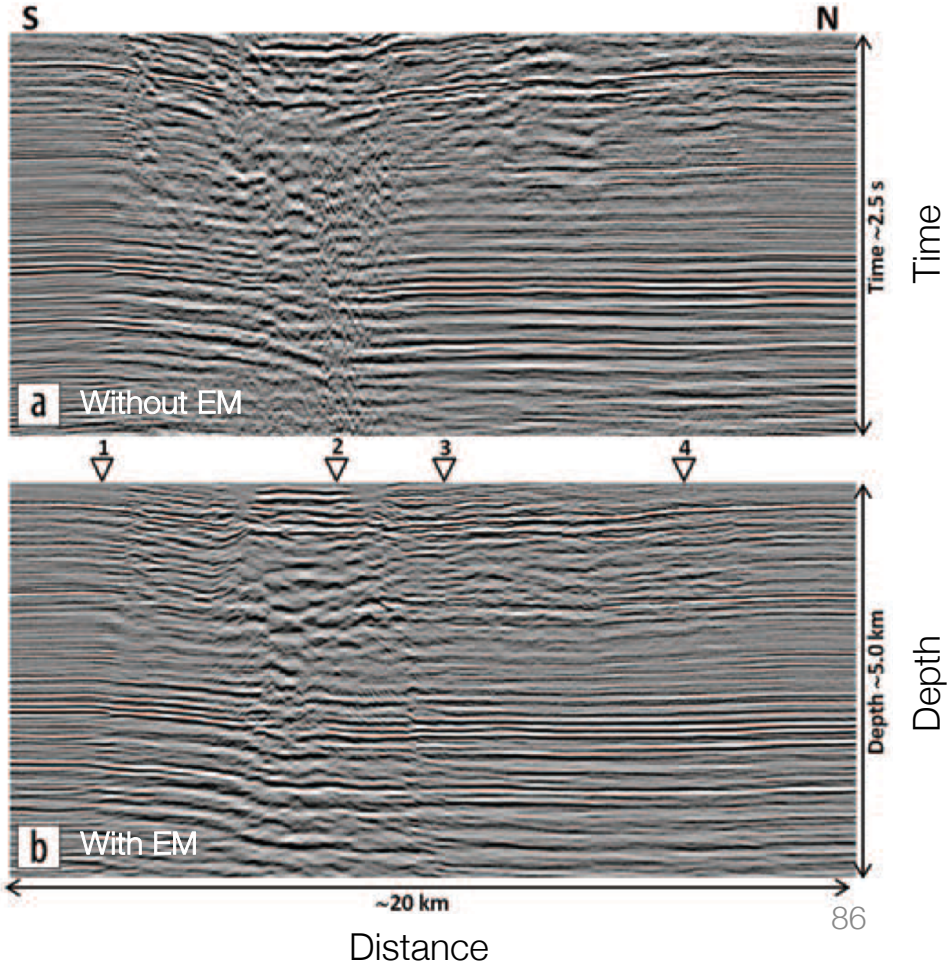
# Pre-stack depth migration

- Impact of the improved $v_p$ model to a pre-stack depth migration:

$v_p$ cross sections at A-A'

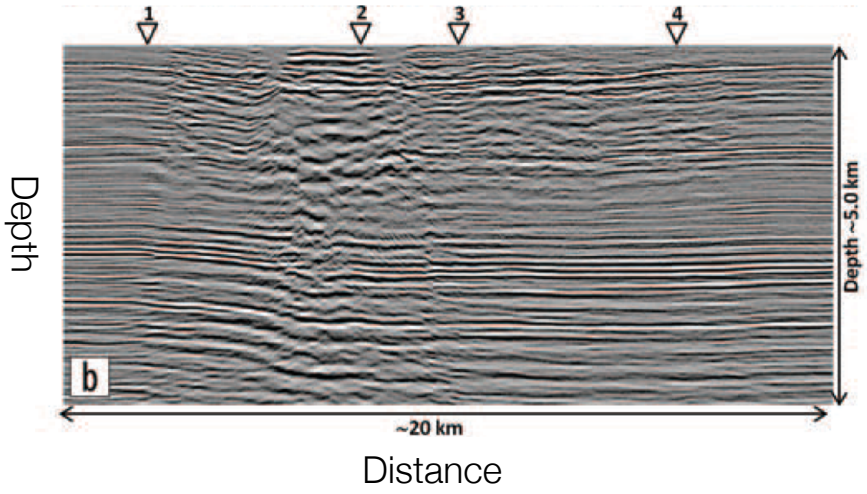



Cross sections at A-A'

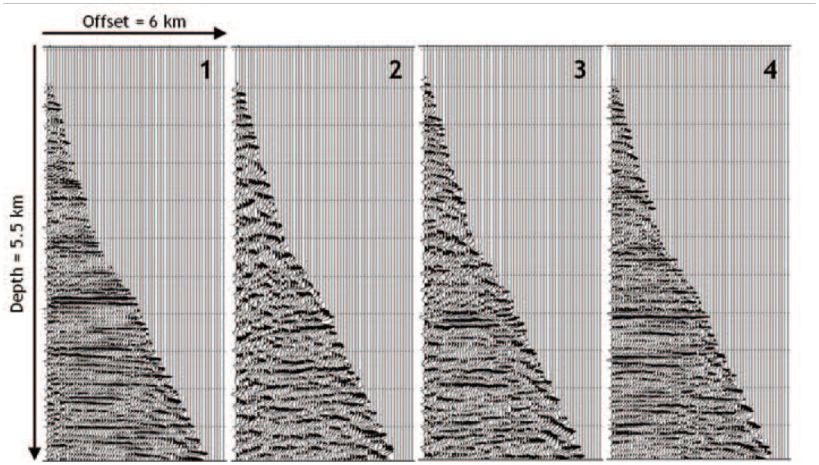


# Interpretation and Synthesis

Depth section at A-A’

