Enhancing Geophysical Signals from Archaeological Sites Trough the Use of Wavelet Transforms

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Abstract: - Various levels and types of noise are responsible for hindering the valuable information obtained through shallow depth geophysical exploration of archaeological sites. Wavelet transform techniques were tested as a method for decomposition of the original geophysical data in order to eliminate the noise levels inherent to the geophysical measurements. Unsupervised classification techniques were employed for the final fusion of different datasets originating from various surveys or processing procedures. The resulting images were able to enhance the subsurface targets, eliminating the noise levels and exploiting fully the properties of the geophysical techniques used.

Key-Words: - wavelets, classification, fusion, geophysical prospection, archaeological data, Sikyon, Greece.

1. Introduction

Shallow depth geophysical prospection suffers from the influence of anthopogenic features, both on the surface and below it, creating certain difficulties in the presentation and interpretation of the results. For this reason, multiple geophysical techniques are preferably employed since their complementary measurements offer a better insight about the subsurface of the archaeological sites. The image constructed from these data, through different graphics and processing techniques, makes it easier to detect the location of the relics and visualize their extent within the subsurface. Still, the interpretation of the geophysical data is a difficult task as they are masked by cultural noise originating by the diachronic usage of the landscape or the modern agricultural or the construction activities in an area of cultural interest. As a result of the above processes, the image resulting by the interpolation of the geophysical measurements is often of poor quality, containing high percentages of random or systematic noise which hinder the valuable information related to the subsurface targets. Therefore, the suppression of the noise levels and the enhancement of the signals carrying the useful information is an important process in any processing approach. In addition to the above, the fusion of different datasets, originating from different geophysical survey or processing procedures is a practicable measure, although not easy to perform, to detect the detailed information about the subsurface.

The images constructed by interpolation of the geophysical measurements are often contaminated with noise, which distorts the signal coming from shallow depth features. The noise in geophysical data usually has high frequency content and characteristic frequencies depending on the causing sources, while in many cases it is distributed across all spatial scales. In denoising, traditional spatial filters can usually smooth the data and reduce the noise, having the risk to blur the data to some extent [1]. For instance, the brightness filter helps removing dark areas but may introduce new noise levels to certain sections of the image. Sometimes, the noise from the micro relief of the ground surface is coherent and pseudorandom and thus it can be separated from other sources of noise [2]. Still, denoising just by conventional filtering is difficult without affecting the signal's sharp variations and even harder to separate the different components of noise in the signals. In most cases, it is hard to give prominence to the target and eliminate the useless signal just through enhancement techniques.

Lately, new image processing techniques, such as wavelet-based approaches [3], non-negative sparse coding (NNSC) shrinkage techniques [4], principal components analysis (PCA) [5] and sparse coding (SC) shrinkage [6], have been explored and applied to a variety of measurements in various fields, such as astrophysics, geophysics, medical signal analysis, a.o. These methods have been proven to have a relatively successful impact in denoising and enhancing images by using different skills and strategies. Concerning the geophysical data, Tsivouraki and Tsokas [7] investigated a wavelet denoising scheme for magnetic archaeological prospecting data recently. On the other hand, no similar experiments have been carried out to measurements from archaeo-geophysical prospection surveys. For this reason, in the particular paper denoising and fusion processes in wavelet domain were employed in an experimental basis to enhance diverse geophysical data obtained from shallow depth surveys of archaeological sites.

In this paper, all of the geophysical data, originating from different types of measurements (resistivity tomography, resistivity, magnetics, a.o.), were pre-processed by calculating the different directional derivatives and constructing the corresponding image in Surfer 8.0. Similarly, the original images were classified utilizing an ISODATA unsupervised classification within ERDAS software package. Then, the discrete wavelet transformation was used for denoising purposes and fusing the different datasets to separate the noise levels from the useful signal.

2. The Archaeological Site of Sikyon and Geophysical Approaches

The Sikyon survey project was initiated in 2004 consisting of different research modules, including surface surveys and geophysical prospection techniques. The project is carried out under the collaboration of the University of Thessaly, the Institute for Mediterranean Studies – FORTH and the 37th Ephoreia of Prehistoric and Classical Antiquities of Corinth, with the participation of the American School of Classical Studies and the Universities of Cambridge and York.

