electromagnetic geophysics across the scales

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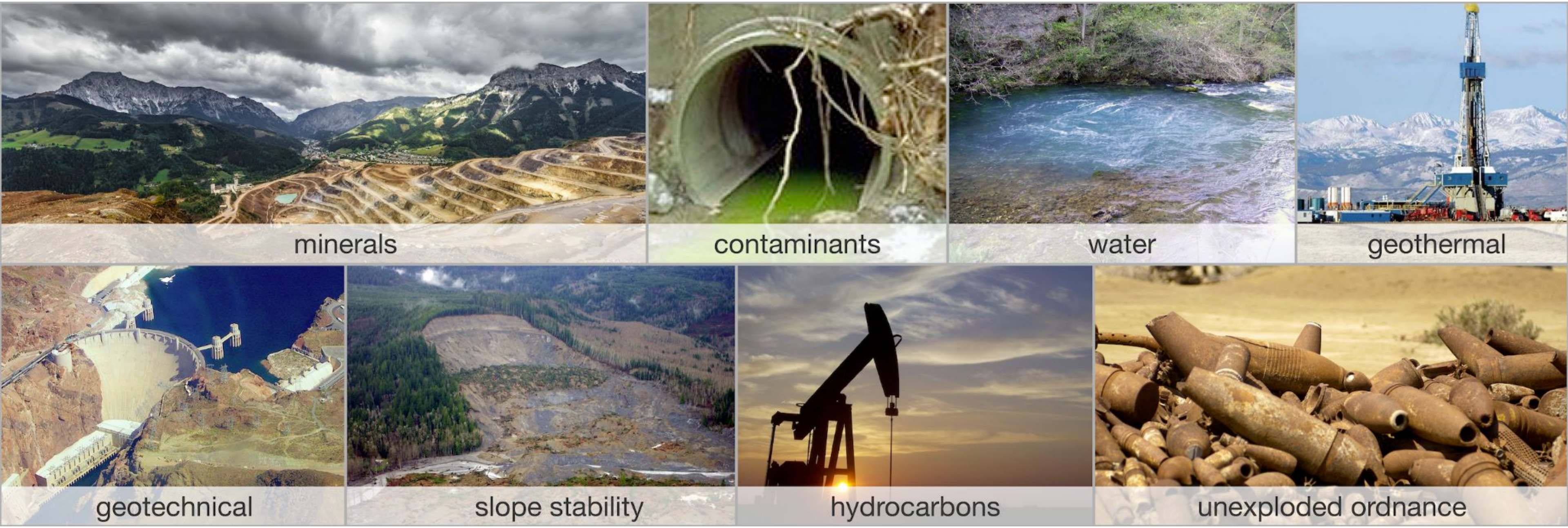
some important problems



have in common: electrical conductivity can be a diagnostic physical property

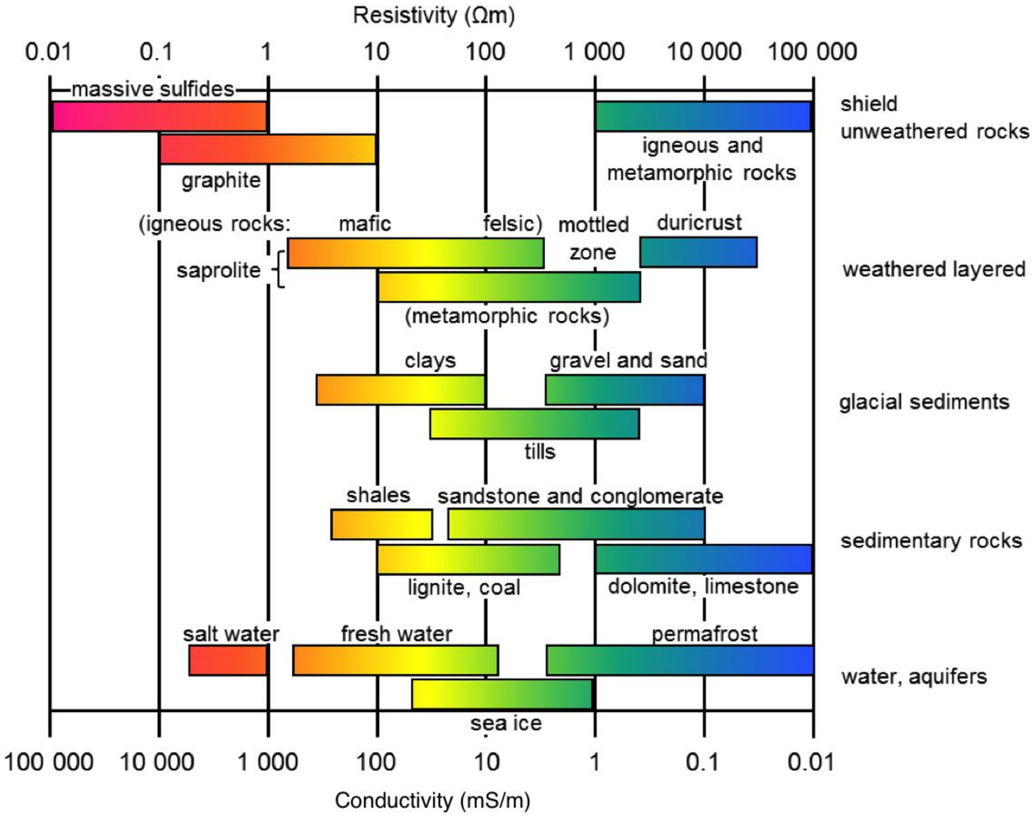
electrical conductivity / resistivity

A measure of how easily current passes through a material

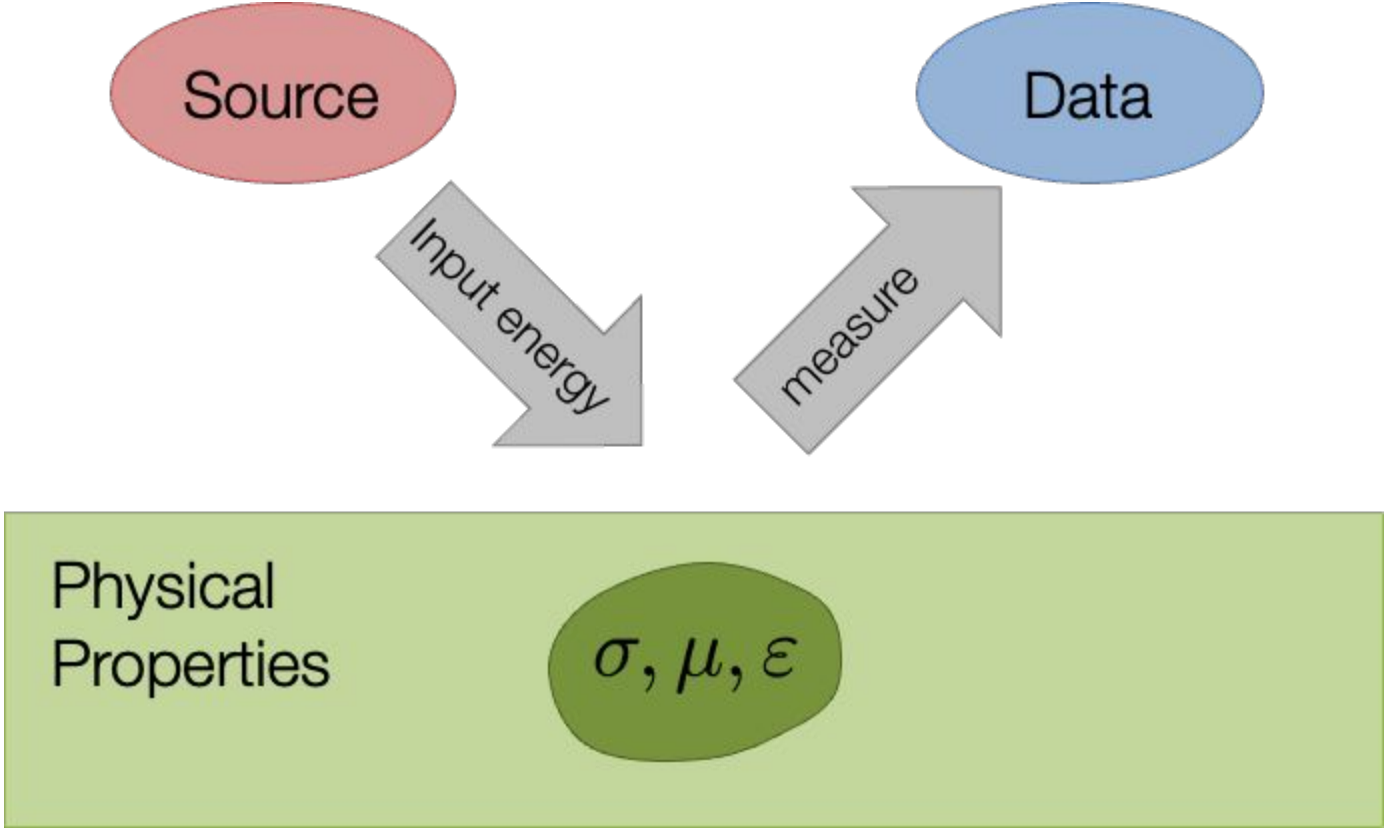
- σ: conductivity [S/m]
- ρ: resistivity [Ωm]
- $\rho = 1/\sigma$

Depends on many factors

- Mineralogy
- Porosity
- Permeability
- Nature of pore fluid



geophysical experiments & physical properties



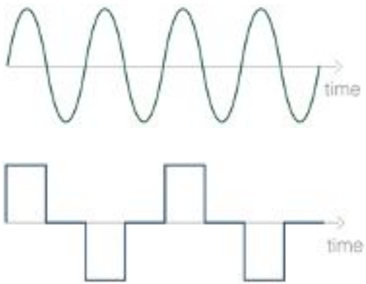
electromagnetic experiments

Sources:

- grounded or inductive
- controlled or natural

Waveform

- harmonic (FDEM)
- transient (TDEM)

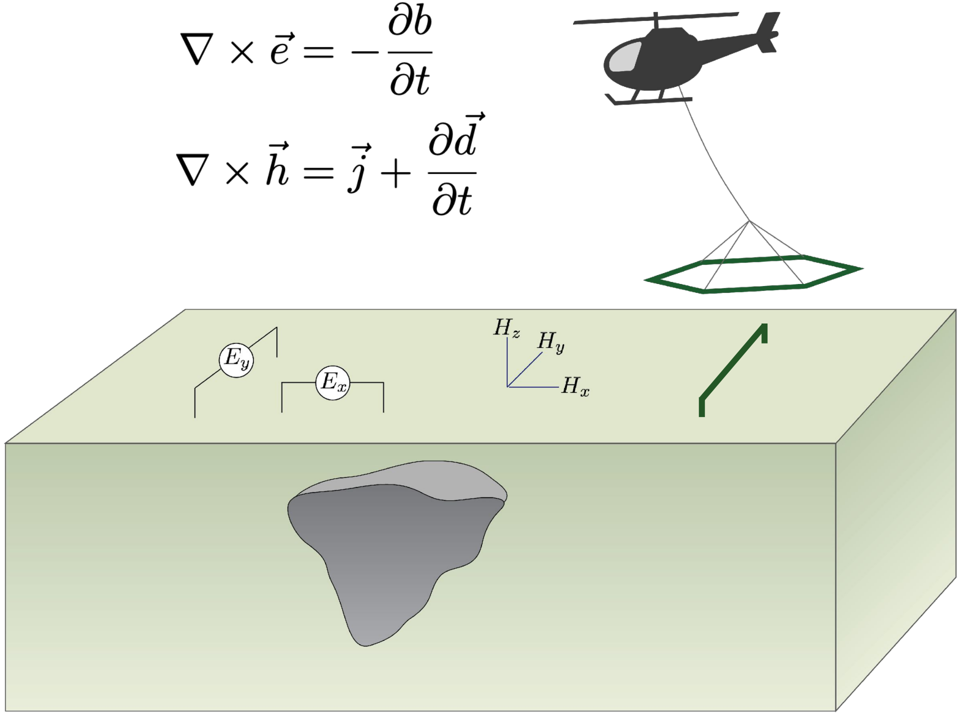


Survey location

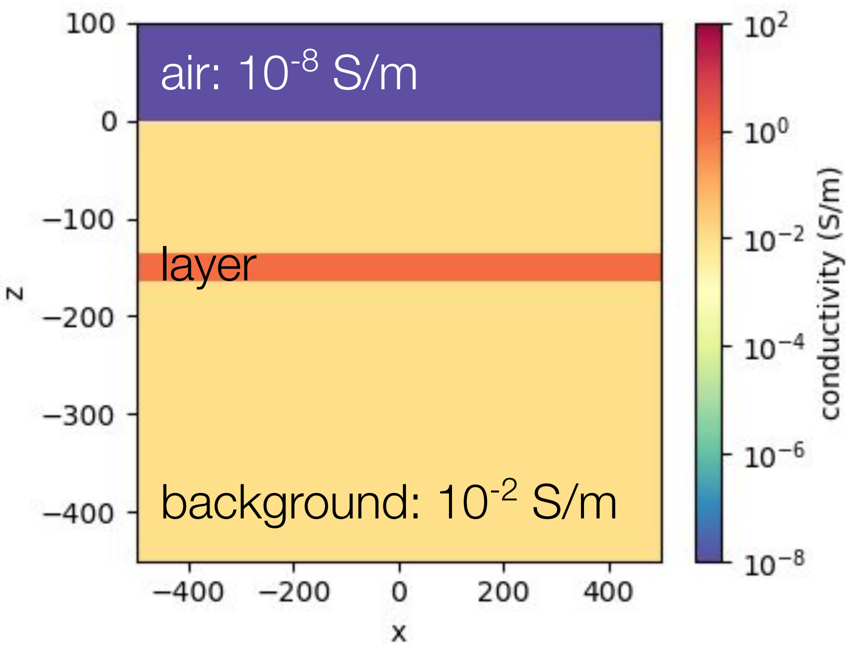
- airborne
- ground
- boreholes

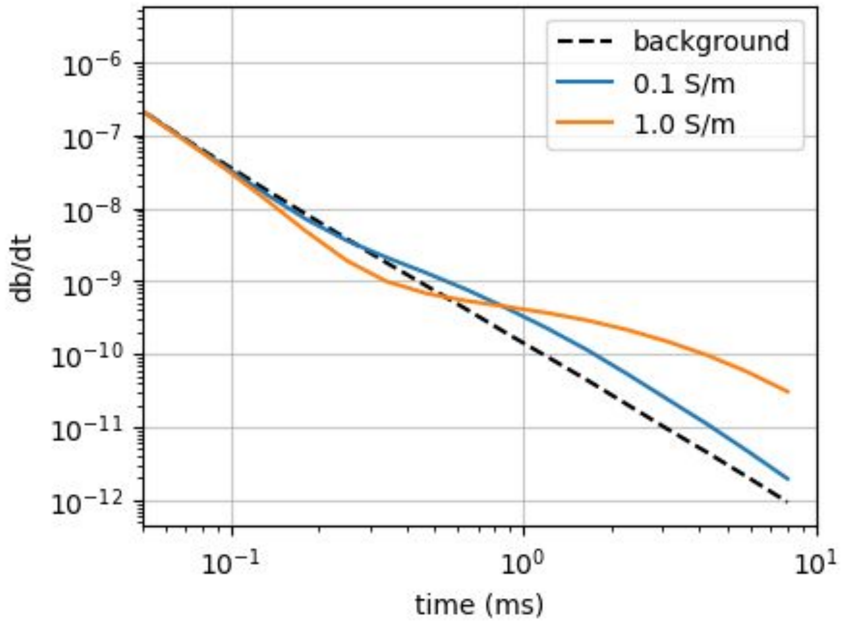
$$\nabla \times \vec{e} = -\frac{\partial \vec{b}}{\partial t}$$

$$\nabla \times \vec{h} = \vec{j} + \frac{\partial \vec{d}}{\partial t}$$



physics: time-domain





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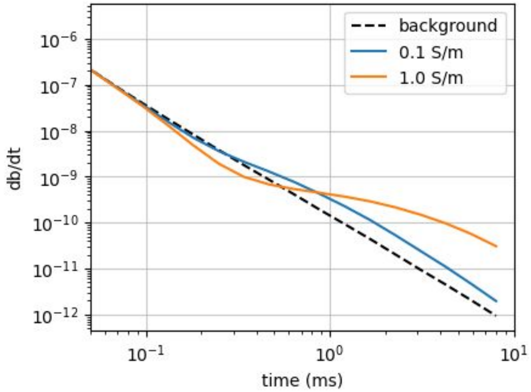
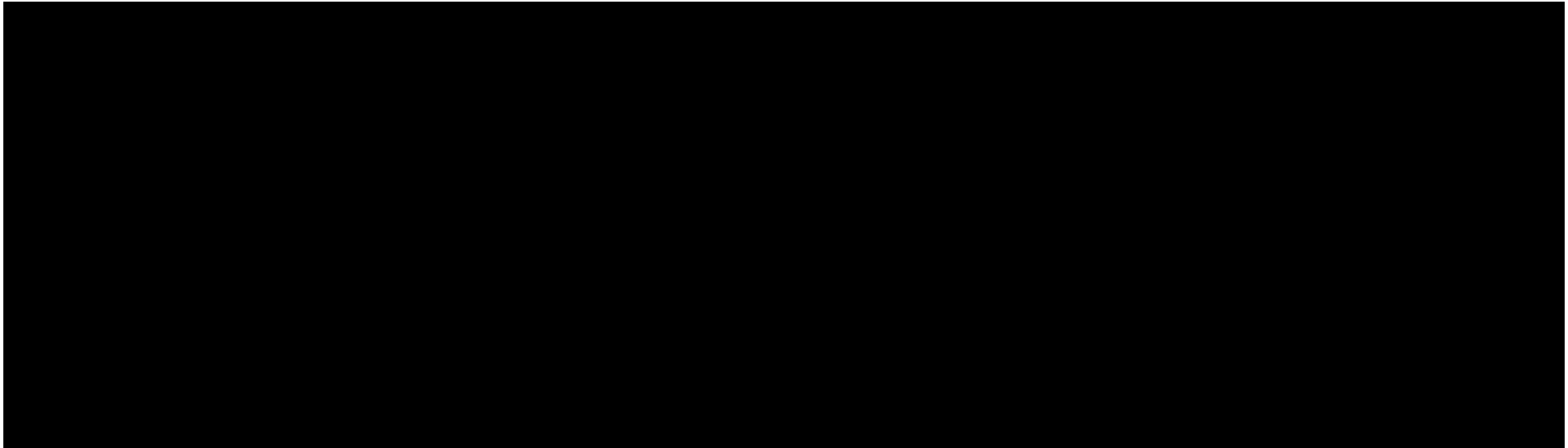


current density

db/dt



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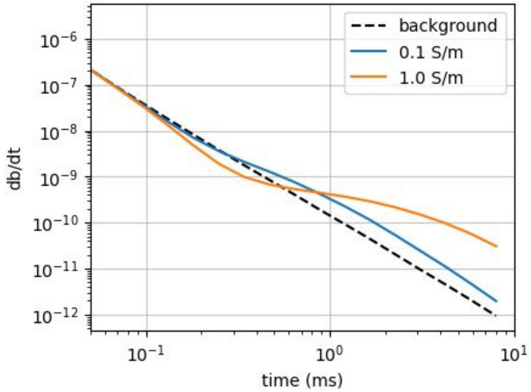

