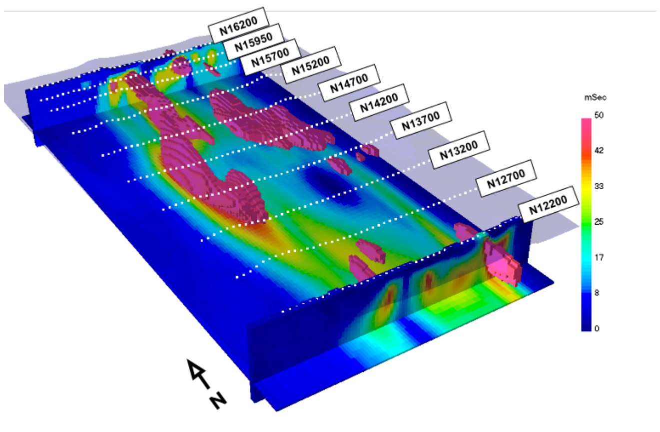
“All charged up”

Advances and applications for IP surveys

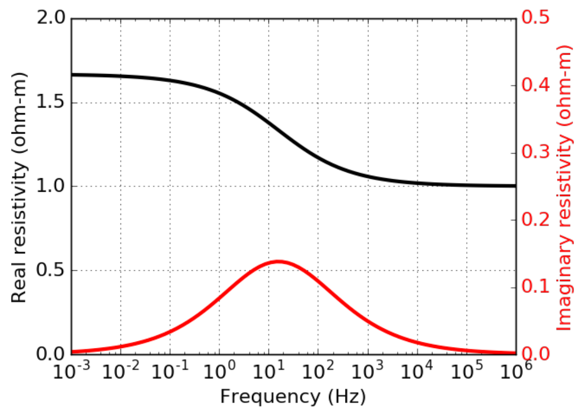
Douglas Oldenburg and **Seogi Kang**

Motivation

Minerals

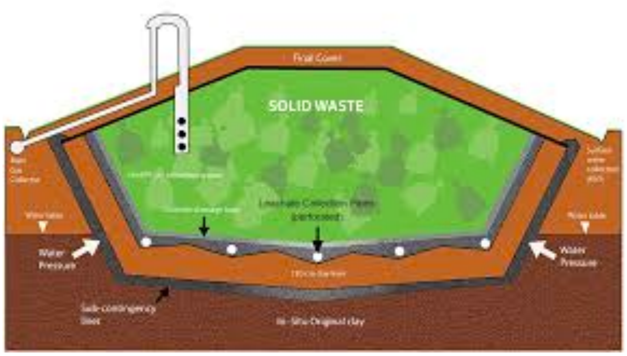


Complex resistivity



Permafrost

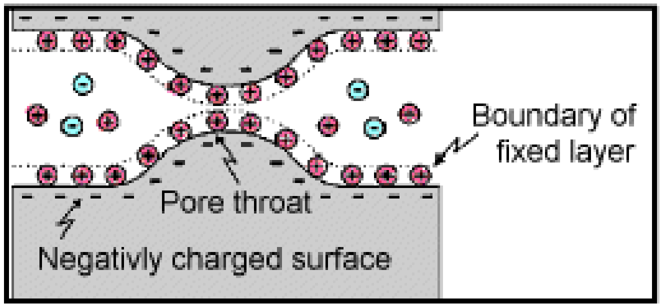
Geotechnical



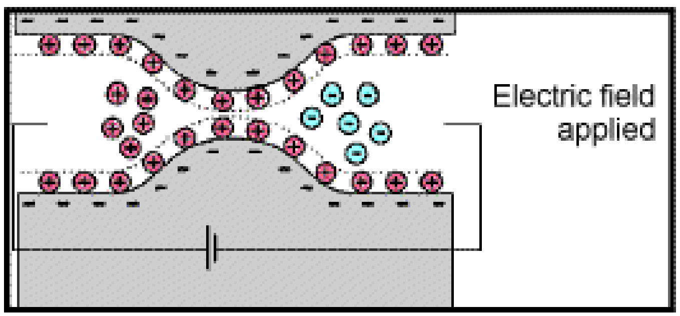
Groundwater

Chargeability

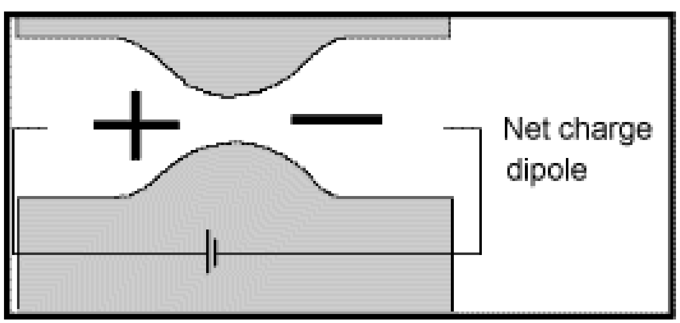
Initially - neutral



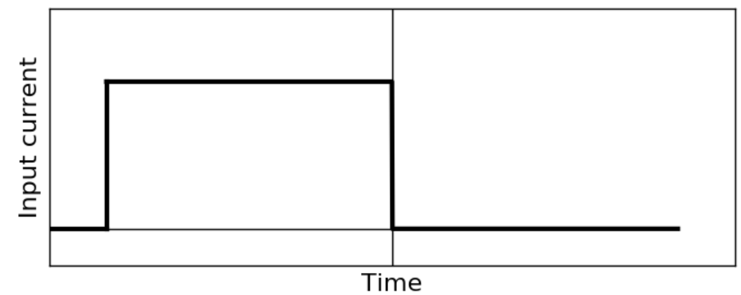
Apply electric field, build up charges



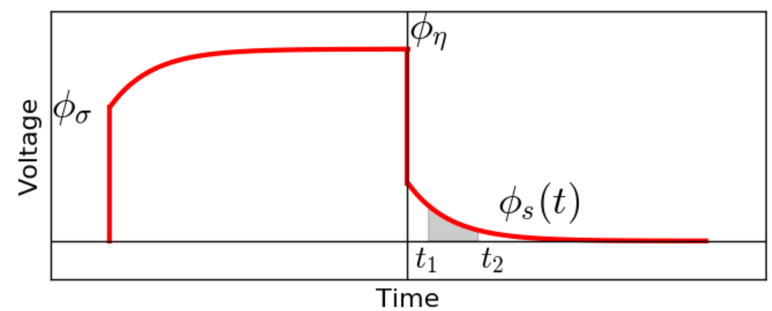
Charge polarization, Electric dipole



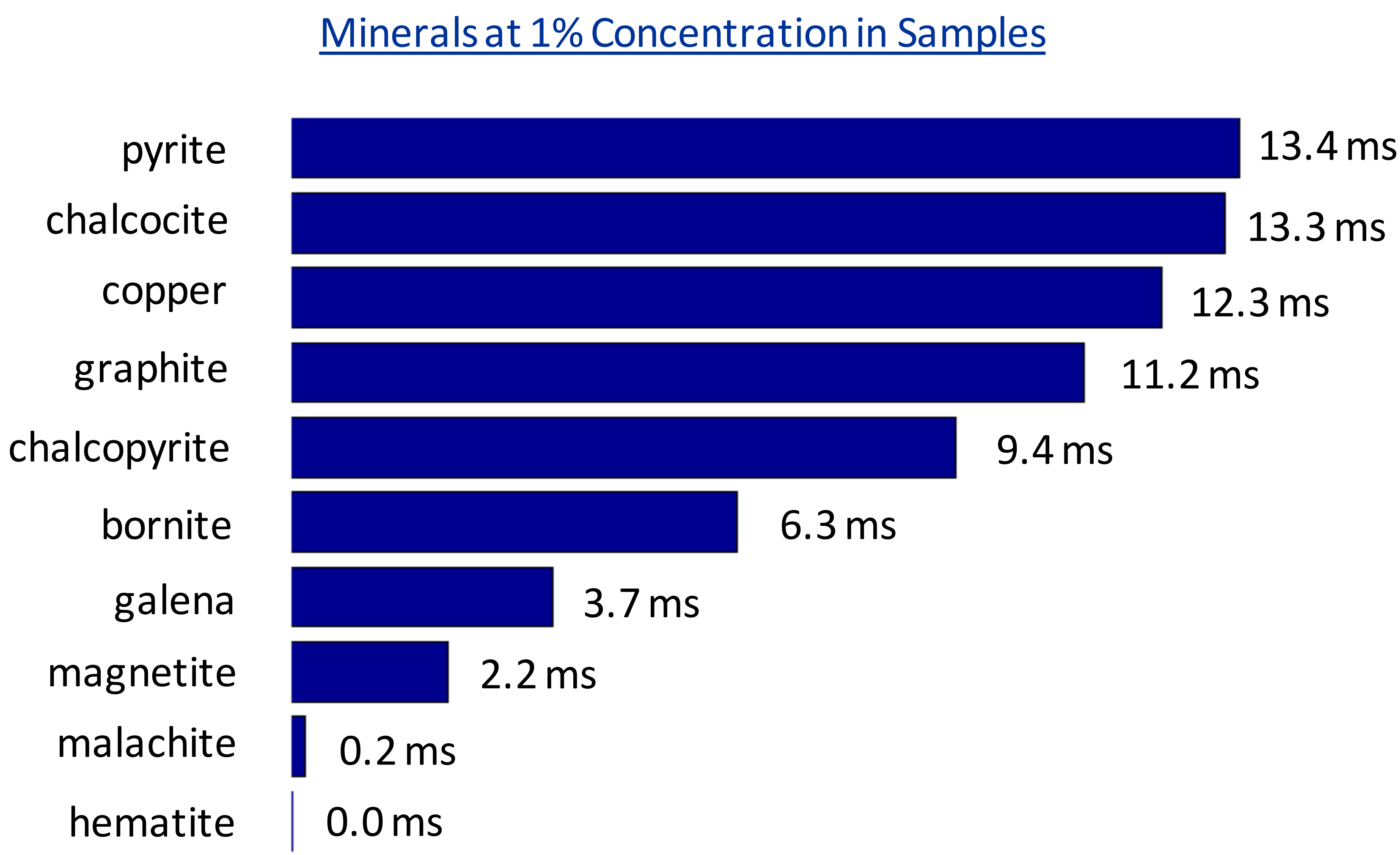
Input current



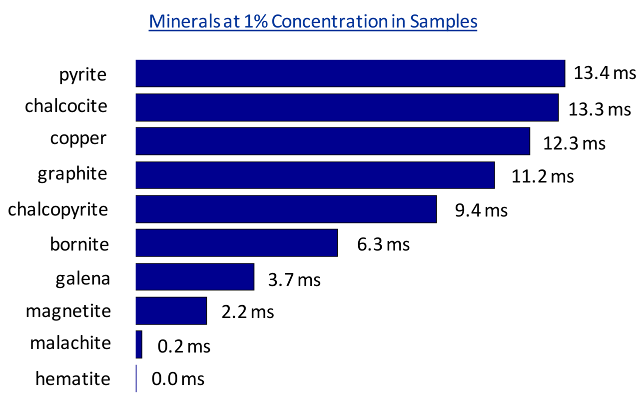
Measured voltage



Chargeability



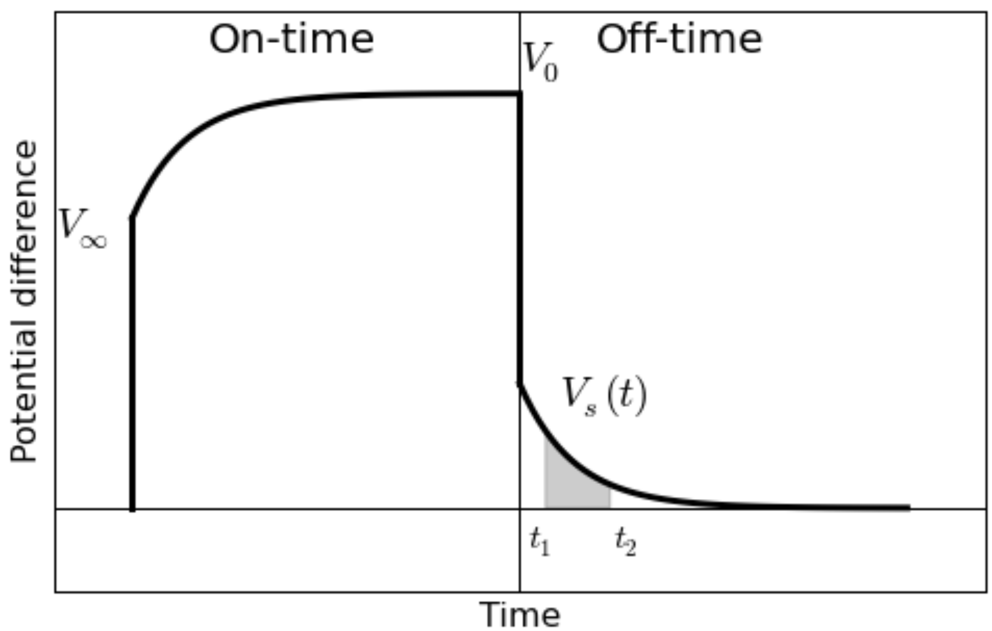
Chargeability

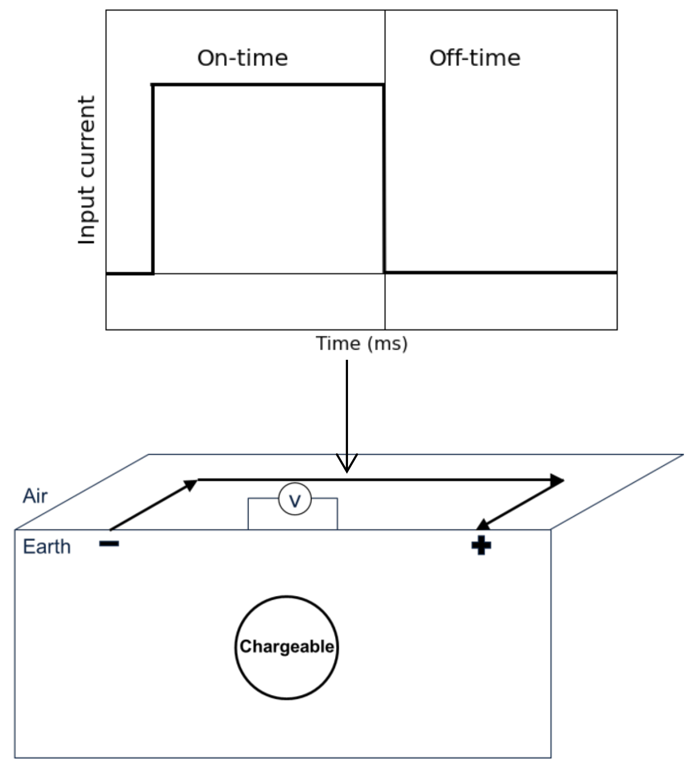


Material type	Chargeability (msec.)
20% sulfides	2000 - 3000
8-20% sulfides	1000 - 2000
2-8% sulfides	500 - 1000
volcanic tuffs	300 - 800
sandstone, siltstone	100 - 500
dense volcanic rocks	100 - 500
shale	50 - 100
granite, granodiorite	10 - 50
limestone, dolomite	10 - 20

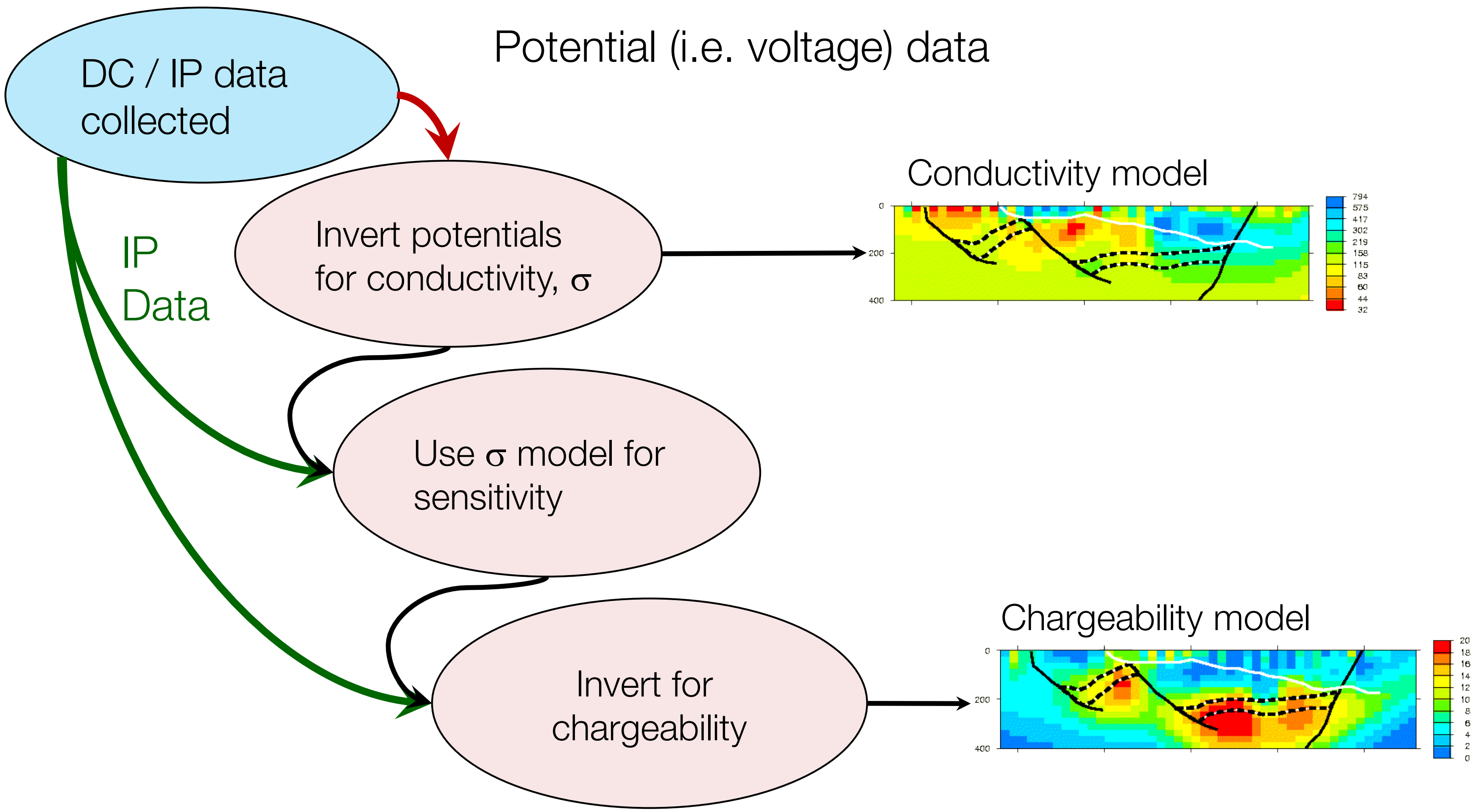
Material type	Chargeability (msec.)
ground water	0
alluvium	1 - 4
gravels	3 - 9
precambrian volcanics	8 - 20
precambrian gneisses	6 - 30
schists	5 - 20
sandstones	3 - 12

Overvoltage

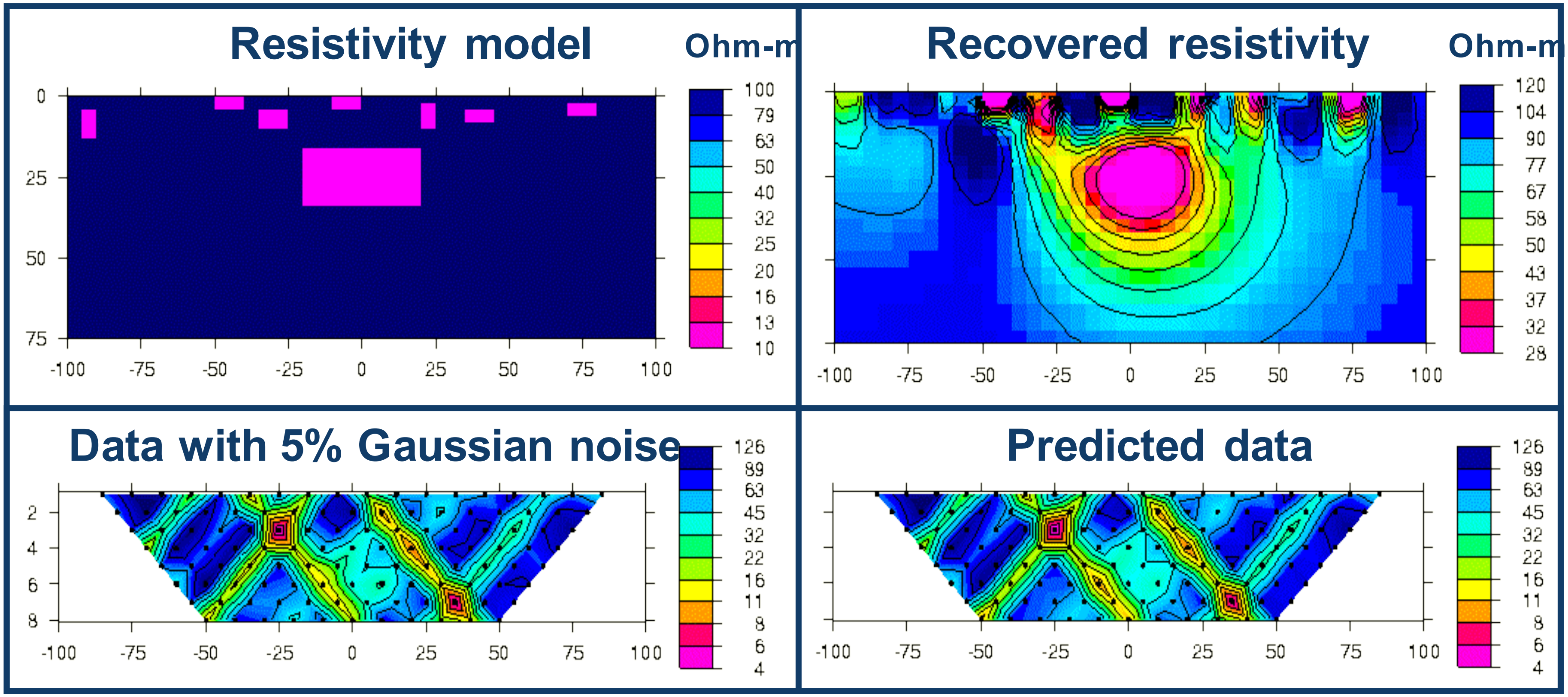




IP Inversion

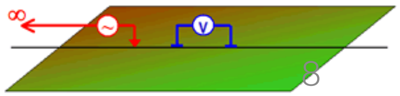


Example DC: prism with geologic noise

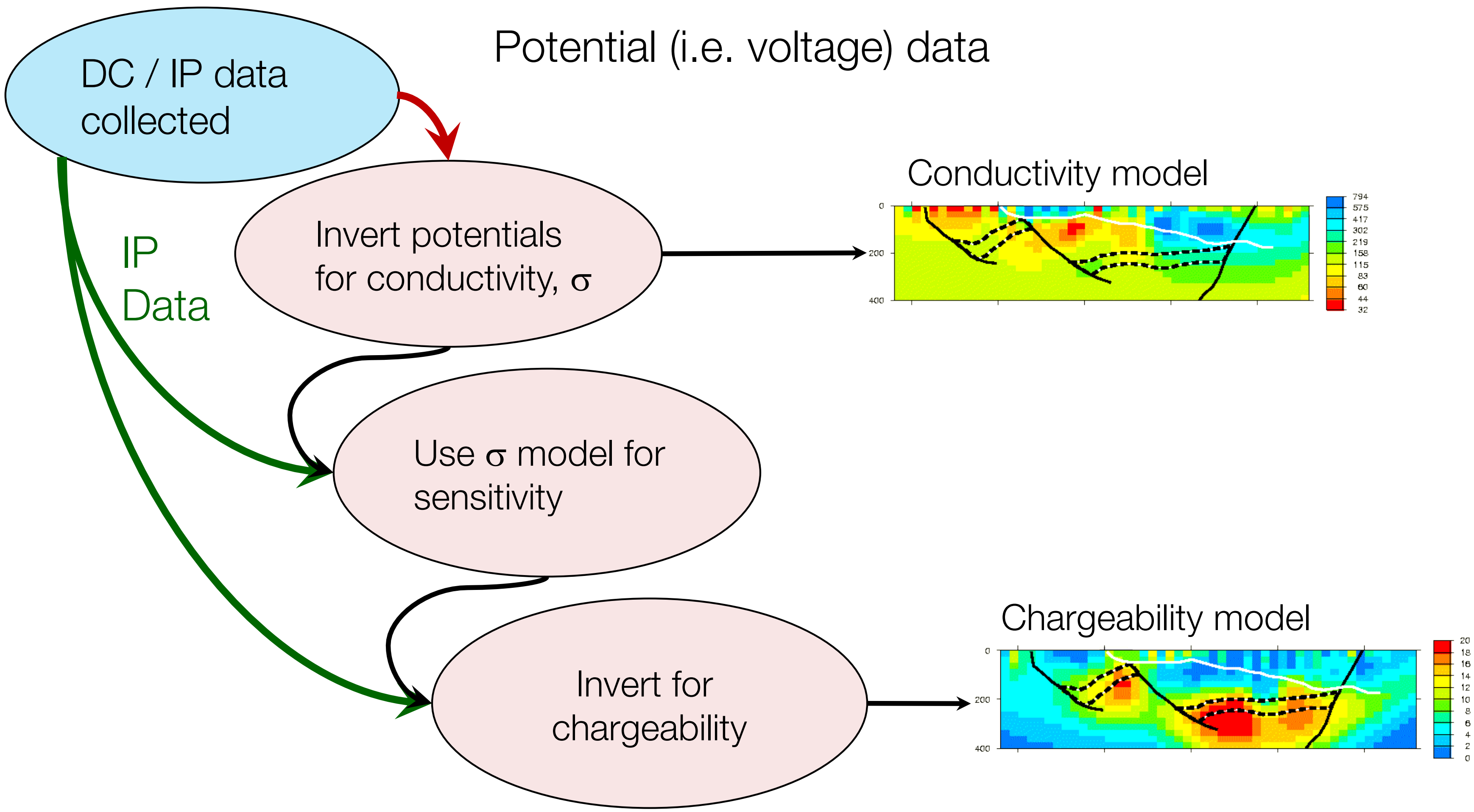


- Pole-dipole; n=1,8; a=10m; N=316; $(\alpha_s, \alpha_x, \alpha_z)$=(.001, 1.0, 1.0)

