Advances in open-source software for 3D electromagnetics using SimPEG

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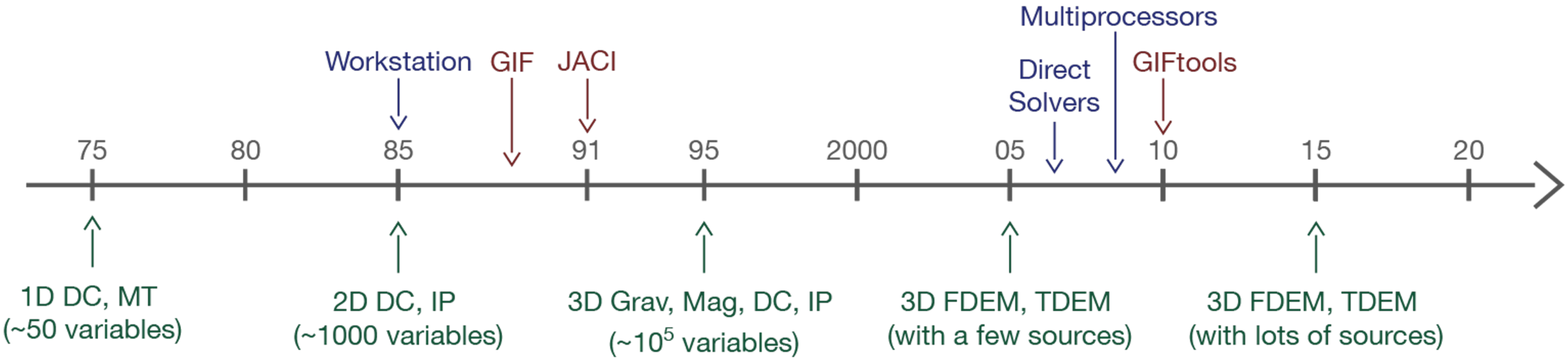
some background: UBC-GIF

GIF Fortran Codes & GIF Tools



slide from: [Oldenburg, 2016: Looking back and moving forwards (BIRS)]

some background: UBC-GIF

Transition to open-source

By 2010's…

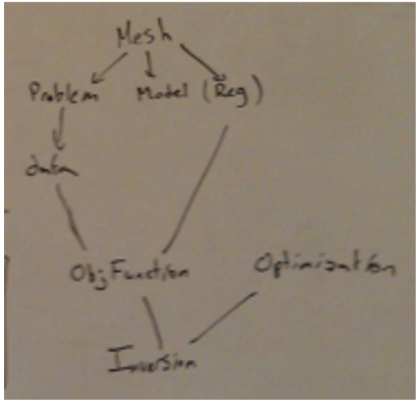
most forward simulations "solved"

next generation of research in inversions

- physical properties: anisotropy, high contrasts, magnetic permeability, IP in EM
- experimenting with inversion methods: choice of norm, including physical property & geologic information
- role of machine learning
- …

In 2013… started SimPEG

goal: common framework for inversions in geophysics to serve researchers



R. Cockett L. Heagy S. Kang

A framework for geophysical inversions

with application to vadose zone parameter estimation

by

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B.Sc. Applied and Environmental Geology, University of Calgary, 2010

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(Geophysics)

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(Vancouver)

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simpeg

simulation and parameter estimation in geophysics

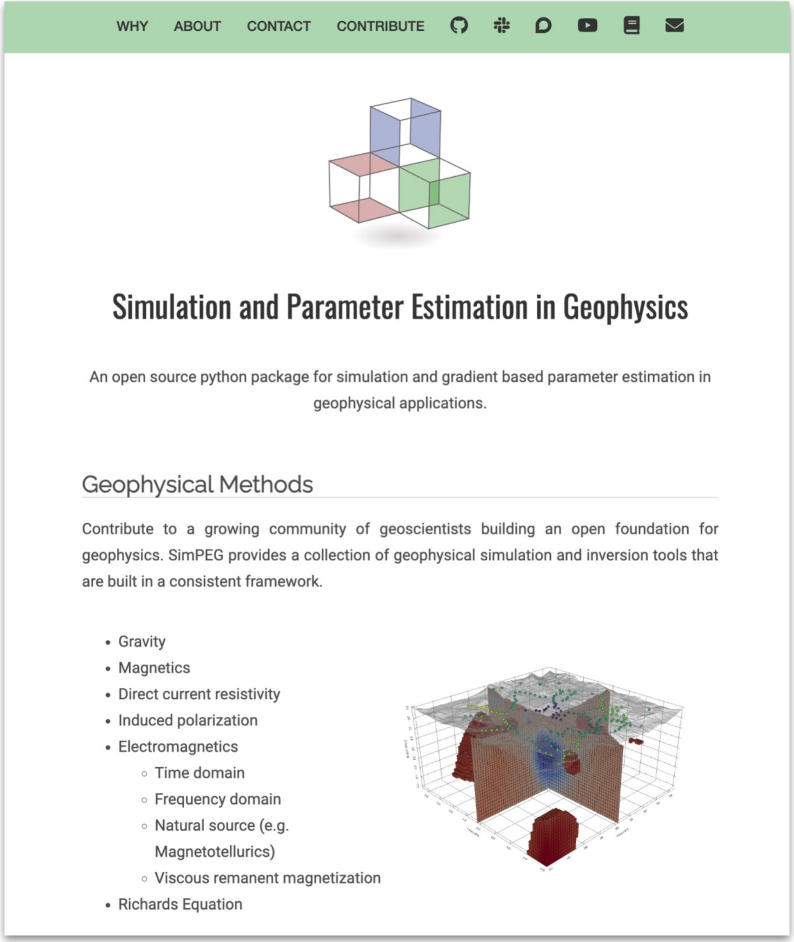
common framework for simulations & inversions

accelerate research: build upon others work

facilitate reproducibility of results

build & deploy in python

open-source



what simpeg solves

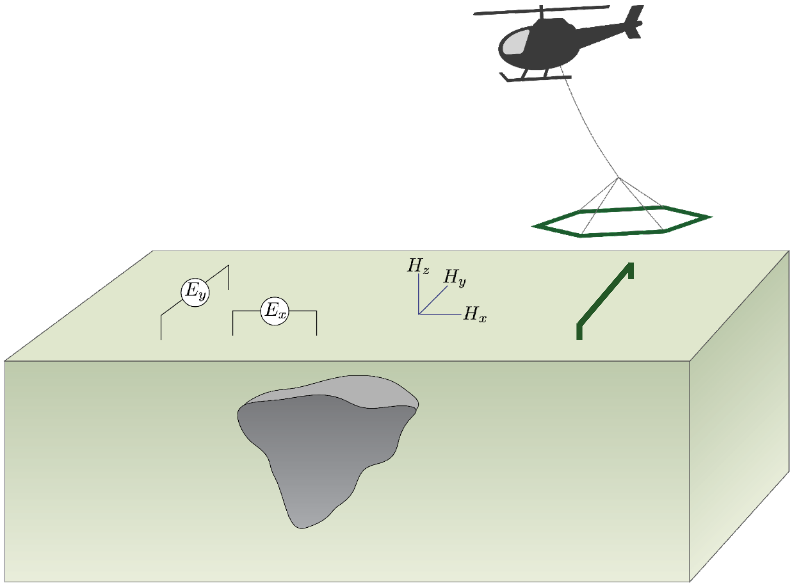
Given

- observations: $d_j^{obs}, \quad j = 1, \ldots, N$
- uncertainties: ϵ_j
- ability to forward model: $\mathcal{F}[m] = d$

