

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

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¹University of British Columbia Geophysical Inversion Facility

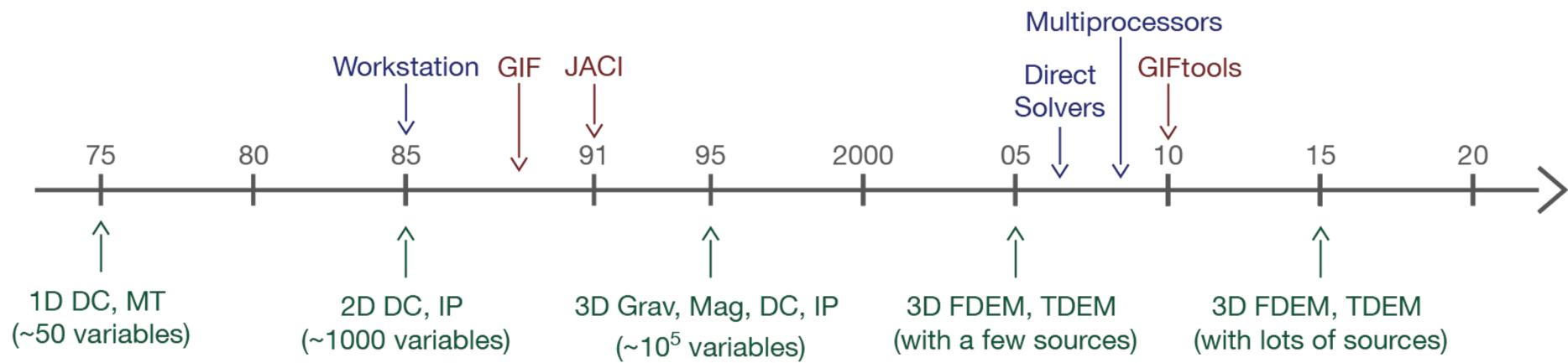
²Colorado School of Mines

³Stanford Geophysics

⁴Mira Geoscience

some background: UBC-GIF

GIF Fortran Codes & GIF Tools



some background: UBC-GIF

Transition to open-source

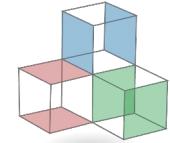
By 2010's...

most forward simulations “solved”

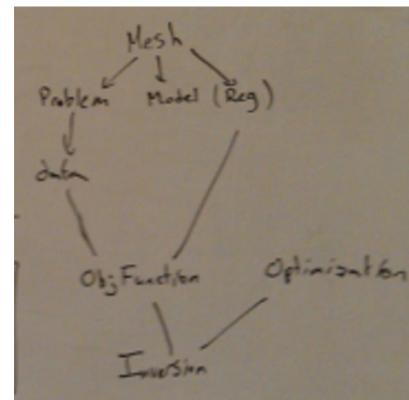
next generation of research in inversions

- 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

Archa Rowan B. Cockett

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

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Doctor of Philosophy

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL
STUDIES
(Geophysics)

The University of British Columbia
(Vancouver)

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simpeg

simulation and parameter estimation in geophysics

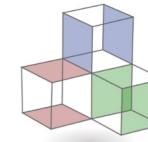
common framework for simulations & inversions

accelerate research: build upon others work

facilitate reproducibility of results

build & deploy in python

open-source



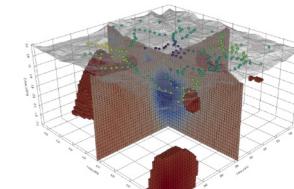
Simulation and Parameter Estimation in Geophysics

An open source python package for simulation and gradient based parameter estimation in geophysical applications.

Geophysical Methods

Contribute to a growing community of geoscientists building an open foundation for geophysics. SimPEG provides a collection of geophysical simulation and inversion tools that are built in a consistent framework.

- Gravity
- Magnetics
- Direct current resistivity
- Induced polarization
- Electromagnetics
 - Time domain
 - Frequency domain
 - Natural source (e.g. Magnetotellurics)
 - Viscous remanent magnetization
- Richards Equation



what simpeg solves

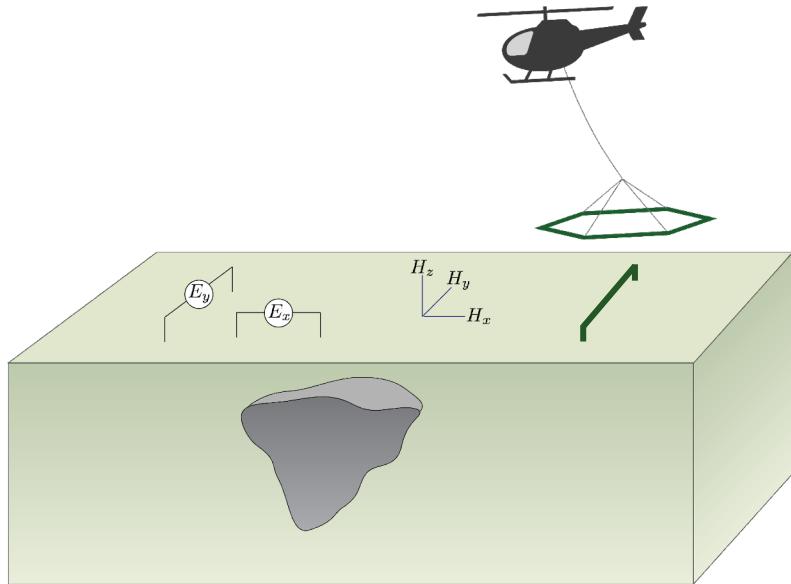
Given

- observations: d_j^{obs} , $j = 1, \dots, N$
- 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

