SUSTech Southern University of Science and Technology

南方科技大学
SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY

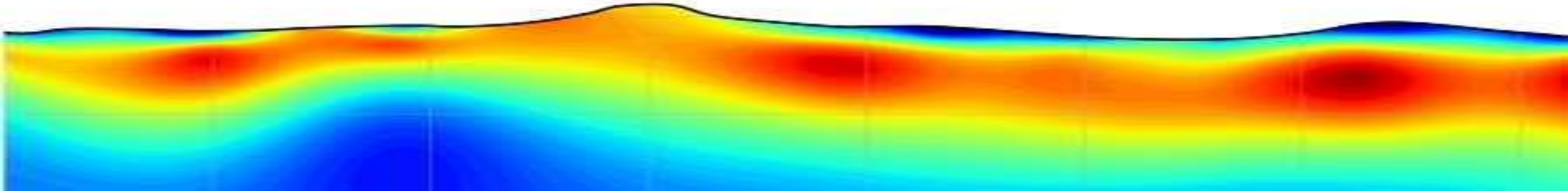
地球与空间科学系
DEPARTMENT OF EARTH AND SPACE SCIENCES

ESS302 Applied Geophysics II

Gravity, Magnetic, Electrical, Electromagnetic and Well Logging

Electromagnetic 5: Induction Part C

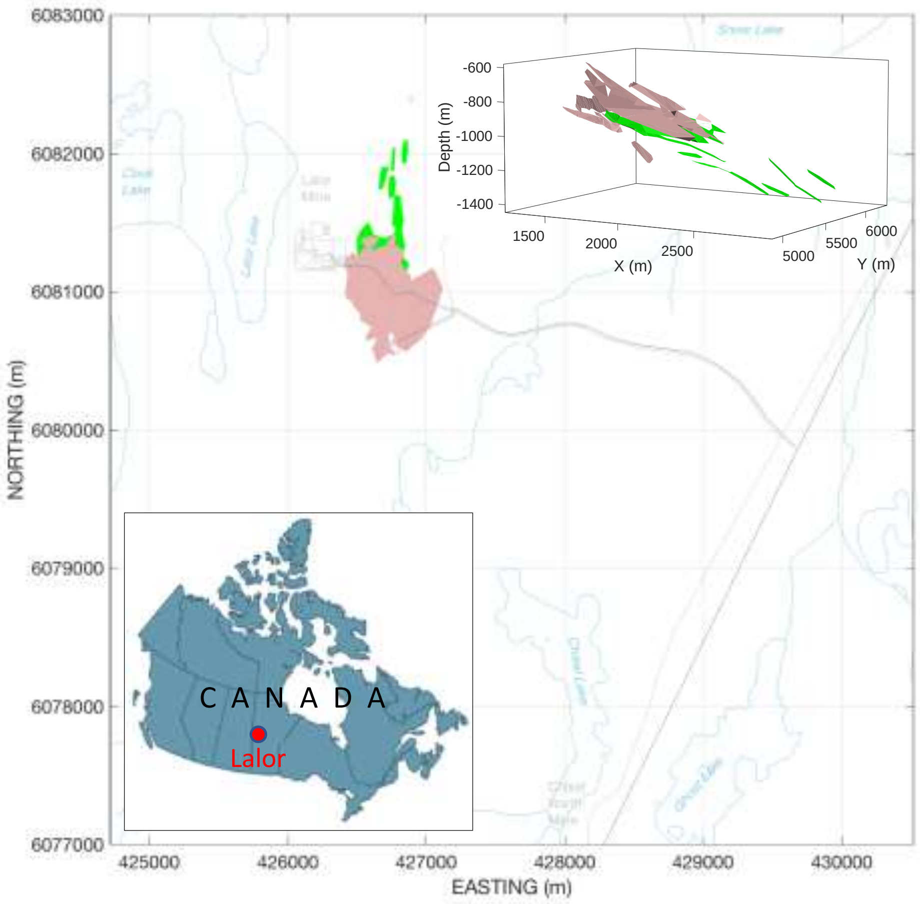
Instructor: Dikun Yang   Feb – May, 2019

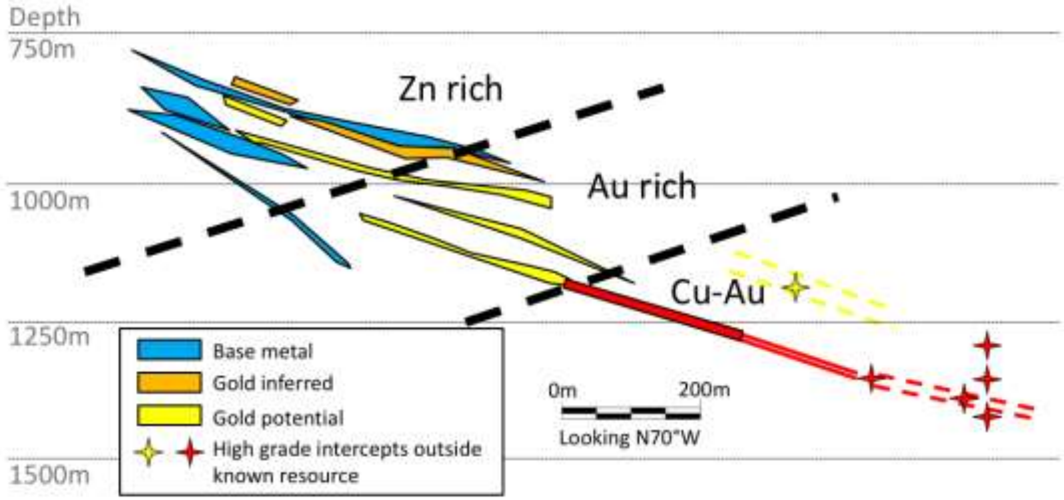


EM Research Frontier – Multi-scale 3D EM

A Case Study at Lalor Mine, Manitoba, Canada

Lalor VMS Mine





EM Surveys at Lalor

- HELITEM
- Jessy HTS SQUID
- ZTEM
- VTEM
- UTEM3/UTEM5
- Borehole TEM (DigiAtlantis, Crone, Volterra)

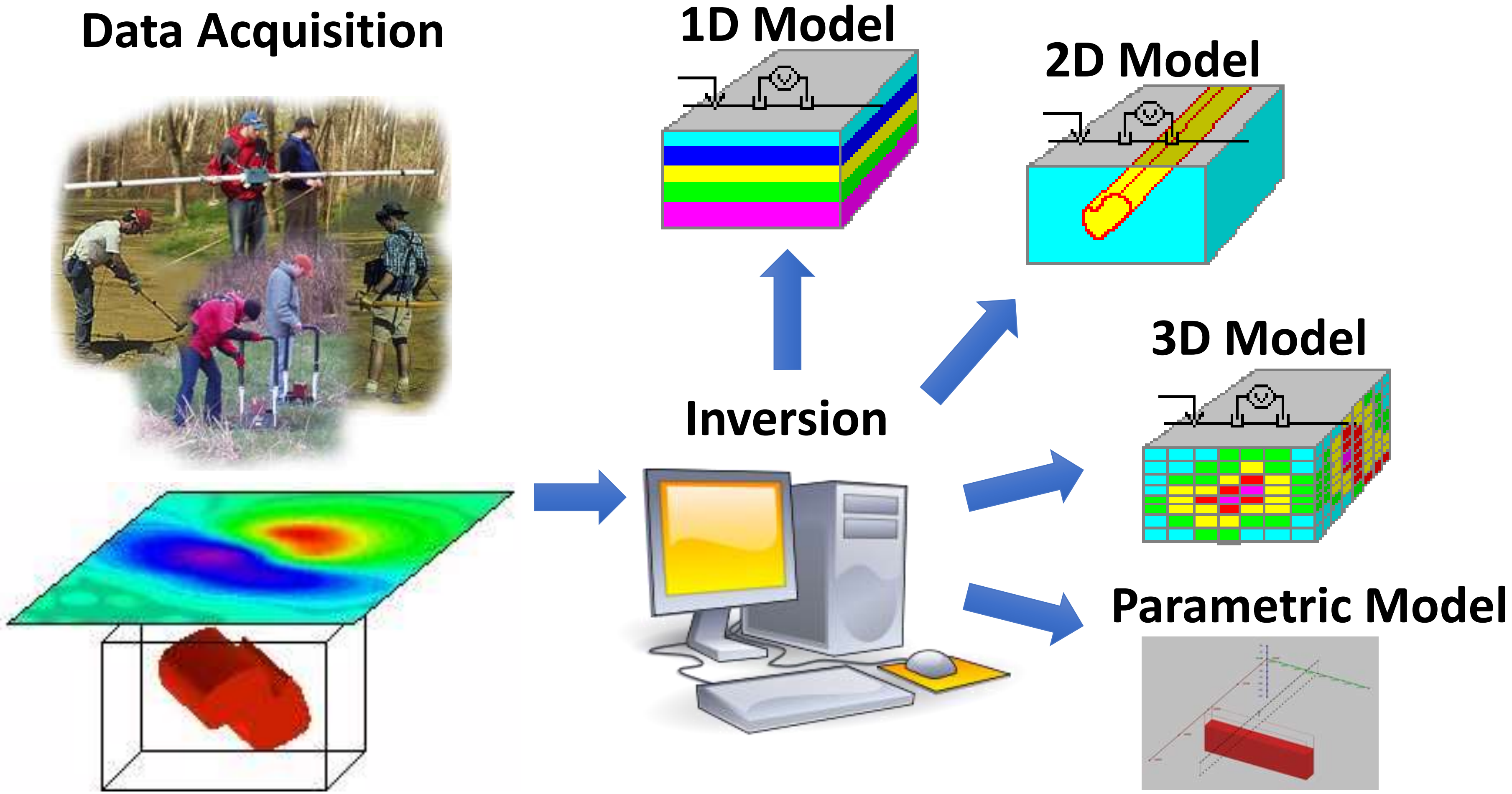
- ELF
- MT/AMT
- DCIP
- Ground FDEM

What do different surveys tell us about the mineral deposit at depth?

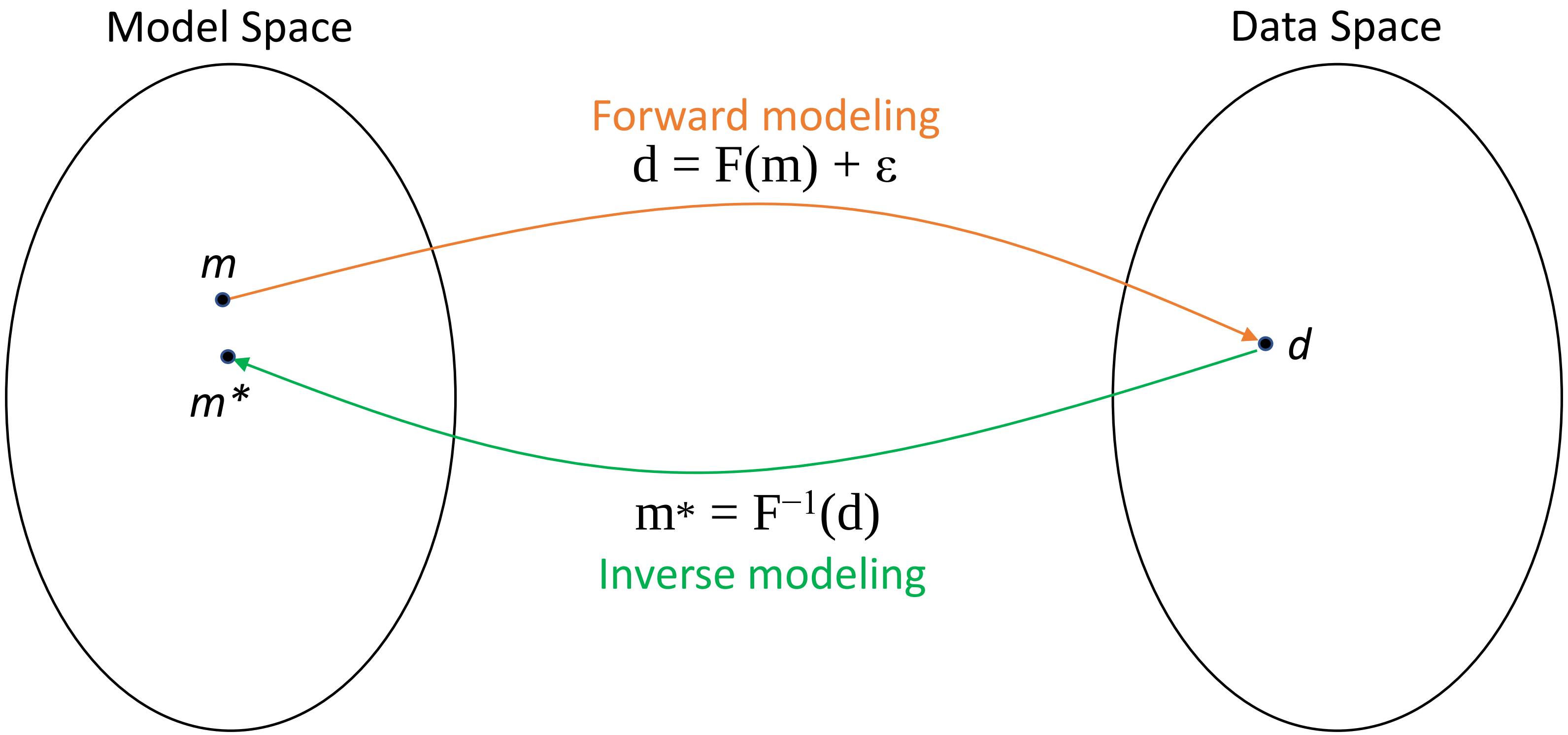
OUTLINE

- Capability: 3D inversion of EM data
- Select EM data sets at Lalor
  - Natural source: ZTEM
  - Airborne: HELITEM
  - Ground: SQUID
  - Borehole: Crone Pulse-EM
- 3D inversion results
- Unified model: Joint and cooperative inversion
- Conclusions