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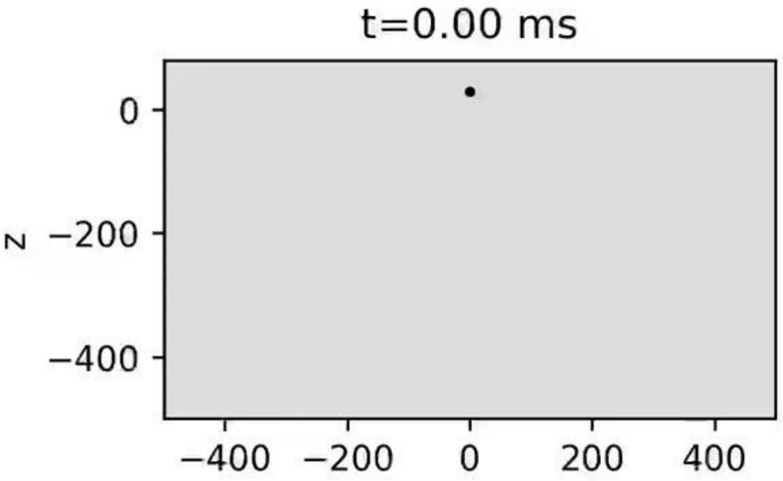
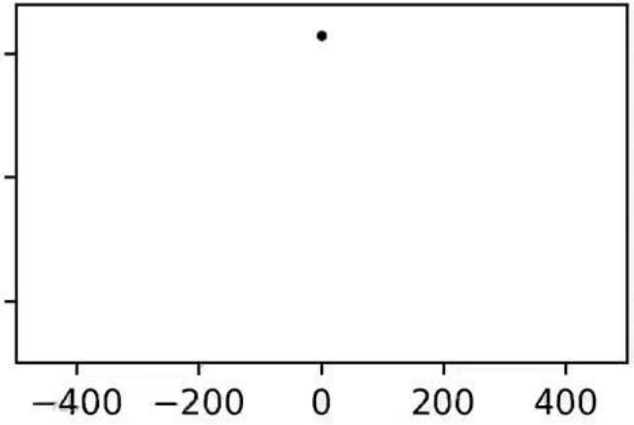




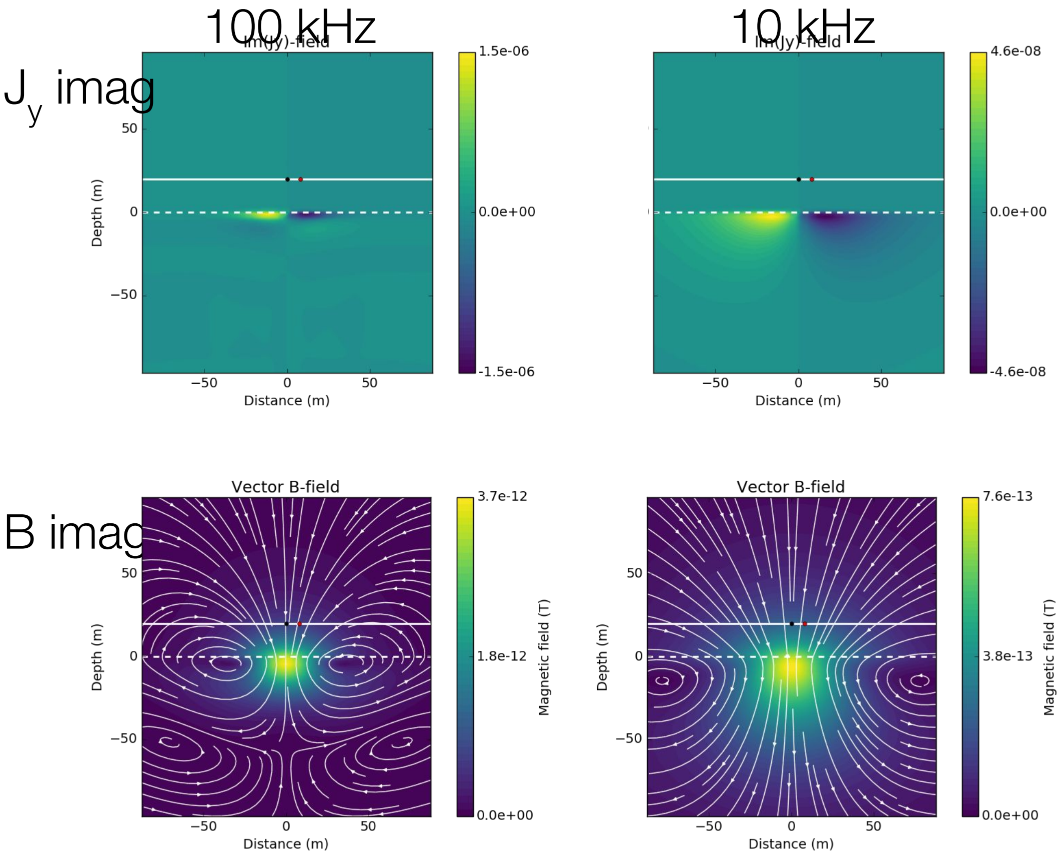
physics: frequency domain

high frequency ~ early times,
low frequency ~ later times

skin depth

$$\delta = 503\sqrt{\frac{\rho}{f}}$$

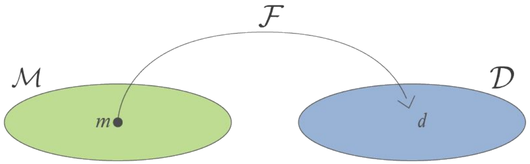
ρ : resistivity [Ωm]
f : frequency [Hz]



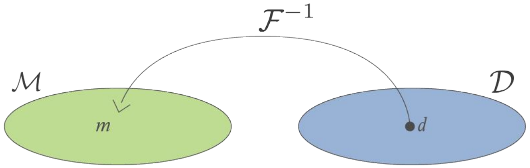
statement of the inverse problem

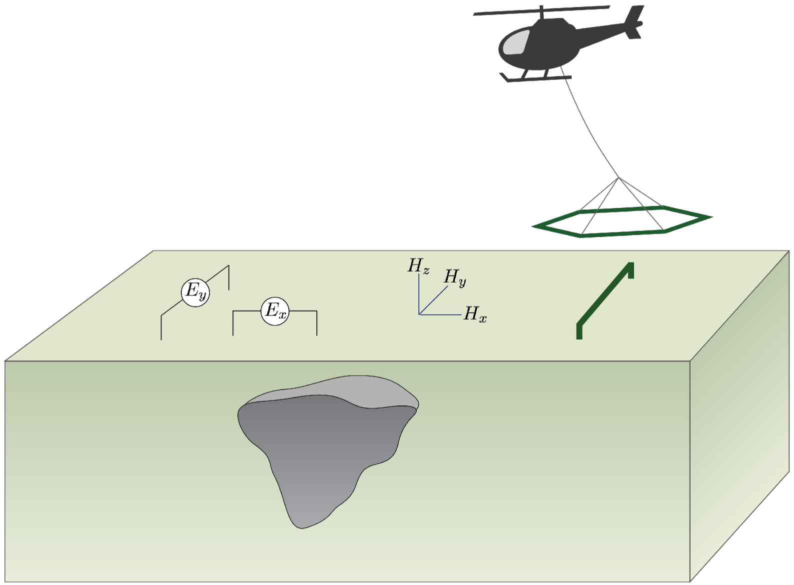
Given

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



Find the Earth model that gave rise to the data





statement of the inverse problem

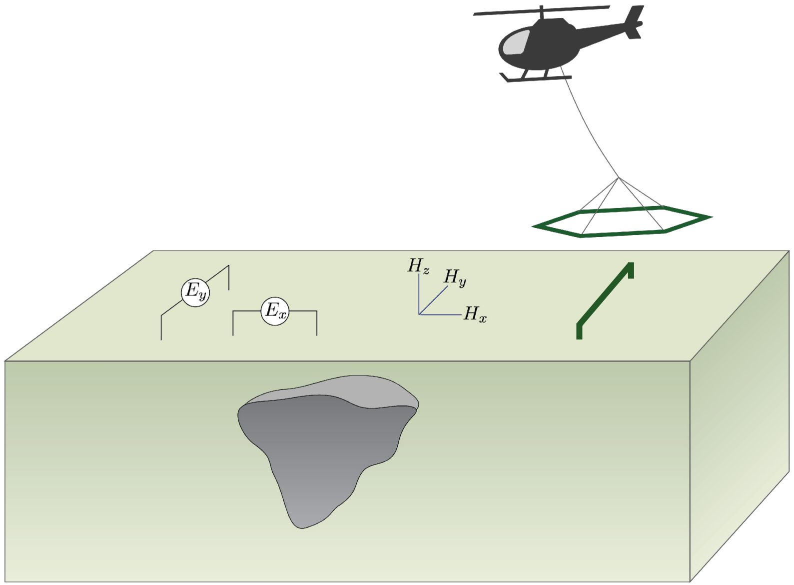
Given

- 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

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

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



simpeg

Simulation and parameter estimation in geophysics

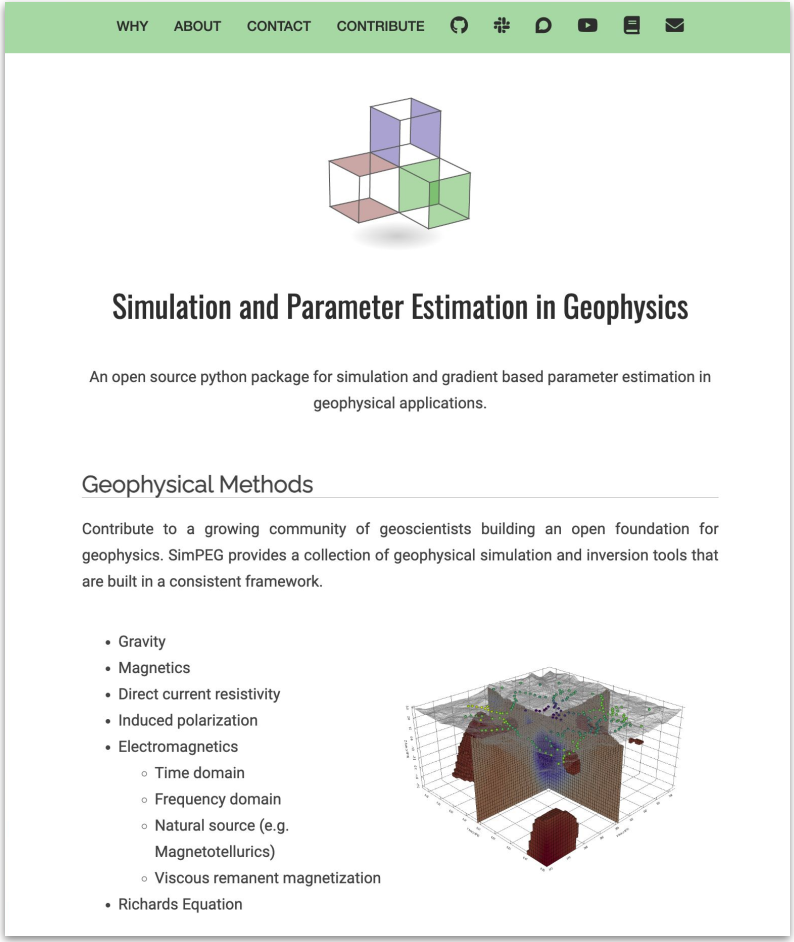
common framework for simulations & inversions

accelerate research: build upon others work

facilitate reproducibility of results

build & deploy in python

open-source


WHY ABOUT CONTACT CONTRIBUTE

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.

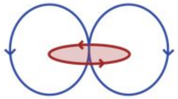
- Gravity
- Magnetics
- Direct current resistivity
- Induced polarization
- Electromagnetics
  - Time domain
  - Frequency domain
  - Natural source (e.g. Magnetotellurics)
  - Viscous remanent magnetization
- Richards Equation

Multi-scale EM geophysical methods

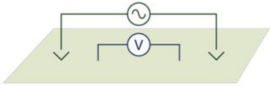
Controlled-source EM

Natural source EM

Inductive



Grounded



Depth from the surface

meters

Tens of meters

Hundreds of meters

Kilometers

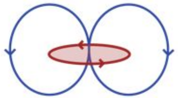
Tens of kilometers

Hundreds of kilometers

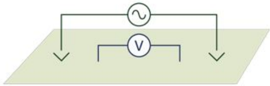
Multi-scale EM geophysical methods

Controlled-source EM

Inductive



Grounded



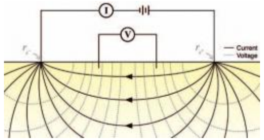
Natural source EM

Depth from the surface

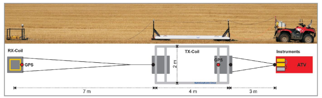
meters | Tens of meters | Hundreds of meters | Kilometers | Tens of kilometers | Hundreds of kilometers

Ground-based EM

ERT

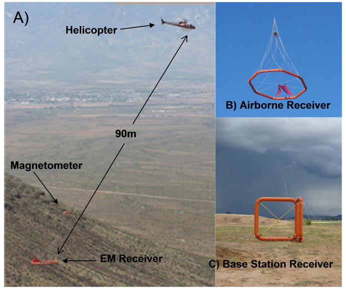


Towed-TEM



Airborne EM (AEM)

Z-axis Tipper EM (ZTEM)



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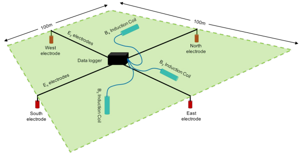
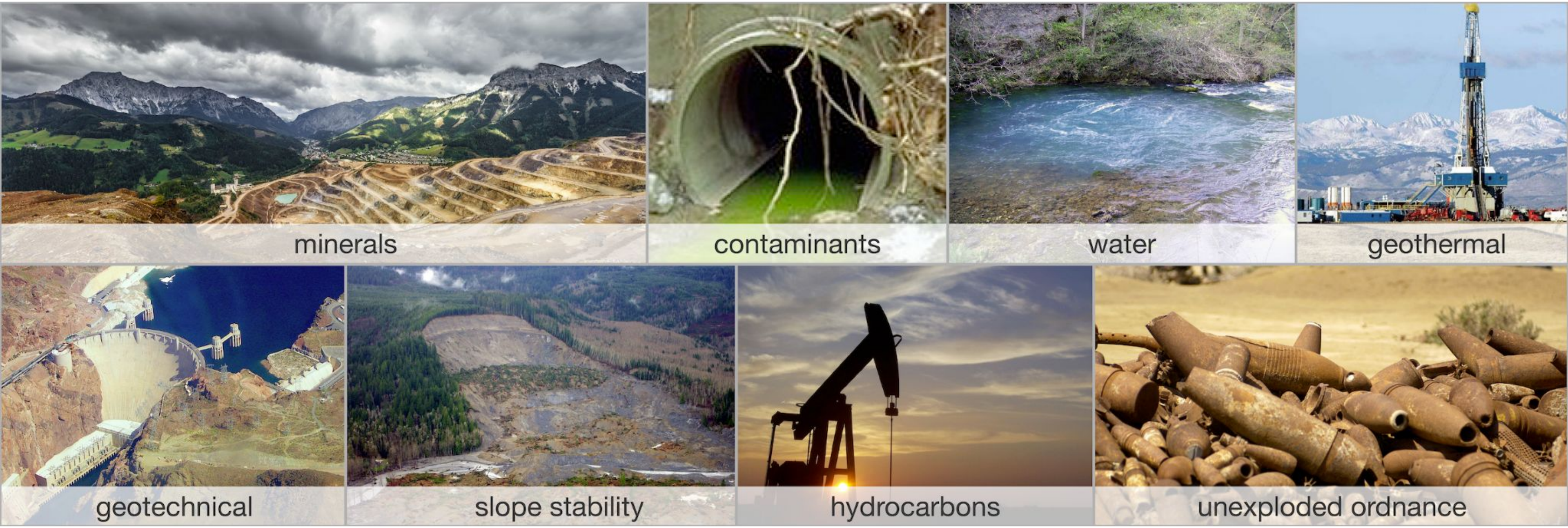
Magnetotellurics (MT)



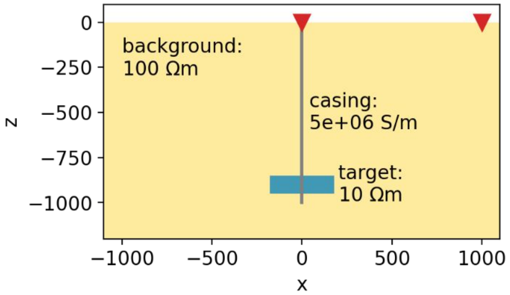
important problems: scales and surveys

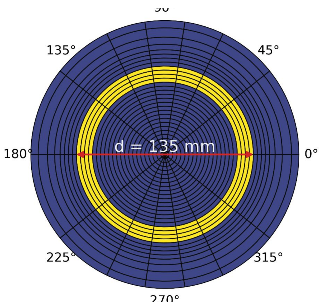


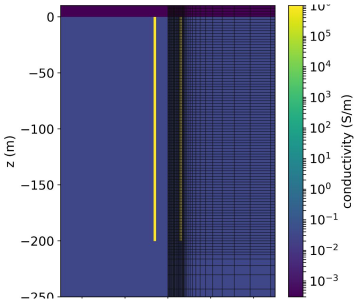
CO_2 sequestration, hydrocarbons: fine scales & large contrasts