The campaign aims to the study of the diachronic human presence on the plateau of ancient Sikyon which rises about 3.5km SW of the Corinthian gulf and covers some 250 hectares. The plateau, which is accessible from the coastal plain to the east, is naturally divided into an upper (altitude 180-260m) and a lower section (altitude 100-180m). Previous investigations of the site include large scale excavations by the American School of Classical Studies and the Archaeological Society, bringing to light sections or the whole of monumental buildings, including the theatre, palaistra complex, bouleuterion, a long stoa, and a Roman bath complex.

During the last four years of investigations, various sections of the site focusing in the area of the ancient Agora were surveyed through a multi-component geophysical approach. The ancient Agora is located to the south of the Roman Baths and contains a number of monumental architectural structures, such as the Bouleuterion, the Gymnasium, the temple of Artemis Limnaia and a large Stoa structure limiting the Agora to the South (Fig. 1). Most of the structural remains of the site span from the Classical-Hellenistic period to the Byzantine times.

Fig. 1. The wider region of the Agora of ancient Sikyon. The map indicates the main architectural relics of the site, most of which were excavated in the past, but remain still under the current surface of the ground.

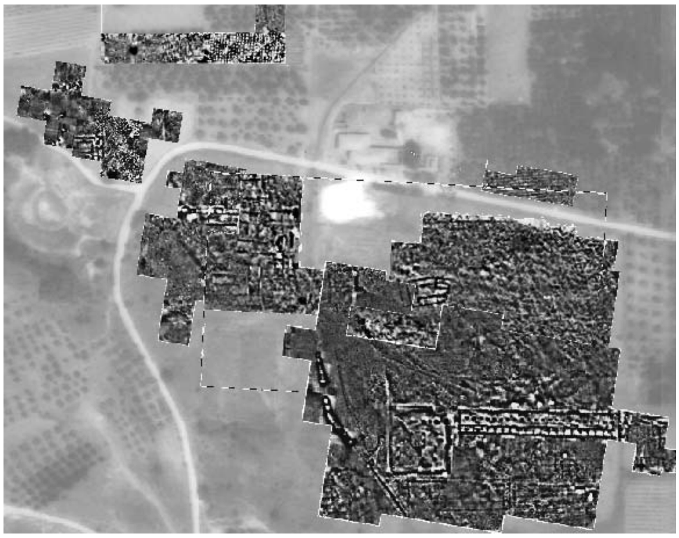

Fig. 2. The integrated results of the magnetic survey in the area of Sikyon. Magnetic data were collected through 3 different seasons employing a Bardington GRAD 601 and a Geoscan Research FM256 fluxgate gradiometer, using a 0.5m sampling strategy.

Until today, more than 90,000m^2 of the wider region of the Agora have been covered through magnetic (Fig. 2), resistivity, resistivity tomography and ground penetrating radar (GPR) techniques. Two fluxgate gradiometers, FM256 of Geoscan Research and GRAD 601 of Bardington Instruments, were employed in the high resolution (0.5m sampling) magnetic scanning of the site. A Geoscan Research resistivity meter RM15 with a multiplexer MPX15 and a Twin probe electrode configuration with 0.5 and 1m electrode separation covered large sections of the region for comparison with the magnetic methods.

Furthermore, electrical resistivity tomography (ERT) and GPR techniques provided detailed information of specific sections of the site through different depth layers, allowing a 3D reconstruction of the subsurface relics. The specific experiments were carried out systematically above a three-aisled basilica, which was located to the south of the temple of Artemis Limnaia. ERT measurements were conducted with SYSCAL Pro and multiplexer along 28 parallel profiles, 1m apart, using the Dipole-Dipole electrode configuration. A 450MHz antenna and an EKKO 1000 GPR unit were employed to obtain stratigraphic information along 55 parallel transects, 0.5m apart, above the region of basilica. Horizontal slices were created for different depths allowing the 3D mapping of the basilica ruins, which are suggested to extend at a depth less than 150-160cm below the current surface of the ground. In the particular paper, two slices of the electrical tomography data were used, corresponding to depths of 0.35-0.75m (ERT2) and 0.75-1.22m (ERT3) respectively.