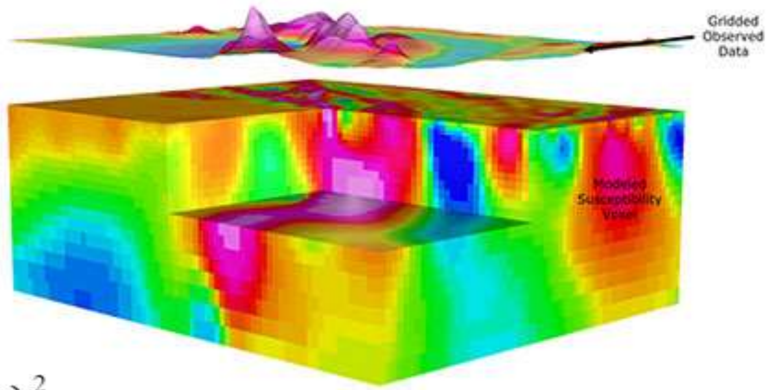
Geophysical Inversion



Inverse Problem as Parameter Estimation



Regularized (Pixel/Voxel) Inversion



Objective functional $$\underset{\mathbf{m},\beta}{\text{minimize}} \quad \phi_d(\mathbf{m}) + \beta\,\phi_m(\mathbf{m})$$

Data misfit $$\phi_d = \frac{1}{2}\sum_{i=1}^{N}\left(\frac{F_i(\mathbf{m}) - \mathbf{d}_i^{obs}}{\varepsilon_i}\right)^2$$

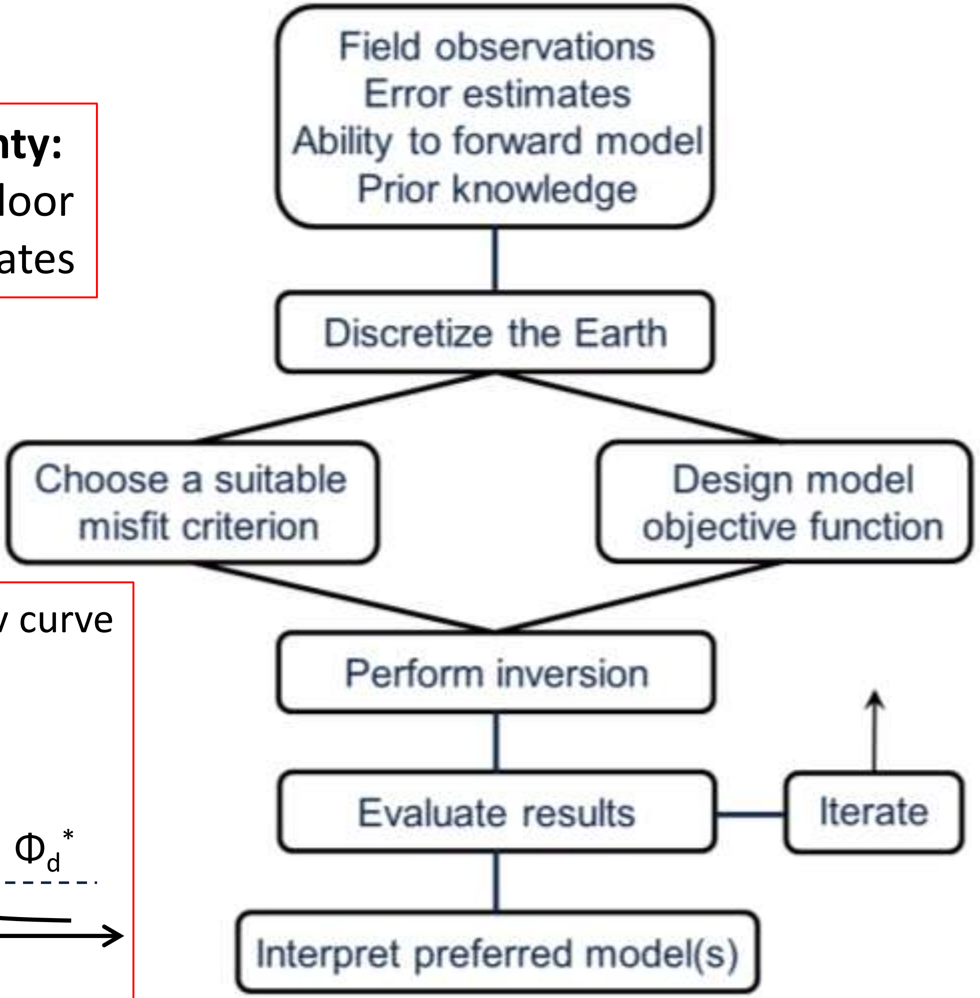
Model norm $$\phi_m = \frac{1}{2}\alpha_s \int_{\Omega} \{\mathbf{w}_s(\mathbf{m}-\mathbf{m}^{ref})\}^2 dv + \frac{1}{2}\sum_{i=x,y,z} \alpha_i \int_{\Omega} \left\{\mathbf{w}_i \frac{\partial(\mathbf{m}-\mathbf{m}^{ref})}{\partial_i}\right\}^2 dv$$

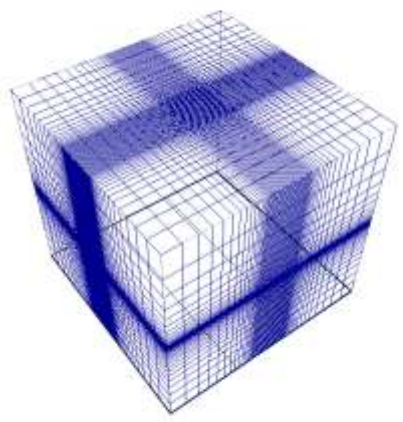
Inversion Parameters

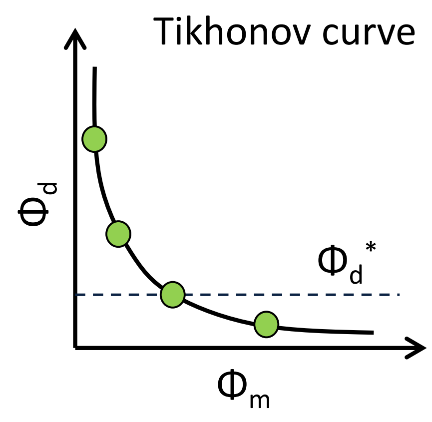
Forward modeling $F_i(\mathbf{m})$: solving the governing equations
Data uncertainty ε_i : relative weighting of data
Trade-off parameter β : balance wellness of data fitting and the complexity of model
Reference model $\mathbf{m}^{ref}$: a prior information about the model
Model norm weighting: α_s smallest model; α_i flattest model
Cell weighting $\mathbf{w}_s$ and $\mathbf{w}_i$: amount of structure at each cell or cell faces

