3D Inversion of Controlled-Source Radio-Magnetotelluric (CSRMT) data of a waste-site in Cologne, Germany

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SUMMARY

Applied geophysics often employs electromagnetic methods for shallow subsurface investigations. Among these, the Radiomagnetotelluric method stands out, utilizing radio transmitters in the 10 kHz to 1 MHz frequency range to induce current systems in the conductive earth, generating secondary electric and magnetic fields. Despite its effectiveness, Radiomagnetotelluric faces challenges in remote areas lacking suitable radio transmitters, limiting its penetration depth.

A modified method, Controlled-Source Radiomagnetotelluric, addresses these limitations by using specific base frequencies and their subharmonics to enhance data quality and increase penetration depth. Initial attempts at lower frequencies down to 1 kHz have shown promise. Recent research in Cologne, Germany, utilized two perpendicularly located Horizontal Electric Dipole sources to obtain full impedance tensor elements in the frequency range between 1kHz and 1 MHz, enabling 3D inversion of Controlled-Source Radiomagnetotelluric data. The results, compared with RMT data, successfully identified waste deposit with resistivity values aligning with geological information.

Although some adjustments were needed to fulfill the Magnetotelluric approximation, the primary objective of waste-site distribution and depth detection was achieved. This study underscores the effectiveness of Controlled-Source Radiomagnetotelluric in overcoming limitations of traditional Radiomagnetotelluric, particularly in remote areas, and highlights its potential for accurate subsurface characterization in various geological contexts.

Keywords: electromagnetic, CSRMT, inversion, conductivity, waste-site

INTRODUCTION

Applied geophysics commonly employs electromagnetic (EM) methods for shallow subsurface investigations. Radiomagnetotelluric method (RMT) (e.g., Tezkan 1999; Pedersen et al. 2005) is widely used in the frequency domain of EM techniques and has proven successful across diverse environmental, engineering, and geological targets in recent decades (Tezkan et al. 2005; Bastani et al. 2011; Malehmir et al. 2013; Bastani et al. 2013). RMT operates by utilizing radio transmitters within the 10 kHz to 1 MHz frequency range, where EM signals penetrate the conductive earth, inducing current systems that generate secondary electric and magnetic fields. Electric antennae and magnetic coils at receiver stations measure these fields on the surface, offering insights into subsurface conductivity distribution, with a depth of investigation (DOI) that can extend up to 100 m, depending on ground resistivity. Displacement currents can be disregarded for frequencies below 1 MHz and resistivities under 1000 Ωm. The plane wave assumption remains valid in RMT measurements, owing to the significant distance between radio stations and receivers.

However, despite the ease of setup and the rapid measurement system of RMT, it presents a significant weakness when surveying remote regions lacking suitable LF and MF (30-1000 kHz) radio transmitters. In such cases, only the signals of VLF (very low frequency) transmitters (10-30 kHz) can be detected, and with no radio transmitters broadcasting below 10 kHz. This leads to a limited penetration depth (Saraev et al. 2017) that may result in resolution issues, particularly in investigations such as conductive waste sites.

To address these limitations, Controlled-Source Radiomagnetotelluric (CSRMT) offers a modified approach. By utilizing specific base frequencies and their subharmonics in the transmitter(s), data quality can be improved, and a wider frequency range provided, thus enhancing penetration depth. Bastani (2001) pioneered this advancement, achieving lower frequencies down to 1 kHz using a horizontal magnetic dipole as a transmitter.

Nevertheless, RMT has been extensively applied across various environmental, engineering, and geological targets in recent decades, including groundwater (Turberg et al. 1994) and waste-site (Tezkan et al. 2000) explorations. In ongoing research, two perpendicularly located Horizontal Electric Dipole (HED) sources were employed to acquire full impedance tensor elements, enabling a 3D inversion of CSRMT data. Both RMT and CSRMT were concurrently measured at each station, ensuring results comparability.

METHOD

The RMT-C system (Saraev et al. 2017) can receive signals from 1 kHz to 1 MHz and measuring the $\mathrm{E_x}$, $\mathrm{E_y}$, $\mathrm{H_x}$, $\mathrm{H_y}$ and $\mathrm{H_z}$ components of the EM field. The electric cables and the magnetic coils at the stations are all located orthogonal. In a 2D case, the electromagnetic fields are separated into two polarizations:

- E-polarization or transverse electric (TE), where electric fields are parallel to the strike direction.
- B-polarization or transverse magnetic (TM), where magnetic fields are parallel to the strike direction.

