Airborne Natural Source Electromagnetics for an Arbitrary Base Station

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SUMMARY

Airborne magnetotelluric (AirMT) systems generate transfer function data from magnetic fields measured in the air, and either electric or magnetic fields measured at a base station. The transfer function data collected during an AirMT survey is system dependent. Therefore, data collected by various AirMT systems may not recover the same conductivity model when inverted using the same set of inversion parameters. In this abstract, we describe fundamental similarities and differences between AirMT systems that measure magnetic fields versus electric fields at the base station. Synthetic modeling is used to show that AirMT anomalies are fundamentally controlled by the anomalous magnetic fields within the survey region. AirMT data acquired using a magnetic field base station are not directly sensitive to the conductivity at the base station, whereas AirMT data acquired using an electric field base station are scaled by the inverse square root of the conductivity at the base station. Using an unconstrained inversion approach and assuming a distant base station, we determined that when a-priori knowledge of the host conductivity within the survey region is available, AirMT inversion effectively recovers conductive and resistive structures within the survey region. This is true regardless of the fields that are measured at the base station.

Keywords: TDEM, mineral exploration, numerical modeling

INTRODUCTION

Magnetotelluric (MT) methods have long been used to characterize the distribution of subsurface electrical conductivities (Tikhonov, 1950; Cagniard, 1953; Ward, 1959). MT surveys collect impedance and/or tipper data, which define transfer functions relating directional components of the Earth's natural source electric and magnetic fields. Impedance data, which relate horizontal electric and horizontal magnetic fields, can be interpreted directly to infer subsurface conductivity. Impedance data Z_{ij} are defined according to a 2x2 tensor (Chave et al, 2012):

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

where superscripts (x) and (y) represent fields produced by 2 incident planewave polarizations. Tipper data, which relate horizontal and vertical magnetic fields, are sensitive to conductivity contrasts across vertical interfaces. Tippers T_{zx} and T_{zy} are defined according to (Chave et al, 2012):

$$\begin{bmatrix} H_z^{(x)} \\ H_z^{(y)} \end{bmatrix} = \begin{bmatrix} H_x^{(x)} & H_y^{(x)} \\ H_x^{(y)} & H_y^{(y)} \end{bmatrix} \begin{bmatrix} T_{zx} \\ T_{zy} \end{bmatrix} \quad (2)$$

Airborne magnetotelluric (AirMT) systems were developed to rapidly collect MT data over large areas and in regions where ground MT surveys are infeasible. AirMT systems generate transfer function data from magnetic fields measured in the air, and either electric or magnetic fields measured at a base station. For example, Z-axis Tipper EM (ZTEM) data are acquired by measuring vertical magnetic fields in the air and horizontal magnetic fields at a remote base station (Lo and Zang, 2008), while Quantum Audio Magnetotelluric (QAMT) data are acquired by measuring 3-component magnetic fields in the air and horizontal electric fields at a base station (Larnier et al, 2021). For the latter, it was thought that by measuring electric fields at the base station, AirMT systems could acquire MT-like impedance data, which we will call "quasi-impedances".

The data collected during an AirMT survey is system dependent. Therefore, data collected by various AirMT systems may not recover the same conductivity model when inverted using the same set of inversion parameters. Here, we analyze fundamental similarities and differences between AirMT systems that measure magnetic fields versus electric fields at the base station. Assuming a remote base station, numerical forward simulation is used to compare quasi-impedance anomalies to true MT-impedance anomalies. We then analyze the impact of the conductivity at a remote base station on AirMT anomalies. Finally, an unconstrained inversion approach is used to determine whether a-priori knowledge of the conductivity at the remote base station, or the conductivity of the host region, is best-suited for constructing a starting model for the inversion.

UNDERSTANDING AIRMT ANOMALIES

Here, we analyze MT data for the problem geometry in Figure 1, which consists of a conductor (1e-2 S/m) and a resistor (1e-4 S/m) buried within a σ_h = 1e-3 S/m host quarter-space. We simulate MT-impedance data, tipper data for a ZTEM configuration, and quasi-impedance data for a QAMT configuration. Each of these data types is simulated using base station quarter-space conductivities of σ_{bs} = 1e-4 S/m, 1e-3 S/m, and 1e-2 S/m; 9 datasets total. The remote base station for AirMT data is located at (-30000 m, 0 m, 0 m).