Inversion Work Flow

Data uncertainty:
percentage + floor
or other estimates

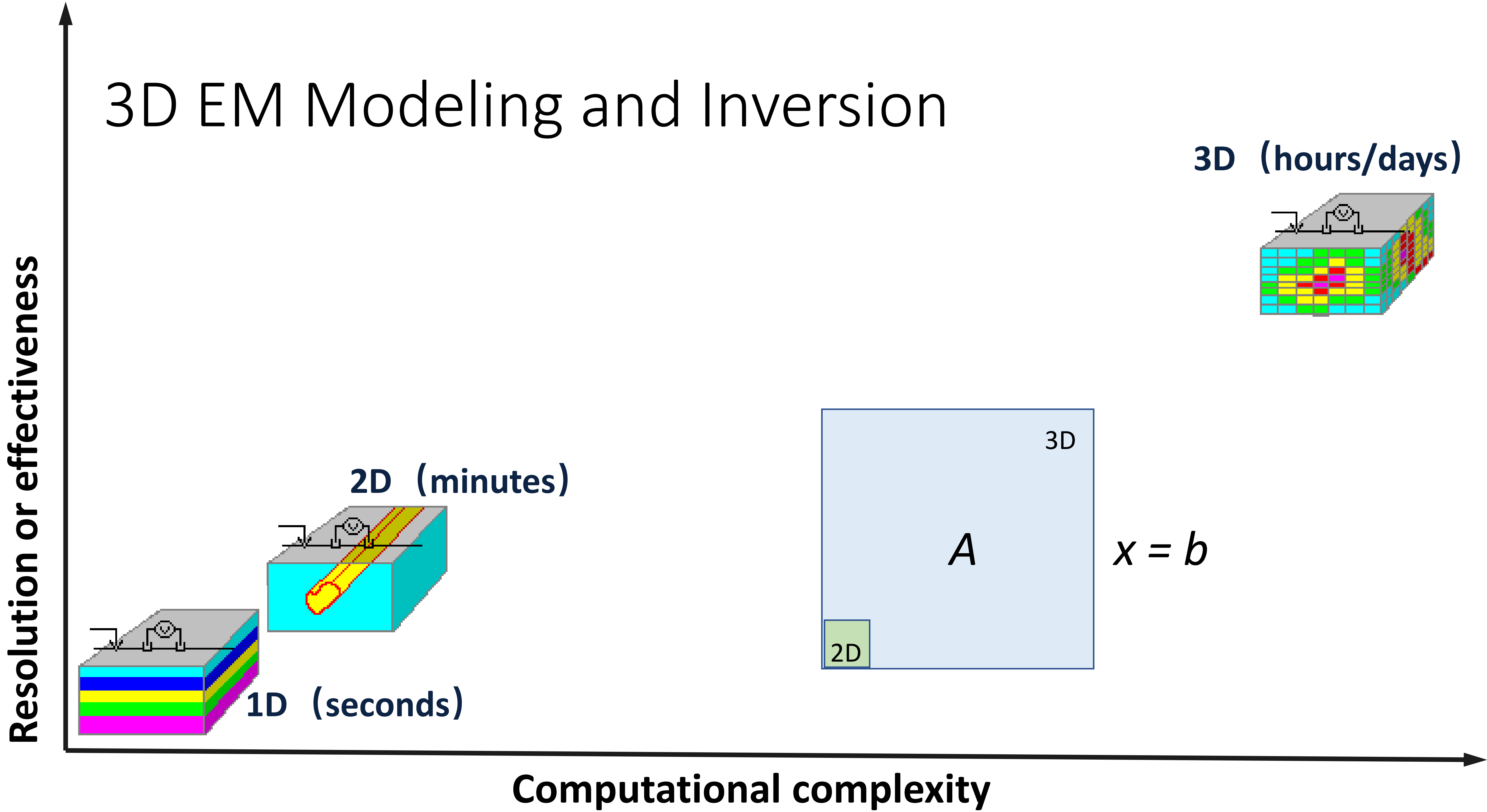




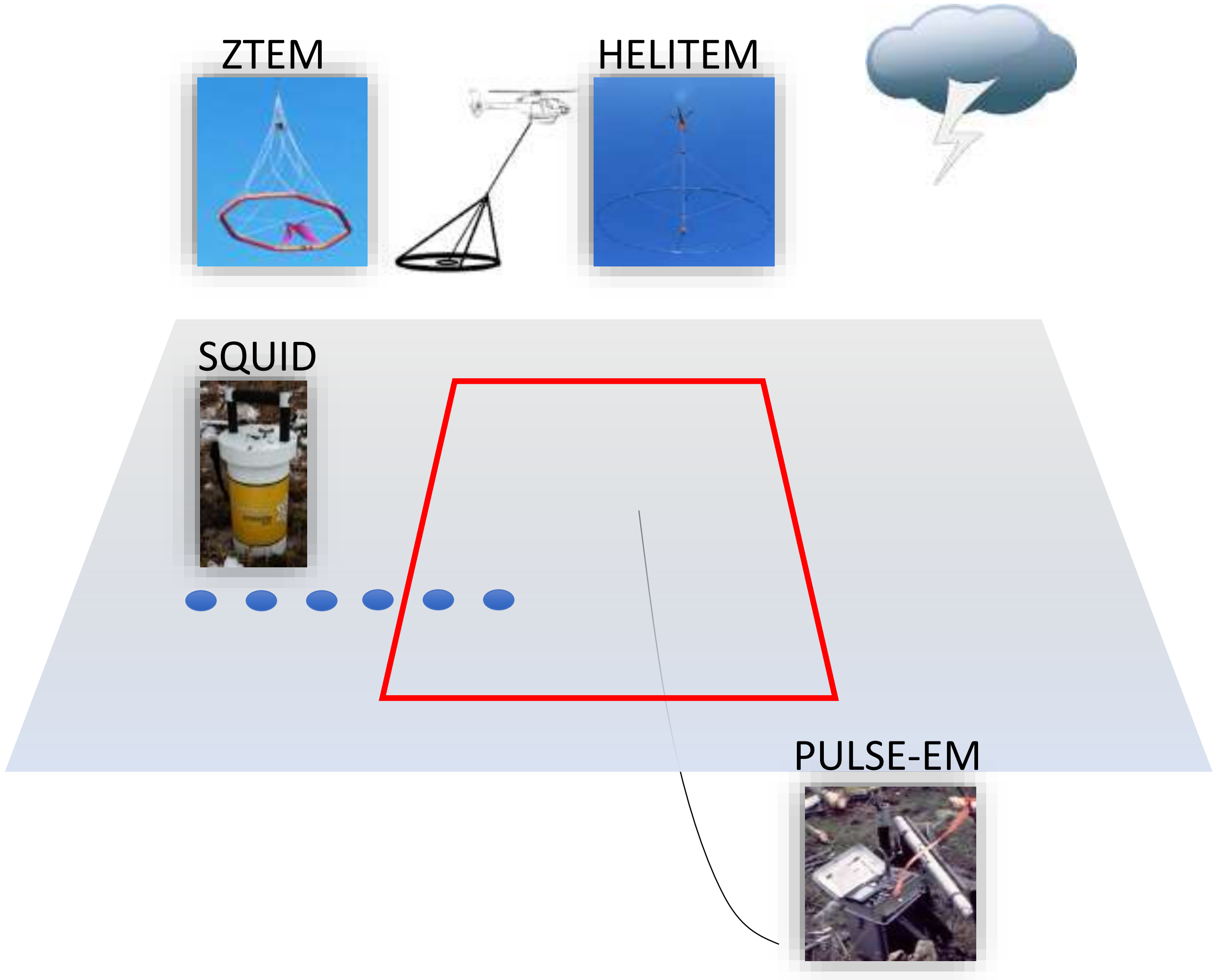


Reference model:
Half-space or
other reasonable
guess

3D EM Modeling and Inversion



EM Data Sets at Lalor



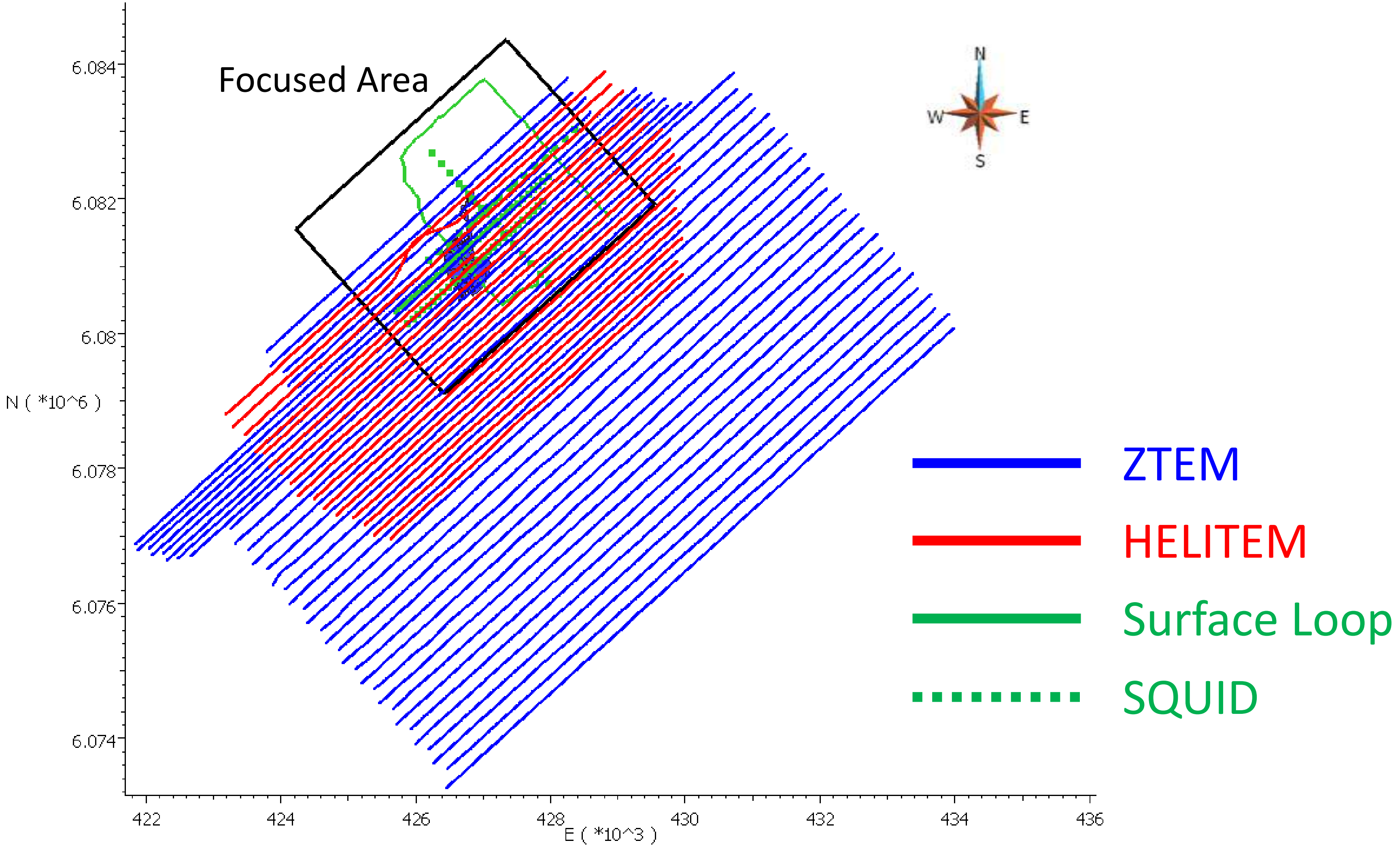
HELITEM:
- airborne
- time-domain

ZTEM:
- airborne
- frequency-domain
- natural source

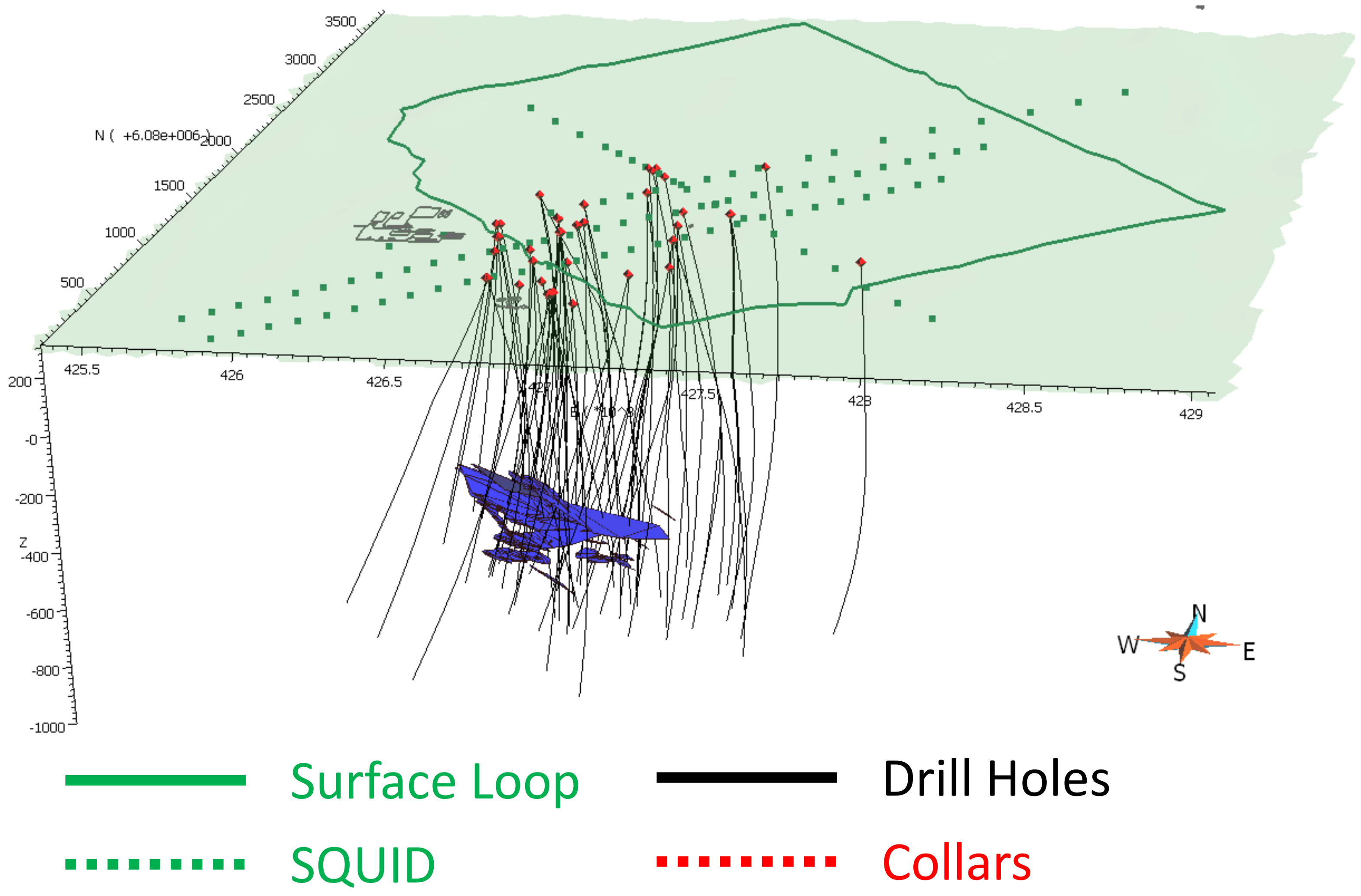
SQUID:
- surface
- time-domain

PULSE-EM:
- borehole
- time-domain

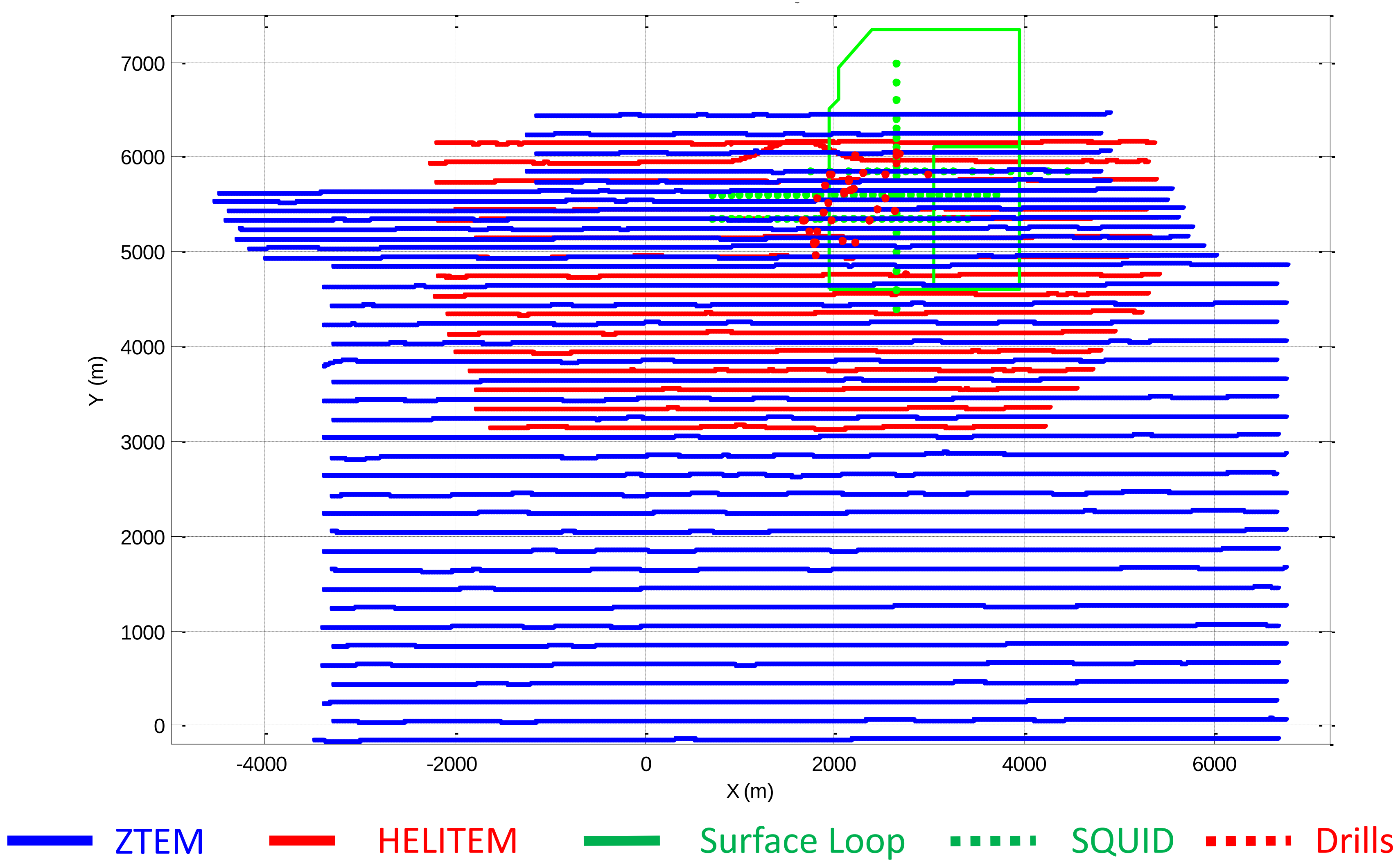
Data Locations



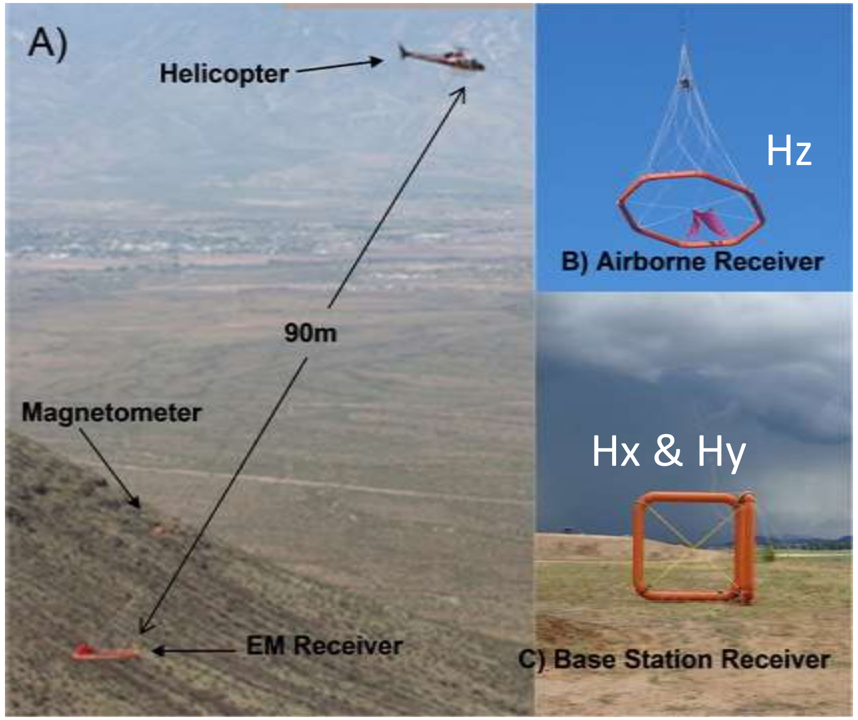
Data Locations



Data Locations

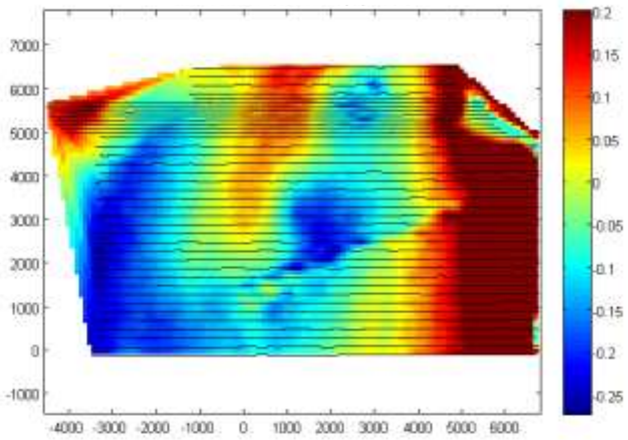


ZTEM Data

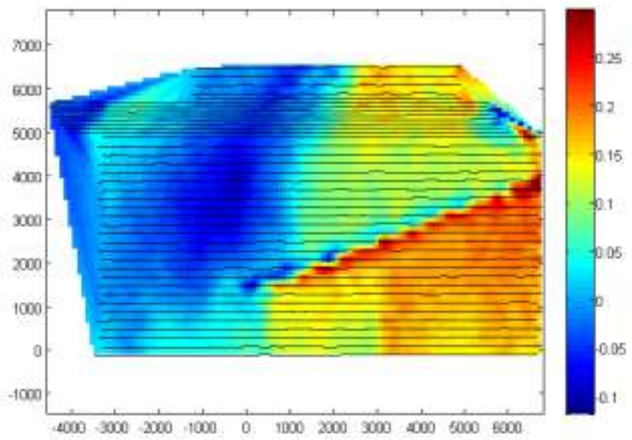


Frequencies:
30, 45, 90, 180, 360, 720 Hz

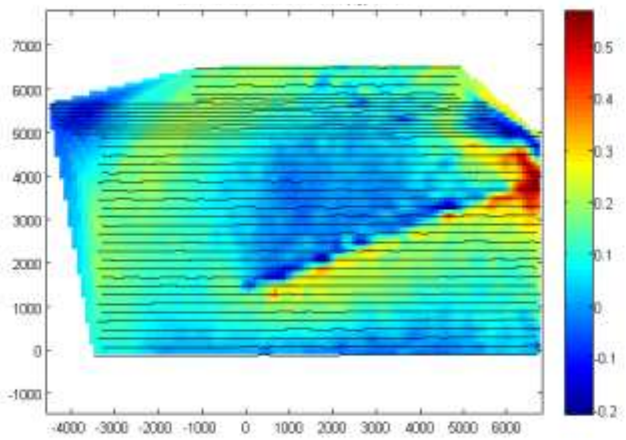
30 Hz Real(Tzx)



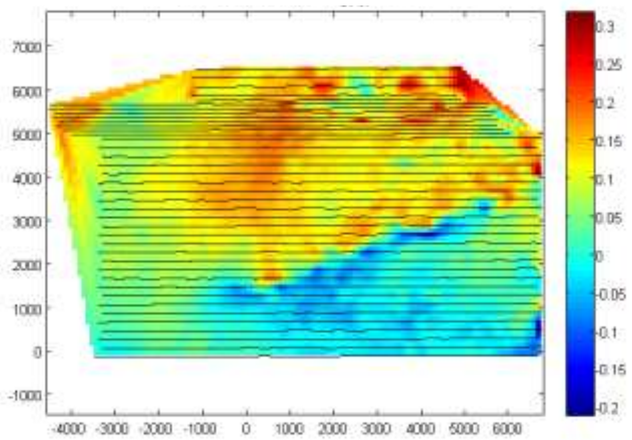