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

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

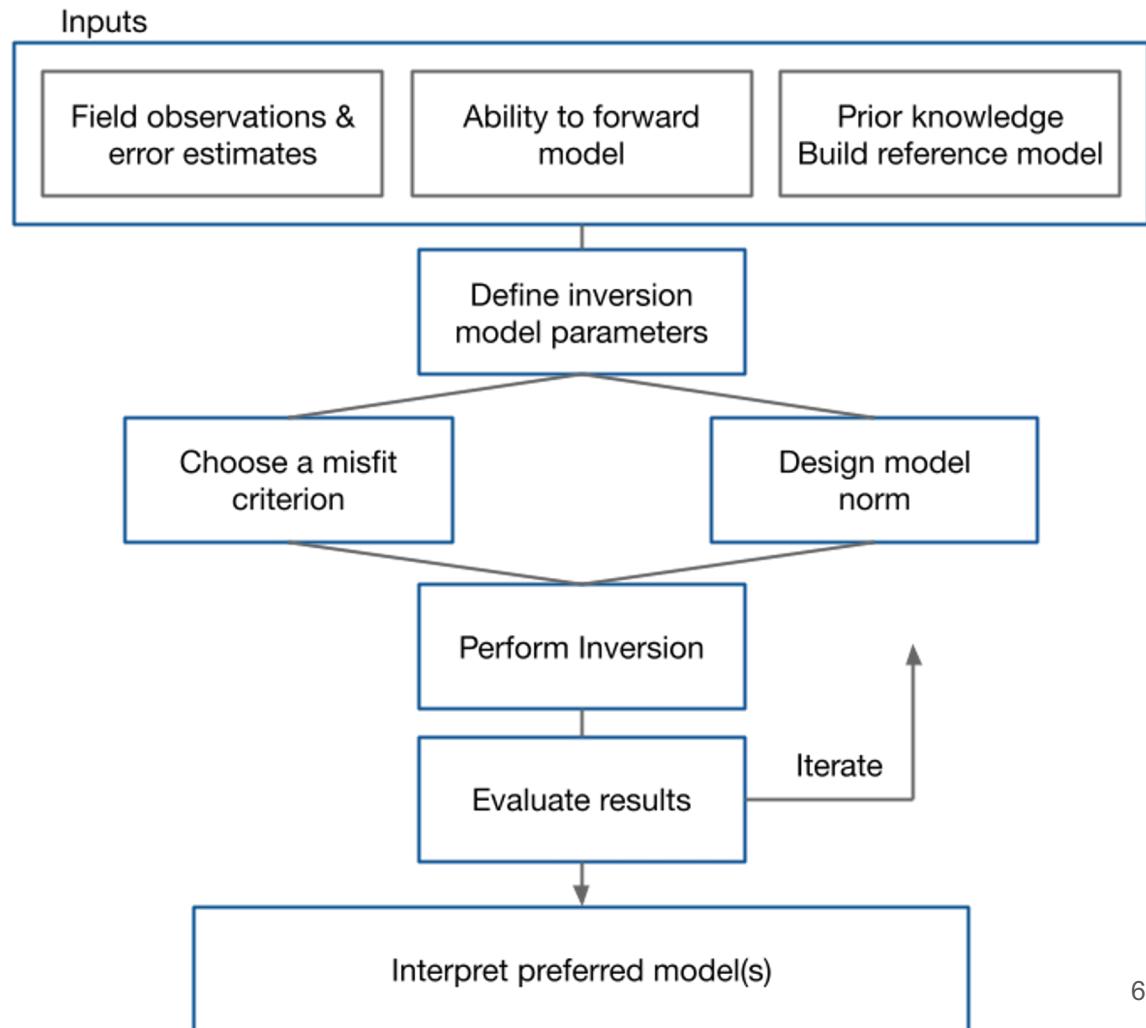


flow chart for the inverse problem

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

* Solve with sources and boundary conditions

electromagnetics: frequency domain equations

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

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

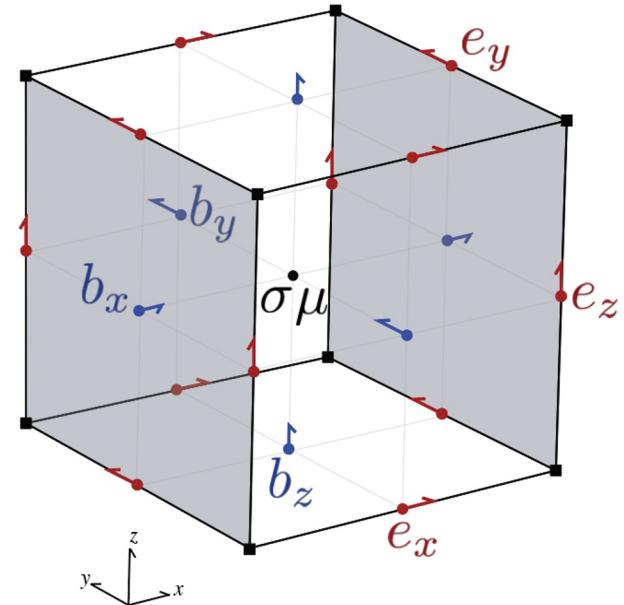
$$\nabla \times \mu^{-1} \vec{B} - \sigma \vec{E} = \vec{J}_s$$

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

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

$$\mathbf{Ce} + i\omega \mathbf{b} = 0$$

$$\mathbf{C}^T \mathbf{M}_{\mu^{-1}}^f \mathbf{b} - \mathbf{M}_\sigma^e \mathbf{e} = \mathbf{M}^e \mathbf{j}_s$$

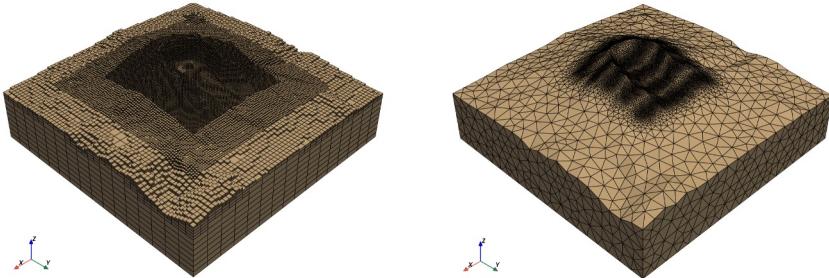


Solving an FDEM problem

Mesh types:

- Tensor
- OcTree
- Curvilinear
- Tetrahedral

$$\underbrace{(\mathbf{C}^T \mathbf{M}_{\mu^{-1}}^f \mathbf{C} + i\omega \mathbf{M}_\sigma^e)}_{\mathbf{A}(\sigma, \omega)} \underbrace{\mathbf{e}}_{\mathbf{u}} = \underbrace{-i\omega \mathbf{M}^e \mathbf{j}_s}_{\mathbf{q}(\omega)}$$