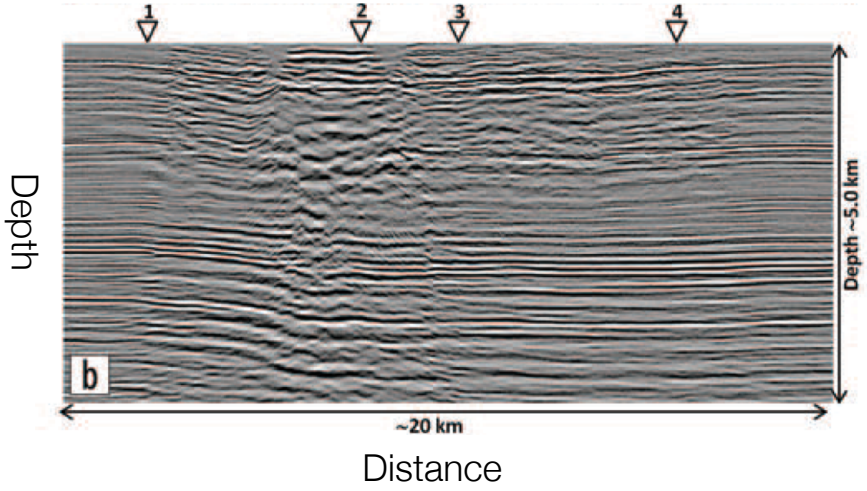



Common image gathers

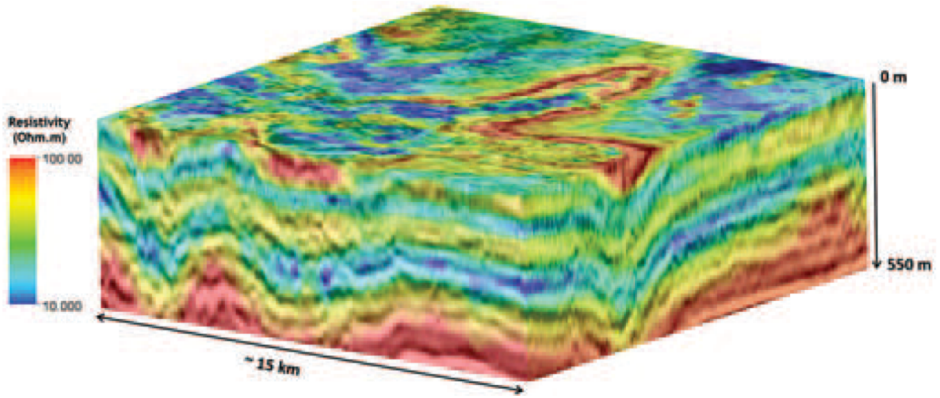


# Interpretation and Synthesis

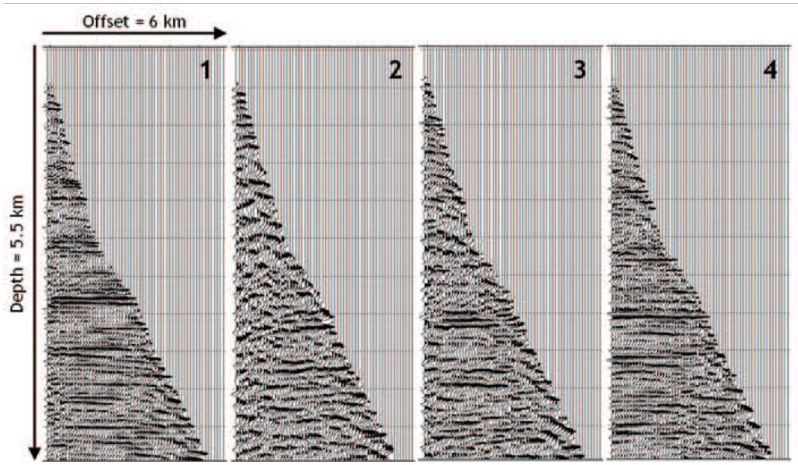
Depth section at A-A’




3D prestack depth migration co-rendered with EM

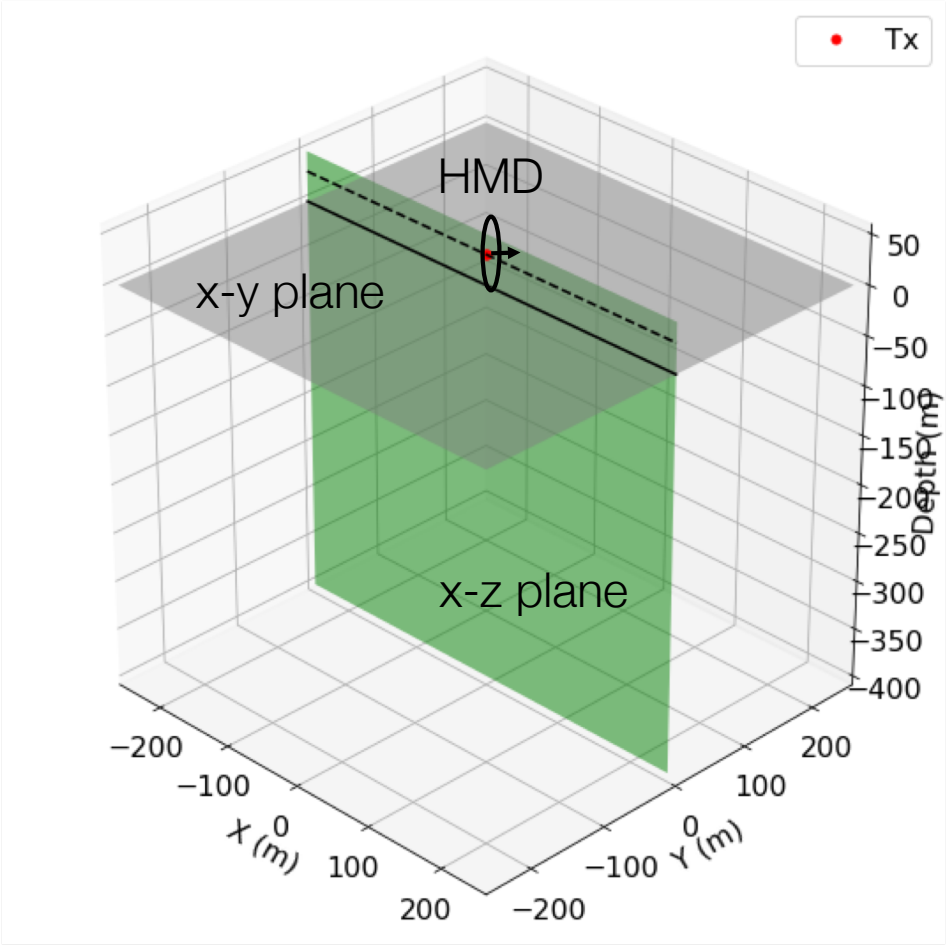



Common image gathers



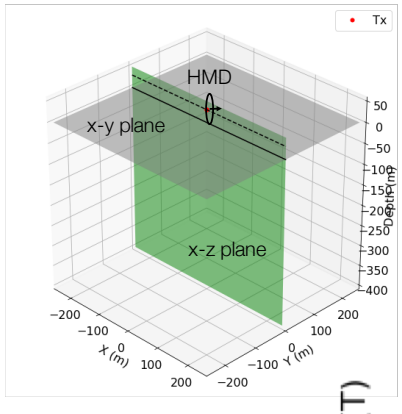

- High resolution near surface conductivity from EM improves velocity model
- Helps seismic imaging:
  - Static correction
  - Pre-stack depth migration

# Horizontal Magnetic Dipole (HMD)



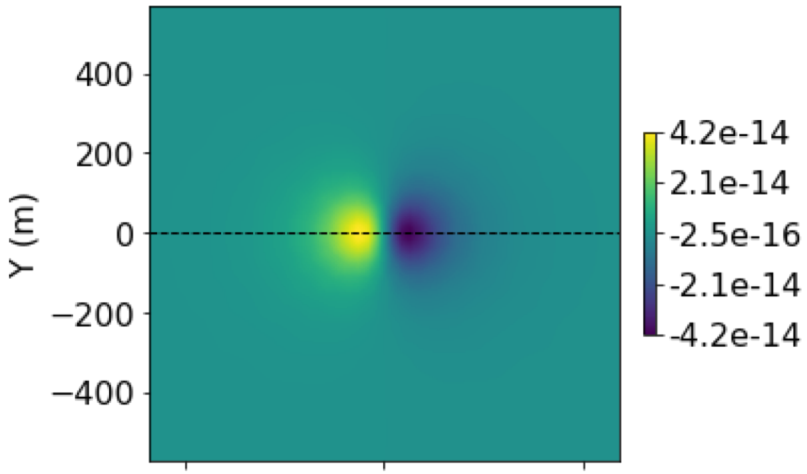

- Same physical principles as VMD, but different source geometry
- Focus on magnetic field and currents
- Different coupling for conductive targets

