Exploring the influence of various transfer functions on airborne magnetotelluric inversion

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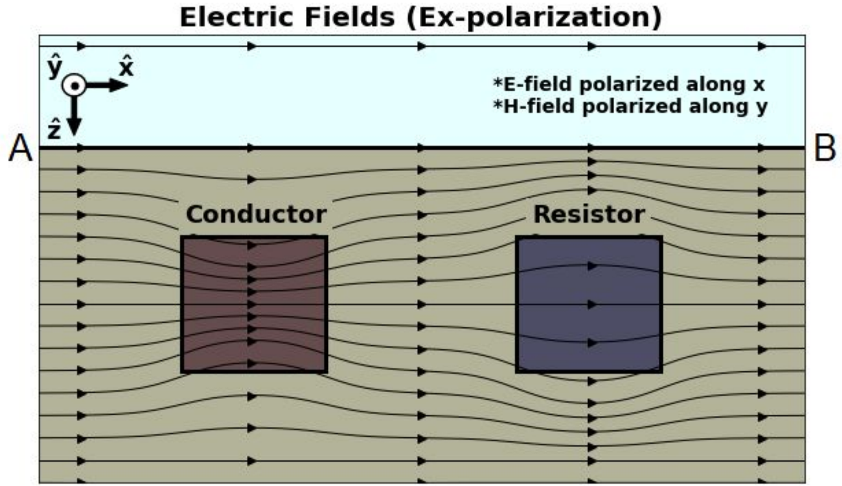
Presentation Outline

1. Introduction to airborne magnetotellurics (AirMT)
2. Influence of base station structures on AirMT anomalies
3. Influence of transfer functions on AirMT inversion
4. Future work

1. Introduction to Airborne Magnetotellurics

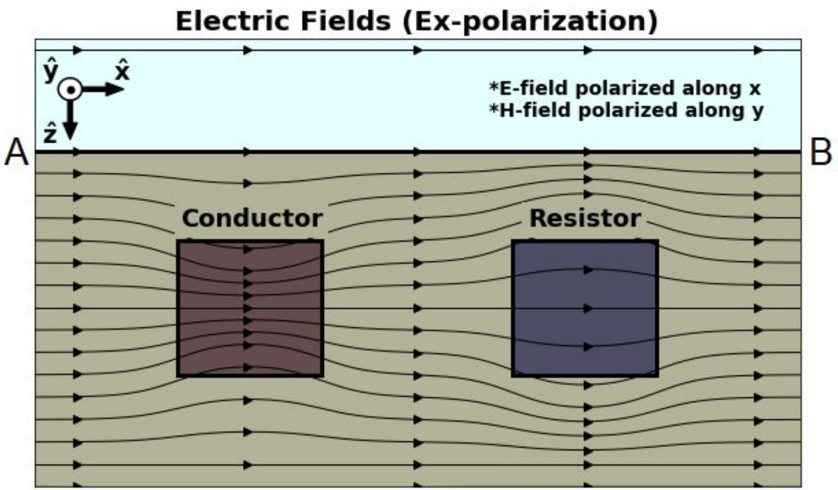
What are Magnetotellurics?

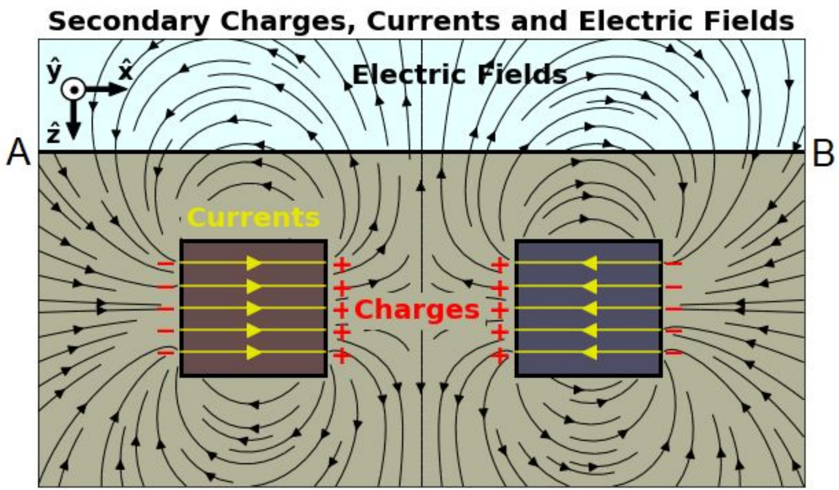
- Naturally occurring EM signals from lightning strikes and solar storms
- Primary signal treated as an incoming planewave



What are Magnetotellurics?

- Naturally occurring EM signals from lightning strikes and solar storms
- Primary signal treated as an incoming planewave
- Magnetic fields (Hx, Hy, Hz) measured in air or on surface
- Electric fields (Ex, Ey) measured on surface





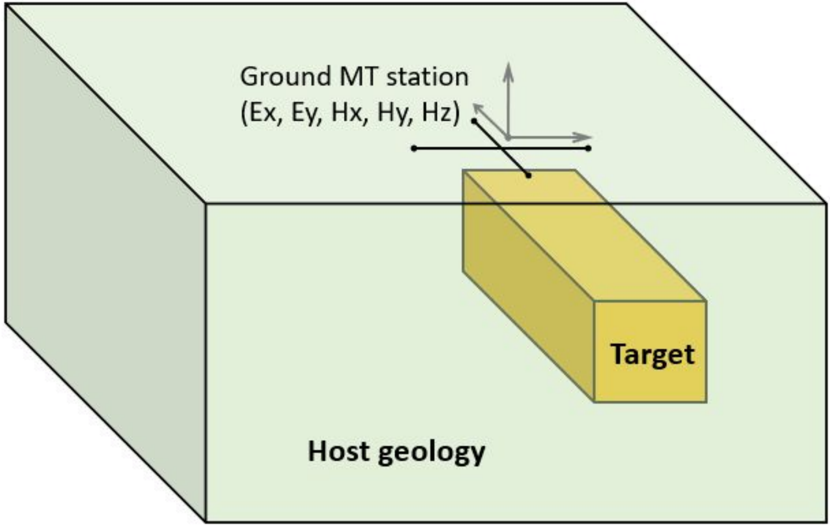
(Ground) MT-Impedance Data

- Measure fields Ex, Ey, Hx and Hy at many **surface locations**
- Decompose the fields into contributions from 2 plane wave polarizations
- Impedances are **transfer functions** defined as:

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

- Directly sensitive to subsurface conductivity

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



(Ground) Tipper Data

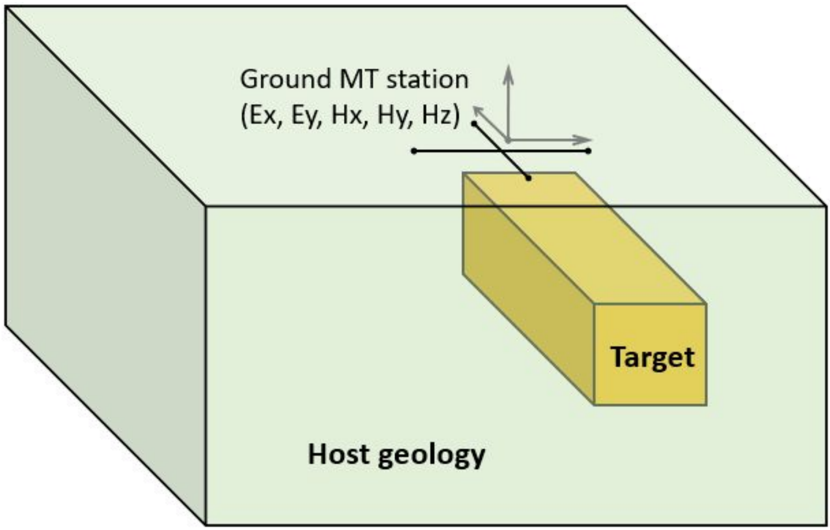
- Measure fields Hx, Hy and Hz at many locations