J. Capriotti

```
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
```

```
from SimPEG import electromagnetics
```

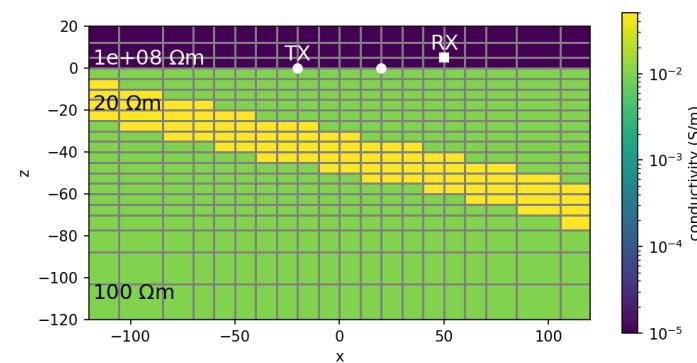
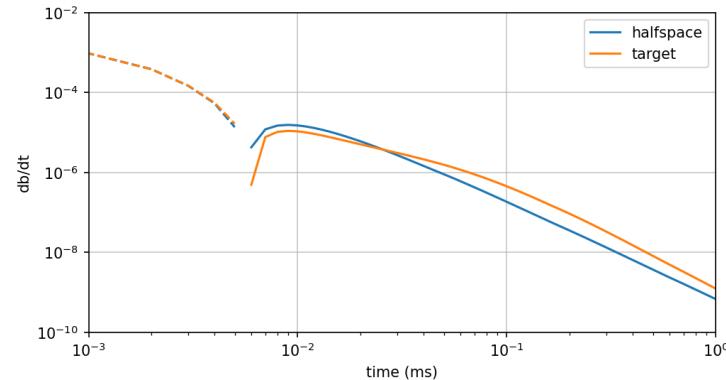
modules:

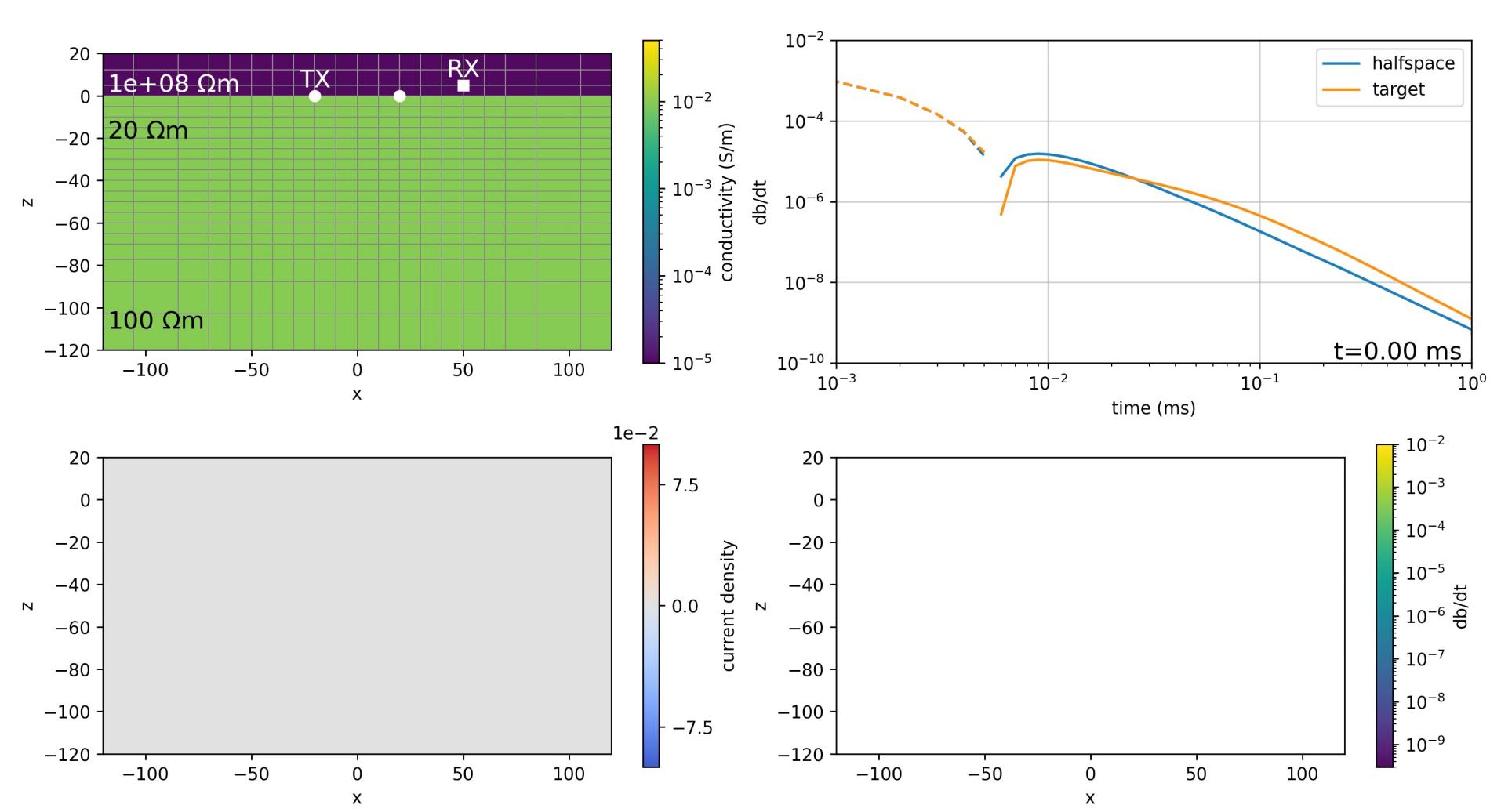
- frequency domain
- natural sources
- time domain

