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Optimization of electrical resistivity tomography protocols for detecting archaeological structures in a shallow water marine environment

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INTRODUCTION: THEORY

Electrical resistivity tomography (ERT) has proven to be a valuable tool in onshore archaeological prospection applications (e.g., Papadopoulos *et al.* 2011). There is an increasing tendency in recent years to incorporate this technique in 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

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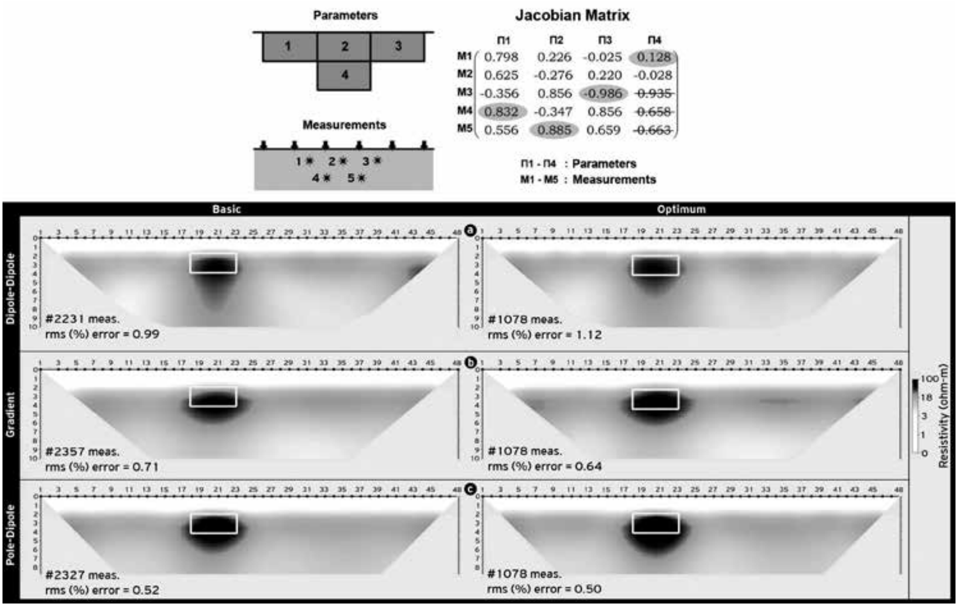

Fig. 1. (top) Array optimization using a Jacobian Matrix criterion; (bottom) inversion results with synthetic data between protocols (a) dipole–dipole, (b) gradient and (c) pole–dipole (rows), comparing basic and optimum protocols (columns). Black dots indicate electrode position. The target (indicated 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)

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., seawater is a very conductive medium in comparison with 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 in an investigation area. For an ERT survey considering a 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 the 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 dataset (known as comprehensive) that have the ability to highlight and extract the maximum possible information

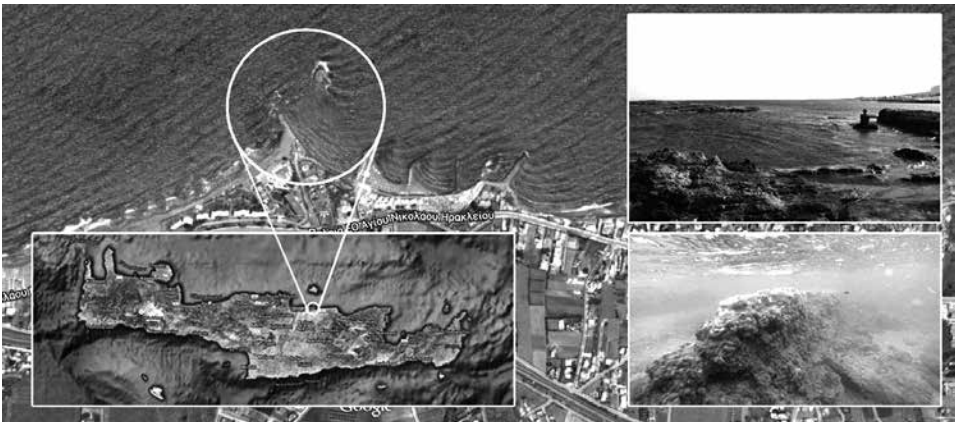

Fig. 2. Site for marine investigation and detecting archaeological targets (Heraklion, Crete)

