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Optimized Arrays for Surface-to-tunnel ERT Measurements

K. Simyrdanis* (Institute for Mediterranean Studies), P. Tsourlos (Aristotle University of Thessaloniki), N. Papadopoulos (Institute for Mediterranean Studies) & P. Soupios (Technological Educational Institute of Crete)

SUMMARY

In this work optimum protocols using the criterion of Jacobian matrix were tested to increase the resolvable power of surface-to-tunnel electrical resistivity tomography measurements. The problem was approached through synthetic numerical modeling, experimental data collected in a controlled tank environment that was constructed for this purpose and data that were retrieved from a real case scenario in Crete, where an aqueduct tunnel exists in the archaeological site of Eleftherna. The resistivity inversion images were reconstructed through a 2-D inversion algorithm that was modified to account for the special surface-to-tunnel ERT measurements. The optimized data sets contained fewer measurements with respect to the original data sets (~30%) but the optimized inversion images show comparable resolvable capabilities with the original inversion models.

Introduction

Nowadays the development of methodologies for extracting optimum electrical resistivity tomography measurements that result in a high resolvable inversion image is a dynamic and constantly evolving research procedure. Those algorithms are able to recover a small amount of measurements out of many possible electrode combinations, in order to produce an optimum subsurface geoelectric image. Many algorithms have been presented the last few years employing surface electrodes in 2-D and 3-D resistivity modes (Al Hagrey 2011; Stummer et al., 2004), and electrodes installed inside (Wilkinson et al. 201; Loke et al., 2014).

In present study a different strategy is used to produce the optimum ERT surface-to-tunnel measurements. Instead of producing a comprehensive data set that contained all the possible electrode combinations, the optimization algorithm was applied to individual surface-to-tunnel ERT protocols which exhibit their own specific characteristics regarding the case. So, after the selection of the appropriate protocol, the algorithm based on the Jacobian matrix selects the minimum amount of measurements required for optimum results. With this approach optimum measurements consist only of a small part of the initial protocol. In this sense the optimized protocol is considered superior with respect to the initial one due to the relatively decreased time for acquiring and inverting the data, which is extremely useful especially when a time-lapse phenomenon is being studied.

Methodology

Athanasiou et al. (2007) proposed a technique for creating optimum protocols based on the usage of Jacobian matrix (or sensitivity matrix). The technique is based on the appropriate selection of those measurements that have the higher absolute sensitivity value concerning the inversion parameters. Assuming an original protocol containing all the possible electrode combinations (m), the subsurface is divided into a set of model parameters (p) and so the Jacobian matrix (J) showing the relation of each measurement with respect to parameters is calculated.

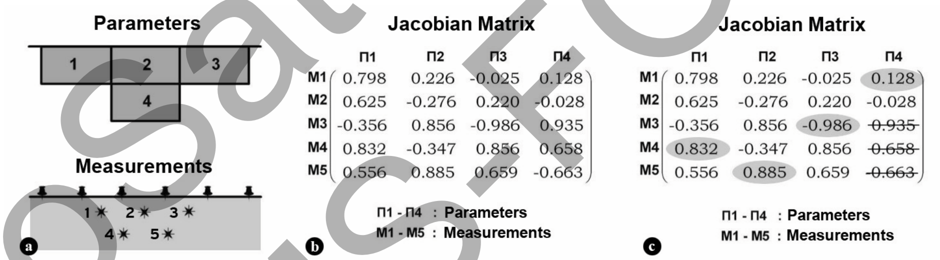

Figure 1. (a) Model parameters and measurements, b) Jacobian matrix, c) Optimum measurements for a 4th parameter model using 5 measurements protocol.

Figure 1 presents a simple example of how the algorithm operates for the simple case of 5 measurements and 4 parameters. Initially for each parameter the measurement with the higher absolute sensitivity value for the particular parameter is chosen. In case where a measurement has already chosen as an optimum measurement for a previous parameter, then the new optimum measurement will be the measurement with the next higher absolute sensitivity value. The procedure continues the same way till a group of optimum measurements is equal with the number of the model parameters, as shown in Figure 1c. After selecting the optimum measurements that correspond to each one of the model parameters, the same procedure is repeated to add some extra measurements in order to enhance those parameters that are not well resolved. The whole methodology was implemented in MATLAB to account for the surface-to-tunnel ERT measurements.