3. Wavelets

The wavelet transformation is a practical signal analysis tool having applied to many topics involving tomographic reconstruction, image compression, noise reduction, image enhancement, texture analysis/segmentation and multi-scale registration in a variety of scientific and engineering areas including geophysics. Wavelets are mathematical functions with special properties that enable processing and analysis of data distributions at different resolutions at the same time. The main properties of the wavelets include the ability to concentrate the energy of a smooth signal in a few wavelet coefficients while at the same time the transformation of white noise still has the attributes of white noise [8, 9]. Based on that, wavelet analysis offers a scale-independent and robust method to filter out noise. The basic technique involves computing the wavelet transform of the input data and then decreasing or discarding the smallest wavelet coefficients. The inverse transform of these coefficients is then a filtered version of the input data. Therefore, it is reasonable to assume that small coefficients represent the noise and can be set to zero, while the large ones contain the signal's energy and need to remain for further processing. Moreover, the decomposition and reconstruction of wavelets makes possible an efficient fusion of different signals by calculating the low frequency approximations of these signals. The fused data from the reconstruction of the approximation calculated with one of the high frequency detailed signals decomposed above can lead to a reduction or minimization of the noise levels to some extent. It is well know, however, that shift dependency is the characteristic of wavelet transform when applied to image fusion, namely, simple shift of the input signal may lead to complete different transform coefficients. The shift dependency of the wavelet fusion scheme also provides an opportunity to test different combinations of possible circular shifts of the input signals to achieve a resulting wavelet representation, which contains valuable signals with minimal noise levels. It is possible to develop an efficient computation or fusion scheme for the geophysical datasets since there are different images originating from different types of measurements.

The wavelet transform is a linear transform and as such, wavelet algorithms are faster and more efficient than conventional algorithms. On the other hand, the performance of the method is affected by the choice of the wavelet functions. There are no unique denoising and fusion recipes covering all data types, especially the wide range and complicated nature of geophysical data. Each data type needs an empirical selection of the proper combination of the above-mentioned filters and fusion scheme.

4. Data Processing

4.1 Data pre-processing

Interpolation algorithms were employed in order to create maps of the corresponding geophysical data using Surfer 8.0. Originally, soil resistance and magnetic data were despiked and statistically processed. Inversion routines were applied to the ERT datasets based on a non-linear smoothness constrained algorithm. The images were further processed through the calculation of the first directional derivatives for directions of 30^0, 45^0 and 90^0. Some of the original data images and directional derivative images are illustrated in Figure 3.

4.2 Image classification

Digital image classification assigns pixels to classes. Each pixel is treated as a set of values in several spectral bands, derived from the brightness of the same area. These classes are, in theory, homogeneous - pixels within classes are spectrally more similar to one another than they are to pixels in other classes. In practice, of course, each class will display some variation, because categories exhibit natural variation. Image classification forms one of the most important tools for examination of digital images - sometimes as one of several analytical

