Optimization of Electrical Resistivity Tomography Protocols for detecting archaeological structures in shallow water marine environment

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Abstract

The present work studies the optimization of the Electrical Resistivity Tomography (ERT) protocols and their employment in mapping archaeological targets in a shallow marine environment. In an effort to achieve an integrated research, various tests were made using synthetic data where different arrays were used (dipole-dipole, gradient and pole-dipole). The knowledge gained from the results is applied afterwards at an existing archaeological site, where the validity of the methodology is proved.

Keywords: Marine, electrical tomographies, archaeological survey, protocol optimization

Introduction – Theory

Electrical Resistivity Tomography (ERT) has proven to be a valuable tool in onshore archaeological prospection applications (e.g. Papadopoulos *et al.*, 2011). The last years, there is an increasing tendency to incorporate this technique within offshore geophysical surveys for solving geological and engineering problems (Rucker *et al.*, 2011), since there is no need to use any special equipment. However its employment in marine environments for the detection of buried cultural features close to the coastline is rather limited (Passaro, 2010). Still there are some methodological issues that need to be solved, mainly dealing with the installation of the electrodes on the bottom or on the surface of the sea and the data processing using appropriate modeling and inversion approaches (Loke 2004) able to cope with the special conditions found in such environments (i.e. the seawater is a very conductive medium in comparison with the resistive archaeological targets).

The maximum number of independent and non-reciprocal resistivity measurements that can be collected with four-, three- and two-electrode arrays depends on the actual probes that are installed on an investigation area. For an ERT survey considering N number of electrodes, the total number of resistivity measurements (S) regarding four-electrode arrays is given by the formula S=N(N-

1)(N-2)(N-3)/8 (Xu and Noel, 1993). For example even for a small number of electrodes (e.g. 30) the data points exceed the 80,000 independent measurements.

The inability to capture this amount of data is mainly related to instrument's memory limitations and actual field time constraints. Conventional ERT surveys use specific electrode configurations like dipole-dipole, wenner, gradient or pole-dipole. Recent advances in ERT include the extraction of specific resistivity measurements from a wider data set (known as comprehensive) that have the ability to highlight and extract the maximum possible information of the subsurface resistivity structure. These methodologies use specific optimization criteria based on the numerical calculation of the resolution matrix and exclude from the original data set "weak" measurements that carry minimal subsurface information (Stummer *et al.*, 2004; Wilkinson *et al.*, 2006; Wilkinson *et al.*, 2012; Simyrdanis *et al.*, 2015).

Methodology

This work focuses on the optimization of the marine ERT protocols using the Jacobian (or Sensitivity) matrix criterion (Athanasiou *et al.*, 2009) in order to reduce the measurements of the "basic" protocol without compromising the quality of the inversion results by rejecting some "weak" measurements. The Jacobian Matrix is a metric that represents the sensitivity of every resistivity measurement to changes of the subsurface parameter property. The Jacobian matrix criterion was incorporated in an existing forward and inversion resistivity algorithm ("2DInvCode", Simyrdanis 2013). The algorithm divides the subsurface into a specific number of blocks known as parameters and the Jacobian matrix is calculated given the number of measurements and model parameters. At the same time the norm of the Jacobian for each parameter is also calculated. The measurements that exhibit the highest sensitivity absolute values for each parameter are chosen, through an iterative procedure, to compromise the optimum data set on the condition that they are not been already chosen in previous step (Fig. 1 top). Thus based on an original data set of measurements (called "basic") assuming a specific array configuration (e.g. dipole-dipole or gradient or pole-dipole) the algorithm selects only a set of measurements (called "optimum") that exhibit the highest resolving capability given a specific subsurface discretization. After the compilation of the optimized protocols the 2.5D inversion software "DC2DPro" (Kim and Yi, 2010) was then used to reconstruct the resistivity models using the basic and the optimized array protocols. All synthetic data are corrupted intentionally with random Gaussian noise (e.g, 3%).