Inverse problem: Find an Earth model that fits those data and a-priori information

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

$$\text{s.t. } \phi_d \leq \phi_d^* \quad \mathbf{m}_L \leq \mathbf{m} \leq \mathbf{m}_U$$



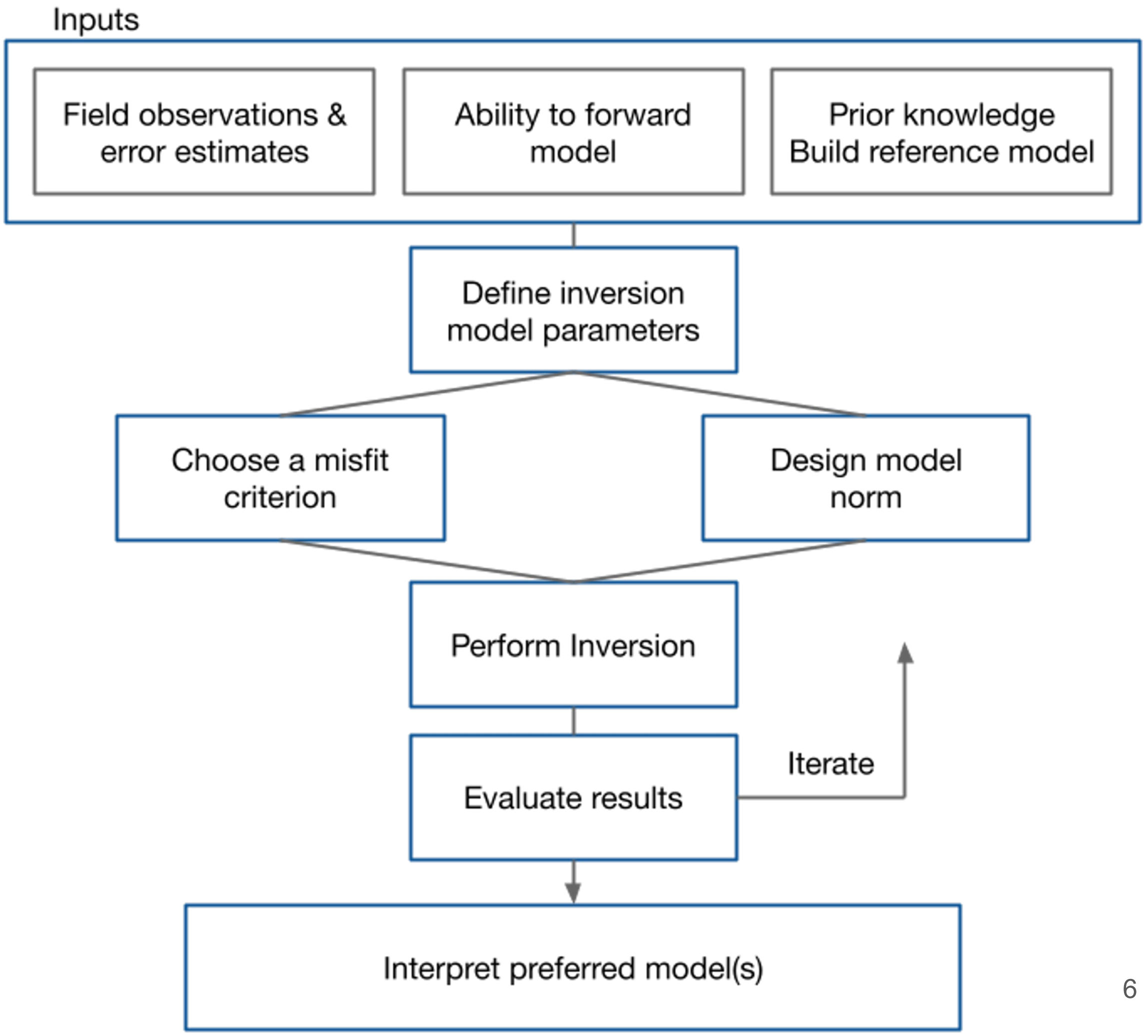
flow chart for the inverse problem

- many components
- iterative process to obtain solution
- each component requires evaluation, adjustment by user



Fundamentals of Inversion – D. Oldenburg
Capturing knowledge in code – L. Heagy

http://www.mtnet.info/EMinars/EMinars.html



electromagnetics: basic equations (quasi-static)

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

* Solve with sources and boundary conditions

electromagnetics: frequency domain equations

Use constitutive relations, reduce to two equations, one field, one flux

$$\nabla \times \vec{E} + i\omega \vec{B} = 0$$

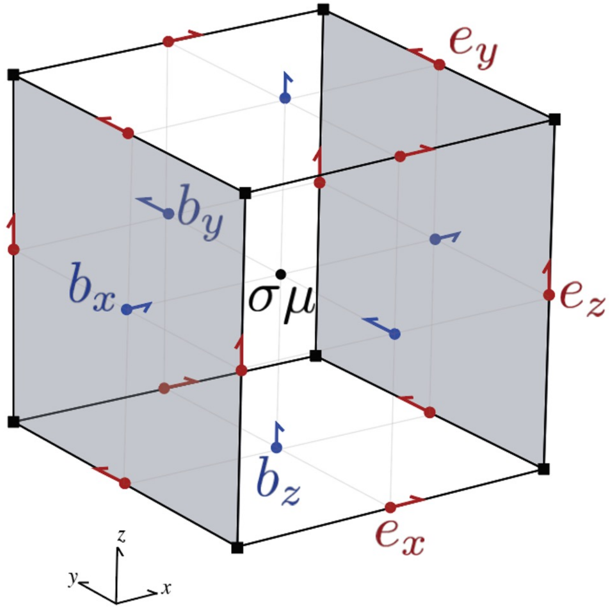
$$\nabla \times \mu^{-1} \vec{B} - \sigma \vec{E} = \vec{J}_s$$

$$\hat{n} \times \vec{B}|_{\partial\Omega} = 0$$

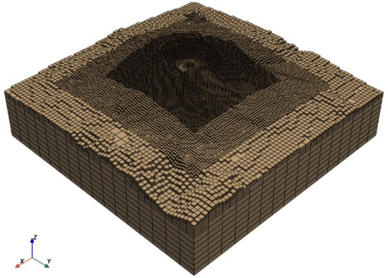
Finite volume discretization
(e.g. Haber, 2014; Cockett et al., 2016)

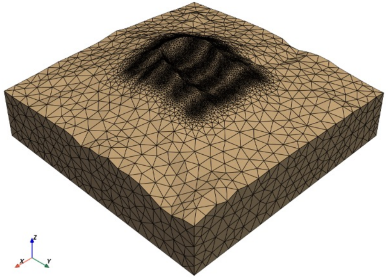
$$\mathbf{C}\mathbf{e} + i\omega \mathbf{b} = 0$$

$$\mathbf{C}^\top \mathbf{M}^f_{\mu^{-1}} \mathbf{b} - \mathbf{M}^e_\sigma \mathbf{e} = \mathbf{M}^e \mathbf{j}_s$$