In Figures 2a-c, we plot the real component of MT-impedance Z_{xy} at 360 Hz for σ_{bs} = 1e-4 S/m, 1e-3 S/m, and 1e-2 S/m. Since all of the fields used to compute these data are measured inside the survey region, the data are insensitive to the remote geology and the data maps in Figures 2a-c are identical.

In Figures 3a-c, we plot the real component of tipper T_{zx} at 360 Hz for σ_{bs} = 1e-4 S/m, 1e-3 S/m, and 1e-2 S/m. The consistency in the shape and amplitude of the tipper anomalies indicates that tipper data are more or less insensitive to the base station conductivity. This makes sense given that tipper anomalies are produced by vertical magnetic field anomalies in the survey region, and that the horizontal fields measured at the base station are robust to subsurface geology.

In Figure 4a-c, we plot the real component of quasi-impedance Q_{xy} at 360 Hz for σ_{bs} = 1e-4 S/m, 1e-3 S/m, and 1e-2 S/m. The quasi-impedance anomalies are much smoother and lower in amplitude than the MT-impedance anomalies in Figures 2a-c. This is because MT-impedance anomalies are primarily driven by anomalous electric fields within the survey region, while quasi-impedance anomalies are driven by anomalous magnetic fields; consider Eq. 1. Figures 4a-c also show that the quasi-impedance data are scaled proportional to the inverse square-root of the conductivity at the base station, as the electric fields are directly sensitive to the geology there.

Quasi-impedances are clearly not analogous to true MT-impedance data. Regardless of the fields measured at the base station, AirMT anomalies are produced by anomalous magnetic fields within the survey region. Quasi-impedances are directly sensitive to subsurface conductivity at the base station, whereas tipper data are more or less insensitive.

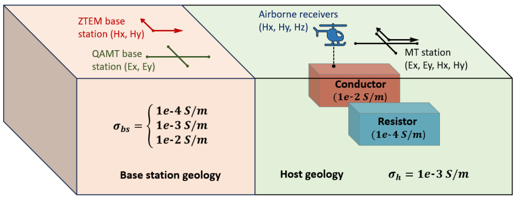

Figure 1: Problem geometry.

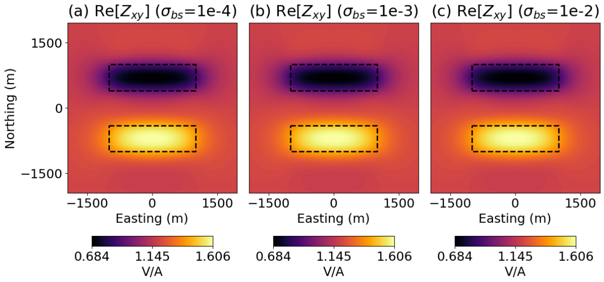

Figure 2: Re[Z_{xy}] simulated for base station conductivities of (a) σ_{bs} = 1e-4 S/m, (b) σ_{bs} = 1e-3 S/m, and (c) σ_{bs} = 1e-2 S/m.

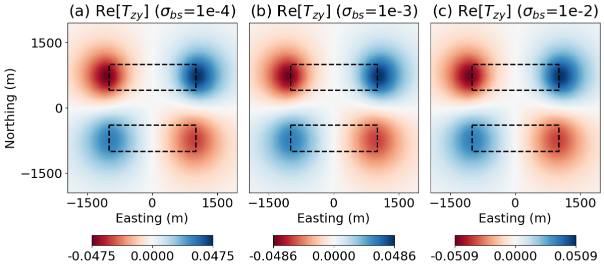

Figure 3: Re[T_{zx}] simulated for base station conductivities of (a) σ_{bs} = 1e-4 S/m, (b) σ_{bs} = 1e-3 S/m, and (c) σ_{bs} = 1e-2 S/m.

