Airborne Natural Source Electromagnetics for an Arbitrary Base Station

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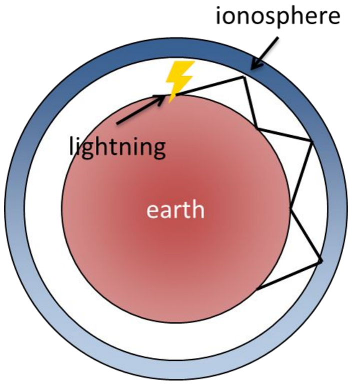
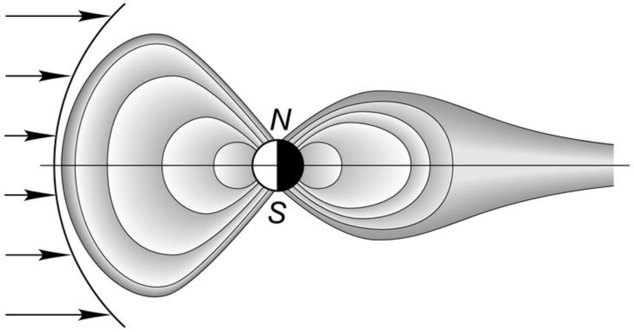
Presentation Outline

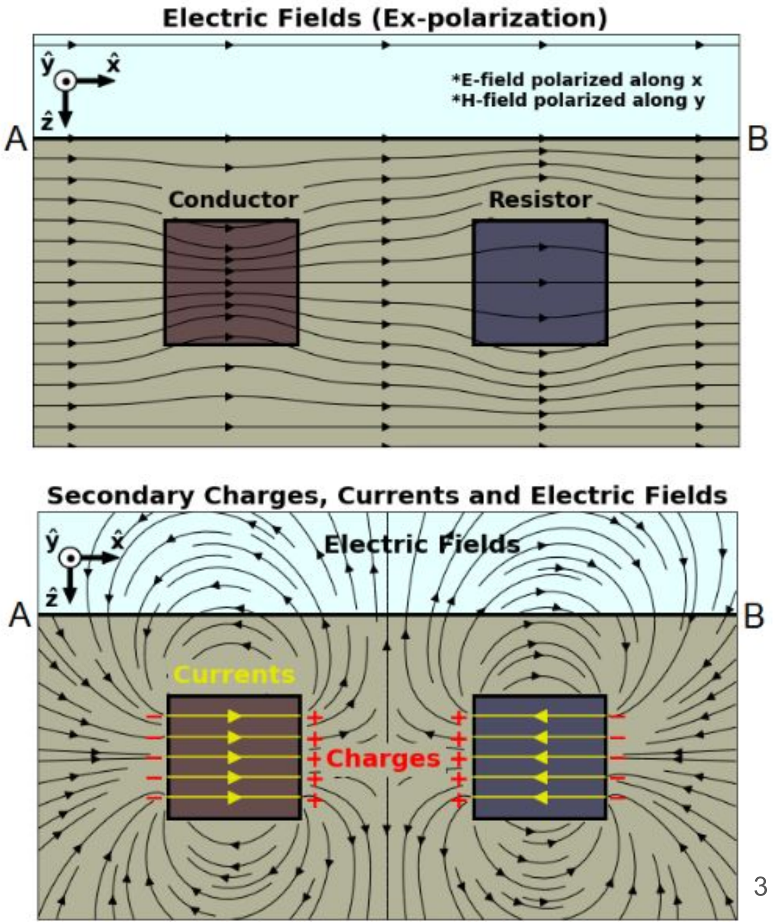
1. Introduction to NSEM
2. Motivation
3. Understanding anomalies
4. Unconstrained inversion
5. MT-assisted ZTEM inversion
6. Final thoughts

NSEM Fundamentals

Natural sources







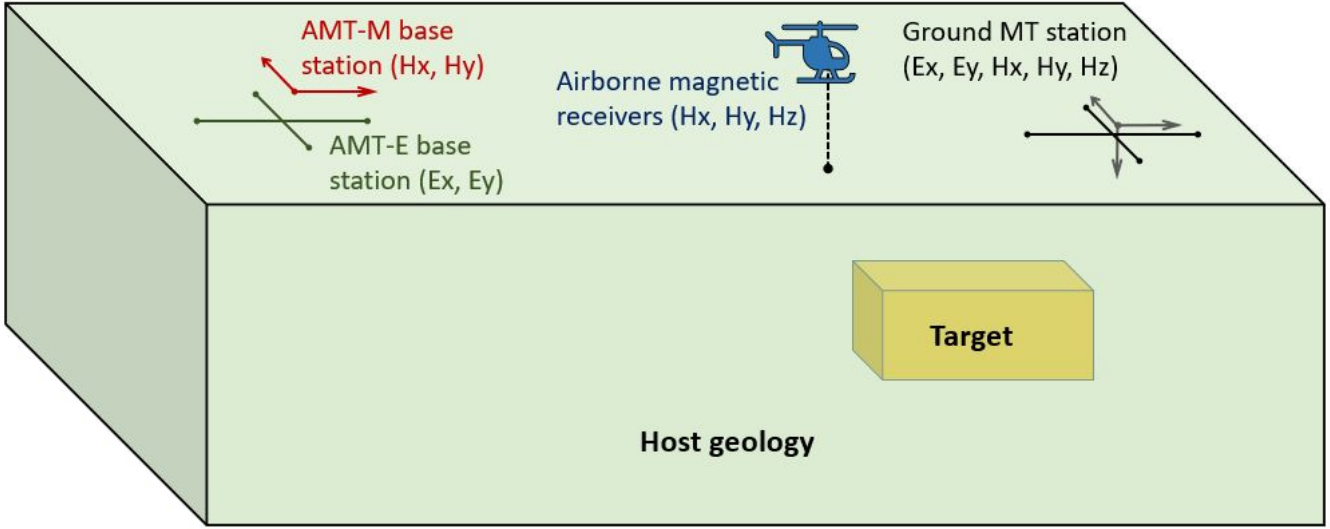
- Lightning and solar wind
  → Incoming planewave

- Conductor and resistors
  → Anomalous currents

- Anomalous electric and magnetic fields

NSEM Survey Geometry

- Magnetic fields (Hx, Hy, Hz) measured in air or on surface
- Electric fields (Ex, Ey) measured on surface
- Systems include: MT, AFMag, ZTEM, and others…



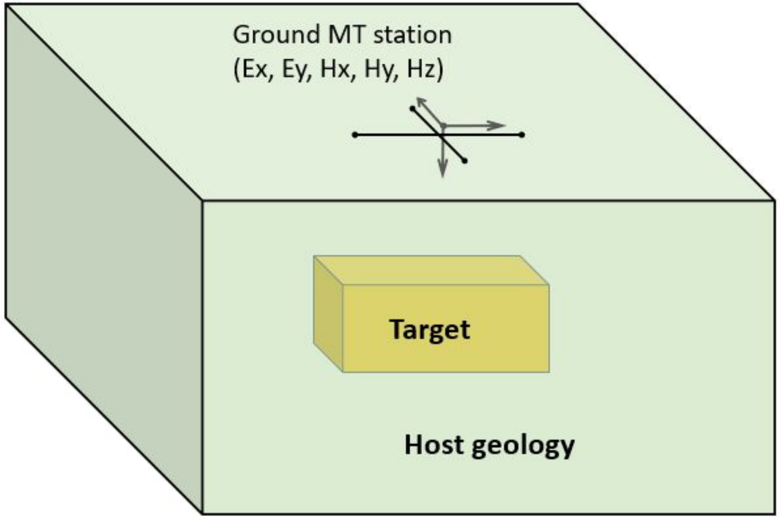
Magnetotellurics (Impedances)

- Measure fields Ex, Ey, Hx and Hy at many surface locations
- Compute impedances, such that

$$\begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} = \begin{bmatrix} E_x^{(x)} & E_x^{(y)} \\ E_y^{(x)} & E_y^{(y)} \end{bmatrix}_{RX} \begin{bmatrix} H_x^{(x)} & H_x^{(y)} \\ H_y^{(x)} & H_y^{(y)} \end{bmatrix}_{RX}^{-1}$$

- Directly sensitive to subsurface conductivity

$$\sigma_{app} = \frac{\mu\omega}{\left|Z_{ij}\right|^2}$$

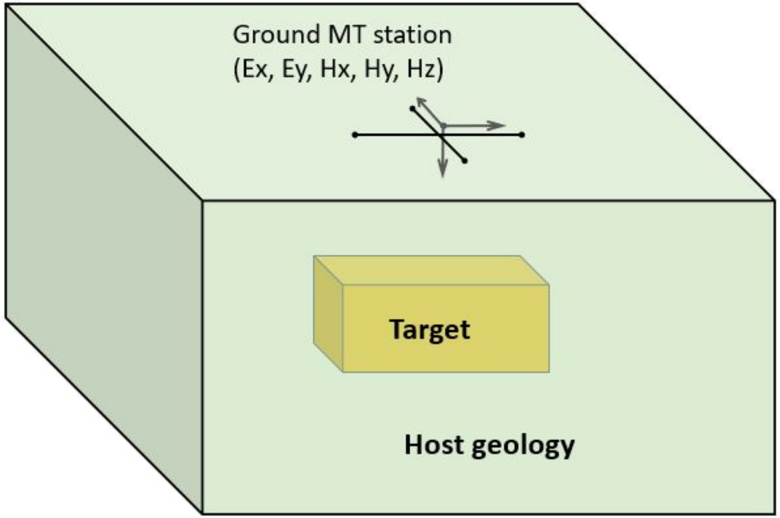


Magnetotellurics (Tippers)