# Magnetic field

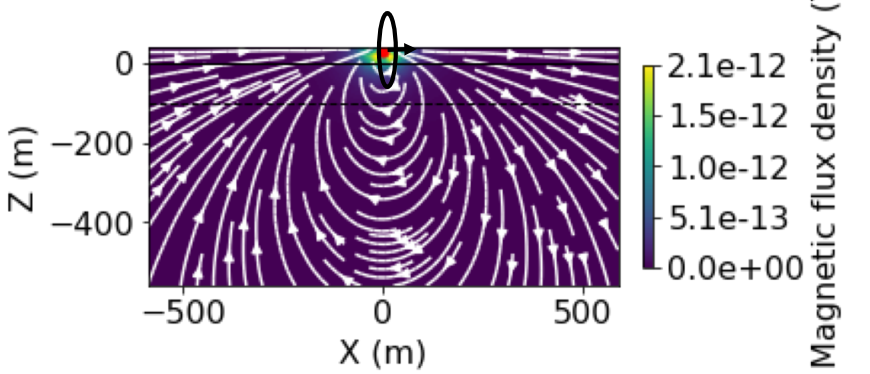



Magnetic field

$b_z$ component

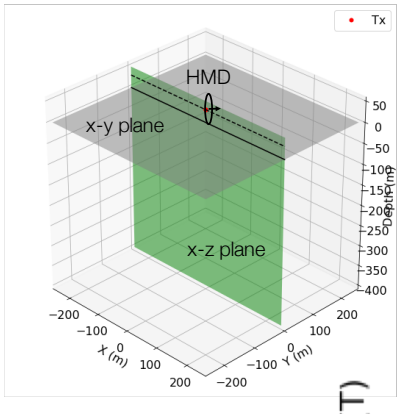



HMD



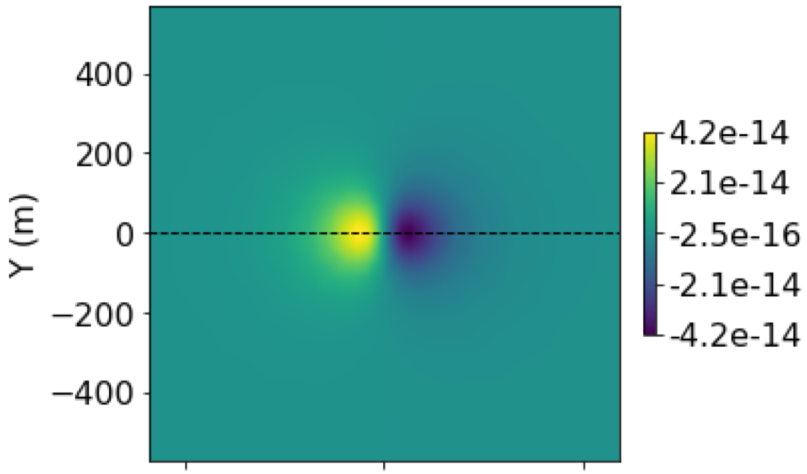

What currents can generate these magnetic fields?