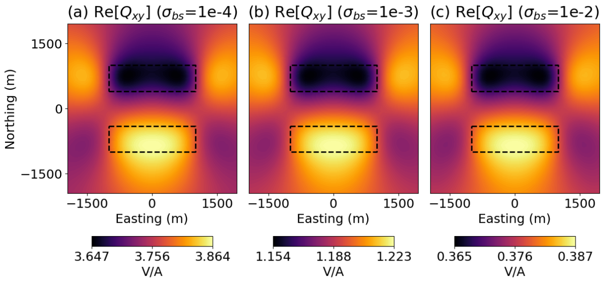

Figure 4: Re[Q_{xy}] simulated for base station conductivities of (a) σ_{bs} = 1e-4 S/m, (b) σ_{bs} = 1e-3 S/m, and (c) σ_{bs} = 1e-2 S/m.

UNCONSTRAINED INVERSION

Here, our goal is to better understand the structures that are naturally recovered by inverting data from AirMT systems. AirMT systems compute each datum from fields measured at two locations. Here, we investigate whether an estimate of the host conductivity within the survey region, or an estimate of the conductivity at a remote base station is a more suitable starting model for AirMT inversion.

Using the Base Station Conductivity

Here, we invert the three ZTEM datasets and the three QAMT datasets generated in the previous section. We use the true base station conductivity (σ_{bs}) as a halfspace starting model (m_0) for each inversion.

The models recovered by inverting the three ZTEM datasets are shown in Figure 5. For all three inversions, the recovered host conductivity within the survey region is approximately equal to the starting halfspace conductivity value. When the host conductivity and base station conductivity differ significantly, the conductor and the resistor are recovered at erroneous depth (Figures 5a and 5c).

The models recovered by inverting the three QAMT datasets are shown in Figure 6. For all three inversions, the recovered host conductivity within the survey region is approximately equal to the starting halfspace conductivity value. When the host conductivity and base station conductivity differ significantly, the conductor and the resistor are recovered at erroneous depth (Figures 6a and 6c).

Our analysis shows that unconstrained inversion of AirMT data is not robust to the choice in halfspace starting model. Additionally, an estimate of the base station conductivity is not generally suitable as a starting model for AirMT inversion when the base station conductivity and host conductivity differ significantly. Failure to choose an appropriate starting model can lead to improper characterization of the host and the recovery of structures at erroneous depths.

Using the Host Conductivity

Here, we invert the three ZTEM datasets and the three QAMT datasets generated in the previous section. The true host conductivity of σ_h = 1e-3 S/m is now used as a halfspace starting model (m_0) regardless of the true base station conductivity (σ_{bs}).

The models recovered by inverting the three ZTEM datasets are shown in Figure 7. Regardless of the true base station conductivity, the conductor and resistor are recovered at the appropriate location and depth. Additionally, the recovered host conductivities are approximately equal to the true host conductivity of σ_h = 1e-3 S/m.

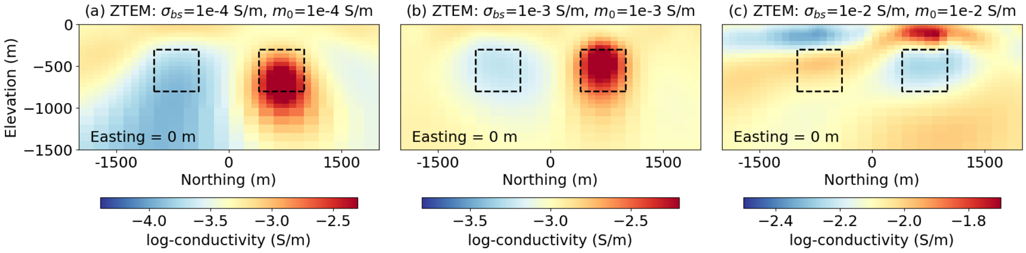

Figure 5: ZTEM inversion for starting halfspace models equal to the true base station conductivity. (a) σ_{bs} = 1e-4 S/m. (b) σ_{bs} = 1e-4 S/m. (c) σ_{bs} = 1e-4 S/m.