- Measure fields Hx, Hy and Hz at many surface locations
- Compute tippers, such that

$$\begin{bmatrix} T_{zx} \\ T_{zy} \end{bmatrix} = \begin{bmatrix} H_x^{(x)} & H_y^{(x)} \\ H_x^{(y)} & H_y^{(y)} \end{bmatrix}_{RX}^{-1} \begin{bmatrix} H_z^{(x)} \\ H_z^{(y)} \end{bmatrix}_{RX}$$

- Sensitive to contrasts in conductivity across vertical interfaces



Airborne Tipper Data (AFMag and ZTEM)

- Ground MT expensive and time consuming

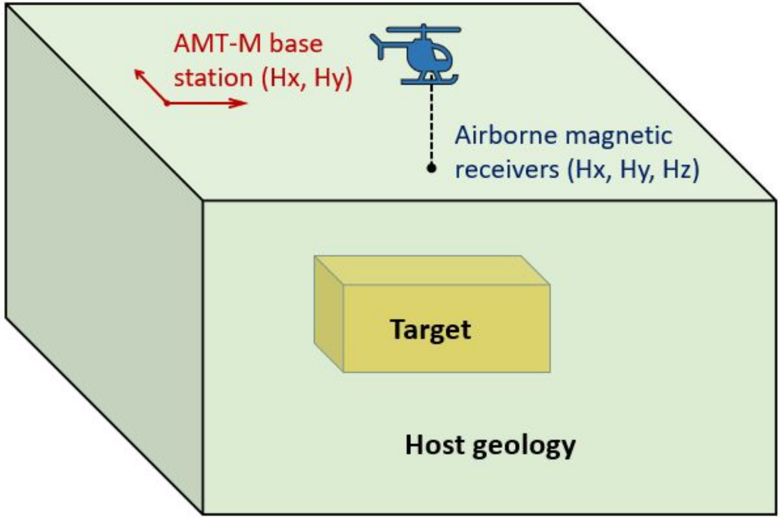
  → Make use of airborne tipper measurements (AFMag)

- AFMag suffers from correlated noise due to receiver orientation

- ZTEM measures Hx, Hy at a base station

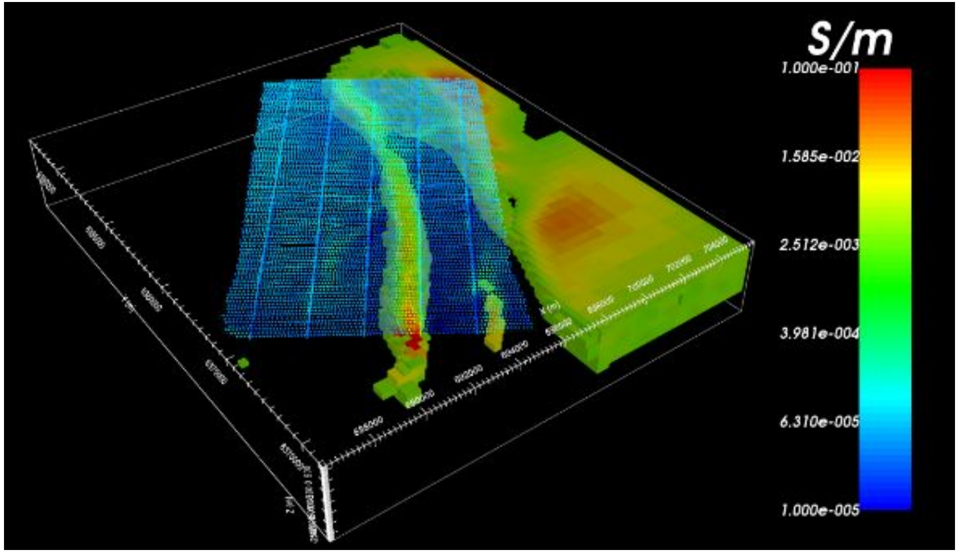
$$\begin{bmatrix} T_{zx} \\ T_{zy} \end{bmatrix} = \begin{bmatrix} H_x^{(x)} & H_y^{(x)} \\ H_x^{(y)} & H_y^{(y)} \end{bmatrix}_{BS}^{-1} \begin{bmatrix} H_z^{(x)} \\ H_z^{(y)} \end{bmatrix}_{RX}$$

- ZTEM not biased by correlated noise!



ZTEM: Industry Standard for Airborne NSEM

- Long track record of successful use in mineral exploration and delineating geological structures
- Reliable algorithm for 3D inversion (Holtham, 2012)
- Published workflow for processing and inverting ZTEM data (Cowan, 2020)
- GIFtools cookbook comprehensive workflows



ZTEM inversion at Dufferin Lake, Saskatchewan

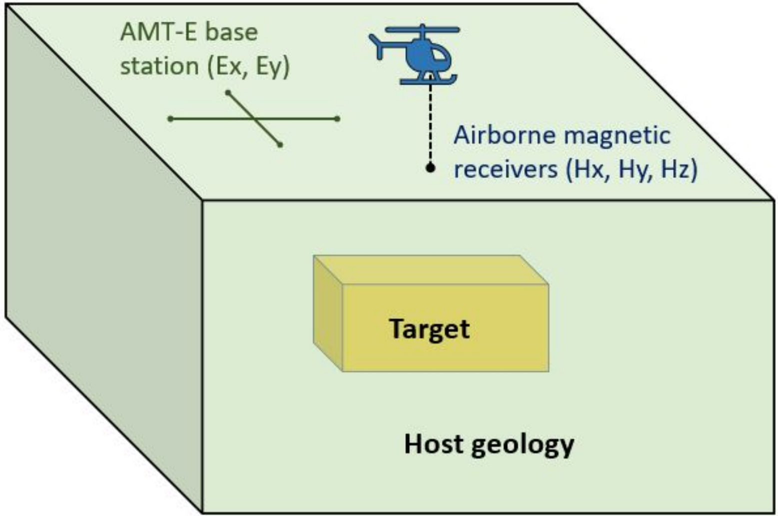
Airborne with an E-field Base Station

- Tipper data insensitive to layered Earth structures
- Can we overcome this challenge with an E-field base station?
- Airborne Hx, Hy, Hz at many locations and surface Ex, Ey at base station
- **Quasi-impedances:**

$$\begin{bmatrix} Q_{xx} & Q_{xy} \\ Q_{yx} & Q_{yy} \end{bmatrix} = \begin{bmatrix} E_x^{(x)} & E_x^{(y)} \\ E_y^{(x)} & E_y^{(y)} \end{bmatrix}_{BS} \begin{bmatrix} H_x^{(x)} & H_x^{(y)} \\ H_y^{(x)} & H_y^{(y)} \end{bmatrix}_{RX}^{-1}$$

- **Apparent conductivity:**

$$\sigma_{mmt} = \omega\mu \frac{\left|\mathbf{H}_{RX}\right|^2}{\left|\mathbf{E}_{BS}\right|^2}$$



To Summarize

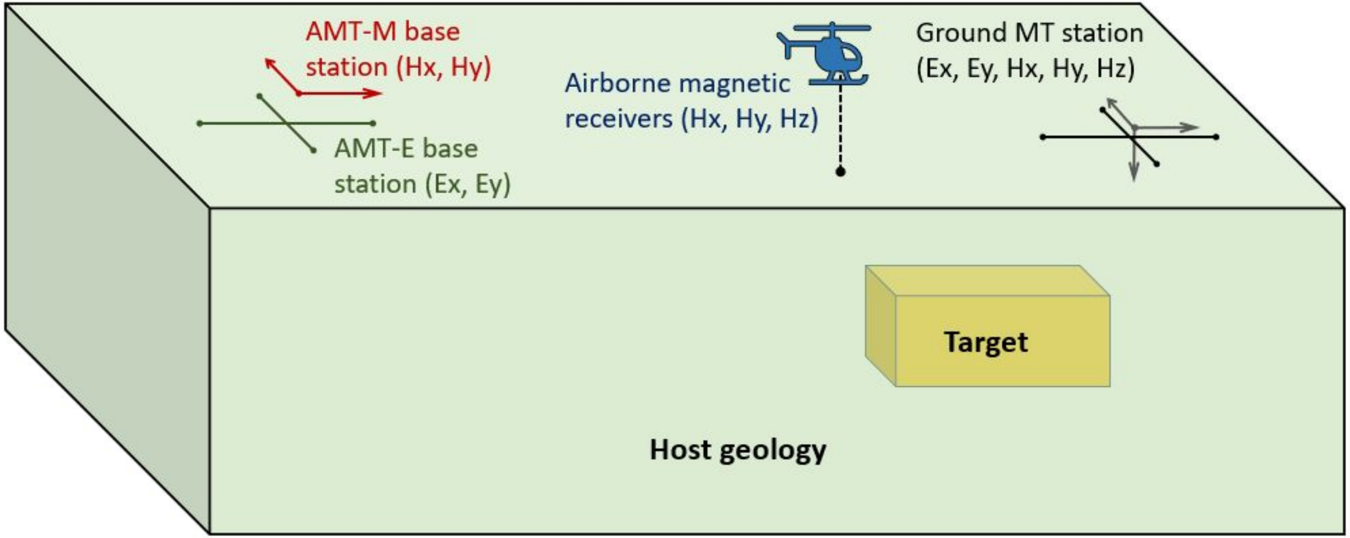
- NSEM fields can be used to compute impedance and/or tipper data
- ZTEM has effectively replaced AFMag
- Three main flavours:
  - MT (ground-based)
  - AirMT-M (airborne with magnetic field at base station)
  - AirMT-E (airborne with electric field at base station)
- Each system defines data according to a different transfer function
  → Collects different information about the Earth