# Magnetic field and Current

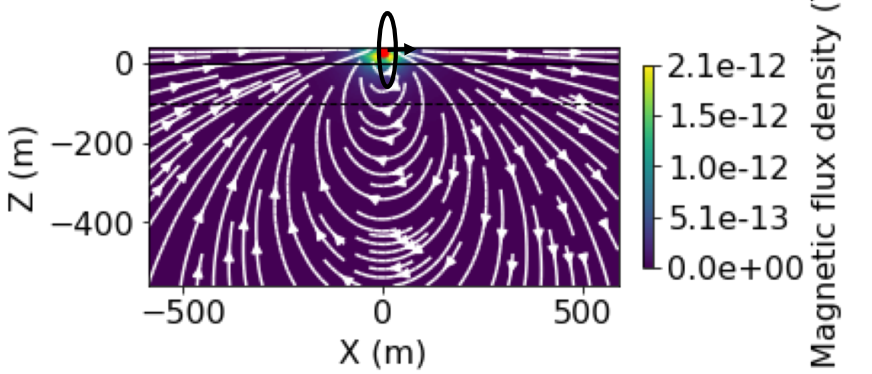



Magnetic field

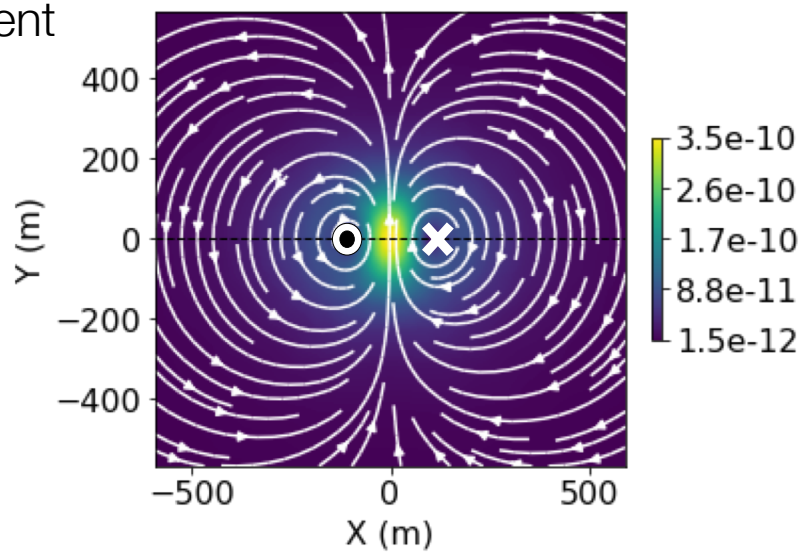
$b_z$ component



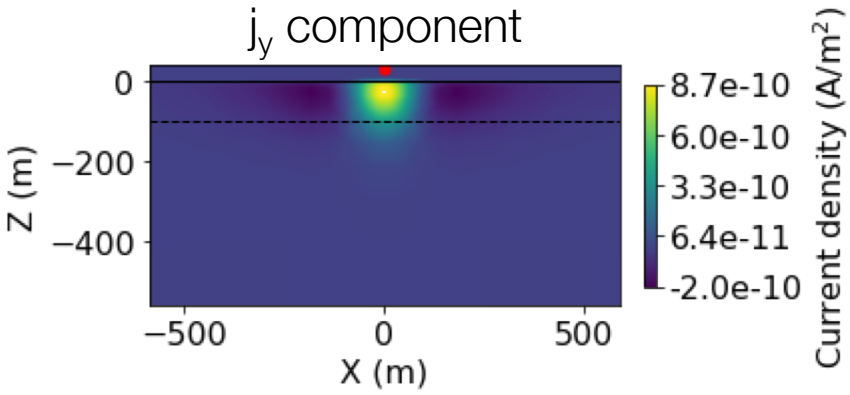

HMD




Current

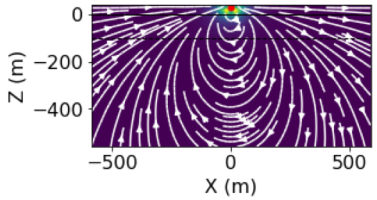



$j_y$ component

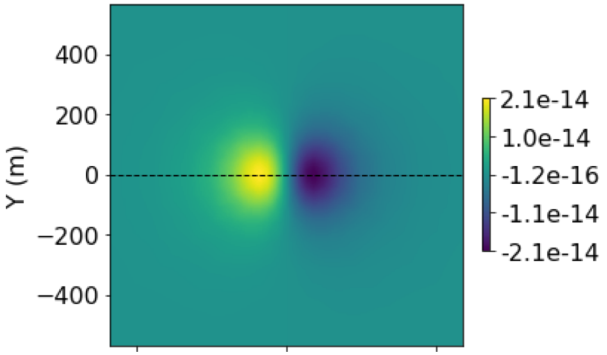


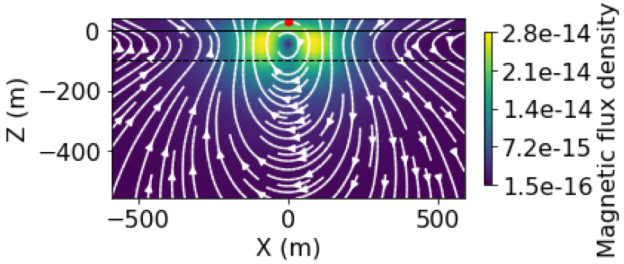
# Magnetic field in time

Primary field



