An application of rotational impedance to handle galvanic distortion in USArray data

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SUMMARY

A number of inversion approaches to handle distorted MT dataset have been developed. One practical solution to invert the distorted data is the phase tensor inversion using the SSQ1D model, the 1-D resistivity model derived from average SSQ impedance. Using the SSQ1D model as an initial or prior model is the key to obtain the stable and reliable results. This work aims to examine this scheme on the real data using the USArray data. For this purpose, we chose two array datasets over the State of Nebraska and Iowa. As indicated by the local distortion indicator, the sub-array over the State of Nebraska are weakly distorted, while that over the State of Iowa strongly distorted. When the given MT dataset is weakly distorted, inverting the phase tensor provides 3-D model with relatively small variance at the near surface, which suggests less heterogeneities. However, when the dataset is severely distorted, inverting the phase tensor produces the near-surface heterogeneous layer. We then investigate inverting the phase tensor and the ssq impedance with the gain correction, which is made by dividing the ssq impedance with the apparent gain. The results suggest that this approach could be another promising option. The inverted model shows less variation at the shallow part for the strongly distorted dataset, while the main feature are similar among the inverted models derived from different data combination.

Keywords: Magnetoellurics, Galvanic distortion, Rotational invariant, USArray

INTRODUCTION

The rotational invariant impedances have been used since the beginning of magnetotellurics (MT). They mostly used to determine the regional structure and measure dimensionality of the impedance tensor. Not until recently, an average of the sum-of-the-squared (SSQ), which was first introduced by Szarka and Menvielle (1997), elements impedance, which is a kind of rotational invariant impedances, was found to be a reliable approach to obtain the regional 1-D resistivity structure (Rung-Arunwan et al, 2016). The SSQ impedance (Zssq) is less sensitive to the geometric distortion compared to the traditional determinant (DET) impedance.

In addition, the strength of galvanic distortion, scaling (gain) and geometric distortion (twist, shear, and splitting in Groom-Bailey framework), is able to be quantified through the apparent gain and the local distortion indicator. However, their applications to the real dataset of these rotational invariant parameters have not been presented.

In this work, we applied an approach presented in (Rung-Arunwan et al, 2016, 2017, 2022) to the USArray data. The arrays over the states of Iowa (IA) and Nebraska (NE) were chosen as an example of strongly and weakly distorted MT data set. Examples of distortion indicator and inversion results were presented. Also, inverting the SSQ impedance with the gain correction and the phase tensor were investigated.

METHODOLOGIES

Rung-Arunwan et al (2016, 2017) has shown that the DET impedance are downward biased by the geometric distortion, which is the change of MT impedance tensor dimensionality due to galvanic distortion. On the contrary, the Zssq are less affected. Hence, the average of SSQ impedances from an MT array is suitable to estimate the regional 1-D resistivity structure. In addition, the local distortion indicators and apparent gains were introduced to evaluate the strength of galvanic distortion.

The local distortion indicator (LDI) of any MT site is defined as the squared ratio of observed (distorted) SSQ to DET impedances:

$$\gamma(\omega) = \frac{Z'^2_{\mathrm{ssq}}(\omega)}{Z'^2_{\mathrm{det}}(\omega)} \approx \frac{1+e^2}{1-e^2}\frac{1+s^2}{1-s^2}\frac{Z^{\mathrm{R}}_{\mathrm{ssq}}(\omega)^2}{Z^{\mathrm{R}}_{\mathrm{det}}(\omega)^2}, \quad (1)$$

where the superscript R denotes the regional or undistorted impedance, ω angular frequency, e and s shear and splitting parameters in Groom-Bailey framework. The apparent gain is the ratio of the individual SSQ impedance to the average:

$$g_{\mathrm{ssq}}(\omega) = Z'_{\mathrm{ssq}}(\omega)/\bar{Z}'_{\mathrm{ssq}}(\omega)\ . \quad (2)$$

The LDI and apparent gain are meant to quantify the geometric distortion and amplitude scaling, respectively. For simplicity, we can average the real part of LDI and apparent gain over the given period range as follows:

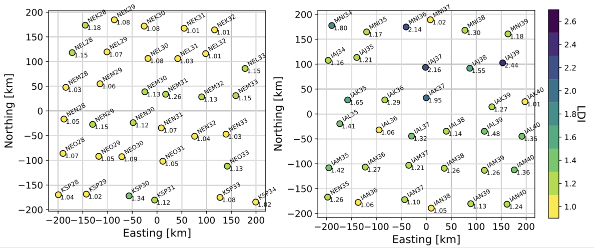
$$\bar{\gamma} = \left[\prod_{j=1}^{N} \Re\{\gamma(\omega_j)\}\right]^{1/N}, \quad (3)$$

and

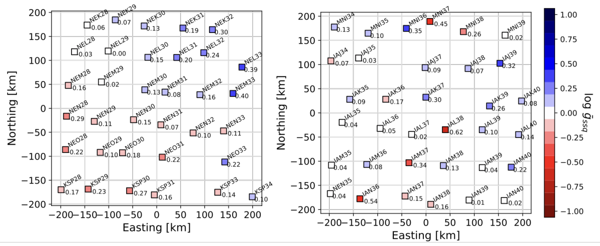
$$\bar{g}_{\mathrm{ssq}} = \left[\prod_{j=1}^{N} \Re\{g_{\mathrm{ssq}}(\omega_j)\}\right]^{1/N}. \quad (4)$$