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 dataset "weak" measurements that carry minimal subsurface information (Stummer *et al.* 2004; Wilkinson *et al.* 2006; 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 have not been already chosen in the previous step (Fig. 1 top). Thus, based on an original dataset 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 used to reconstruct the resistivity models applying the basic and the optimized array protocols. All synthetic data are corrupted intentionally with random Gaussian noise (e.g, 3%).

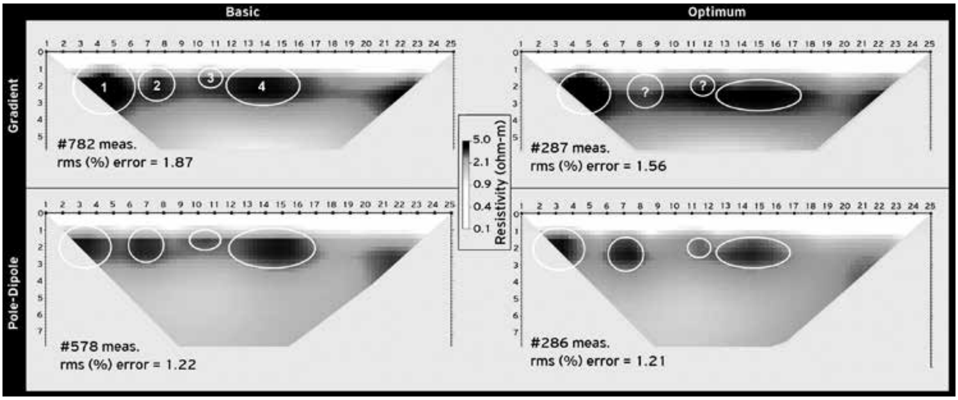

Fig. 3. Inversion results with real data between protocols (a) gradient and (b) pole–dipole (rows), comparing basic and optimum protocols (columns). Black dots indicate electrode position. Areas indicated in white represent target position

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. Figure 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 onto the inversion procedure. Generally, the optimum arrays (dd: #1078 meas., grd: #1078 meas., pd: #1078 meas.) are able to reconstruct the target equally well as the basic arrays (dd: #2231 meas., grd: #2357 meas., pd: #2327 meas.), despite the fact that only 50% of the measurements are used.

REAL DATA

The first effort for testing the optimum ERT protocols was made at the coastline archaeological site in Agioi Theodoroi, 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 structures from Minoan times, continuing towards the sea.

The survey line was laid out in order to cross already known structures mapped by an earlier archaeological underwater survey. This was done to correlate the targets reconstructed by inversion with the already mapped underwater archaeological targets. The line is composed of a total of 25 electrodes equally spaced every a=1 meter. The average water column thickness is less than a meter. The "basic" gradient and pole–dipole protocols use #782 and #578 measurements, respectively. After the optimization procedure #286 measurements are used for both "optimum" arrays. Areas indicated in white depict the position of remains ("1", "2" and "4") that were mapped by the underwater survey.

Generally, as shown in Fig. 3, the inversion models demonstrate comparable accuracy despite the fact that the optimized protocol uses only half of the measurements of the basic protocols. The targets are reconstructed at a depth of d= 2 m below the seawater surface, with resistivity values close to ρ= 5 ohm-m. Comparing the two arrays, the gradient shows itself to be generally 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 merges target "3" with target "4". The pole–dipole optimum array clearly shows target "2" and only faintly target "3".

CONCLUSIONS

The numerical modeling results of this study show that ERT has potential and can be used for detecting archaeological remains in shallow marine environments. Furthermore, optimization of the initial measurement protocol can yield to equally well 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 dataset for selecting the optimum configurations. This strategy will minimize the inferior results indicated by the transition of the "basic" to the "optimum" gradient protocol in our case.

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