Synthetic modeling

The efficiency of the optimum protocols was evaluated through synthetic using a Finite Element 3-D forward resistivity solver (Kim & Yi, 2010). A model consisting of a resistive and a conductive target are placed inside homogenous medium (with two horizontal sediments 20 and 100 ohm-m) above a "tunnel". The tunnel is been simulated using very high resistive values (10^9 ohm-m). The electrodes (40 in total) are positioned on surface of the ground and on top (Figure 2) of the "tunnel". The protocols used were bipole-bipole ('bb'), pole-dipole ('pd') and pole-tripole ('pt') with 2572, 2542 and 2558 measurements respectively. After the optimization procedure the outcome gave protocols with 506, 455 and 496 measurements for each protocol.

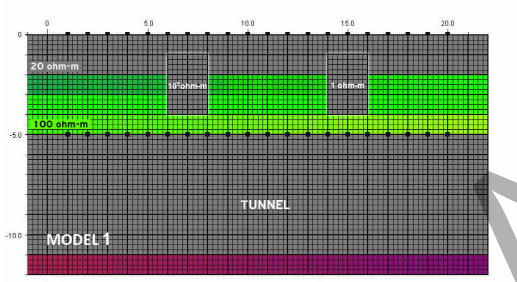

Figure 2. Synthetic model (resistive and conductive target) with surface-to-tunnel measurements. Vertical cross section extracted from the 3-D resistivity model

Figure 3 shows the inverted results where generally there is good correlation between the images resulted by the initial and the optimum protocols. Particularly, optimum protocol bipole-bipole, reconstructs the conductive target (1 ohm-m) and the top layer of the model (20 ohm-m) as well. The resistive target (10^9 ohm-m) is also well reconstructed but there are some artifacts (with high resistivity values) in between the two main targets. Optimum protocol pole-dipole managed to image the conductive target but fails to accurately retrieve the top conductive layer. The resistive target is also not well resolved having lower resistivity values. Optimum protocol pole-tripole, reconstructs both resistive and conductive targets and the top layer equally well comparing with the initial protocol. It should be mentioned that the % percentage of measurements used in optimum protocols is quite impressive: 20% for the protocol 'bb', 18% for the protocol 'pd' and 19% for the protocol 'pt'.

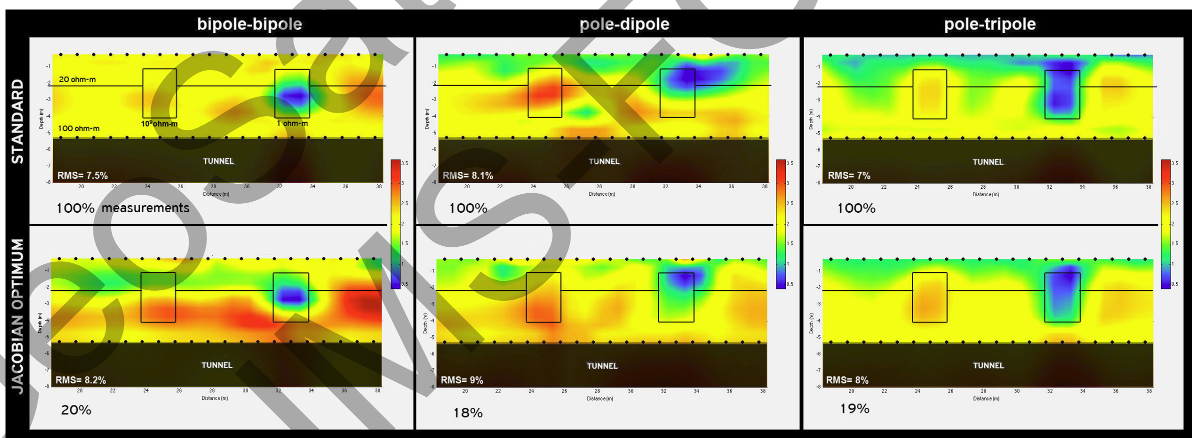

Figure 3. Inversion results comparing initial and optimum measurements for 'bb', 'pd' and 'pt' protocols. Data were corrupted with gaussian random noise of 5%.

