Off-Shore Archaeological Prospection Using Electrical Resistivity Tomography

Kleanthis Simyrdanis[1], Nikos Papadopoulos[1] and Theotokis Theodoulou[2]

[1] Laboratory of Geophysical-Satellite Remote Sensing, Institute for Mediterranean Studies, Foundation for Research & Technology-Hellas (F.O.R.T.H.), Rethymno, Greece
ksimirda@ims.forth.gr, nikos@ims.forth.gr
[2] Marine Archaeological Service, Heraklion, Crete, t_theotokis@hotmail.com

Abstract

This work addresses the applicability and efficiency of Electrical Resistivity Tomography (ERT) in mapping archaeological remains in near off-shore environments. The approach consists of a guideline based on theoretical simulation models followed by a validation of the methodology with real data. The numerical modeling undertaken includes the testing of different electrode arrays suitable for multichannel resistivity instruments (dipole-dipole, pole-dipole) and survey modes (floating or submerged electrode positioning). Additional tests are made concerning the resolving capabilities of ERT with various seawater column thickness and target characteristics (dimensions and burial depth of the targets), in order to suggest the most suitable methodology. Finally, an application of the method at a real site is accomplished not only for verification of the theoretical results but at the same time for proposing techniques to overcome problems that can occur due to challenges imposed by the shallow marine environment.

Keywords: marine, archaeological, electrical resistivity tomography

1. INTRODUCTION

Electrical Resistivity Tomography (ERT) is one of the most developed geophysical methods that is used for near surface surveys and applications. Crucially, this method can be easily applied in a marine environment, since no special equipment is needed for the specific type of survey. Recent studies employing ERT in marine environments include the imaging of the geological stratigraphy beneath water covered areas for tunnel and bridge construction (Kwon et al. 2005, Kim et al. 2002) and the geotechnical characterization of the submerged subsurface prior to a port construction (Apostolopoulos 2007).

Despite its increasing usage in dry-land archaeological applications, the ERT method is less common for off-shore archaeological investigations in shallow marine environments and only limited studies have been reported (Passaro 2010). This work aims to fill the theoretical and practical gap in the employment of ERT for the mapping of cultural structures in near off-shore environments. Before applying the method to a real site, a number of simulations using numerical modeling were performed testing different scenarios. Different survey modes using floating on water surface or submerged cables were examined in an effort to propose the most efficient one. Different electrode arrays were tested and some additional tests were made to evaluate the horizontal and vertical resolution capabilities of the technique. A shallow marine archaeological site in Crete was selected to test and validate the theoretical results.

2. METHODOLOGY

The numerical modeling was performed with ‘DC2DPro’, a two dimensional (2D) forward and inversion algorithm (Kim and Yi 2010). The program is based on a 2.5D finite element routine to solve the forward resistivity problem and an iterative least squares algorithm with Active Constrain Balancing (ACB) constraints for reconstructing the subsurface resistivity models. An indicative synthetic model used in this work is shown in Figure 1. The electrode spacing is set to a=1m and tests are made with the electrodes placed either on the surface of the water (floating, indicated with black dots) or on the sea bottom (submerged, indicated with white dots). The resistivity value of the water, the target and the homogeneous medium is set to ρ_{water}=0.2 ohm-m, ρ_{target}=500 oh-m and ρ_{homog}=10 ohm-m, respectively.