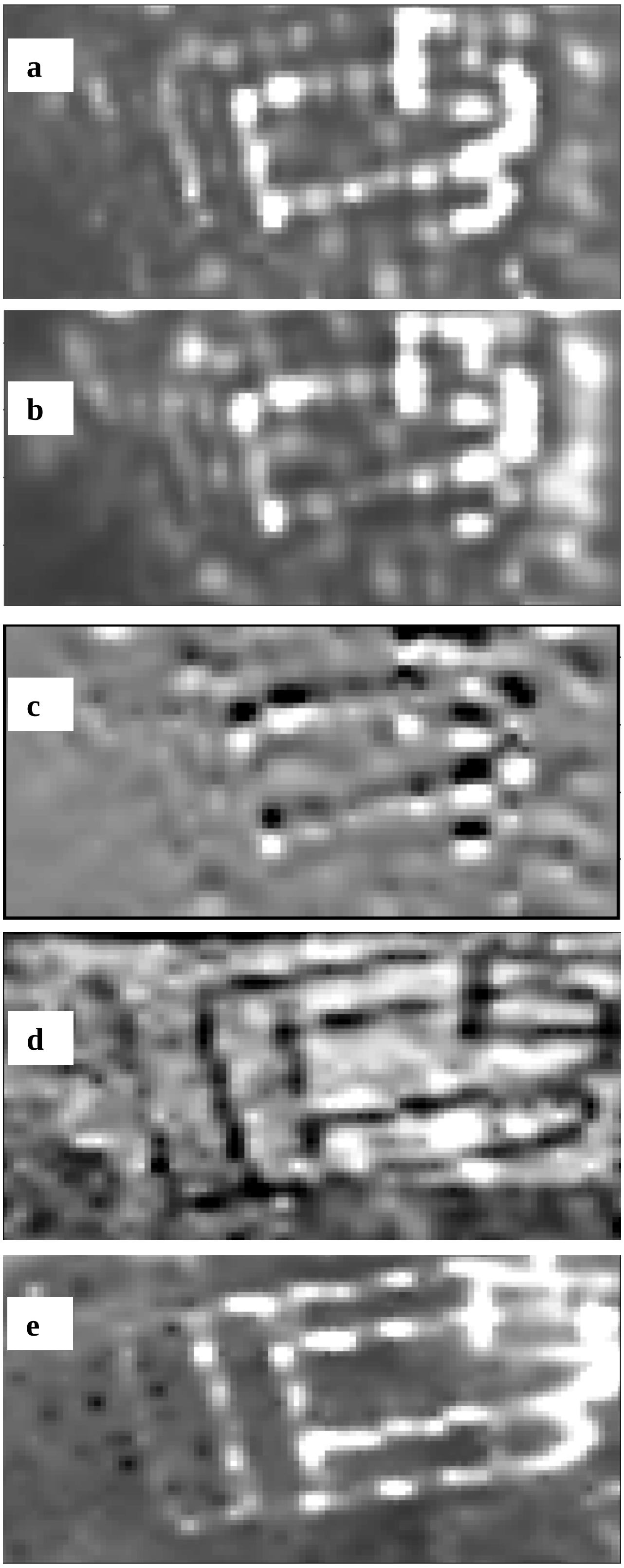

Fig. 3. Original datasets, consisting of a) ERT 2, b) ERT 3, c) ERT 3 directional derivatives at 90^0, d) magnetics and e) resistivity measurements. The different ERT images correspond to different depths.

procedures applied to derive information from an image. The images corresponding to different geophysical measurements were classified using ISODATA unsupervised classification technique. According to it, the resulting classes are assigned based to the common spectral or radiometric characteristics through an iterative process, namely through the repeating classification and calculation of statistics, until a threshold corresponding to the maximum percentage of unchanged pixels is achieved. The performance of unsupervised classification was evaluated based on a fixed classification scheme (six or eight different classes) for each one of the geophysical datasets (Fig.4). The accuracy assessment of the classified image was performed by selecting a set of 200 random points in the classified image and the original images respectively, and then comparing the consistency of the classified type of geophysical anomalies for each point. The overall classification accuracy is 89% and overall Kappa statistics 0.789. The classified images indicate the geophysical information clustered within different ranges that can be used for a comprehensive visualization and later interpretation of the data.

4.3 Image denoise

The above images collectively indicate aspects of the study area. The signals are corrupted with normal white noise with different standard deviation. The signal to noise ratio (SNR) is within the range of 12 to 14. In order to reduce the noise and extract the useful signal from the particular images, wavelet decomposition and reconstruction functions were employed. The following procedures were applied to achieve the above:

● Initially, the wavelet method was used for denoising the original resistivity and magnetic data and their corresponding first directional derivatives.

● Decomposition of the original denoised data images and their directional derivatives was followed using the popular sym4 wavelet basis. The sub-image, composed of the low frequency components, is called an approximated image. The remaining images, containing high frequency components, are termed detail images.

● Fusion of the original images with their directional derivative images was achieved through simple image algebra computations of their approximated images originating from the wavelet decomposition.

● In the final stage, reconstruction of the above results with the detail image from either the original images or directional derivatives was achieved. All possible combinations of the original resistivity and magnetic images with their directional derivative images in 30^0, 45^0 and 90^0 were tested using the same wavelet basis sym4, together with other wavelet functions such as Db1, Db2, and Db4.

The results suggest that the fusion by

subtracting the approximated image of directional derivative image of 90^0 from that of the original magnetic image and then reconstructing with the detail image of original magnetic image can better preserve the characteristics of the signal and reduce the noise at the same time (Fig. 5). The rest of the geophysical data were also processed by performing the same denoising and fusion approaches above, the outcome of which offers new and complementary information of the study area.