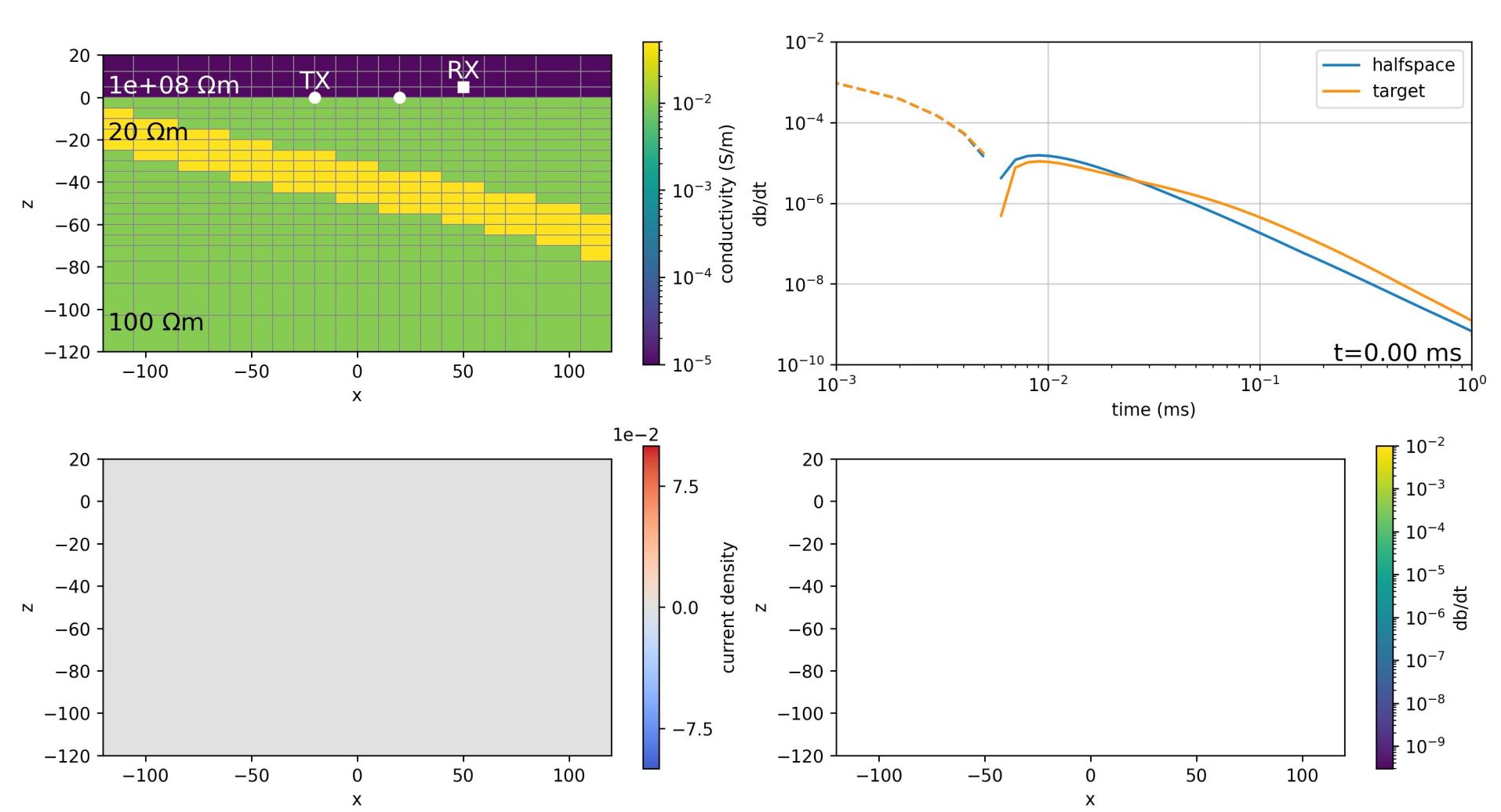
physical properties:

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

multiple formulations: E-B or H-J







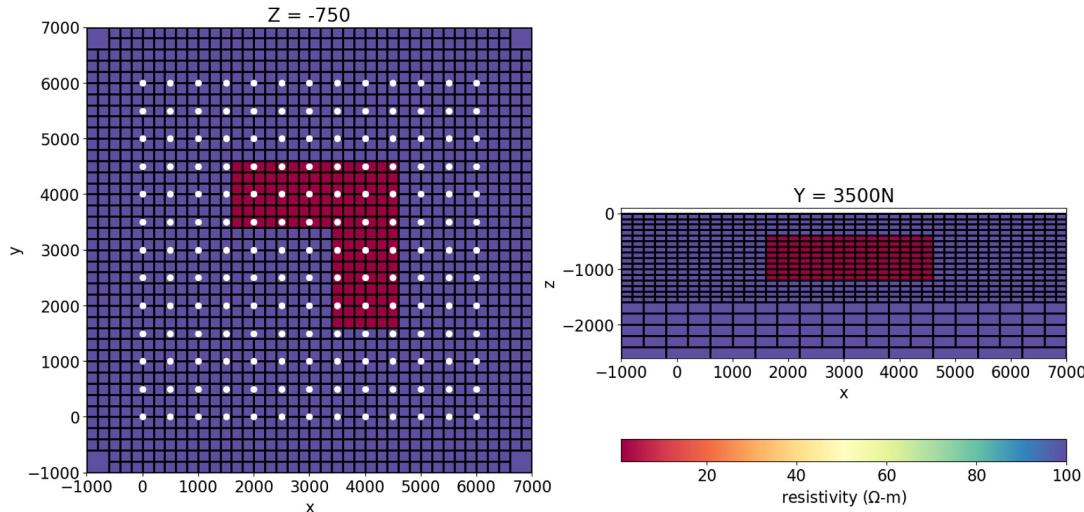
example: 3D simulation & inversion

model:

- conductive L-block ($1 \Omega\text{m}$)
- half-space ($100 \Omega\text{m}$)

survey:

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



simulation

model:

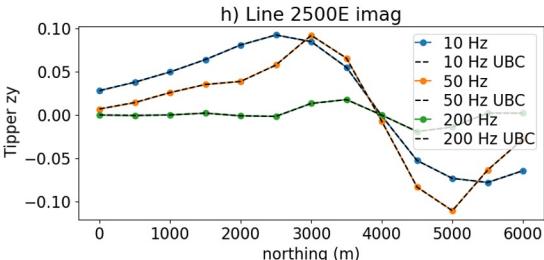
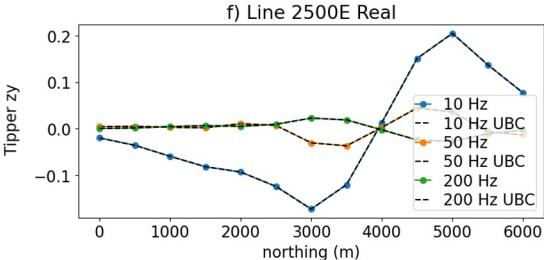
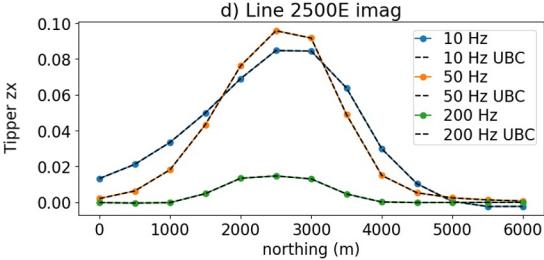
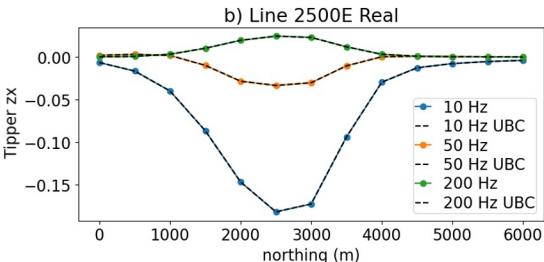
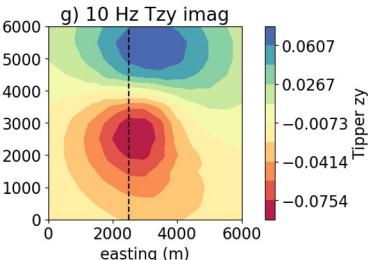
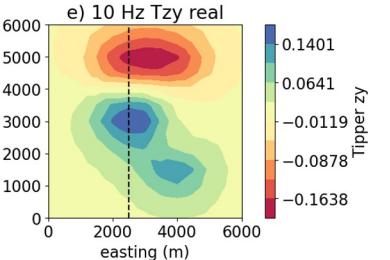
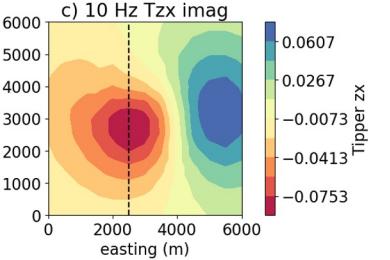
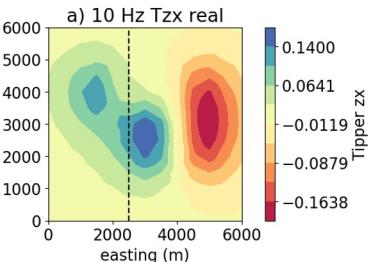
- conductive L-block ($1 \Omega\text{m}$)
- half-space ($100 \Omega\text{m}$)

survey:

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

simulation:

- OcTree mesh
- run SimPEG & UBC E3DMT



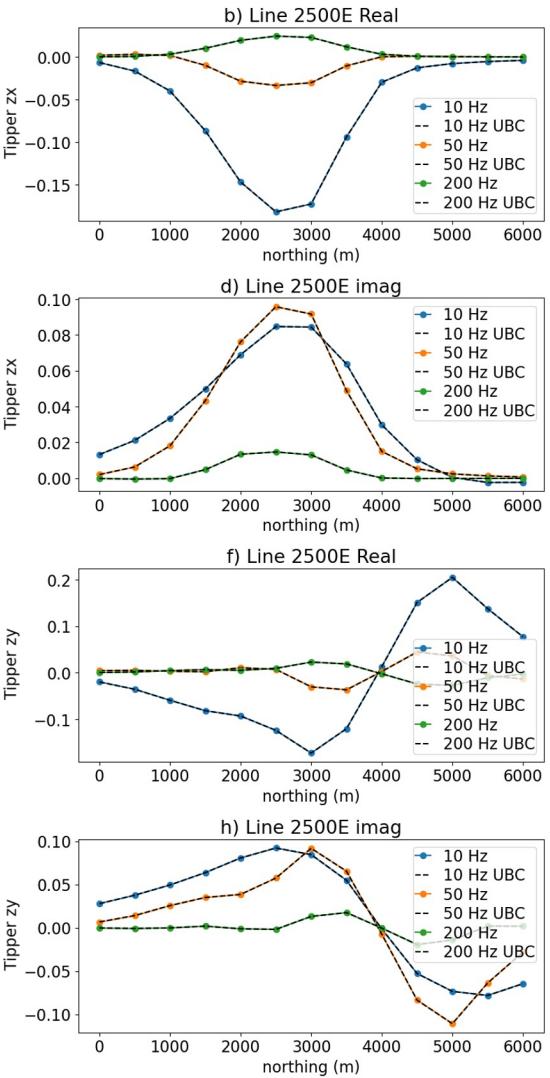
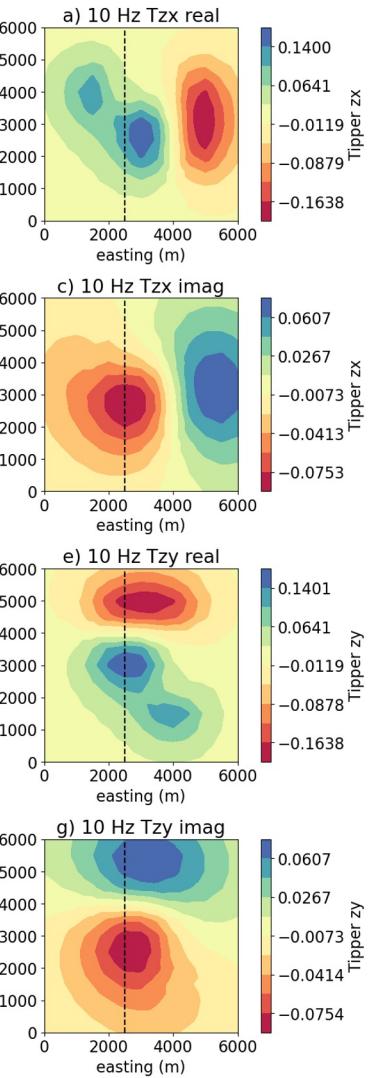
inversion