Synthetic Data

A 2D ERT line was assumed with 48 electrodes equally spaced every a=1 meter. The thickness and the resistivity of the seawater layer were set to D=1 meter and ρ=0.2 Ohm-m respectively. The subsurface below the water layer consists of a homogeneous medium with resistivity ρ=10 ohm-m. A resistive target (ρ=500 Ohm-m) simulating a wall structure with dimensions 5 m by 2 m was placed inside the subsurface layer at a depth d=1 m below the bottom of the sea.

Synthetic modeling was at first implemented in order to compare the inversion results and the reconstructed models employing the optimum protocols for different electrode arrays. Fig. 1 (bottom) shows the comparison between the basic (left side) and the optimum (right side) protocols for the arrays dipole-dipole (“dd”), gradient (“grd”) and pole-dipole (“pd”) where the electrodes are placed on the surface of the water layer (floating electrodes). No extra constraints were imposed into the inversion procedure. Generally the optimum arrays (dd: #1078 meas., grd: #1078 meas., pd: #1078 meas.) are able to reconstruct the target equally good as the basic arrays (dd: #2231 meas., grd: #2357 meas., pd: #2327 meas.), despite the fact that almost 50% of the measurements are used.

Real Data

The first effort for testing the optimum ERT protocols was made to the coastline archaeological site in the Agioi Theodoroi, that is located about 10 Km east of the city of Heraklion in Crete, Greece (Fig. 2). Early surveys revealed the existence of seaside buildings and wall constructions that continue towards the sea, dating to the Minoan Times.

The survey line was laid out in order to cross already known structures that have been mapped by an earlier archaeological underwater survey. This was done to correlate the reconstructed by the inversion targets with the already mapped underwater archaeological targets. The line is composed of totally 25 electrodes equally spaced every a=1 meter. The average water column thickness is less than a meter. The “basic” protocols gradient and pole-dipole are using #782 and #578 measurements, respectively. After the optimization procedure #286 measurements are used for both “optimum” arrays. White indicated areas depict the actual relics’ positions (“1”, “2” and “4”) that were mapped though the underwater survey.

Generally, as Fig. 3 depicts, the inversion models show comparable accuracy despite the fact that the optimized protocol uses only half of the measurements of the basic protocols. The targets are reconstructed at the depth of d= 2 m below the seawater surface, with resistivity values close to ρ= 5 ohm-m. Comparing the two arrays, in general gradient shows to be slightly superior from the gradient array when the basic protocols are used. The walls are more pronounced in the gradient inversion model when the basic protocols are considered. On the contrary the optimum gradient array fails to reconstruct target “2” and smears target “3” with target “4”. On the contrary pole dipole optimum array clearly shows target “2” and faintly shows target “3”.

Conclusions

The numerical modeling results of this study show that ERT has a potential and can be used for detecting archaeological remains in shallow marine environments. Furthermore, optimization of the initial measurement protocol can yield to equally reconstructed resistivity models minimizing at the same the actual field time for data collection, without compromising the quality and resolution of the inversion results. Further improvements on the final inversion images of the optimized protocols can be achieved by using a larger initial data set for selecting the optimum configurations. This strategy will minimize the inferior results indicated from the transition of the “basic” to the “optimum” gradient protocol in our case.