2. Motivation

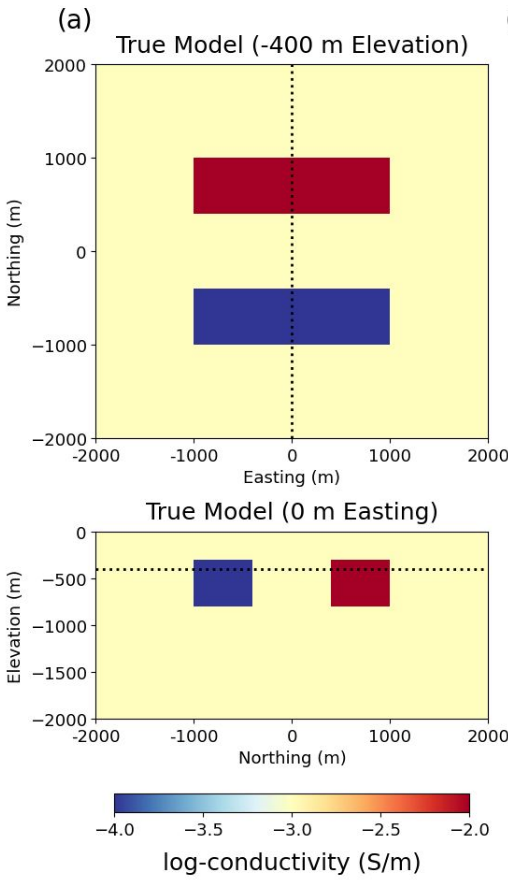
Geophysical Inversion

- Desire to recover models using inversion
- Multitude of AirMT data types
- What structures produce signatures in the data?

  → What structures can the inversion recover?



Smoothest Model Inversion Example



- Inverting different data → different recovered models

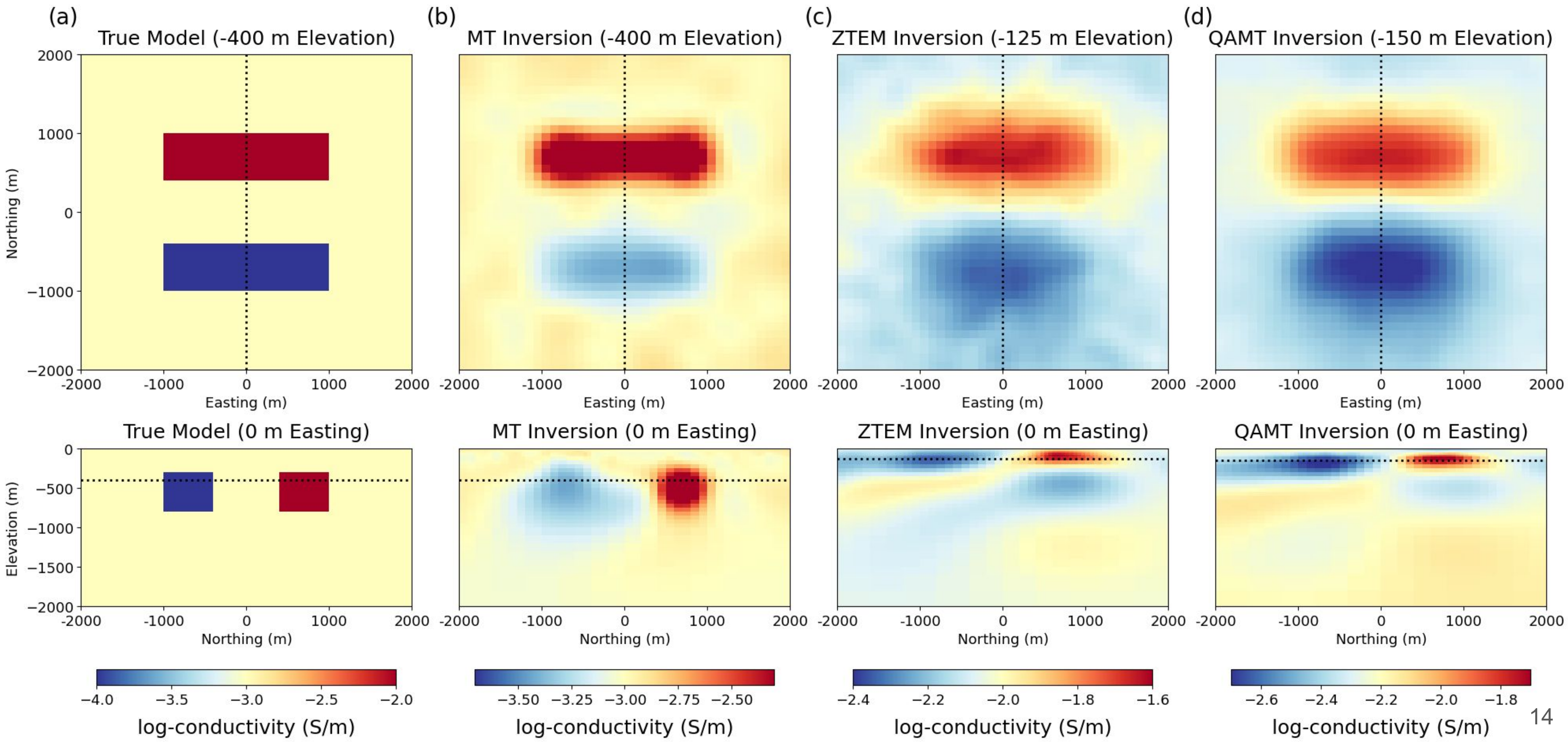
- True model:
  - 0.001 S/m host
  - 0.0001 S/m resistor
  - 0.01 S/m conductor

- Generate MT-impedance, ZTEM and quasi-impedance data

- Carry out smoothest inversion

- Invert with 0.01 S/m starting model (overestimated!!!)

Smoothest Model Inversion Results



Questions

Understanding NSEM Anomalies and Data:

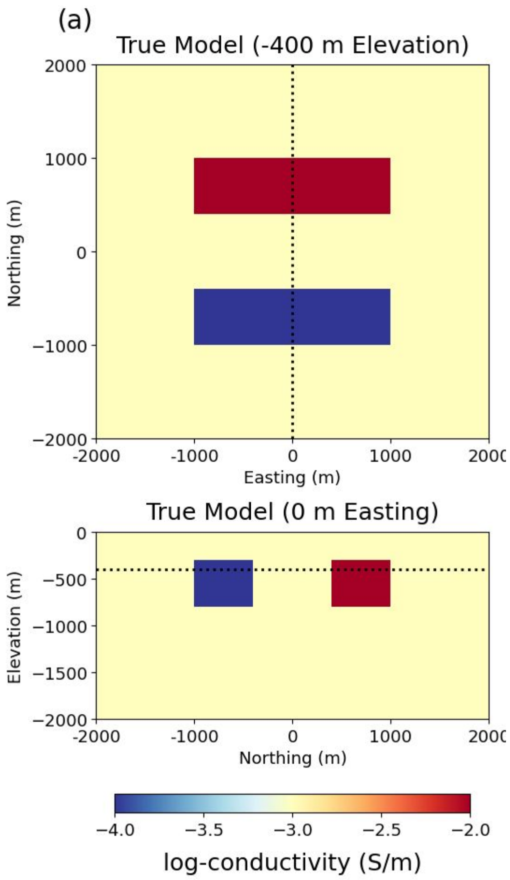
- What field components drive tipper anomalies?
- How are MT-impedances and quasi-impedances different?
- What is the influence of the conductivity at the base station on airborne NSEM data?

Understanding AirMT Inversion:

- How are inversion results influenced when the base station and host conductivity differ significantly?
- How does the inversion naturally recover features to fit the data?