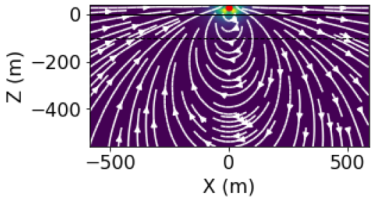

t=0.03ms



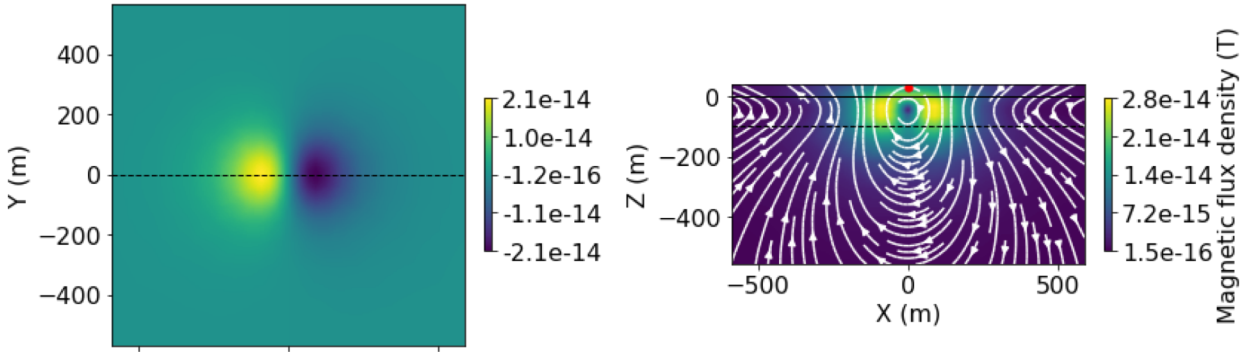



# Magnetic field in time

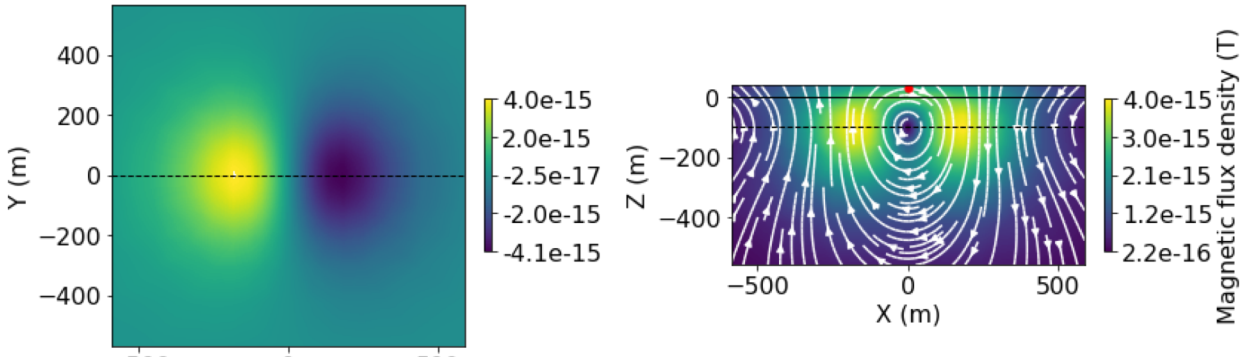
Primary field




t=0.03ms

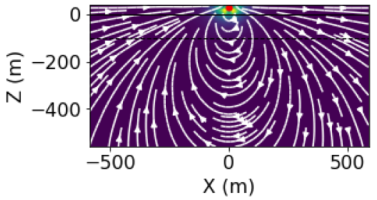



t=0.13ms

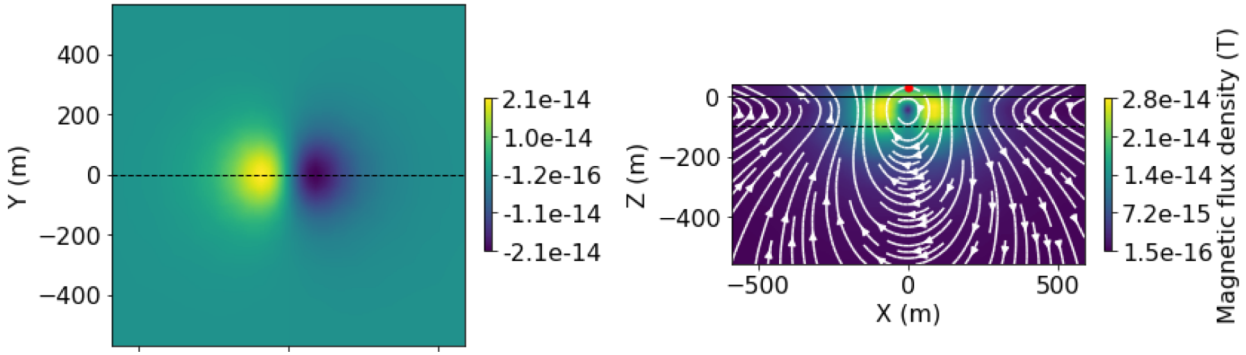


# Magnetic field in time

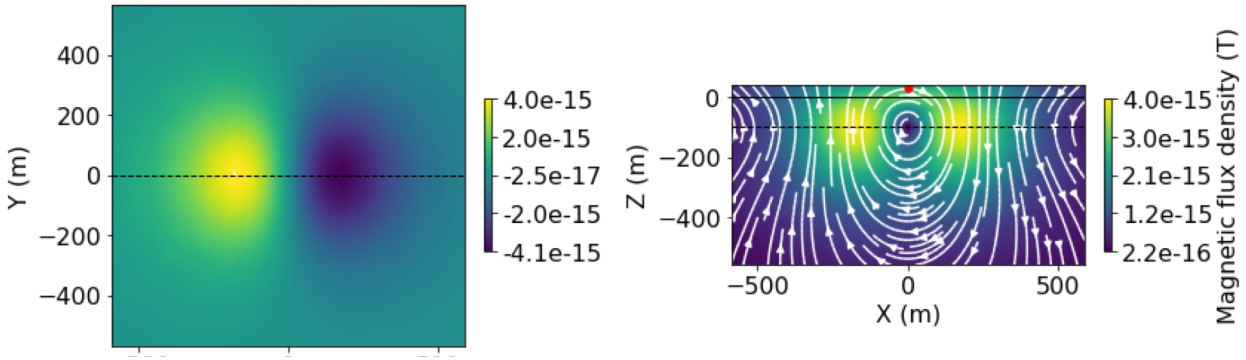
Primary field



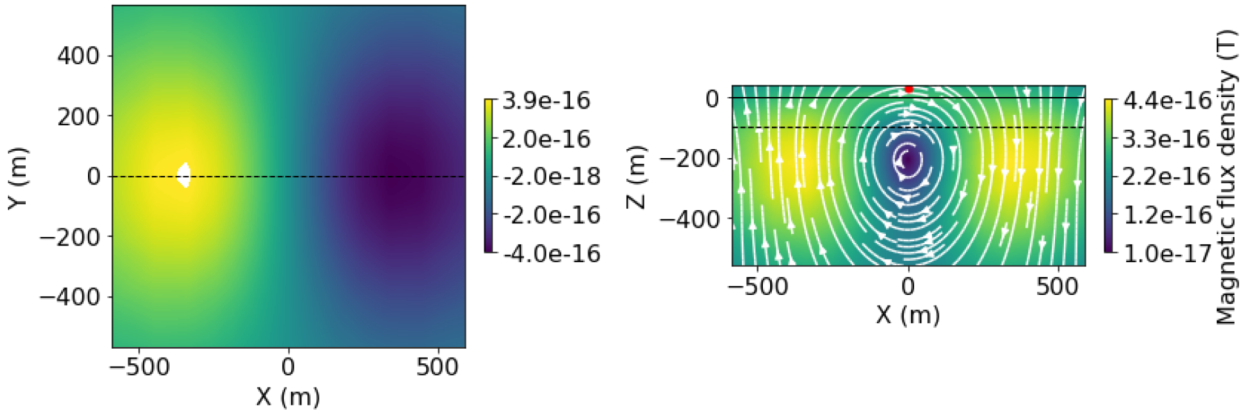