Just like Magnetotelluric method, the horizontal electric and magnetic field components are related through the impedance tensor Z that considering two orthogonal transmitter lines that we used in CSRMT, can be written as (Li and Pedersen 1991):

$$\begin{bmatrix} E_x^1 & E_x^2 \\ E_y^1 & E_y^2 \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x^1 & H_x^2 \\ H_y^1 & H_y^2 \end{bmatrix} \tag{1}$$

where superscripts 1 and 2 refer to the fields generated by two orthogonal electric dipoles. Using these impedance tensor elements, transfer functions (TF) as apparent resistivity and impedance phase can be calculated for all four components. There is also magnetic transfer function called tipper and relates the vertical magnetic component to the horizontal ones and is given by:

$$\begin{bmatrix} H_z^1 & H_z^2 \end{bmatrix} = \begin{bmatrix} A & B \end{bmatrix} \begin{bmatrix} H_x^1 & H_x^2 \\ H_y^1 & H_y^2 \end{bmatrix} \tag{2}$$

DATA ACQUISITION

The survey area is a waste-site in the north of Cologne, Germany. The measurement setup is shown in Figure 1 and spans approximately $250 \times 400\ \mathrm{m}^2$, with receiver stations spaced at 10 m and profile intervals at 30 m. Both RMT and CSRMT were carried out at identical stations. Perpendicularly positioned HED transmitter lines were employed to administer a 100% duty cycle rectangular current of 1 A, utilizing three base frequencies of 0.5, 5, and 50 kHz. The sampling frequencies were set at 39, 312, and 2496 kHz, respectively, generating a signal range from 1 to 10 kHz, 10 to 100 kHz, and 100 to 1000 kHz, encompassing the odd sub-harmonics of the same base frequencies. At each receiver station, seven recordings were conducted: one with both transmitters off for RMT, three recordings (one for each base frequency) with only transmitter Tx active, and three additional recordings with only transmitter Ty active.

DISCUSSIONS

The 3D inversion results of CSRMT and RMT data from all profiles and using ModEM algorithm (Egbert and Kelbert 2012), are indicated in Figure 2a and 2b respectively. Among the frequencies left after tensor processing of CSRMT data, 6 frequencies of 45, 75, 95, 150, 350 and 550 kHz were selected to be used in inversion. Also, for RMT the frequencies of 16, 19.5, 37.5, 52, 62.5, 139 and 302 kHz were selected for the inversion. Error floor of 5% and thus, the error of $0.05 * \sqrt{|\mathrm{Z_{xy}\,Z_{yx}}|}$ was considered for all the impedance components. A homogeneous half-space with resistivity of 50 Ωm was chosen as the starting model. The grid has a size of $100 \times 95 \times 30$ with the horizontal cell size of 2.5 m in the main grid increasing with a factor of 1.5 for 10 padding cells in X direction and 5 m in Y direction. The first layer thickness selected to be 1m increasing with a factor of 1.2 in Z direction. The RMS value is 1.068 and 1.017 for RMT and CSRMT models respectively. Sections from left to right in Y axis, corresponds to profile 1 to 13 in the survey area. In both results, the waste deposit boundary which is shown as a white line in Figure 1, can be clearly observed. The conductive bodies in red with the maximum depth of 10 m, are related to the waste-site and are quite consistent. Based on the available geological information from the area, the resistive top layer in blue is corresponding to the gravelly sand with maximum depth of about 18 m that is followed by the conductive brown coal. However, this lower conductive body can be observed in RMT results but is not clearly visible in CSRMT ones. The reason is that due to the close distance between transmitters and the stations in some locations (especially for Tx), the far-field condition could not be fully valid and therefore, the data from some stations and specific frequencies (mostly lower frequency range) had to be taken out from the inversion. That is why the resolution of tensor CSRMT results and for the south-west area close to Tx transmitter, is lower that RMT results in which all the data and the frequencies were included in inversion. For the same reason and omitting the low frequencies in tensor CSRMT case, we cannot see the brown coal structure below the gravelly sand as clear as in RMT results. The tipper data are also inverted with the same input parameters as mentioned above for CSRMT data. The sections from 3D tipper inversion results indicate the same pattern as Fig. 2. In general, the conductive waste-body and the resistive gravelly sand can be observed clearly, and the results look consistent with the ones from RMT and CSRMT.

CONCLUSIONS

This study provides a brief discussion on the 3D inversion results of CSRMT and RMT data collected in Cologne, Germany. Two horizontally positioned HED sources were utilized to capture complete impedance tensor elements for enabling 3D inversion. The findings from both methods distinctly reveal the presence of the waste deposit, with resistivity values from the sections aligning closely with geological information from the survey area. To meet the MT approximation, certain data corresponding to specific stations and frequencies had to be excluded from the tensor CSRMT inversion. Nevertheless, the primary objective of the study, which focused on waste-site distribution and depth detection, was successfully accomplished.