Results and Discussion

Both IA and NE arrays are located in the interior plains of North America. The stations with poor-quality data were excluded. The NE array are weakly geometrically distorted, as indicated by the LDIs (Figure 1a), while some stations in the IA array exhibit significant geometric distortion (Figures 1b and 2). The site gain in both areas are comparable (Figures 1c and 1d).

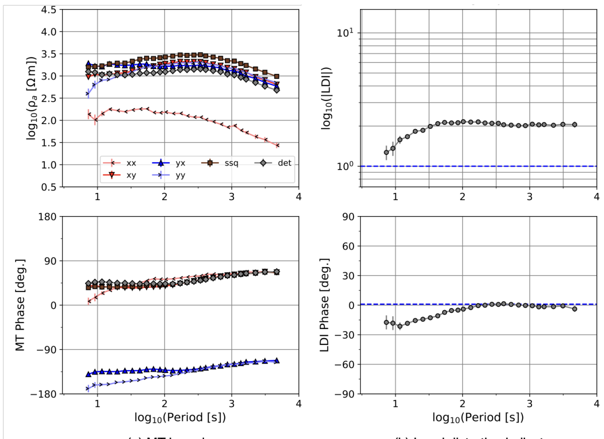


(a) LDI from NE array (b) LDI from IA array



(c) Apparent gain from NE array (d) Apparent gain from IA array

Figure 1: Local distortion indicators and apparent gains from MT stations in IA and NE arrays.



(a) MT impedance (b) Local distortion indicator

Figure 2: (a) MT data and (b) Local distortion indicator from the station IAK37 in the IA array. The geometric distortion is evidenced, particularly at the periods greater than 30 s. The average LDI for this station is 1.98.

To reduce the effect of galvanic distortion in the inversion, several approaches have been developed. Inverting the phase tensor (PT; Caldwell et al, 2004) is one of them (e.g. Tietze et al, 2015). PT itself is lack of subsurface resistivity information. Consequently, inverting PT without the optimal initial and prior models would be disadvantageous.

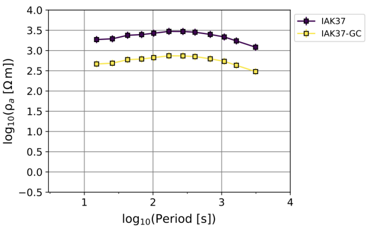


Figure 3: Example of the gain correction applied to Site IAK37, where the apparent gain is 0.30.

Here, the 1-D model derived from average SSQ impedance (SSQ1D) was used as an initial and prior models as it is proven to be less affected by galvanic distortion and it provides reliable inversion results (see Rung-Arunwan et al, 2022).

In this 3D inversion, the total 12 periods of data ranging between 15.1–3120.8 s were used. The minimum skin depth is approximately 33.8 km, assuming the uniform resistivity of 300 Ω m. In addition to inverting the MT impedance tensor and PT, the 3D MT data-space inversion (Siripunvaraporn et al, 2005) was modified to include the SSQ impedance. The gain correction (GC) with the apparent gain (4) was also examined (see Figure 3).

The inverted results from the IA array are shown in Figure 4. The main features of the models inverted from different data types are similar at the depth greater than the skin depth.

Here, we determine the distribution of the resistivity model from the standard deviation of the inverted models as a function of depth (Figure 5. Rung-Arunwan et al (2022) assumed that inverting PT alone with the SSQ1D will be theoretically equivalent to inverting Zssq with gain correction and PT. However, the model distribution from the IA array shows that inverting PT alone may cause more near-surface heterogeneities than using PT and Zssq with gain correction.

As with the IA array, the inverted models from different data types of the NE array are similar (Figure 6). However, the SD of resistivity of the models from different data type of the NE array are comparable at the shallow part, <15 km deep, (see Figure 5b). This may be because the NE array has weak geometric distortion.

CONCLUSIONS

Galvanic distortion is a problem in magnetotelluric surveys. An indication for galvanic distortion are crucial. The definition of LDI to quantify the strength of geometric distortion is simple, yet efficient. From our examples, the LDI successfully indicates the strong and weak geometric distortion in IA and NE arrays, respectively. We can then select proper treatments or inversion strategies to handle the distorted dataset. The phase tensor is intrinsically galvanic distortion-free. Integrating it in the inversion is favorable.