t=0.03ms




t=0.13ms

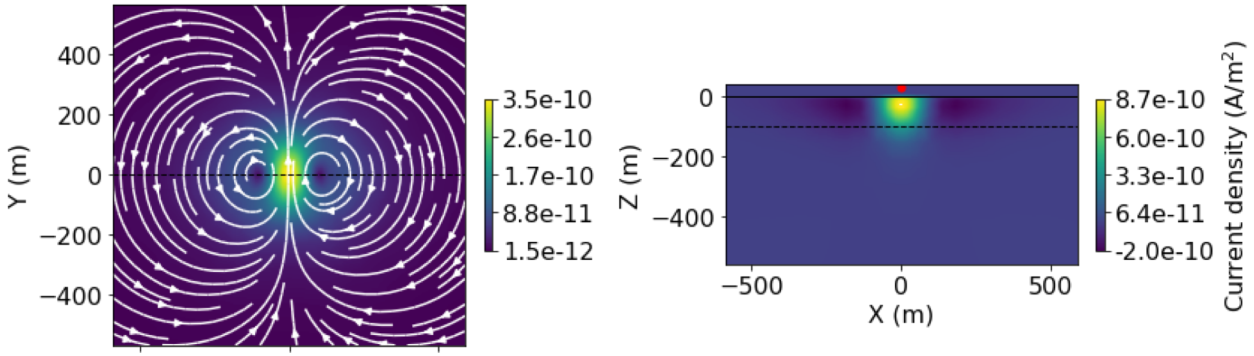



t=0.63ms

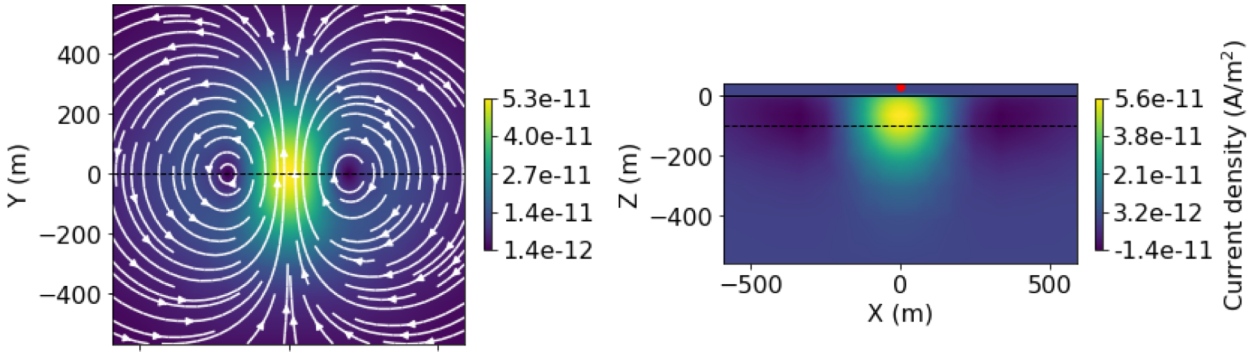


# Current in time

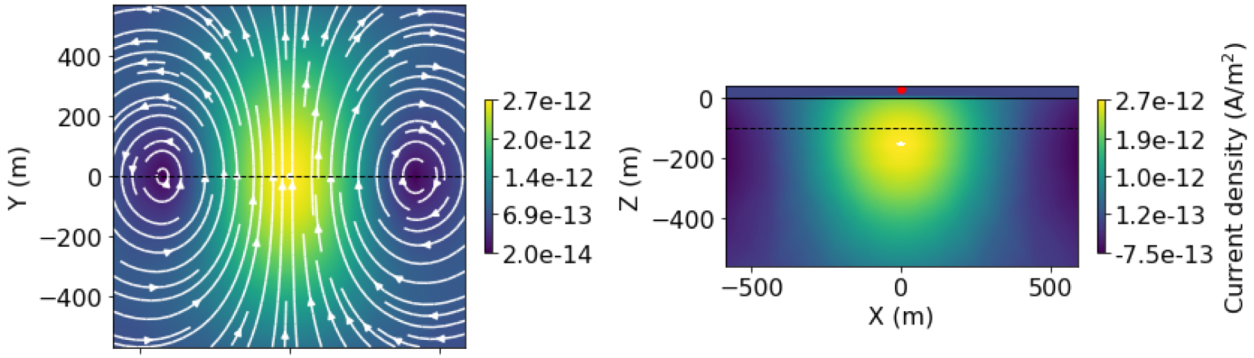
t=0.03ms




t=0.13ms

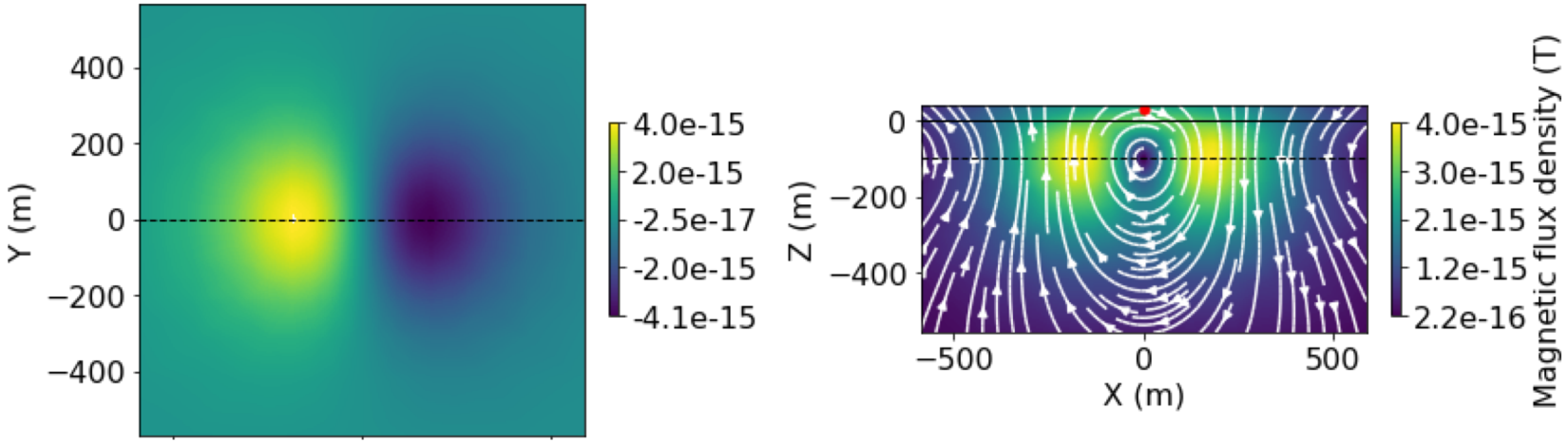



t=0.63ms

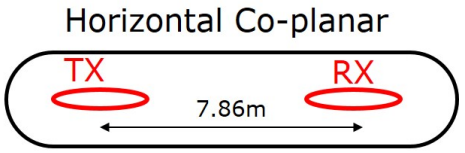


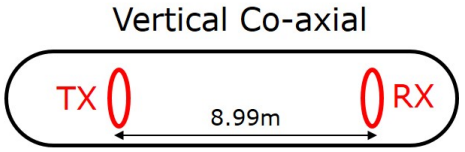
# Data: where and what to measure?