- Compute tippers, such that

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

- Sensitive to contrasts in conductivity across vertical interfaces

$\rightarrow$ Maps 3D structure



Airborne Magnetotelluric (AirMT)

- Ground measurements expensive and time consuming

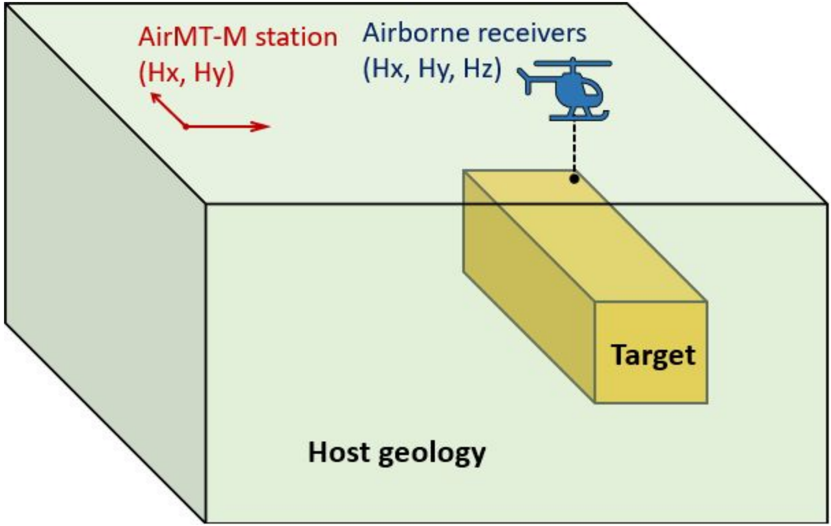
- Magnetic fields can be collected in the air!!!

  → Map structures with airborne magnetotelluric fields (AirMT)

- Higher quality tippers by measuring Hx, Hy at a **base station** (**AirMT-M**).

- E.g. ZTEM data:

$$\begin{bmatrix} H_z^{(x)} \\ H_z^{(y)} \end{bmatrix}_{\boxed{r}} = \begin{bmatrix} H_x^{(x)} & H_x^{(y)} \\ H_y^{(x)} & H_y^{(y)} \end{bmatrix}_{\boxed{b}} \begin{bmatrix} T_{zx} \\ T_{zy} \end{bmatrix}$$



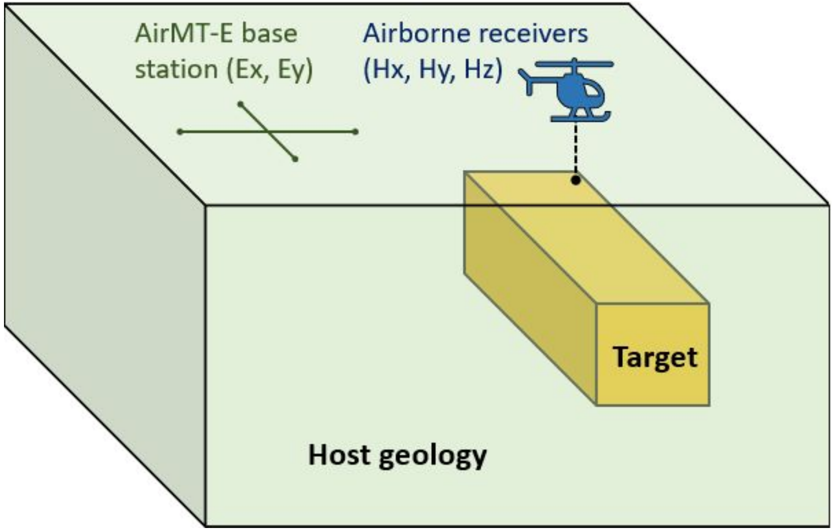
AirMT with an E-field Base Station (AirMT-E)

- Tipper data not directly sensitive to conductivity
- What if we use an E-field base station?
- Airborne Hx, Hy, Hz at many locations and surface Ex, Ey at a **base station**
- **Quasi-impedances (QAMT):**

$$\begin{bmatrix} Q_{xx} & Q_{xy} \\ Q_{yx} & Q_{yy} \end{bmatrix} \begin{bmatrix} H_x^{(x)} & H_x^{(y)} \\ H_y^{(x)} & H_y^{(y)} \end{bmatrix}_{\boxed{r}} = \begin{bmatrix} E_x^{(x)} & E_x^{(y)} \\ E_y^{(x)} & E_y^{(y)} \end{bmatrix}_{\boxed{b}}$$

- **Apparent conductivity (MobileMT):**

$$\sigma_{mmt} = \omega\mu \frac{|H_r|^2}{|E_b|^2}$$

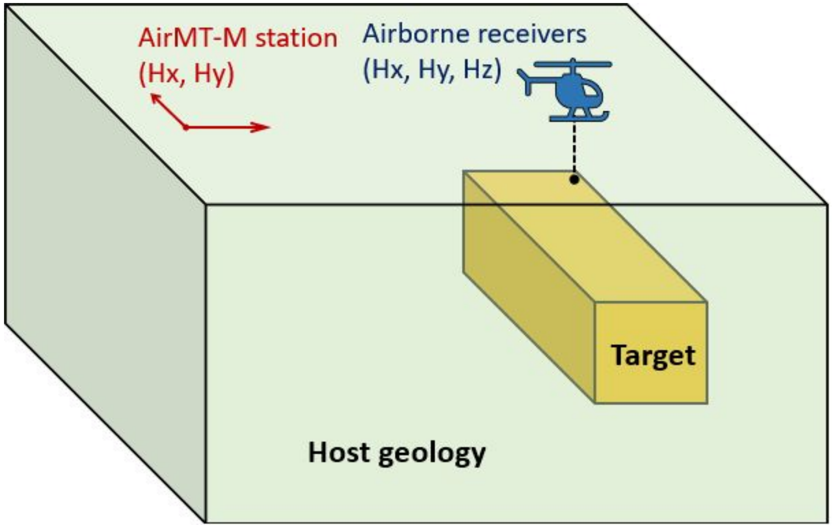


Fundamental AirMT Transfer Functions

AirMT-M Data

$$\mathbf{H}(r) = \mathbf{H}(b)\,\mathbf{T}$$

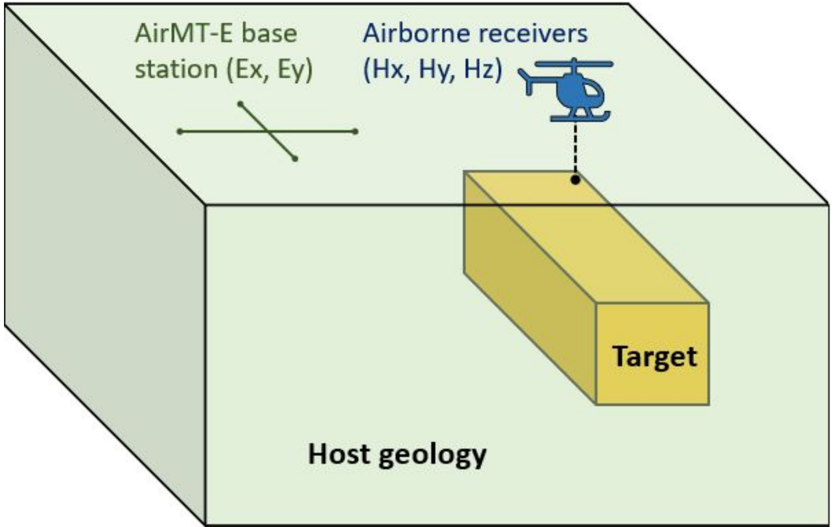
- Magnetic fields (Hx, Hy, Hz) in the air
- Magnetic fields (Hx, Hy) at a base station



AirMT-E Data

$$\mathbf{H}(r) = \mathbf{E}(b)\,\mathbf{Y}$$

- Magnetic fields (Hx, Hy, Hz) in the air
- Electric fields (Ex, Ey) at a base station