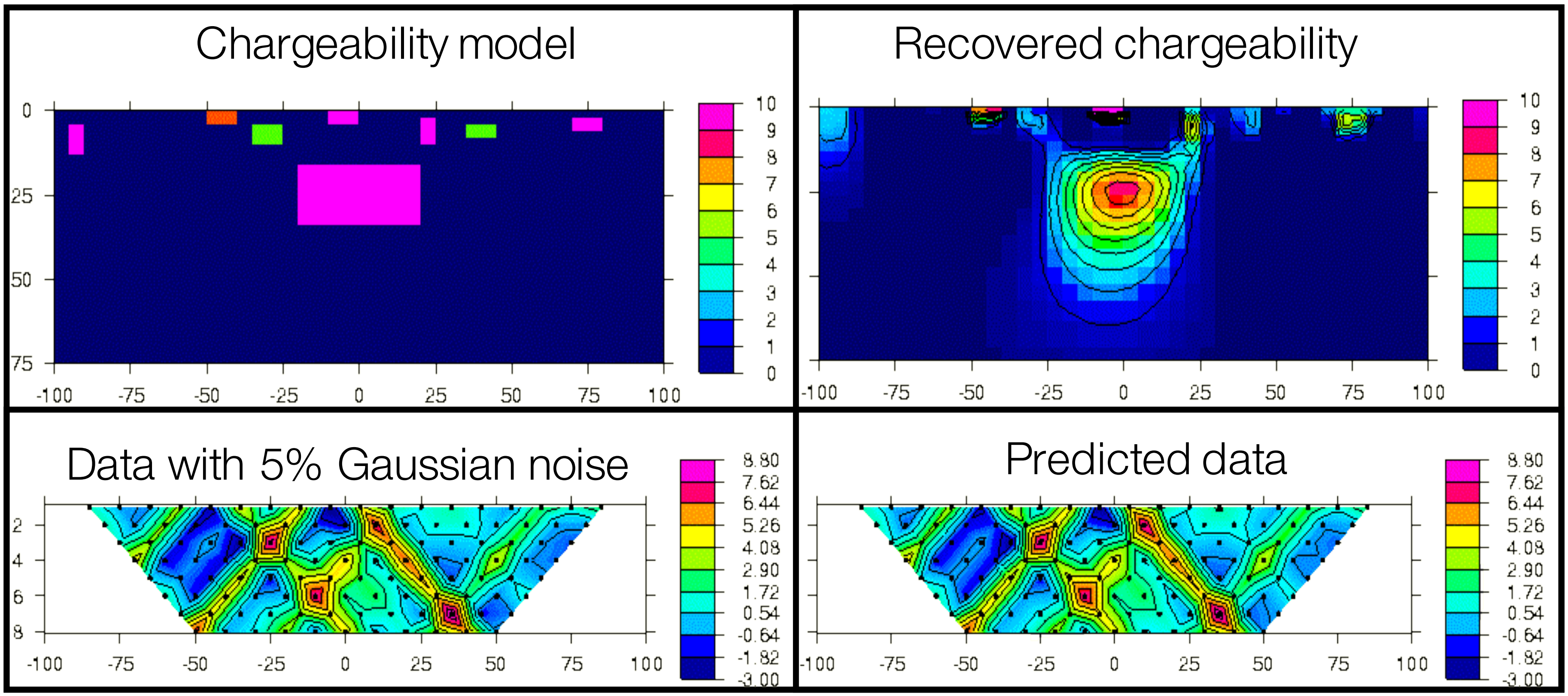
Pole-Dipole



IP Inversion



Example IP: prism with geologic noise



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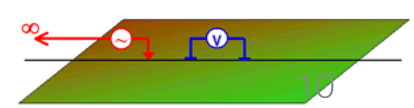
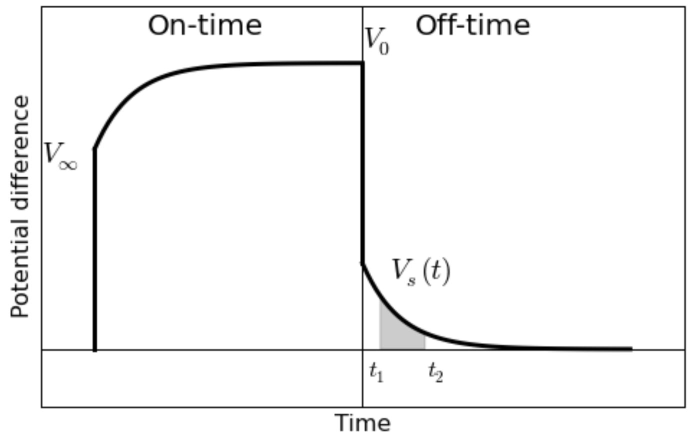
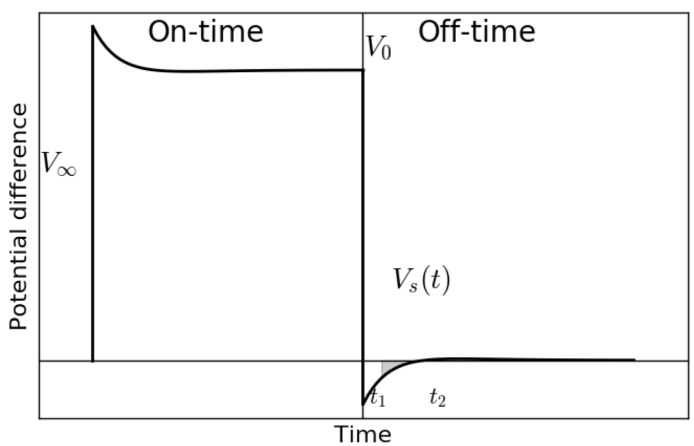
Pole-Dipole

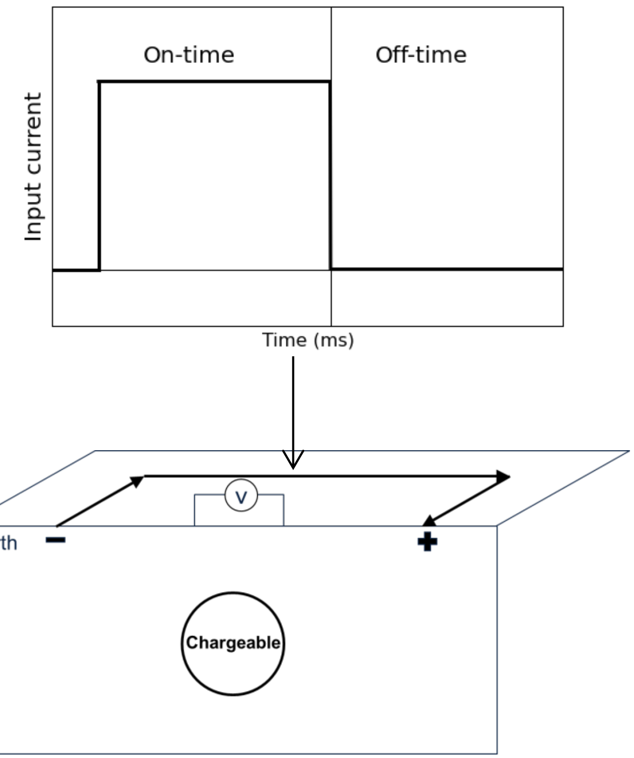


Challenge: EM coupling, grounded sources

- DC-IP: overvoltage

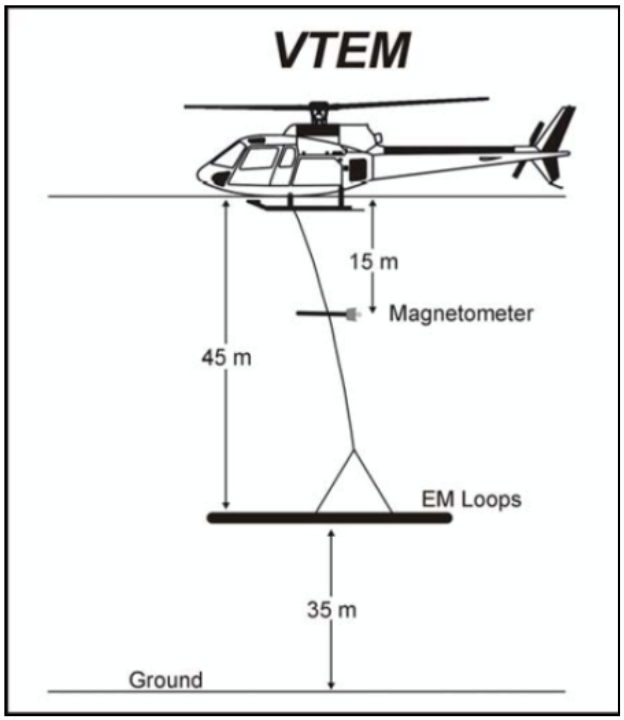




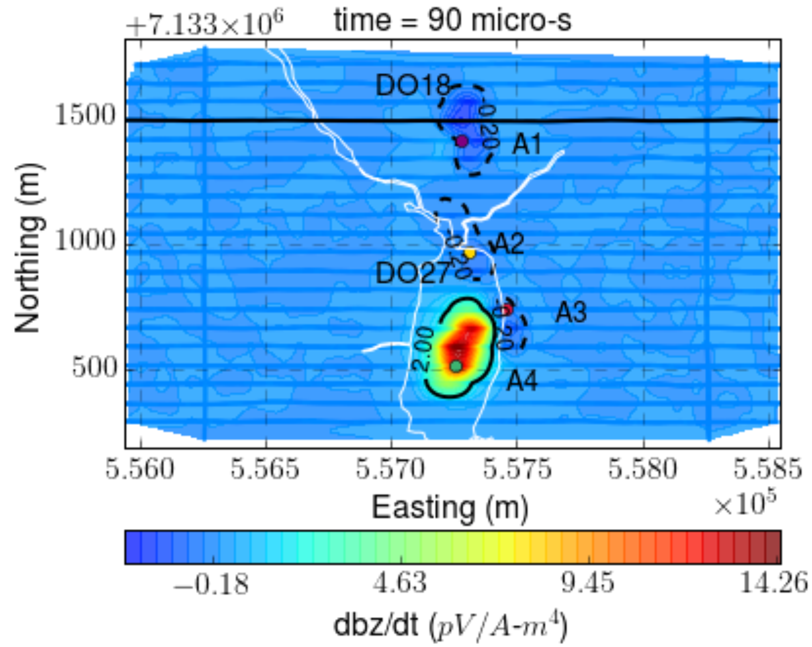


Challenge: inductive sources

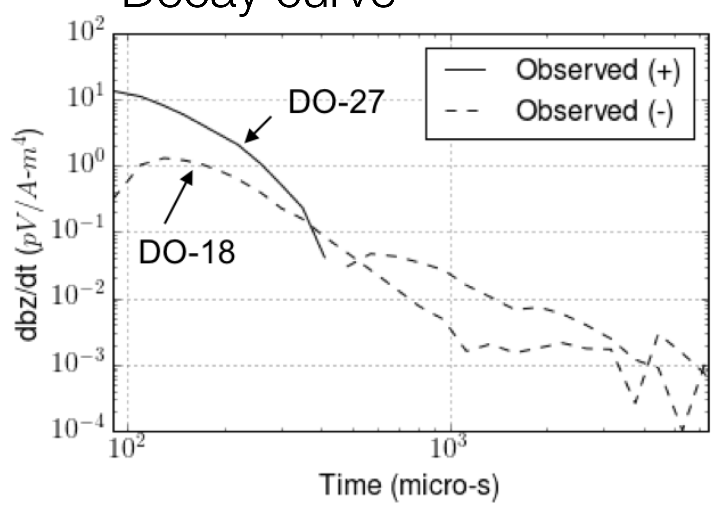
VTEM set-up



At 90 micro-s

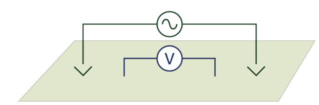


Decay curve

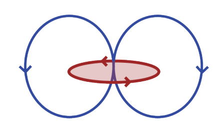


Outline

- Background
- Grounded IP
  - How to remove EM contamination?
  - How to extract valuable conductivity?
  - Gradient array example



- Inductive source IP
  - Revisit physics
  - IP inversion workflow
  - Tli Kwi Cho kimberlites



Simulation of TEM data

- Maxwell's equations:

Frequency domain

$$\vec{\nabla} \times \vec{E} = -\imath\omega\vec{B}$$

$$\vec{\nabla} \times \mu^{-1}\vec{B} - \vec{J} = \vec{J}_s$$

Time domain

$$\vec{\nabla} \times \vec{e} = -\frac{\partial \vec{b}}{\partial t}$$

$$\vec{\nabla} \times \mu^{-1}\vec{b} - \vec{j} = \vec{j}_s$$

Ohm's law in **frequency** domain

$$\boxed{\vec{J} = \sigma\vec{E}}$$

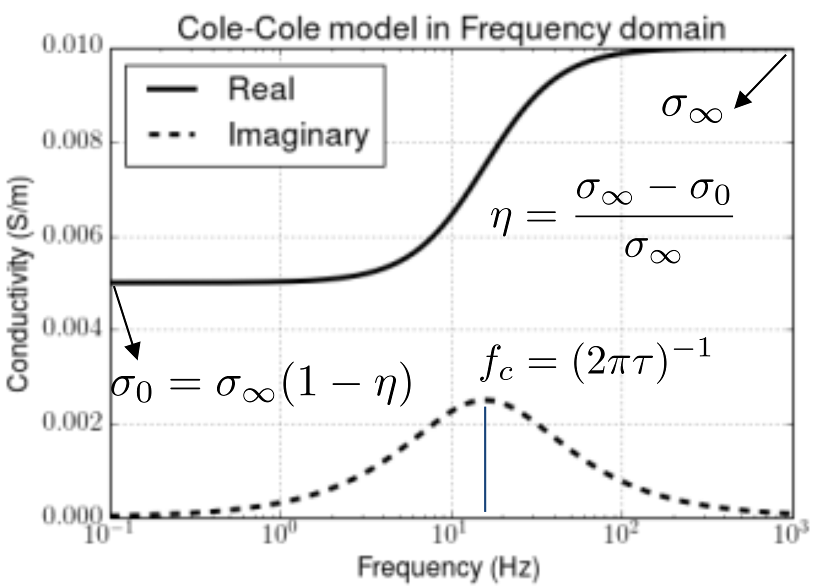
Ohm's law in **time** domain

$$\boxed{\vec{j} = \sigma\vec{e}}$$

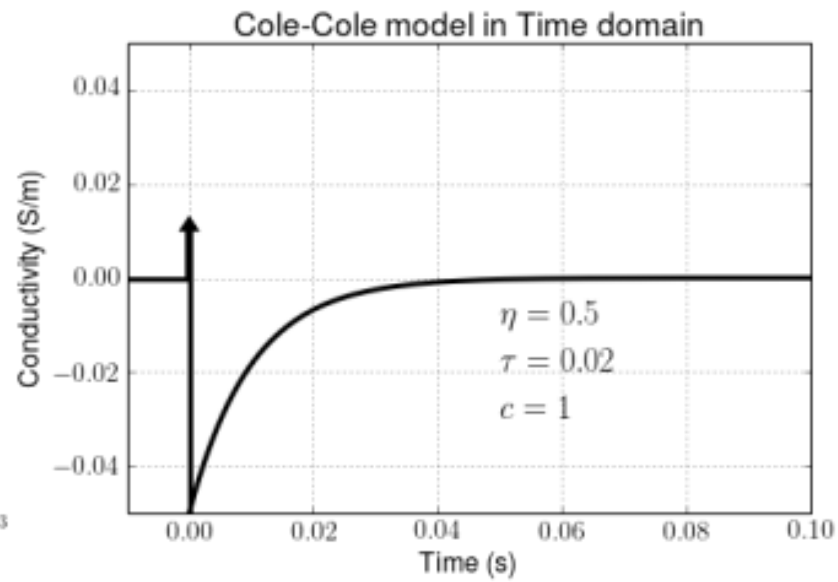
Complex conductivity

- Cole-Cole model (Pelton et al., 1978)

Frequency domain



Time domain



σ_∞: Conductivity at infinite frequency
σ_0: Conductivity at zero frequency
η: Chargeability
τ: Time constant (s)
c: Frequency dependency

Inverse Fourier transform

$$\sigma(\omega) = \sigma_\infty + \sigma_\infty \frac{\eta}{1 + (1-\eta)(\imath\omega\tau)^c} \longrightarrow \mathcal{F}^{-1}[\sigma(\omega)] = \sigma(t)$$

Simulation of TEM data with IP

- Maxwell's equations:

EMTDIP code
(Marchant et al., 2015)

Frequency domain

$$\vec{\nabla} \times \vec{E} = -\imath\omega\vec{B}$$
$$\vec{\nabla} \times \mu^{-1}\vec{B} - \vec{J} = \vec{J}_s$$

Time domain

$$\vec{\nabla} \times \vec{e} = -\frac{\partial \vec{b}}{\partial t}$$
$$\vec{\nabla} \times \mu^{-1}\vec{b} - \vec{j} = \vec{j}_s$$

Ohm's law in **frequency** domain

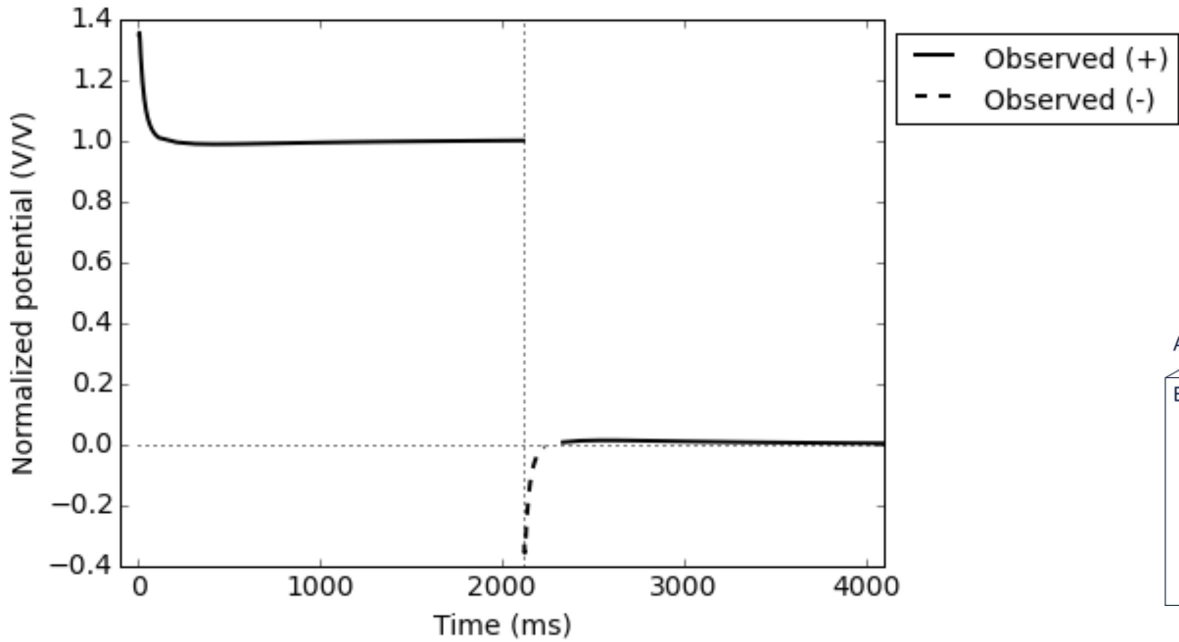
$$\boxed{\vec{J} = \sigma(\omega)\vec{E}}$$

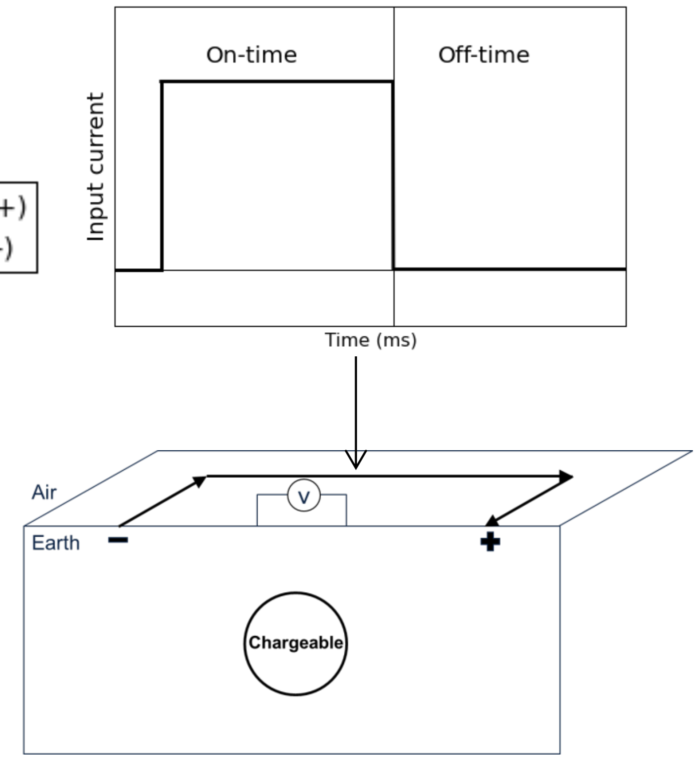
Ohm's law in **time** domain

$$\vec{j} = \sigma(t) \otimes \vec{e}(t)$$

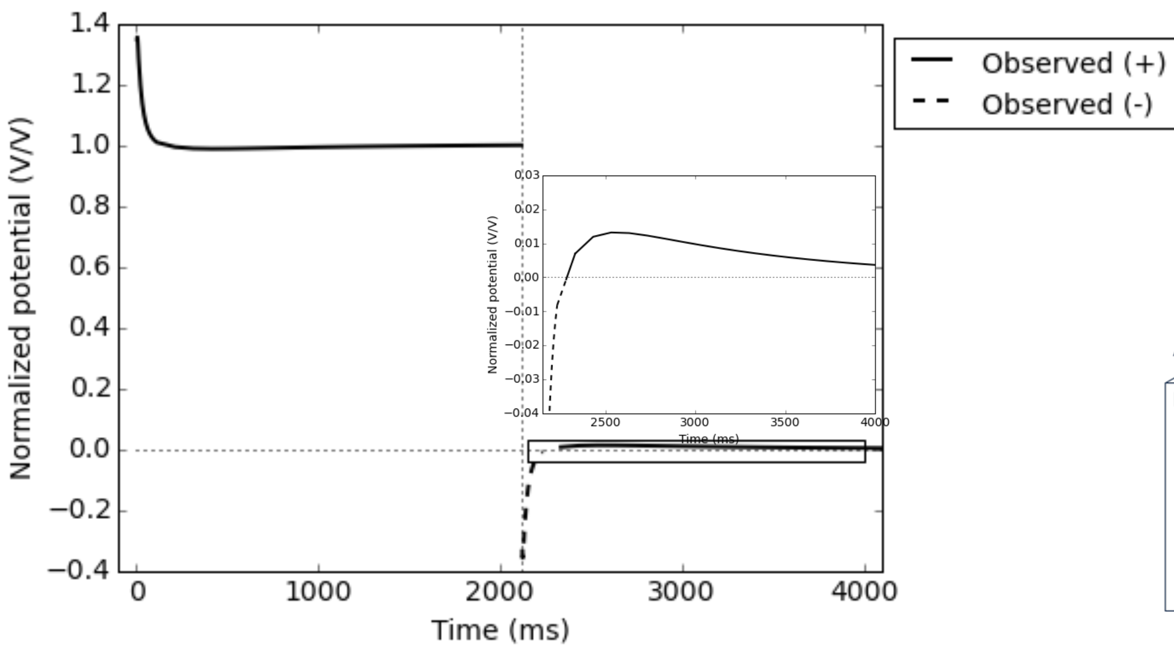
$\otimes : convolution$

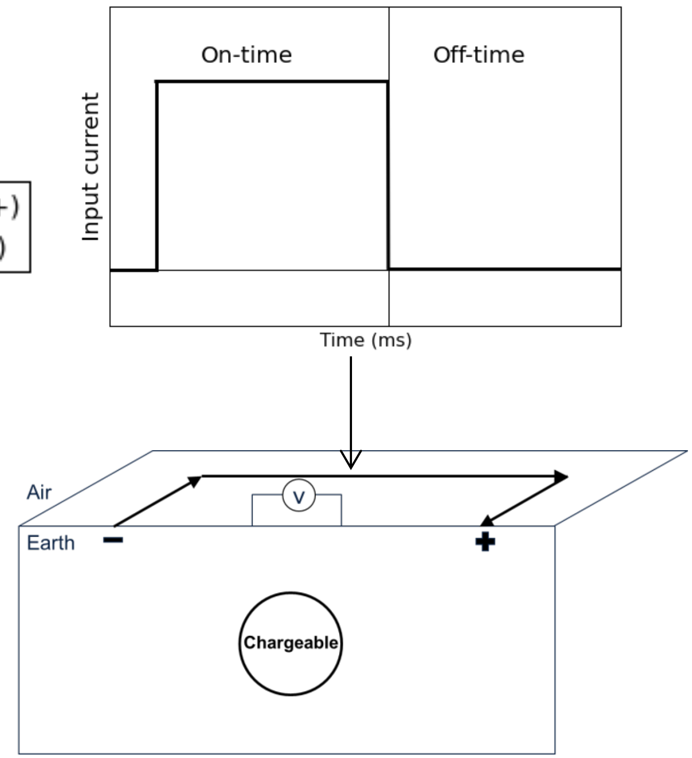
Observed response



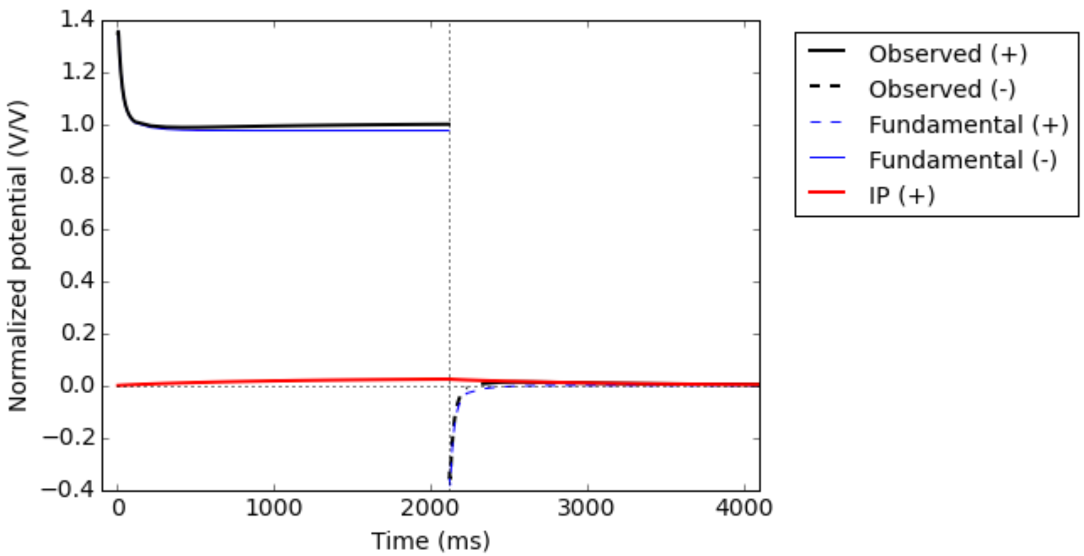


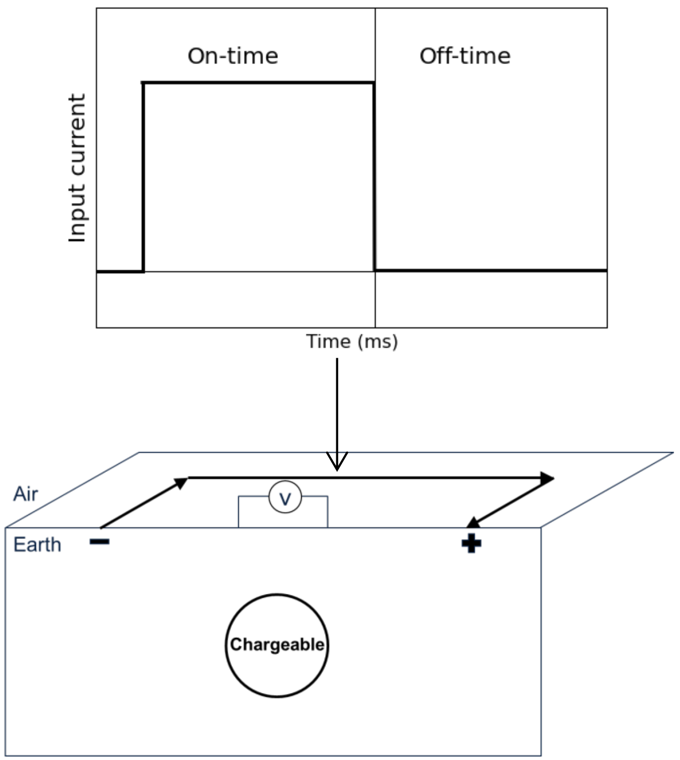
Observed response





Define IP datum





- IP datum:

IP = Observation - Fundamental

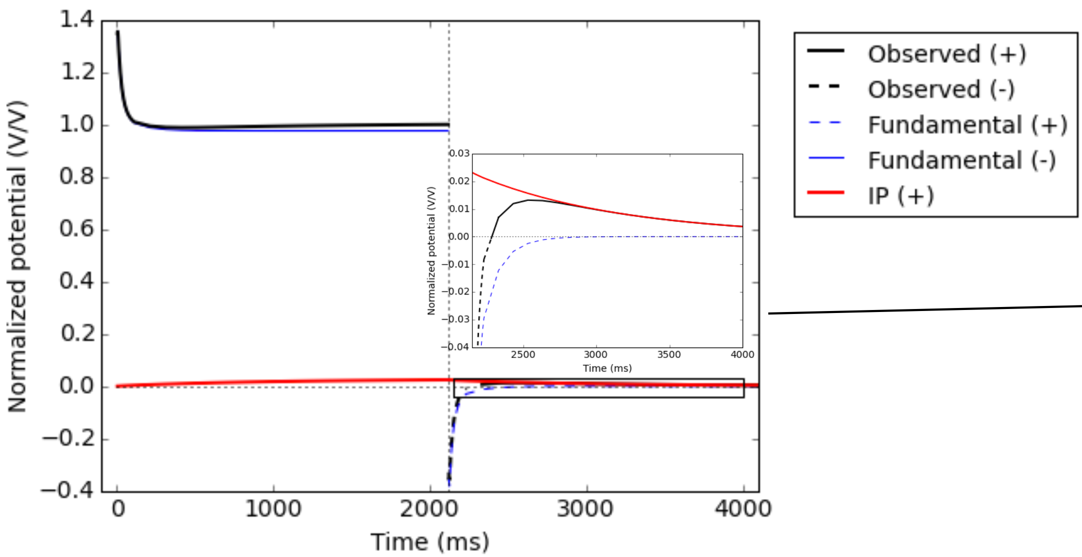
$$d^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty]$$

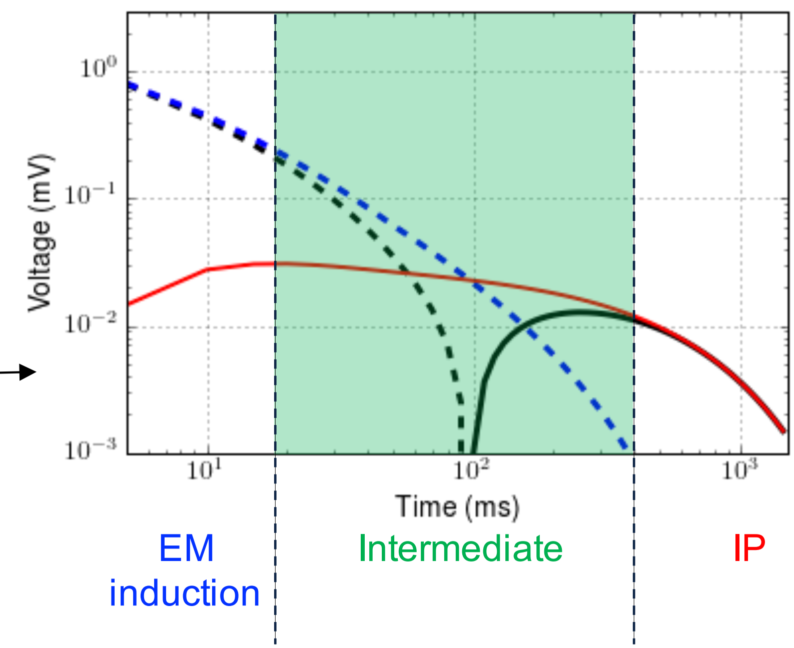
$F[\sigma(t)]$ Observation

$F[\sigma_\infty]$ Fundamental

$F[\cdot]$: Maxwell's operator

Define IP datum





- IP datum:

IP = Observation - Fundamental

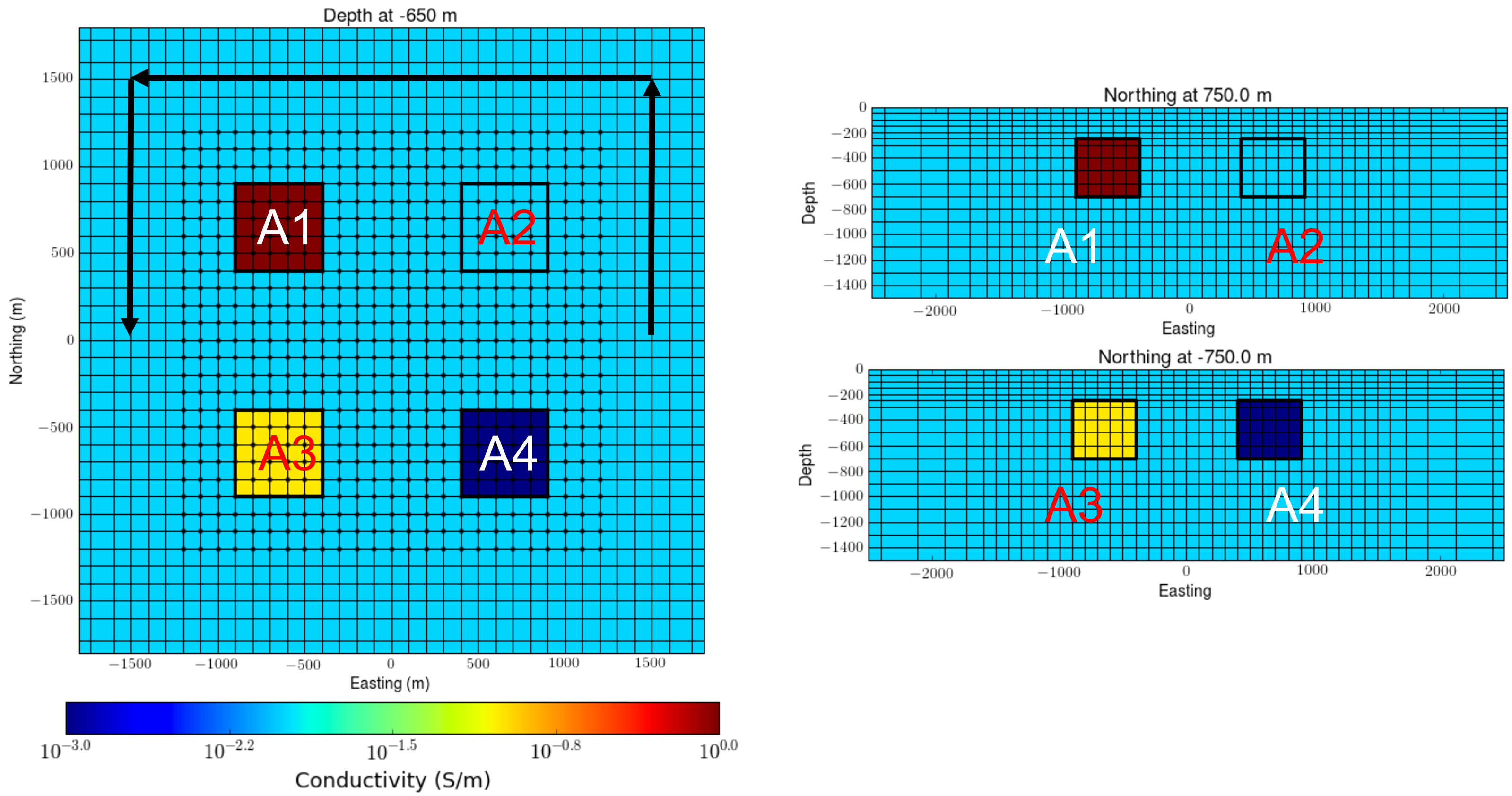
$$d^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty]$$

$F[\sigma(t)]$ Observation

$F[\sigma_\infty]$ Fundamental

$F[\cdot]$: Maxwell's operator

Synthetic model



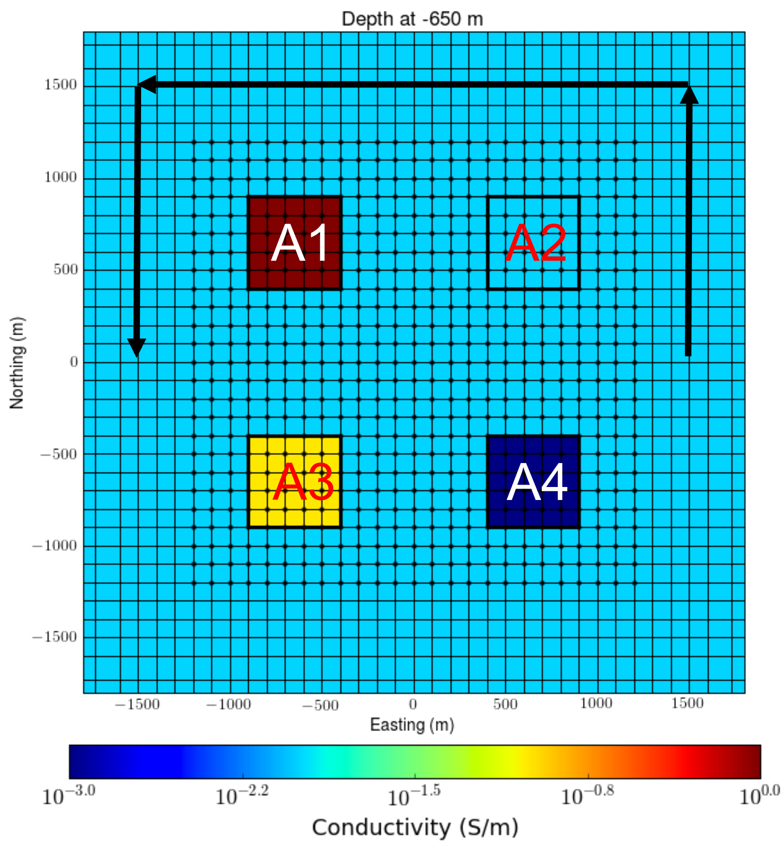
- Conductivity at Infinite frequency:

$$
\begin{aligned}
&\text{halfspace} = 0.01 \text{ S/m} \\
&\text{A1} = 1 \text{ S/m} \\
&\text{A2} = 0.01 \text{ S/m} \\
&\text{A3} = 0.1 \text{ S/m} \\
&\text{A4} = 0.001 \text{ S/m}
\end{aligned}
$$

- Chargeable objects: A2 and A3

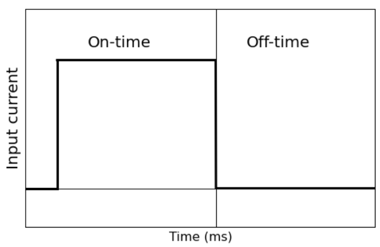
$$
\begin{aligned}
&\eta = 0.1 \\
&\tau = 0.5 \text{ s} \\
&c = 1
\end{aligned}
$$

Forward modelling set up



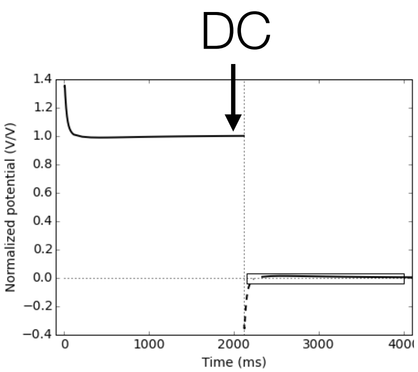
- Measure potential difference
  - 200 m bi-pole (625 mid points)

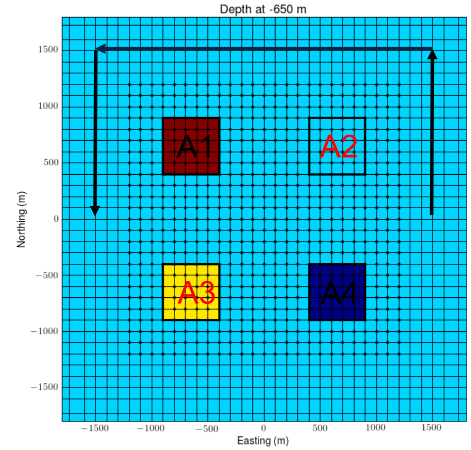
- Step-off waveform:

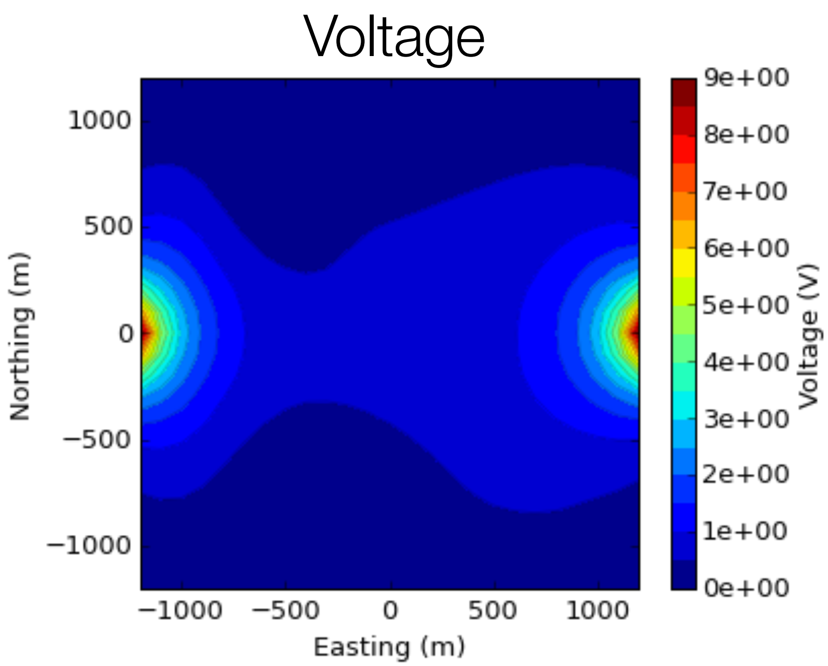


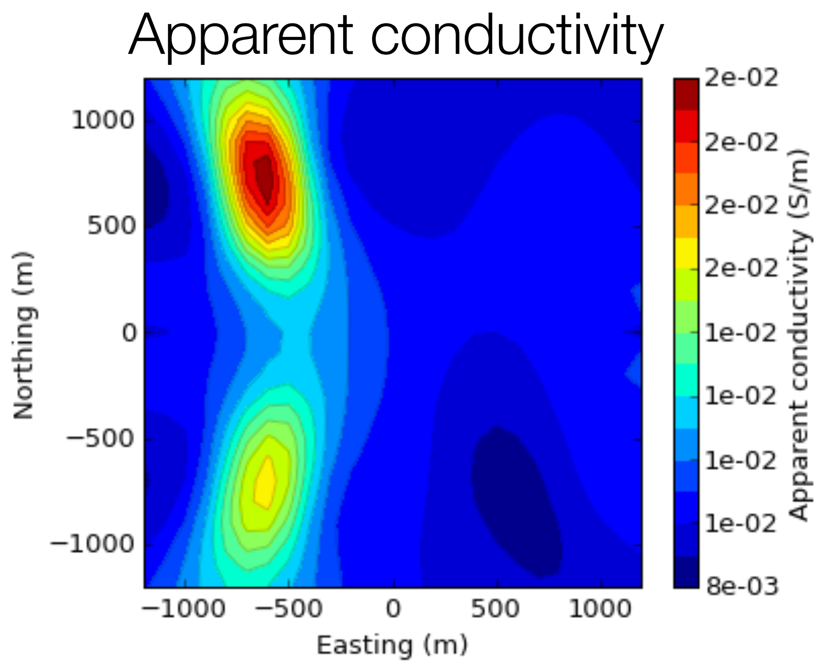
- Time range: 1 – 600 ms (off-time)
  - Chargeable objects: A2 and A3

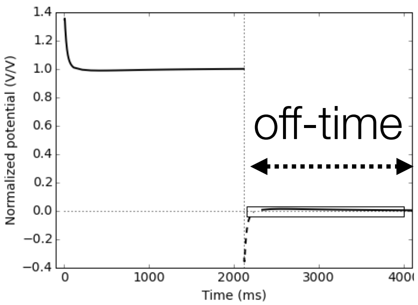
Observed DC data



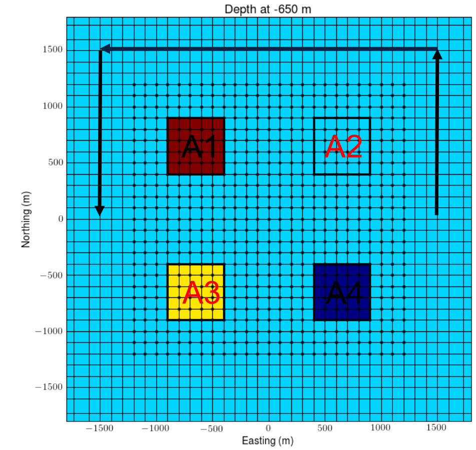




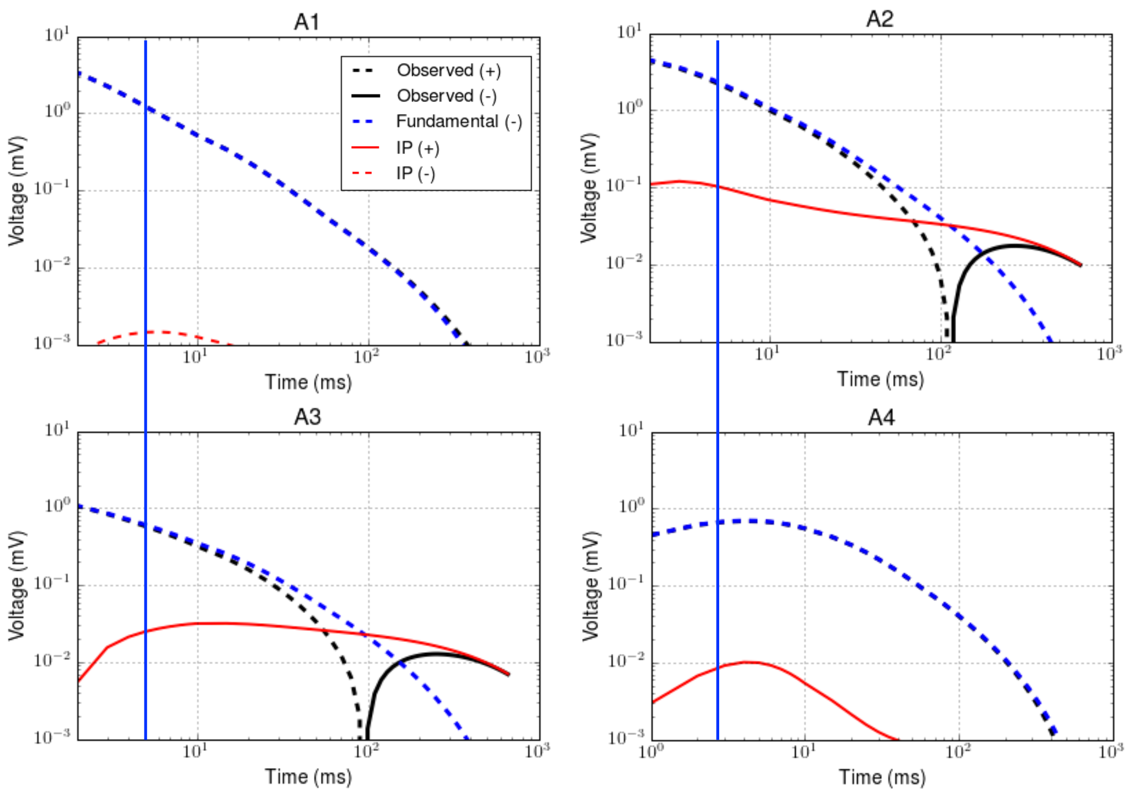




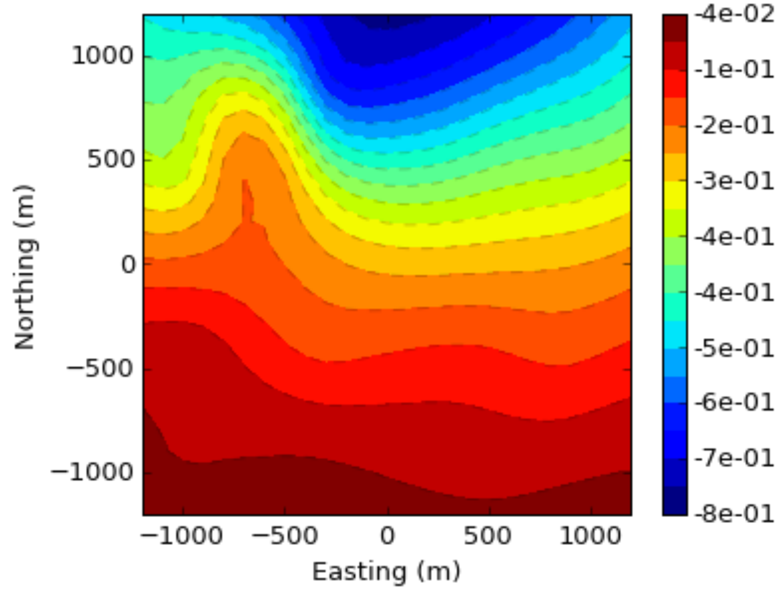
Observed data (off-time)



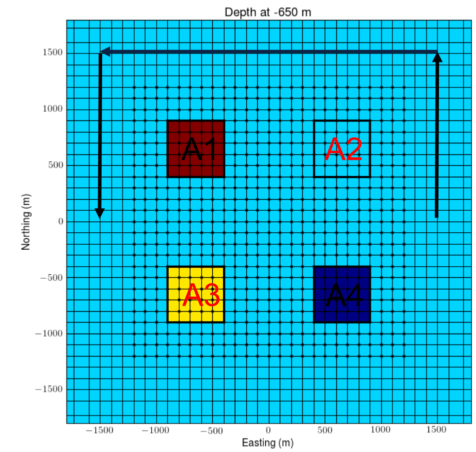
- Decaying curves at A1-A4



Off-time at 5 ms



Observed data (off-time)