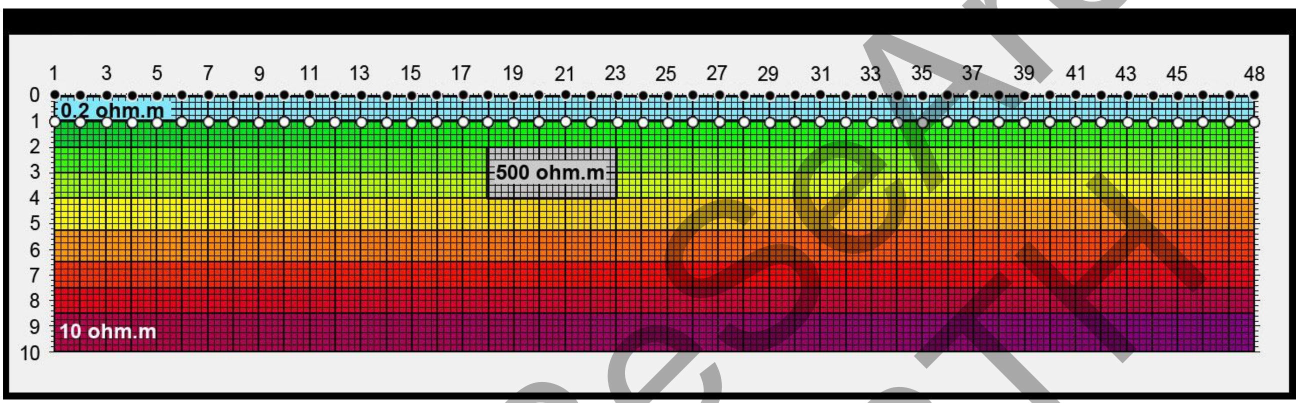

Figure 1. Basic synthetic model with electrodes (sensors) placed on surface of the water (black dots) or on bottom of the sea (white dots). The thickness of the seawater is D=1m and the chosen resistivity value ρ_{water}=0.2 ohm-m. The targets’ resistivity is ρ_{target}=500 ohm-m.

Electrode Arrays

The data were obtained using specific arrays that are primarily used in field studies employing a multichannel instrument. These arrays are: dipole-dipole (‘dd’) and pole-dipole (‘pd’), as shown in Figure 2. Current electrodes are indicated with the letters ‘A’, ‘B’ and potential electrodes with letters ‘M’, ‘N’. When the pole-dipole array is used, the current electrode ‘B’ is positioned away from the other electrodes (“infinite” distance, which is approximately five to ten times the largest electrode separation). All simulation data are corrupted with noise of ±0.05mV/V into the potential values in order to simulate better a real world scenario. The inversion images can be used for validation of the results using the % rms error and the position of the target that is indicated using a black line (the line shows the exact theoretically expected position of the target). The resistivity scale is common in all inversion figures (for comparison purposes) and it ranges from 0 to 100 ohm-m.

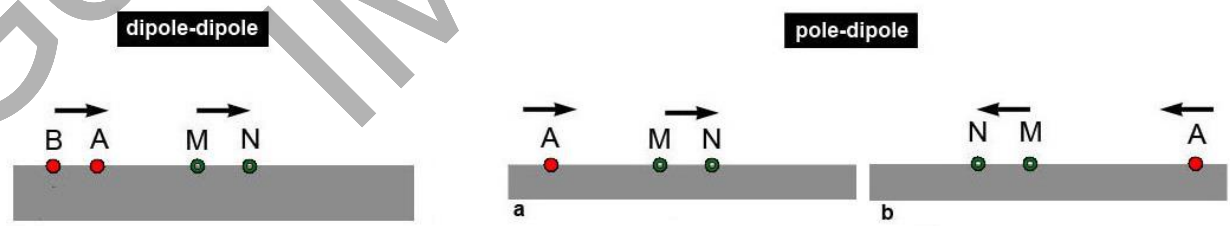

Figure 2. Dipole-Dipole (left) and Pole-Dipole in forward and reverse mode (right) electrode arrays used for marine ERT measurements.

A comparison between the arrays (‘dd’, ‘pd’) and the electrode position (floating, submerged) is shown in Figure 3. The water thickness is D=1m and the target (with dimensions 5x2m) is buried at a depth of d=2m below the sea surface.

On the left side of the Fig. 3, where the electrodes are situated on the water surface (floating), it is evident that the ‘dd’ array is not able to reconstruct the target with great accuracy as the inversion image shows some shape distortions of the target that seem to continue towards deeper levels. On the other hand, improved results are seen when array ‘pd’ is used, which has smaller % rms errors (‘pd’:0.56%) in comparison with the ‘dd’ array (‘dd’: 1.51%). The target and the background resistivity, after the inversion reconstruction is close to ρ_{target}=100 ohm-m and ρ_{back}=5 ohm-m, respectively.