Solving an FDEM problem





J. Capriotti

Mesh types:

- Tensor
- OcTree
- Curvilinear
- Tetrahedral

$$\underbrace{(\mathbf{C}^\top \mathbf{M}^f_{\mu^{-1}} \mathbf{C} + i\omega \mathbf{M}^e_\sigma)}_{\mathbf{A}(\sigma,\omega)} \underbrace{\mathbf{e}}_{\mathbf{u}} = \underbrace{-i\omega \mathbf{M}^e \mathbf{j_s}}_{\mathbf{q}(\omega)}$$

```
ω = 2 * pi * frequency

C = mesh.edge_curl
Mfμi = mesh.get_face_inner_product(1/mu_0)
Meσ = mesh.get_edge_inner_product(sigma)

A = C.T * Mfμi * C + i * ω * Meσ
Ainv = Solver(A)  # acts like A inverse

Me = mesh.get_edge_inner_product()
q = -i * ω * Me * js

u = Ainv * q
```

```python
from SimPEG import electromagnetics
```

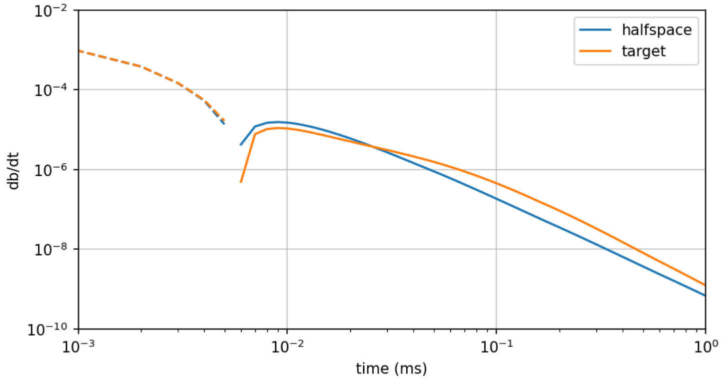
modules:

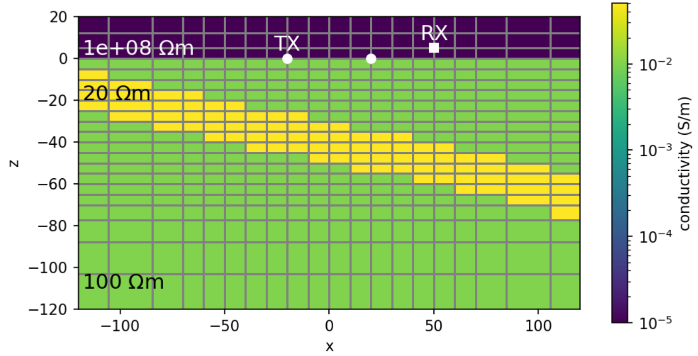
- frequency domain
- natural sources
- time domain

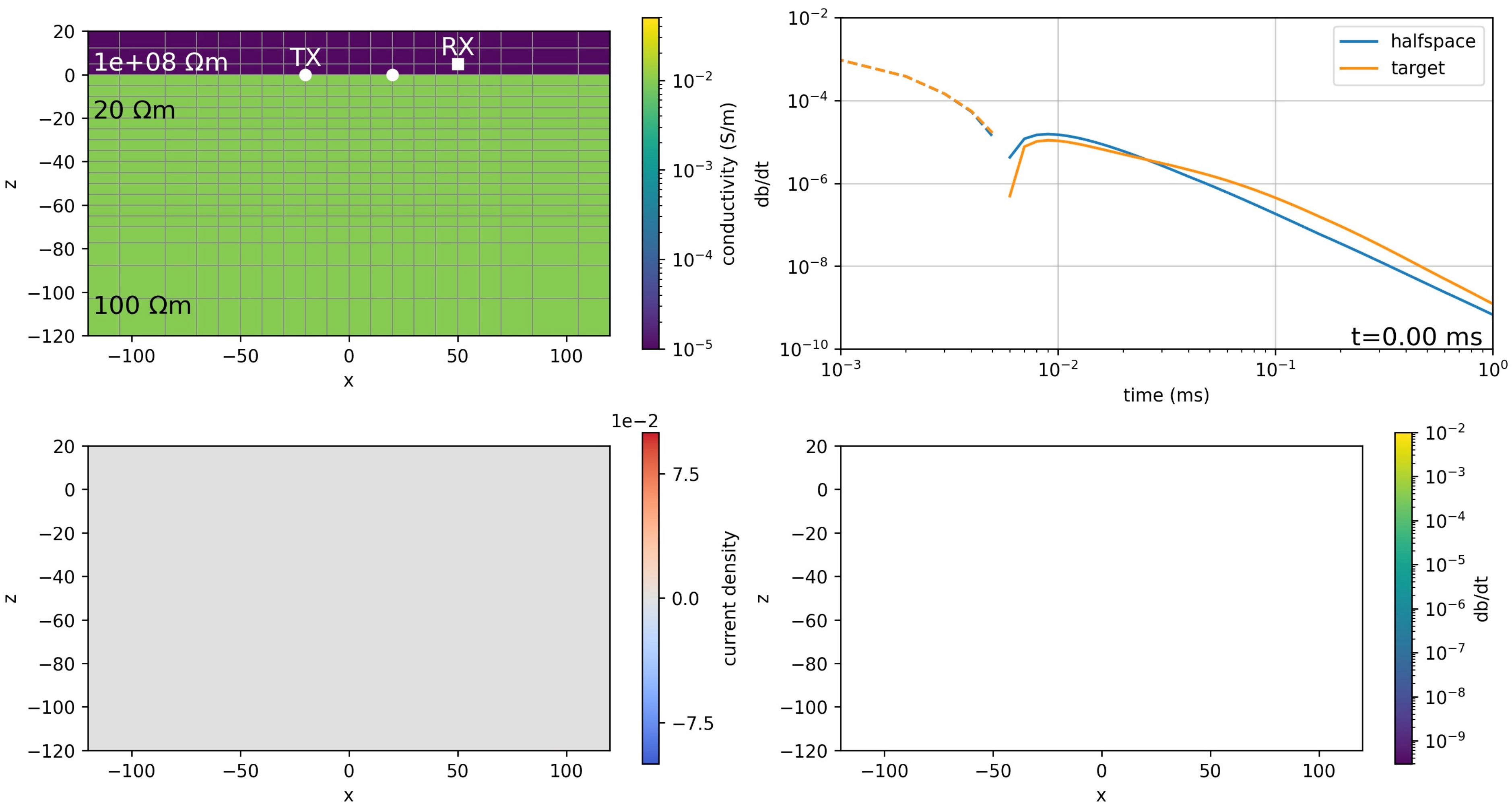
physical properties:

- supports anisotropic conductivity
- variable magnetic permeability
- IP parameters (1D fdem, tdem)