Controlled experimental Data

The experimental data were acquired from, a tank (Figure 4a) which was filled with deionized water (100 ohm-m). A handmade apparatus (Figure 4b) was embedded into the tank where the electrodes were placed in parallel series. In particular the surface electrodes were placed on the pipe colored with green and the "tunnel" electrodes were placed on top of the pipe colored black, that simulates the tunnel conditions (filled with air). The blue pipe could be moved during the experiment to account for different surface-to-tunnel distances.

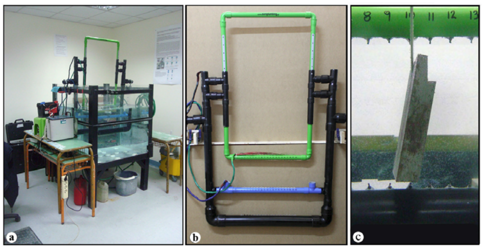

Figure 4. (a) Tank used for experimental data, (b) A handmade apparatus constructed for taking surface-to-tunnel measurements (c) Metal target embedded into water for testing optimum measurements.

All electrodes (40 in total) have inner probe distance 0.02m. The vertical distance between the two electrode series is chosen to D=0.15m. The target that was used is a metal plate, placed in between the two electrode series as shown in Figure 4c. The protocols used were 'bb' (1952 measurements), 'pd' (1942 measurements) and 'pt' (1971 measurements).

The Jacobian procedure for creating optimum protocols is quite promising judging by the inversion results as shown in Figure 5. The target is reconstructed quite well using only 29%, 31% and 31% of the measurements of initial protocols 'bb', 'pd' and 'pt', respectively. All protocols show some artifacts close to the tunnel area that can be explained due to the tunnel effect, since tunnel can be considered as an object with infinite resistance close to the bottom series of electrodes.

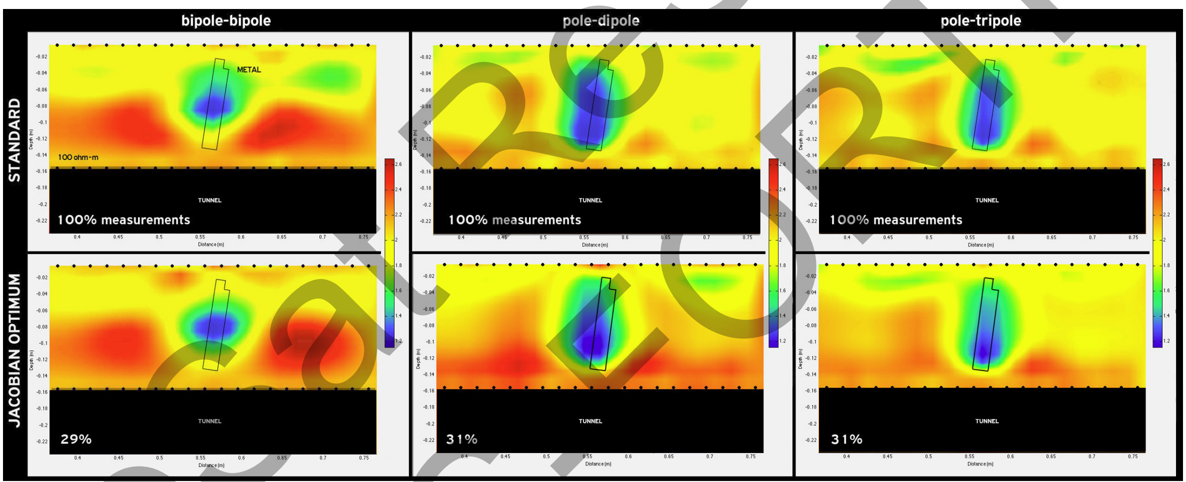

Figure 5. Inversion results comparing initial and optimum measurements with tank experimental data.