Magnetic field at 0.63 ms



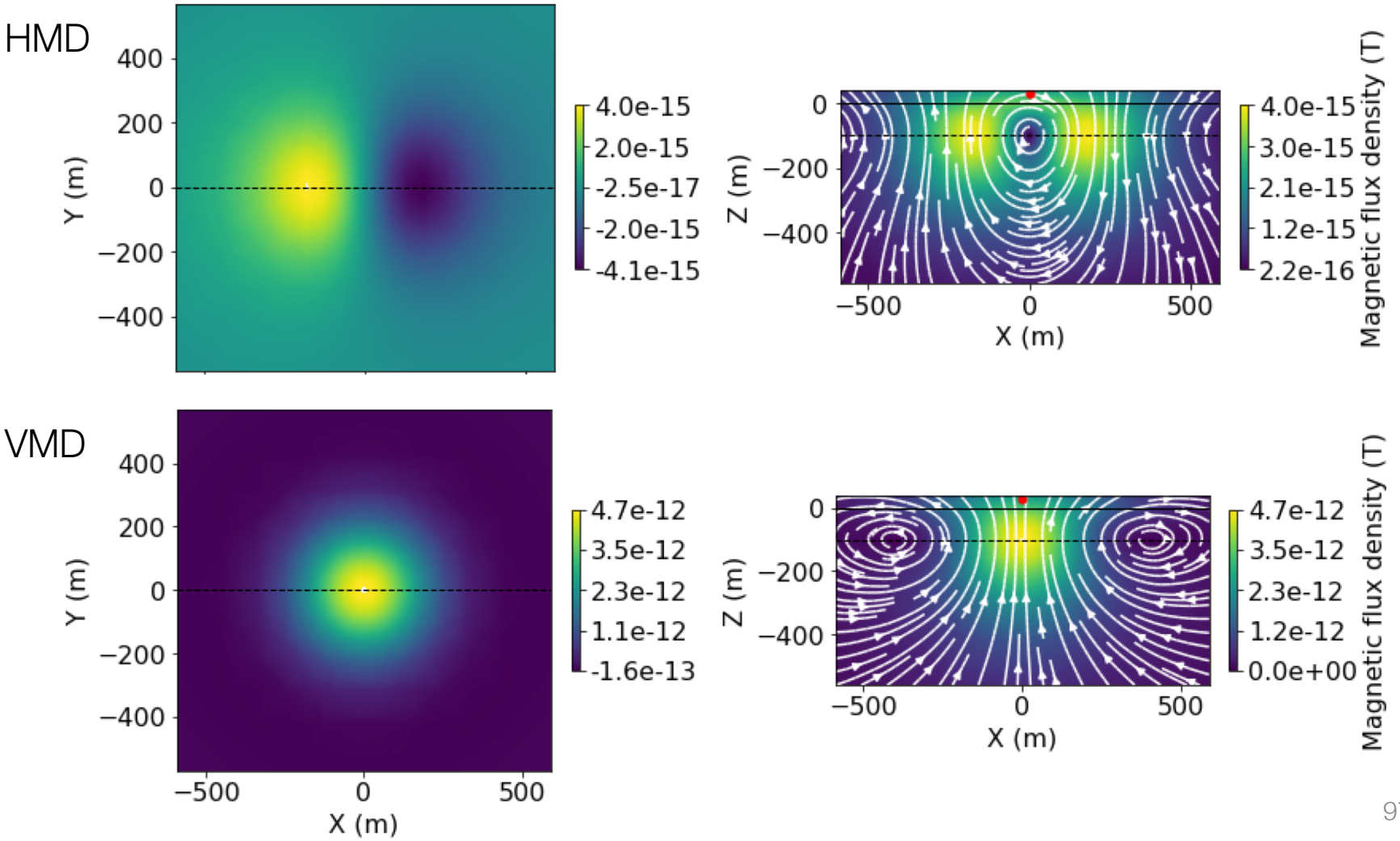




# How different from VMD?

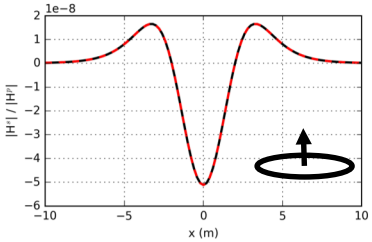
Magnetic field at 0.63 ms

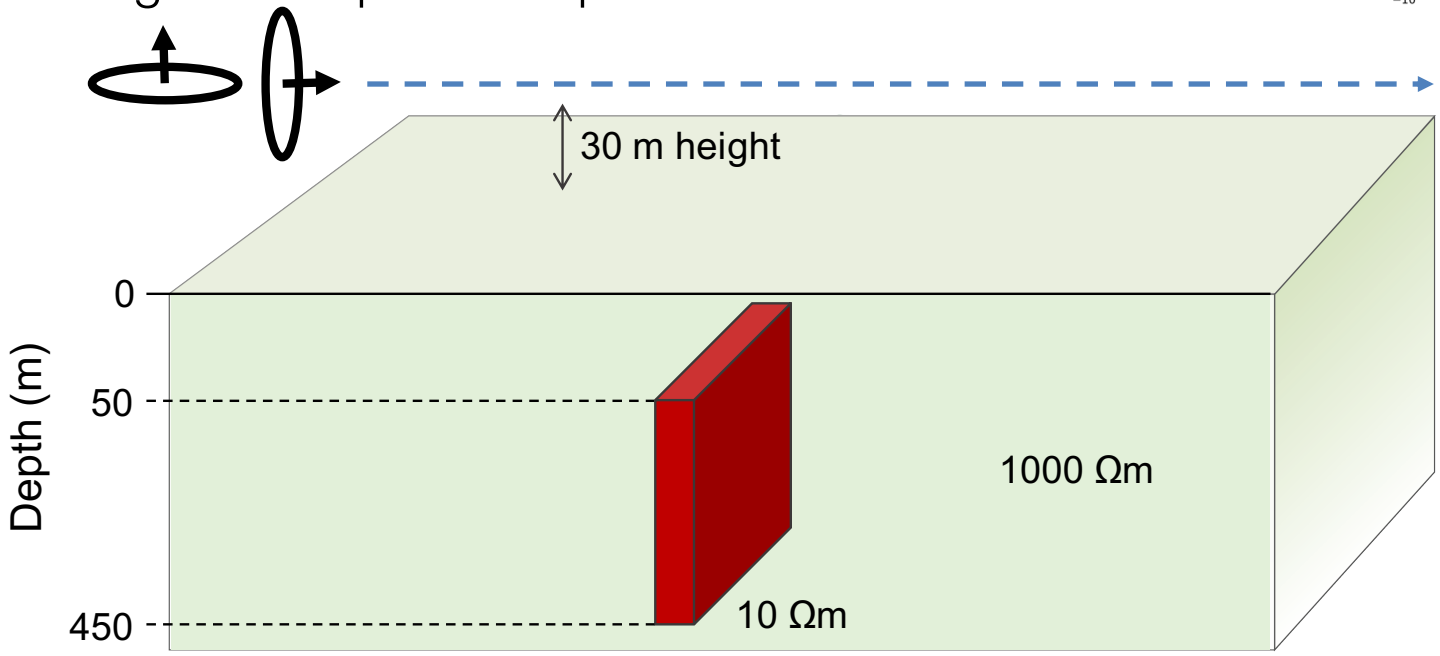


# Coupling to a vertical plate

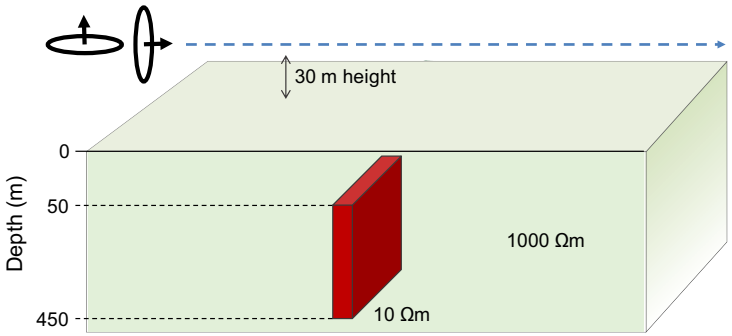
- Assume coincident loop case (Tx and Rx are coincident)
  - Both VMD and HMD
- Consider a profile line data (multiple time channels)
- Imagine how profile response will look like?