data

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

regularization

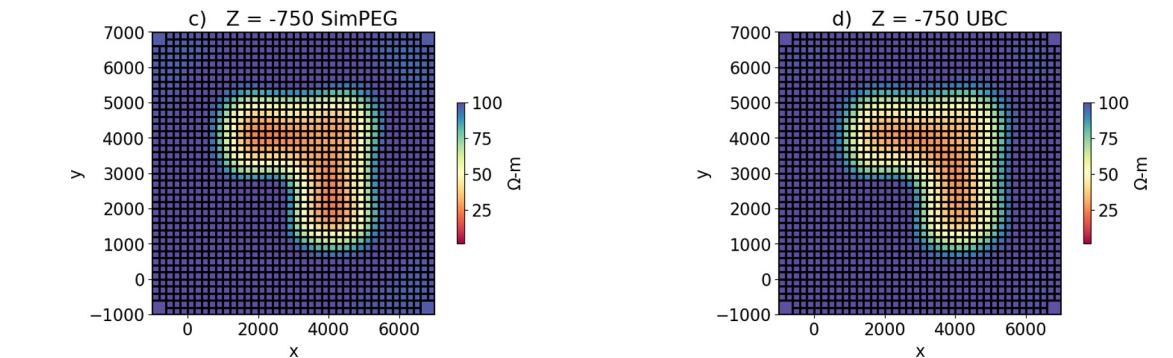
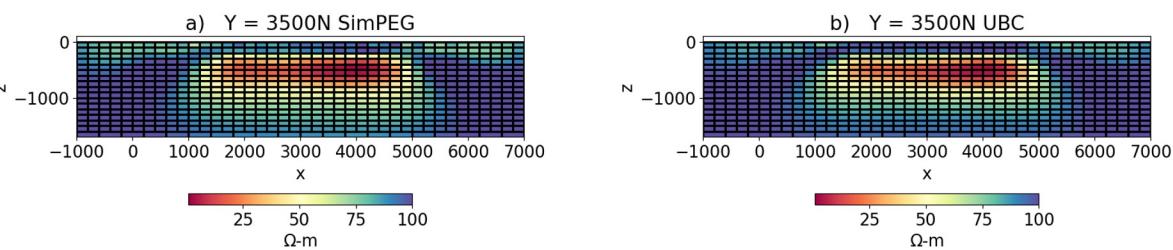
- L_2 smooth model
- identical beta-cooling schedule



inversion

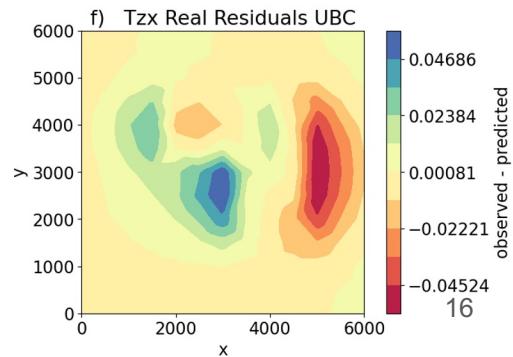
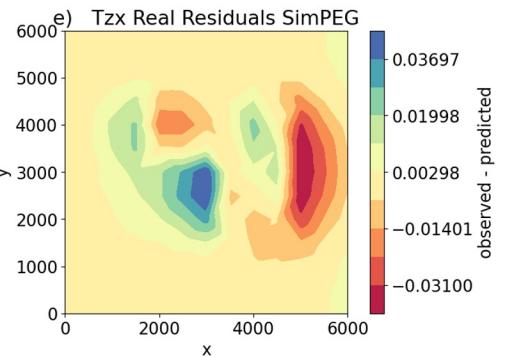
SimPEG

- 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

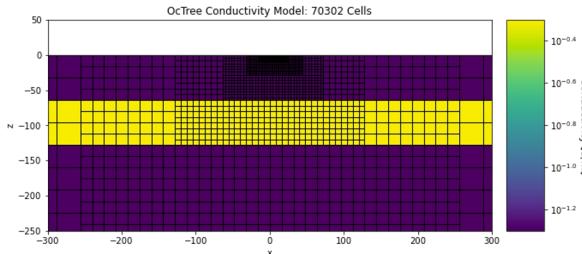
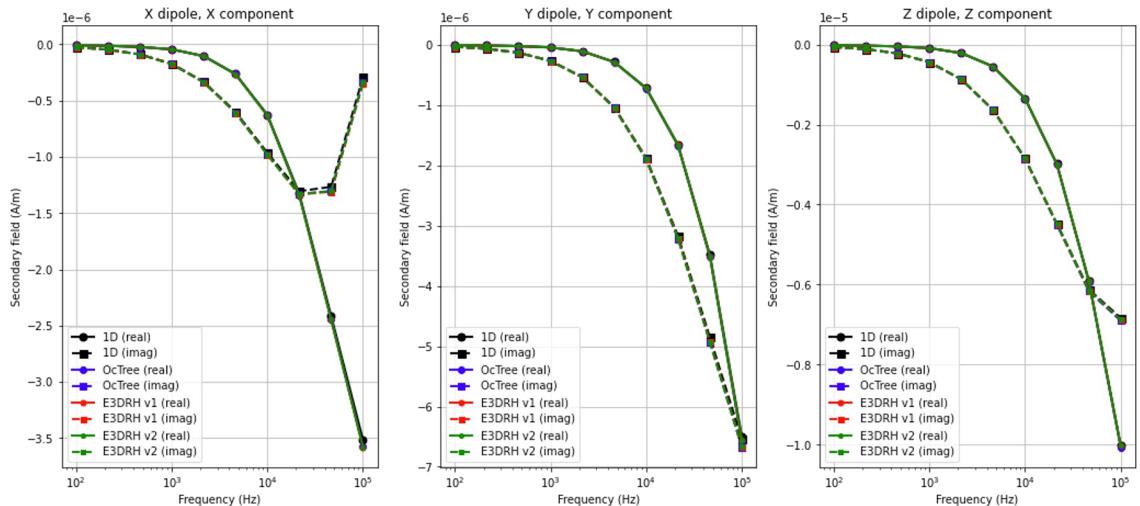


code validations

compare analytic, UBC Fortran, SimPEG

fDEM dipole:

- $z=5\text{m}$
- separation: 10m



The interface for the "SimPEG Code Validations Book" is shown. It features a sidebar with navigation links for "SimPEG Code Validations Book", "Gravity", "Magnetics", "DC / IP", "Frequency-Domain Electromagnetics", "Time-Domain Electromagnetics", and "Natural Source Electromagnetics". The main content area displays the "SimPEG Code Validations Book" logo and the title "SimPEG Code Validations Book". Below the title, it states: "The SimPEG Code Validations Book is a space for publishing notebooks used to validate the SimPEG coding package. The goal of this project is to assess the accuracy and benchmark the performance of SimPEG against analytic solutions and other coding packages." To the right, there is a diagram illustrating the validation process: "SimPEG" is at the top, connected by double-headed arrows to "Analytic Solutions" (containing equations for $\nabla \cdot \mathbf{D} = \rho$, $\nabla \cdot \mathbf{B} = 0$, $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$, and $\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$) and "Other Packages" (represented by a question mark icon). In the center, "UBC-GIF" is shown with its logo, indicating its role in the validation process.