3. Understanding NSEM Anomalies and Data

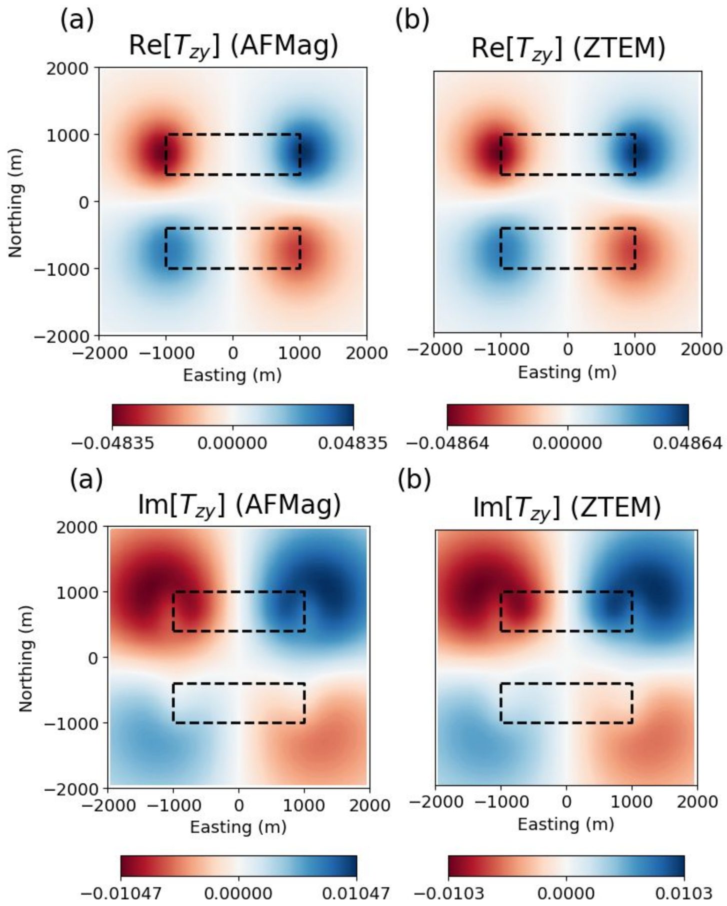
Our Synthetic Model



- Here, we compute all the NSEM fields for:
  - a 0.001 S/m halfspace
  - the block model
- From this, we can compute:
  - Tipper data (AFMag, ZTEM)
  - MT-impedances
  - Quasi-impedances
- Assume NSEM fields at base station characterized by 0.001 S/m halfspace

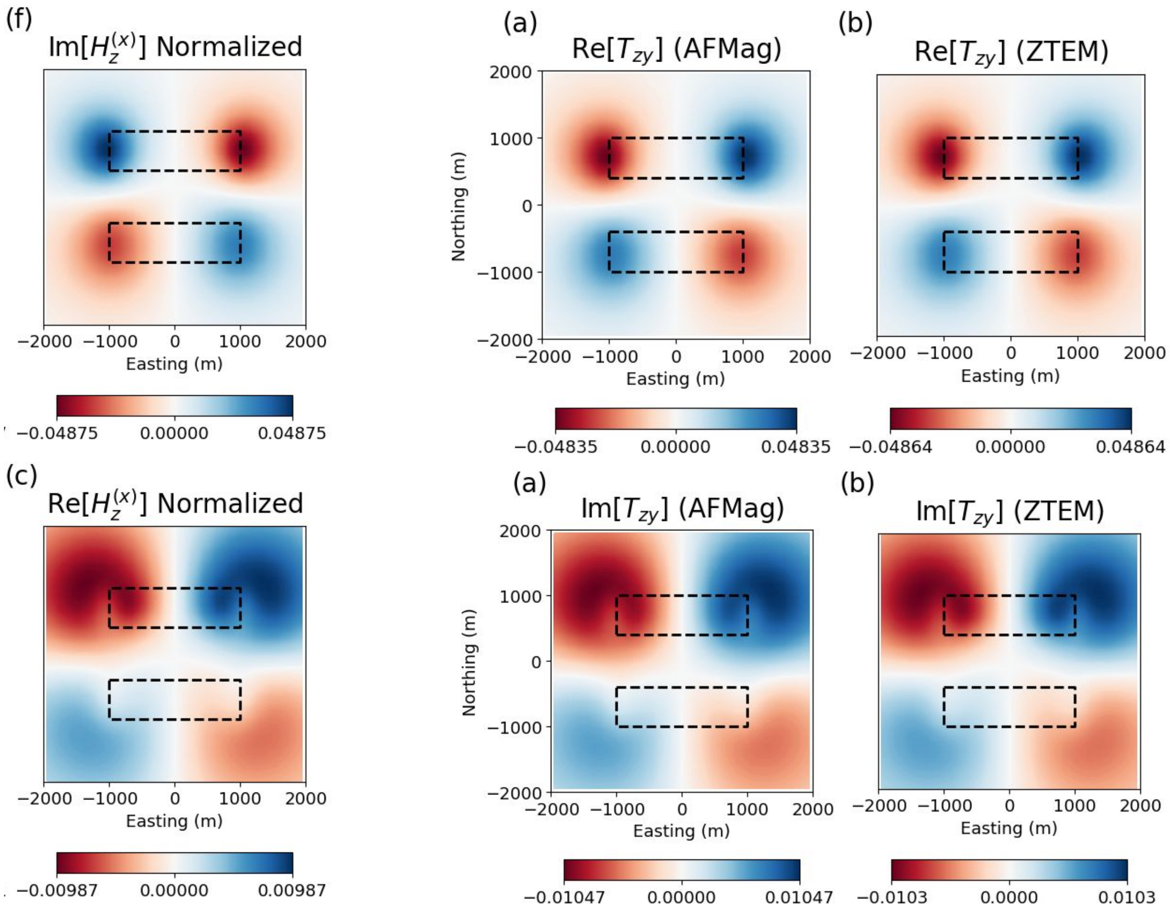
AFMag and ZTEM Anomalies

- ZTEM anomalies approximate to AFMag
- Hx and Hy effects negligible (except extreme cases)

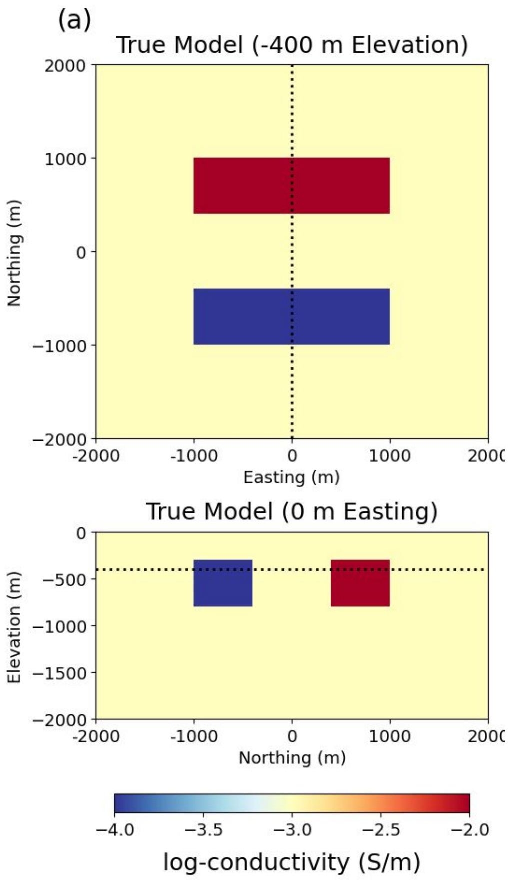


AFMag and ZTEM Anomalies

- ZTEM anomalies approximate to AFMag
- Hx and Hy effects negligible (except extreme cases)
- Re[Tzy] related to Im[Hz]
  Im[Tzy] related to Re[Hz]
- Lower noise more important than geology for ZTEM base station



MT-Impedances and Quasi-Impedances



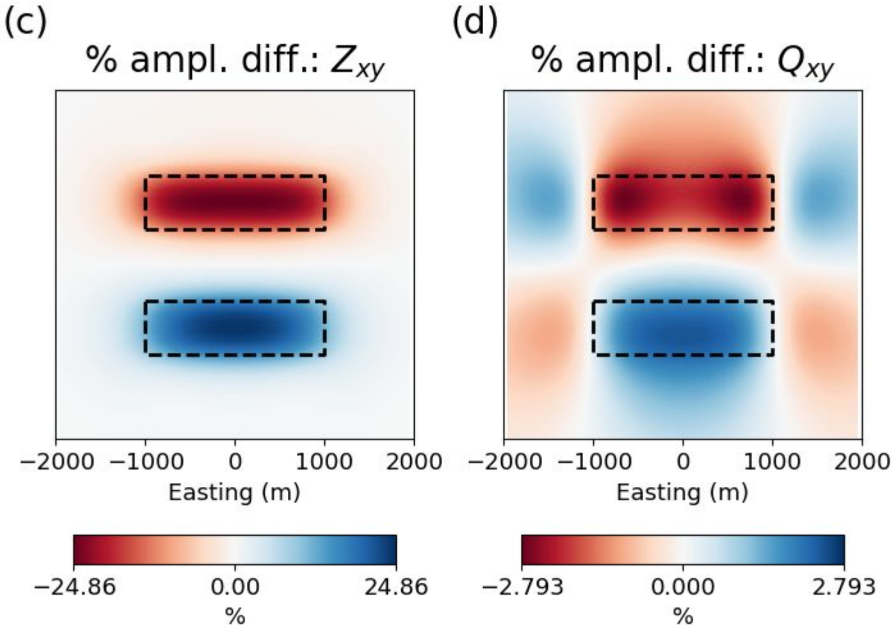
- How does structure impact MT-impedances and quasi-impedances?