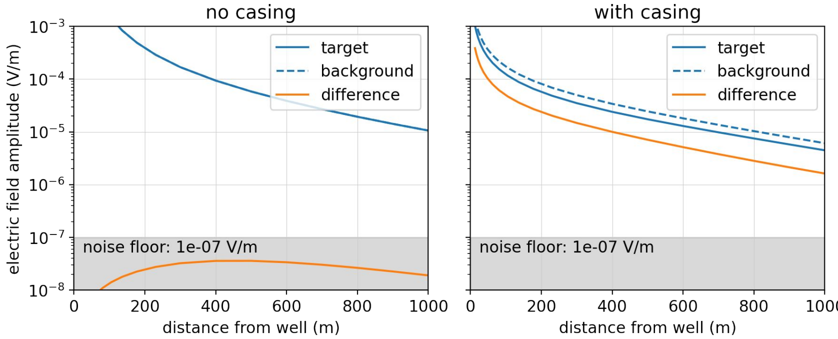
steel casings: highly conductive, magnetic

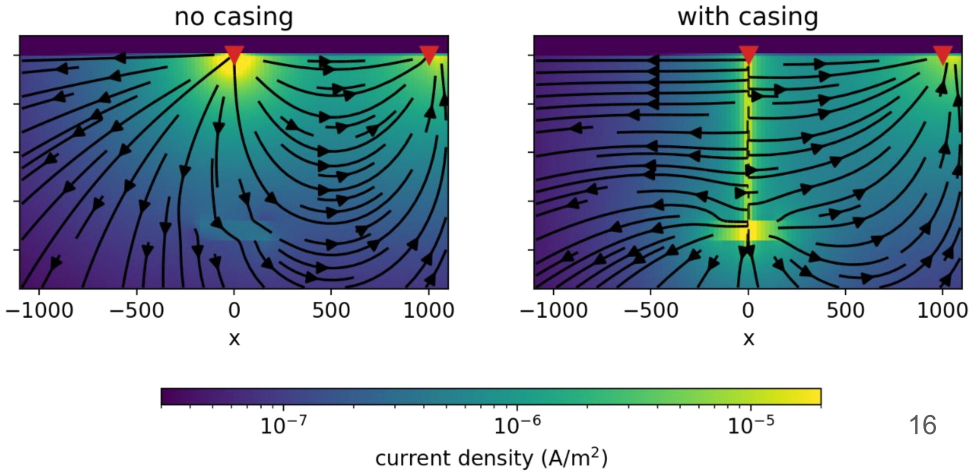
grounded sources: helpful for exciting & detecting deep targets





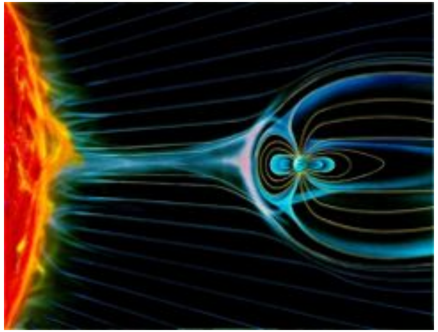


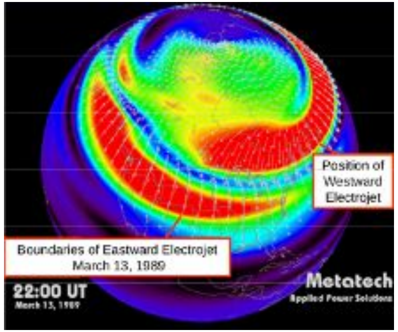




minerals, geothermal: large scales & seeing deep

natural source: rely on lightning strikes, solar wind as our source (unknown strength)



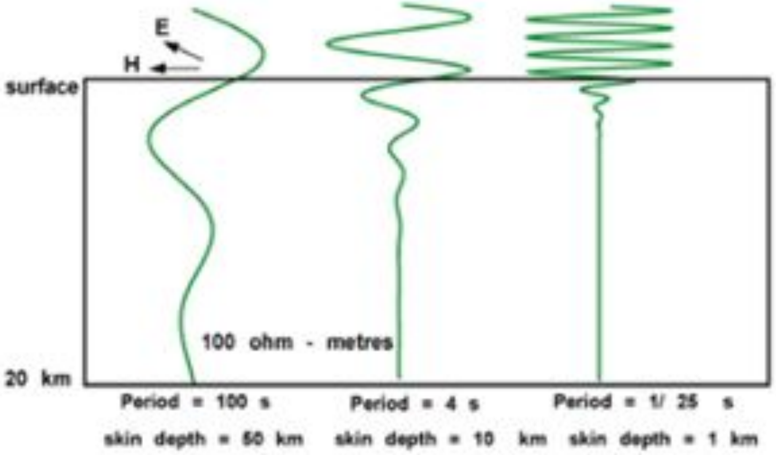


lightning

aurora

skin depth (m)

$$\delta = 503\sqrt{\frac{\rho}{f}} \quad \rho: \text{ resistivity } [\Omega \text{m}] \quad f: \text{ frequency } [\text{Hz}]$$



unexploded ordnance: small scales

near surface (or seafloor), need to detect & classify UXO vs clutter

This rocket warhead was found in September, 2008.
DEPARTMENT OF NATIONAL DEFENCE

?

A sign at the Goose Lake Range, on Okanagan Indian Band territory, warns of the presence of UXO. JEFF BASSETT/THE GLOBE AND MAIL

UXO

Not UXO

case studies

case studies

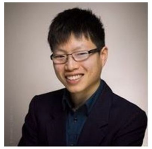
groundwater in Myanmar

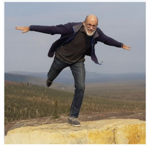
GEOSCIENTISTS without BORDERS®

Improving Water Security in Mon state, Myanmar via Geophysical Capacity Building

- Bring geophysical equipment to Mon state Myanmar
- Train local stakeholders
- Provide open-source software & educational resources


Doug Oldenburg


Kevin Fan


Michael (Max)


Devin Cowan


Seogi Kang


Lindsey Heagy

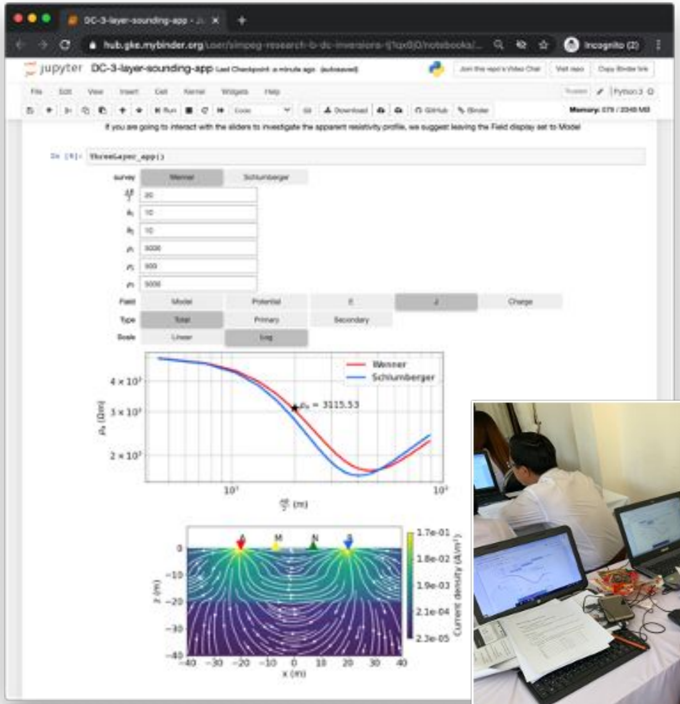
groundwater in Myanmar: important components

7 step framework for case studies

- Setup
- Physical properties
- Survey
- Data
- Processing
- Interpretation
- Synthesis

Open source software and resources

- Jupyter notebook “apps” for concepts and data processing



https://courses.geosci.xyz/gwb2020

groundwater in Myanmar

7 step framework

- **Setup**
- Physical properties
- Survey
- Data
- Processing
- Interpretation
- Synthesis

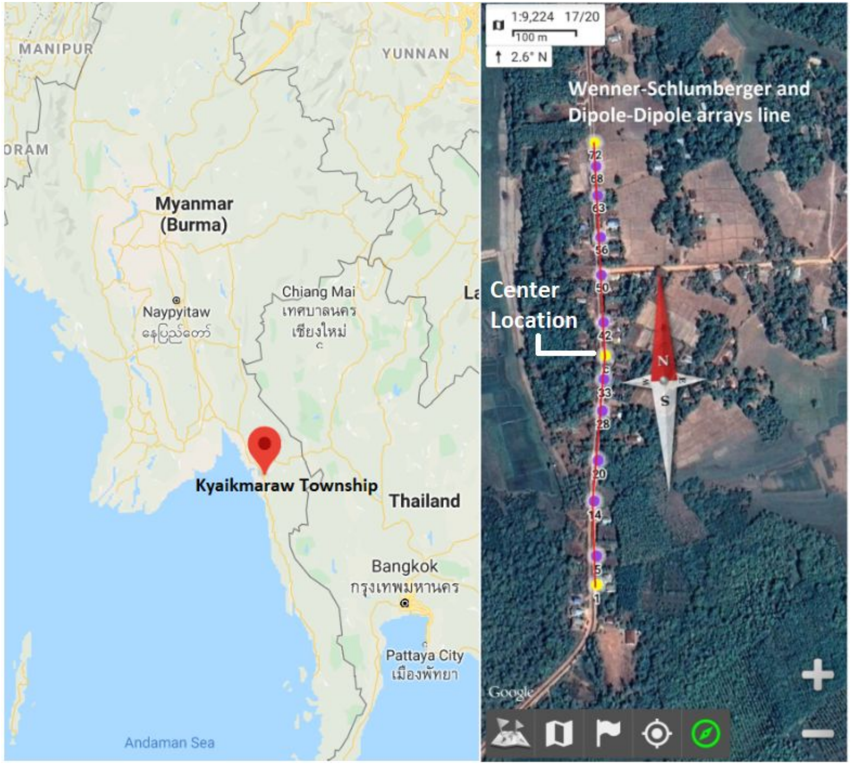
Phayar Ngoteto Village

In 2018: 1D inversion suggested aquifer at 30-50 m

- Well drilled to ~60 m: no significant water

In 2020 (before covid...):

- return and conduct a 2D survey



groundwater in Myanmar

7 step framework

- Setup
- **Physical properties**
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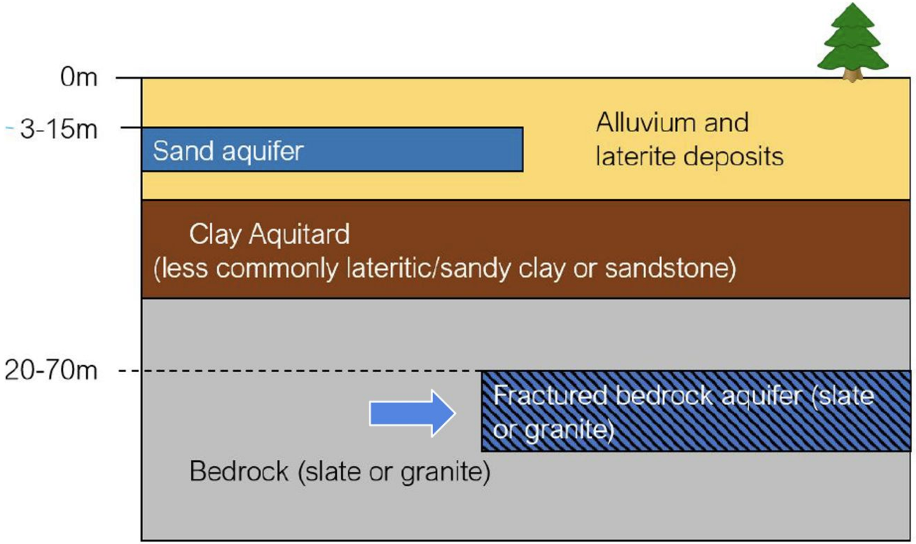
Main diagnostic:
Water bearing region ~ 40-140 Ωm



Hydrogeological Unit	Resistivity (Ωm)
Alluvium and laterite (dry)	200-800
Alluvium and laterite (saturated)	30
Sand aquifer	50-100
Clay aquitard	10-20
Bedrock (eg. granite)	500-1000
Fractured/Weathered bedrock (with fresh water)	40-400

groundwater in Myanmar

7 step framework

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- **Survey**
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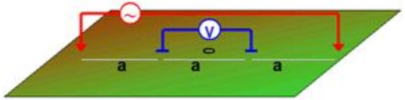
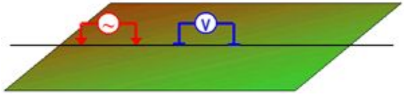
Survey: 2D DC resistivity

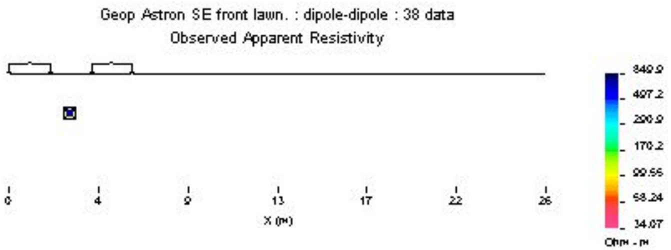


Wenner-Schlumberger



Dipole-Dipole

data plotted in pseudosections



groundwater in Myanmar

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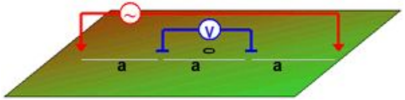
Survey: 2D DC resistivity



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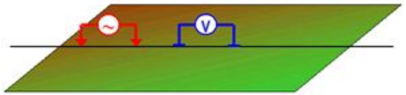
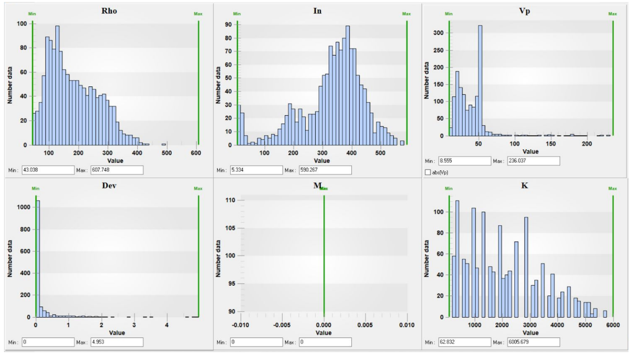
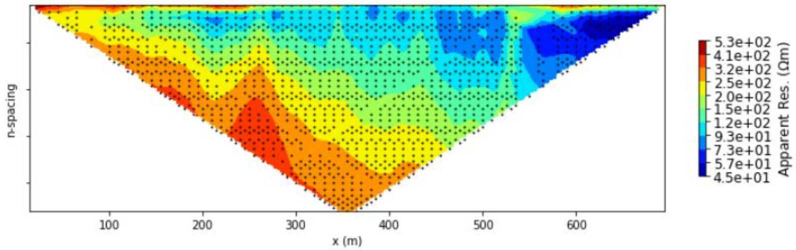


Dipole-Dipole





groundwater in Myanmar

7 step framework

- Setup
- Physical properties
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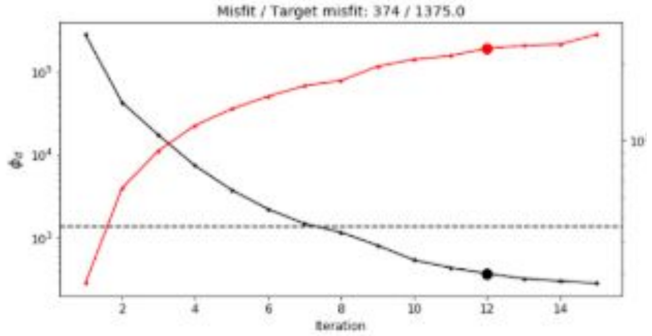
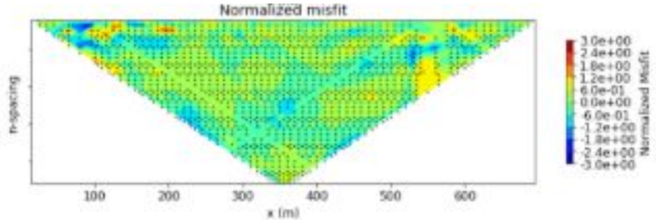
- **Processing**
- Interpretation
- Synthesis

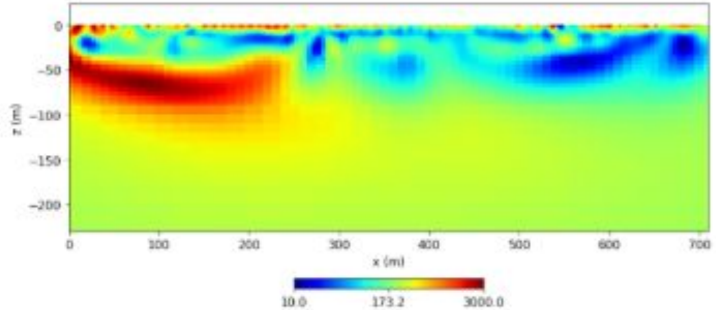
Inversion: estimate a model of the subsurface

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

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



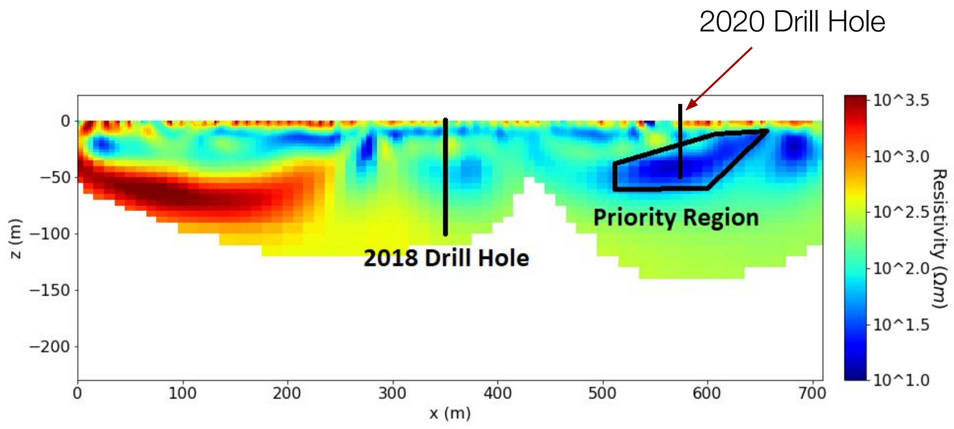




groundwater in Myanmar

7 step framework

- Setup
- Physical properties
- Survey
- Data
- Processing
- **Interpretation**
- Synthesis