On the right side of the image, where the electrodes are placed on the sea bottom (submerged), it is noticed in all arrays that the final targets’ position is shifted slightly downwards. The ‘dd’ array is unable to reconstruct the target and once more it has the largest % rms error (‘dd’:1.49%), versus the protocols ‘pd’ where the target is better reconstructed with lower % rms error values (‘pd’:0.73%).

Furthermore, all of the inversion resistivity images show some inversion artifacts on both sides of the target and close to the edges of the model. This can be interpreted as being due to the limitations of the inversion procedure, since the resistivity contrast between the resistive target and the conductive seawater layer is large and it is difficult for the algorithm to account for these large resistivity contrasts.

Based on the above synthetic experiment it is advisable to use pole-dipole protocol in order to map archaeological remains in shallow marine environments.

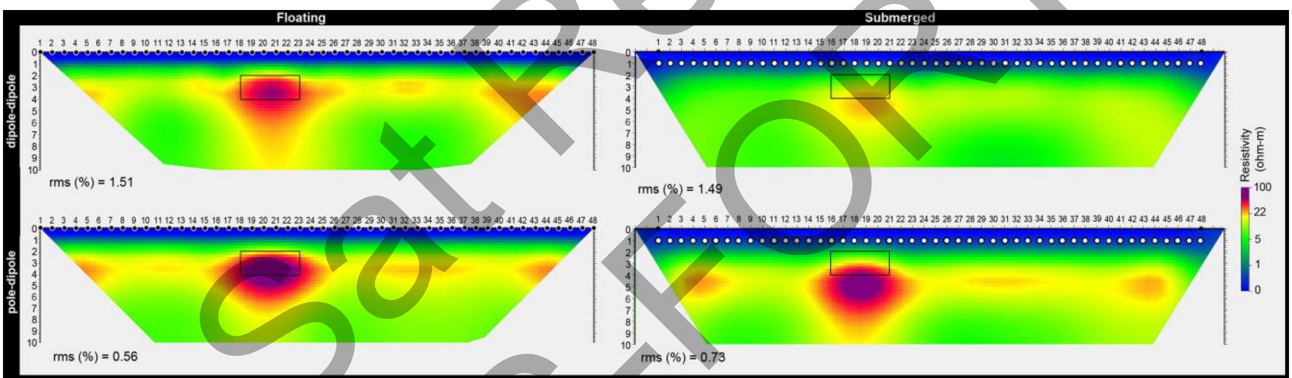

Figure 3. Inversion results with different protocols (dipole-dipole and pole-dipole) using 48 floating (black dots, left column) or submerged (white dots, right column) electrodes with spacing a=1m. Water column thickness is set to D=1m.

Seawater column thickness

The water thickness of the sea is a crucial parameter since there is a depth limit above which the resolving capability of the method decreases due to the absorption of the current energy from the conductive sea layer. For this reason, different water thicknesses (D=1 and 2m) were tested, as shown in Figure 4 (left column), where only floating electrodes are used with a ‘pd’ array protocol. On the right side of Fig. 4, the inversion results show that the water column thickness of D=1m is the actual limit at which the resistive target can be located. In case of water thicknesses of more than D=1m it becomes rather impossible to outline the target. Thus in such cases a submerged ERT survey is suggested since the sensors are closer to the target.