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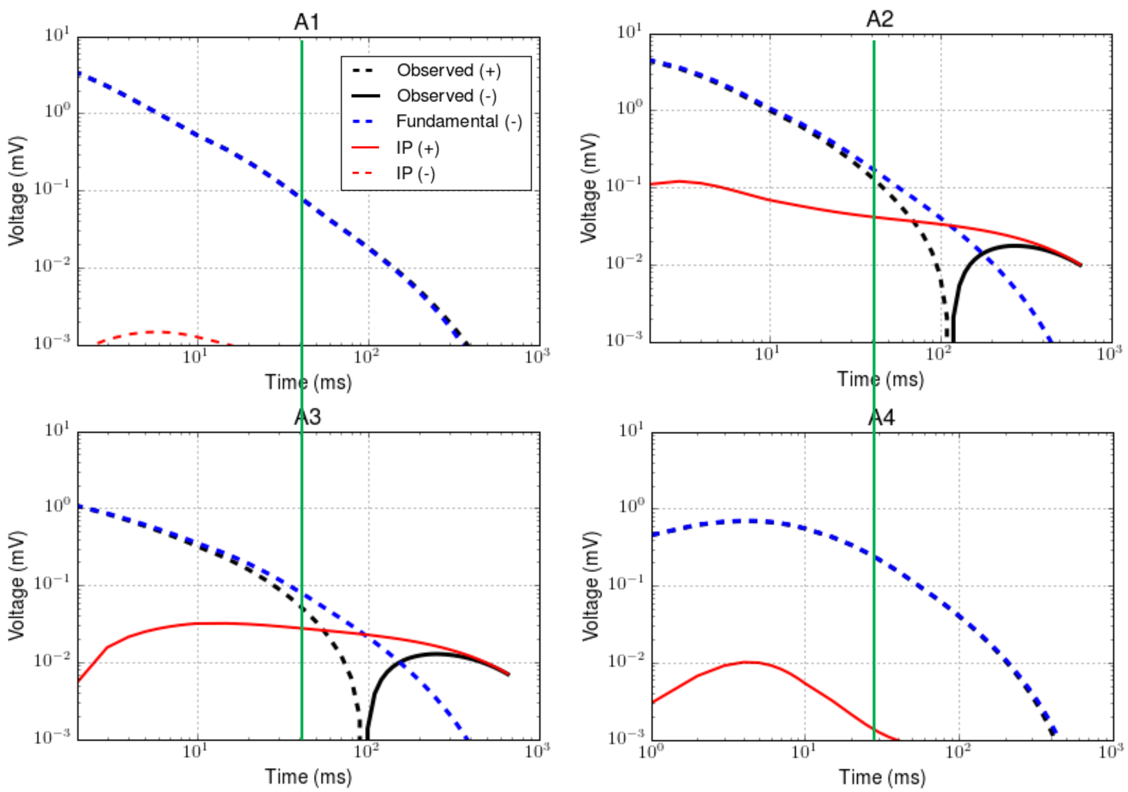
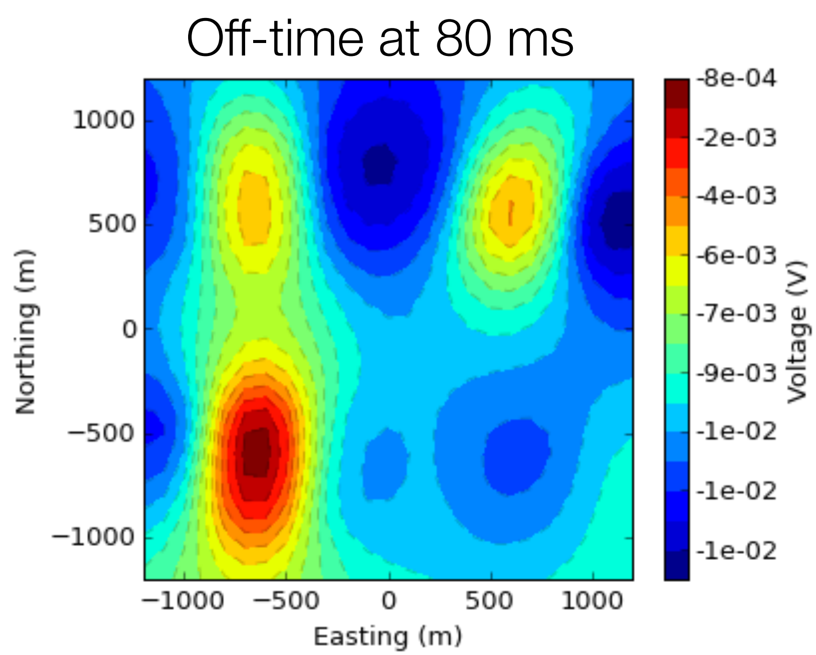
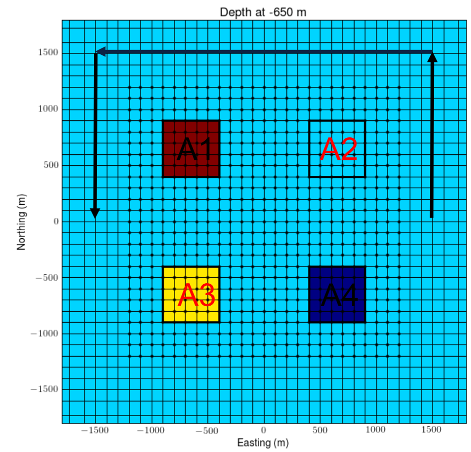
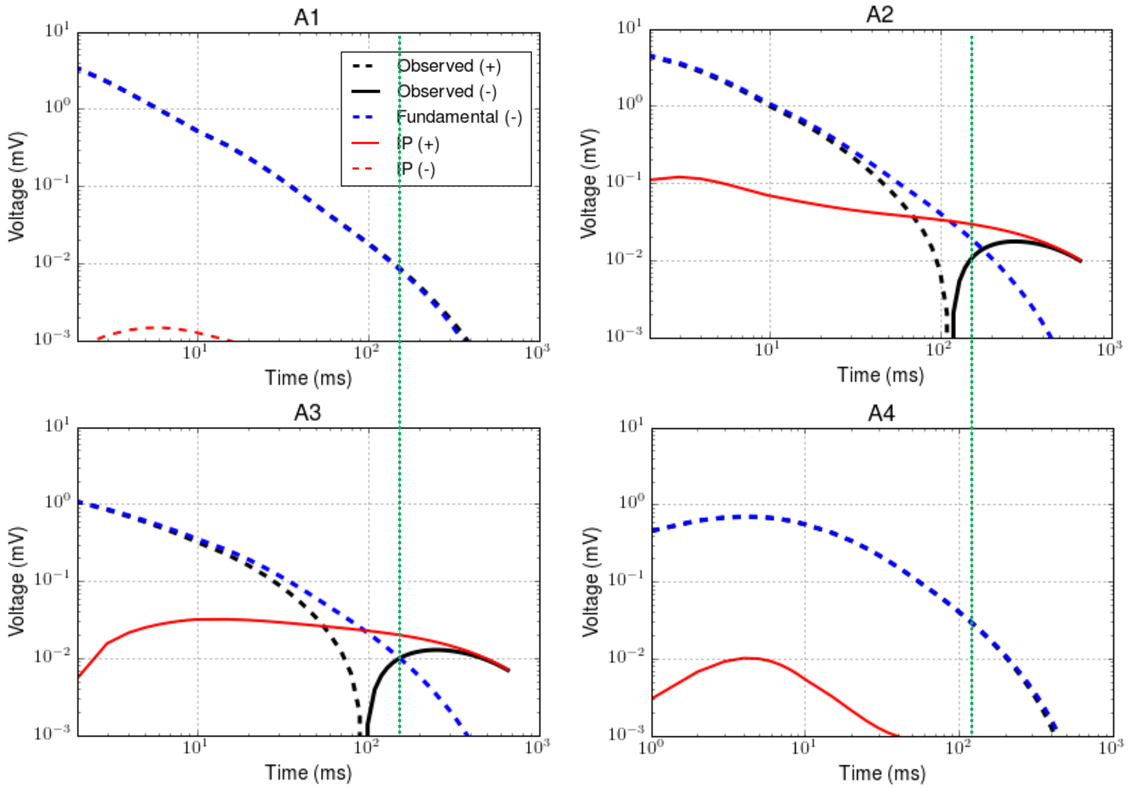


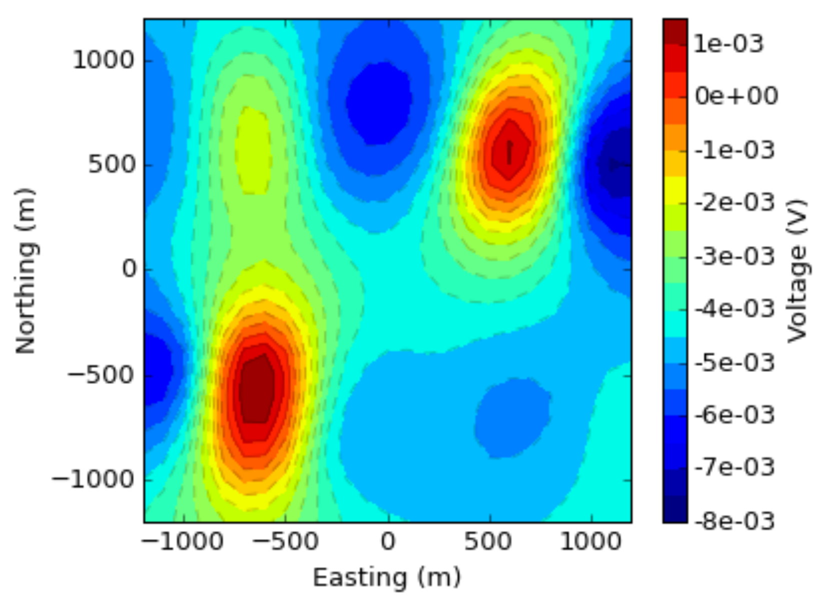


Observed data (off-time)

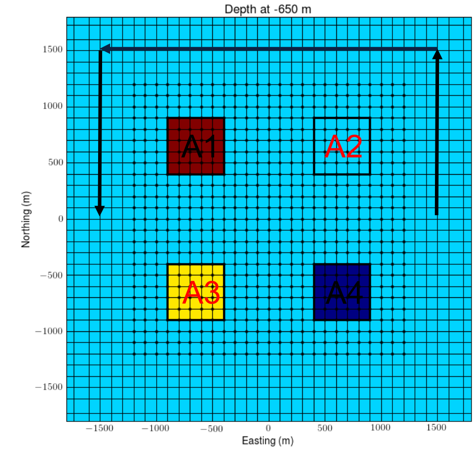


- Decaying curves at A1-A4

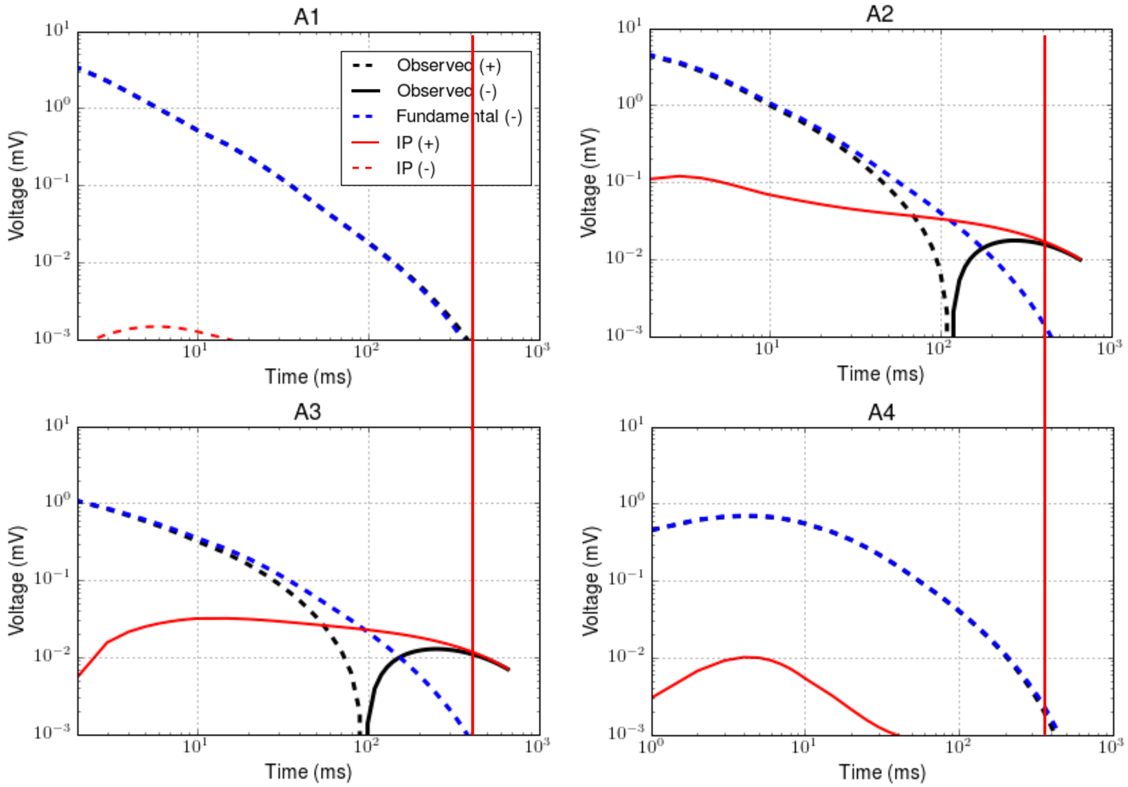


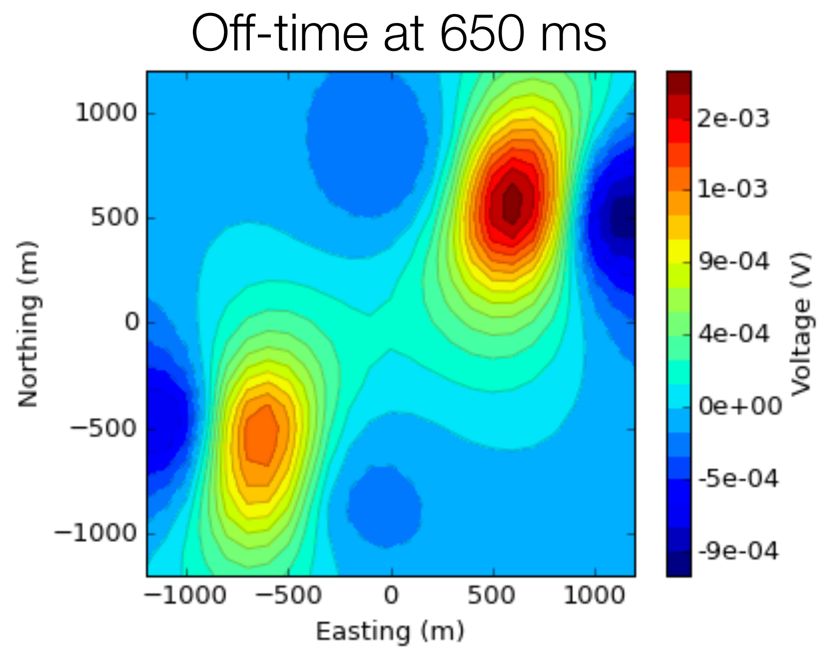


Observed data (off-time)

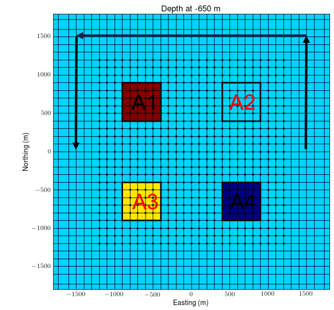


- Decaying curves at A1-A4

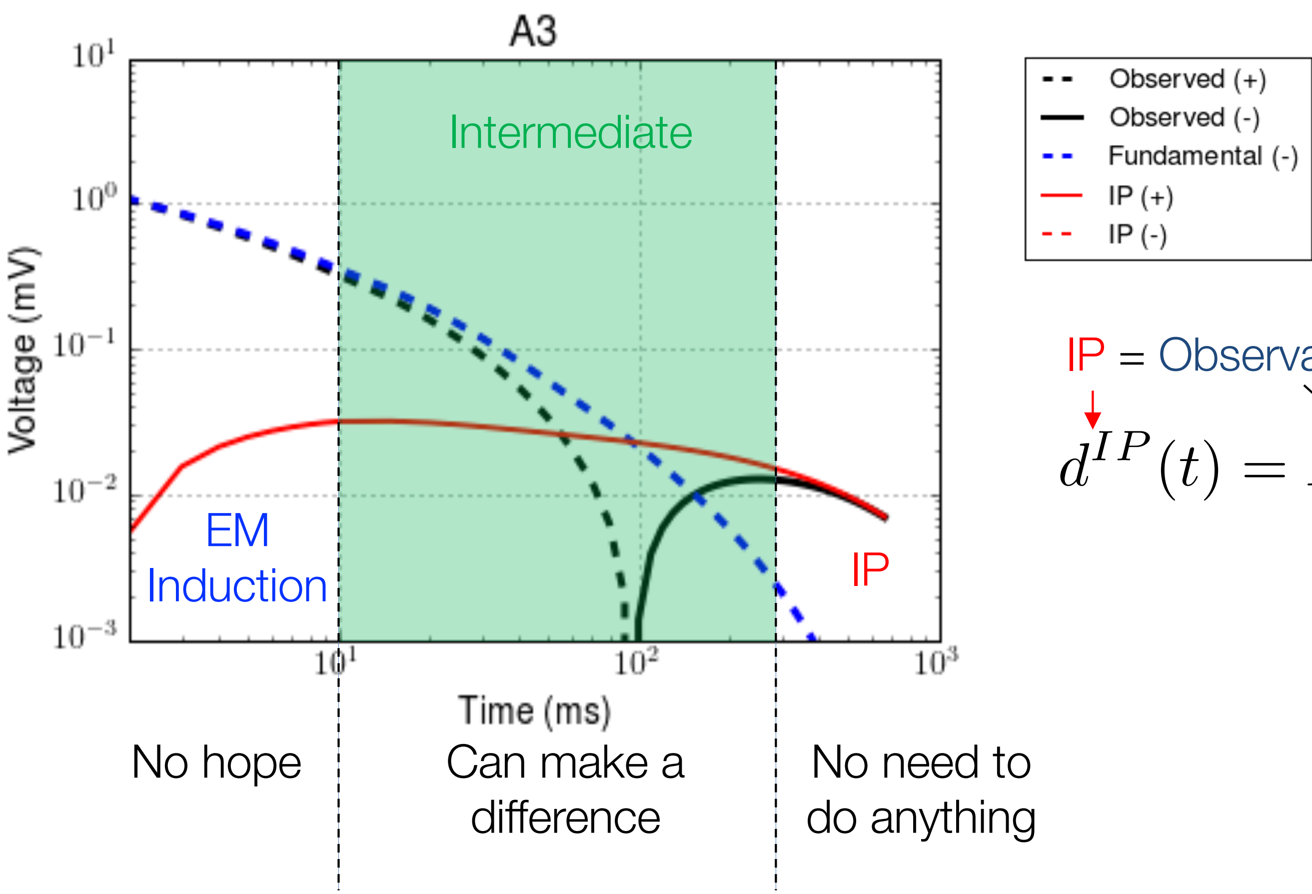




EM decoupling



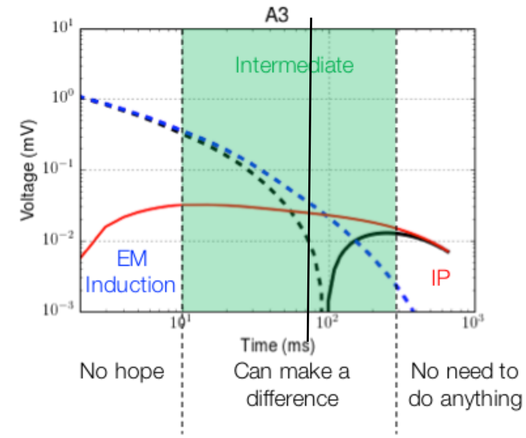
- Time decaying curves (off-time)



IP = Observation - Fundamental

$$d^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty]$$

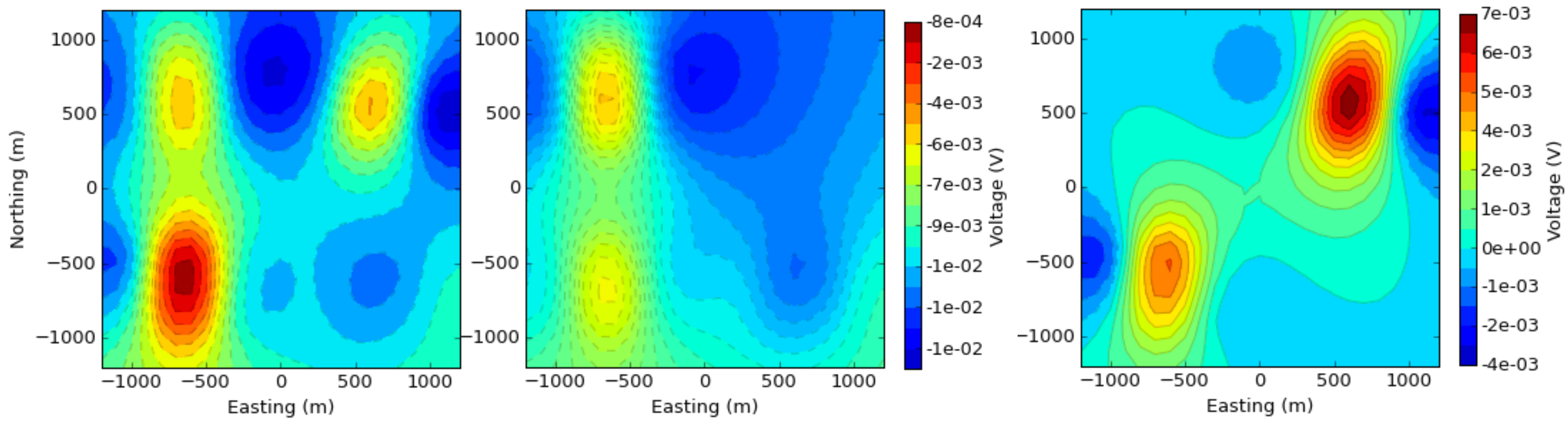
EM decoupling: true σ_∞



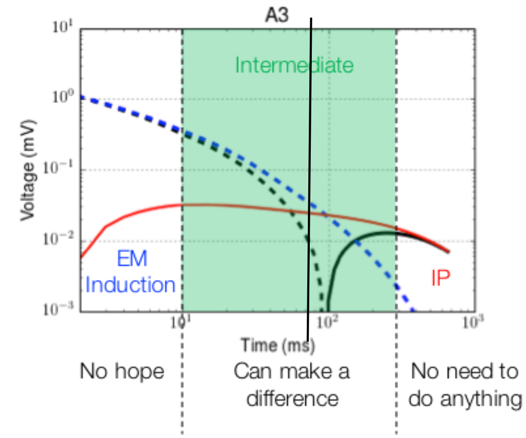
- Off-time at 80 ms

$$d^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty]$$

Observation Fundamental IP



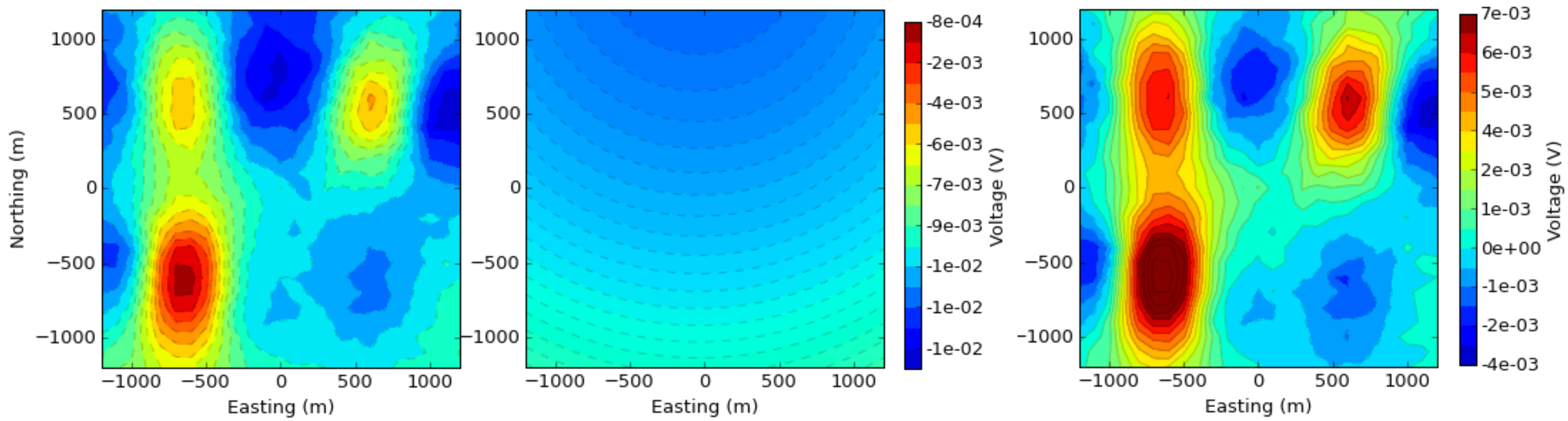
EM decoupling: σ_∞^{half}



- Off-time at 80 ms

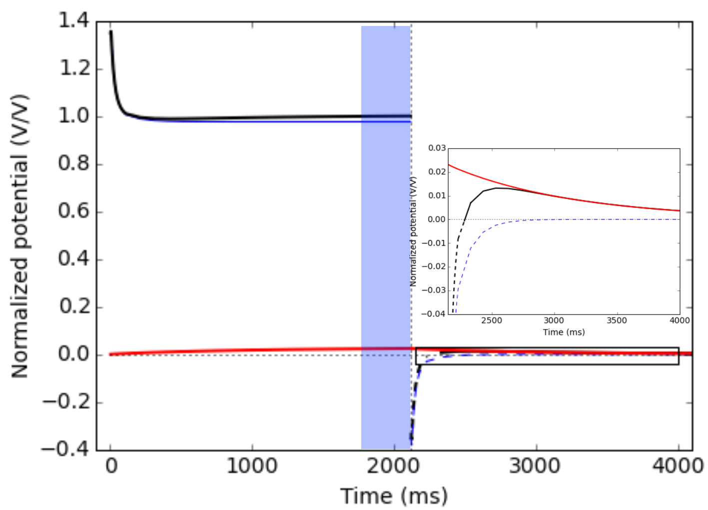
$$d_{raw}^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty^{half}] + noise(t)$$

Observation Fundamental IP

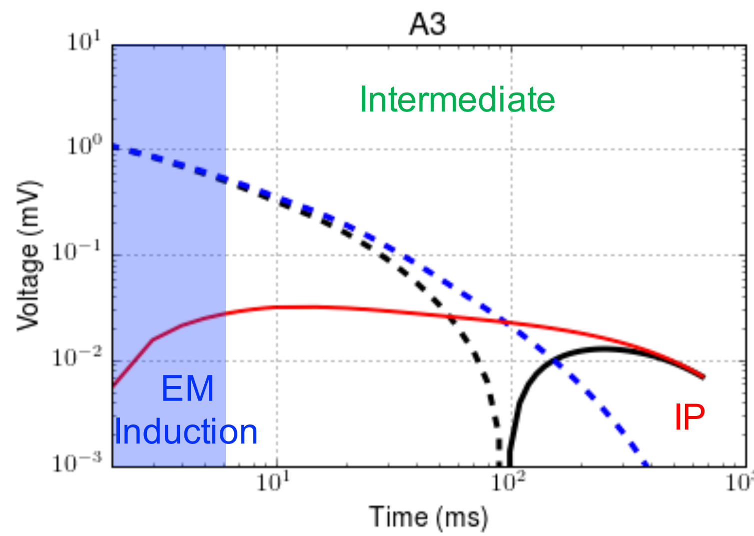


How do we estimate conductivity, σ_∞?