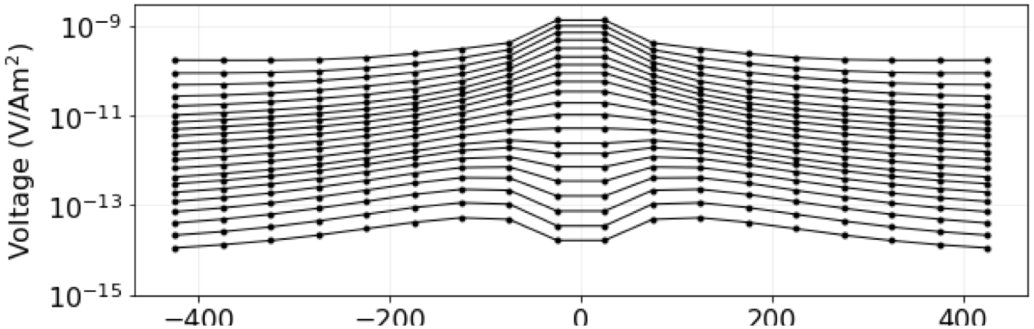
Recall three loops



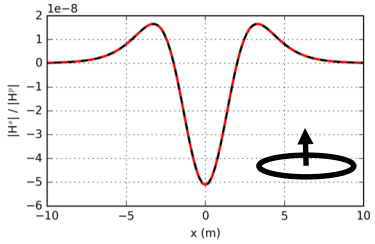



# VMD vs. HMD: profile line data

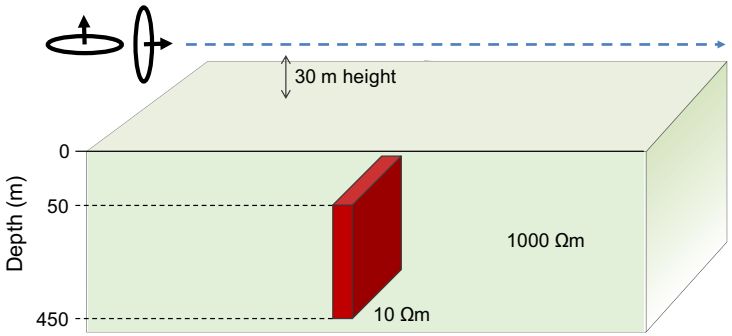


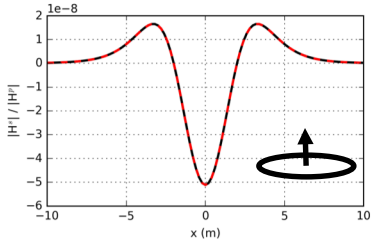

Recall three loops

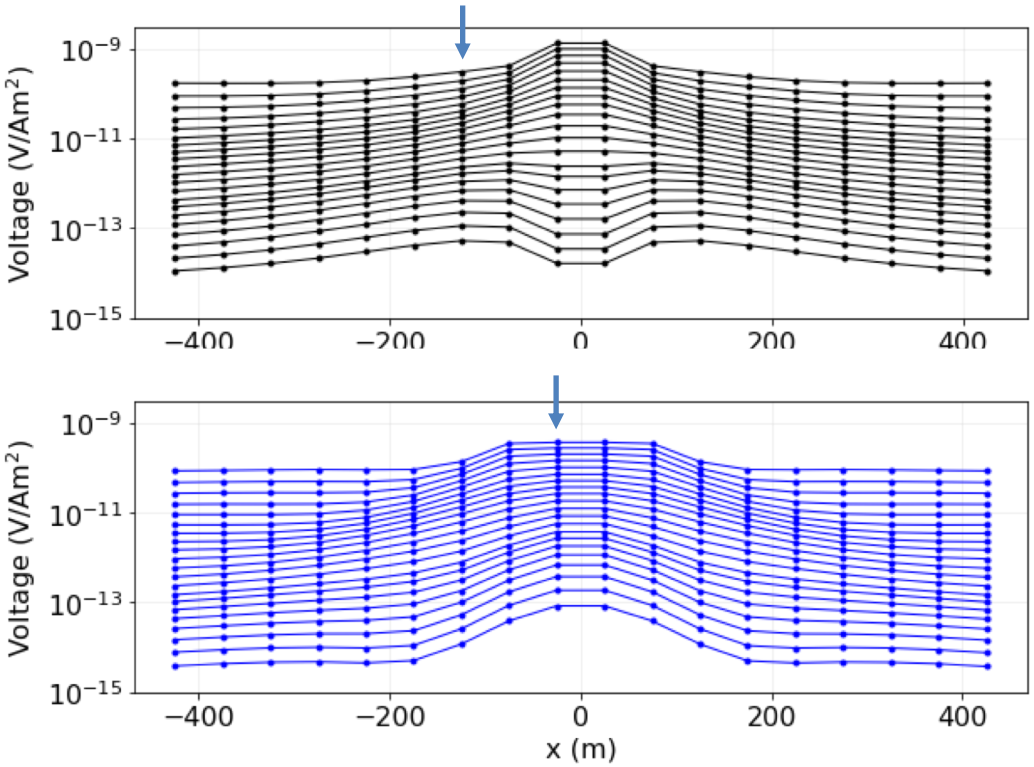


# VMD vs. HMD: profile line data

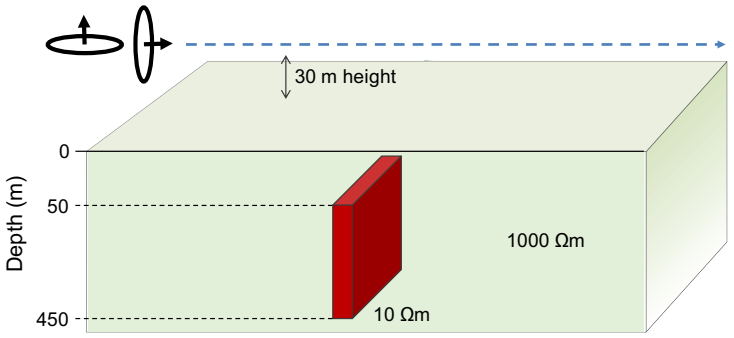


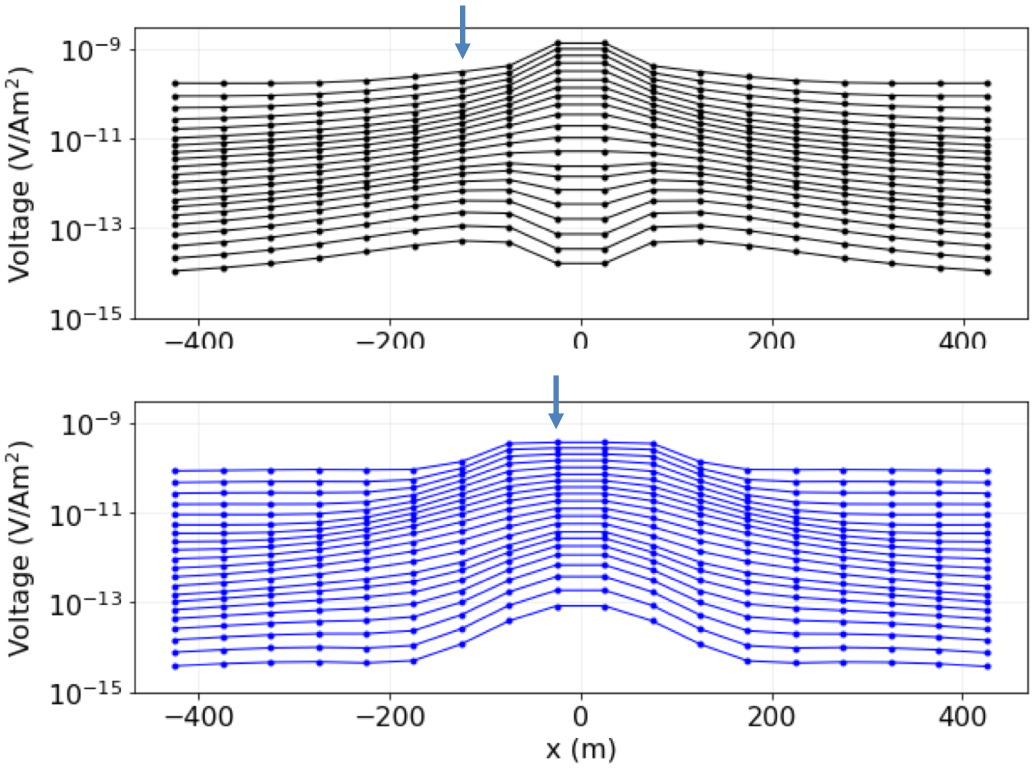

Recall three loops



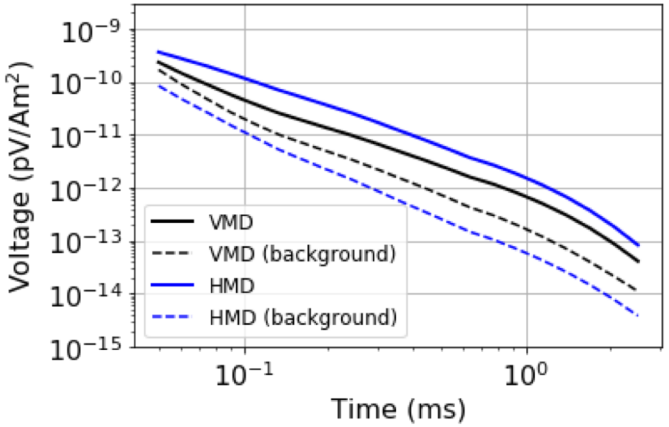



# VMD vs. HMD: time decays



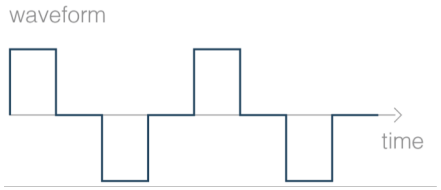

HMD is better coupled to the vertical conductor



# End of inductive source (TDEM)

Setup

Time Domain EM




- Vertical Magnetic Dipole
- Propagation with Time
- Effects of Background Conductivity
- Transmitters and receivers
- Decay Curves
- Case History: Groundwater, Minerals, Hydrocarbons
- Horizontal magnetic Dipole

Next up: Frequency domain EM