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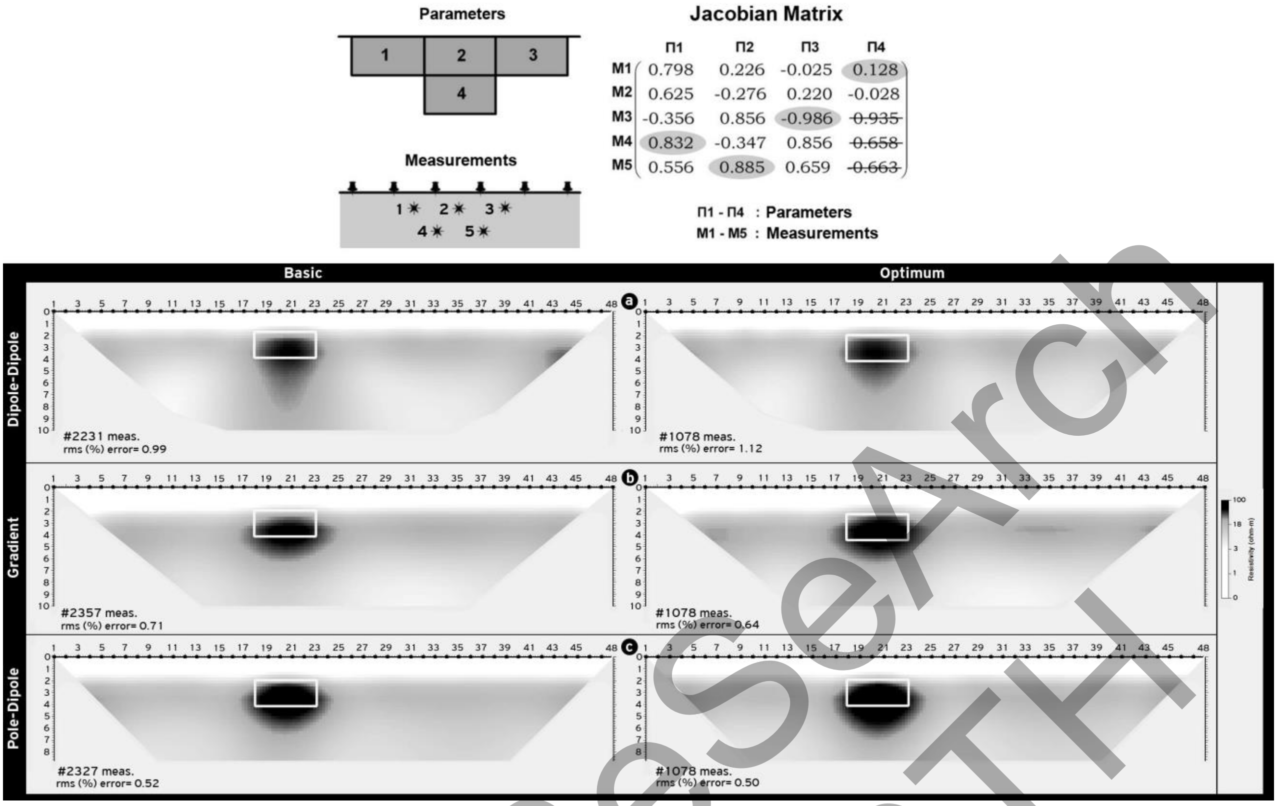

Figure 1. (top) Array Optimization using Jacobian Matrix criterion. (bottom) Inversion results with synthetic data between protocols (a) dipole-dipole, (b) gradient and (c) pole-dipole (rows), comparing basic and optimum protocols (columns). Black dots indicate electrode position. The target (indicated with white rectangular, ρ=500 ohm-m) is embedded in a homogeneous medium (ρ=10 ohm-m). Seawater column depth is set to D=1 m (resistivity ρ=0.2 ohm-m).