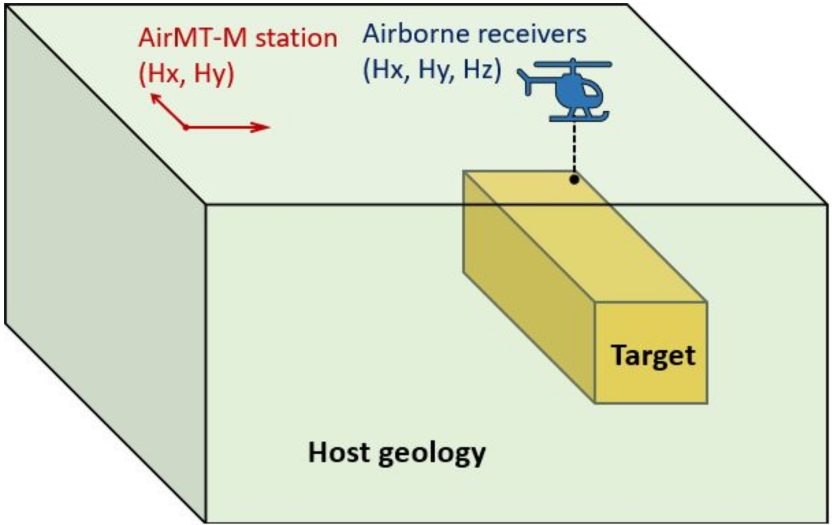


Fundamental AirMT Transfer Functions

AirMT-M Data

$$\begin{bmatrix} H_x^{(x)} & H_y^{(x)} & H_z^{(x)} \\ H_x^{(y)} & H_y^{(y)} & H_z^{(y)} \end{bmatrix}_r = \begin{bmatrix} H_x^{(x)} & H_y^{(x)} \\ H_x^{(y)} & H_y^{(y)} \end{bmatrix}_b \begin{bmatrix} T_{xx} & T_{yx} & T_{zx} \\ T_{xy} & T_{yy} & T_{zy} \end{bmatrix}$$

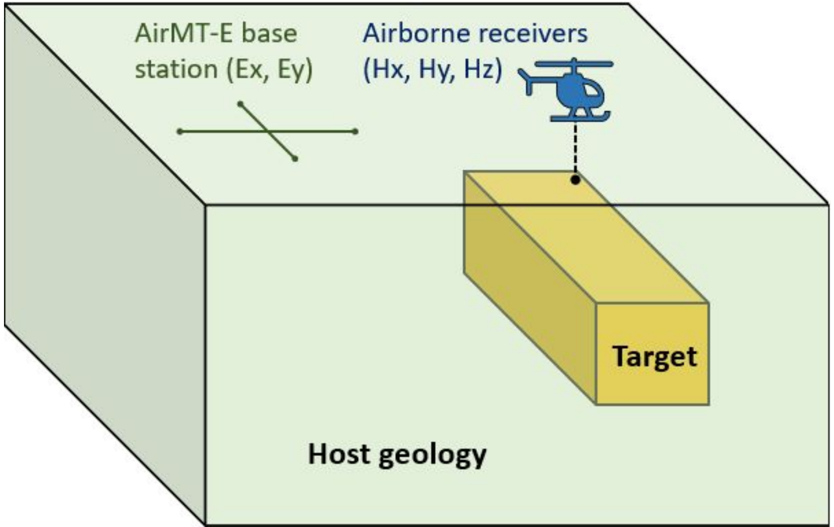
- Magnetic fields (Hx, Hy, Hz) in the air
- Magnetic fields (Hx, Hy) at a base station



AirMT-E Data

$$\begin{bmatrix} H_x^{(x)} & H_y^{(x)} & H_z^{(x)} \\ H_x^{(y)} & H_y^{(y)} & H_z^{(y)} \end{bmatrix}_r = \begin{bmatrix} E_x^{(x)} & E_y^{(x)} \\ E_x^{(y)} & E_y^{(y)} \end{bmatrix}_b \begin{bmatrix} Y_{xx} & Y_{yx} & Y_{zx} \\ Y_{xy} & Y_{yy} & Y_{zy} \end{bmatrix}$$

- Magnetic fields (Hx, Hy, Hz) in the air
- Electric fields (Ex, Ey) at a base station



Nature of AirMT Data

- Information about target from roving airborne magnetic field measurements
  - Not directly sensitive to conductivity
  - Sensitive to vertical interfaces (3D structures)
- Magnetic base station (AirMT-M)
  → Robust to structures at the base station
- Electric base station (AirMT-E)
  → Directly sensitive to the conductivity <u>at the base station</u>