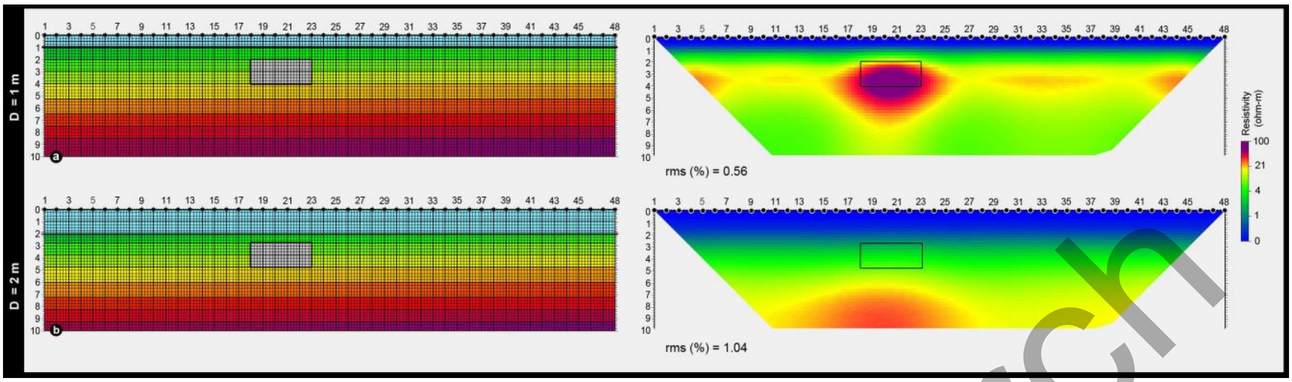

Figure 4. (left column) Synthetic model for comparing different water column thickness using protocol pole-dipole with floating (black dots) electrodes. Water depths: (a) D1=1m and (b) D2=2m, ρ_{water}= 0.2 ohm-m, ρ_{target}= 500 ohm-m, ρ_{back}= 10 ohm-m. Electrode spacing a=1m, (right column) 2-D Inversion results.

Target Characteristics

Some additional tests were made concerning the characteristics of the submerged target such as its dimensions (Figure 5) and its burial depth (Figure 6). An extra overburden layer with 1m thickness and resistivity value of ρ_{overb}=1ohm-m was used. The target resistivity was common for all targets and set to ρ_{target}=500 ohm-m. Submerged electrodes with the pole-dipole array were used in both cases. Targets with different dimensions (A: 3x2m, B: 5x2m, C: 2x2 and D: 1x2m) buried in the same depth (d=2m) below sea bottom were simulated. As far as the target burial depth is concerned, a target with the same dimensions was placed at different depths (d=1, 2, 3m).

The corresponding inversion results are shown in Figure 7 where on top of the figure, the smallest targets C and D can hardly be reconstructed. As a rule of thumb, it can be said that the minimum target dimension that can be detected, should be at least twice as large as the inner probe spacing. On the bottom of the figure, where the target burial depth is examined, the target can be located up to a depth of 3-4m and as expected, submerged electrodes were able to reconstruct the deeper buried targets with clarity.

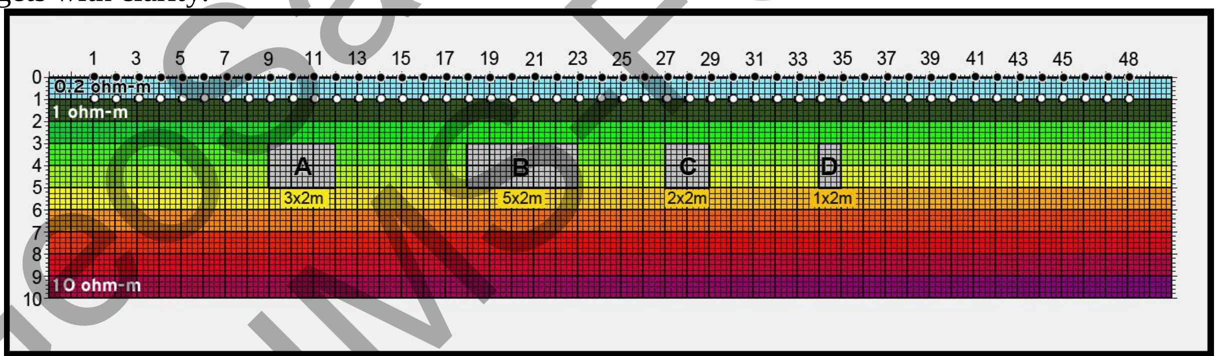

Figure 5. Model for studying different target sizes (A, B, C and D) using protocol pole-dipole with submerged (white dots) electrodes. Water depth D=1m, ρ_{water}= 0.2 ohm-m, ρ_{target}= 500 ohm-m, ρ_{back}= 10 ohm-m. Overburden layer 1m thick with ρ_{overb}=1 ohm-m. Electrode spacing a=1m.