30 Hz Imag(Tzx)



30 Hz Real(Tzy)

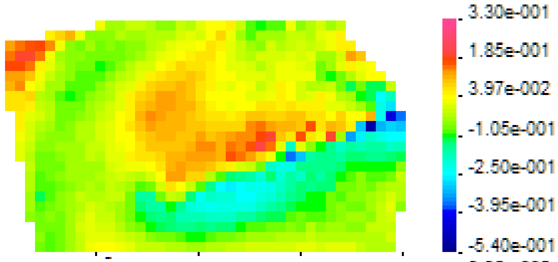


30 Hz Imag(Tzy)

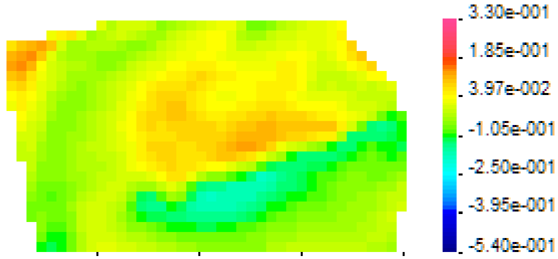


ZTEM Data Fitting

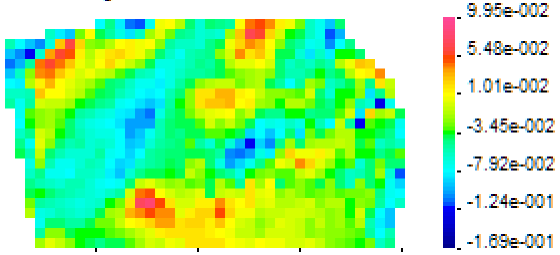
Obs.
Real(Tzx)
180 Hz



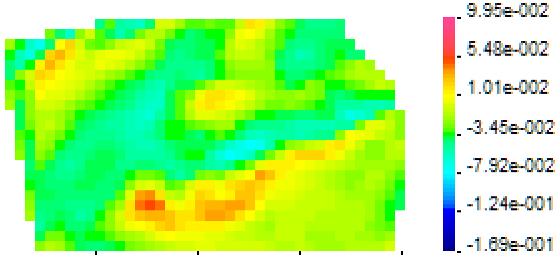
Pred.
Real(Tzx)
180 Hz



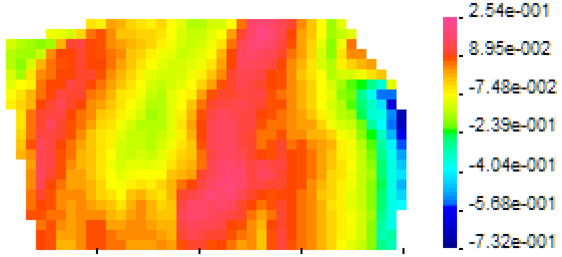
Obs.
Imag(Tzx)
180 Hz



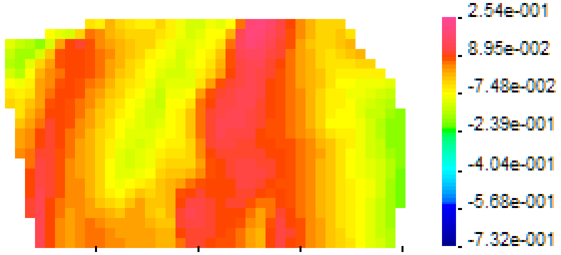
Pred.
Imag(Tzx)
180 Hz



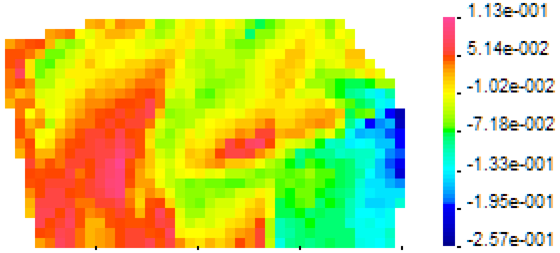
Obs.
Real(Tzy)
180 Hz



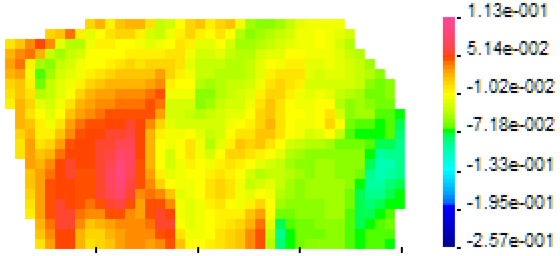
Pred.
Real(Tzy)
180 Hz



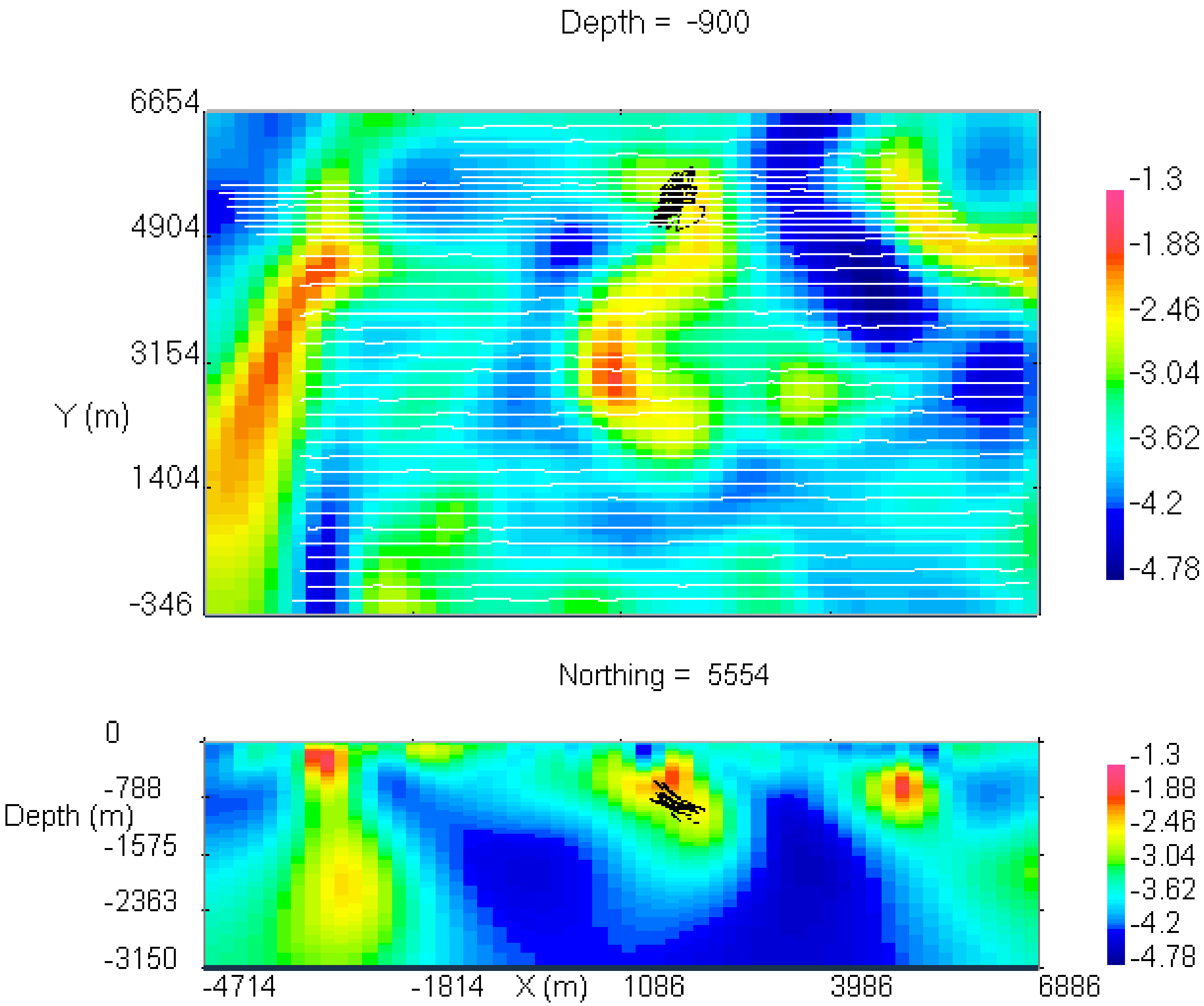
Obs.
Imag(Tzy)
180 Hz



Pred.
Imag(Tzy)
180 Hz



ZTEM Model

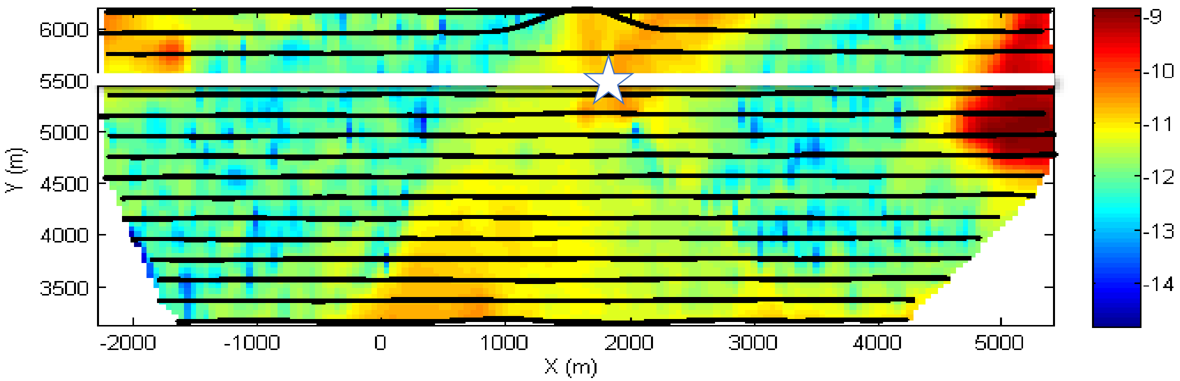


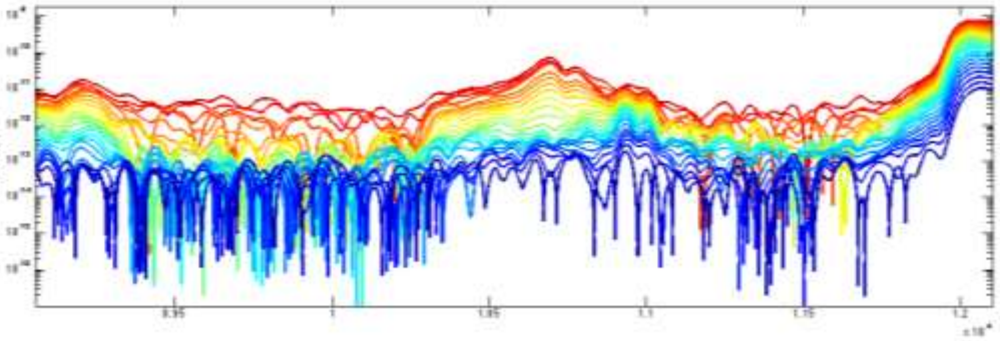
Pros:
- Regional structure
- Good depth resolution

Cons:
- Conductivity of the VMS ore body underestimated?