Real Data

After examining the optimum protocols using synthetic and experimental data, the procedure is tested at an actual case scenario where an existing tunnel was used for placing the bottom series of electrodes. The tunnel is situated in the Eleftherna archaeological site close to Rethymno city in the Crete island of Greece. The optimum procedure used measurements that were acquired using 60 in total electrodes (inner probe spacing was 1m), as shown in Figure 6. Initial measurements for protocols 'bb', 'pd' and 'pt' are 3470, 3286 and 3832 and the optimum protocols contained 752, 750 and 752 measurements respectively.

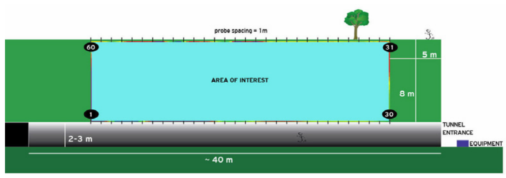

Figure 6 Schematic diagram depicting the array used for surface-to-tunnel measurements.

The comparison of the inversion results between initial and optimum data (Figure 7) show that optimum data can depict the stratigraphy equally well, despite the fact that only 20% of initial measurements are used. Furthermore, the inversion results are comparable with previous ERT results that were produced by previous work of Papadopoulos et al. (2012).

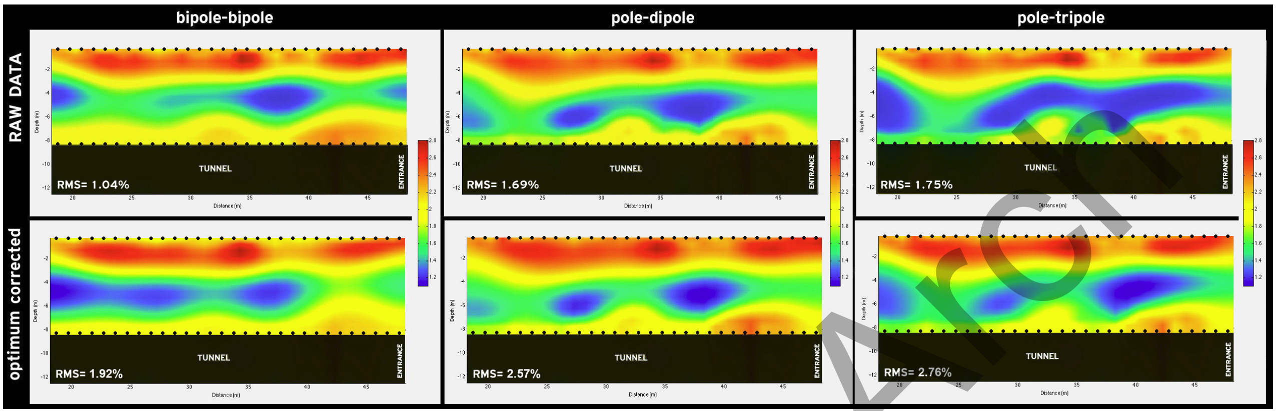

Figure 7. Inversion results for testing optimum measurements in a real case scenario.

Conclusions

An existing procedure for creating optimum protocols based on the Jacobian matrix is used for surface-to-tunnel measurements. The algorithm for the production of the optimum protocols is simple to apply due to the fact that the Jacobian matrix is already calculated with the existing algorithm for inversion. Synthetic, experimental and real data have proven that the optimum protocols can reconstruct the targets equally well with the initial protocols. The amount of initial measurements is decreased to 1/5 reducing the acquisition time of the data. This is extremely useful when a time-lapse phenomenon is monitored.

Acknowledgements

The work is co-funded by the European Social Fund and National Resources in the framework of the project THALIS-MIS 380207:‘‘GEODIAMETRIS–Integrated Geoinformatics Technologies for Time Lapse Monitoring of Land Pollution from the Disposal of Olive-Oil Mills Waste’’.

Part of this work was also performed in the framework of the PEFYKA project within the KRIPIS Action of the GSRT. The project is funded by Greece and the European Regional Development Fund of the European Union under the NSRF and the O.P. Competitiveness and Entrepreneurship.

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