Late on-time data (DC)



Early off-time data (TEM)



3D inversion methodology

- Data misfit:

$$\phi_d = \|\mathbf{W_d}(\mathbf{Am} - d^{obs}|)\|_2^2$$

- Model objective function:

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

- Tikhonov inversion: minimize

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

- Depth weight:

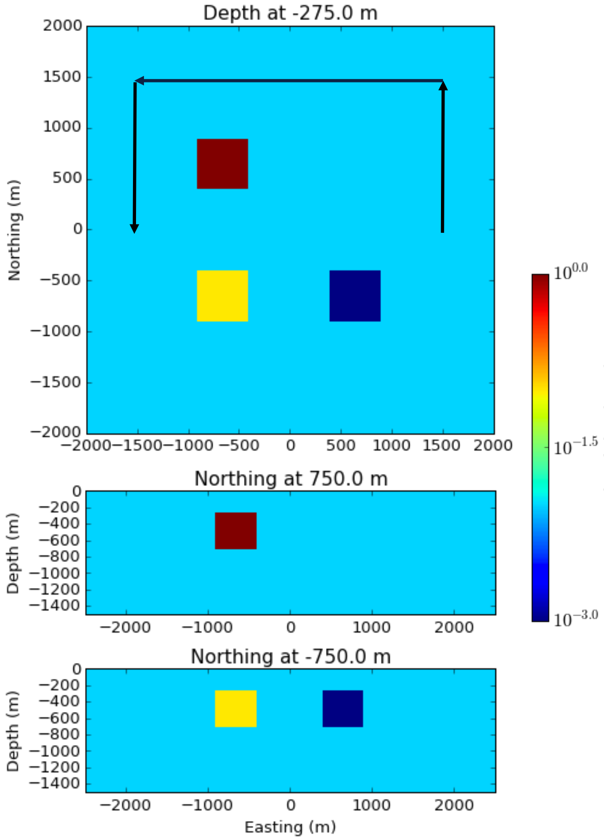
$$\frac{1}{(z - z_0)^3}$$

DC-IP inversion: SimPEG-DCIP
TEM inversion: UBC-H3DTD code

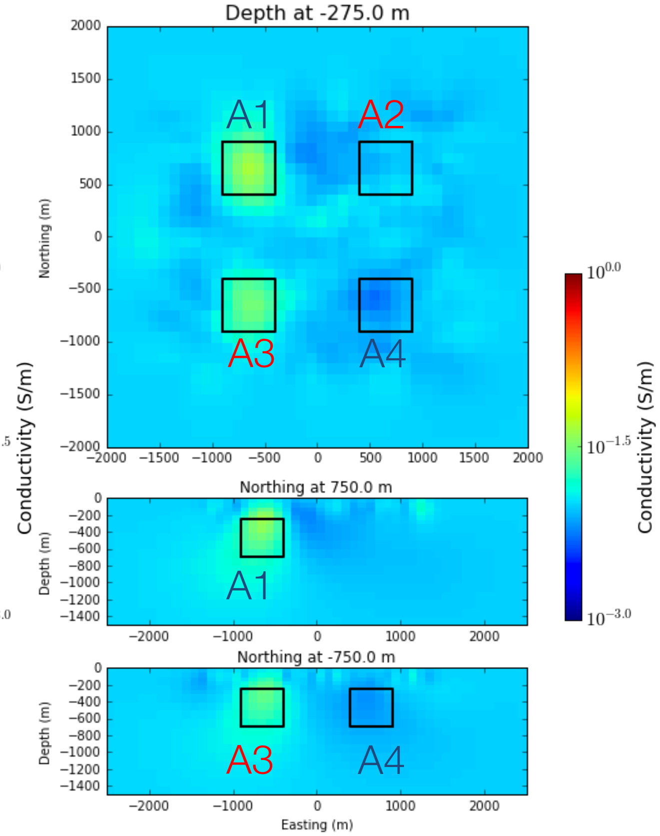
3D DC inversion

- Recover 3D conductivity

True σ_∞



Estimated $\sigma_\infty (= \sigma_{est}^{DC})$



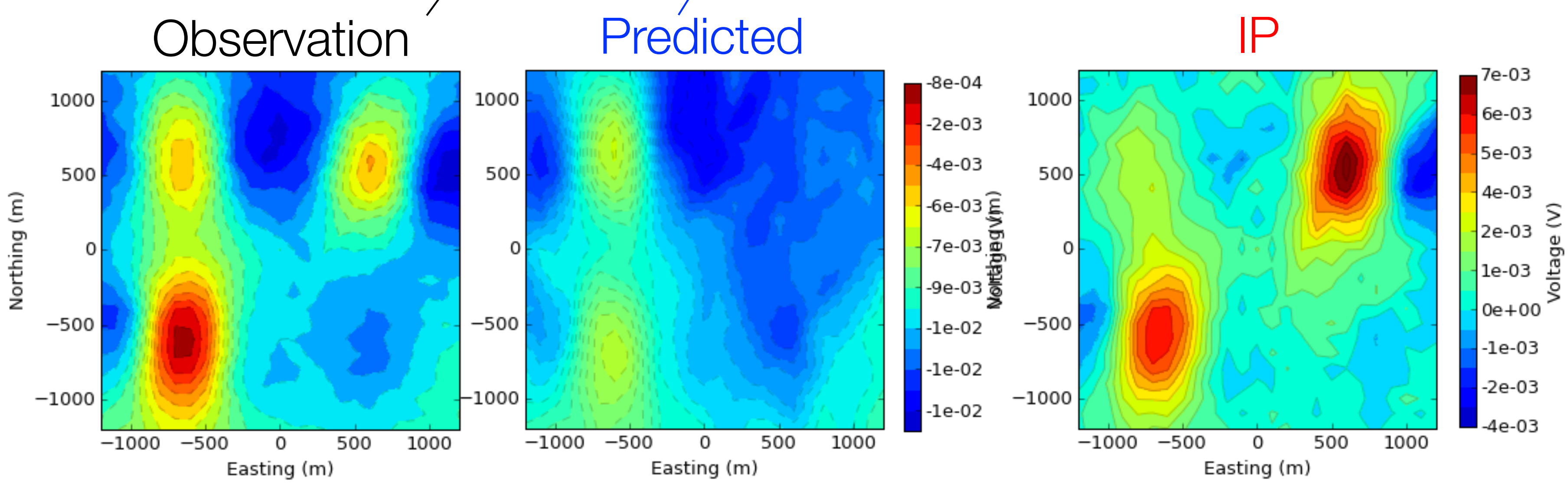
- Depth weighting
  - Compensate for high sensitivity near surface

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

EM decoupling: σ_{est}^{DC}

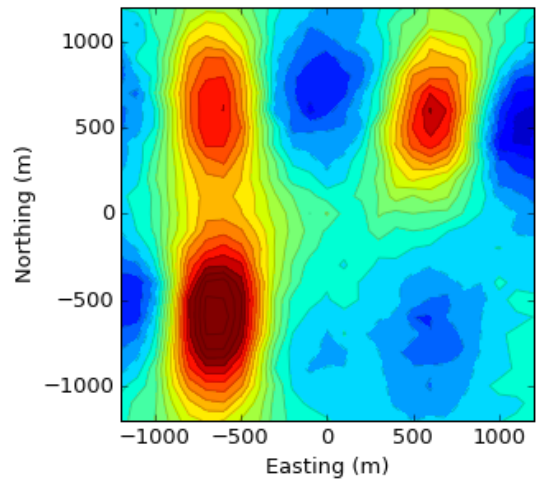
- Off-time at 130 ms

$$d_{raw}^{IP}(t) = F[\sigma(t)] - F[\sigma_{est}^{DC}] + noise(t)$$



EM decoupling: σ^{DC}_{est}

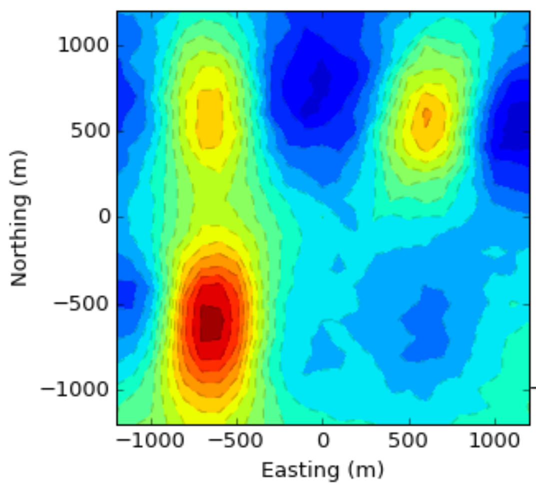
IP: Half-space



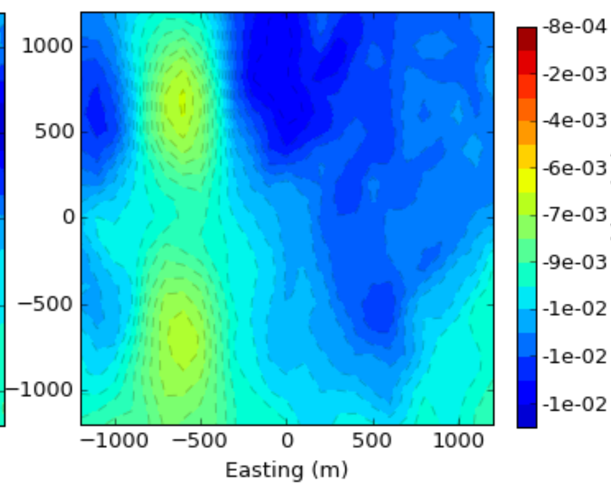
- Off-time at 130 ms

$$d^{IP}_{raw}(t) = F[\sigma(t)] - F[\sigma^{DC}_{est}] + noise(t)$$

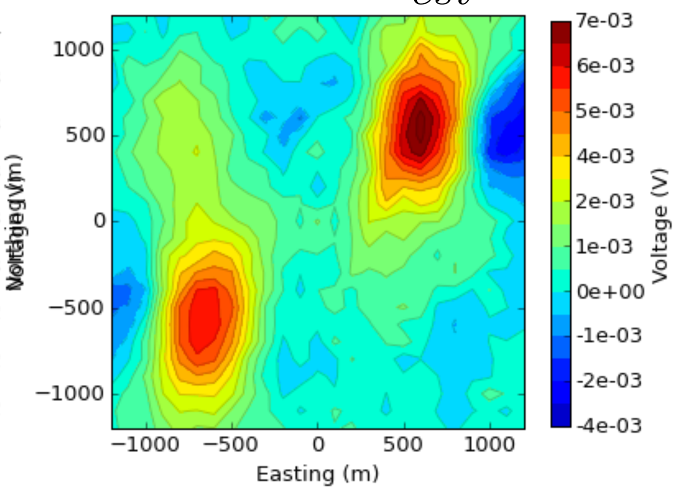
Observation



Predicted



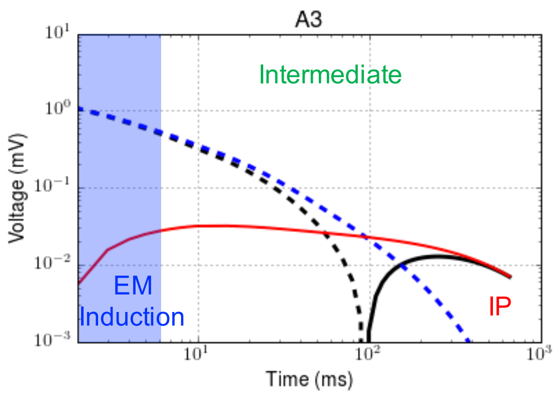
IP: σ^{DC}_{est}



3D TEM inversion

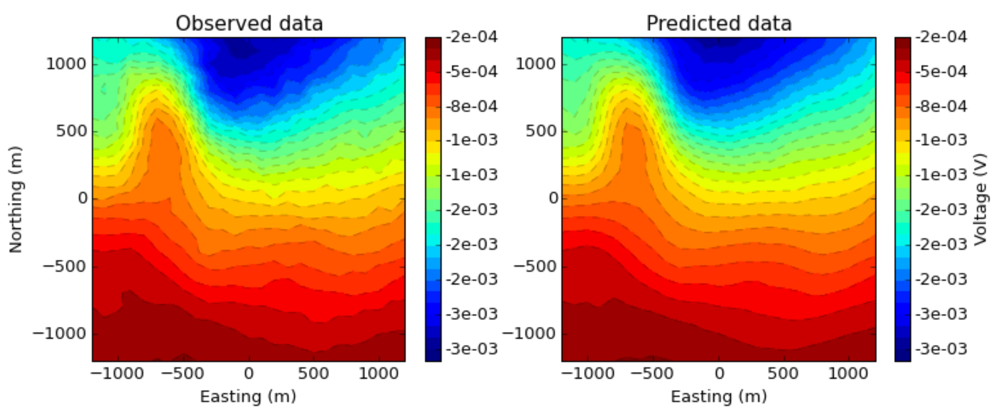
- Recover 3D conductivity

Use uncontaminated EM data

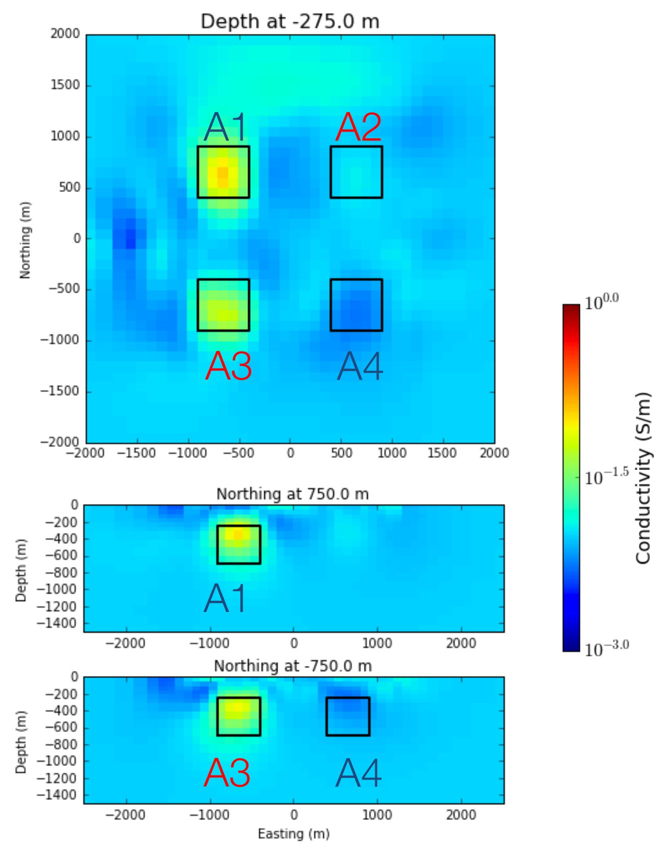


Time range: 1-6 ms
(6 channels)

Observed vs. Predicted

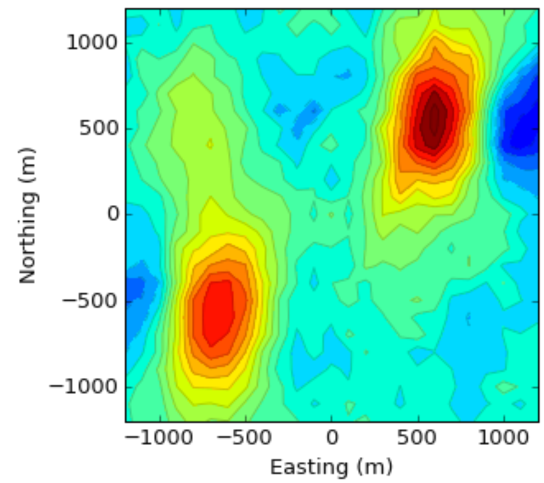


Estimated $\sigma_\infty (= \sigma_{est}^{EM})$



EM decoupling: σ_{est}^{EM}

IP: σ_{est}^{DC}

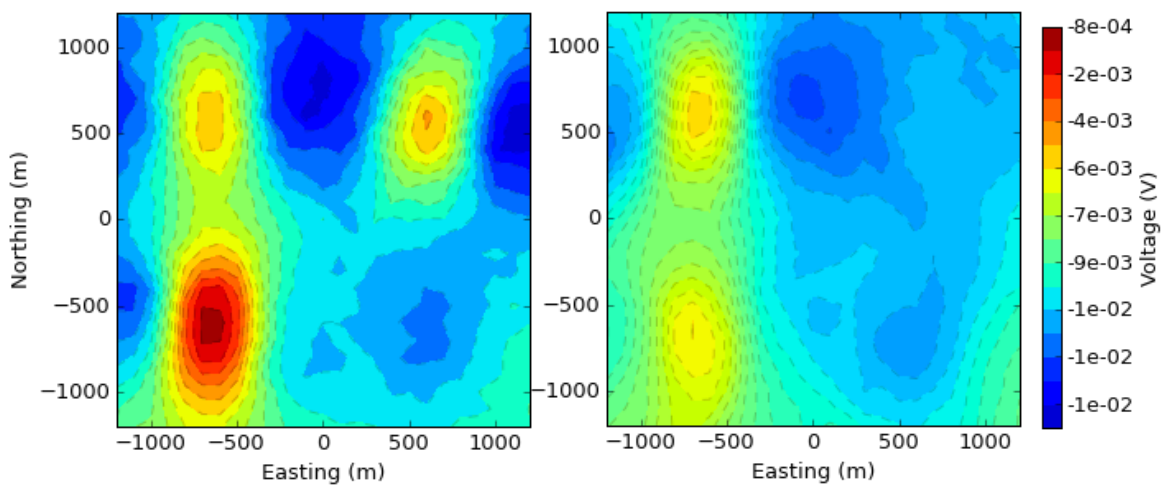


- Off-time at 80 ms

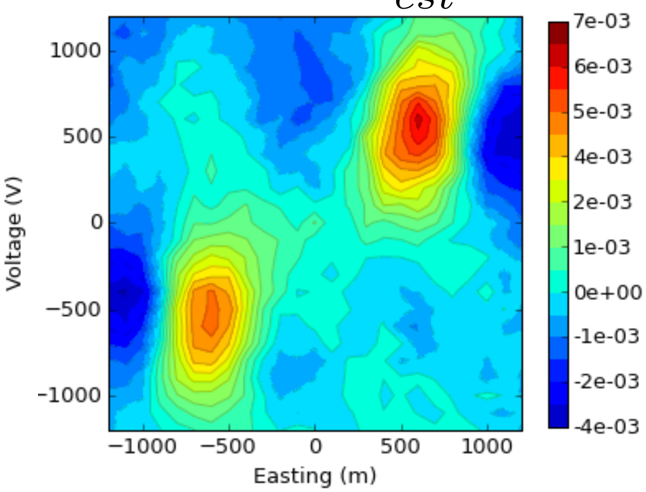
$$d_{raw}^{IP}(t) = F[\sigma(t)] - F[\sigma_{est}^{EM}] + noise(t)$$

Observation

Predicted

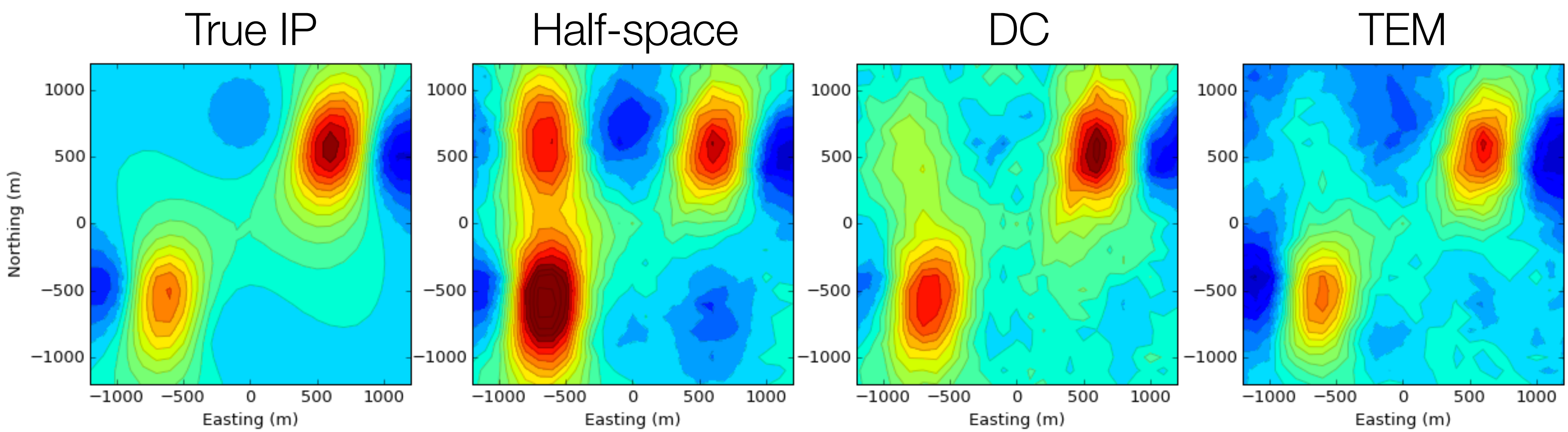


IP: σ_{est}^{EM}



Comparisons of IP

- IP data at 80 ms



IP inversion workflow

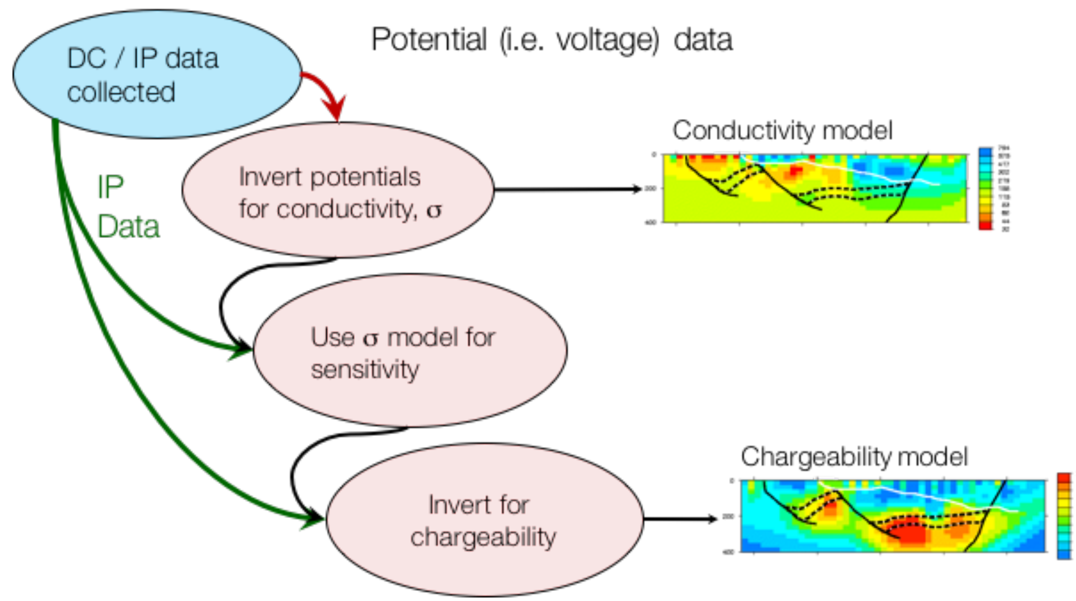
Workflow

Invert TEM data,
to recover σ_∞

Compute IP datum
Remove EM responses

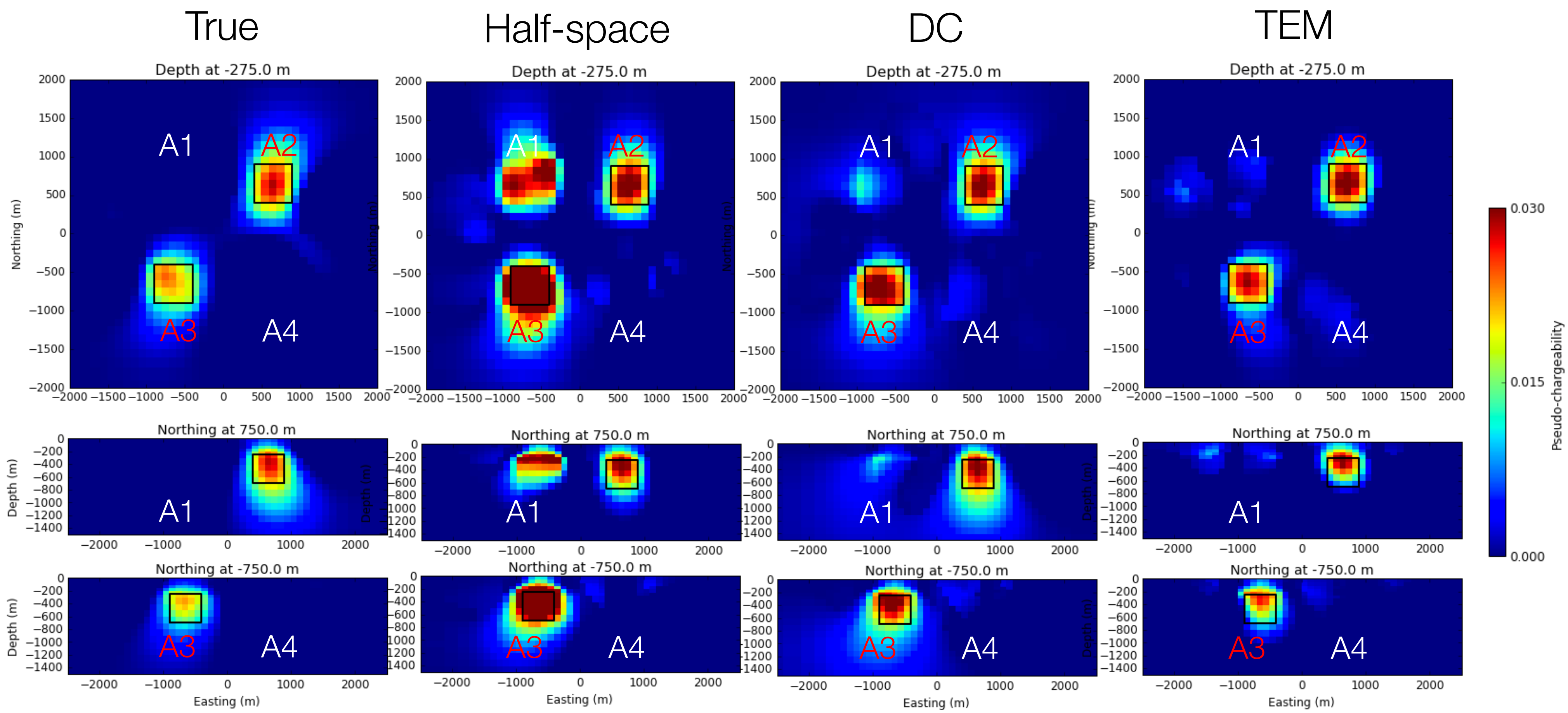
Linearized equations

Invert d^{IP} data,
recover pseudo-chargeability



3D IP inversion

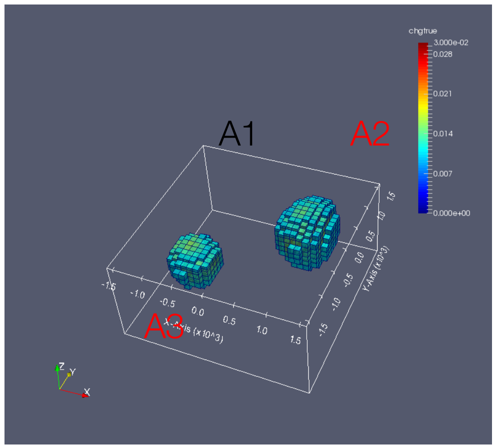
- Chargeability: recovered by inverting:



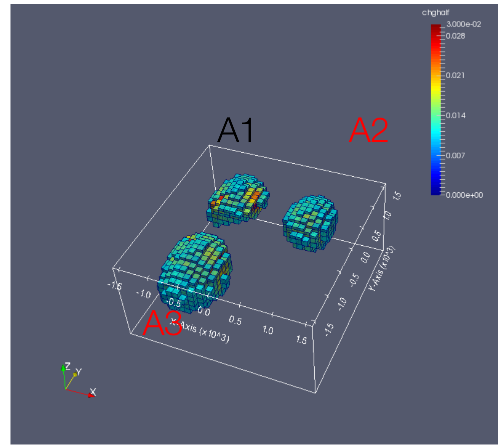
3D cut-off volume

- Pseudo-chargeability > 0.015

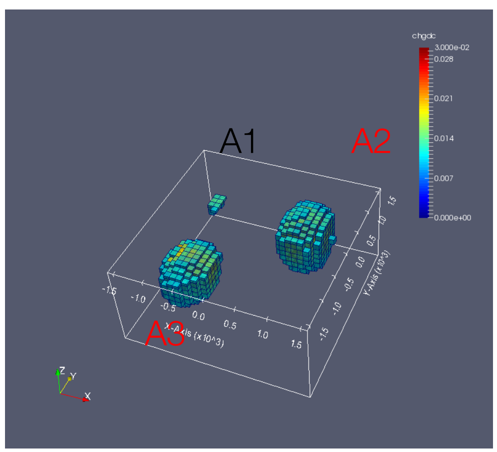
True



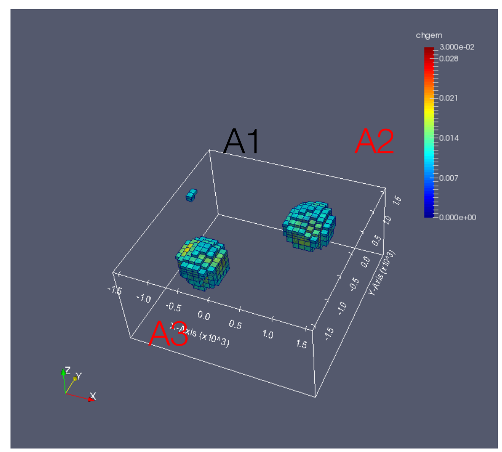
Half-space



DC



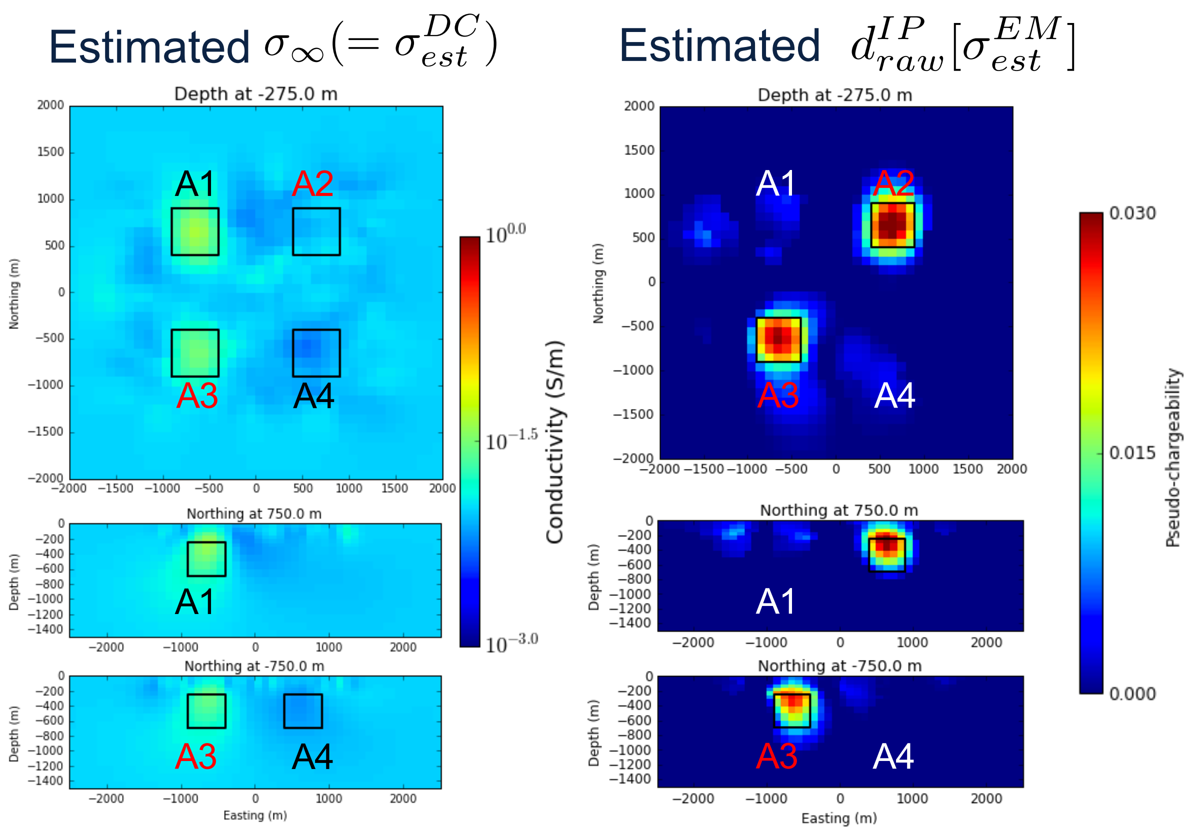
TEM



Take home

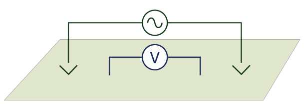
Traditionally, early time TEM data has been discarded

By using these discarded TEM signals we can better estimate both 3D conductivity and chargeability

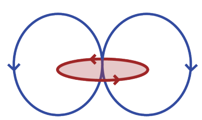


Outline

- Backgrounds
- TEM-IP inversion workflow
- Galvanic source IP
  - Synthetic example: gradient array

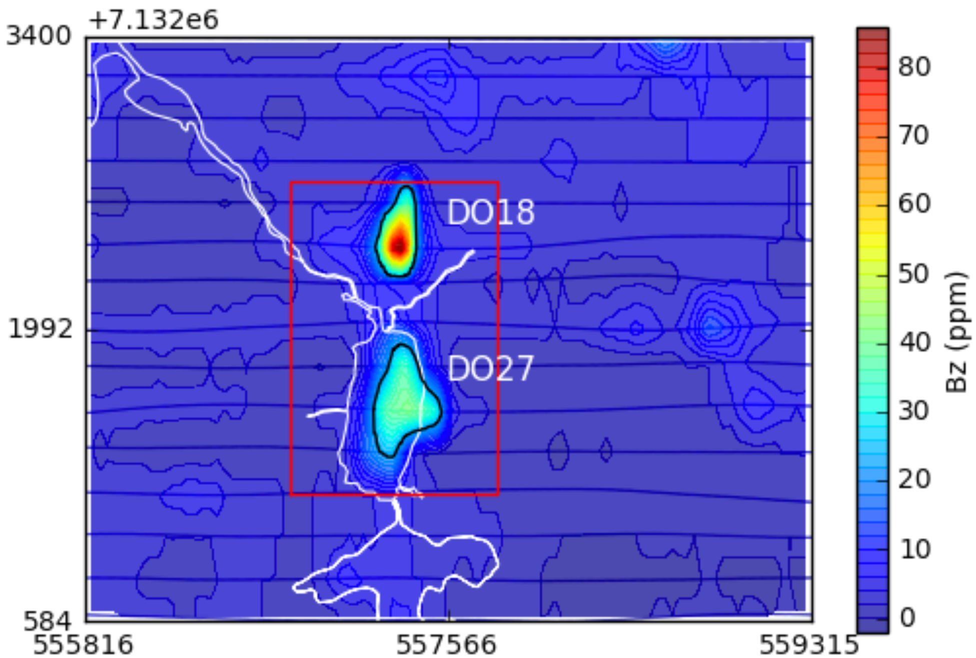


- Inductive source IP
  - Field example: Tli Kwi Cho kimberlites

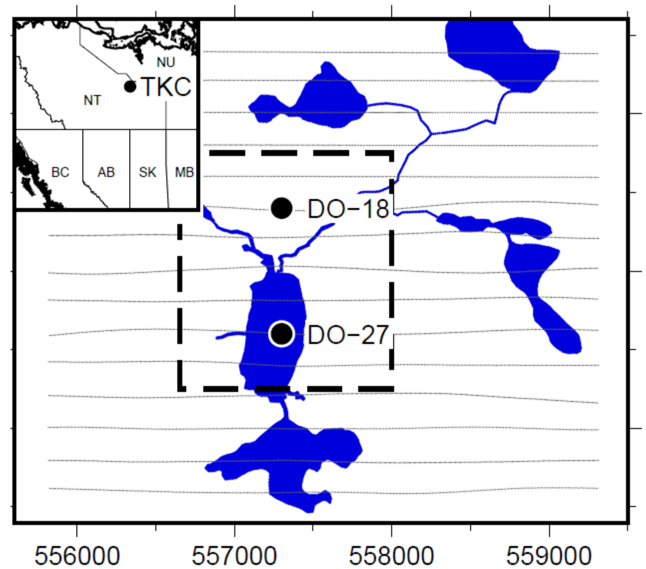


Discovery of Tli Kwi Cho (TKC)

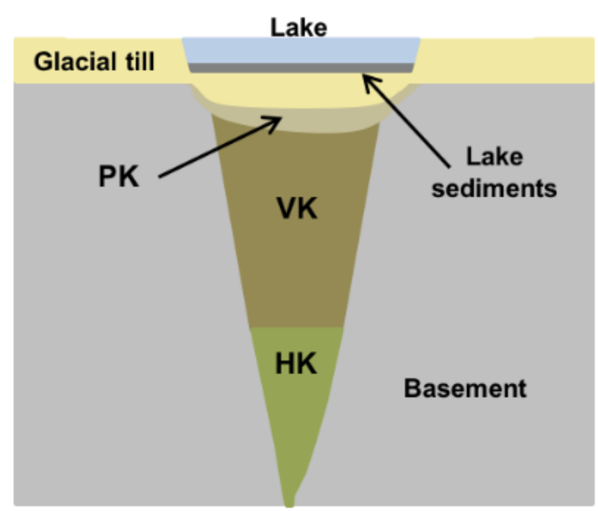
DIGHEM Q7200Hz



Location of TKC, NWT



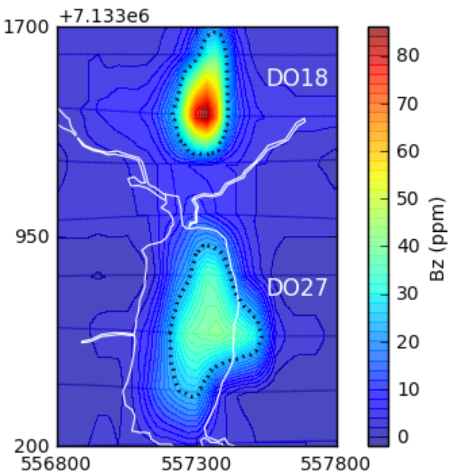
Kimberlite pipe structure



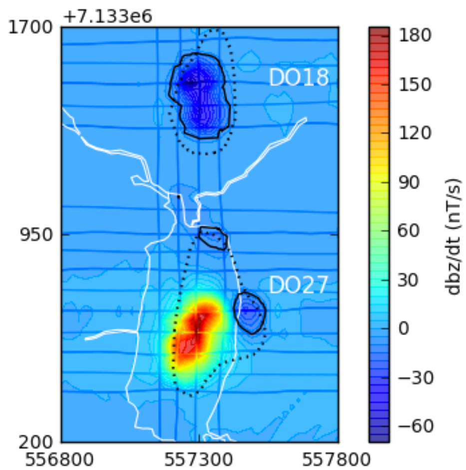
Devriese et al. (2016)

Time domain EM data

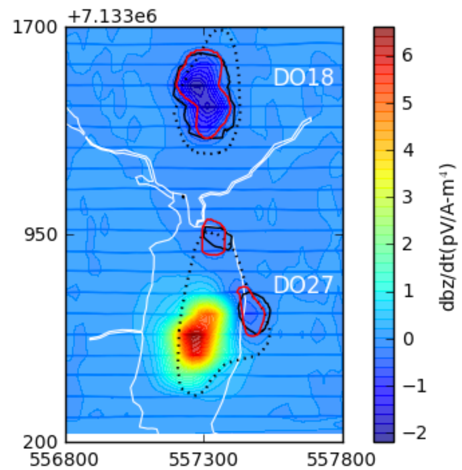
Dighem (1992)

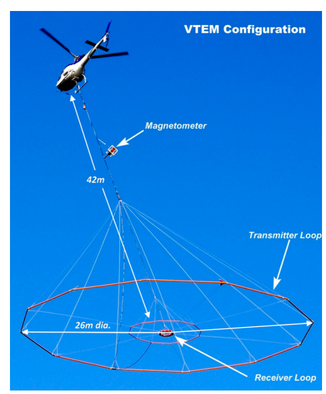


AeroTEMII (2003)

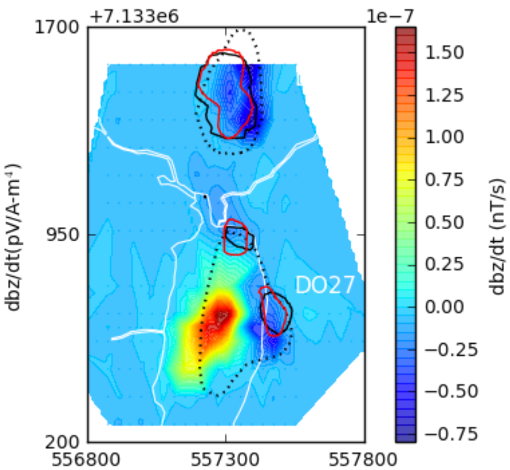


VTEM (2004)

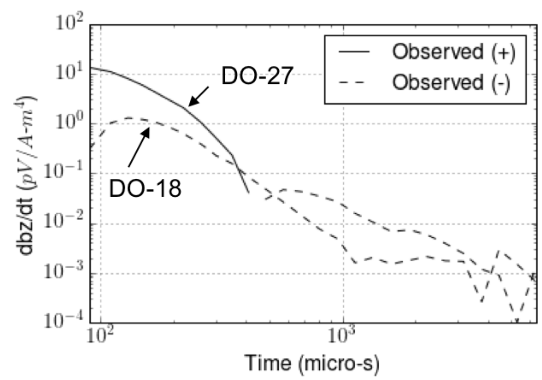




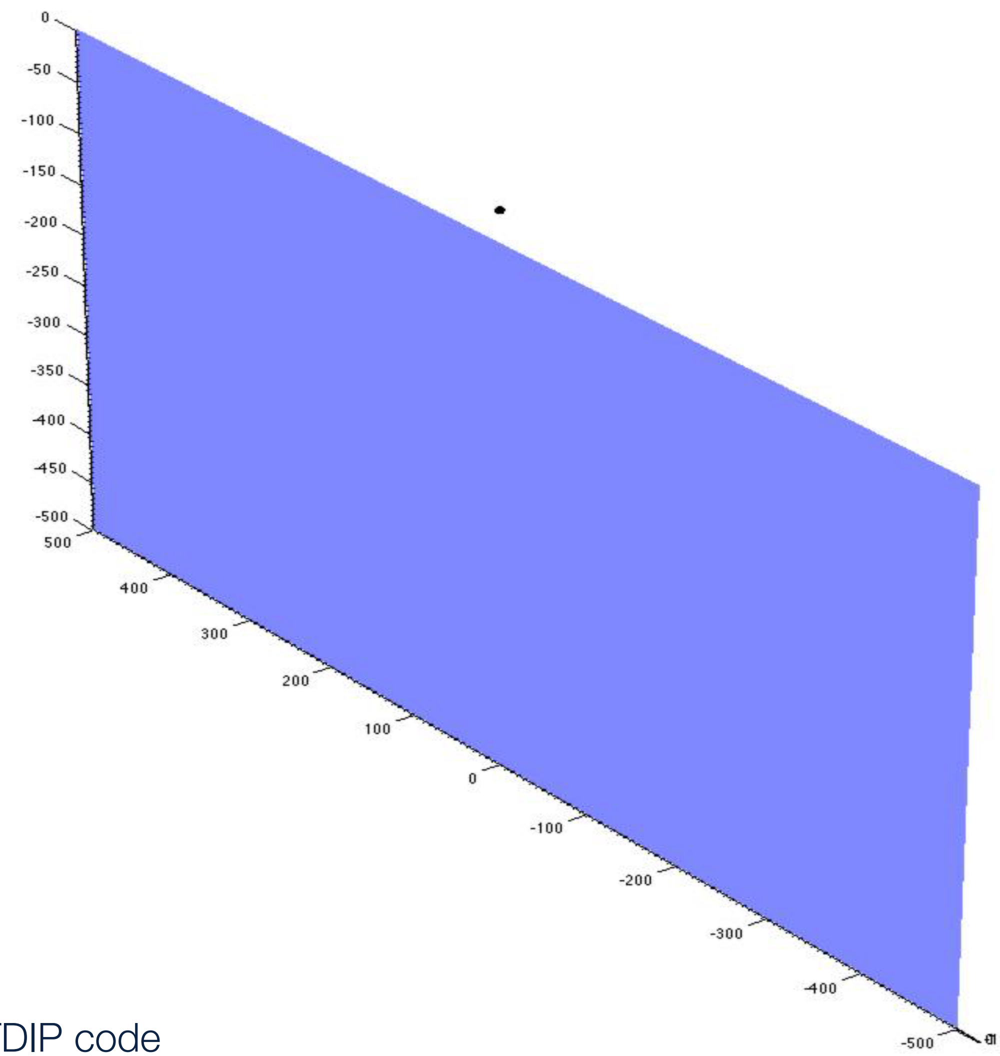
NanoTEM (1993)

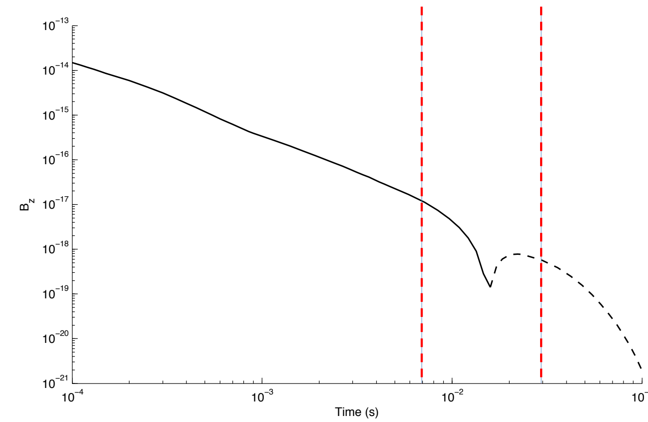


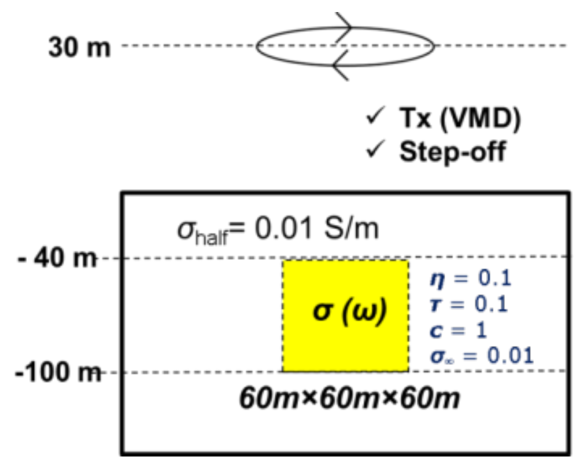
Decay curve



Reversed currents







EMTDIP code
(Marchant et al., 2015)