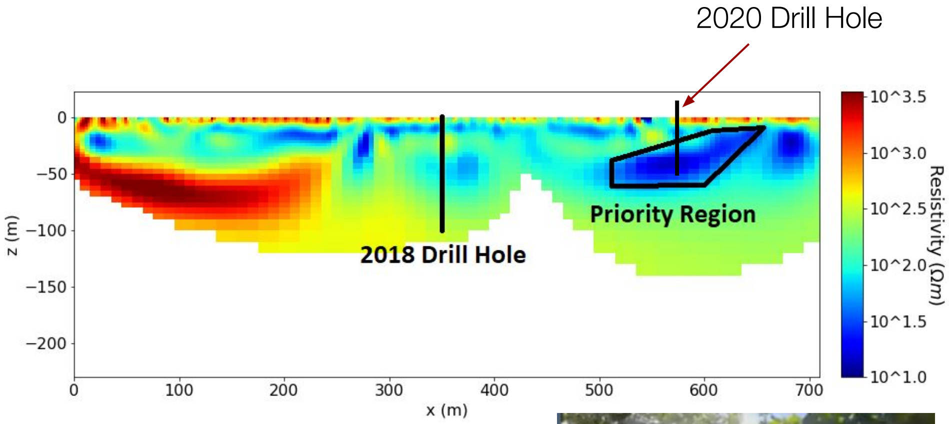
groundwater in Myanmar

7 step framework

- Setup
- Physical properties
- Survey
- Data
- Processing
- Interpretation
- **Synthesis**

Field surveys at 23+ villages by engineers, geoscientists in Myanmar

Acquired data, interpreted, spotted drill holes using open source software



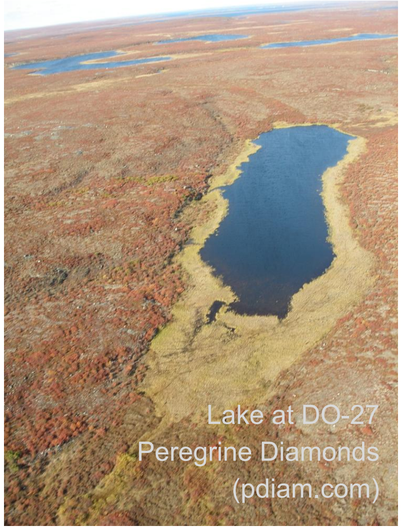
>1000 gph

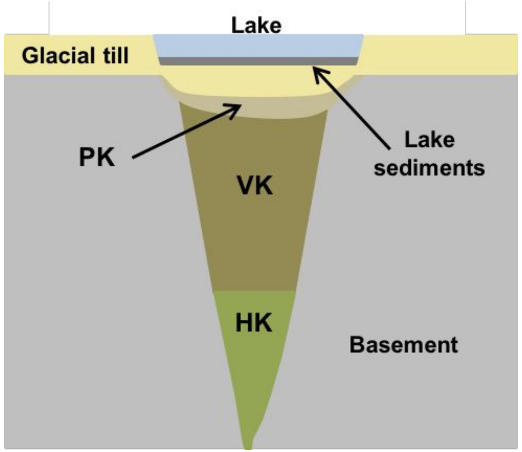
case studies

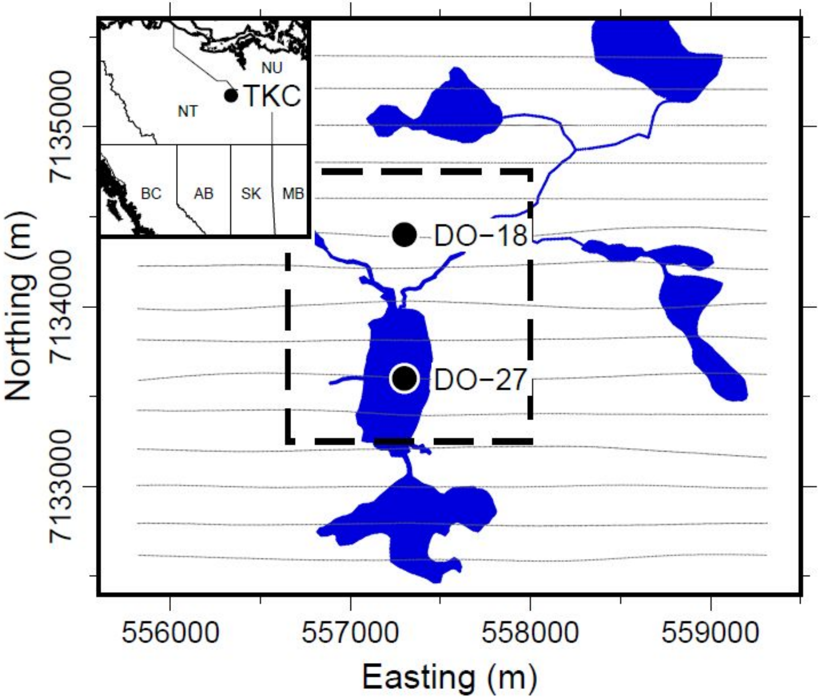
Tli Kwi Cho (TKC) Kimberlite complex

Geophysical discovery in 90's: airborne magnetic and electromagnetic data

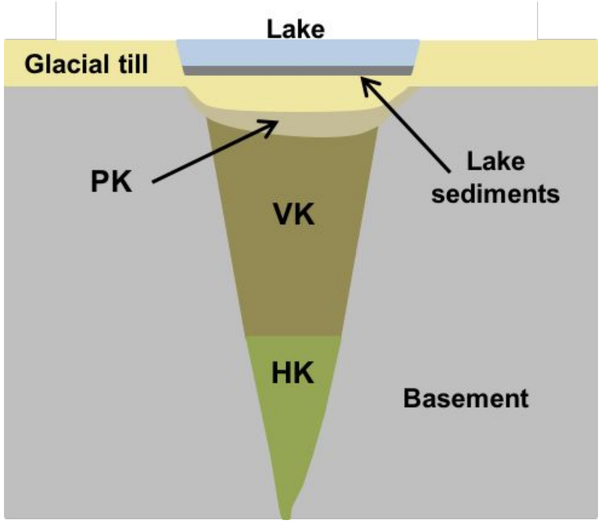
2 kimberlite pipes







physical properties at TKC



Rock type	Glacial till	Host rock	HK	VK	PK
Density	Moderate	Moderate	Low	Low	Low
Susceptibility	None	None	High	Low-moderate	Low-moderate
Conductivity	Moderate-high	Low	Low-moderate	Moderate-high	Moderate-high
Chargeability	Low	Low	?	?	?

- Overall kimberlite: low density
- HK: high susceptibility
- VK and PK:
  - low-moderate susceptibility
  - moderate-high conductivity

TKC: surveys

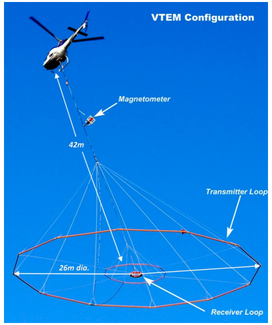
Airborne data

System	Year	Data
DIGHEM	1992	FEM, mag
Falcon	2001	Grav grad
AeroTEM II	2003	TEM, mag
VTEM	2004	TEM, mag

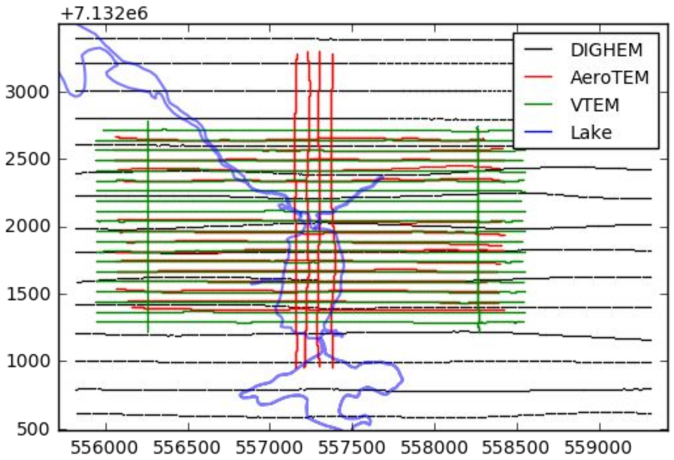
Ground data as well: NanoTEM, magnetics, gravity

DIGHEM

AeroTEM



VTEM



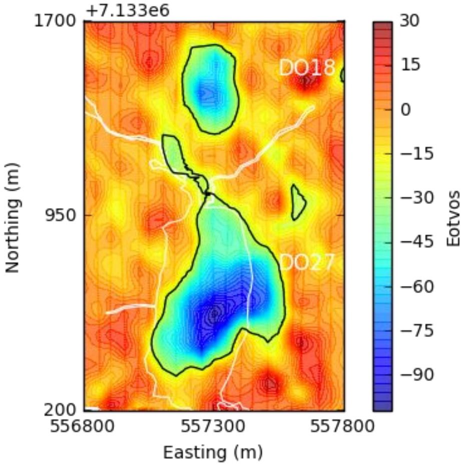
TKC: data

Airborne data

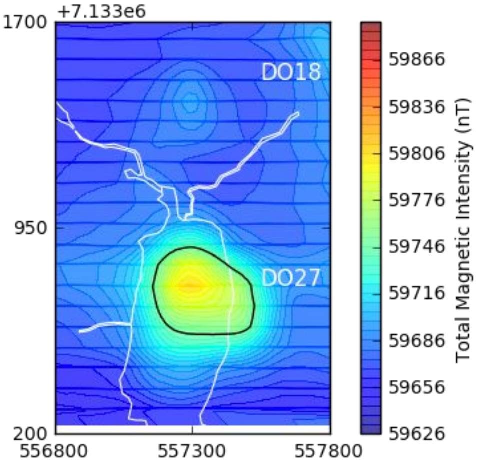
- invert to obtain physical property models
- interpret to build quasi-geology model
- published in 3 papers by the GIF group

Devriese *et al.* 2017,
Fournier *et al.* 2017,
Kang *et al.* 2017

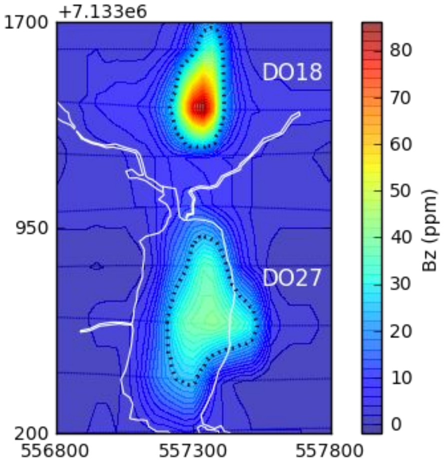
gravity gradiometry



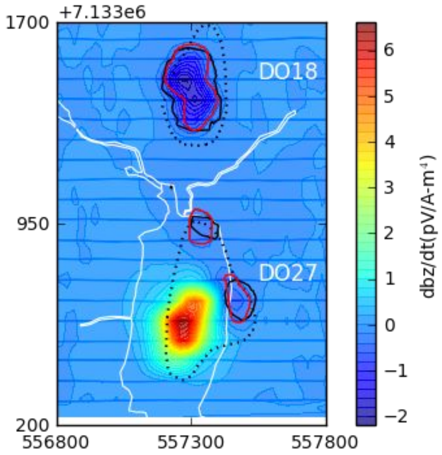
VTEM mag



frequency domain EM



VTEM

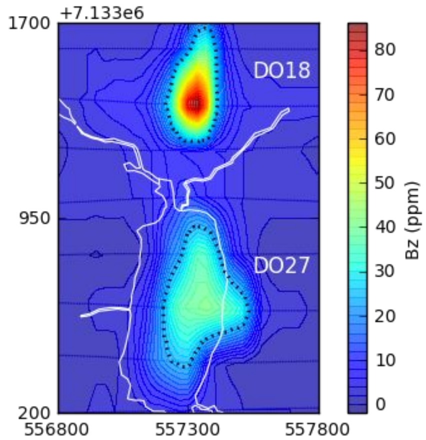


TKC: electromagnetics

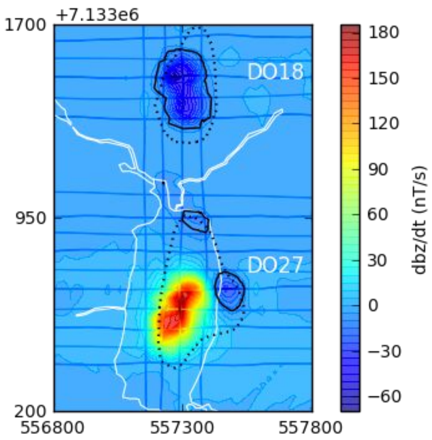
Focus on DIGHEM and VTEM data

Negatives in VTEM data is challenge…

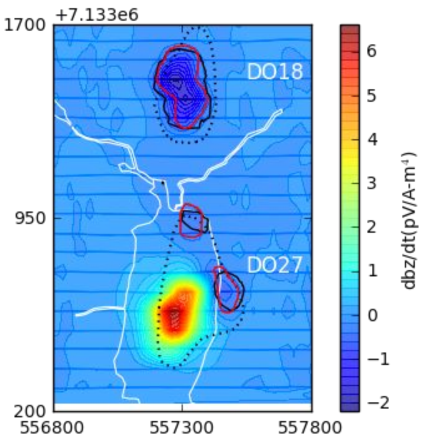
DIGHEM
(1992)



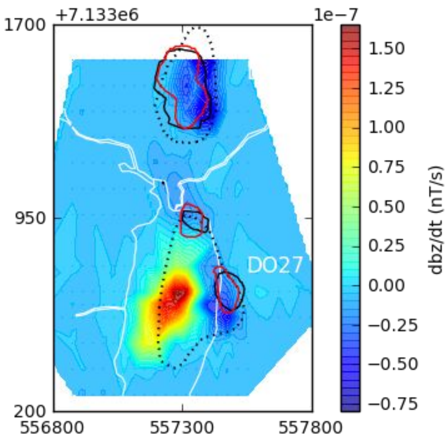
AeroTEMII
(2003)



VTEM
(2004)



NanoTEM
(1993)



IP effects in time domain EM data

Seogi Kang

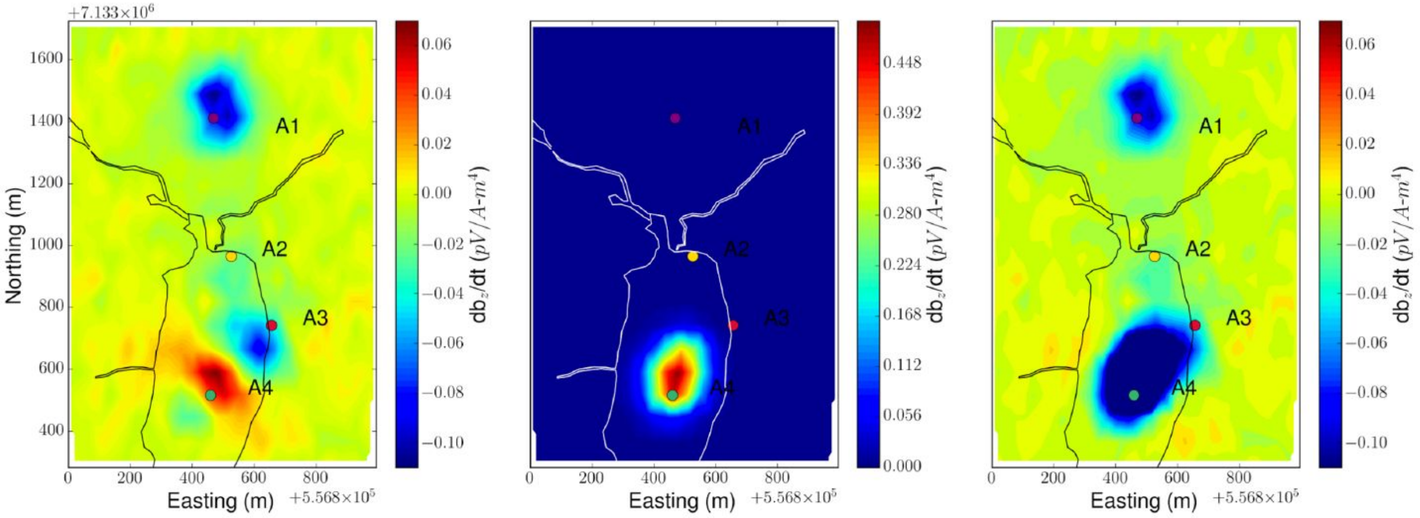
Negative transients in VTEM presents a challenge → motivates research

EM-decoupling: IP = Observation – Fundamental (EM)

Observed

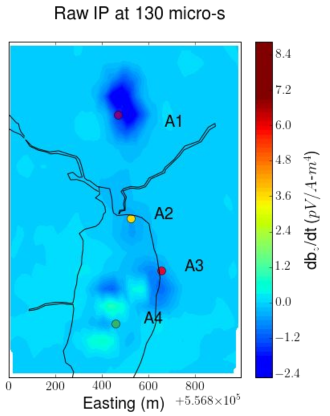
Fundamental (EM)

IP

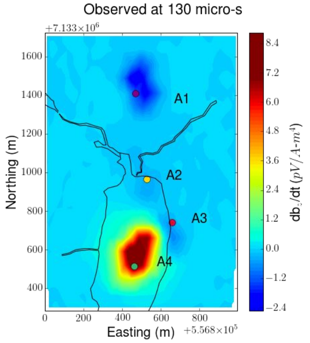


TKC: IP inversion (early time)