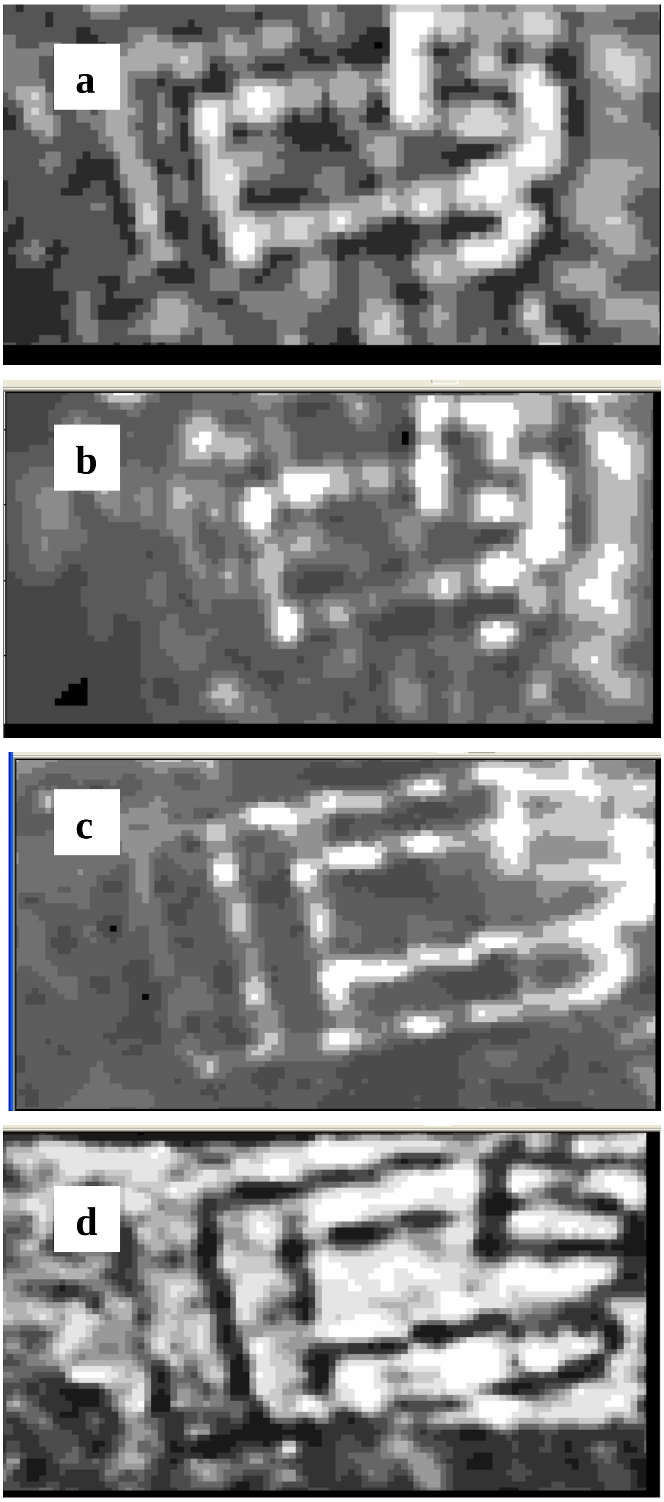

Fig. 4. Classified datasets, consisting of a) ERT 2, b) ERT 3, c) resistivity and d) magnetics.

Similarly, the wavelet fusion was performed between the original magnetic image and its corresponding classified image (instead of the directional derivative image mentioned above). The results suggest that the reconstruction of the difference between the approximated image of the classified data and that of the original magnetic image produced an enhancement offering detailed information for further interpretation.