IP inversion workflow

Workflow

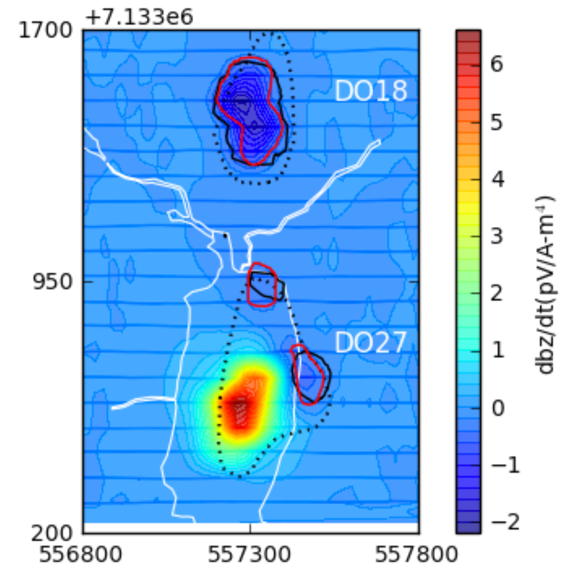
Invert TEM data,
to recover σ_∞

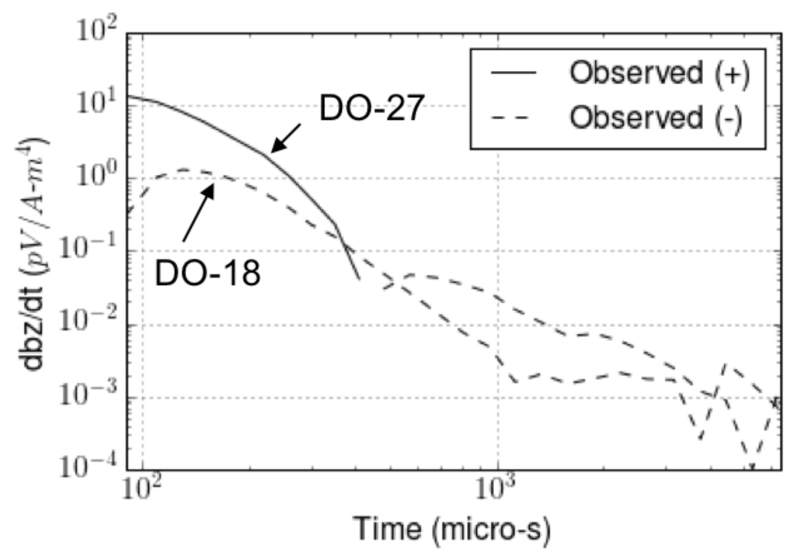
Compute IP datum
Remove EM responses

Linearized equations

Invert d^{IP} data,
recover pseudo-chargeability

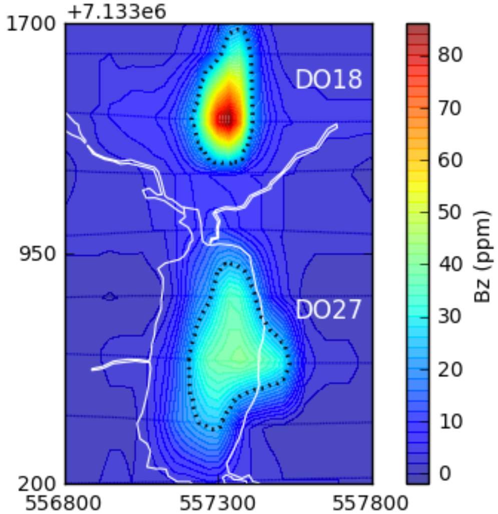
Estimate intrinsic
IP parameters



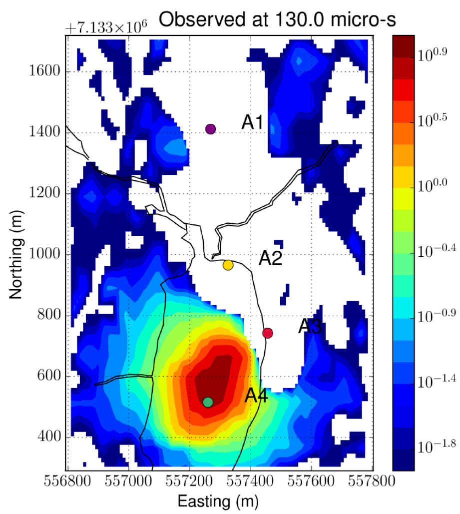


Step 1: Conductivity inversion

DIGHEM

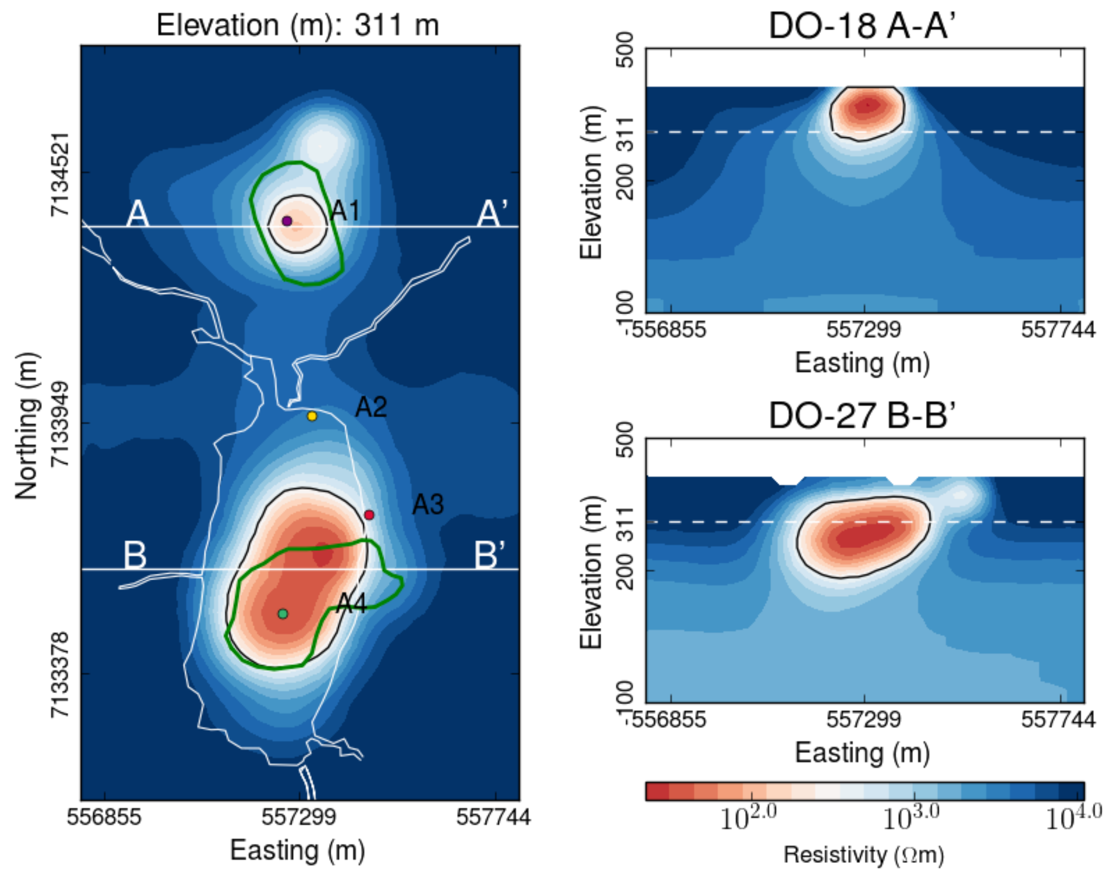


Positive VTEM
(EM-dominant)



Cooperative Inversion

Recovered 3D conductivity



Outline of two pipes

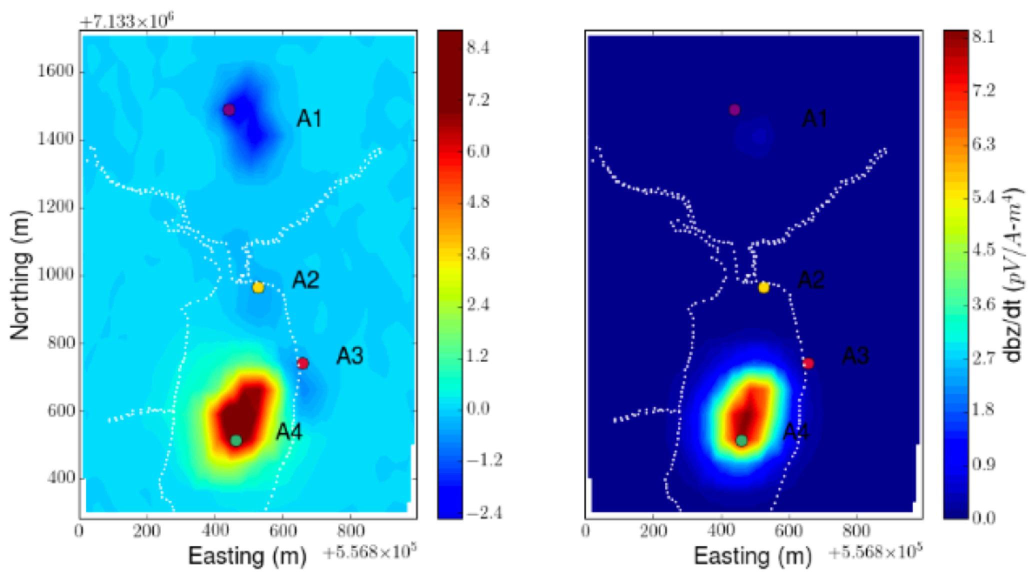
Step 2: EM-decoupling

IP = Observation - Fundamental

$$d^{IP} = F[\sigma(t)] - F[\sigma_\infty] \qquad F[\cdot] : \text{Maxwell's operator}$$

130 micro-s

Observed Fundamental



Step 2: EM-decoupling

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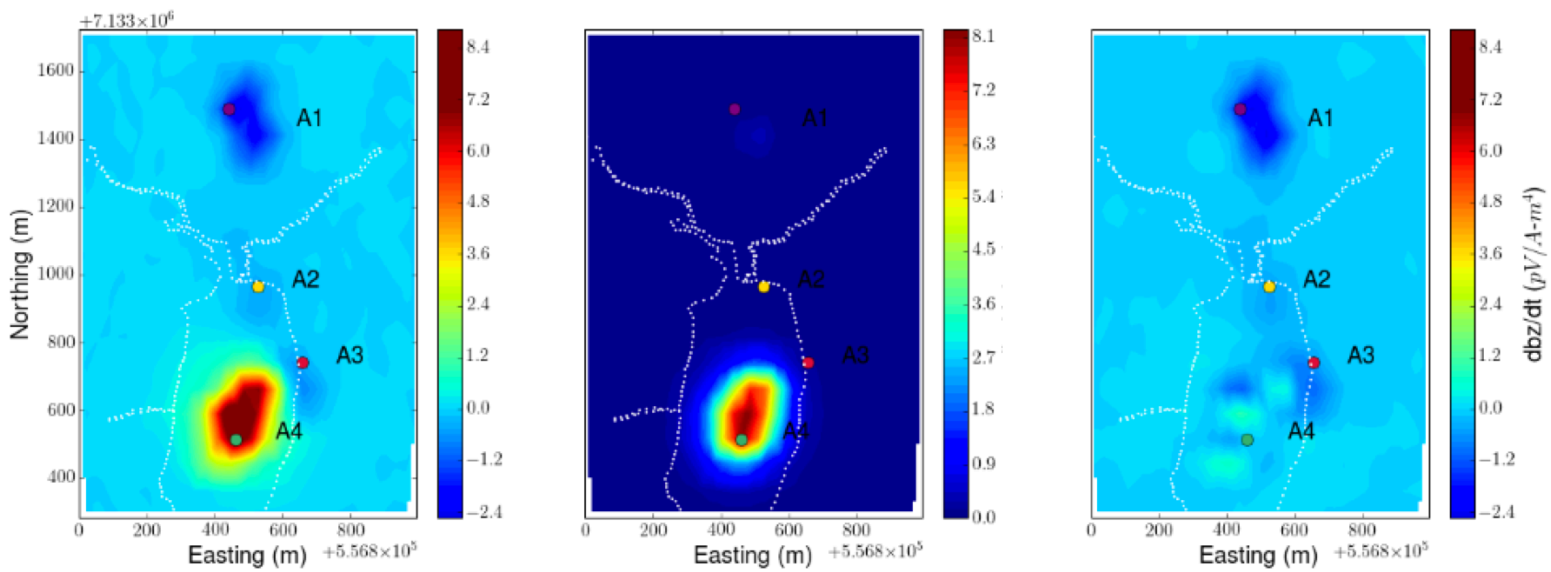
$$d^{IP} = F[\sigma(t)] - F[\sigma_\infty] \qquad F[\cdot] : \text{Maxwell's operator}$$

130 micro-s

Observed Fundamental IP



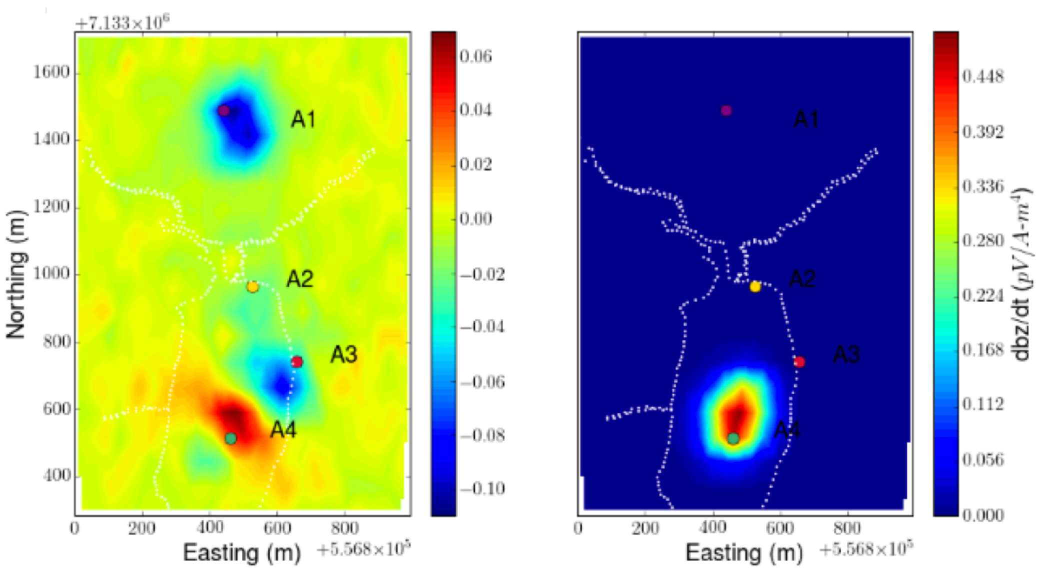
Step 2: EM-decoupling

IP = Observation - Fundamental

$$d^{IP} = F[\sigma(t)] - F[\sigma_\infty] \quad F[\cdot] : \text{Maxwell's operator}$$

410 micro-s

Observed Fundamental



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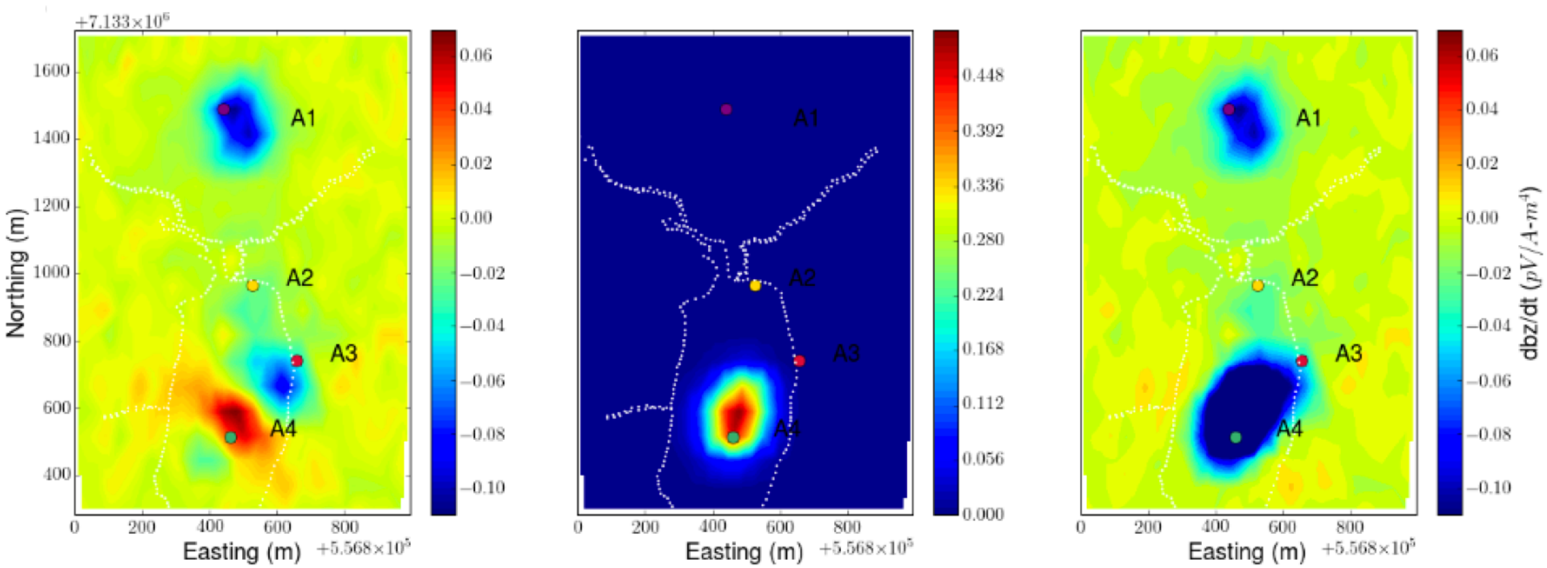
410 micro-s

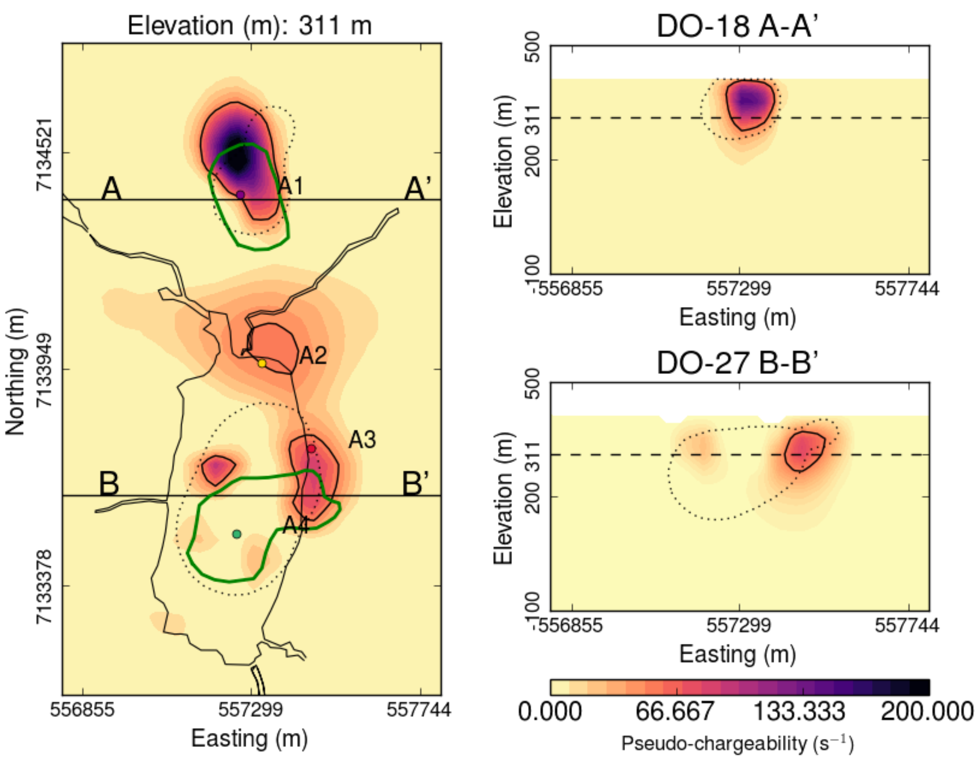
Observed Fundamental IP



Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

130 micro-s

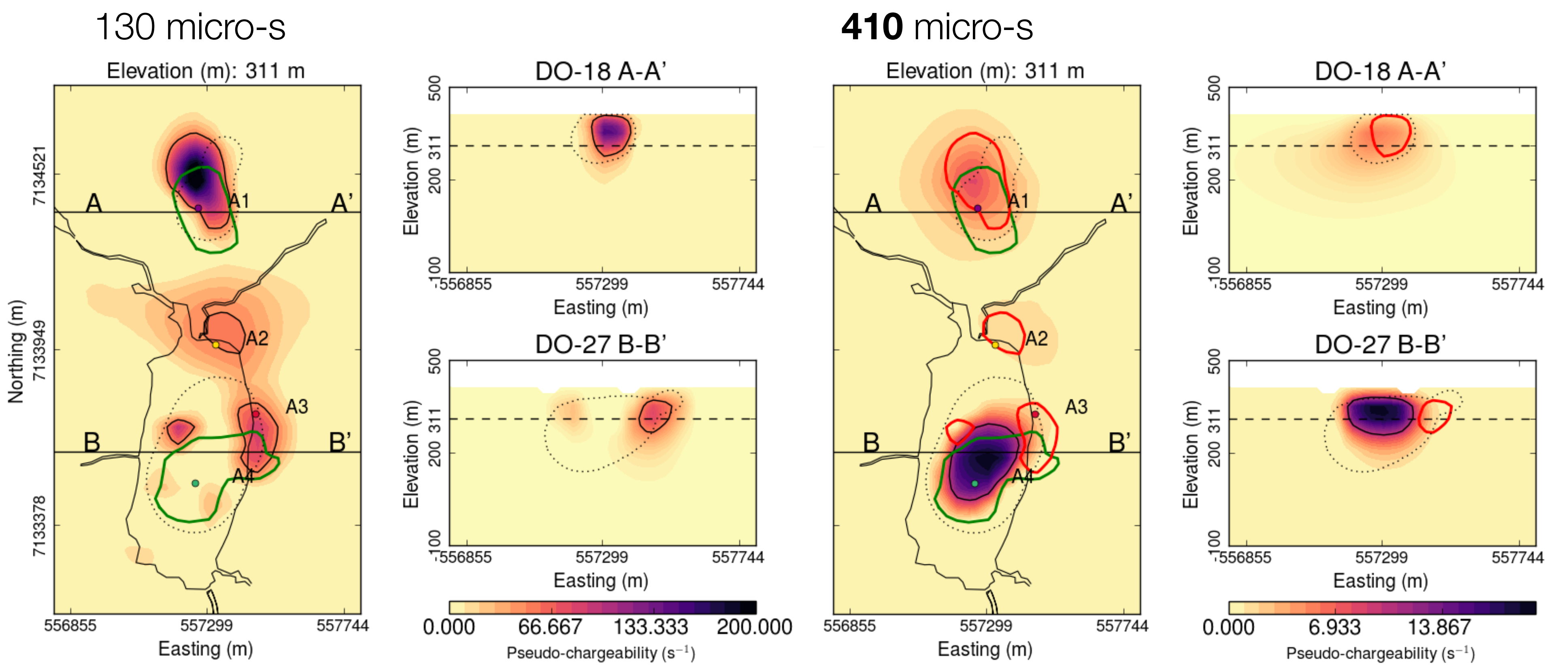


Outline of two pipes

Conductivity contour

Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

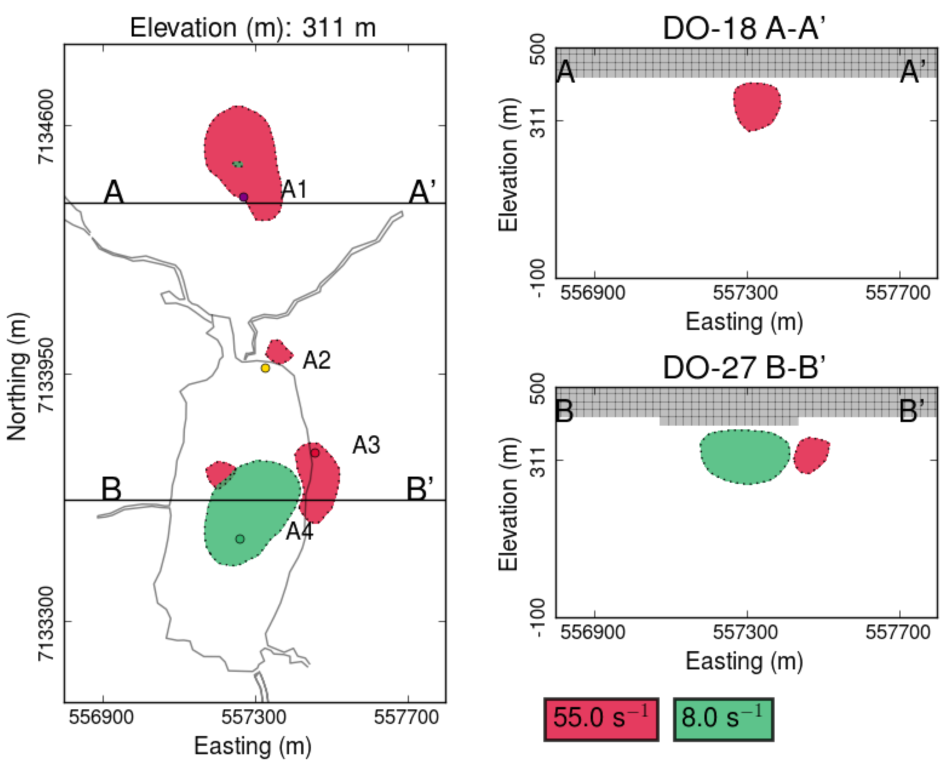


Outline of two pipes

Conductivity contour

Step 4: Estimate η and τ

Anomaly contours

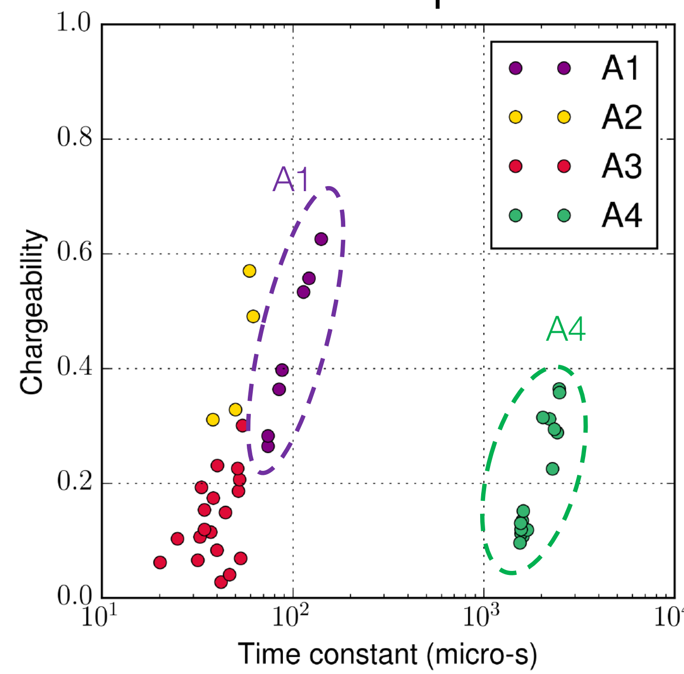


Cole-Cole model

$$\sigma(\omega) = \sigma_\infty + \sigma_\infty \frac{\eta}{1 + (1-\eta)(\imath\omega\tau)^c}$$

σ_∞: Conductivity at infinite frequency
σ_0: Conductivity at zero frequency
η: Chargeability
τ: Time constant (s)
c: Frequency dependency