ACKNOWLEDGEMENTS

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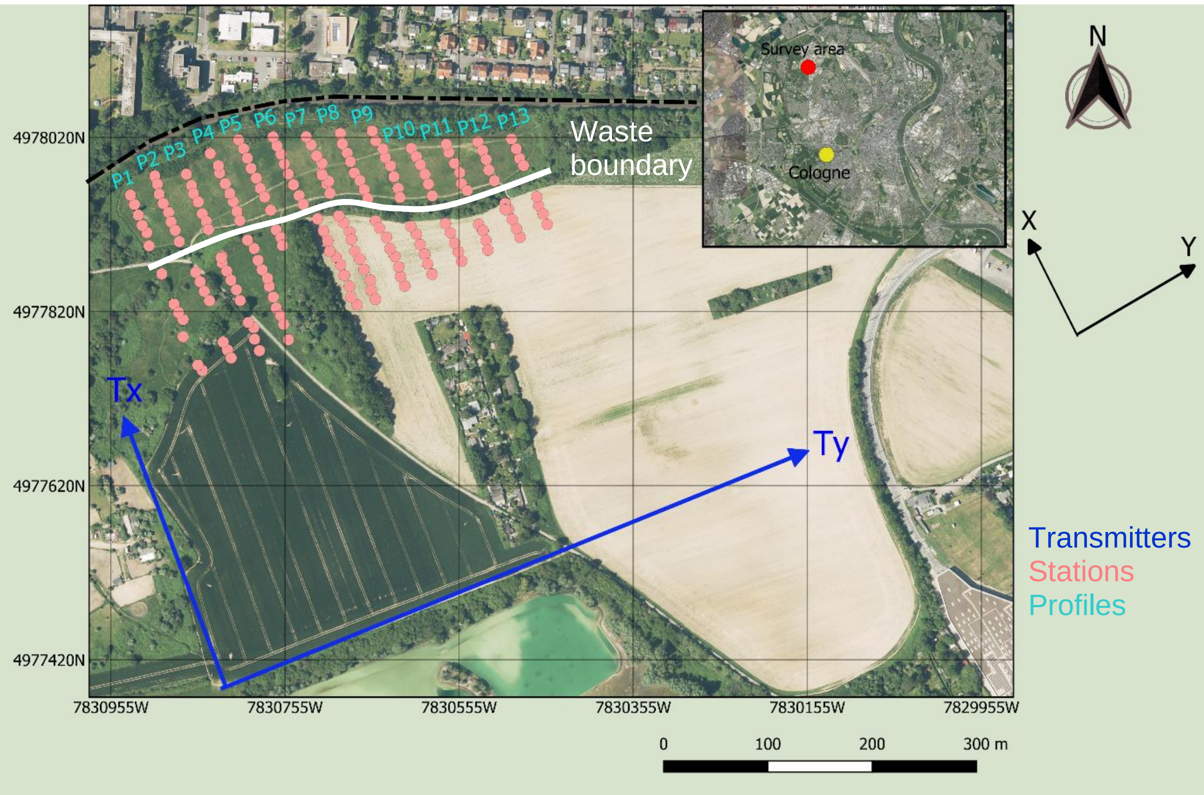

Figure 1. The survey area description. 13 profiles are measured perpendicular to the strike direction of the waste-site. Black dashed line in the northern boundary of the waste body, indicates a railway and the white solid line showing the boundary from the south. Two HED transmitters in blue are located orthogonally to the field-setup. Tx is 265 m and Ty is 580 m long.

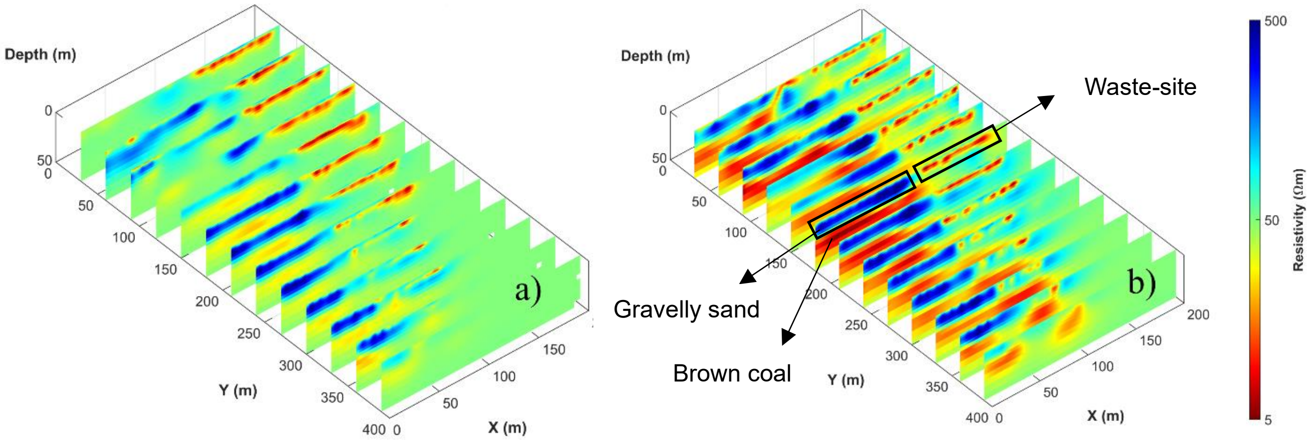

Figure 2. The sections from 3D inversion. a) indicates tensor CSRMT and b) indicates the RMT results. Colorbar limits are corresponding to resistivity values from 5 (red) to 500 (blue) Ω.