Project Summary

Geophysical forward simulation and inversion algorithms have proven to be powerful tools for characterizing subsurface geologies. However, the accuracy, efficiency, computational cost and stability of these algorithms depend on many factors; e.g. the numerical formulation used to define the physics and the numerical grid (mesh) on which the formulation is discretized. Prior to practical implementation, it is therefore beneficial to have confidence in an algorithm and to know how various factors influence its output. Here, we discuss a public code validation project for SimPEG, an open-source Python-based package for simulation and parameter estimation in geophysics. This project aims to promote continual improvement to SimPEG's code base and increase the efficacy of practitioners in using SimPEG to solve applied problems.

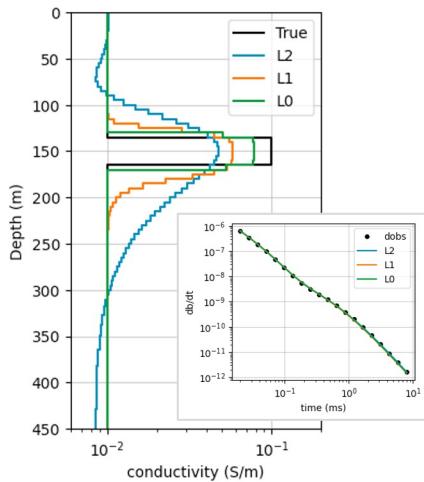


example: AEM inversion with sparse norms

seawater intrusion: TDEM over Salinas Valley in 2017, 2019

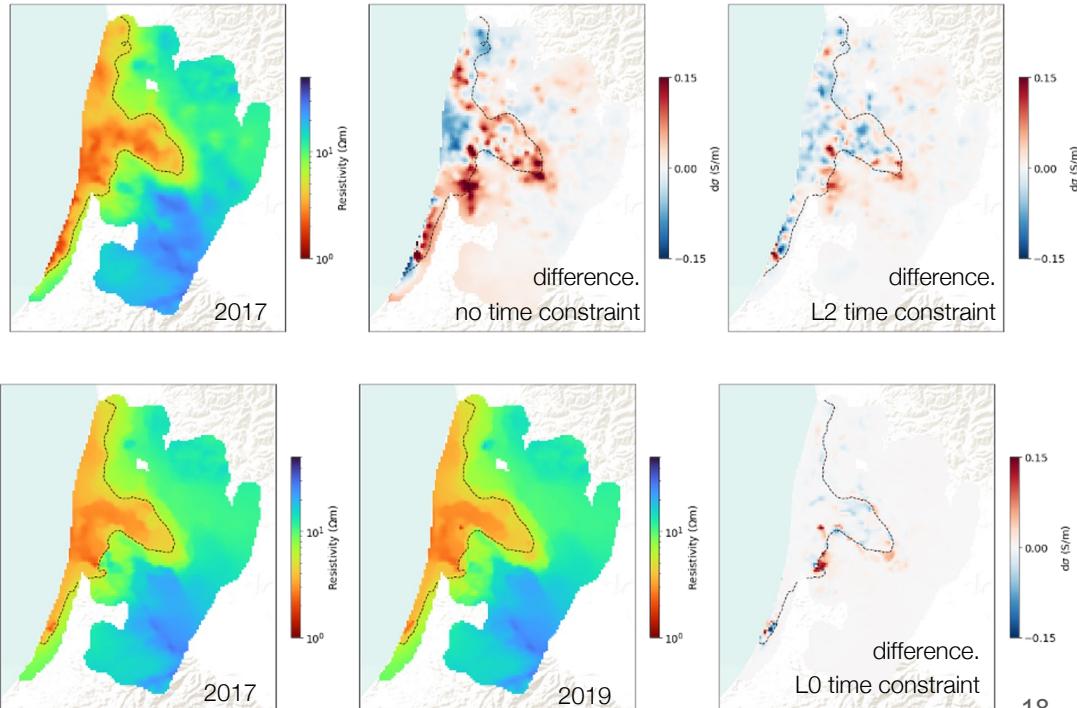
spatially constrained 1D inversions

- introduce time-constraint
- L_0 in space & time



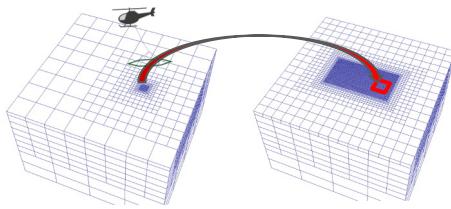
$$\phi_m = \alpha_r \int_V \left| \frac{dm}{dr} \right|^{p_r} + \alpha_z \int_V \left| \frac{dm}{dz} \right|^{p_z} + \alpha_t \int_V \left| \frac{dm}{dt} \right|^{p_t}$$