HELITEM Data

Time Channel = 0.3 msec





Base frequency:
30 Hz

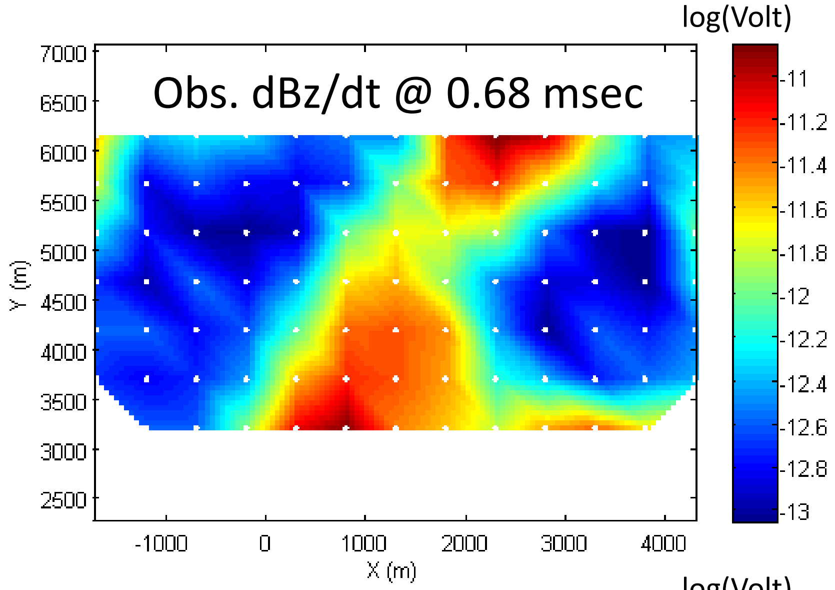
Tx moment:
1.9 millions Am^2

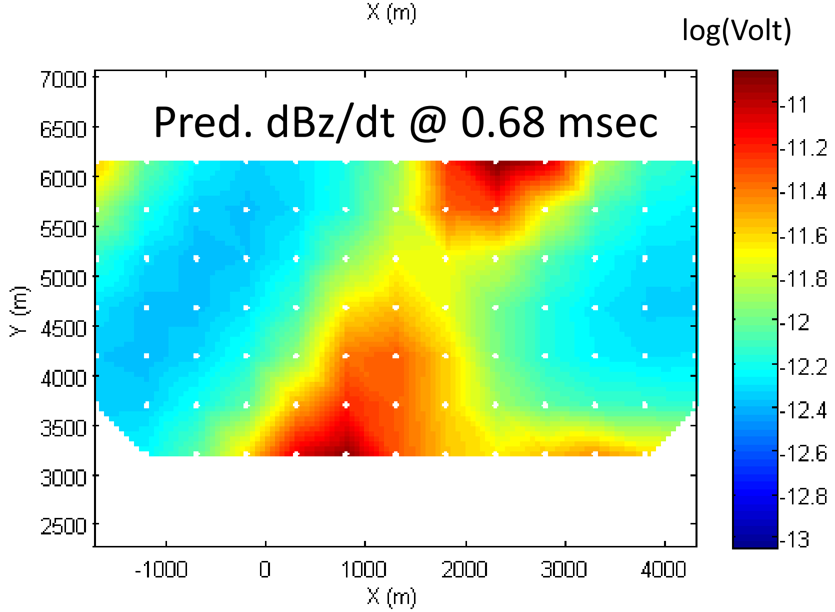
Time channels:
0.0098 ~ 15.77 msec

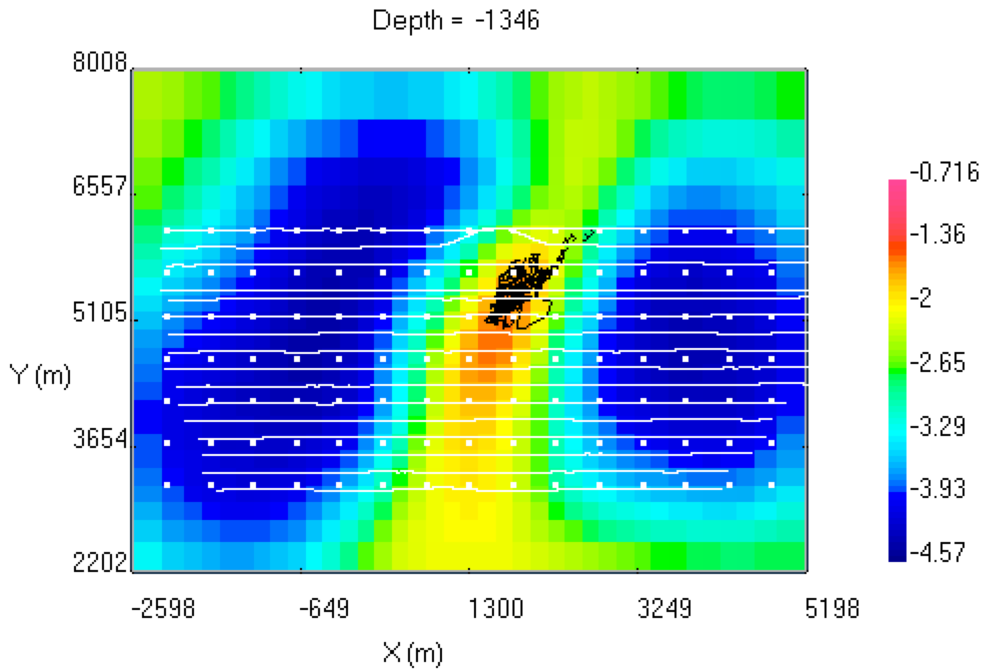
Line spacing:
200 m

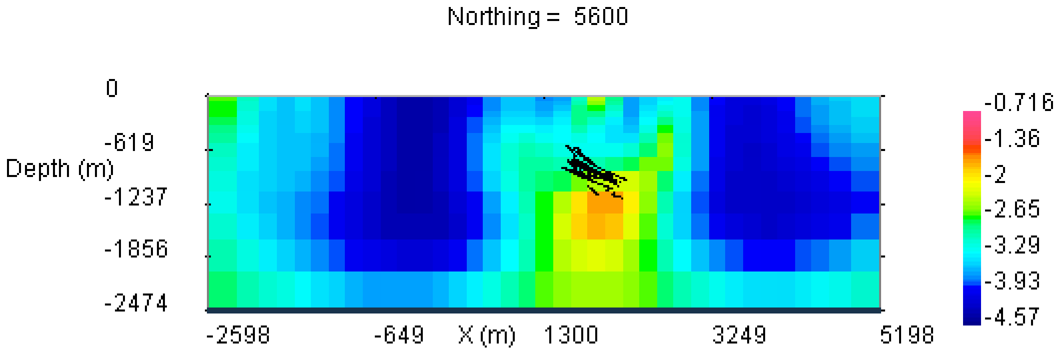
Issues:
Power line
Cultural
Noise

HELITEM Data Inversion









Pros:

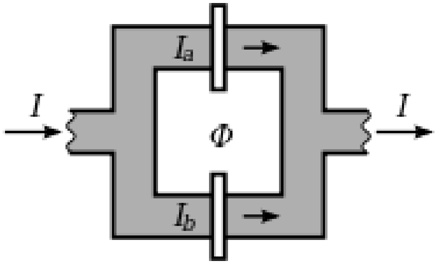
- Good assessment on the overall conductivity
- Regional trend

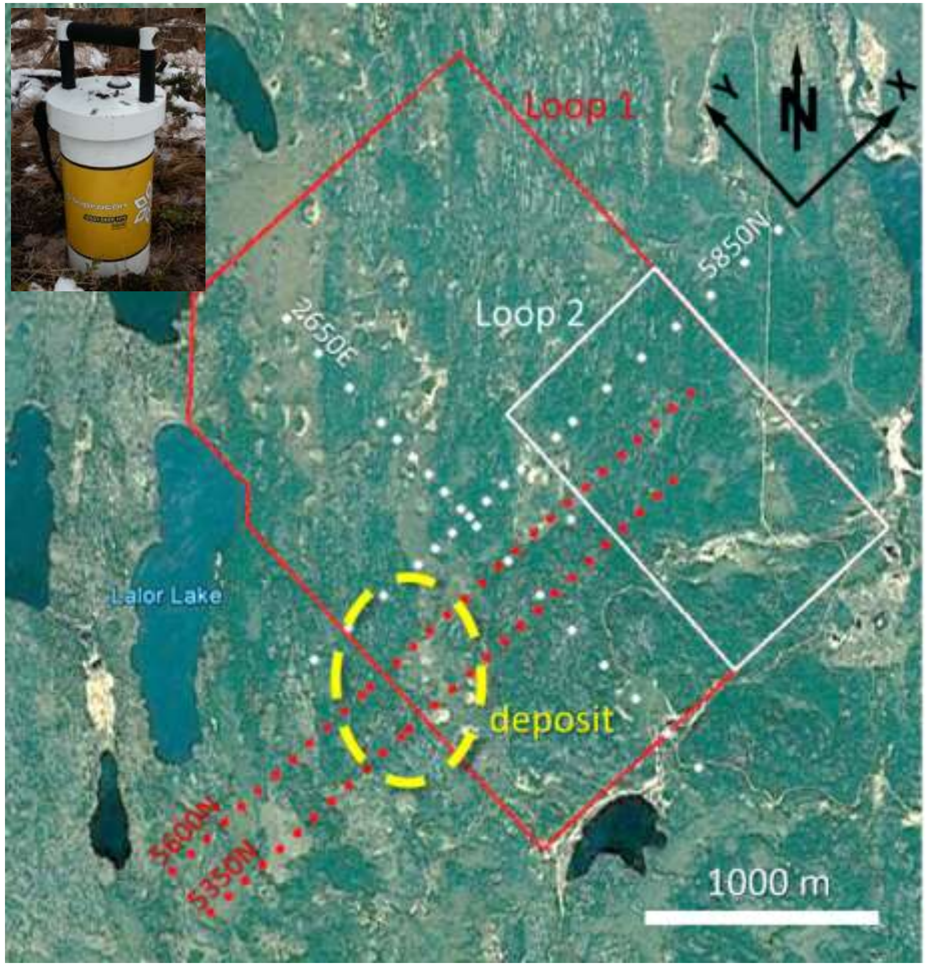
Cons:

- Conductor too deep?

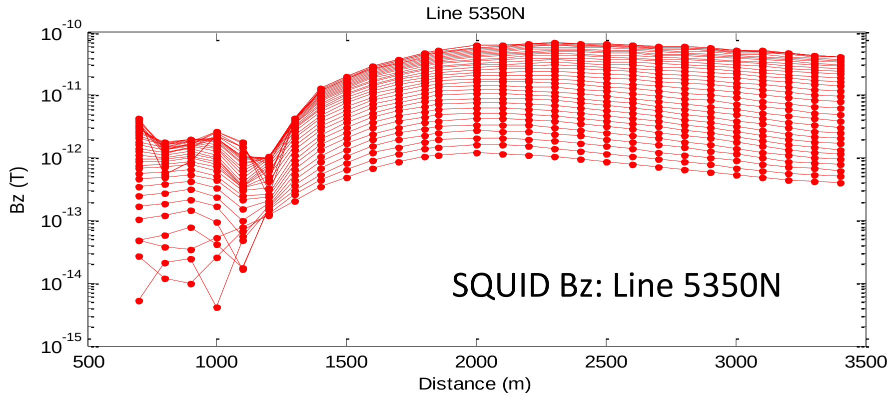
SQUID TEM Data

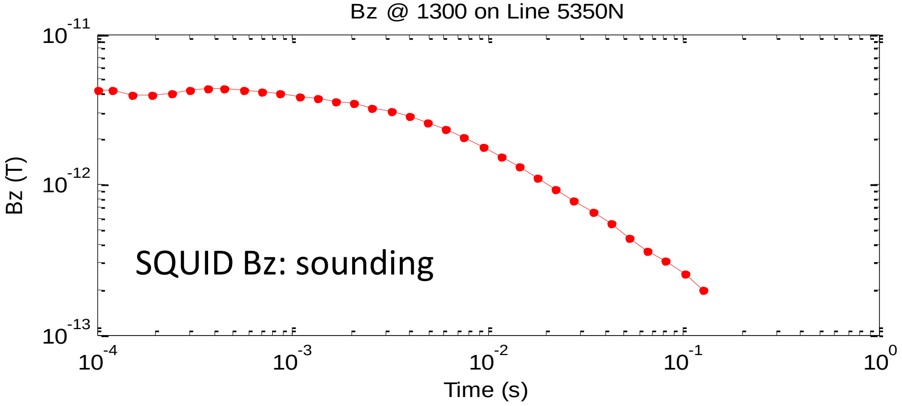
Superconducting
QUantum
Interference Device