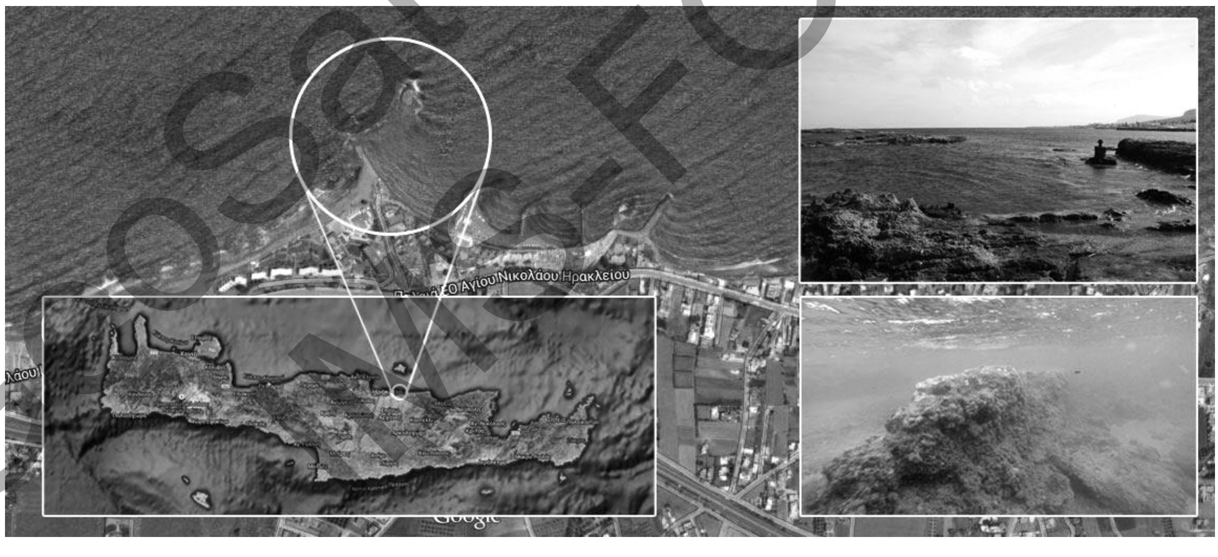

Figure 2. Site for marine investigation and detecting archaeological targets (Heraklion, Crete).

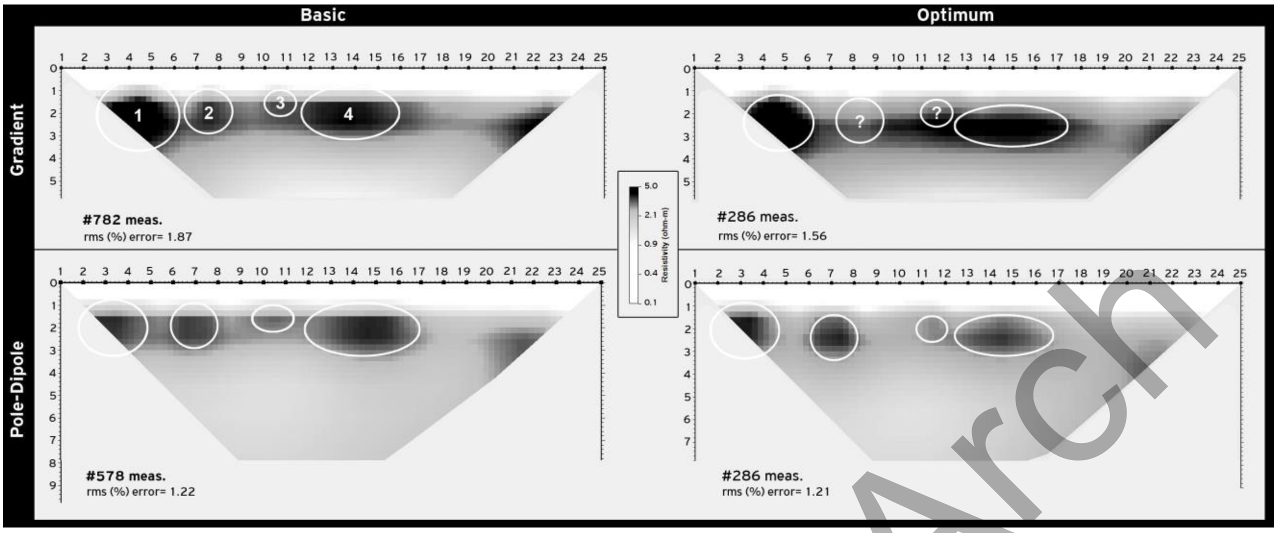

Figure 3. Inversion results with real data between protocols (a) gradient and (b) pole-dipole (rows), comparing basic and optimum protocols (columns). Black dots indicate electrode position. White indicated areas represent targets position.

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