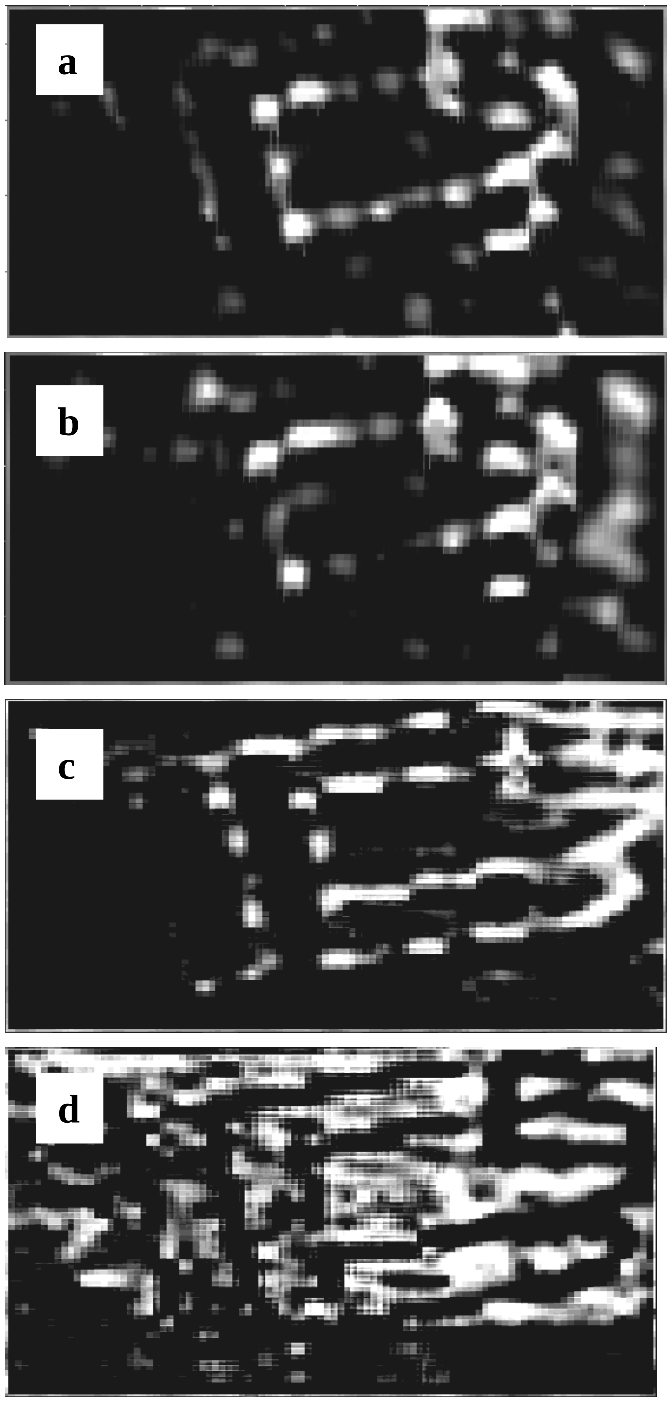

Fig. 5. Denoised images by fusing the original data with

the directional derivative image of 90^0: a) ERT2, b) ERT3, c) resistivity, d) magnetics

4.4 Image fusion
Successful geophysical interpretation of cultural features relies on expertise in the local archaeology and knowledge of the corresponding archaeological signatures in geophysical data, based on a combination of subjective insights and deductive reasoning. In an effort to acquire detail information of the archaeological site from the geophysical data, the above images were integrated through fusion techniques.