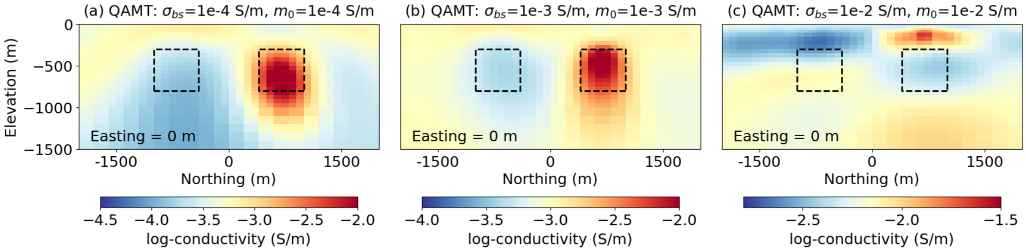

Figure 6: QAMT inversion for starting halfspace models equal to the true base station conductivity. (a) σ_{bs} = 1e-4 S/m. (b) σ_{bs} = 1e-4 S/m. (c) σ_{bs} = 1e-4 S/m.

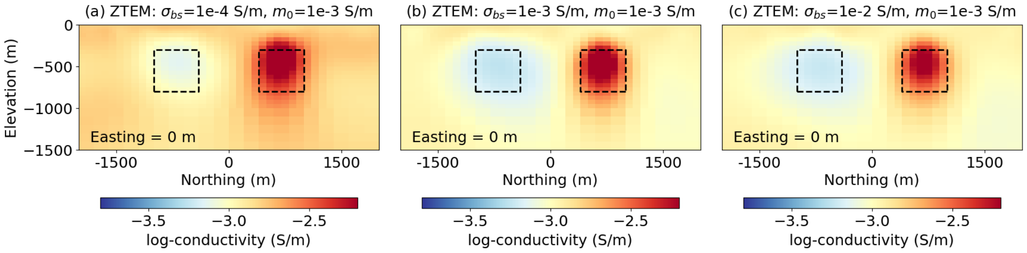

Figure 7: ZTEM inversion for starting halfspace models equal to the σ_h = 1e-3 host conductivity. True base station conductivities of (a) σ_{bs} = 1e-4 S/m. (b) σ_{bs} = 1e-4 S/m. (c) σ_{bs} = 1e-4 S/m.

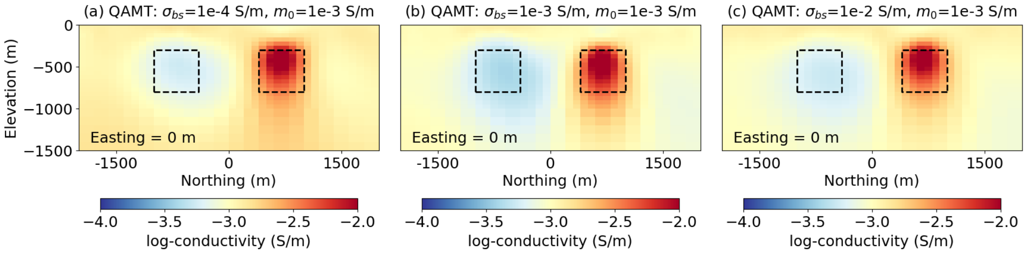

Figure 8: QAMT inversion for starting halfspace models equal to the σ_h = 1e-3 host conductivity. True base station conductivities of (a) σ_{bs} = 1e-4 S/m. (b) σ_{bs} = 1e-4 S/m. (c) σ_{bs} = 1e-4 S/m.

The models recovered by inverting the three QAMT datasets are shown in Figure 8. Regardless of the true base station conductivity, the conductor and resistor are recovered consistently at the appropriate location and depth. Additionally, the recovered host conductivities are approximately equal to the true host conductivity of σ_h = 1e-3 S/m.

Our analysis implies that a-priori knowledge of the host conductivity is of paramount importance for AirMT inversion, regardless of the fields that are measured at the base station. Furthermore, the inversion of tipper data and quasi-impedance data were demonstrated to recover similar models.

CONCLUSION

AirMT systems were developed to rapidly collect MT data over large areas and in regions where ground-MT surveys are infeasible. But before AirMT data can be fully leveraged, it must be fundamentally understood. Our work shows that AirMT data universally identifies 3D conductors and resistors by the anomalous magnetic fields they produce and that true MT-impedance data cannot be collected in the air. AirMT inversion was shown to be capable of recovering both conductive and resistive targets, regardless of which fields are measured at the base station. We determined a-priori knowledge of the host conductivity within the survey region is paramount to successful inversion, whereas a-priori knowledge of the conductivity at a remote base station is minimally significant. The work presented here is intended to provide a basis for future research in the development of AirMT methods.

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