- Here we compute:
  - 0.001 S/m halfspace impedances
  - block model impedances
  - % difference in amplitude

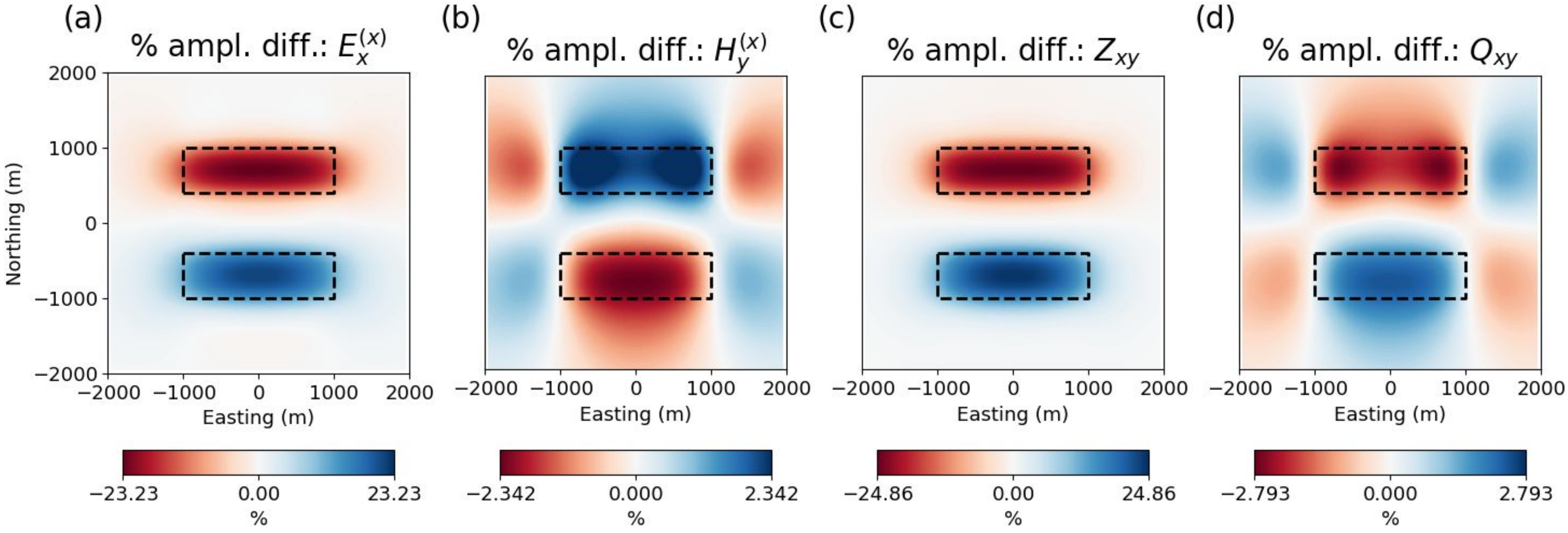
$$100\% \times \left(\frac{|f(\sigma_{block})| - |f(\sigma_{hs})|}{|f(\sigma_{hs})|} \right)$$

- Assume E-field base station characterized by 0.001 S/m halfspace

MT-Impedances and Quasi-Impedances



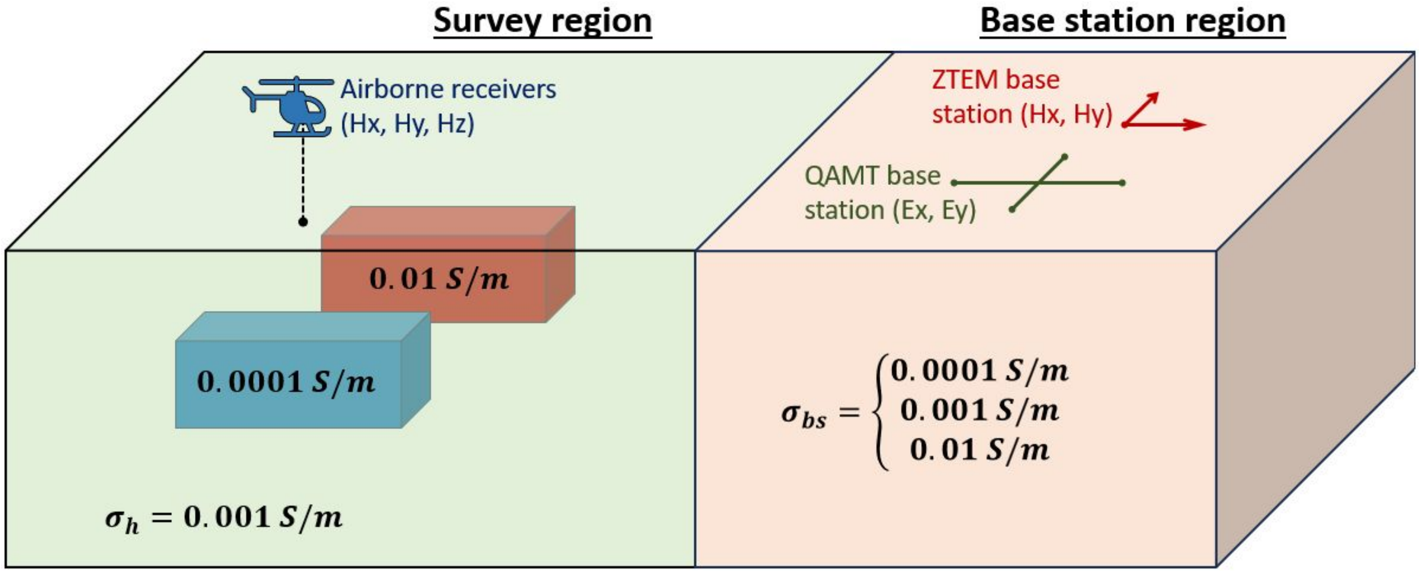
MT-Impedances and Quasi-Impedances



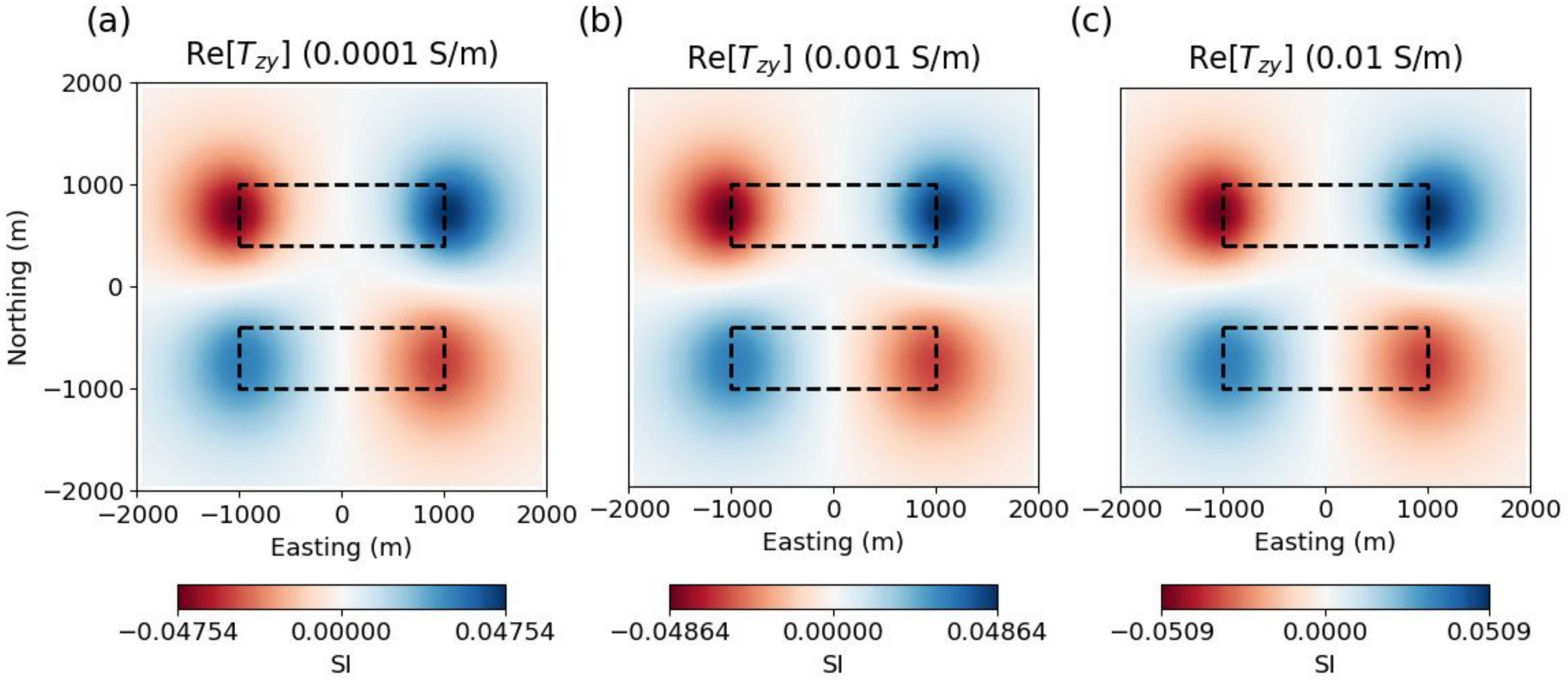
- MT-impedances driven by anomalous electric fields
- Quasi-impedances driven by anomalous magnetic fields
- Same behaviours observed for phase

Impact of Base Station Conductivity

- AirMT-M and AirMT-E systems both measure fields at a base station
- What if base station conductivity very different from host conductivity?
- Assume base station a local half-space
- Impact on ZTEM and quasi-impedance anomalies