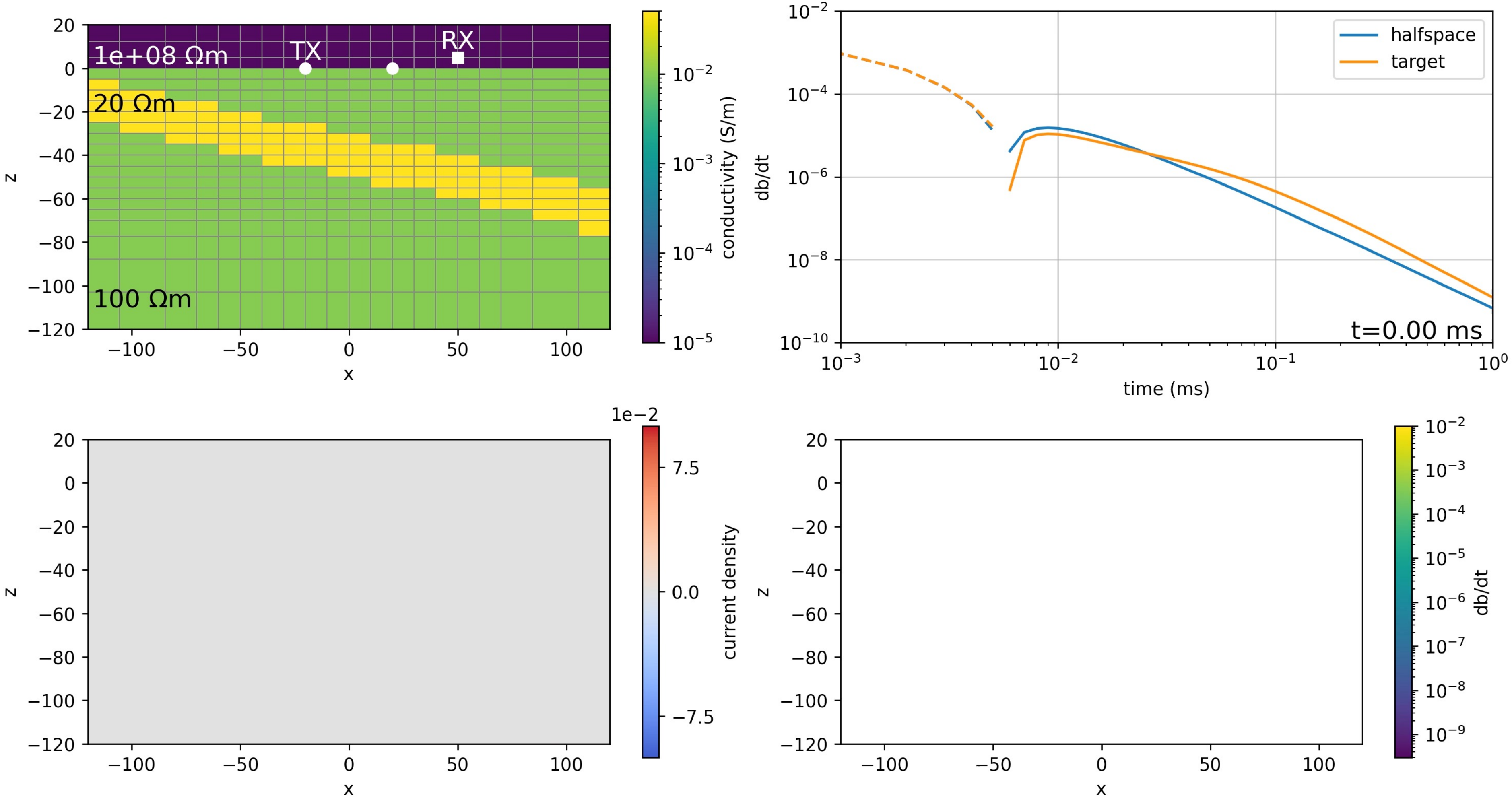
multiple formulations: E-B or H-J







1e+08 Ωm
TX
RX
20 Ωm
100 Ωm
z
x
conductivity (S/m)
halfspace
target
db/dt
time (ms)
t=0.00 ms
1e−2
current density
z
x
z
x
db/dt



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z
x
conductivity (S/m)
halfspace
target
db/dt
time (ms)
t=0.00 ms
1e−2
current density
z
x
db/dt

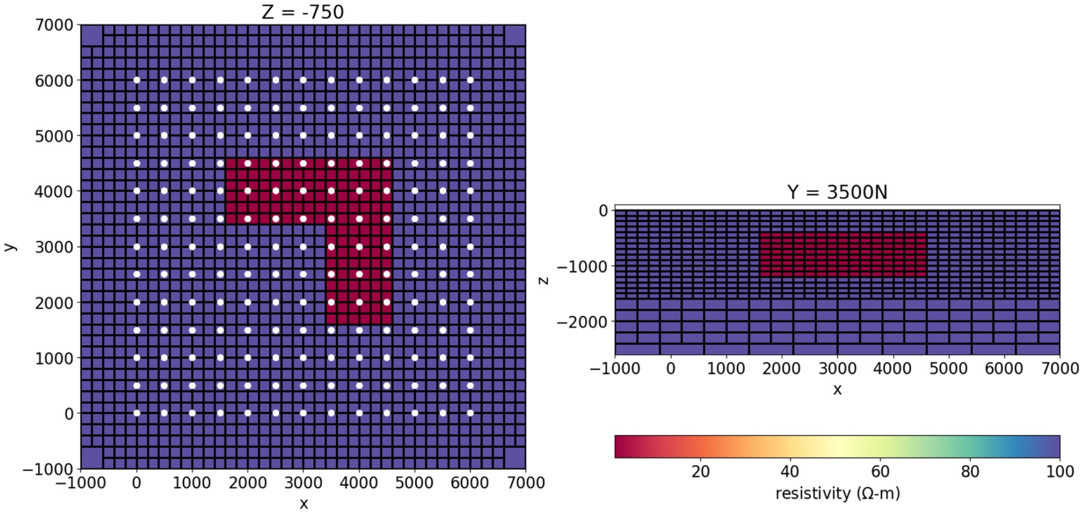
example: 3D simulation & inversion

model:

- conductive L-block (1 Ωm)
- half-space (100 Ωm)

survey:

- natural source EM
- frequencies: 10, 50, 200Hz
- data: ZTEM



simulation

model:

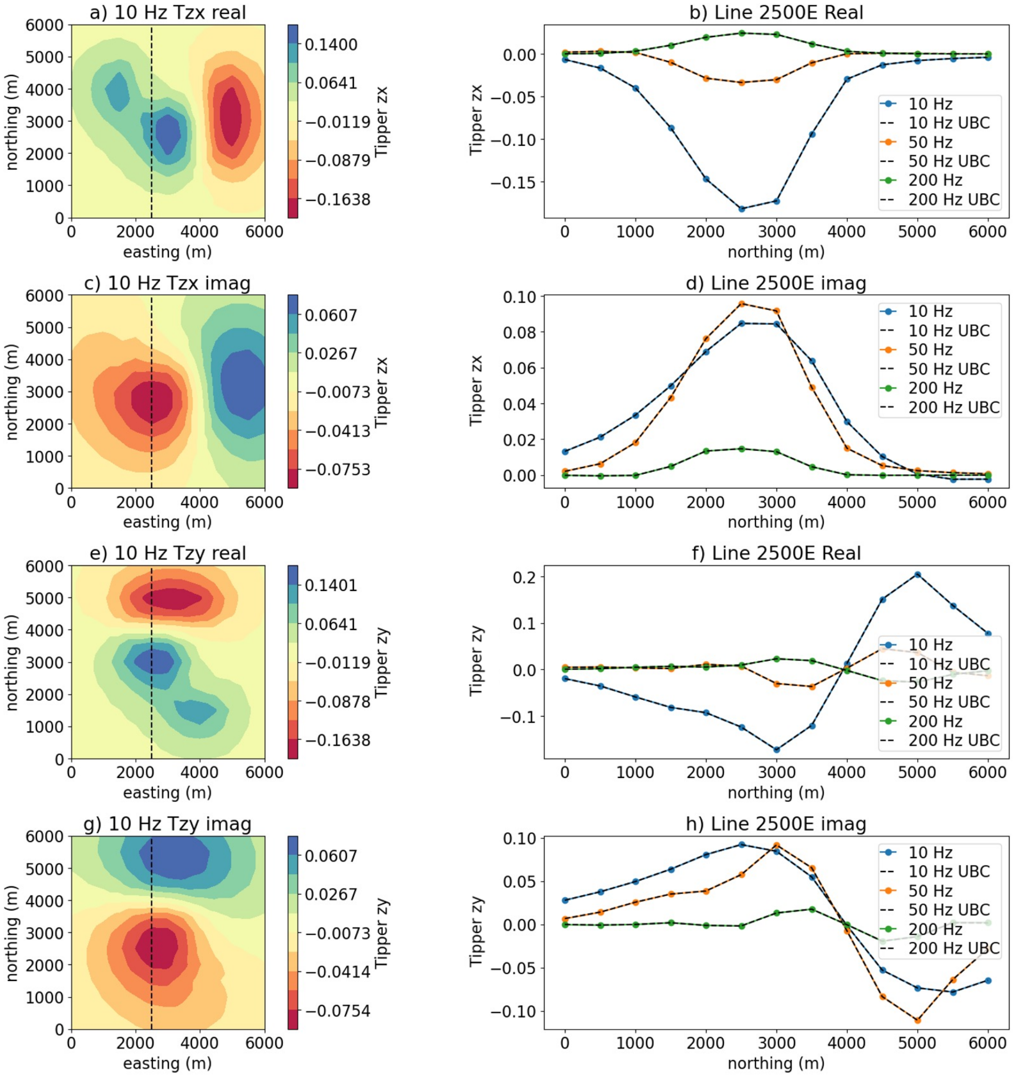
- conductive L-block (1 Ωm)
- half-space (100 Ωm)

survey:

- natural source EM
- frequencies: 10, 50, 200Hz
- data: ZTEM

simulation:

- OcTree mesh
- run SimPEG & UBC E3DMT



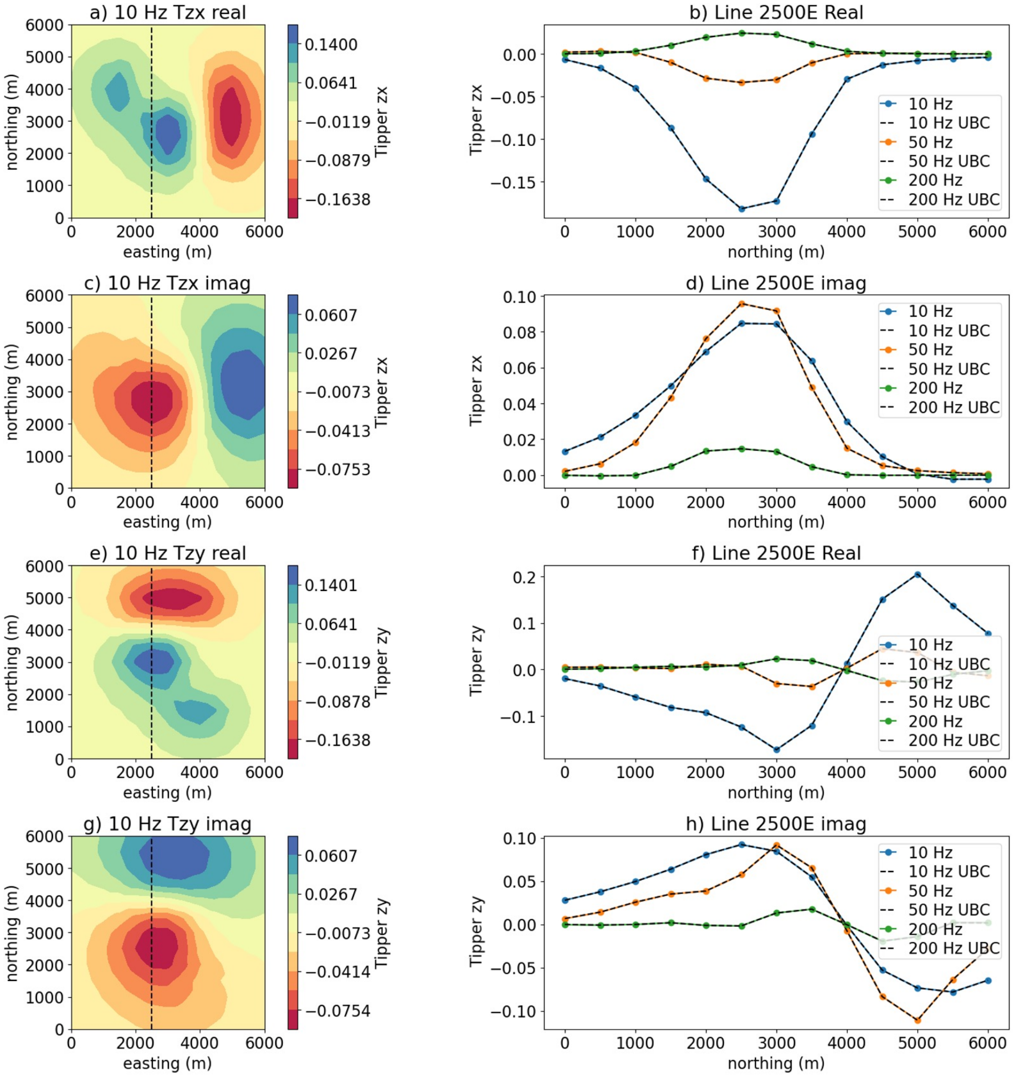
inversion

data

- 2028 data
- uncertainties:
  - 5% relative error
  - floor: 0.01 for 10 Hz, 50 Hz data, 0.005 for 200 Hz data