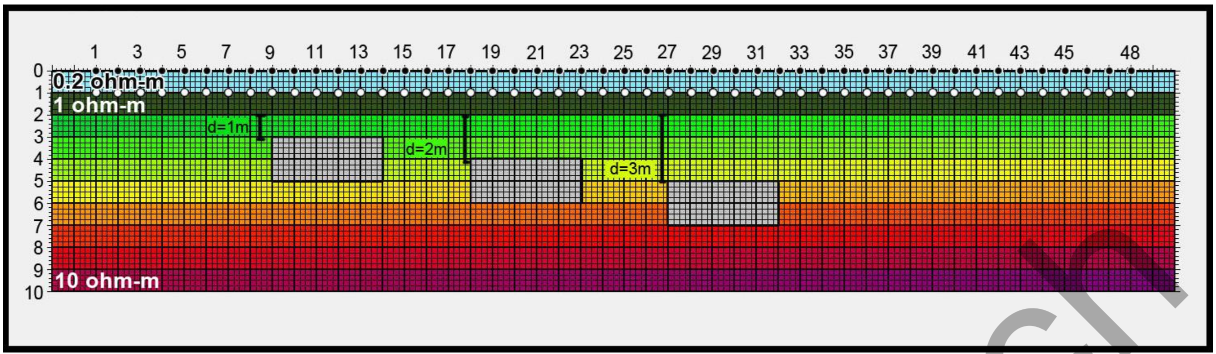

Figure 6. Model for studying different target burial depths (d=1m, 2m and 3m) using pd protocols with submerged (white dots) electrodes. Water depth D=1m, ρ_{water}= 0.2 ohm-m, ρ_{target}= 500 ohm-m, ρ_{back}= 10 ohm-m. Overburden layer 1m thick with ρ_{overb}=1 ohm-m. Electrode spacing a=1m.