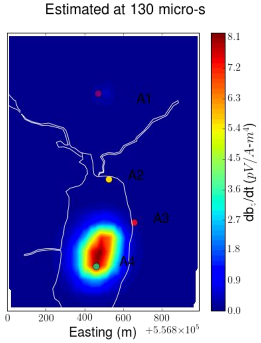
IP data



Observation



Fundamental



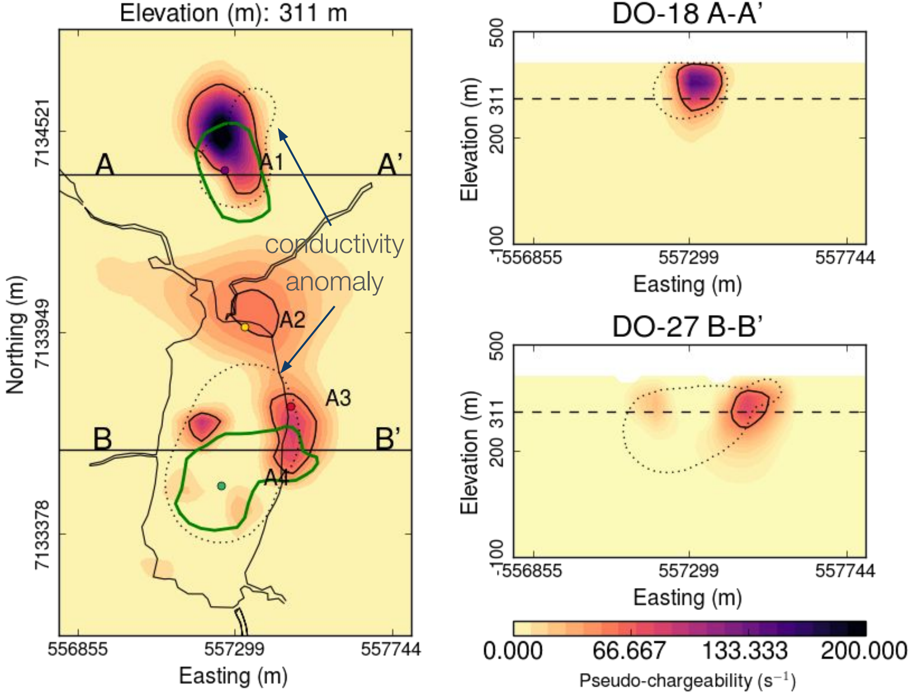
invert

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

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

Kang et al. (2016)

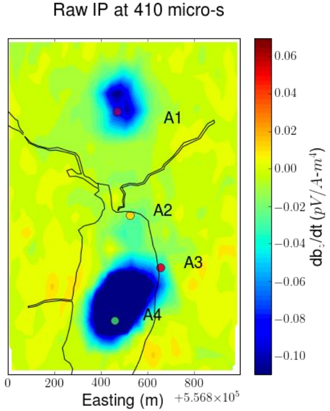
Recovered 3D model



IP = Observation – Fundamental (EM)

TKC: IP inversion (late time)

IP data



invert

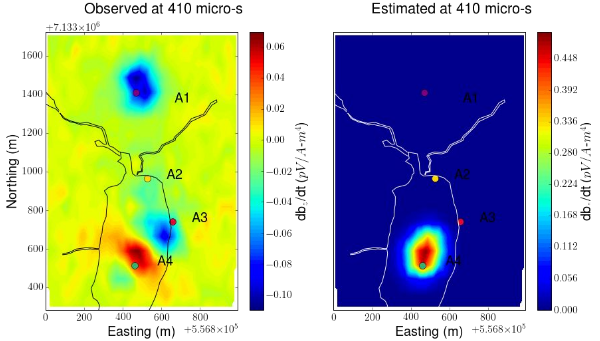
$$d^{IP}(t) = G\tilde{\eta}(t)$$

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

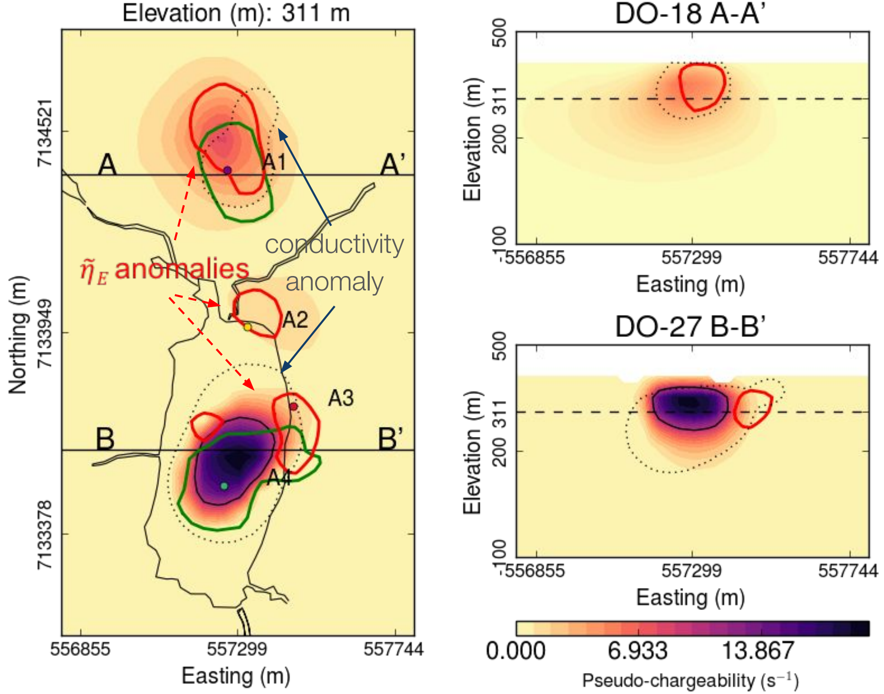
Kang et al. (2016)

Observation

Fundamental



Recovered 3D model



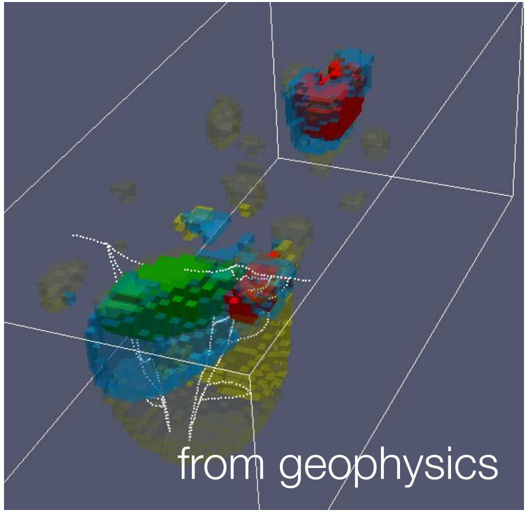
IP = Observation – Fundamental (EM)

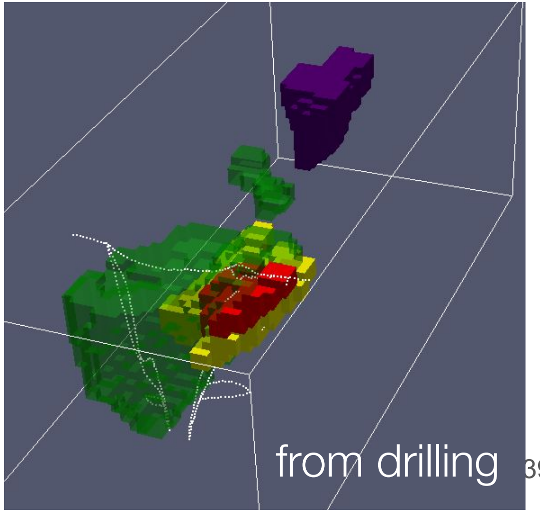
A quasi-geology model from physical properties

Rock type	Glacial till	Host rock	HK	VK	PK
Density	Moderate	Moderate	Low	Low	Low
Susceptibility	None	None	High	Low-moderate	Low-moderate
Conductivity	Moderate-high	Low	Low-moderate	Moderate-high	Moderate-high
Chargeability	Low	Low	?	?	?

small time constant (VK) — large time constant (PK)

- Independently inverted multiple airborne geophysical data sets in 3D, built a representative 3D rock model
- Importance of conductivity, chargeability & related computational tools





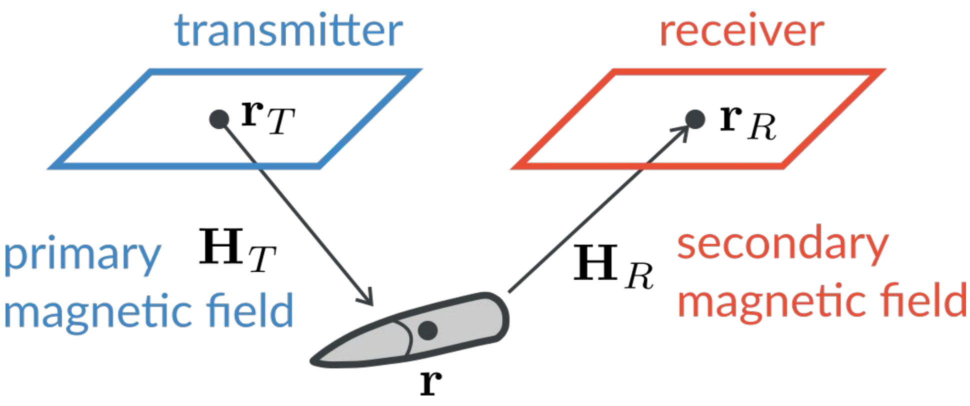
case studies

minerals

water

unexploded ordnance

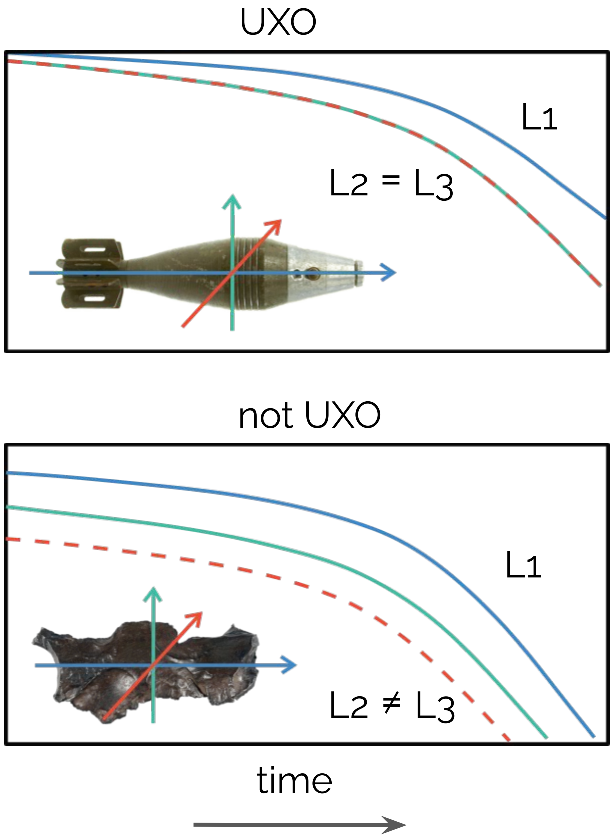
Time-domain EM response of a UXO



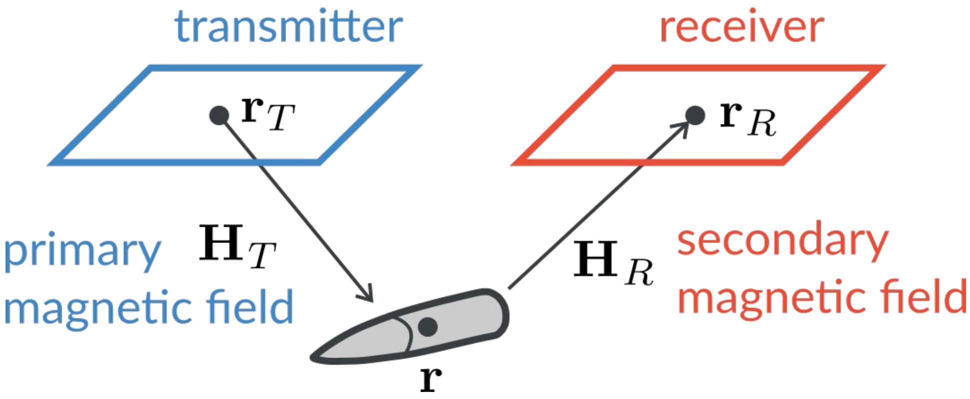
$$d(\mathbf{r}_R, t) = \mathbf{H}_R(\mathbf{r}, \mathbf{r}_R) \cdot \mathbf{P}(t) \cdot \mathbf{H}_T(\mathbf{r}, \mathbf{r}_T)$$

$$\mathbf{P}(t) = \mathbf{A}(\phi, \theta, \psi) \cdot \mathbf{L}(t) \cdot \mathbf{A}^\top(\phi, \theta, \psi)$$

$$\mathbf{L}(t) = \begin{pmatrix} L_1 & & \\ & L_2 & \\ & & L_3 \end{pmatrix}$$



Time-domain EM response of a UXO



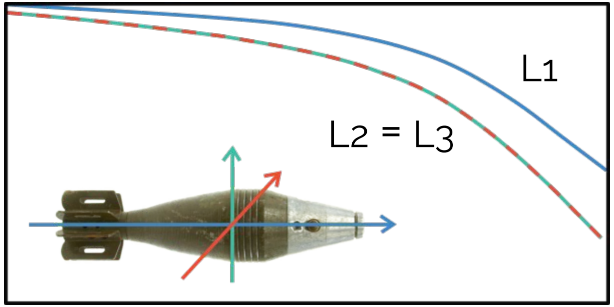
$$d(\mathbf{r}_R, t) = \mathbf{H}_R(\mathbf{r}, \mathbf{r}_R) \cdot \mathbf{P}(t) \cdot \mathbf{H}_T(\mathbf{r}, \mathbf{r}_T)$$

$$\mathbf{P}(t) = \mathbf{A}(\phi, \theta, \psi) \cdot \mathbf{L}(t) \cdot \mathbf{A}^\top(\phi, \theta, \psi)$$

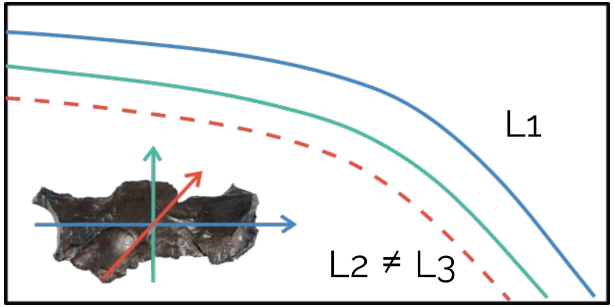
$$\mathbf{L}(t) = \begin{pmatrix} L_1 & & \\ & L_2 & \\ & & L_3 \end{pmatrix}$$

traditional approach: use inversion to get these and then classify by comparing **L**(t) with ordnance library

UXO

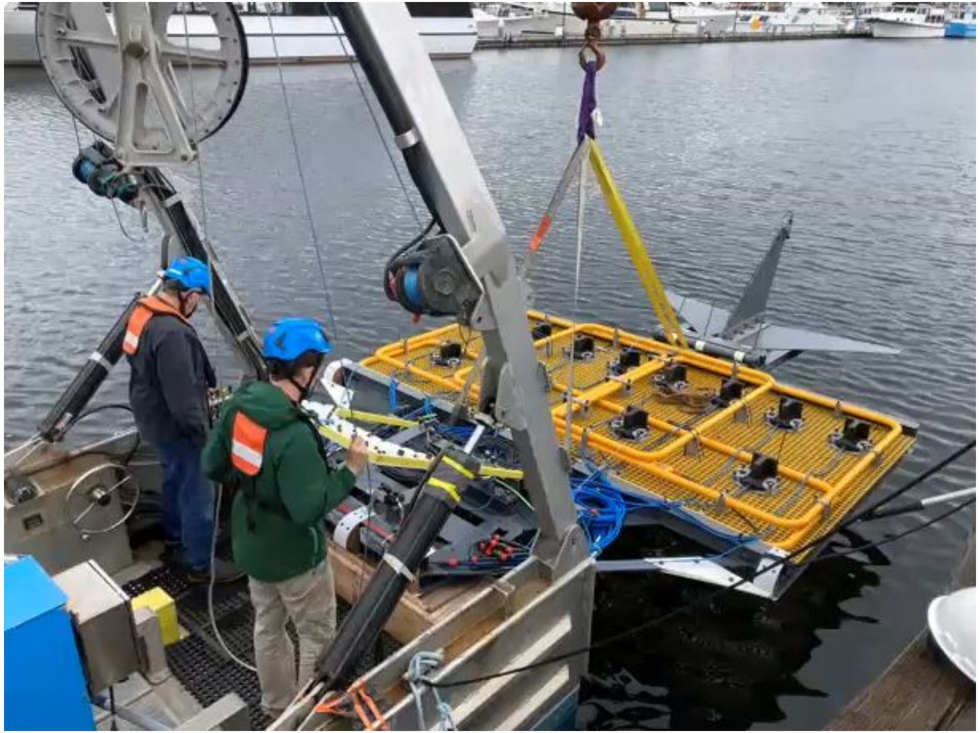


not UXO



time

Survey and system



UltraTEMA-4 system:

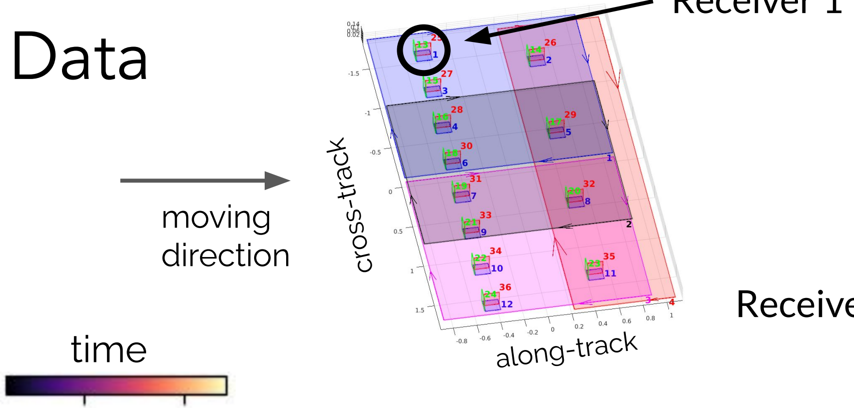
4 transmitters

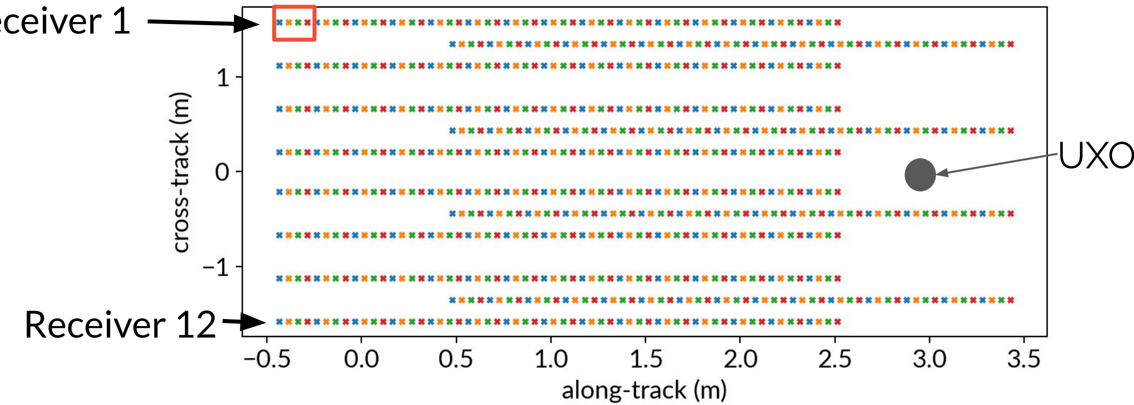
12 receivers (3-component)