regularization

- L_2 smooth model
- identical beta-cooling schedule



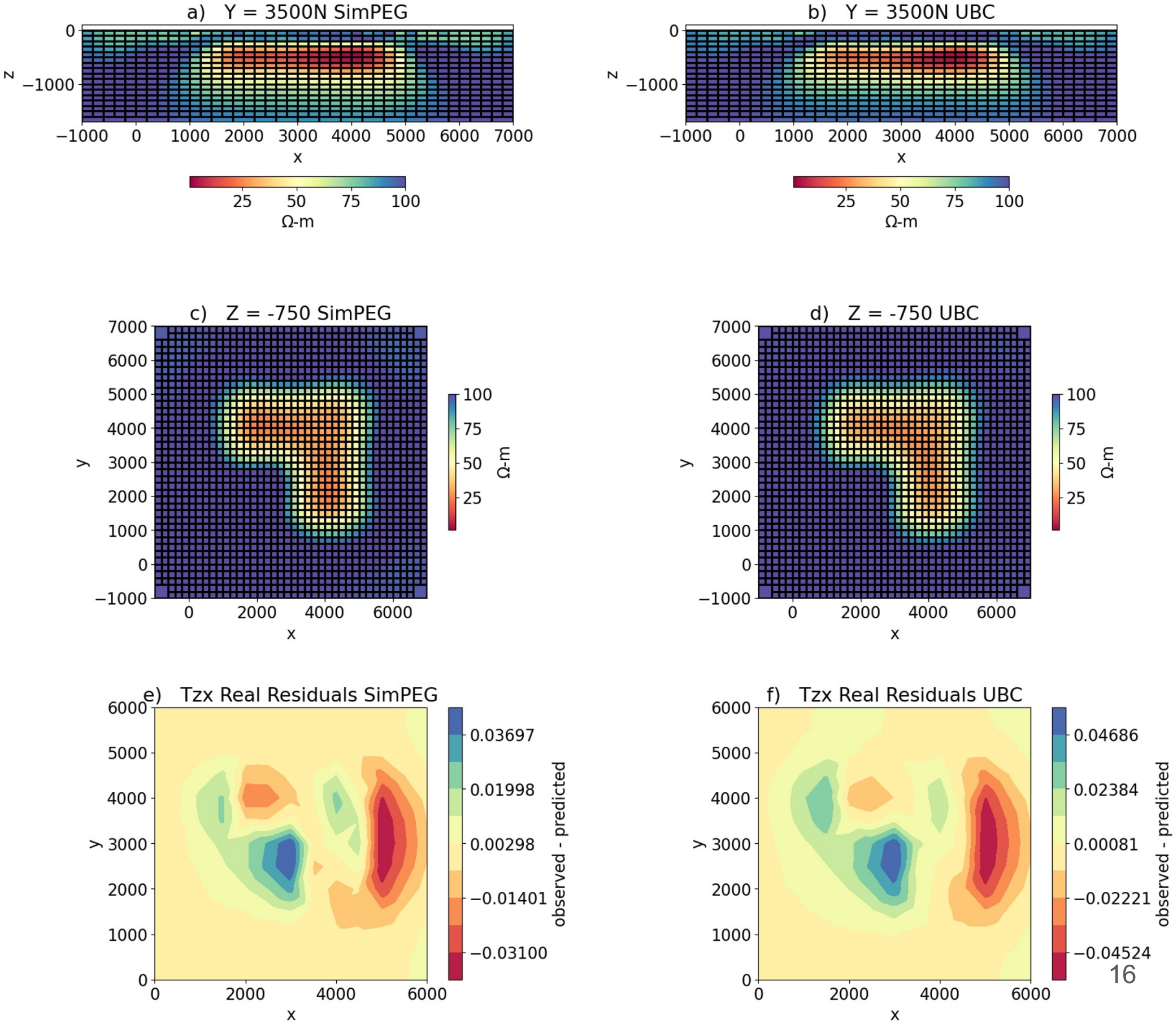
inversion

SimPEG

- 7 iterations
- final χ-factor of 0.47
- parallelized with Python multiprocessing
- runtime: 15 minutes

UBC E3DMT

- 8 iterations
- final χ-factor of 0.55
- parallelized with MPI
- runtime: 11 minutes



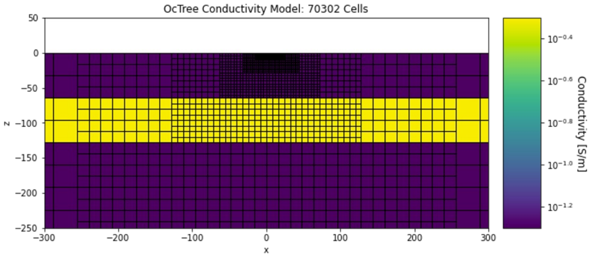
code validations

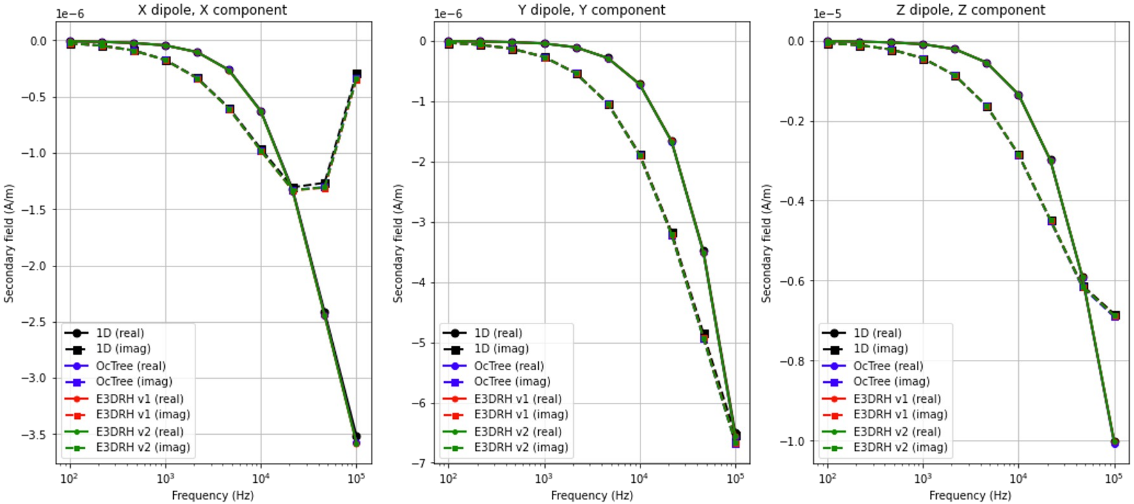
compare analytic, UBC Fortran, SimPEG

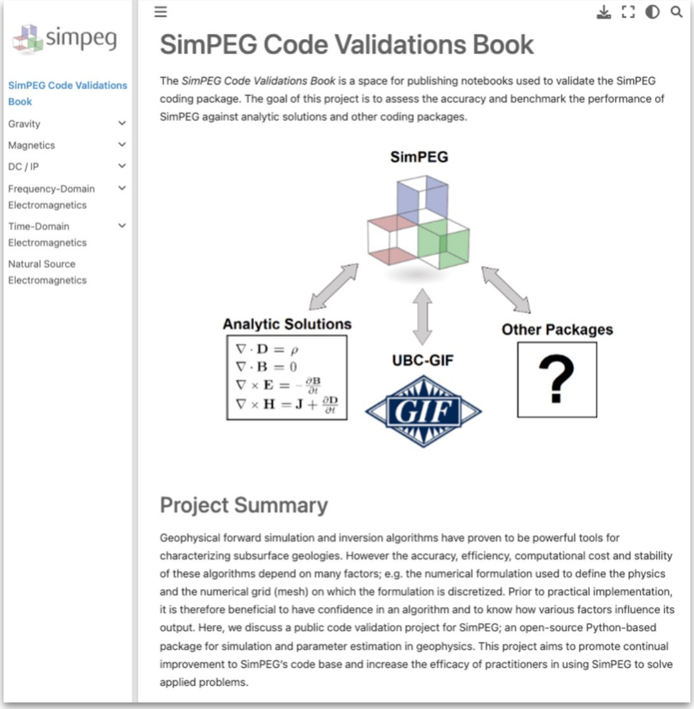
fdem dipole:

- z=5m
- separation: 10m

D. Cowan







simpeg.xyz/validations

example: AEM inversion with sparse norms

S. Kang

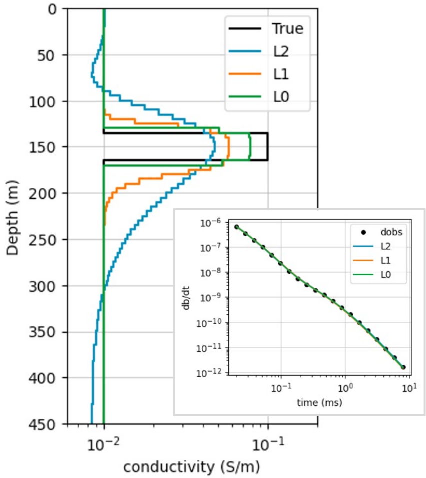
seawater intrusion: TDEM over Salinas Valley in 2017, 2019

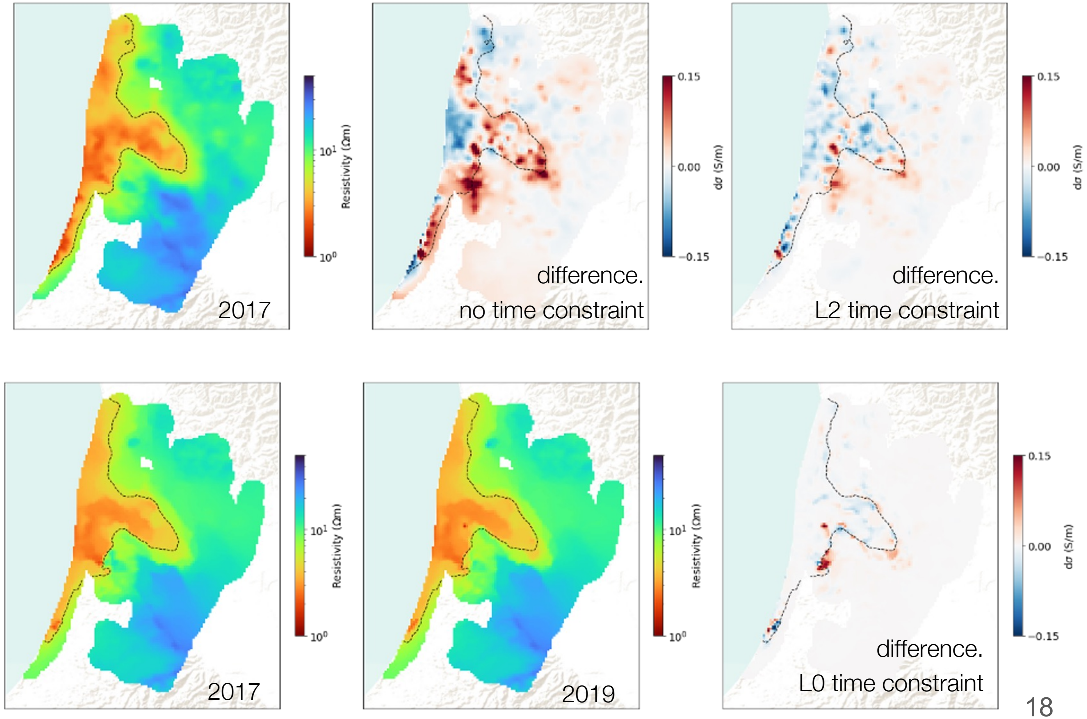
spatially constrained 1D inversions

- introduce time-constraint
- L_0 in space & time

$$\phi_m = \alpha_r \int_V \left|\frac{dm}{dr}\right|^{p_r} + \alpha_z \int_V \left|\frac{dm}{dz}\right|^{p_z} + \alpha_t \int_V \left|\frac{dm}{dt}\right|^{p_t}$$

lateral — vertical — time

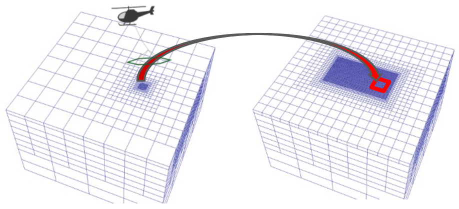




Kang & Knight, 2022; Kang BCGS talk 2022

electromagnetics: advanced capabilities

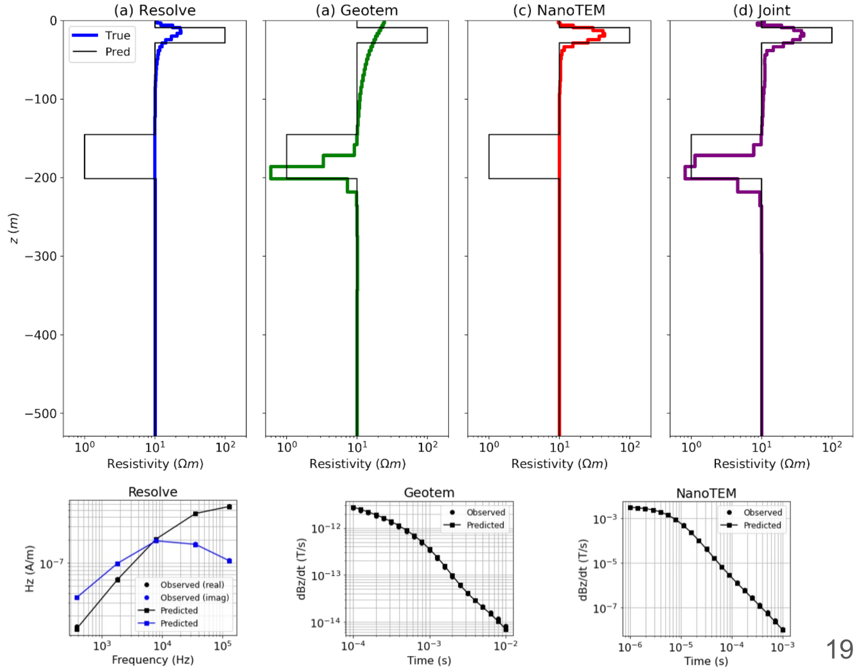
- Parallelization via domain decomposition