Inverting PT alone even using the optimal initial or prior models, e.g., SSQ1D, can cause near-surface heterogeneities which may unknowingly interfere the underlying regional structure of interest. Including the SSQ impedance with gain correction can help suppress the near-surface heterogeneities if the dataset are distorted. However, further investigations on including Zssq and the gain correction, for example, a comparison with inverting the all and off-diagonal elements of MT impedance, and using uniform resistivity as an initial or prior model, are necessary.

ACKNOWLEDGMENTS

The MT data used in this study is a part of US-Array MT data (Schultz et al, 2006-2018), which are available through the IRIS EMTF database (https://ds.iris.edu/spud/emtf).

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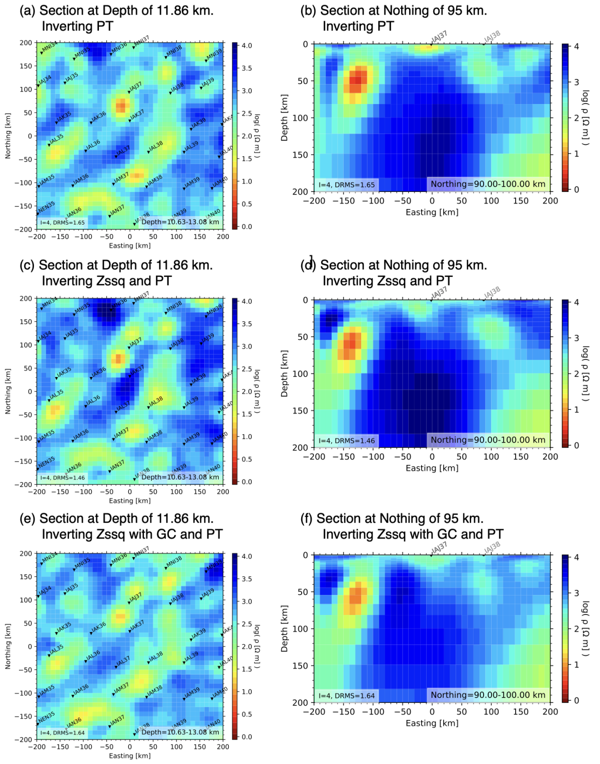
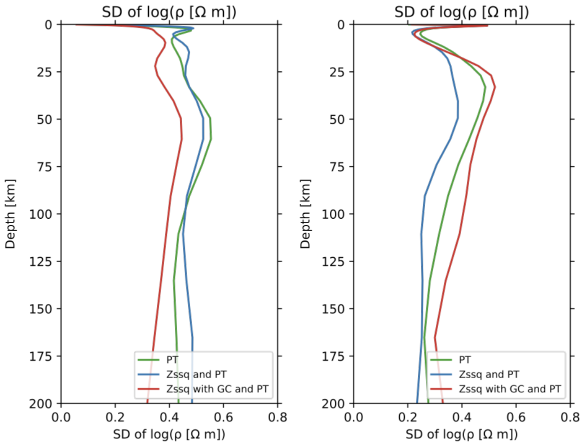


Figure 4: Depth and Vertical sections of 3D model inverted from (a,b) PT, (c,d) Zssq and PT, and (e,f) Zssq with GC and PT from the IA array.



(a) IA array

(b) NE array

Figure 5: Model distribution represented by the SD of the inverted model as a function of depth from the (a) IA and (b) NE arrays.

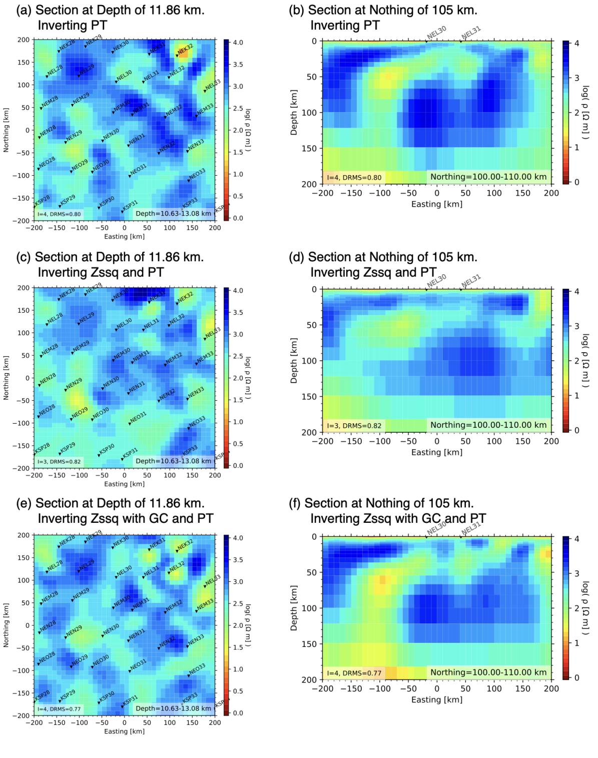


Figure 6: Depth and Vertical sections of 3D model inverted from (a,b) PT, (c,d) Zssq and PT, and (e,f) Zssq with GC and PT from the NE array.