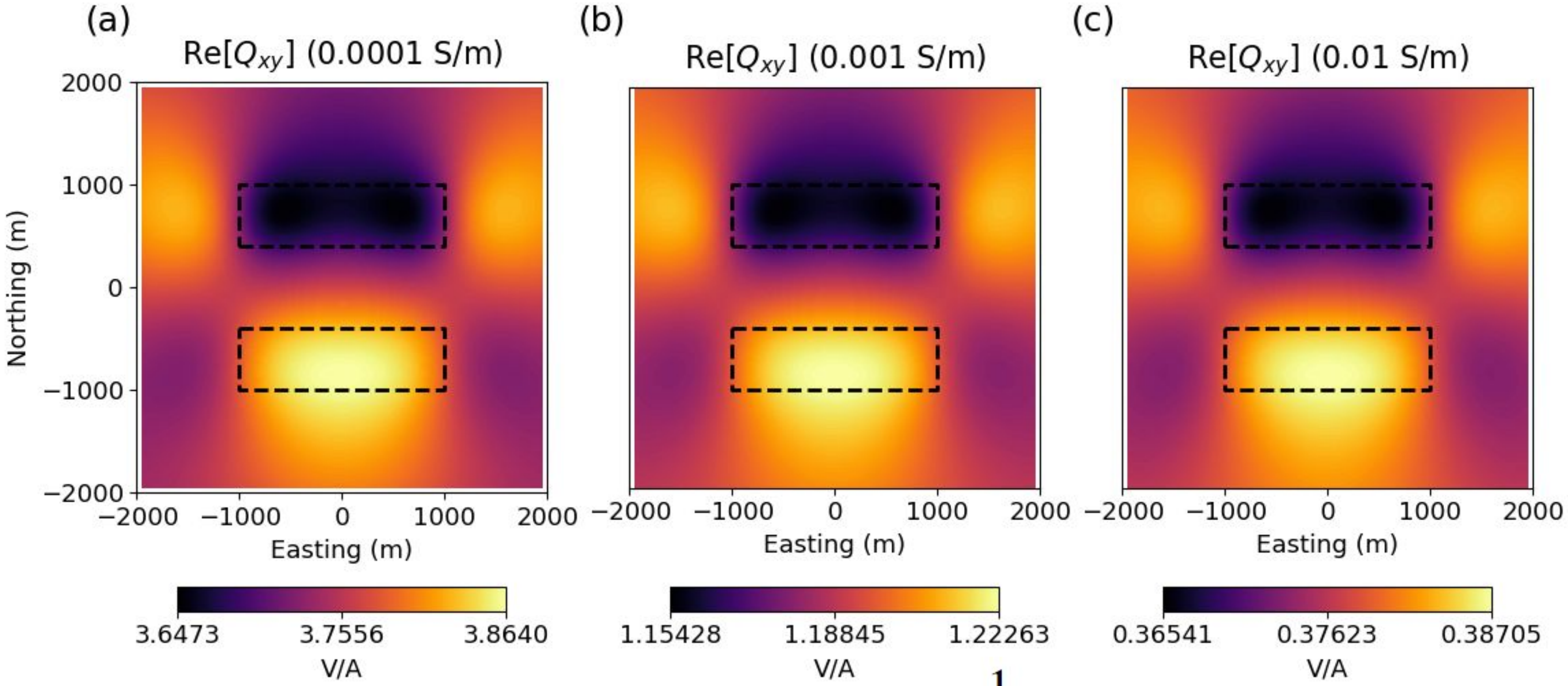


Impact of Base Station Conductivity



Consistent anomaly amplitude!!!

Impact of Base Station Conductivity



Proportional to $\frac{1}{\sqrt{\sigma_{bs}}}$

Section Summary

- **MT-impedances**
  - Directly sensitive to subsurface conductivity throughout survey region
  - Anomalies driven by anomalous electric fields

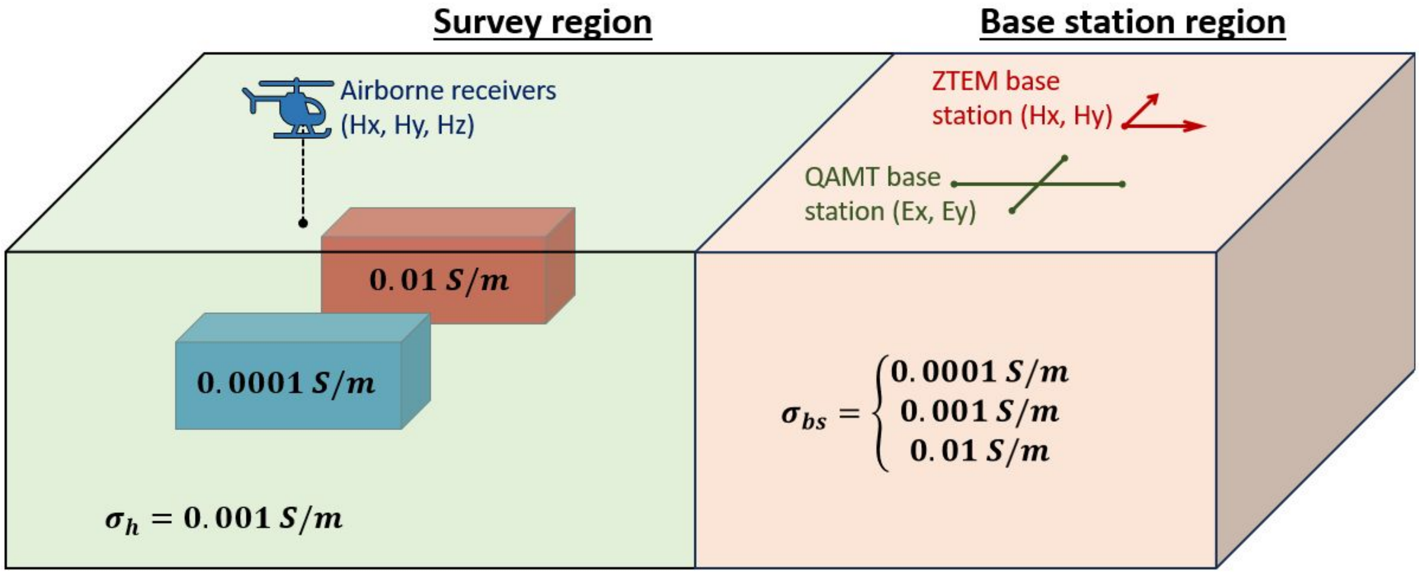
- **ZTEM (AirMT-M data)**
  - Not directly sensitive to subsurface conductivity
  - Anomalies driven by anomalous vertical magnetic fields from vertical interfaces within the survey region!
  - Robust to local geology at base station

- **Quasi-impedances (and other AirMT-E data)**
  - Directly sensitive to conductivity at base station
  - Anomalies driven by anomalous magnetic fields in the survey region

4. Unconstrained Inversion of AirMT Data

Setup

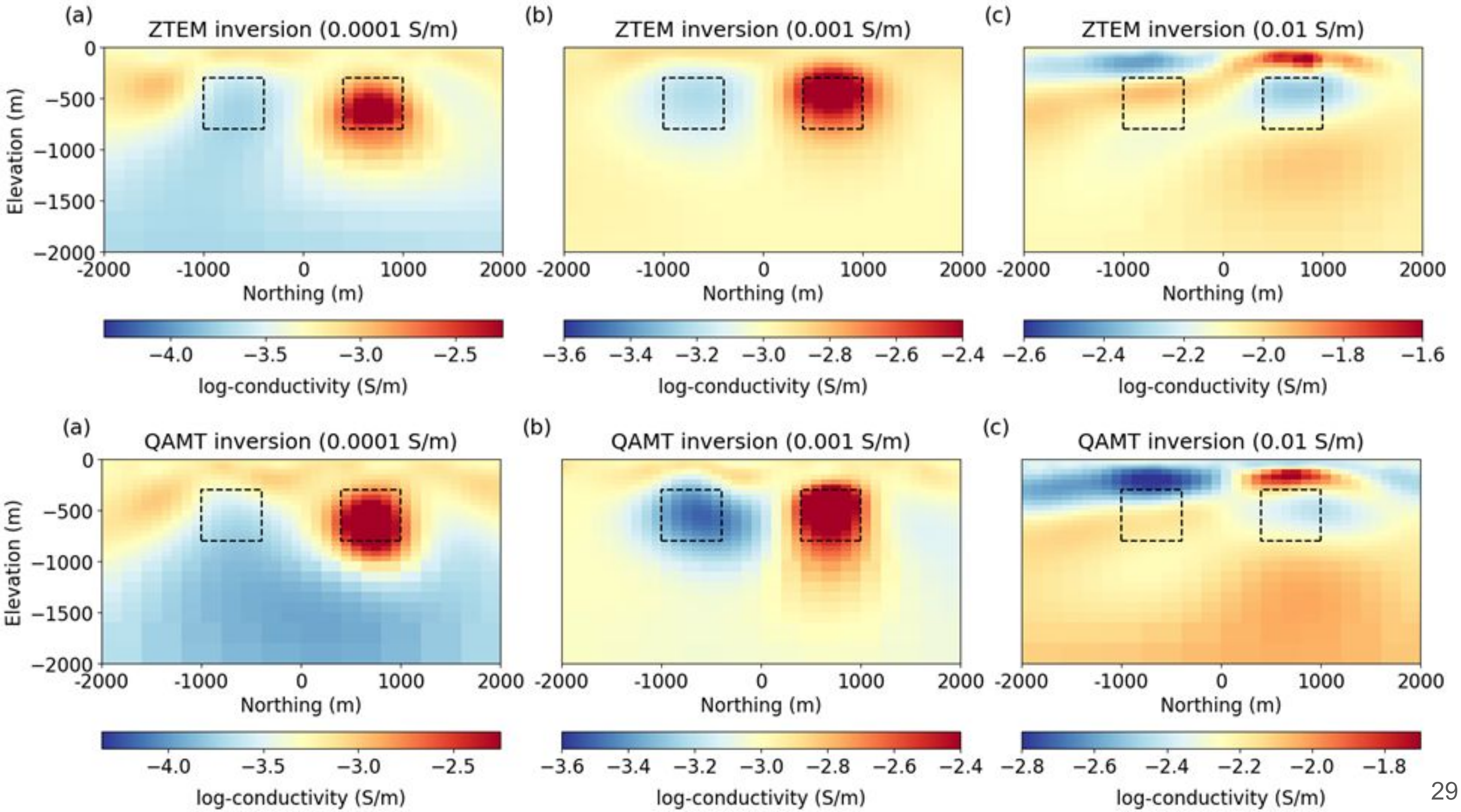
- Host and base station conductivity different
- Generate and invert synthetic ZTEM and quasi-impedance data
- Use base station or host conductivity as starting model?