- Sparse / compact norms
- Parametric inversions
- Petrophysically & Geologically Guided Inversion (PGI)
- Joint inversions
    - same physical property
    - cross gradient, joint total variation, PGI

$$\phi(\mathbf{m}) = \underbrace{\phi_d^{\text{Resolve}} + \phi_d^{\text{Geotem}} + \phi_d^{\text{NanoTEM}}}_{\phi_d(\mathbf{m})} + \beta\phi_m(\mathbf{m})$$

```
phi_d = phi_d_resolve + phi_d_geotem + phi_d_nanotem
```



(Oldenburg et al, 2020)

now and the future

where we are…

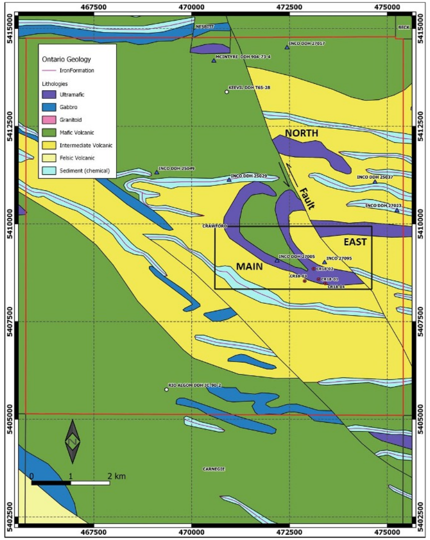
- 1D inversions: spatial constraints, sparse norms
- 3D inversions: fdem & nsem comparable to UBC fortran, tdem still some efficiency improvements
- joint inversions: cross-gradient, joint total variation, PGI

where we are going…

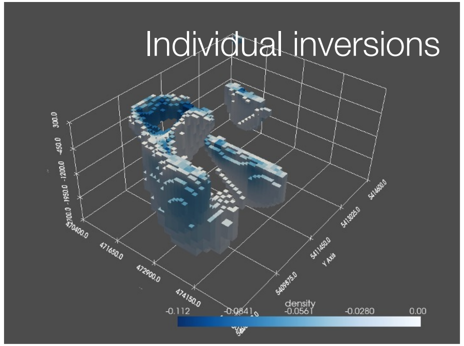
- tutorials, efficiency, simplifying code
- lots of research!

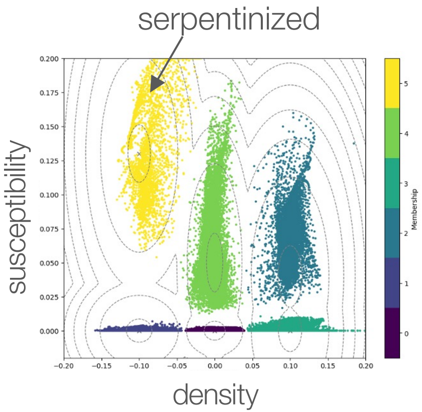
model

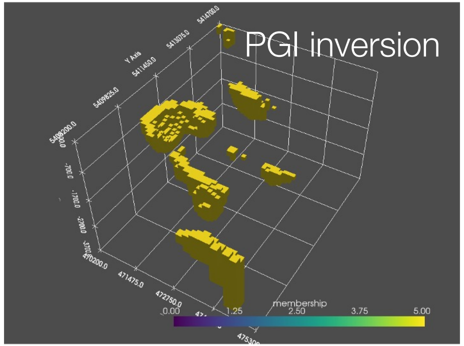
- research drives development
- partnerships with industry
- MIT license: use, adapt, commercialize



locating serpentinized rock: quasi-geology model from multiple geophysical data sets



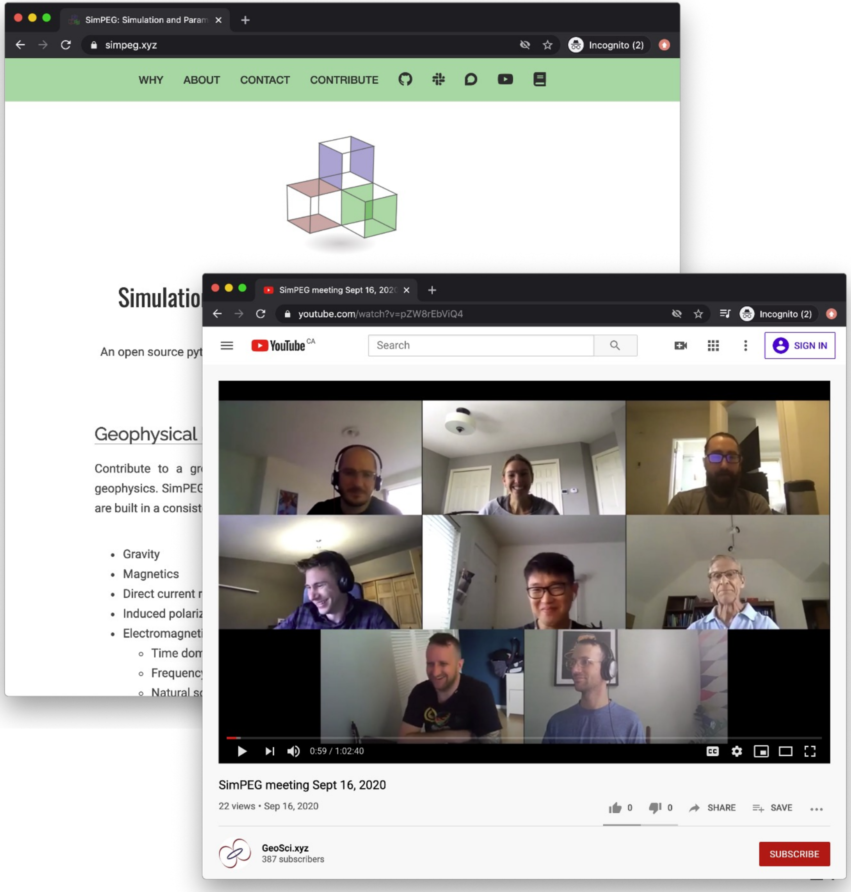




getting connected

```
conda install -c conda-forge simpeg
```

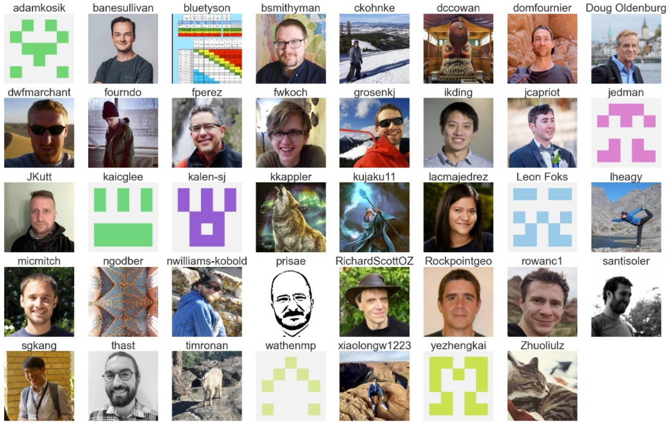
docs: docs.simpeg.xyz
newsletter: newsletter.simpeg.xyz
slack group: slack.simpeg.xyz



thank you!

email: lheagy@eoas.ubc.ca

slides: bit.ly/heagy-2023-aem



… and join us at 3DEM-7

https://3dem-7.geosci.xyz