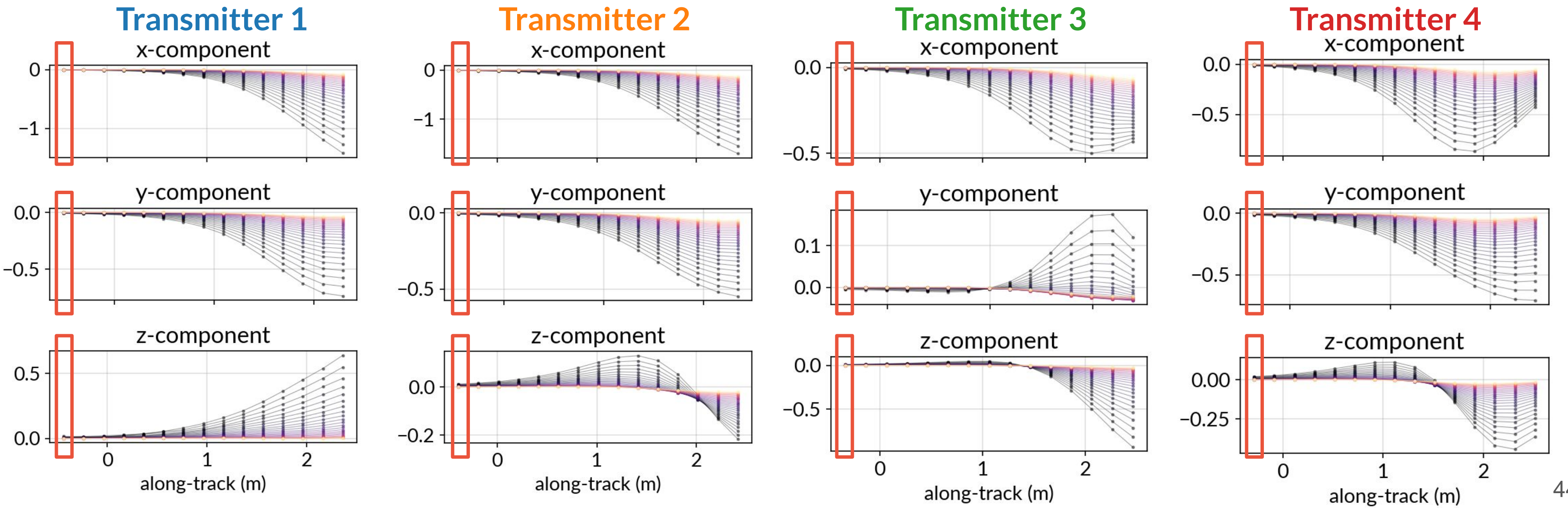
27 time channels

Height above seabed: ~1 m

Data

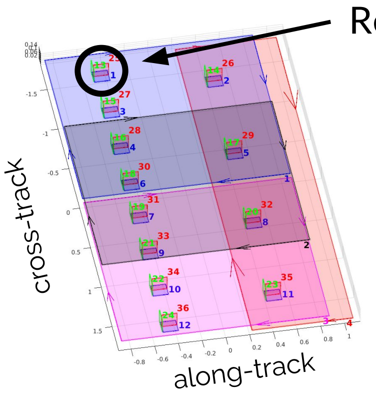

moving direction
cross-track
along-track
time
Receiver 1

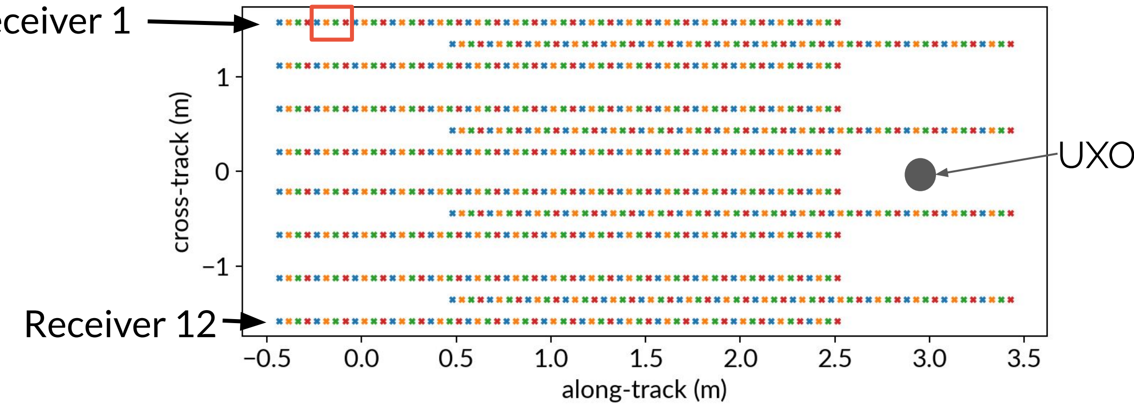

Receiver 1
Receiver 12
UXO
cross-track (m)
along-track (m)

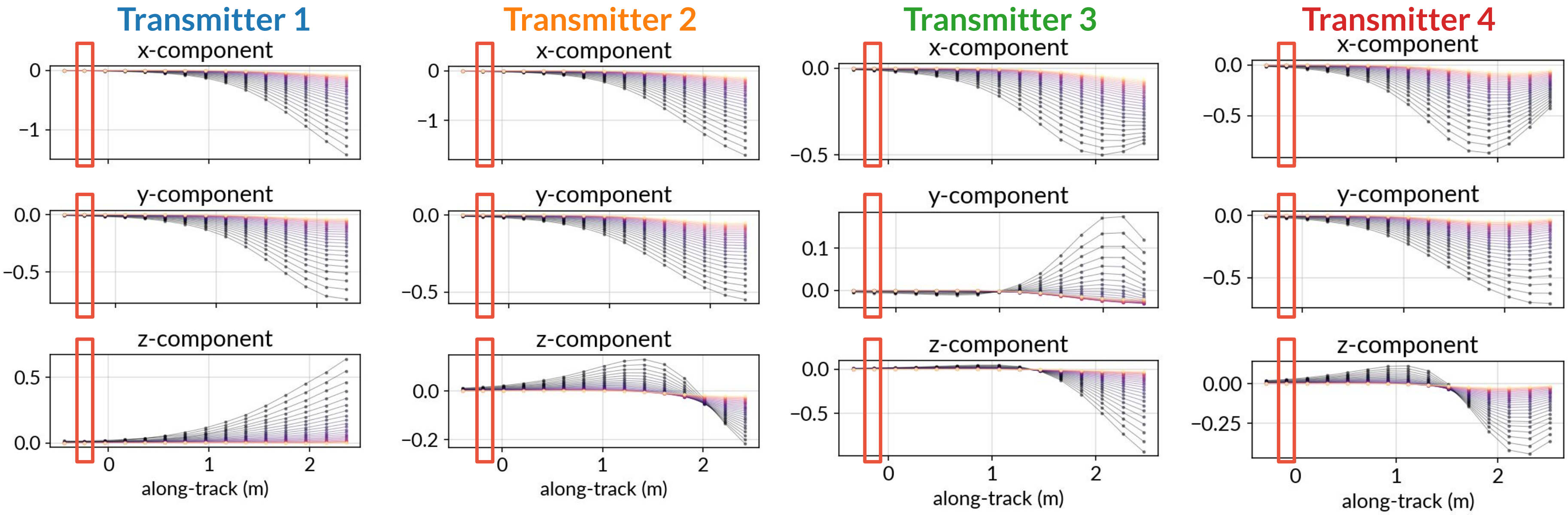

Transmitter 1
Transmitter 2
Transmitter 3
Transmitter 4
x-component
y-component
z-component
along-track (m)

Data

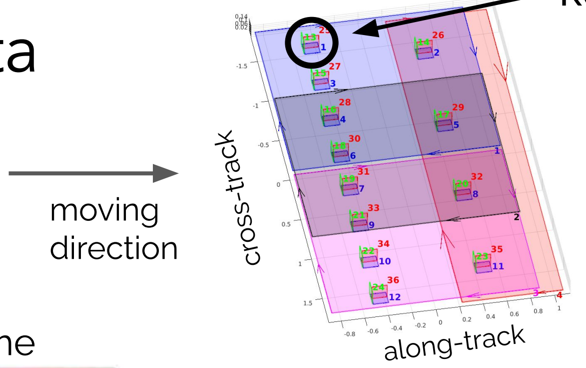
moving direction



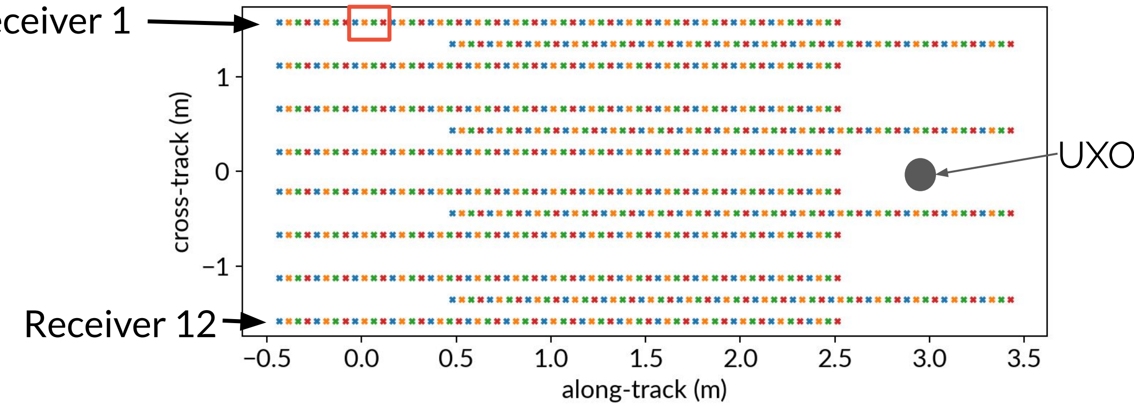




Data

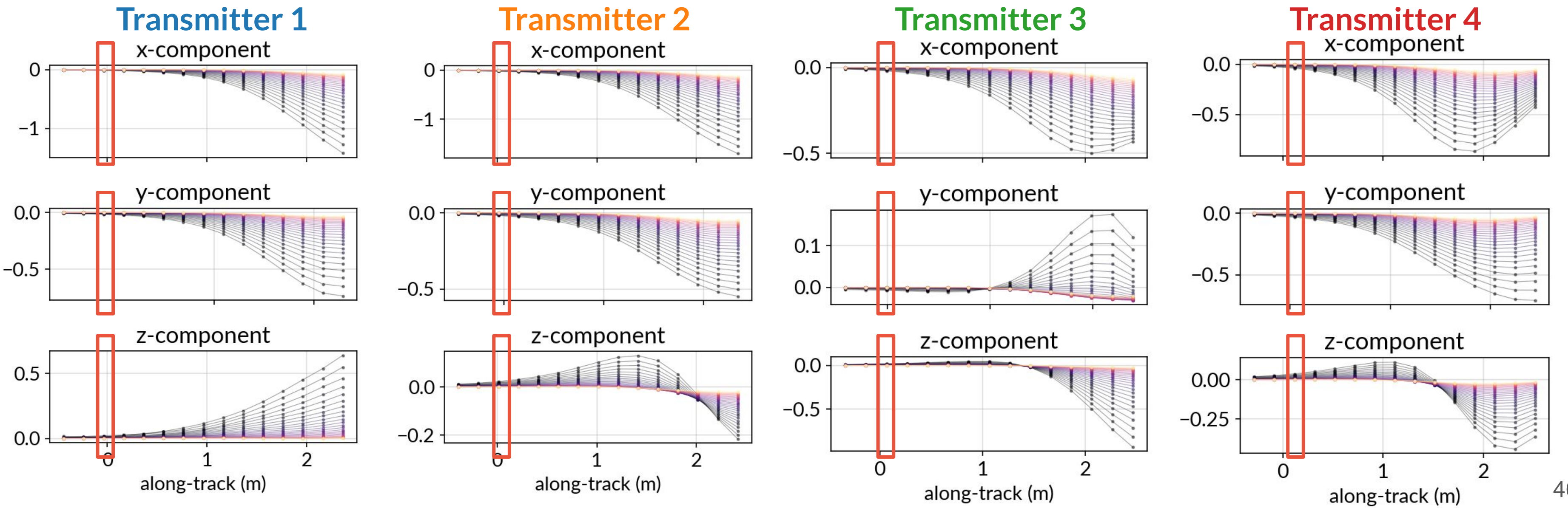


moving direction
cross-track
along-track



Receiver 1
Receiver 12
UXO
cross-track (m)
along-track (m)
1
0
−1
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

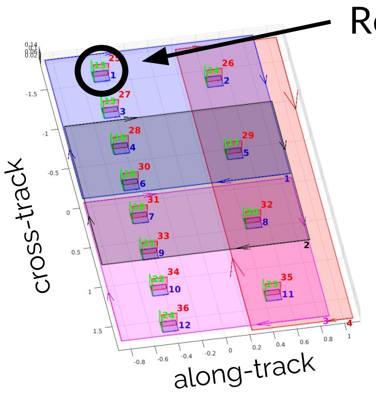
time



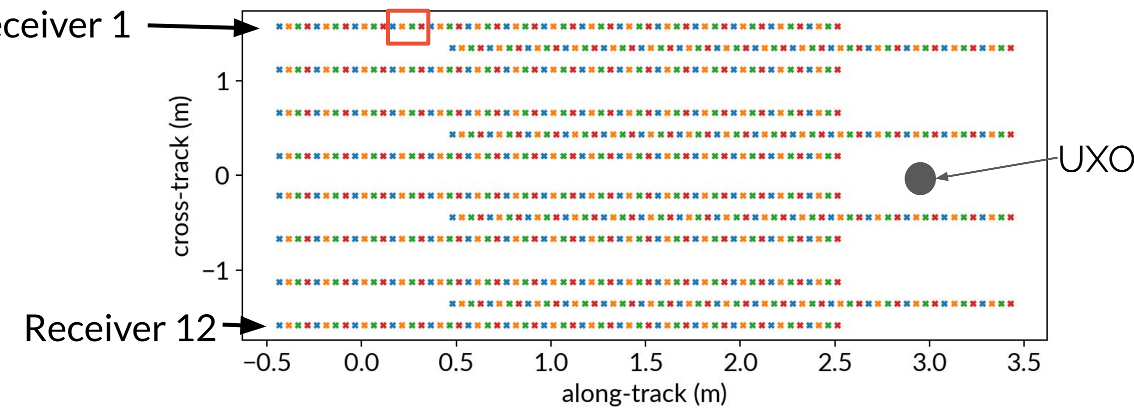
Transmitter 1
Transmitter 2
Transmitter 3
Transmitter 4
x-component
y-component
z-component
along-track (m)

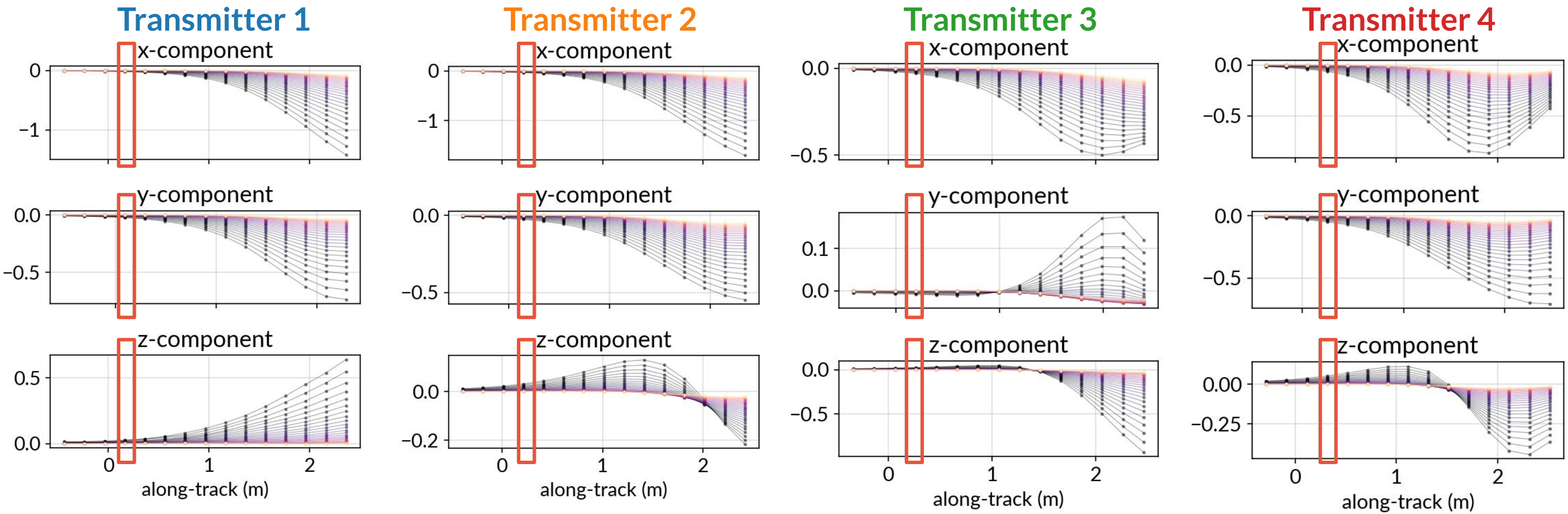
Data


moving
direction


cross-track
along-track


time


Receiver 1
Receiver 12
UXO
cross-track (m)
along-track (m)
1
0
−1
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5


Transmitter 1
Transmitter 2
Transmitter 3
Transmitter 4
x-component
y-component
z-component
along-track (m)

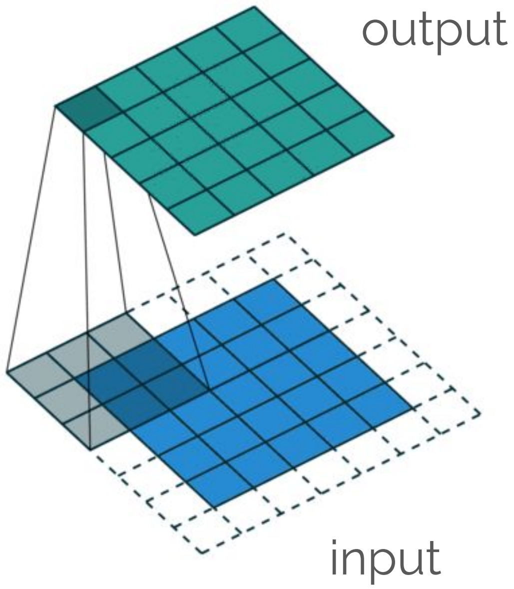
Can we classify directly from EM data?