2. Influence of Base Station Structures on AirMT Anomalies

An Important Consideration

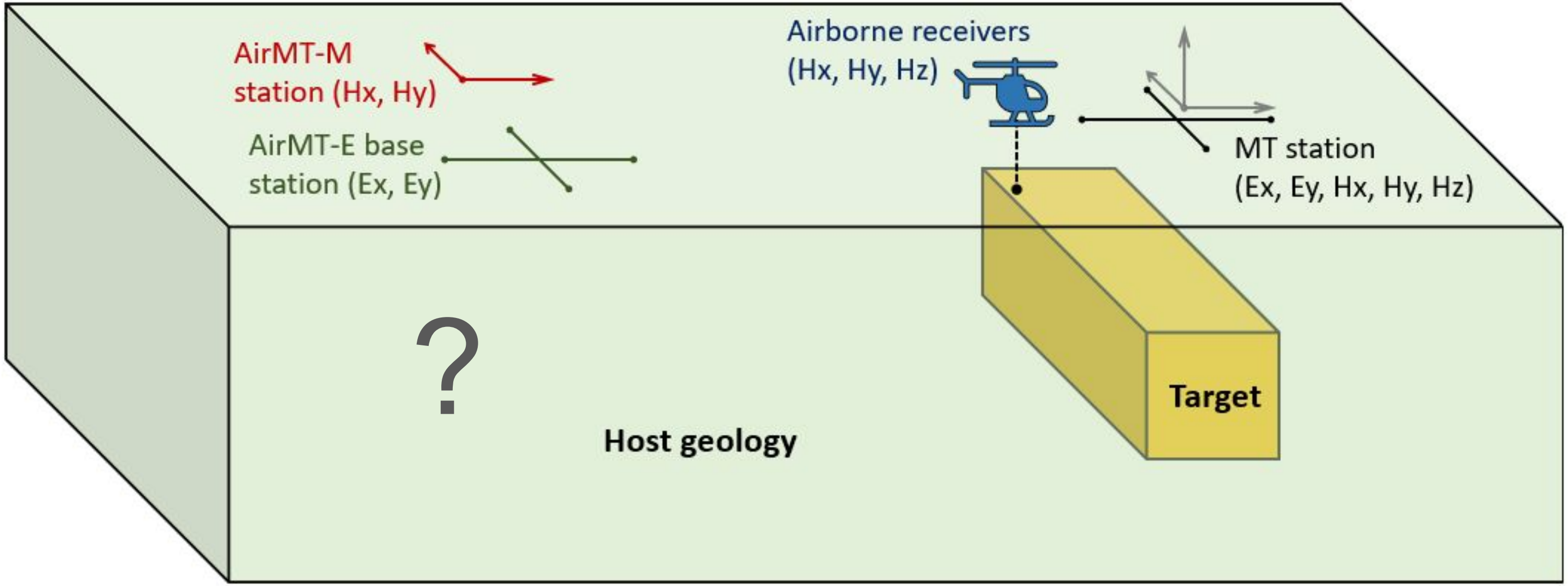
AirMT-M Data

$$\mathbf{H}(r) = \mathbf{H}(b)\,\mathbf{T}$$

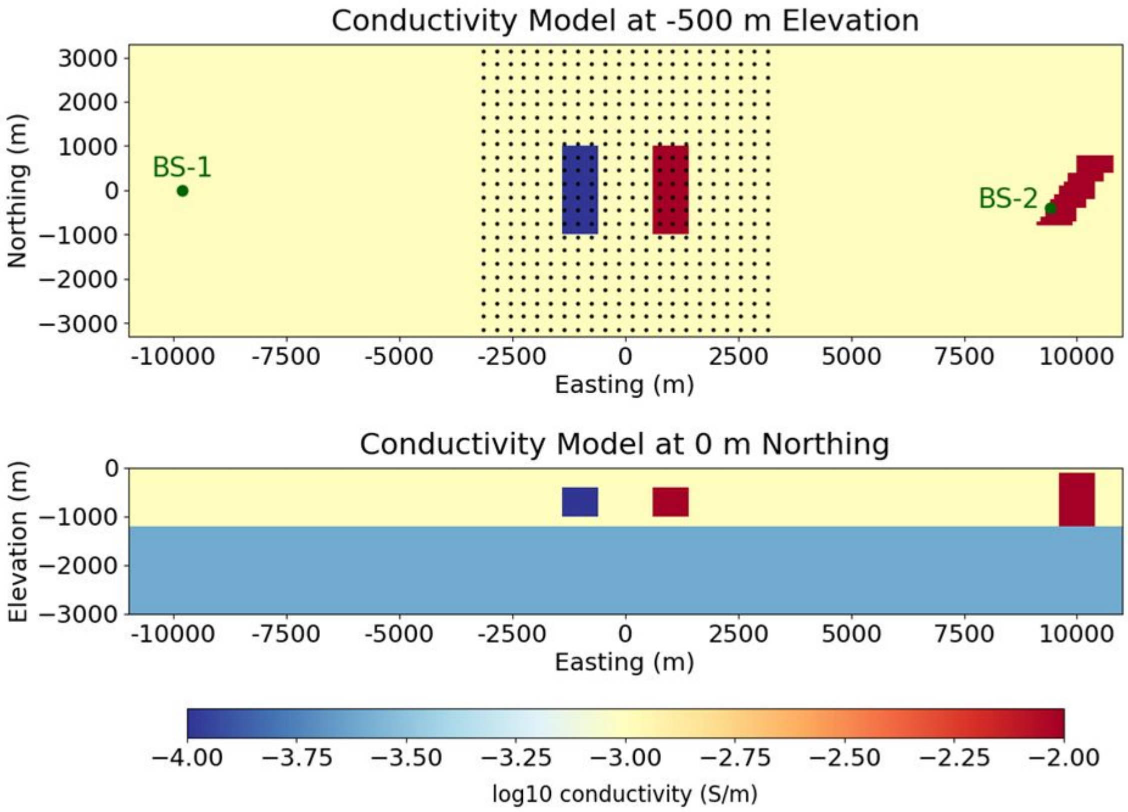
AirMT-E Data

$$\mathbf{H}(r) = \mathbf{E}(b)\,\mathbf{Y}$$

Combining fields at 2 locations to generate each datum!!!

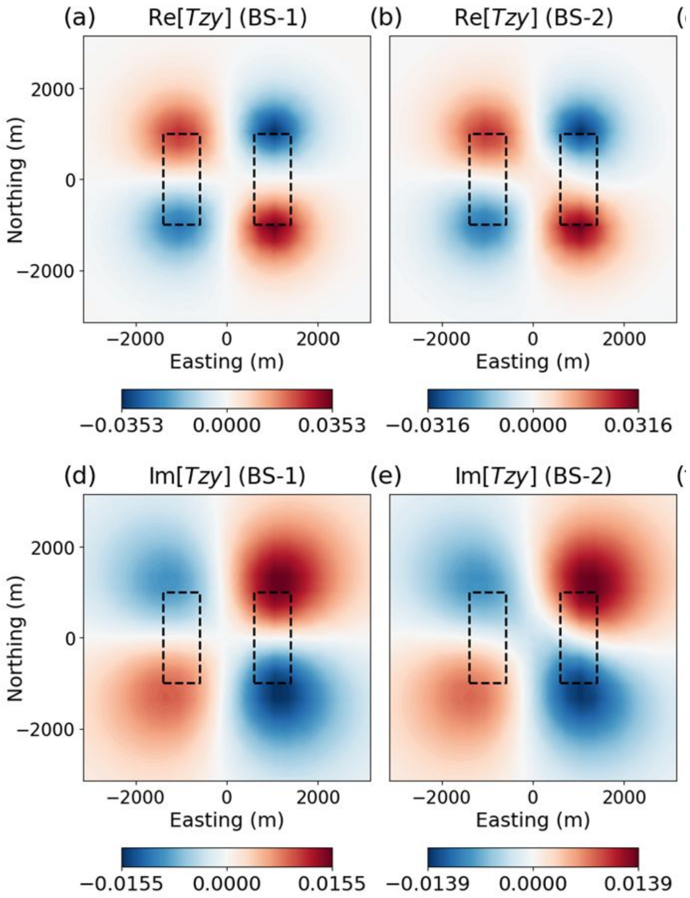


Example



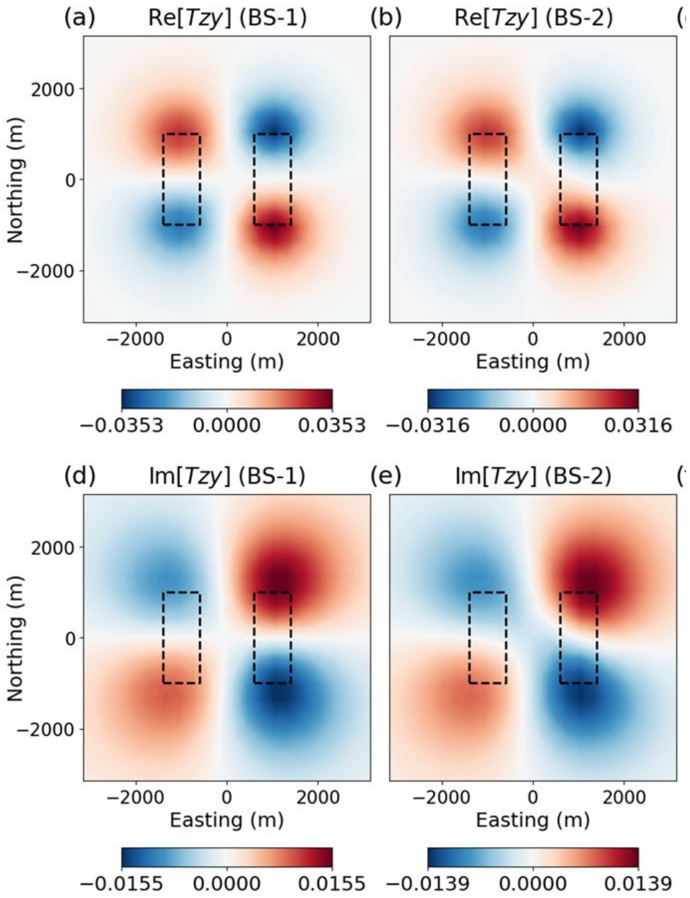
- Compute transfer function data using base stations 1 and 2
- Quantify the influence of the structure at BS-2 on anomaly:
    - Amplitude
    - Shape
    - Phase

Tzy at 270 Hz



(a) Re[Tzy] (BS-1)
(b) Re[Tzy] (BS-2)
(d) Im[Tzy] (BS-1)
(e) Im[Tzy] (BS-2)
Northing (m)
Easting (m)
2000
0
−2000
−0.0353 0.0000 0.0353
−0.0316 0.0000 0.0316
−0.0155 0.0000 0.0155
−0.0139 0.0000 0.0139

Tzy at 270 Hz



Define a <u>distortion matrix</u> **A**:

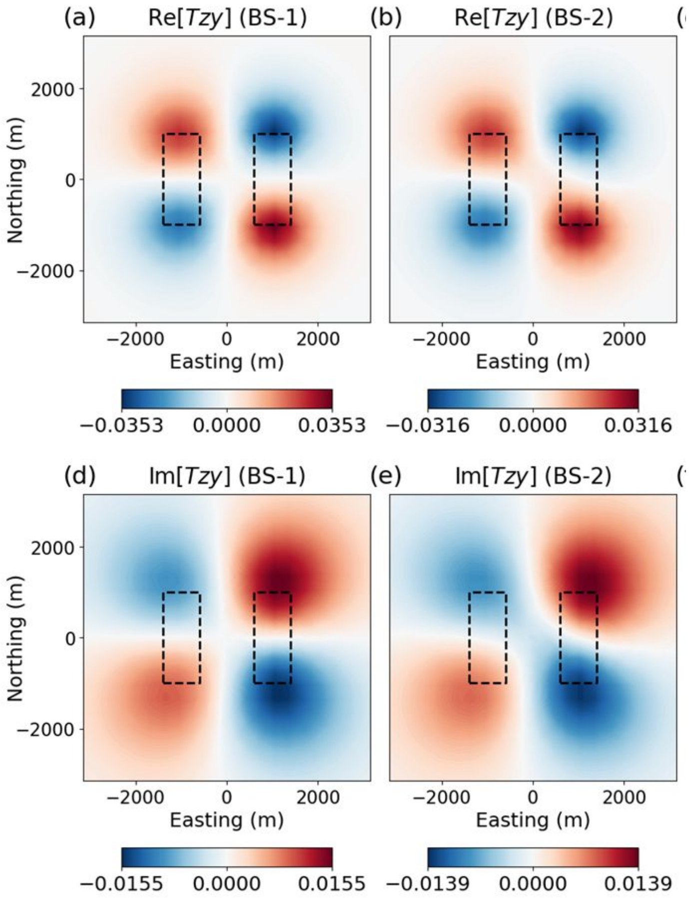
$$\mathbf{H}(b_2)\,\mathbf{A}_{12} = \mathbf{H}(b_1)$$

From definition of AirMT-M data:

$$\mathbf{H}(r) = \mathbf{H}(b_1)\,\mathbf{T}(r, b_1) = \mathbf{H}(b_2)\,\mathbf{T}(r, b_2)$$
$$\Longrightarrow \mathbf{T}(r, b_2) = \mathbf{A}_{12}\,\mathbf{T}(r, b_1)$$

If no influence, $\mathbf{A}_{12}$ is just the identity

Tzy at 270 Hz



Define a <u>distortion matrix</u> **A**:

$$\mathbf{H}(b_2)\mathbf{A}_{12} = \mathbf{H}(b_1)$$

From definition of AirMT-M data:

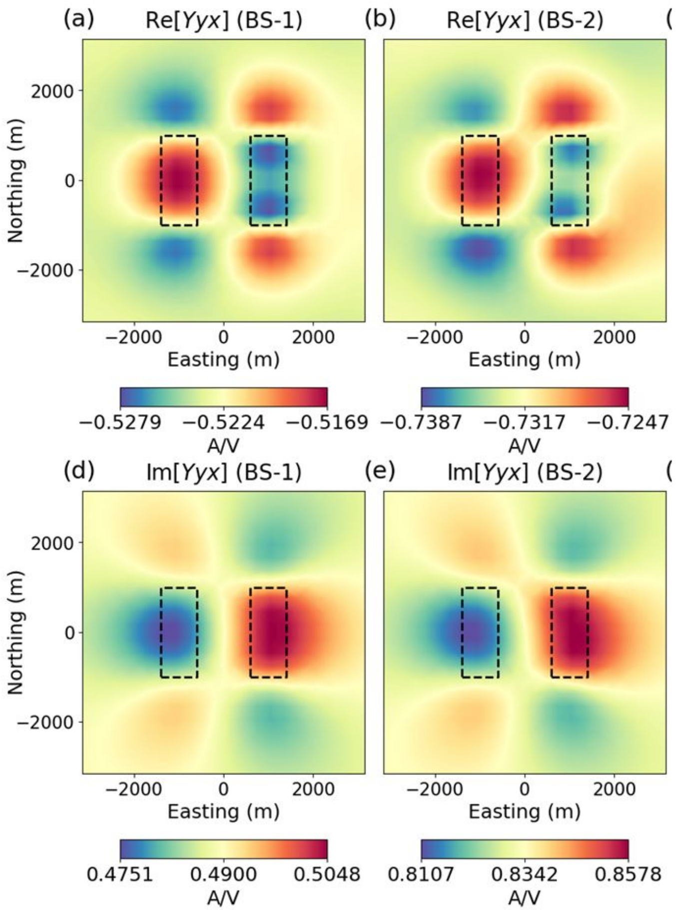
$$\mathbf{H}(r) = \mathbf{H}(b_1)\mathbf{T}(r,b_1) = \mathbf{H}(b_2)\mathbf{T}(r,b_2)$$
$$\Longrightarrow \mathbf{T}(r,b_2) = \mathbf{A}_{12}\mathbf{T}(r,b_1)$$

If no influence, $\mathbf{A}_{12}$ is just the identity

Distortion of AirMT-M anomaly:

$$\mathbf{A}_{12} = \begin{bmatrix} 0.92 + i0.01 & 0.06 - i0.01 \\ 0.05 - i0.01 & 0.89 + i0.01 \end{bmatrix}$$

Yyz at 270 Hz



Distortion matrix **B:**

$$\mathbf{E}(b_2)\,\mathbf{B}_{12} = \mathbf{E}(b_1)$$

Using similar approach:

$$\mathbf{Y}(r, b_2) = \mathbf{B}_{12}\,\mathbf{Y}(r, b_1)$$

Distortion of AirMT-M anomaly:

$$\mathbf{B_{12}} = \begin{bmatrix} 1.54 - i0.15 & -0.08 + i0.02 \\ -0.10 + i0.10 & 1.63 - i0.34 \end{bmatrix}$$

Section Summary

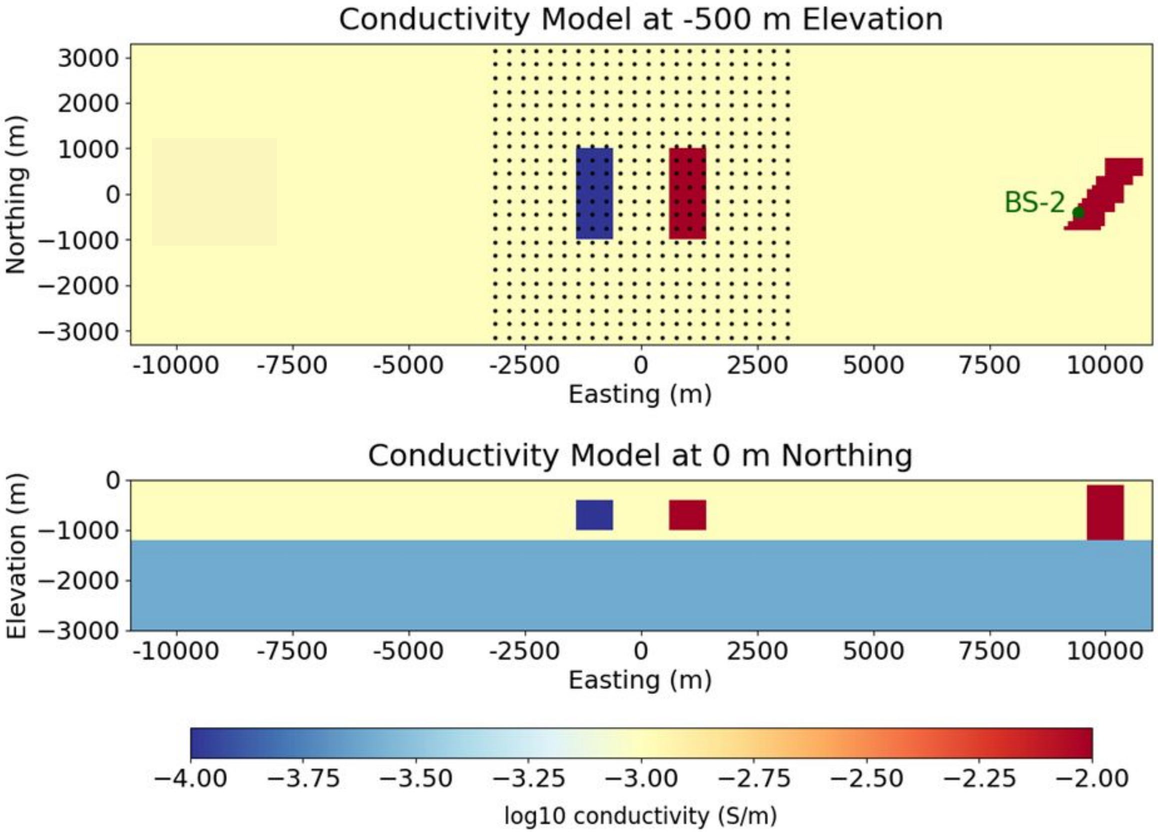
- Structures at base stations primarily influence anomaly amplitudes
- Shape and phase are minimally influenced
- Impact on data interpretation negligible
- AirMT-E anomalies influenced more than AirMT-M anomalies