Inversion with Base Station Conductivity

ZTEM

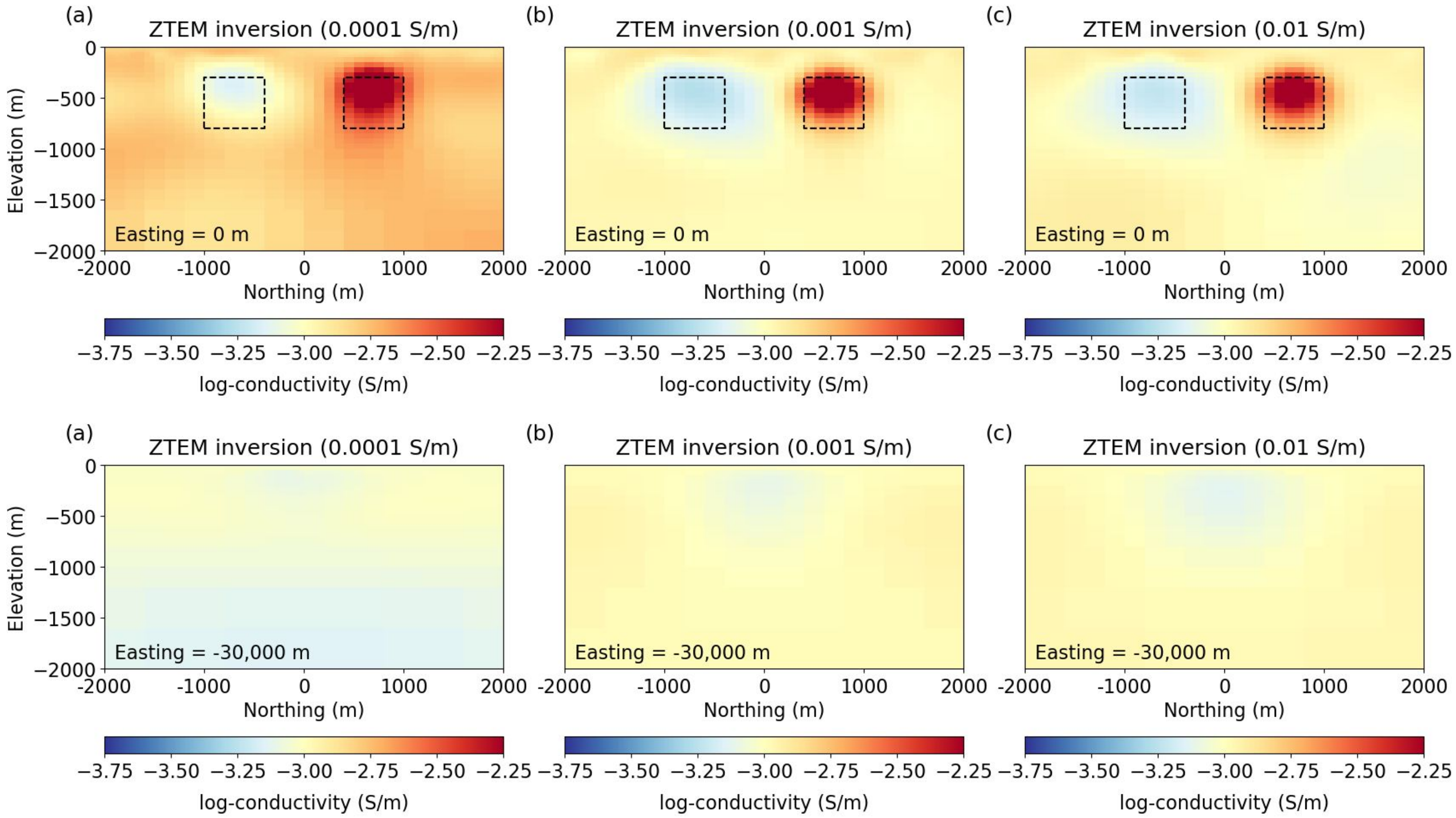
Quasi-impedances



ZTEM Inversion with Host Conductivity

Survey Region

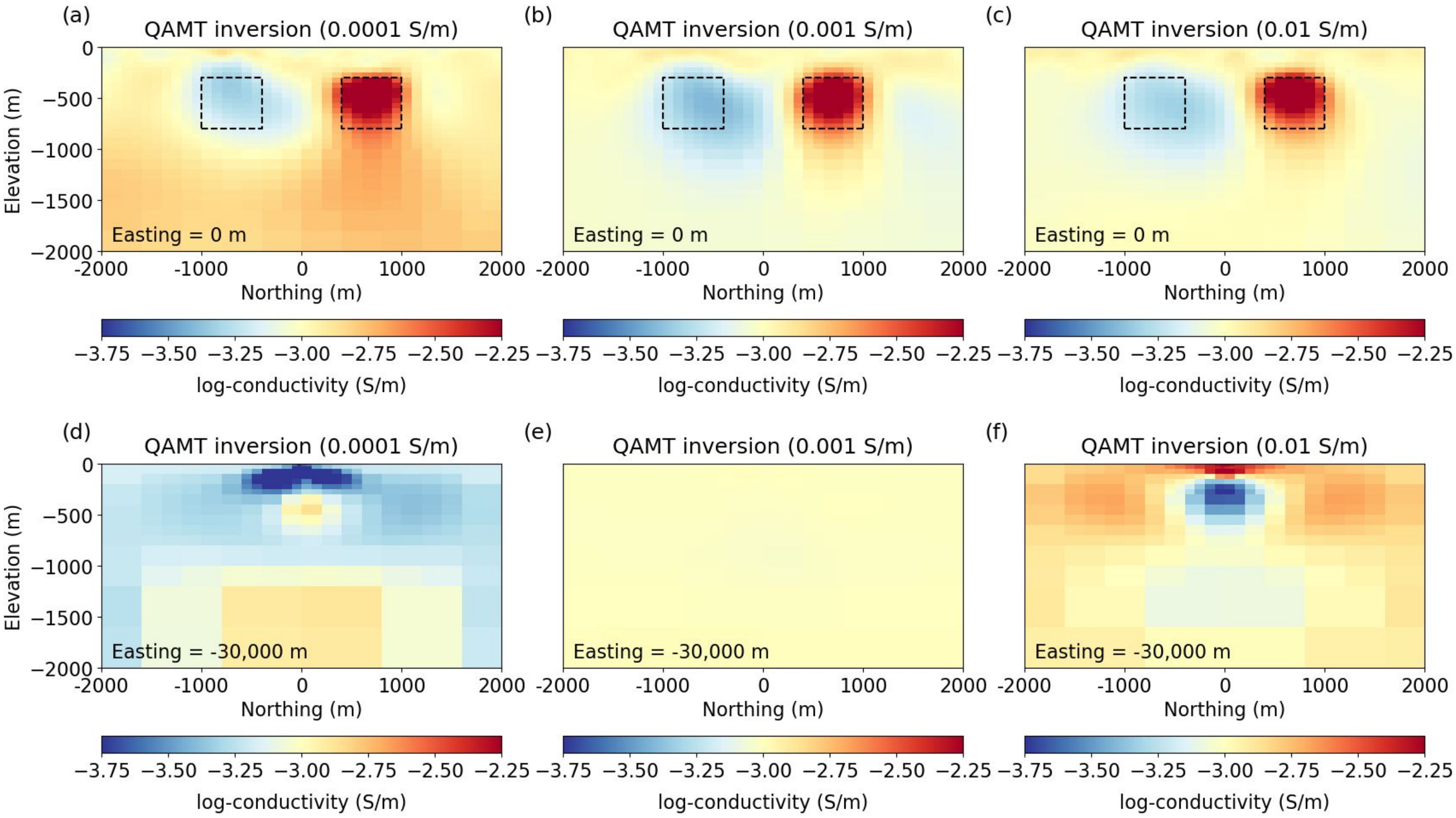
Base Station



Quasi-Impedance Inversion with Host Conductivity

Survey Region

Base Station



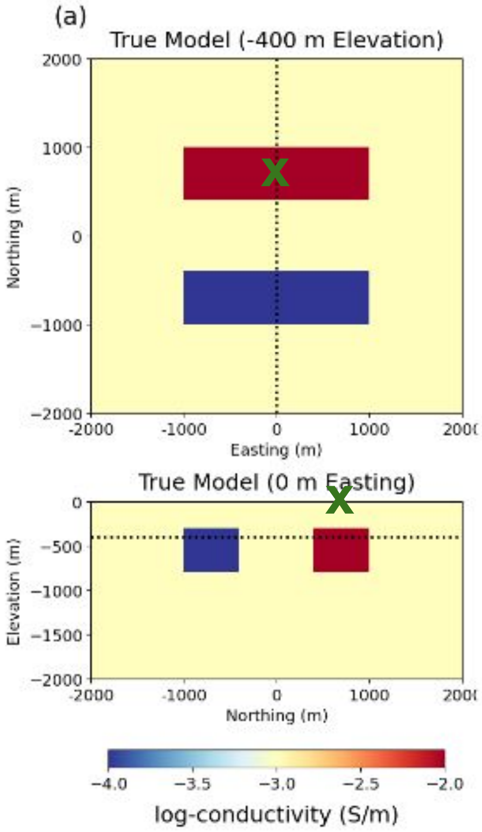
Section Summary

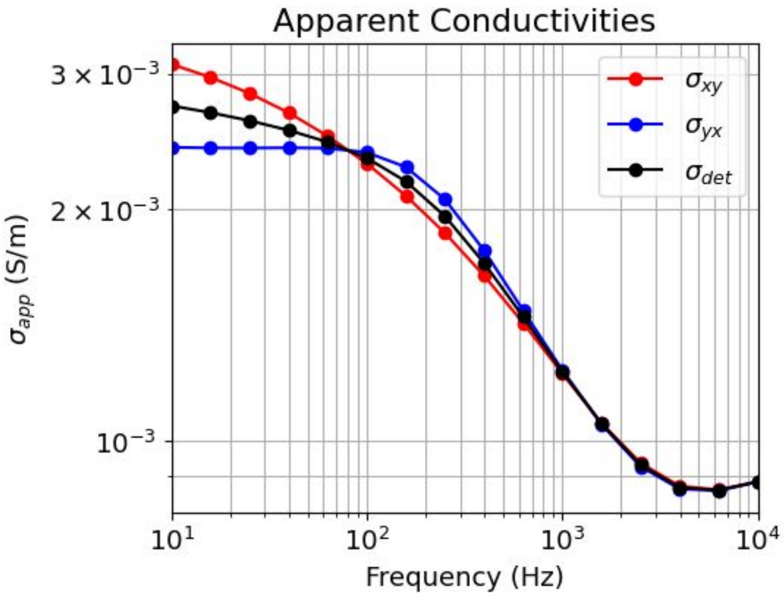
- Choice in starting model impacts both ZTEM and quasi-impedance inversion
- Best to use host conductivity as starting model
- AirMT will recover structures at the base station
- The role of base station structures in fitting the data requires further investigation

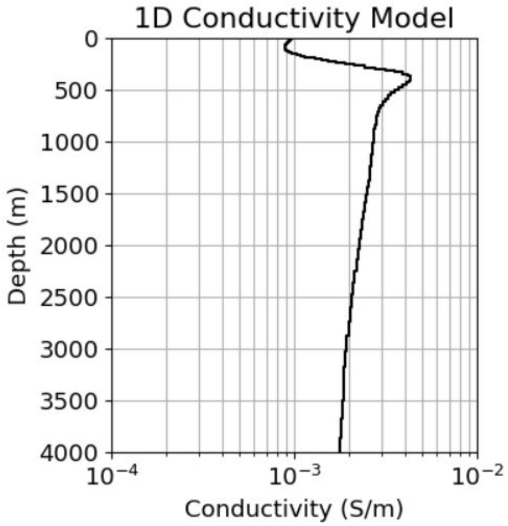
5. Ground MT-Assisted ZTEM Inversion

Setup

- Single MT station at (0, 800, 0)
- Data at 16 frequencies between 10 Hz and 10,000 Hz
- Best-fitting halfspace 0.0018 S/m
- Also invert to get 1D conductivity model



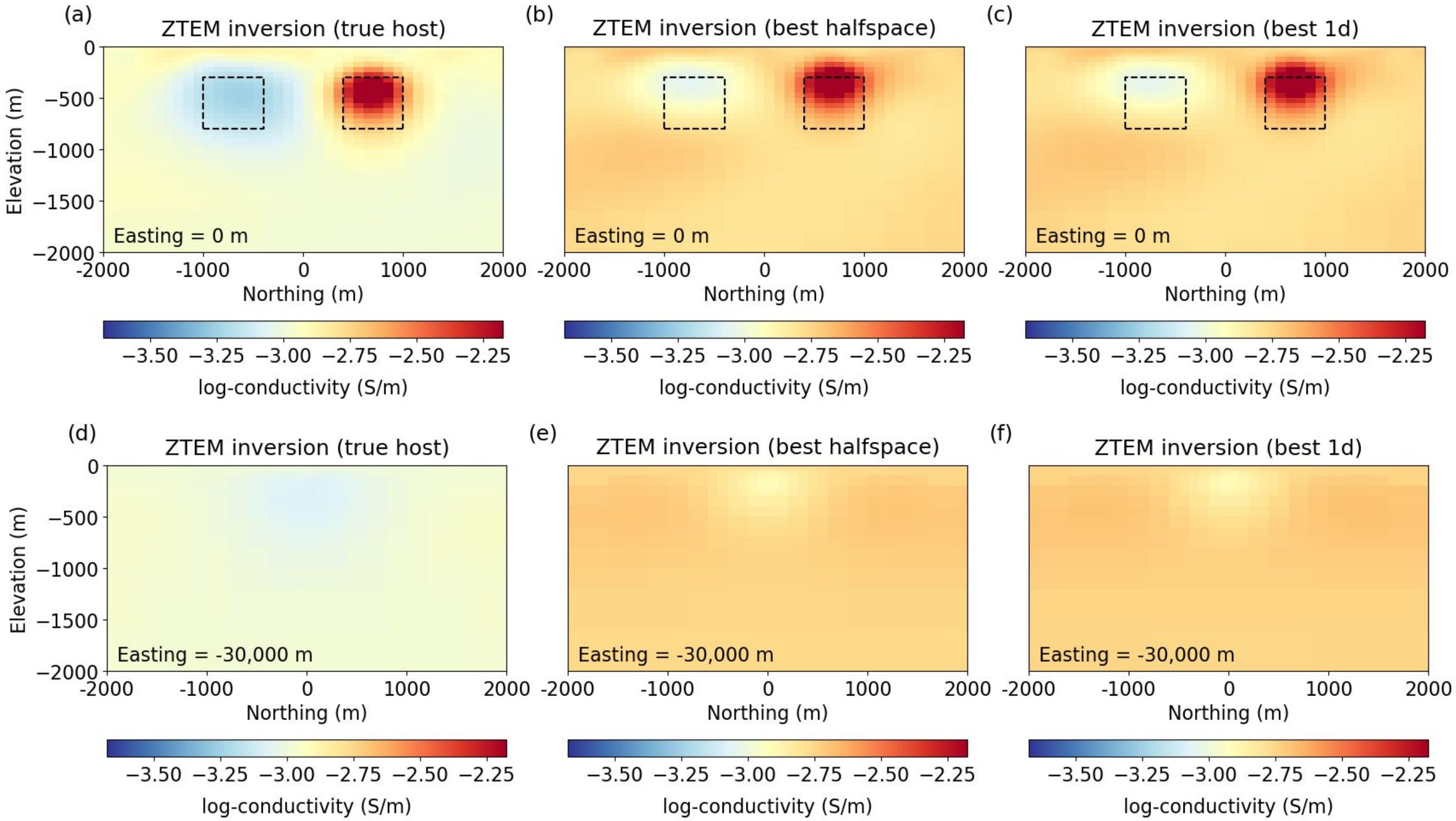