Convolutional neural networks (CNNs)

- Convolutional filters look at spatial / temporal features in the data

Training EM data for UXO classification:

- Available library of ordnance objects with polarizations
- Fast geophysical simulations

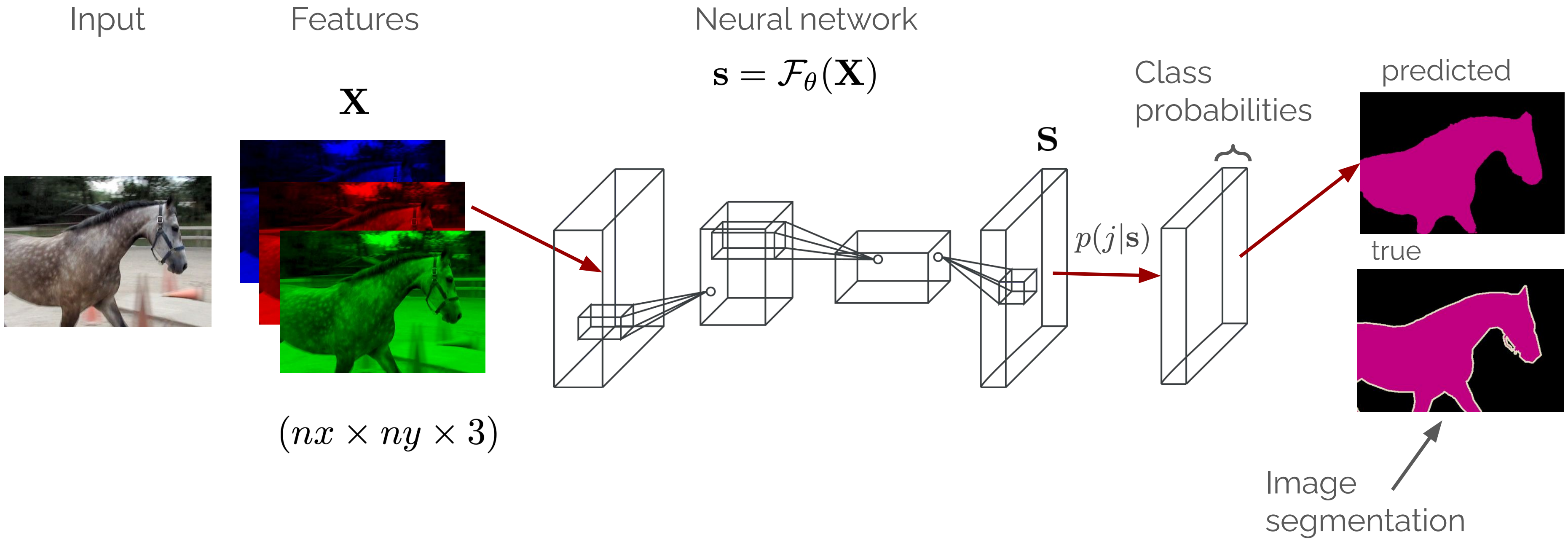


https://towardsdatascience.com/a-comprehensive-guide-to-convolutional-neural-networks-the-eli5-way-3bd2b1164a53

Convolutional Neural Networks (CNNs)

Supervised classification problem

provided data with labels, construct a function (network) that outputs labels given input data



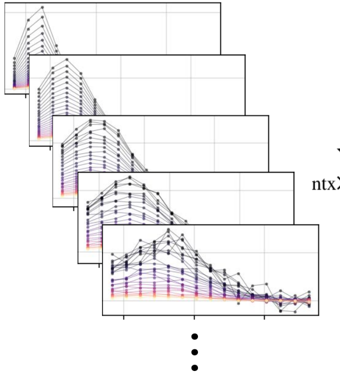
Convolutional Neural Networks (CNNs)

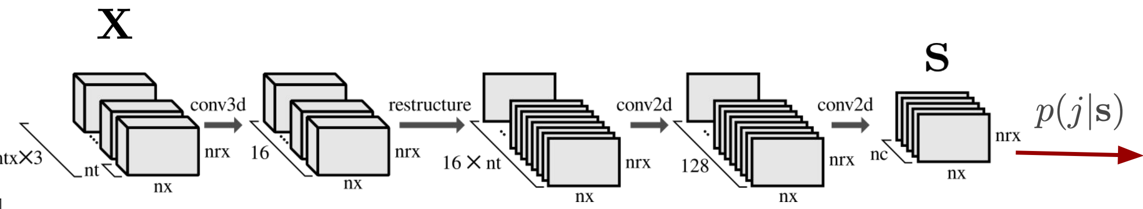
How do we translate these things to the UXO classification problem?

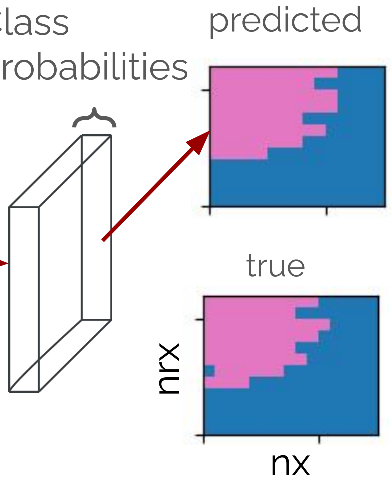
Input

Features

Neural network







$$(\boldsymbol{nx} \times \boldsymbol{nrx} \times \boldsymbol{nt} \times (\boldsymbol{ntx} \times \mathbf{3}))$$

ntx = 4, number of transmitters

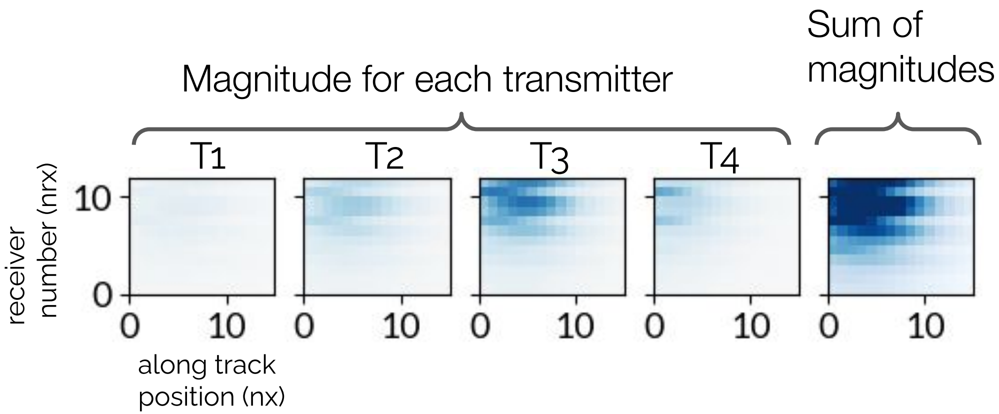
nrx = 12, number of receiver cubes

nt = 27, number of time channels

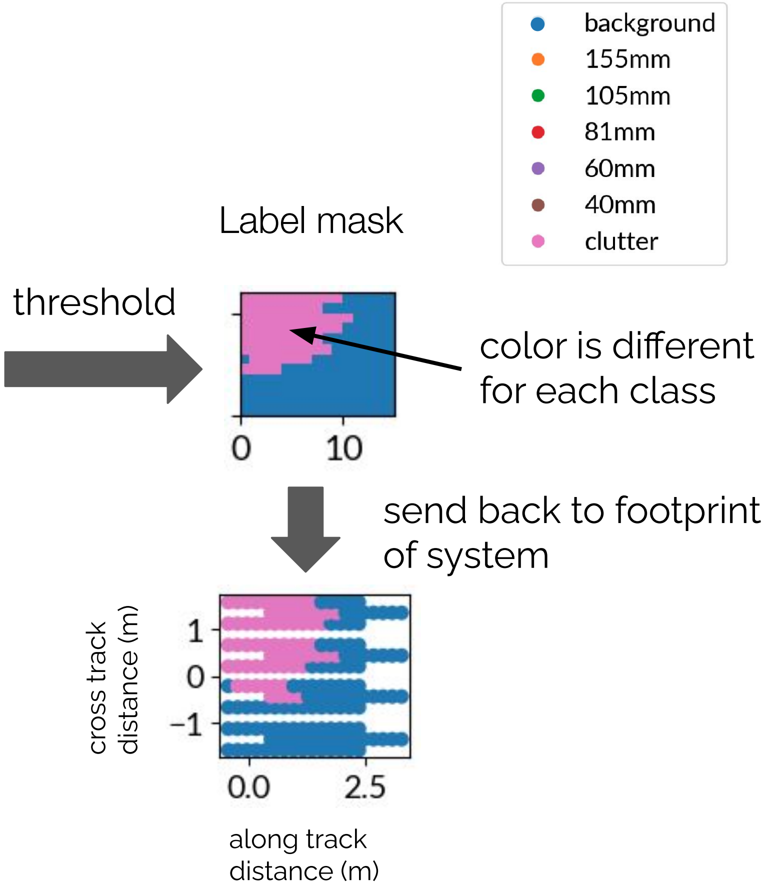
nx = 15, number of positions in spatial window (along track)

nc = 8, number of classes

Defining label masks

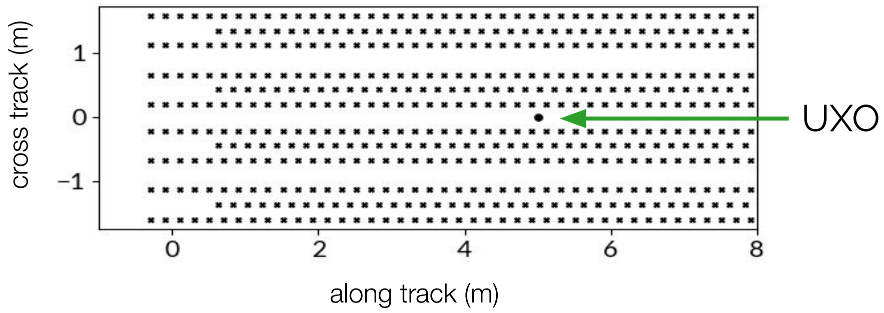


For time channel #5



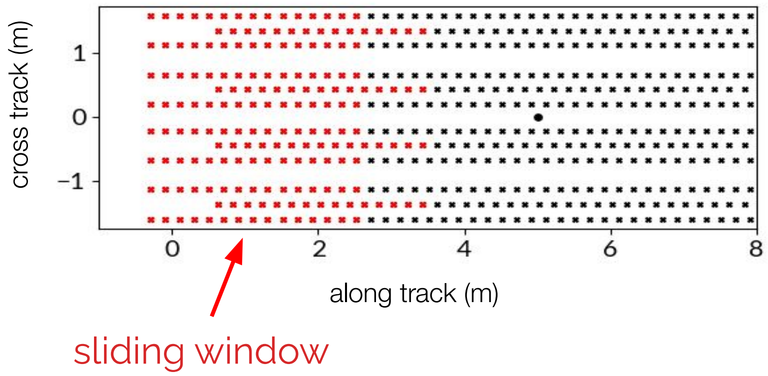
Application to a line of data

Input features are created by using a sliding window:



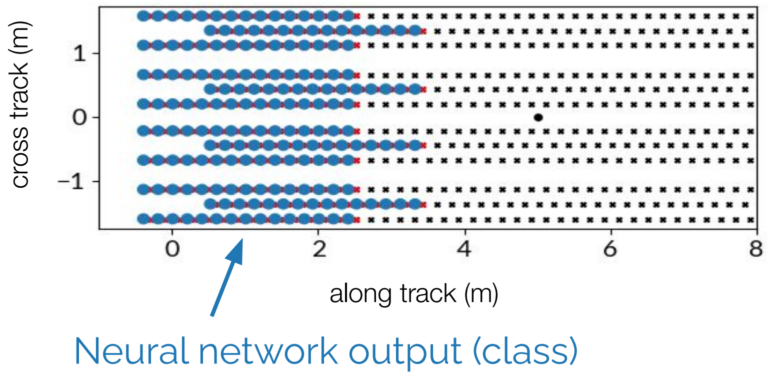
Application to a line of data

Input features are created by using a sliding window:



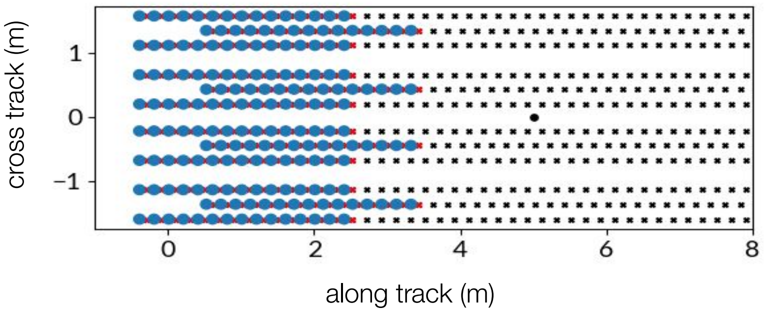
Application to a line of data

Input features are created by using a sliding window:



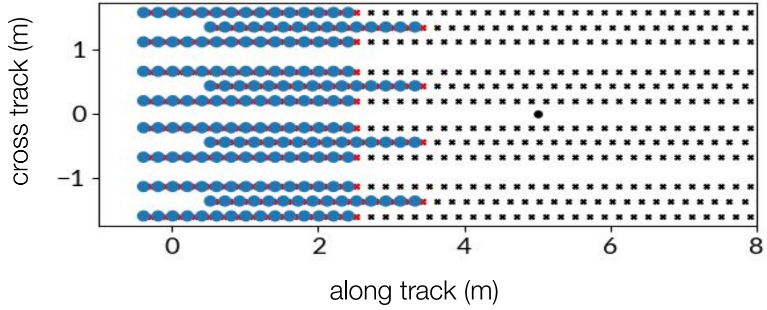
Application to a line of data

Input features are created by using a sliding window:

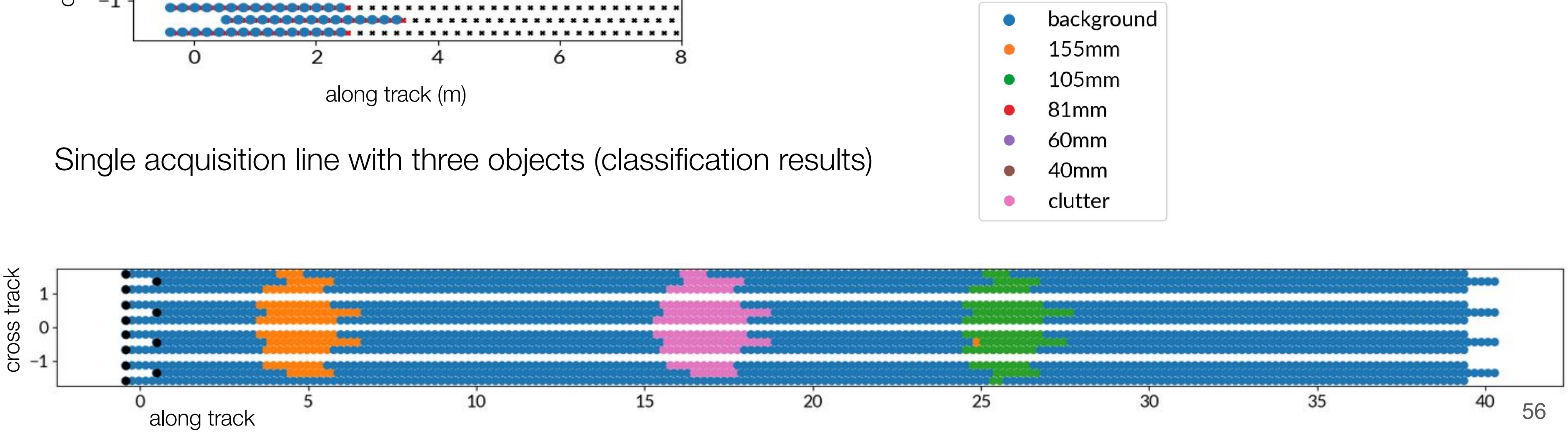


Application to a line of data

Input features are created by using a sliding window:



Single acquisition line with three objects (classification results)



Training dataset: dipole forward model

7 classes:

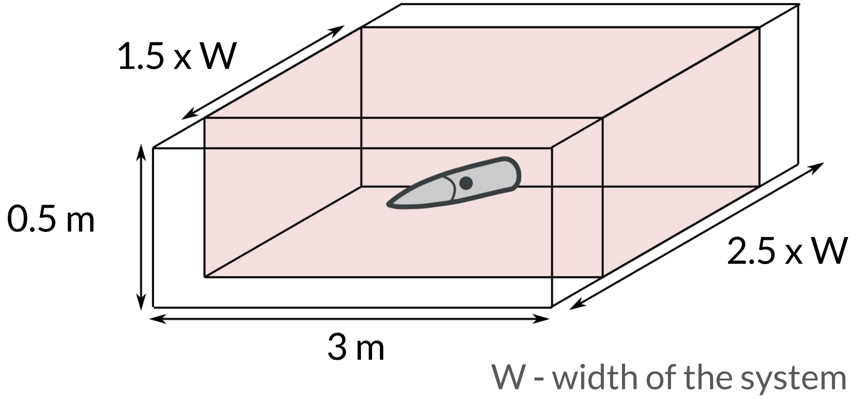
- background
- 155 mm
- 105 mm
- 81 mm
- 60 mm
- 40 mm
- clutter

# of realizations:

- Training (multi-class): 400,000
- Validation: 10,000

Randomly assign:

- Target class
- Location (x, y, z)
- Orientation (ϕ, θ, ψ)
- Noise level: approximate from background areas in the field data