$$\mathbf{B_{12}} = \begin{bmatrix} 1.54 - i0.15 & -0.08 + i0.02 \\ -0.10 + i0.10 & 1.63 - i0.34 \end{bmatrix} \quad \mathbf{A_{12}} = \begin{bmatrix} 0.92 + i0.01 & 0.06 - i0.01 \\ 0.05 - i0.01 & 0.89 + i0.01 \end{bmatrix}$$

- Distortion matrices **A** and **B** are not consistent across all frequencies

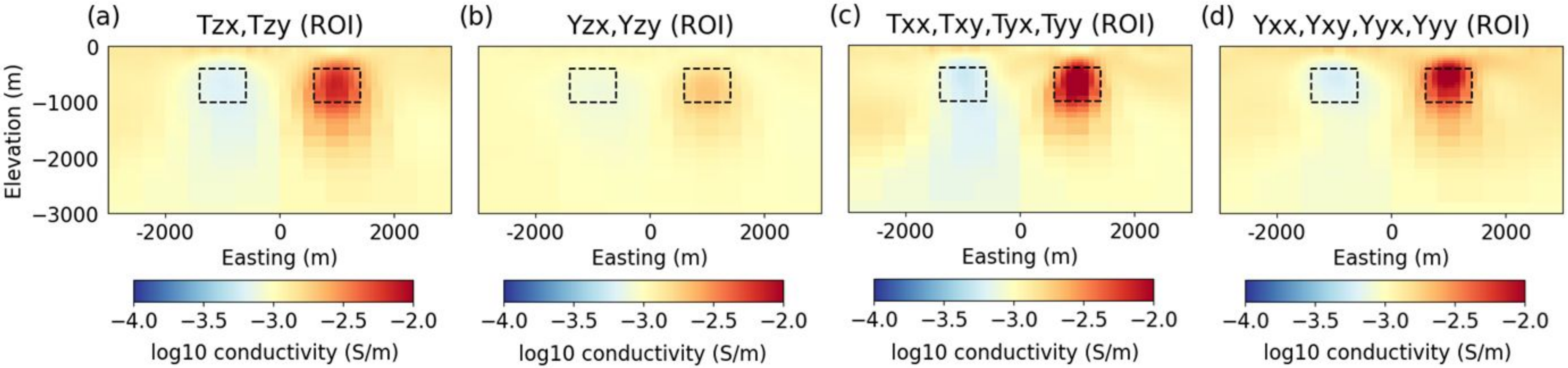
3. Influence of Transfer Functions on AirMT Inversion

Unconstrained Inversion for BS-2



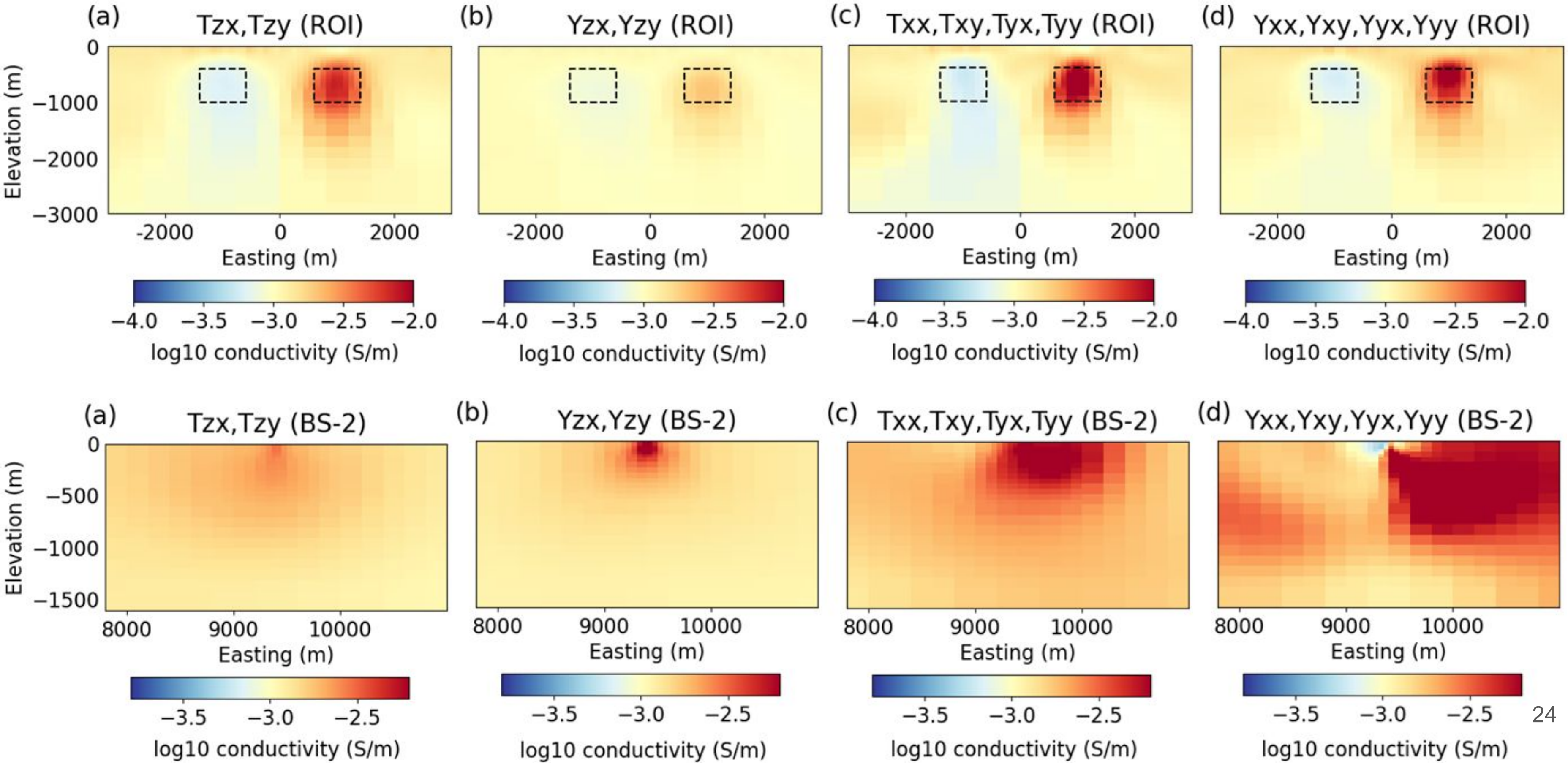
- How different are recovered models?
- Invert the data for 4 configs.:
  - Tzx, Tzy (tipper)
  - Yzx, Yzx
  - Txx, Txy, Tyx, Tyy
  - Yxx, Yxy, Yyx, Yyy
- Base stn at location BS-2
- Smoothest model inversion
- m0 = 1e-3 S/m (true host)

Inversion for Different Transfer Functions

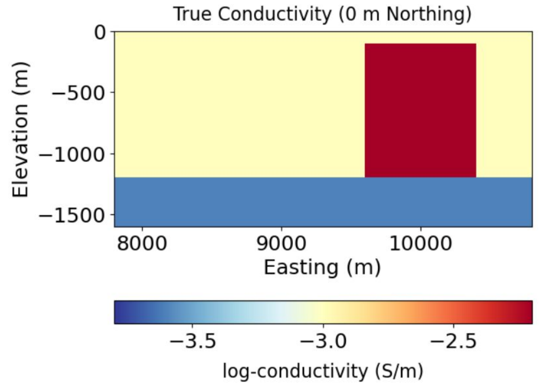


- We do not have identical structure
- All fit the data just as well
- What is recovered at the base station?