lateral vertical time



electromagnetics: advanced capabilities

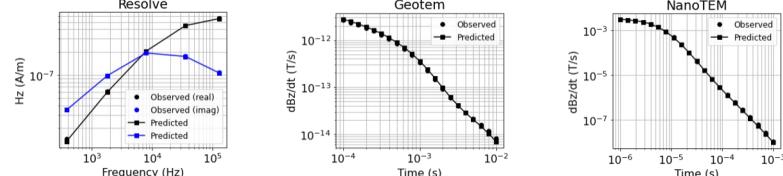
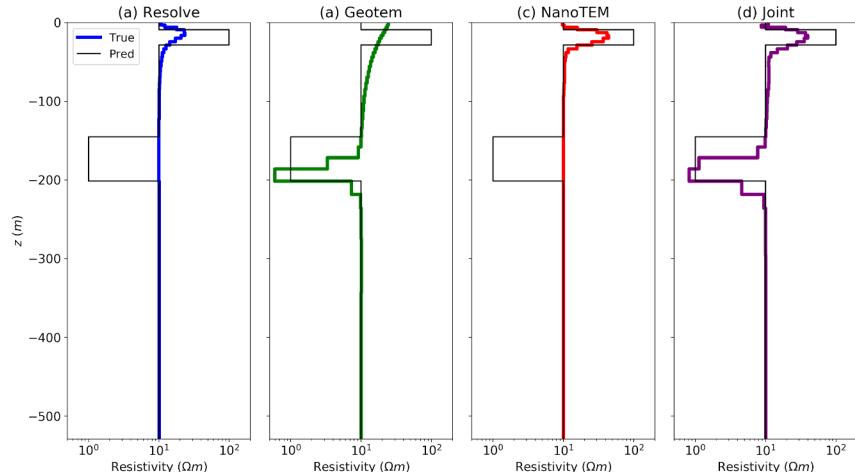
- Parallelization via domain decomposition



- 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`



now and the future

where we are...

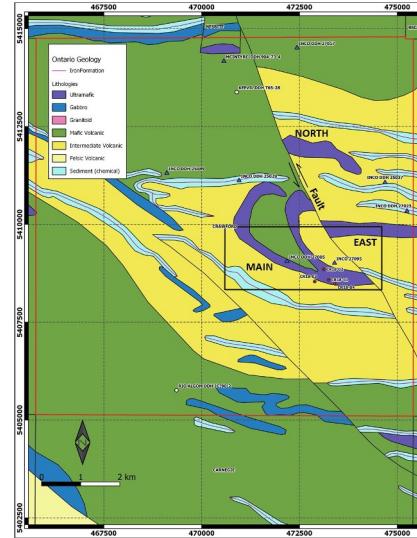
- 1D inversions: spatial constraints, sparse norms
- 3D inversions: fdem & nsem comparable to UBC fortran, tdem still some efficiency improvements
- joint inversions: cross-gradient, joint total variation, PGI

where we are going...

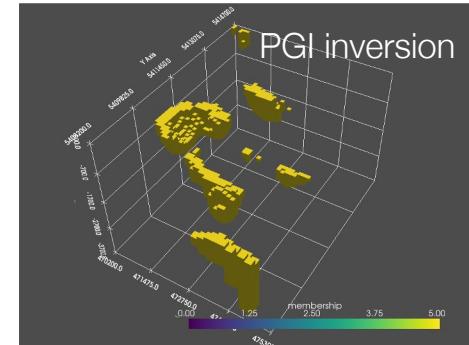
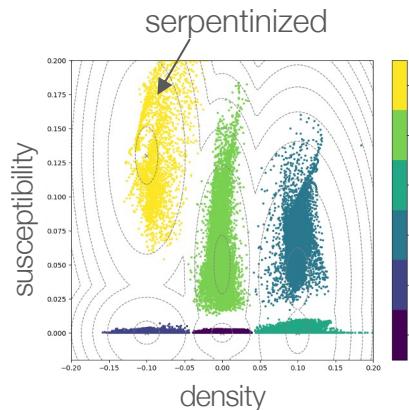
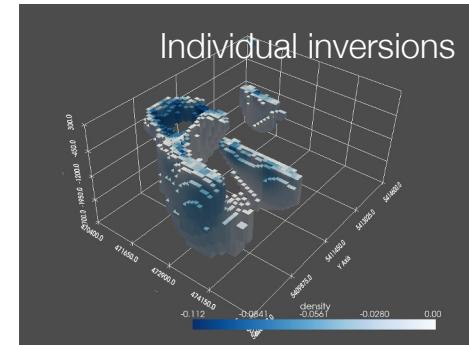
- tutorials, efficiency, simplifying code
- lots of research!

model

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



locating serpentized 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

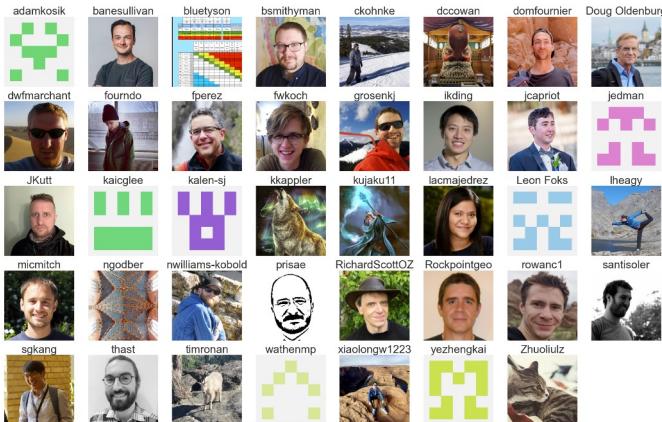
slack group: slack.simpeg.xyz

The image displays two screenshots side-by-side. On the left is a screenshot of the SimPEG website at simpeg.xyz. The page has a green header with links for WHY, ABOUT, CONTACT, CONTRIBUTE, and other site navigation. Below the header is a large image of a 3D cube composed of colored faces (purple, blue, green, red). To the right is a screenshot of a YouTube video titled "SimPEG meeting Sept 16, 2020". The video player shows a grid of nine video feeds of people in a meeting. The video controls at the bottom indicate it's at 0:59 of a 1:02:40 duration. The YouTube interface includes a search bar, a sign-in button, and social sharing icons.

thank you!

email: lheagy@eoas.ubc.ca

slides: bit.ly/heagy-2023-aem



... and join us at 3DEM-7

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

3DEM

The 7th International Symposium on Three-Dimensional Electromagnetics

Nov 13 - 15, 2023
Vancouver, BC

The AEM2023 logo features a photograph of a tropical beach with clear blue water and white sand. Overlaid on the top left is the text "AEM2023" in a large, bold, white font. Below it, smaller text reads "8th International Airborne Electromagnetics Workshop", "3-7 September 2023", "Fitzroy Island, QLD, Australia", and "Contact: semconference@theassociationspecialists.com.au". At the bottom right, there is a circular logo for "HOSTED BY Australian Society of Exploration Geophysicists".

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