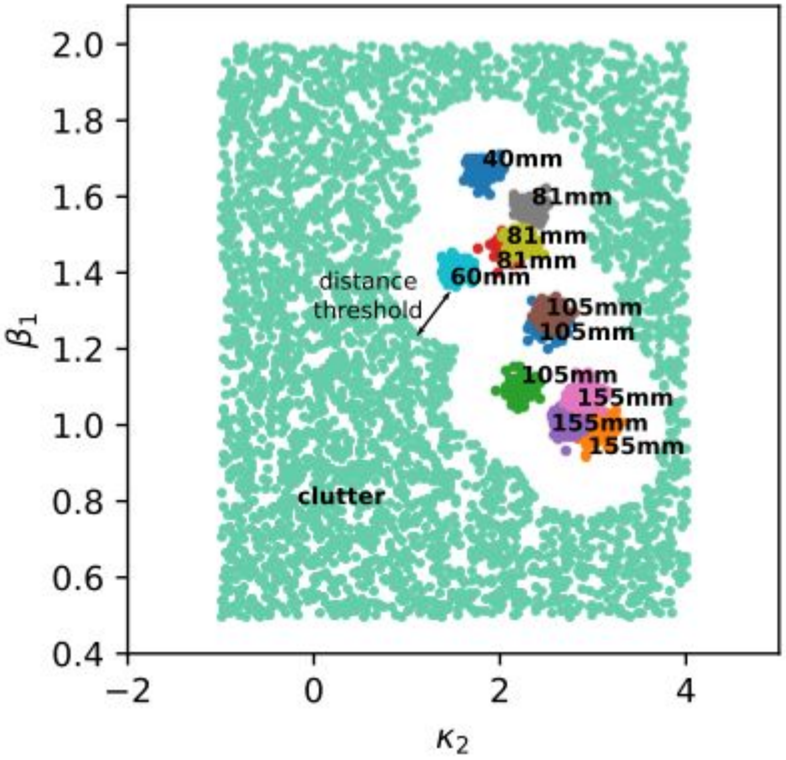
Clutter design

Physics-based parameterization of EM decay:

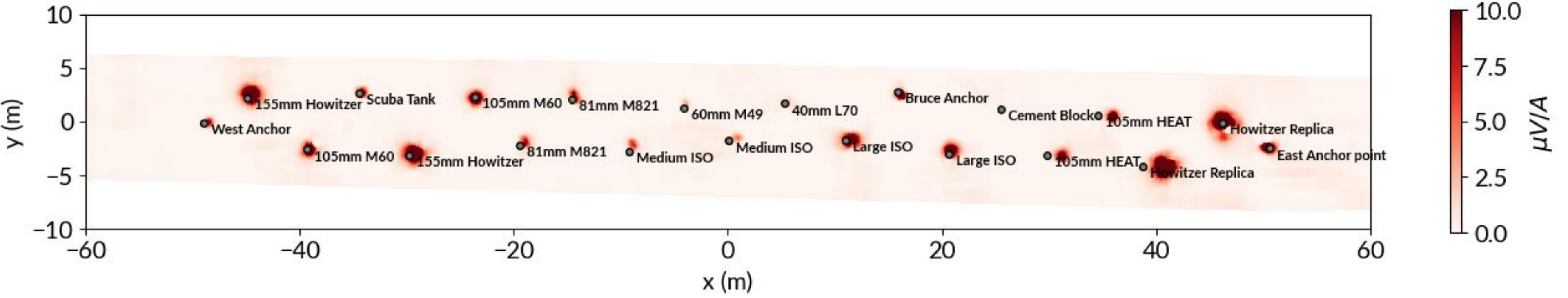
$$L(t) = kt^{-\beta}exp(-t/\gamma)$$

9 parameters in total:

1. Estimate values for UXOs in ordnance library
2. Define a distance threshold
3. Fill the remaining space with clutter objects

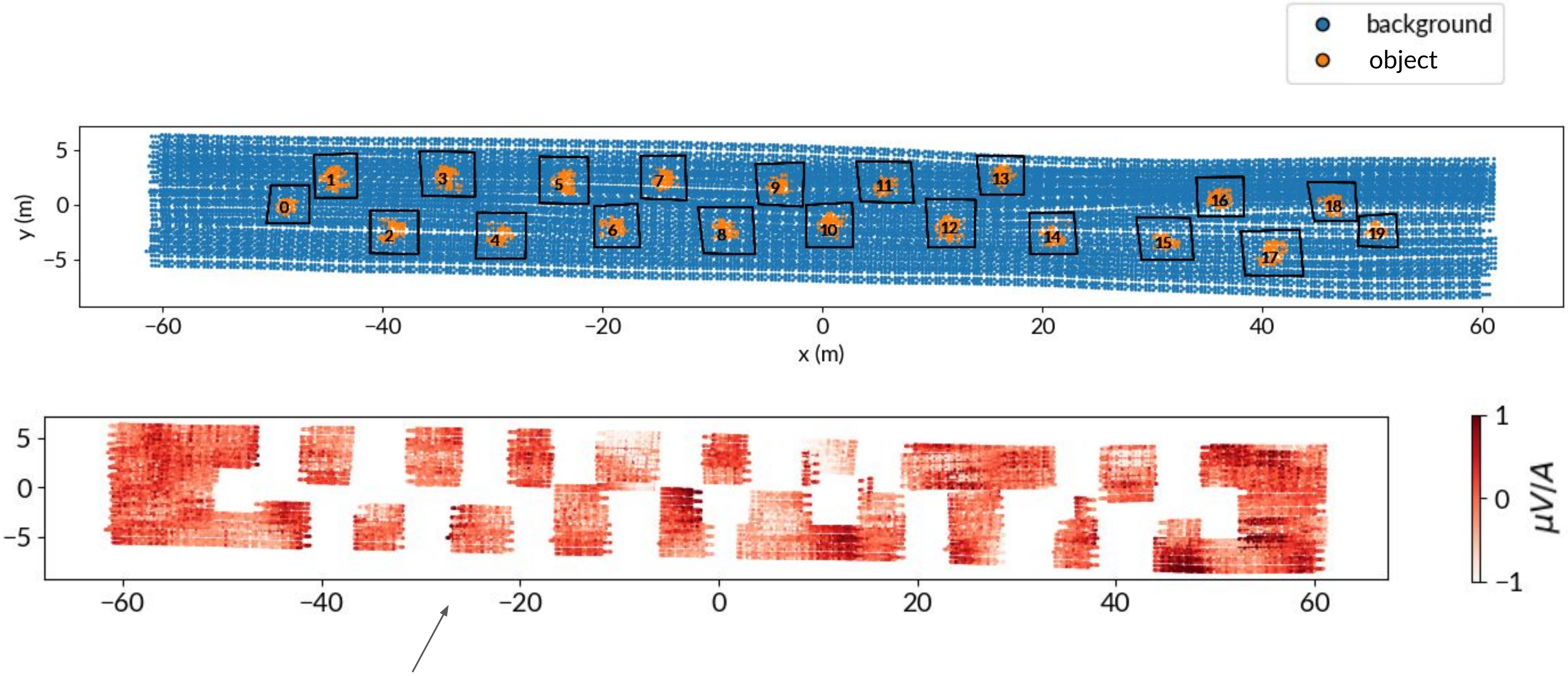


Field data - Sequim Bay test site (2022)



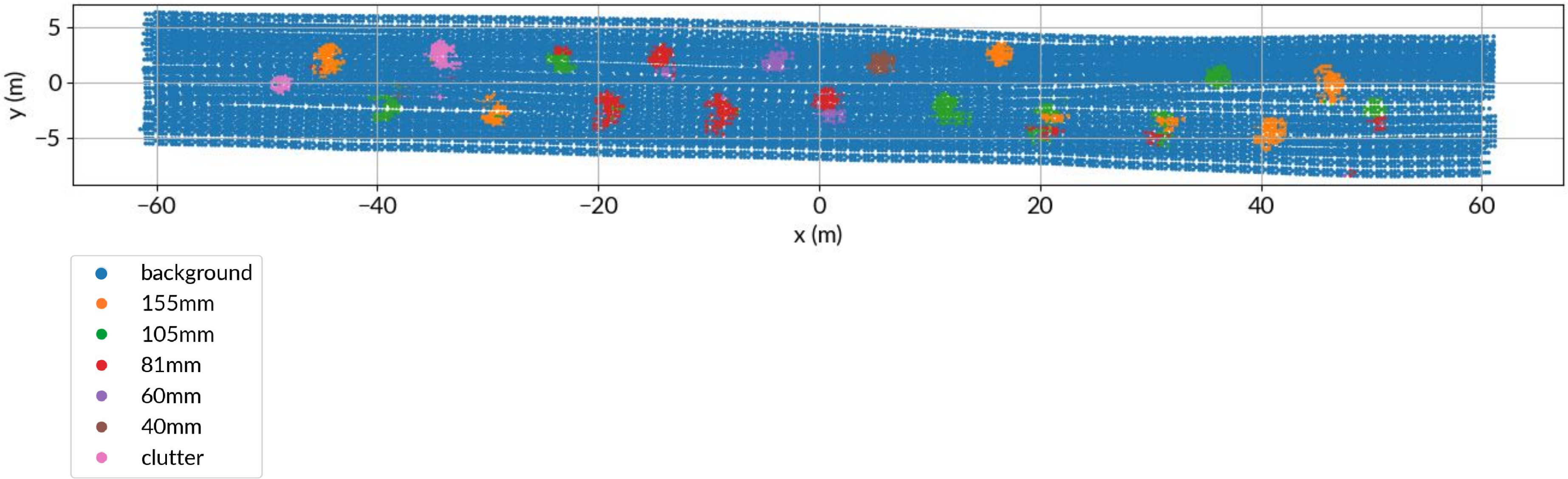
- 7 acquisition lines
- Current workflow requires seawater response removed
- Some ISOs present, we used only UXO objects to train (e.g. medium ISO ~ 81mm)

Get correlated noise using a binary classifier

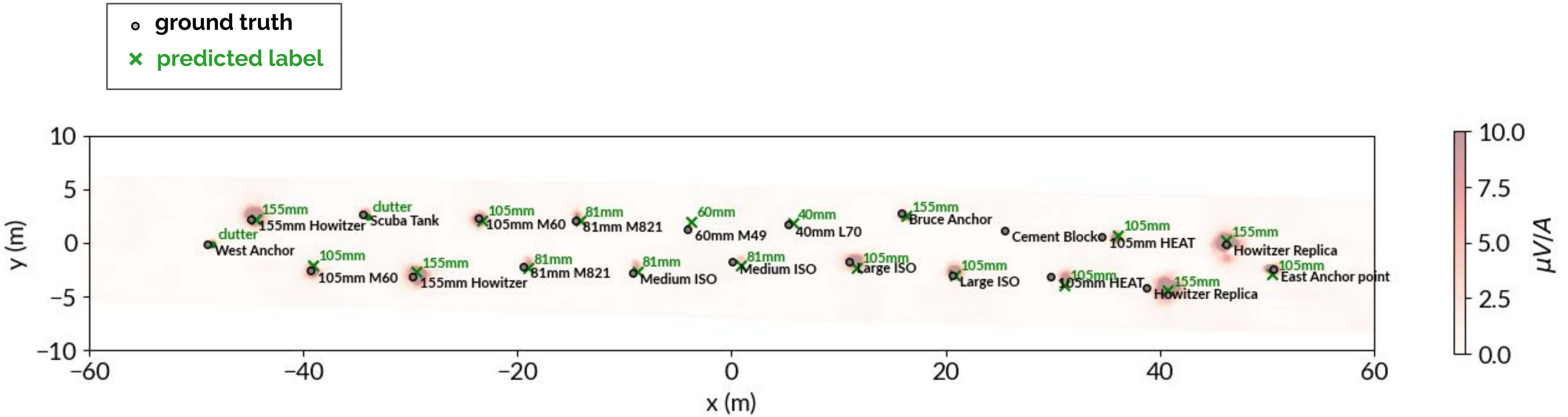


get spatially correlated noise from this subset of field data

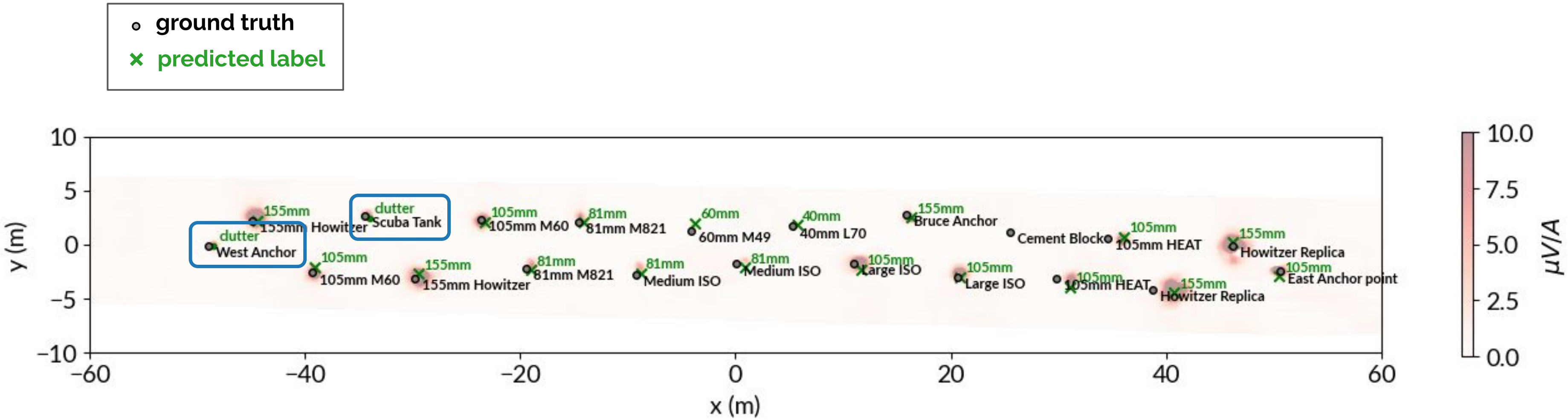
Classification map (output of CNN)



Predicted labels vs truth labels - field data

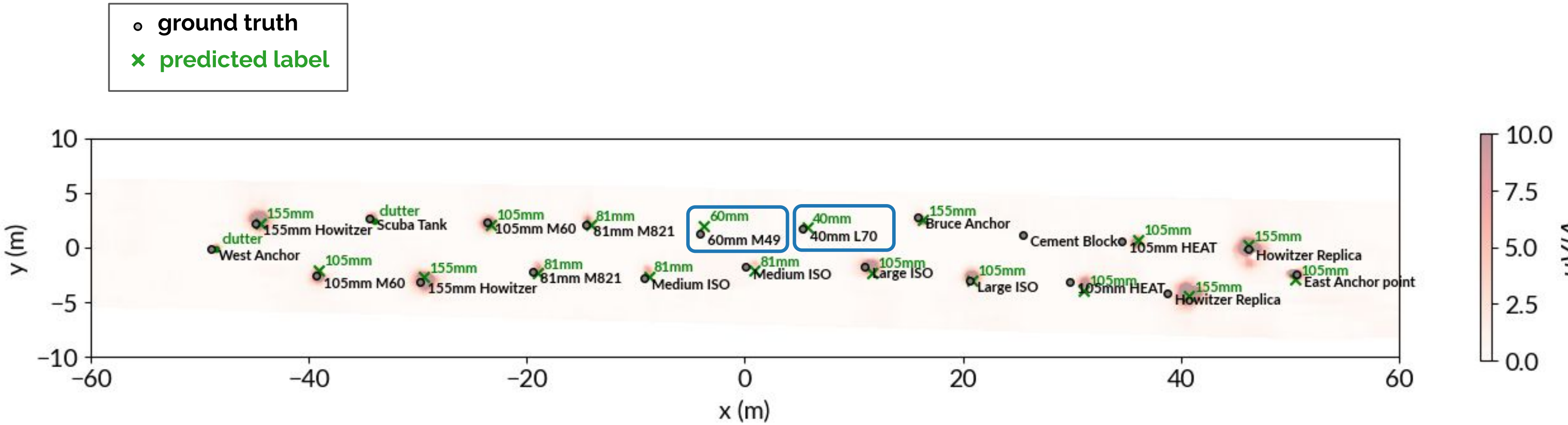


Predicted labels vs truth labels - field data



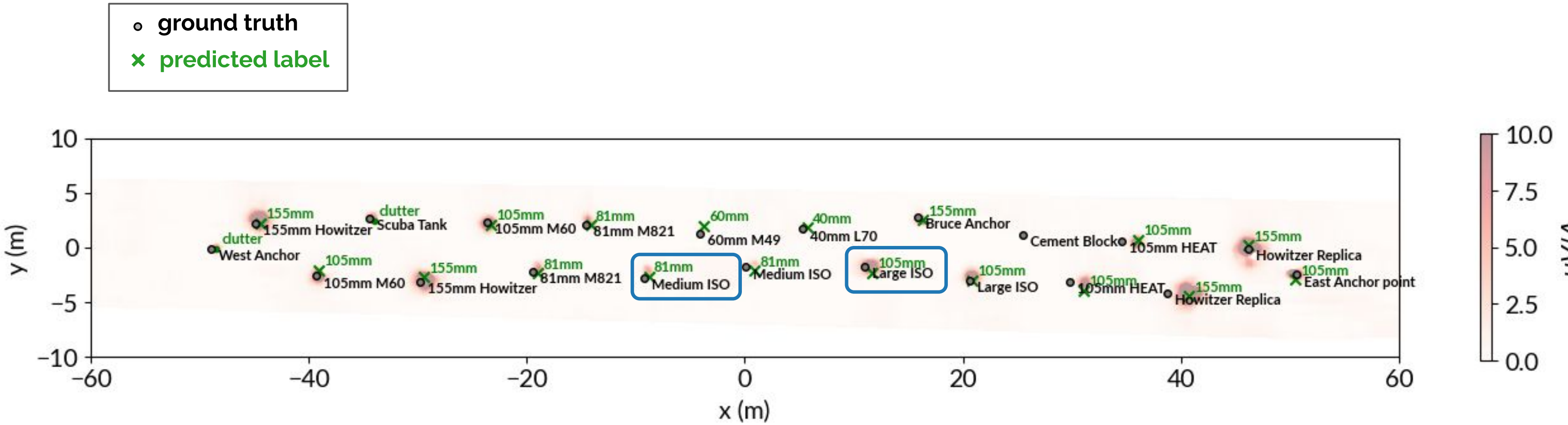
- Discriminated clutter

Predicted labels vs truth labels - field data



- Discriminated clutter
- Did not miss any UXO

Predicted labels vs truth labels - field data



- Discriminated clutter
- Did not miss any UXO
- Classified to closest object in training dataset

UXO classification

Key points:

- image-segmentation architecture
- clutter design and correlated noise are important

Some limitations:

- not trained to handle multiple objects in the same window
- objects used to generate synthetic data should be close to the objects on the field

Future work:

- explore multi-target scenario (maybe instance segmentation)
- combining with traditional approach

important problems

Electrical conductivity can be a diagnostic physical property in many settings

Electromagnetic methods can be useful across a wide range of scales

Numerical tools for simulation, inversion, machine learning enable understanding of physical responses, invaluable for interpretation of data

Thank you!

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