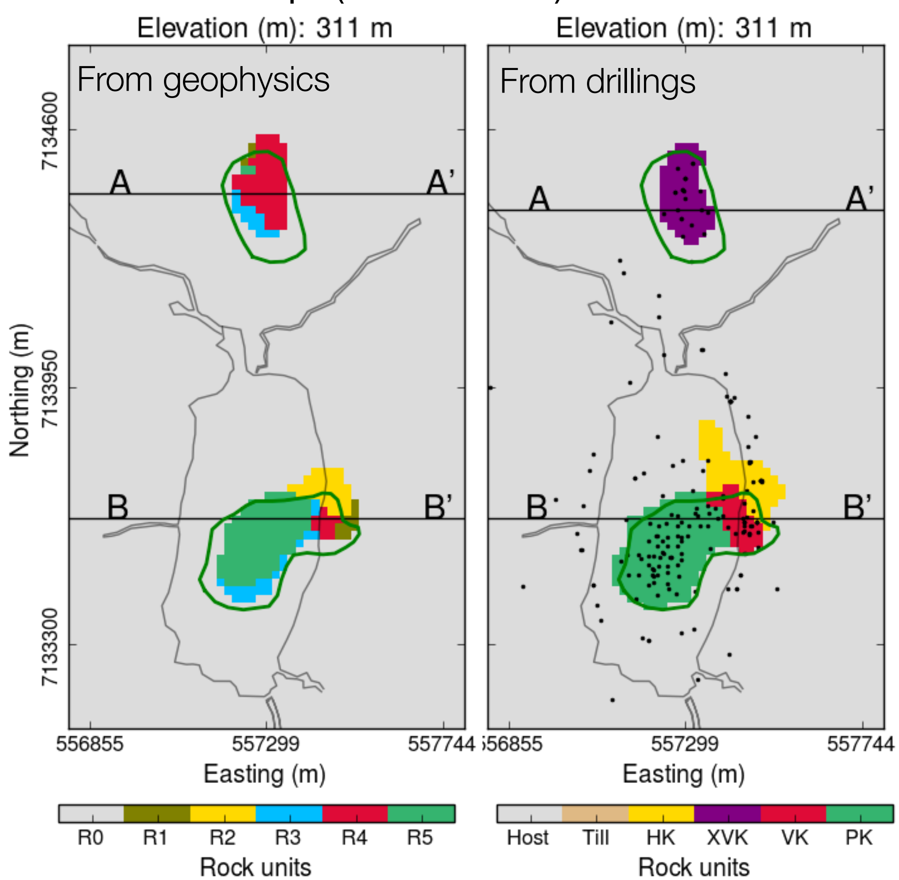
Recovered η and τ

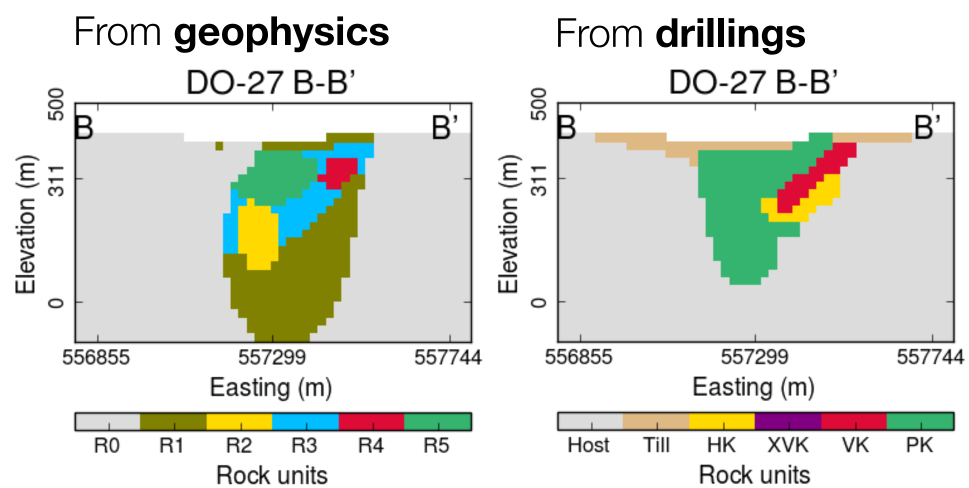


- A1-A3 has small time constant
- A4 has greater time constant

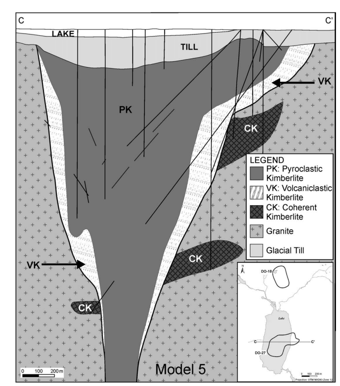
Impact on kimberlite exploration

Plan map (100 mbsf)





- HK, PK, and VK are delineated in 3D



Harder et al. (2009)

Summary

Workflow

Invert TEM data,
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Compute IP datum
Remove EM responses

Linearized equations

Invert d^{IP} data,
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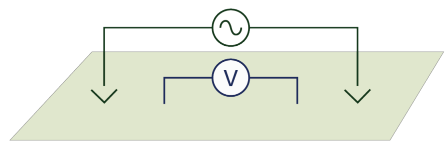
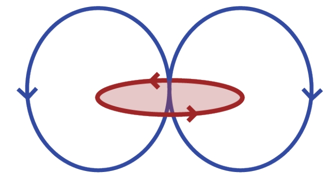
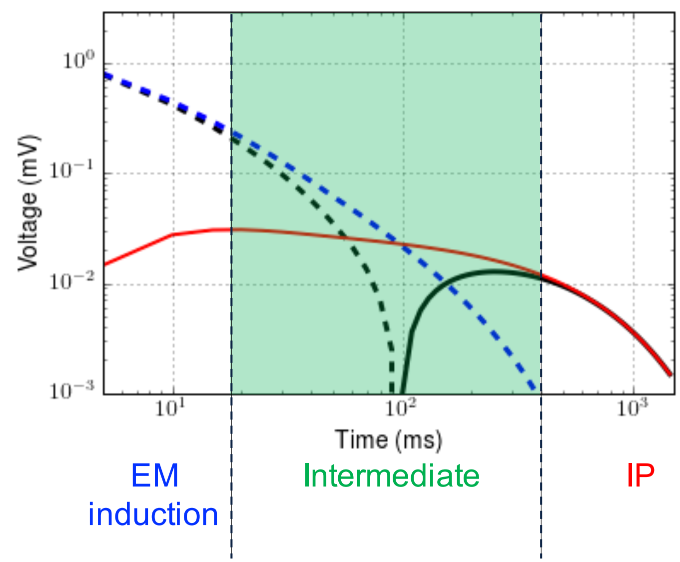
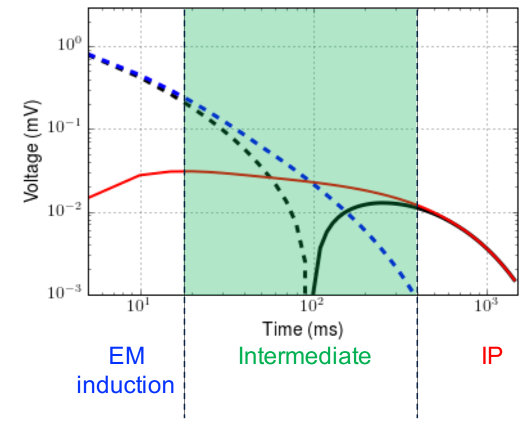
Estimate intrinsic
IP parameters







Summary



Workflow

Invert TEM data, to recover σ_∞

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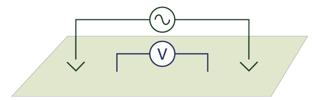
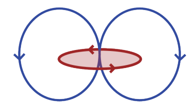
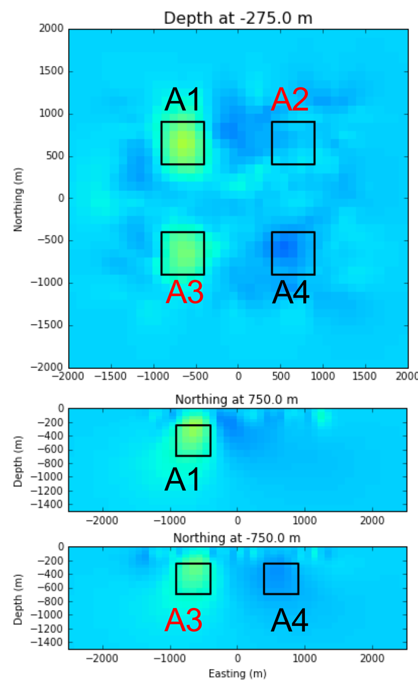
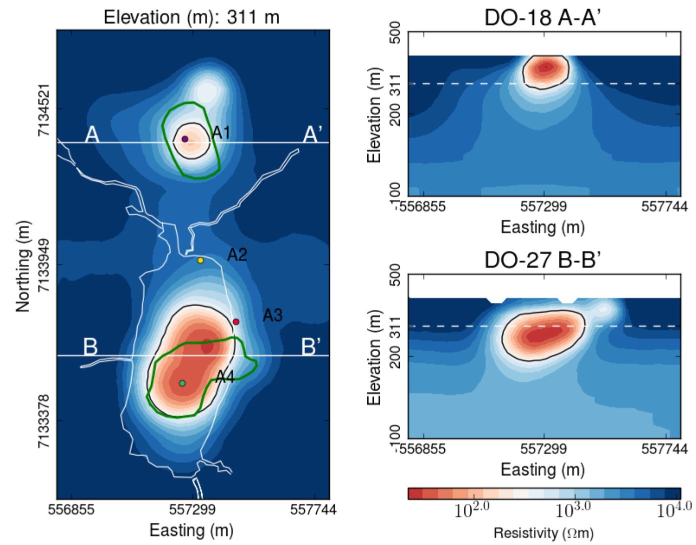
Invert d^{IP} data, recover pseudo-chargeability

Estimate intrinsic IP parameters









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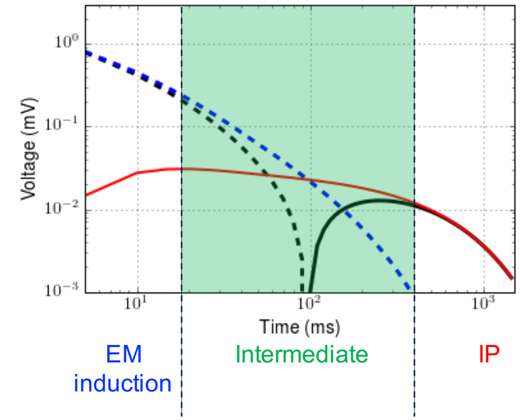
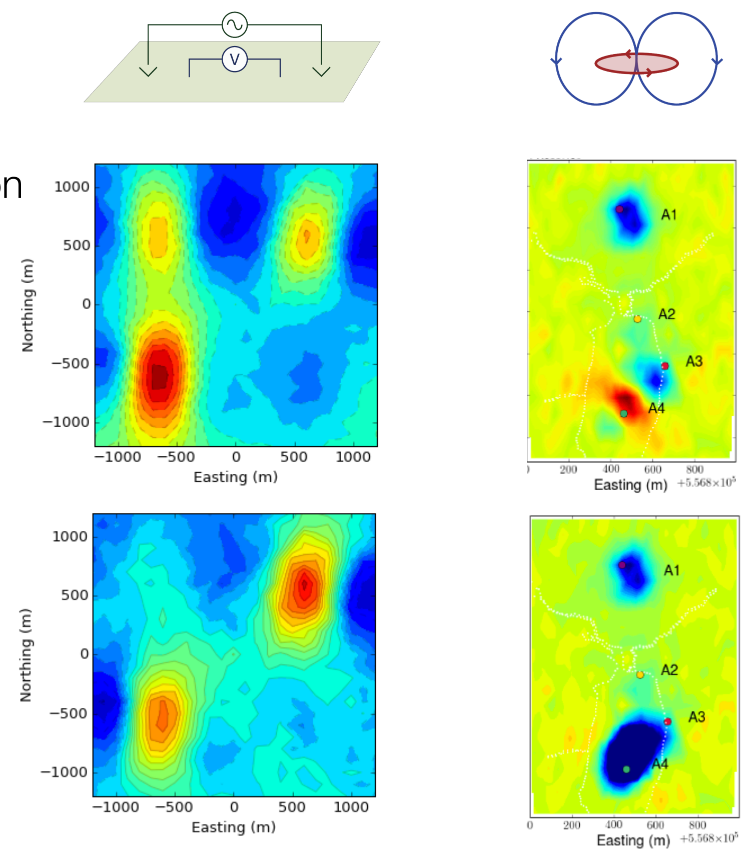
Estimate intrinsic
IP parameters

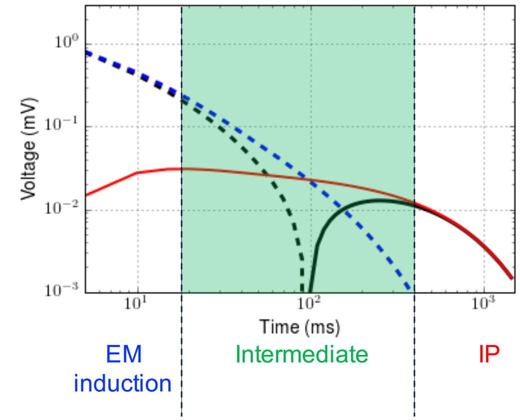


Observation

IP



Summary



Workflow

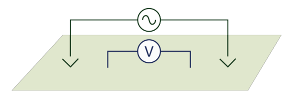
Invert TEM data,
to recover σ_∞

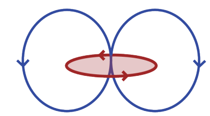
Compute IP datum
Remove EM responses

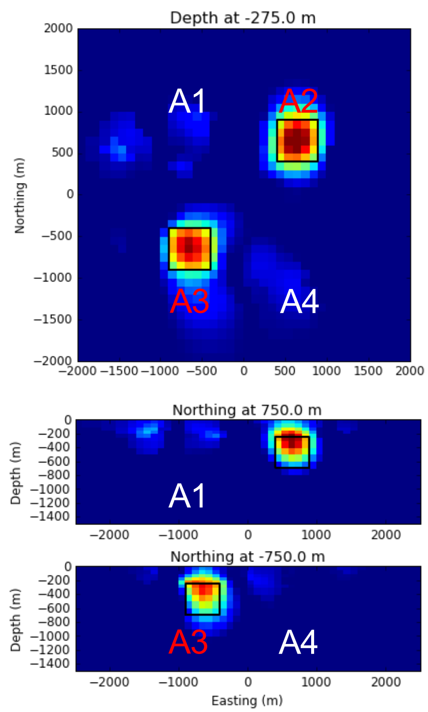
Linearized equations

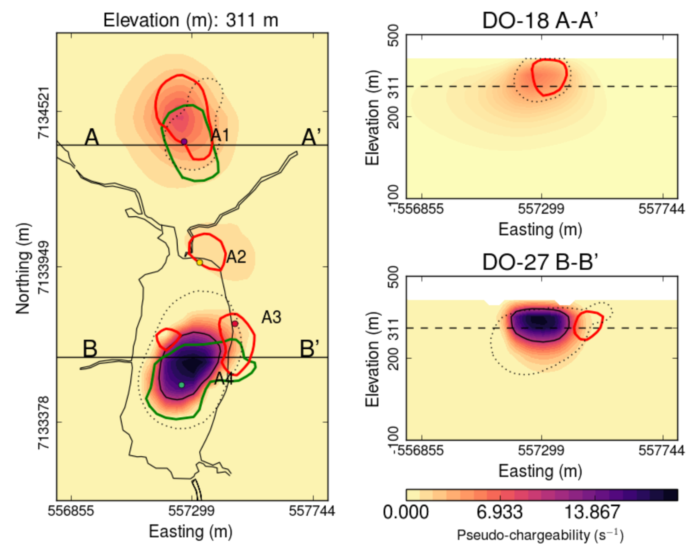
Invert d^{IP} data,
recover pseudo-chargeability

Estimate intrinsic
IP parameters

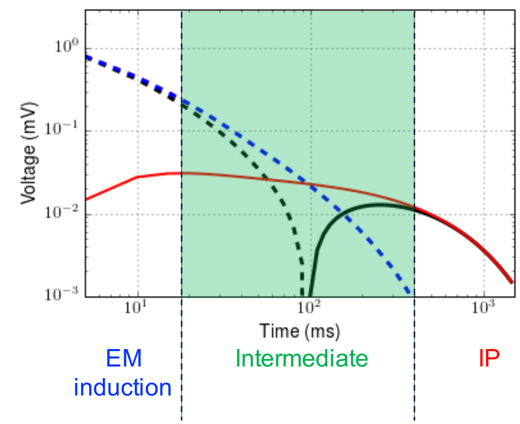








Summary



Workflow

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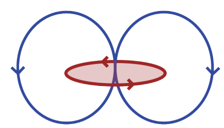
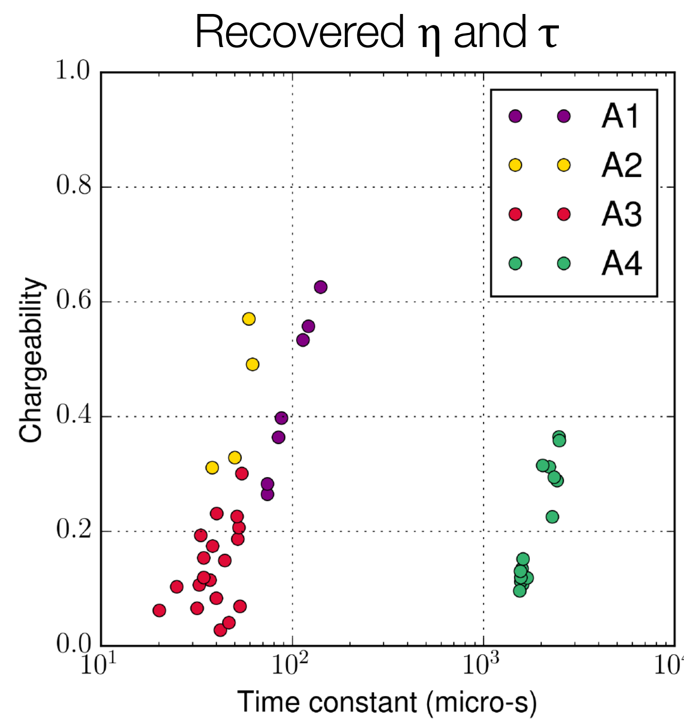
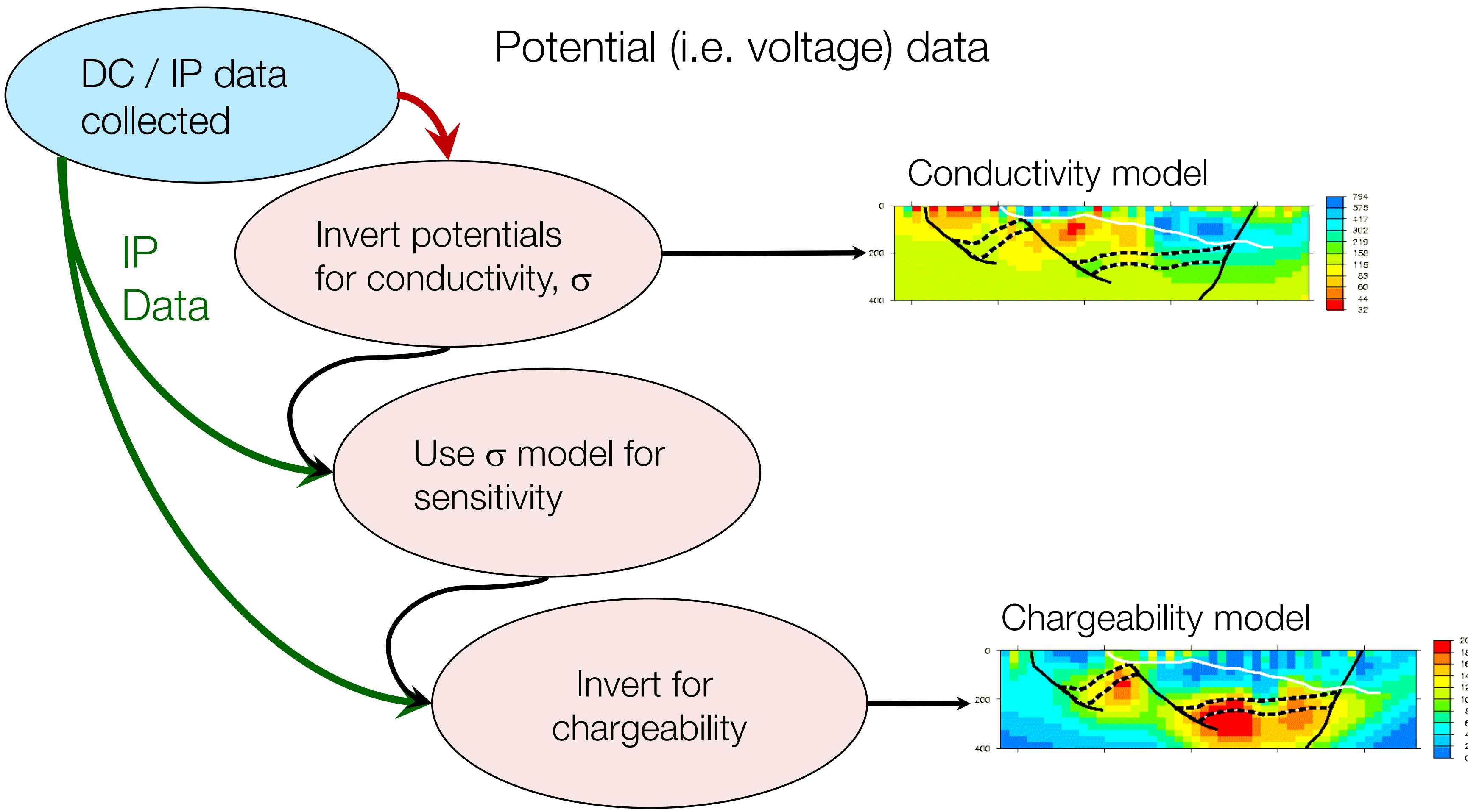




We may distinguish different rock types

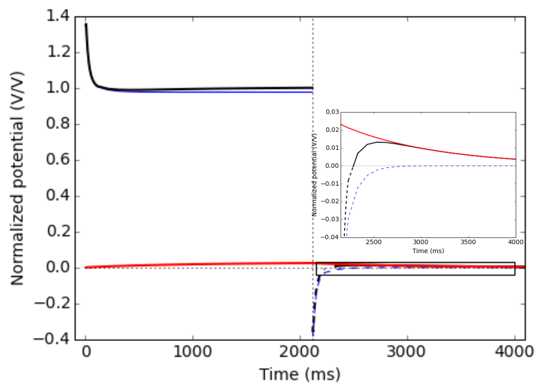
Thank you

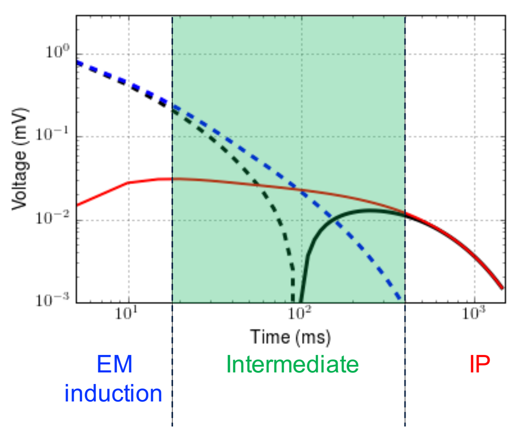
IP Inversion



TEM-IP inversion workflow

- Kang and Oldenburg (2016)





Invert TEM data, to recover σ_∞

Compute IP datum
Remove EM responses

Linearized equations

Invert d^{IP} data, recover pseudo-chargeability

Estimate intrinsic IP parameters

IP = Observation - Fundamental

$$d^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty]$$

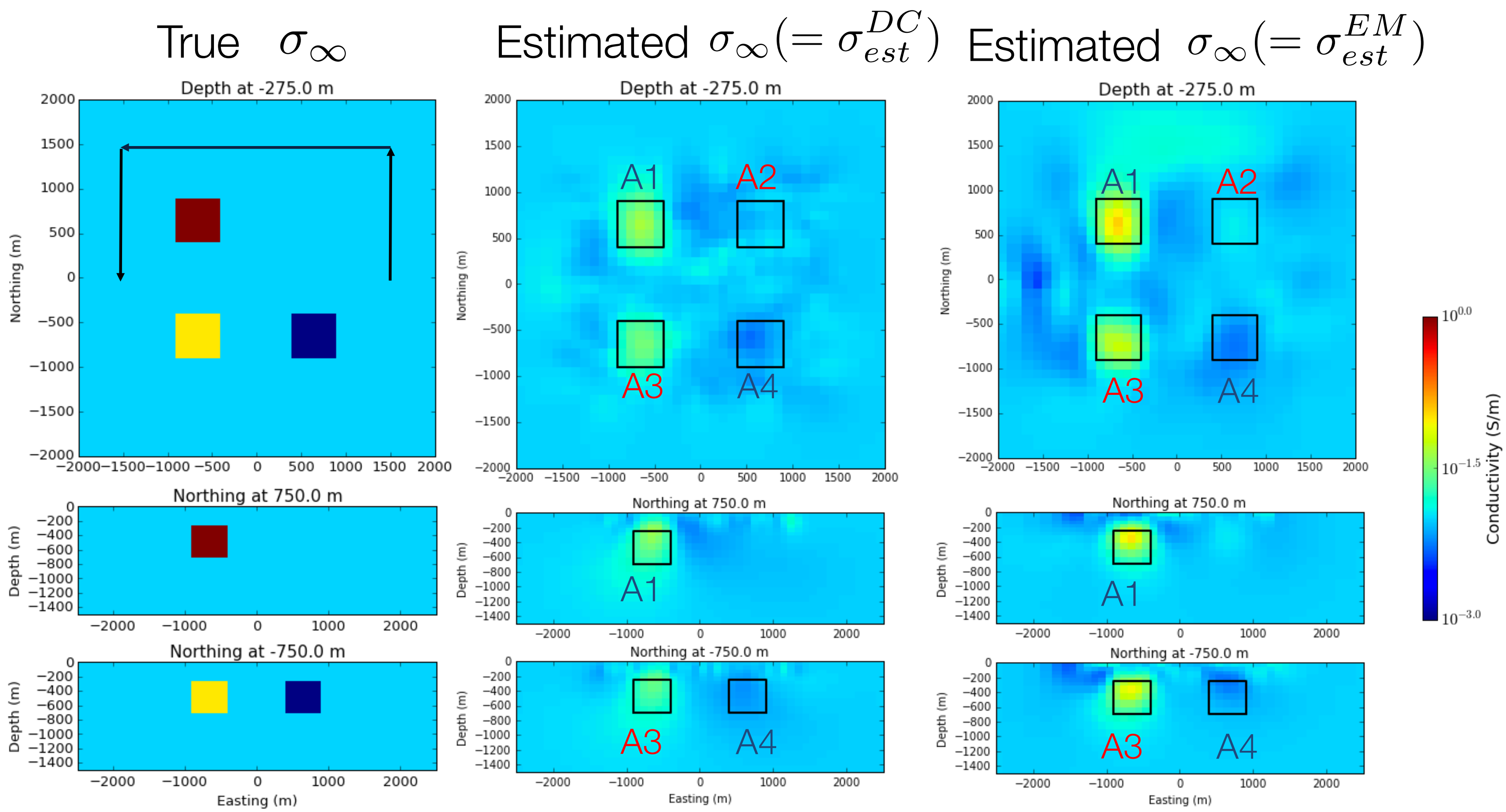
$F[\cdot]$: Maxwell's operator

$$d^{IP}(t) = G\tilde{\eta}(t)$$

$G(\sigma_\infty)$: Sensitivity function
$\tilde{\eta}$: Pseudo-chargeability

Comparison of 3D conductivities

- Recovered 3D conductivity



Comparisons of Fundamental

- Fundamental data at 80 ms