Inversion for Different Transfer Functions



Role of Recovered Base Station Structures



Q: How is data fit by placing structure in survey region and near base station?

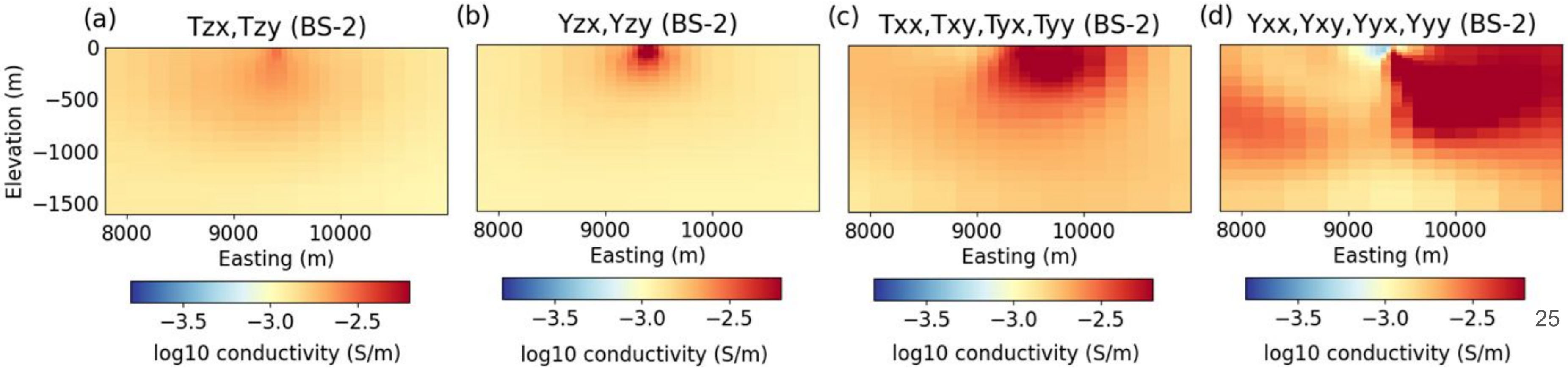
Q: How could this bias target recovery?

AirMT-M Data

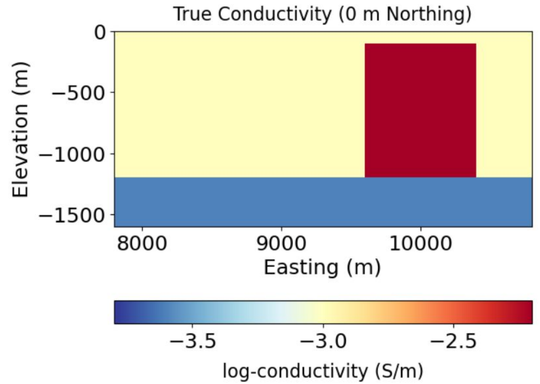
$$\mathbf{H}(r) = \mathbf{H}(b)\,\mathbf{T}$$

AirMT-E Data

$$\mathbf{H}(r) = \mathbf{E}(b)\,\mathbf{Y}$$



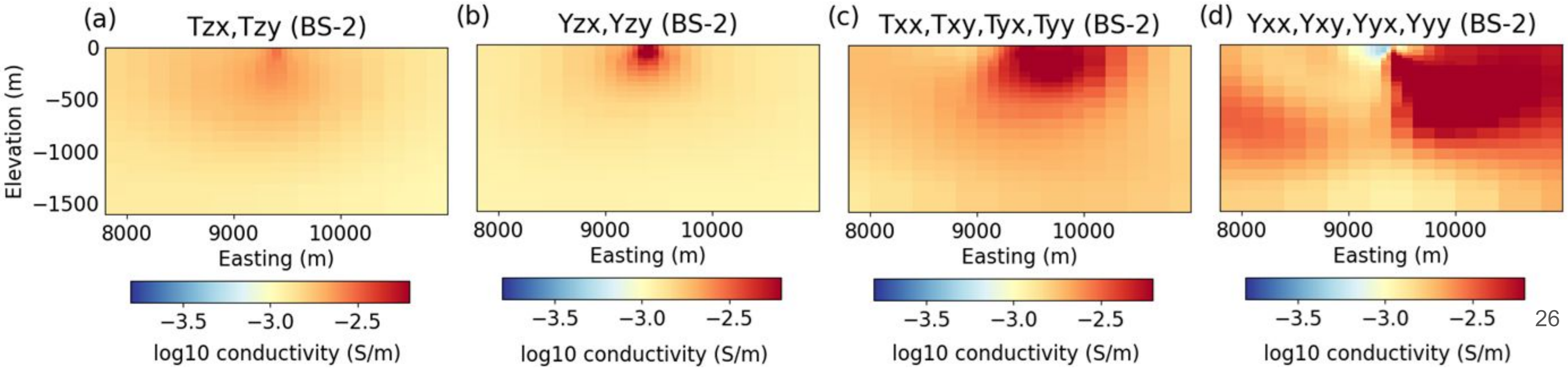
Role of Recovered Base Station Structures



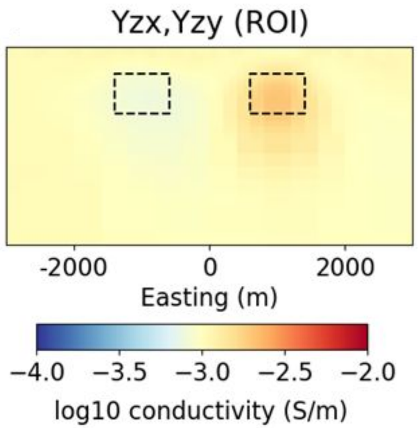
- Compute the base station fields **H(b)** or **E(b)** for the recovered model <u>and</u> the true model
- Compute the "distortion matrix", either:

$$\mathbf{H}(b, pred) = \mathbf{A}\,\mathbf{H}(b, true) \text{ or}$$

$$\mathbf{E}(b, pred) = \mathbf{B}\,\mathbf{E}(b, true)$$



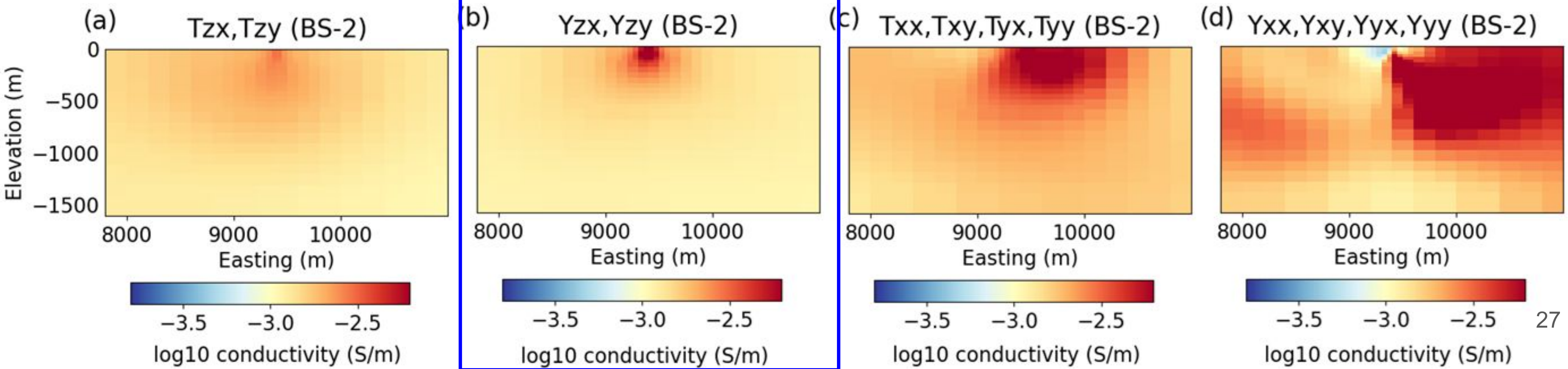
Role of Recovered Base Station Structures



$$\mathbf{B} = \begin{bmatrix} 0.20 + i0.03 & 0.00 + i0.00 \\ 0.00 + i0.00 & 0.17 + i0.04 \end{bmatrix}$$