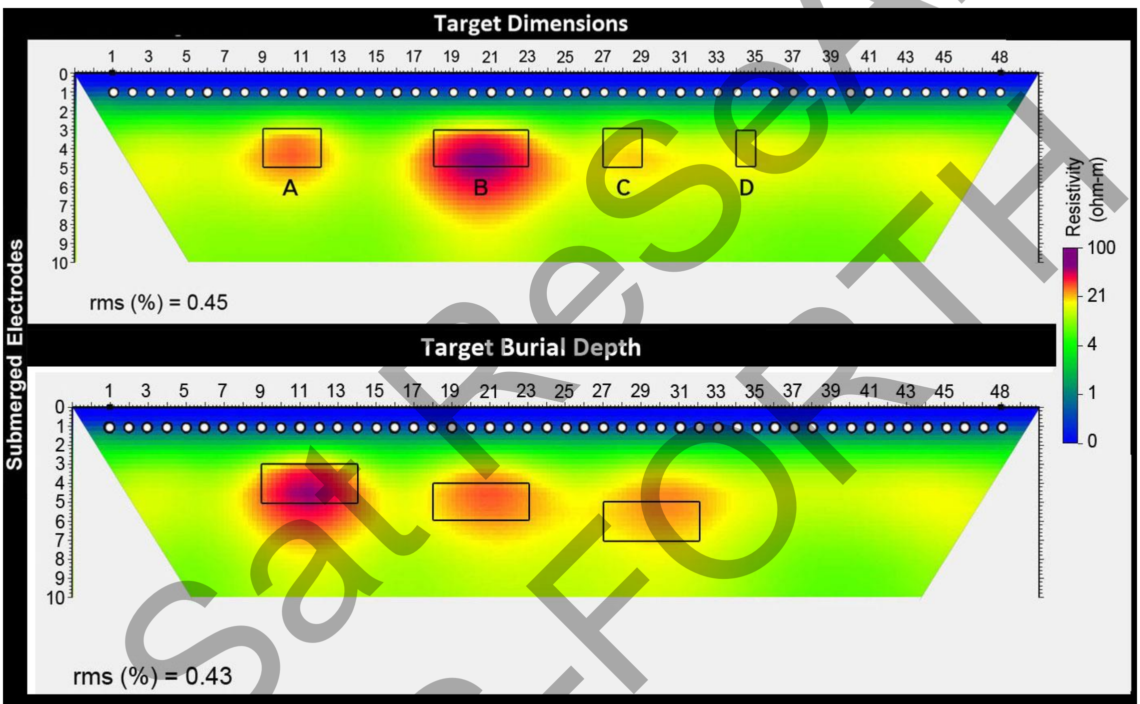

Figure 7. Inversion results with protocol pole-dipole using submerged (bottom row) electrodes with spacing a=1m, where the target dimensions and the target burial depth are examined.

3. TEST CASE: Agioi Theodoroi, Crete

Site Location and History

The shallow marine archaeological site of ‘Agioi Theodoroi’, located on the island of Crete about 10 km away from Heraklion city was chosen to test the ERT simulation results (Figure 8). The site was subjected to excavations during the early 20th century (Marinatos, 1926). These early surveys revealed the existence of seaside buildings and wall constructions that continue towards the sea, dating from the Minoan period. Recent archaeological surveys included the mapping and photography of the submerged structural remains with an underwater camera.

Figure 8. Site of Agioi Theodoroi for marine investigation and detecting archaeological targets (Heraklion, Crete).

Setup

In an effort to validate the efficiency of marine resistivity archaeological investigations in real situations, an ERT line crossing known structures was laid out in the sea, as shown in Figure 9. The line was composed of 25 electrodes equally spaced every 1 meter. Protocol pole-dipole was used and the survey line's position was chosen in such way to cross three walls whose position had already been identified by diving. Specifically, electrodes '3', '4', '13', '14', '15' and '21', '22' were exactly above the wall remains.

For the floating survey mode, long wooden sticks were driven into the seabed at the beginning and at the end of the survey line to keep the cable fixed and steady during the measurements. Plastic floats were tied along the cable to allow the floatation of the electrodes (Figure 10). During the submerged mode survey, no extra weight was needed as an anchor as the cable's weight itself was enough to keep it on the seabed during the measurements. The seawater depth was measured with plastic calibrated stick and varied from D=0.5m to 0.9m across the survey line.

Figure 9. Aerial photo of the survey area in Agioi Theodoroi. The yellow line shows the float positions that were used to keep the cable floating. The red lines outline the submerged archaeological relics that were mapped in the sea. The direction of the line is from the coast to the sea.

Figure 10. Photo with floating electrodes set up, equipment used (embedded right), water column thickness calculation with a plastic calibrated stick (embedded left).

Results

Inversion results for the floating electrodes (Figure 11, top) show that the protocol pole-dipole after 7 iterations with rms error 1.22%, has reconstructed the targets (shown with letters 'A', 'B' and 'C') that have already been identified with diving. The remains seem to be located at a depth of d=2m below sea level with maximum resistivity value calculated to ρ_{target}=5 ohm-m. Some smaller targets are also shown in the results that cannot be seen by diving. As previously seen in the synthetic data, some artifacts are created during the inversion at the edges of the survey line and should be taken into account for the real data also. For that reason, the survey line is recommended to be longer than the target area in order not to have artifacts at the edges that may be confused as potential targets. When submerged electrodes are used (Figure 11, bottom), the targets are well reconstructed (after 7 iterations with rms error 1%) although slightly shifted downwards, as expected from the corresponding simulation.