Ground MT-Assisted ZTEM Inversion

Survey Region

Base Station



6. Take-Home Messages

Take Home Messages

$$\begin{bmatrix} T_{zx} \\ T_{zy} \end{bmatrix} = \begin{bmatrix} H_x^{(x)} & H_y^{(x)} \\ H_x^{(y)} & H_y^{(y)} \end{bmatrix}_{BS}^{-1} \begin{bmatrix} H_z^{(x)} \\ H_z^{(y)} \end{bmatrix}_{RX}$$

$$\begin{bmatrix} Q_{xx} & Q_{xy} \\ Q_{yx} & Q_{yy} \end{bmatrix} = \begin{bmatrix} E_x^{(x)} & E_x^{(y)} \\ E_y^{(x)} & E_y^{(y)} \end{bmatrix}_{BS} \begin{bmatrix} H_x^{(x)} & H_x^{(y)} \\ H_y^{(x)} & H_y^{(y)} \end{bmatrix}_{RX}^{-1}$$

- AirMT provides useful information about the Earth's conductivity
- True MT-impedance data cannot be collected in the air
- ZTEM is more or less synonymous with ground tipper data
- Inversion is able to recover subsurface conductivity, provided we have a reasonable estimate of the host conductivity.
- Frequently, a single MT station provides sufficient information about the host

Thank you GEOTECH

Jean Legault

Paolo Berardelli

David Hitz