Predicted base station fields ~20% of true amplitude

Must recover very small contrast in recovered targets

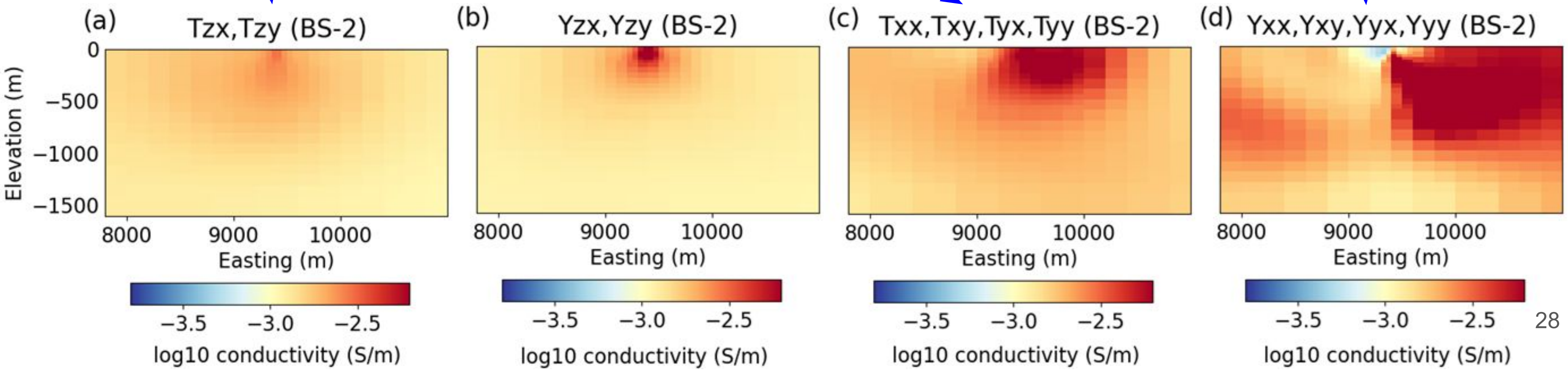


Role of Recovered Base Station Structures

Predicted base station fields 1-10% error in amplitude, <5% error in phase

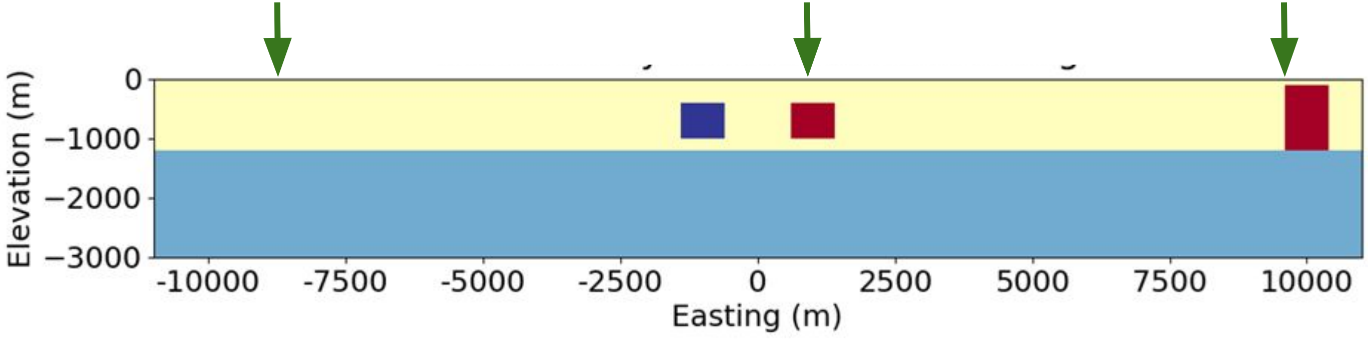
→ Bias in recovered targets is minimal

$$\mathbf{A} = \begin{bmatrix} 1.09 + i0.02 & 0.00 - i0.00 \\ 0.00 - i0.00 & 1.10 + i0.06 \end{bmatrix} \quad \mathbf{A} = \begin{bmatrix} 1.02 - i0.02 & 0.00 + i0.00 \\ 0.00 + i0.00 & 1.02 - i0.01 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 1.03 - i0.02 & 0.00 + i0.00 \\ 0.00 + i0.00 & 1.01 - i0.01 \end{bmatrix}$$



Section Summary

- Recovered structures dependent on transfer functions
- Location and margins generally robust
- Base station structures can bias recovered conductivity contrast
  - Minimal impact (<10%) for most transfer functions
  - Problematic for Yzx, Yzy data
- **Side note:** similar behaviors for other base station locations



Take Home Messages

- (Indirect) information about targets from H-field measurements in the air

- Beneficial to collect full MT fields at base station:
  - E-field → infer conductivity at base station
  - H-field → AirMT-M data robust to base station structures

- Base station structures influence amplitudes of AirMT data (mostly AirMT-E)

- Various AirMT-M and AirMT-E data can be inverted to recover targets

- Significant structure can be recovered at the base station
  → Biases conductivity contrast of recovered targets
  → Artefacts if placed within survey region

4. Future Work

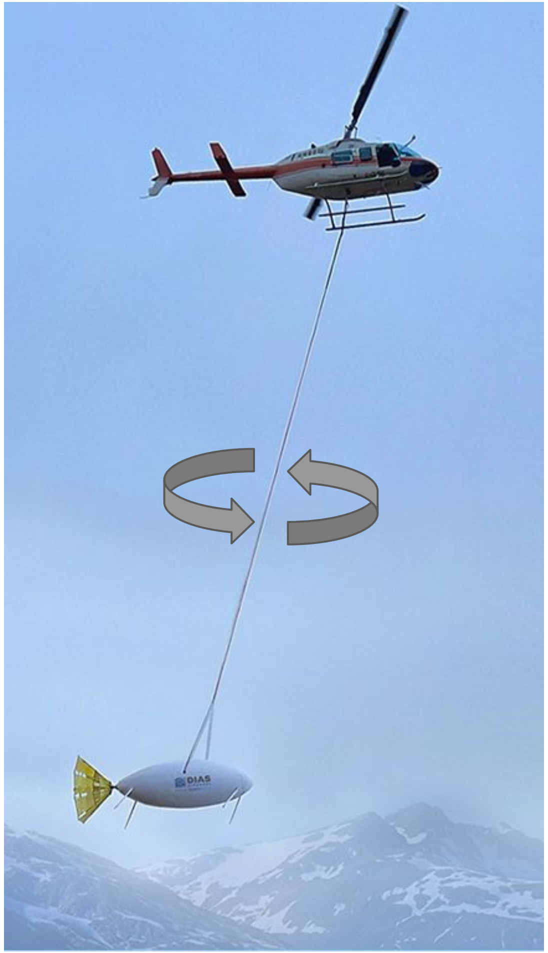
Receiver Orientation

- Airborne receiver motions a dominant source of noise
- Rotational motion about tow cable

  → horizontal airborne magnetic fields challenging
- MobileMT data invariant but dismisses phase information
- Determinant of horizontal transfer functions, e.g.

$$\det \begin{bmatrix} T_{xx} & T_{yx} \\ T_{xy} & T_{yy} \end{bmatrix} \qquad \det \begin{bmatrix} Y_{xx} & Y_{yx} \\ Y_{xy} & Y_{yy} \end{bmatrix}$$

- Advantages:
  - Invariant to rotational motion
  - Preserve (potentially) useful phase information



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