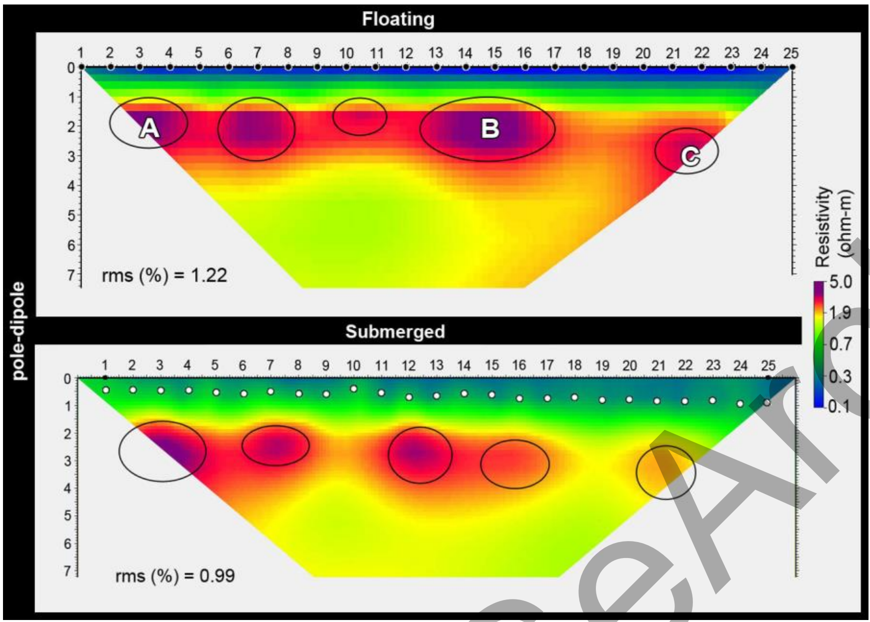

Figure 11. Inversion results with both floating (top) and submerged (bottom) electrodes using the pole-dipole array. The archaeological targets are highlighted with black circles. Letters A, B and C indicate relics that are exposed from the sea bottom and can be easily seen.

4. CONCLUSIONS - GUIDELINES

- This work examined the efficiency of ERT in mapping isolated archaeological targets in marine environments using both numerical simulations and validation with real data, in an attempt to offer a guideline for field surveys. The synthetic inversion results show that the targets simulating walls can be detected and among the tested arrays used, pole-dipole seems to have superior results in relation to dipole-dipole arrays.
- When the seawater thickness is less than D=1m, both floating and submerged electrodes give equally comparable results. In deeper marine environments the submerged mode survey is recommended for outlining isolated targets.
- The target burial depth is a crucial parameter and if it is buried in depth more than d=2 meters below sea bottom, locating it becomes problematic. In general, as a rule of thumb it can be said that the minimum target dimension should exceed at least twice the inner probe spacing.
- The methodology was applied in a real situation of a submerged archaeological site on Crete. The real field data verified the numerical modeling results and was also successful in mapping already known archaeological remains.
- In general this work shows the applicability, the potential, as well as the constraints of ERT in mapping isolated archaeological structures (e.g. walls or buildings) in shallow marine environments.

ACKNOWLEDGEMENTS

This work was 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.

REFERENCES

Apostolopoulos, G., Amolochitis, G., Stamataki, S., 2006. Marine resistivity tomography prior excavation works in port construction. EAGE 69th Conference, London 11–14 June 2007, p. E006.

Kwon, H., J. Kim, H. Ahn, J. Yoon, K. Kim, C. Jung, S. Lee, and T. Uchida, 2005. Delineation of a fault zone beneath a riverbed by an electrical resistivity survey using a floating streamer cable, Exploration Geophysics, 36, 50–58.

Kim J.H, Yi M.J., 2010. 'DC3D_PRO', Geoelectrical Modeling and Inversion, User's Manual, Korea Institute of Geoscience and Mineral Resources, Korea.

Kim J.-H., Yi, M.-J.., Song, Y., Cho, S.J., Chung, S.H. and Kim, K.-S., 2002. DC Resistivity Survey to Image Faults Beneath a Riverbed: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2002), 13IDA10, Las Vegas, USA.

Marinatos S., 1926. The Excavation of Nirou Chani Crete *(in greek)*, Proceedings of the Archaeological Society, 142-147.