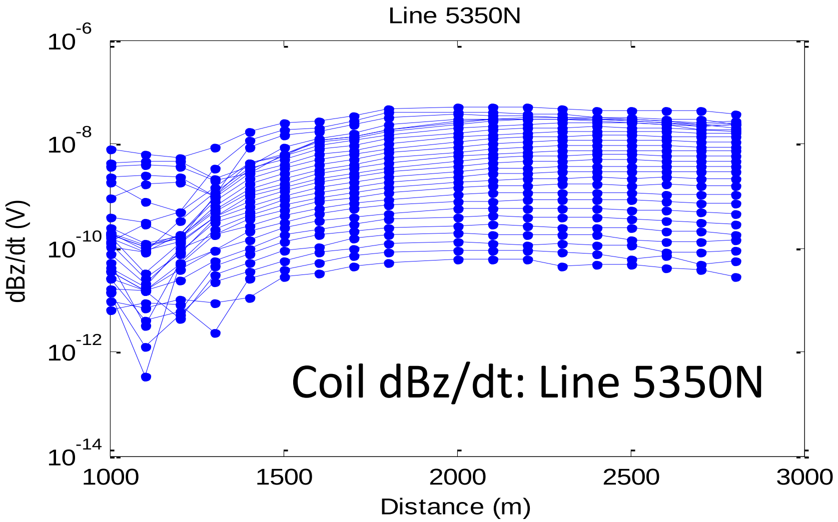


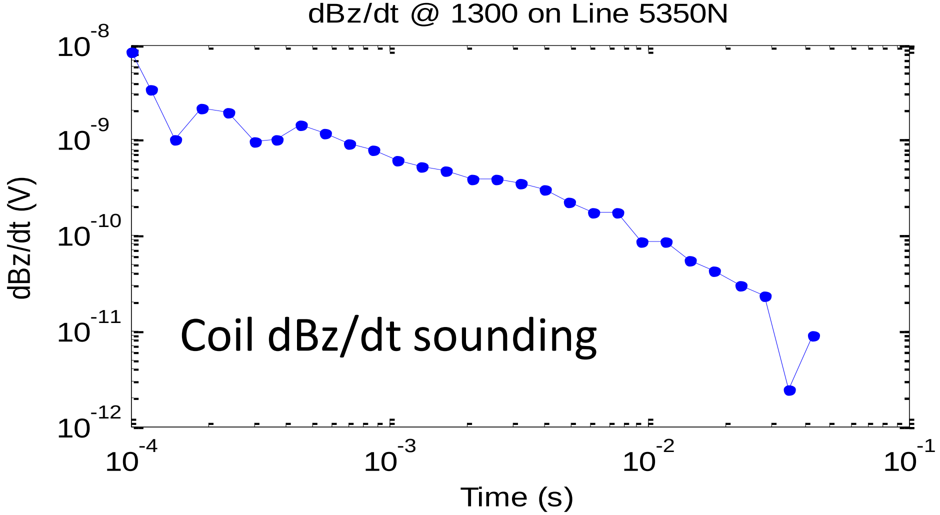
- Jessy Deep HTS (50 fT/√Hz above 100Hz)
- High quality three-component B-field data
- Wideband data

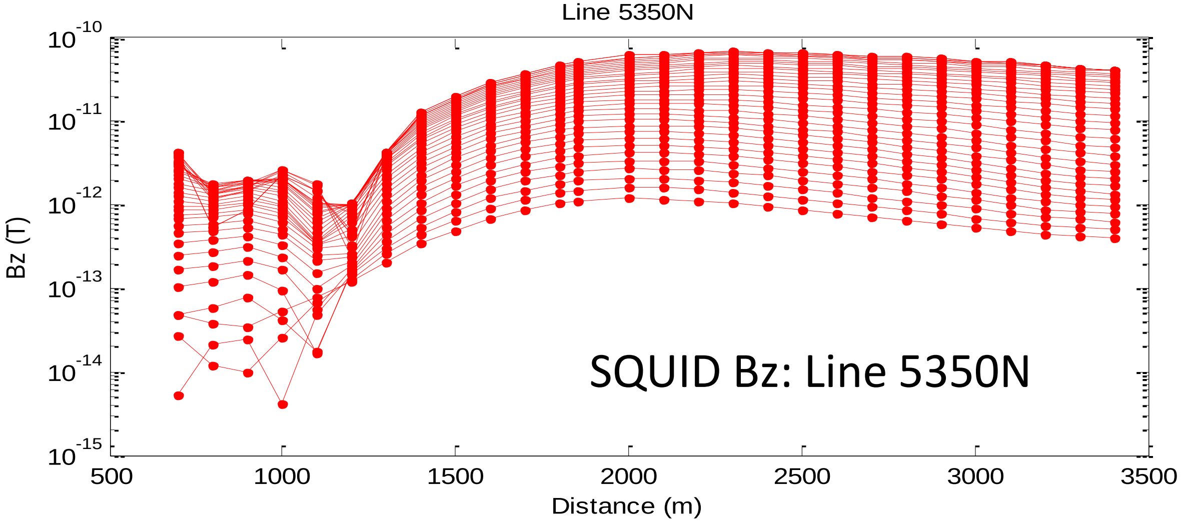


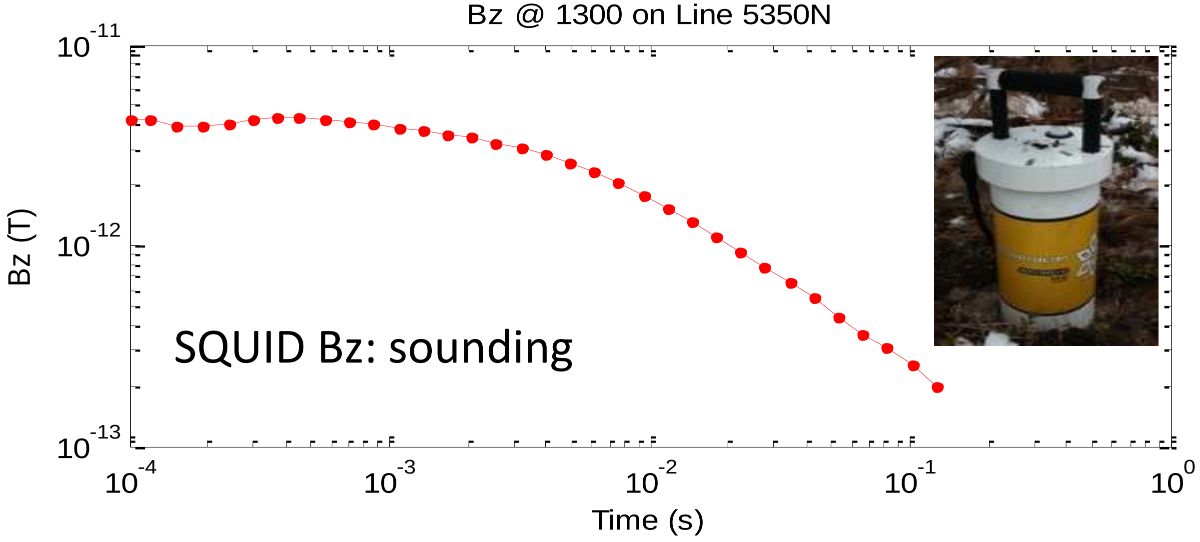


SQUID Data vs. Coil Data

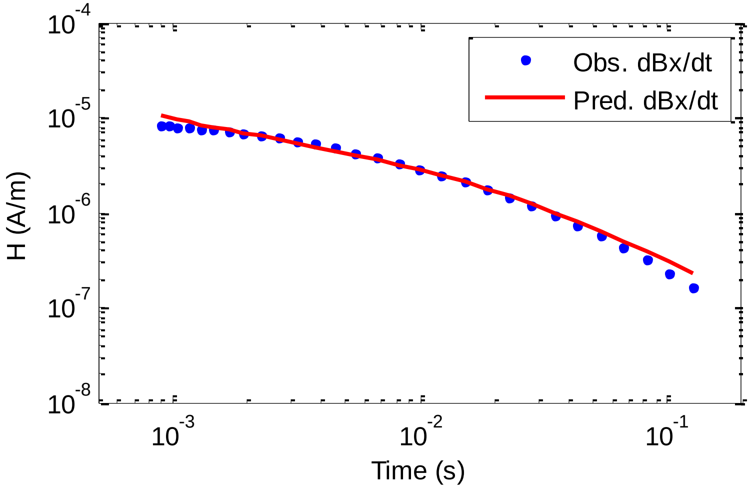


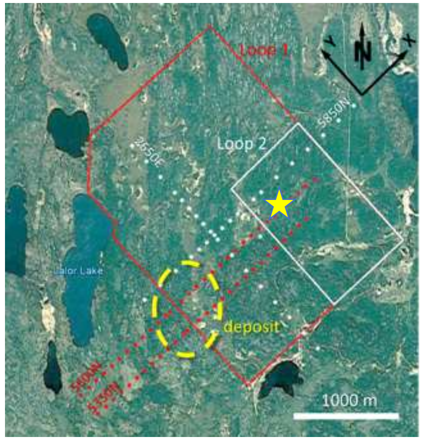


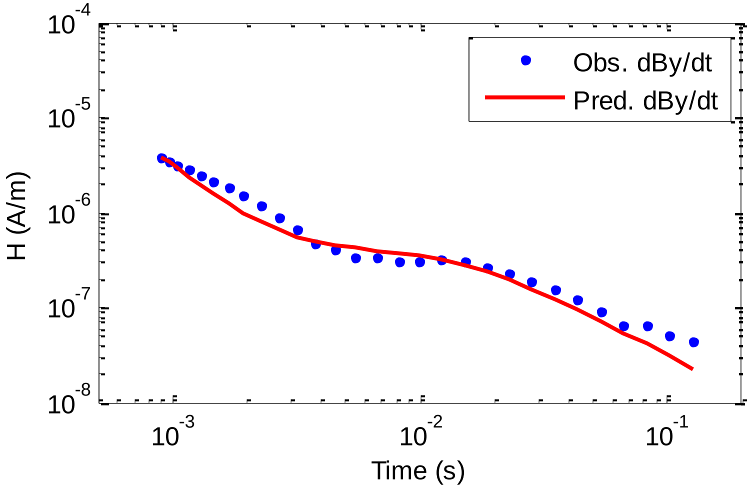


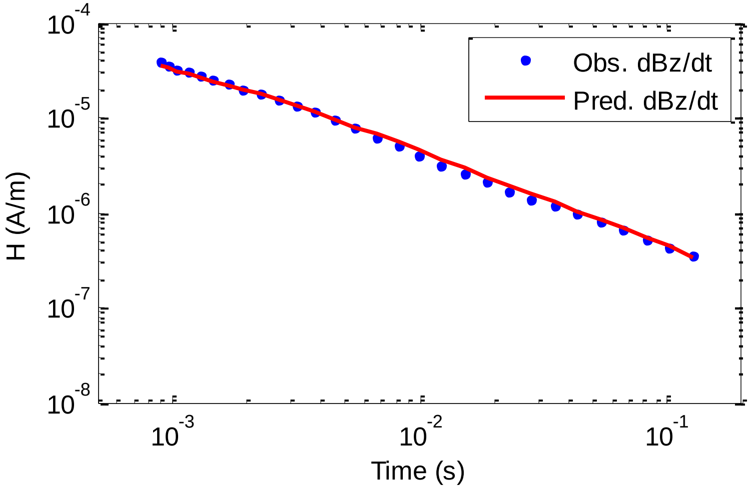


SQUID Data Fitting

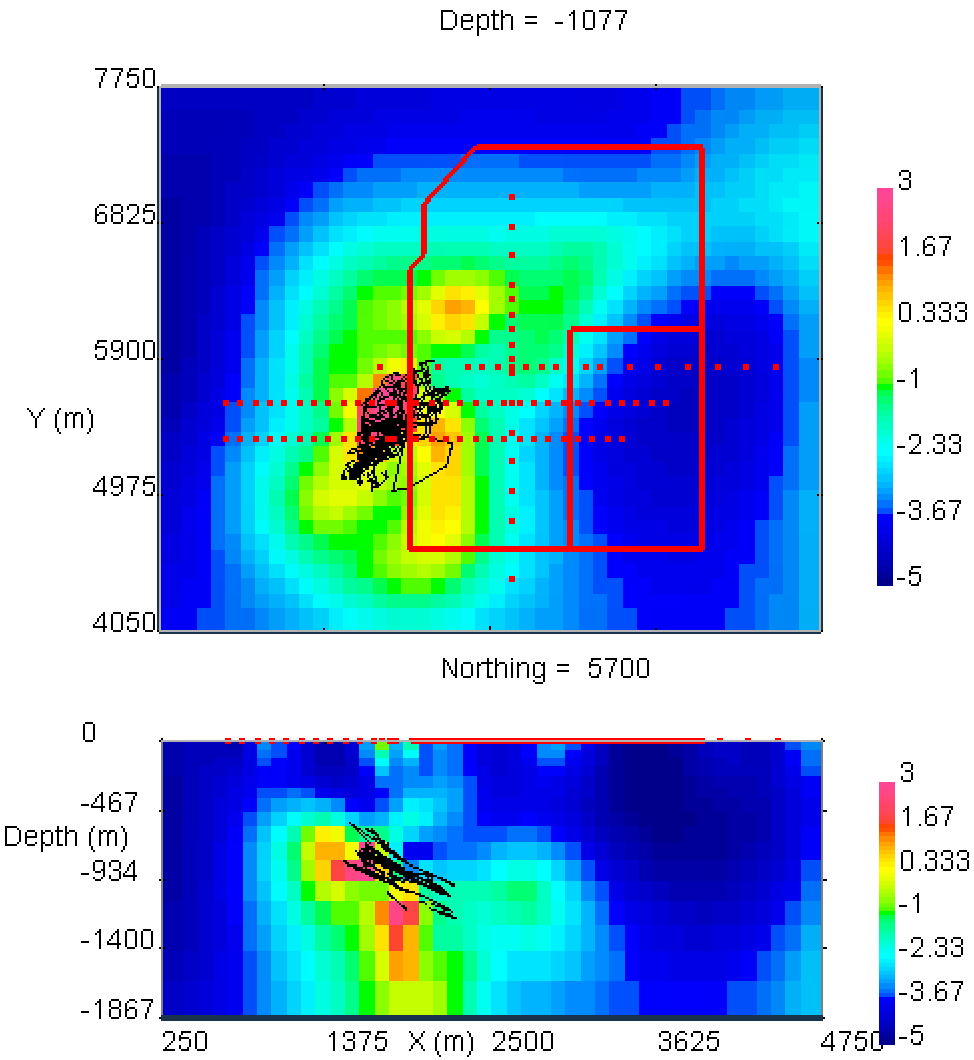








SQUID Data Inversion Model



Pros:

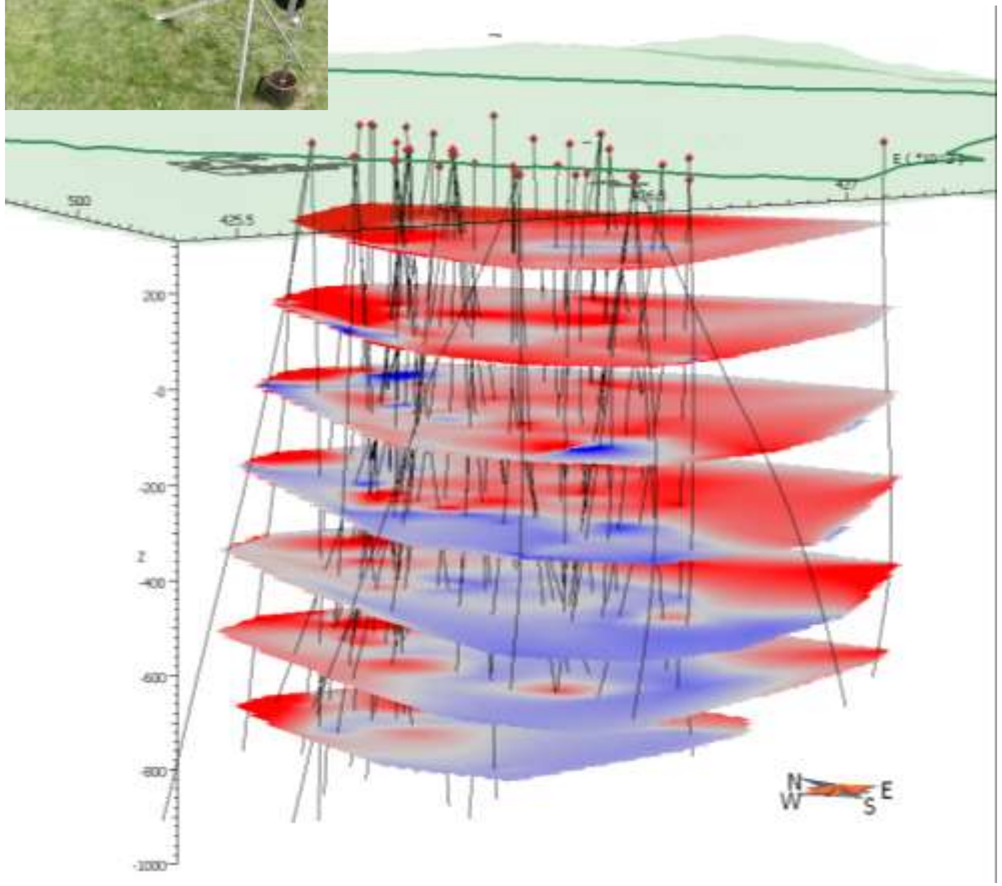
- Deep penetration
- Discrete conductors
- Top of target

Cons:

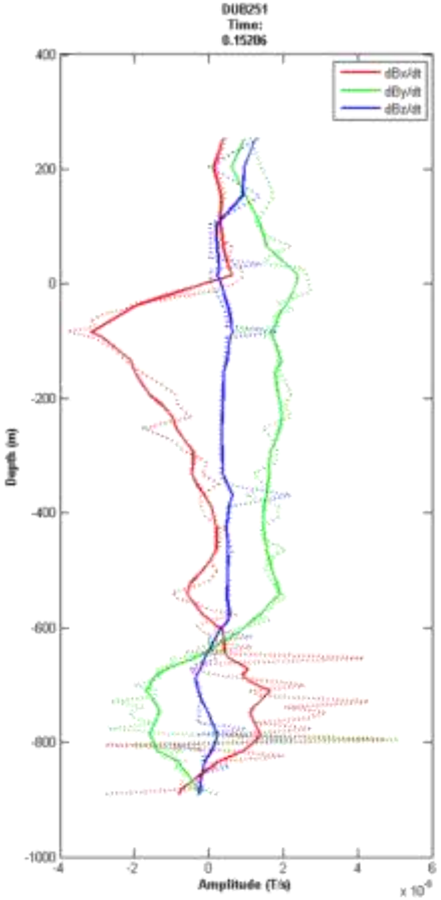
- Localized information
- Conductivity overestimated?

Borehole Data: PULSE-EM

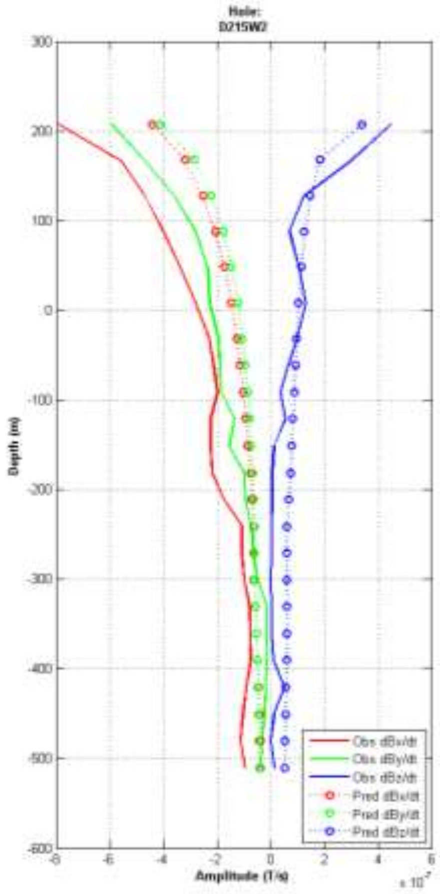
Data Volume



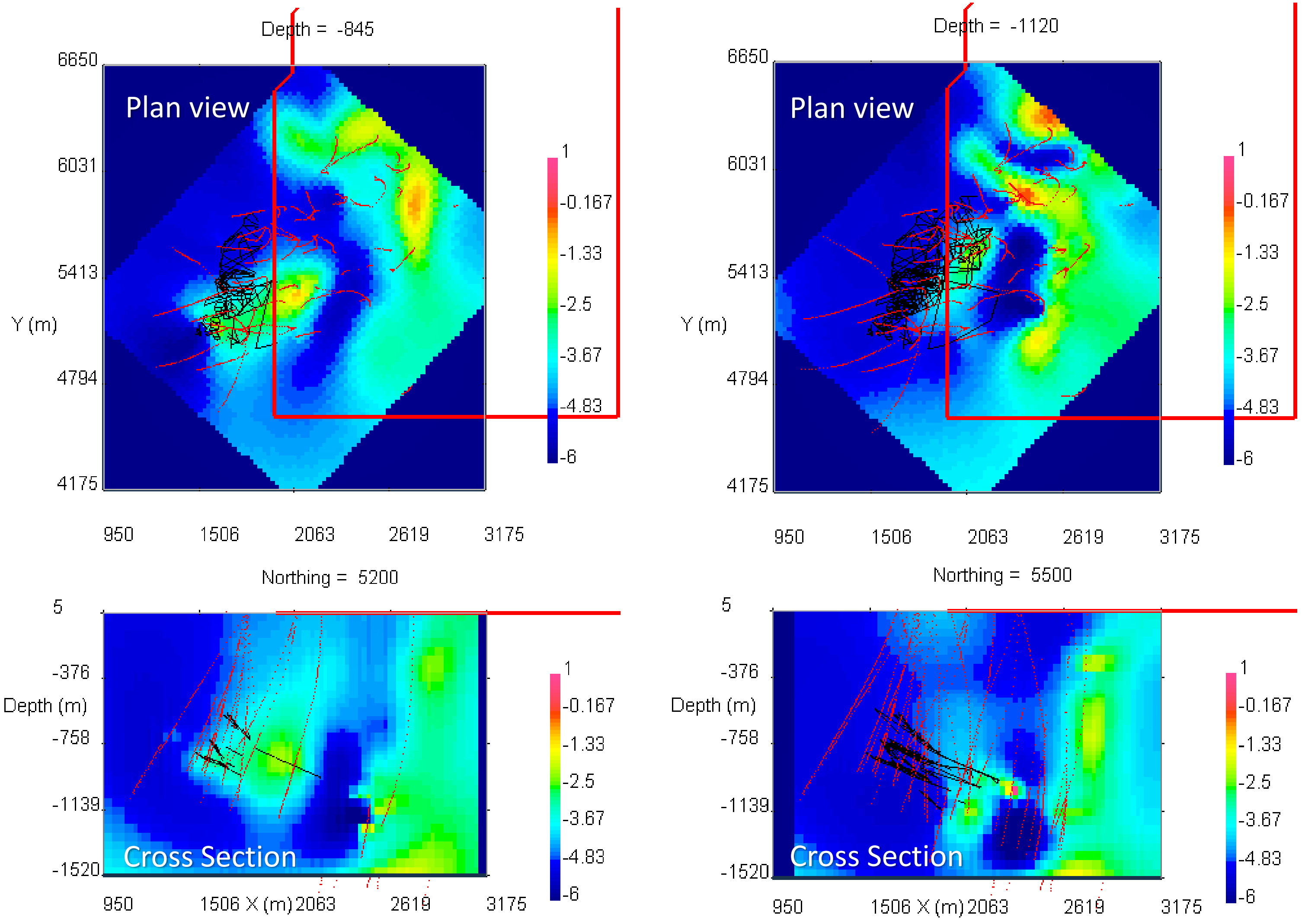
Smoothing



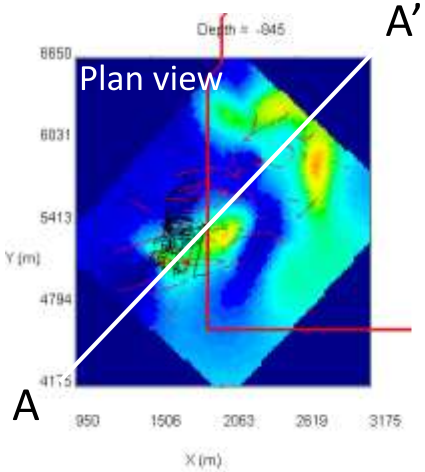
Data Fitting

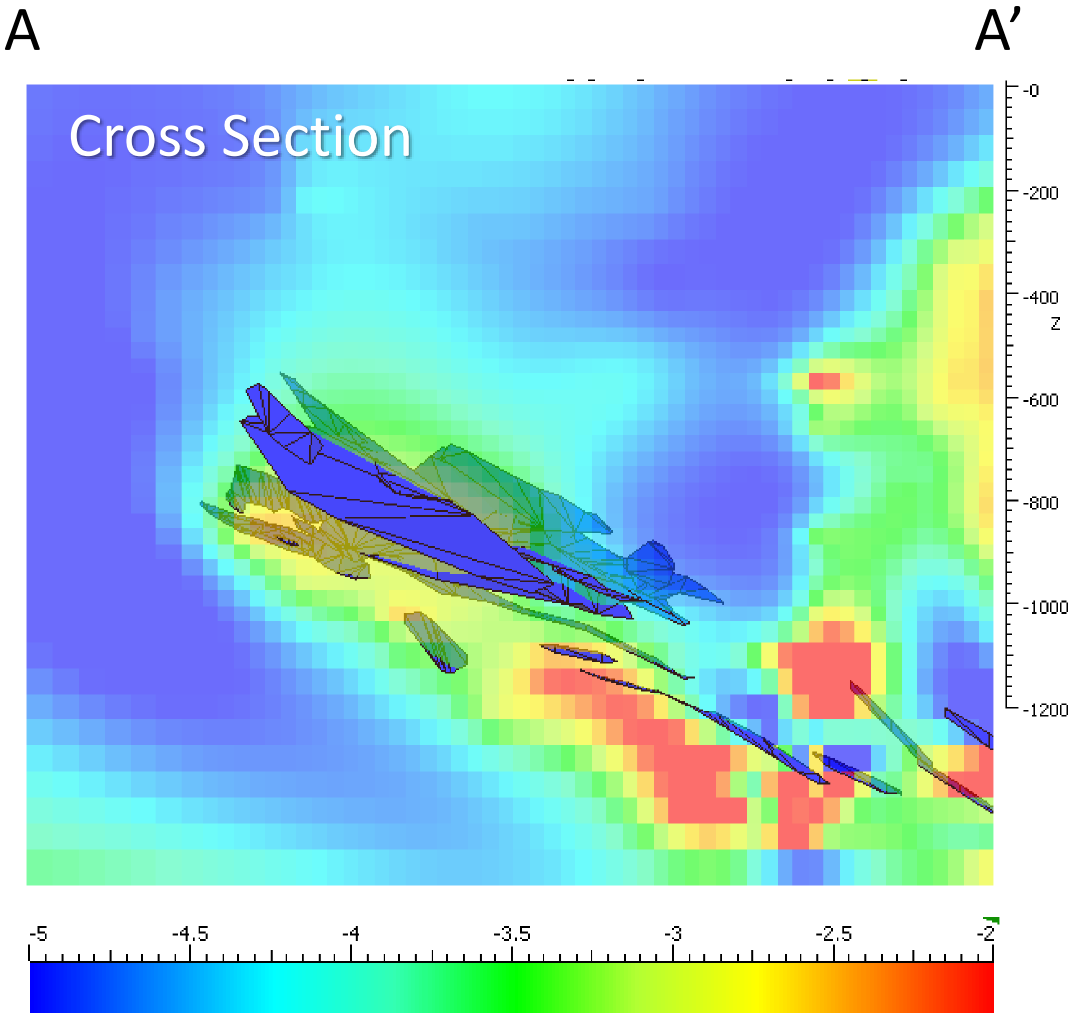


PULSE-EM Inversion Model



PULSE-EM Inversion Model





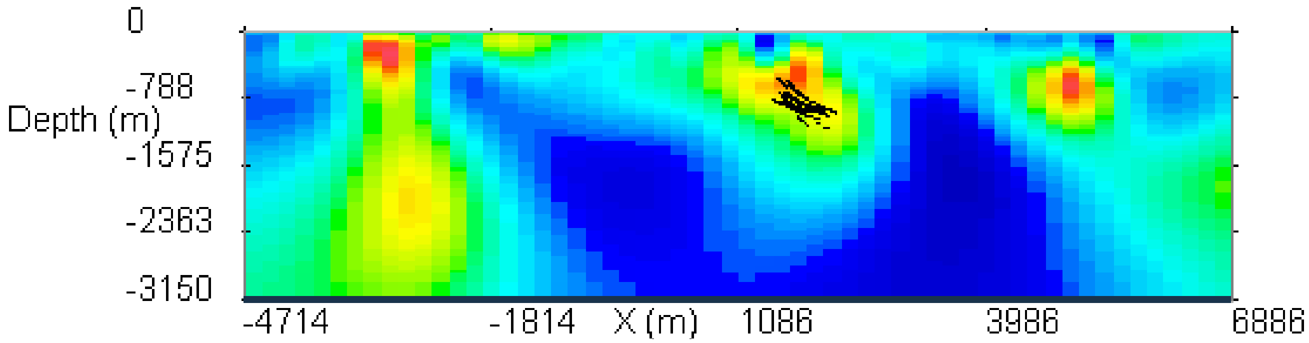
Pros:

- High resolution close to the target

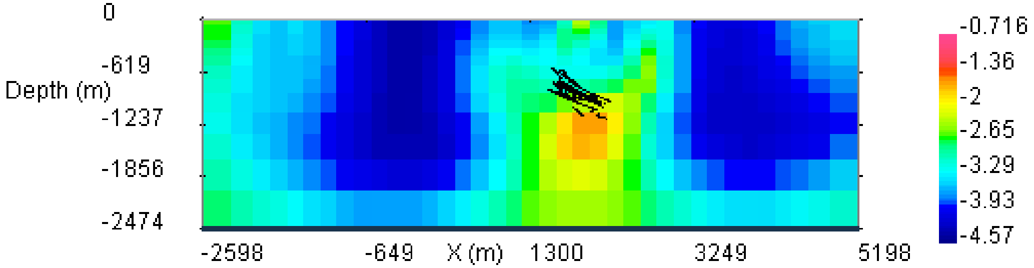
Cons:

- Localized information
- Complicated data…

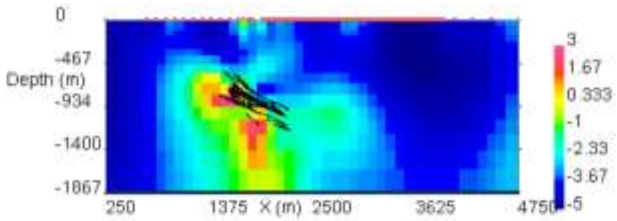
Comparison of Cross Sections



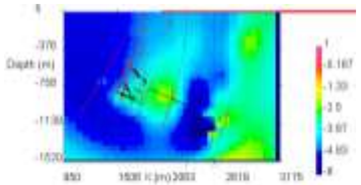
ZTEM
large-scale
good depth



HELITEM
large-scale
deeper conductor

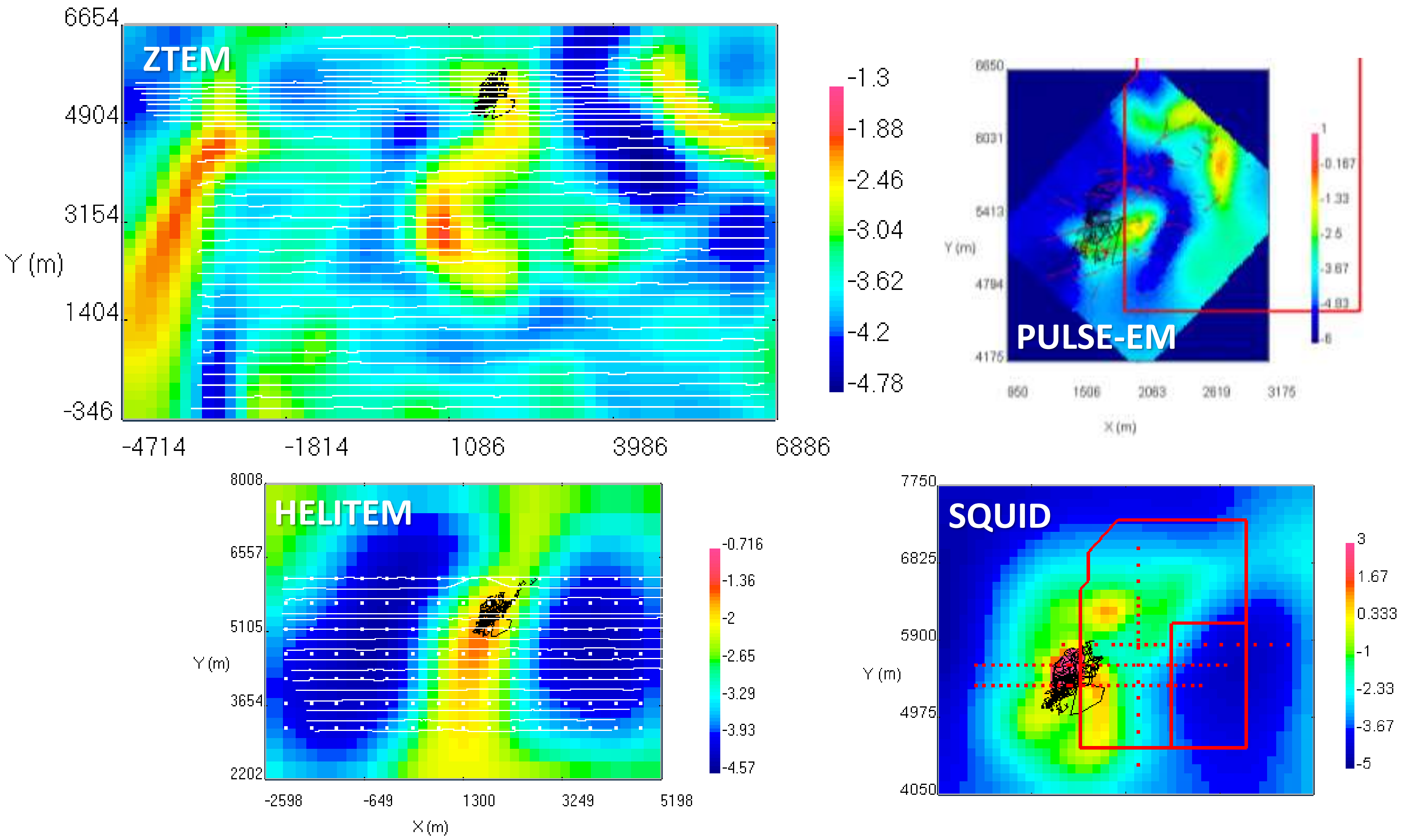


SQUID
deposit-scale
deeper conductors



PULSE-EM
fine-scale
high resolution at the target

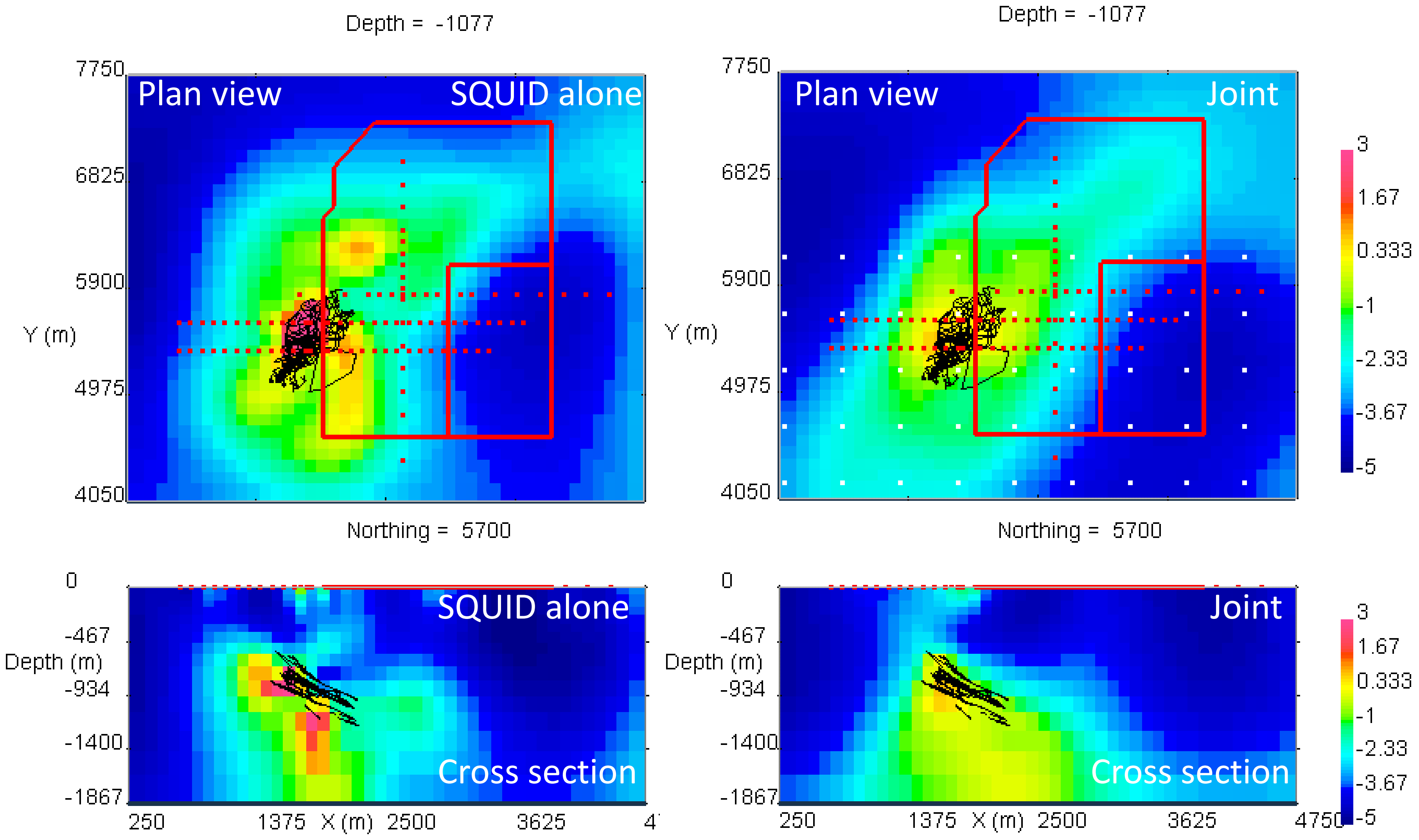
Comparison of Depth Slices



Blind Inversions

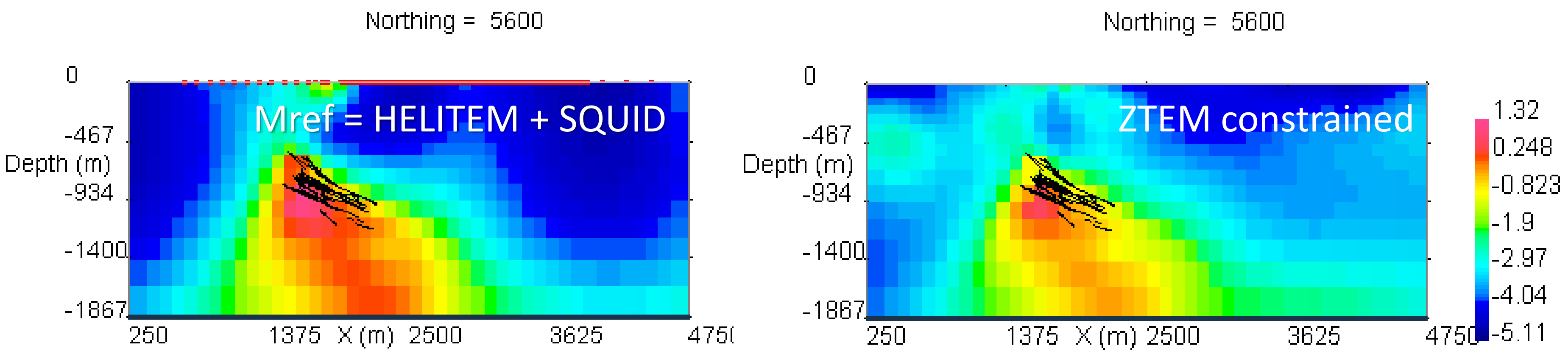
- Four very different data sets inverted in 3D
- All models show the Lalor deposit at different scales
- Bad news: they look different…
- Good news: they bear independent information!
- Unified model: incorporating information from multiple data sets

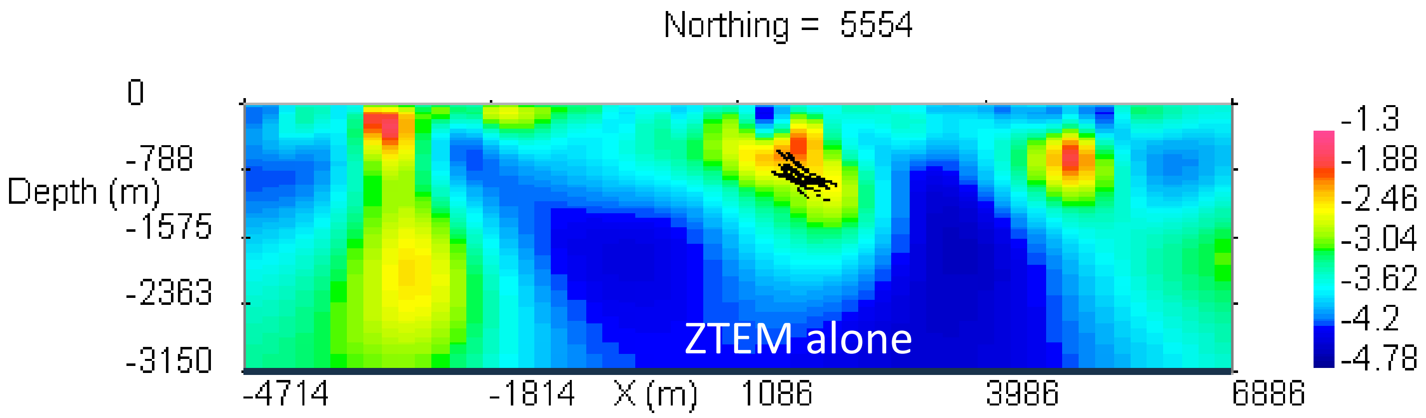
Joint HELITEM + SQUID Model



- Top of the target stays the same
- Conductivity more realistic
- More compatible with regional trend

Cooperative ZTEM + SQUID Inversion





- Target more conductive (closer to typical VMS)
- Top of the target consistent with drill hole model

Lalor Case Study

- Four EM data sets at Lalor inverted in 3D: quantitative tool for interpretation
- The Lalor deposit is recovered but appears different in different surveys
- Attempt to obtain a unified model
  - Joint inversion
  - Cooperative inversion
- More plausible models can be recovered by incorporating multiple data sets