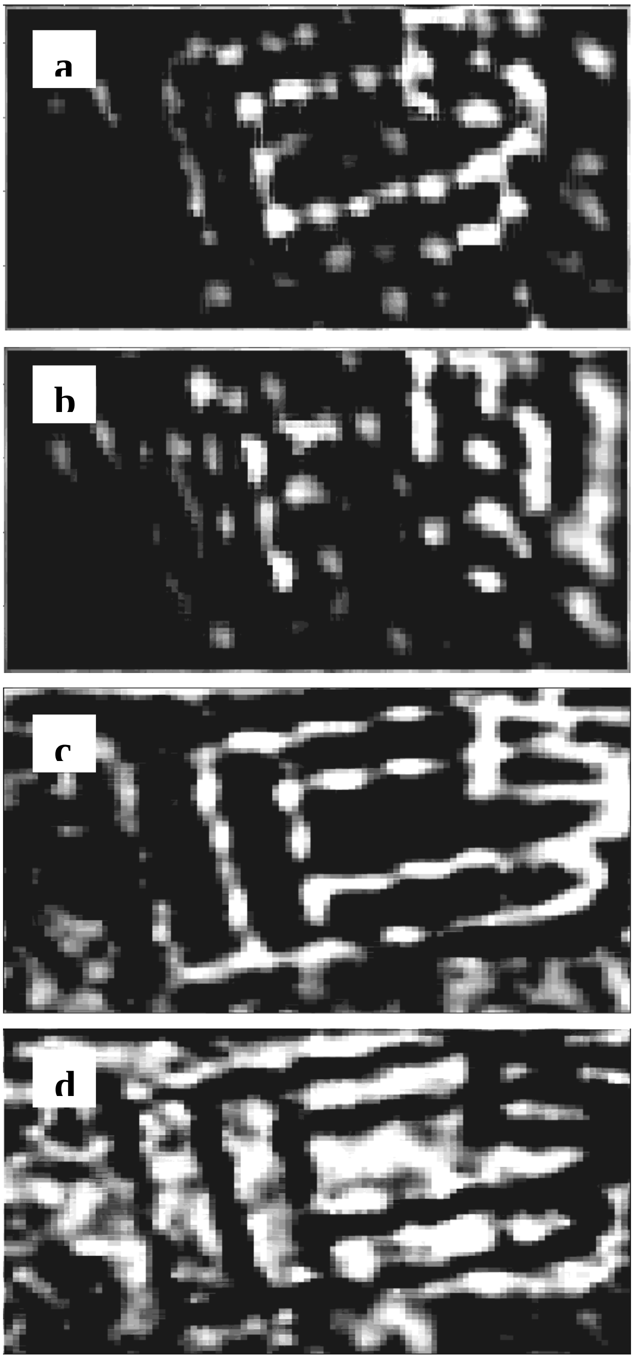

Fig. 6. Processing results. a) ERT2, b) ERT3, c) integration by fusing classified resistivity image with the denoised magnetic image, d) integration by fusing classified magnetic image with the denoised resistivity image.

The wavelet method was used for fusing the denoised geophysical data with the corresponding classified images. The wavelet basic function used was still Sym4 and fusion method was LR_fusion in approximation and Max in detail parts respectively. Furthermore, the resistivity and magnetic data were integrated by fusing the classified resistivity image with the denoised magnetic image and the classified magnetic image with the denoised resistivity image respectively (Fig. 6). Thus, the entire workflow of the proposed method can be described as follows:

(i) Creation of maps of the corresponding geophysical data using interpolation algorithms and then calculating their the first directional derivatives for directions of 30^0, 45^0 and 90^0.

(ii) Classification of the geophysical datasets.

(iii) Image denoising through wavelet decomposition and reconstruction functions (Fig. 5)

(iv) Image fusion of the denoised image with the corresponding classified images through the wavelet basic function (Fig. 6).

Figures 5 and 6 suggest that more detail information is available after the fusion of the classified image with the denoised image of ERT data, whereas the integration of magnetic and resisitivity data via wavelet fusion made the outline of the structural remains more clearly defined. The suppression of small noisy artifacts is obvious.

ERT2 data were used as an example to perform further analysis. The contour map and shaded relief map of original ERT2 data are shown in Figure 7, respectively. The anomalies associated with the ancient building base are clearly indicated. These data were denoised with the use of the proposed scheme and the results also shown in Figure7. The same level was set in both original data and denoised data contour maps. Note that the weak anomalies around the ancient building foundations have been eliminated .Both in the contour map and shaded relief map, the suppression of noise is obvious and archaeological target is emphasised.

In order to test the efficiency of the above methodology, a new dataset from another archaeological site, Priniatikos Pyrgos at Istron, E. Crete, was used. The site of Priniatikos Pyrgos is located at Mirabello bay, close to Agios Nikolaos, and a number of architectural remnants have been found through the application of EM soil conductivity, soil resistivity and magnetic techniques. Test excavations verified some of the geophysical targets that were detected through the above methods. For the particular dataset, the fusion was performed between the enhanced image and the denoised image. The two images come from the wavelet enhancing and denoising processing, the former being the fusing outcome of the original magnetic and its corresponding classified image, while the latter being the fusing outcome from the original magnetic data and their directional derivatives. The wavelet basic function used was also Sym4 for conductivity, but Db4 for magnetics. Trials with different fusion techniques indicated that the scheme using max function for both approximation and detail parts, and min function for approximation and max function for detail part respectively can give a relative better estimation of the original signal with a significant suppression of the noise, without a loss of the characteristic signature of the signal (Fig.8).

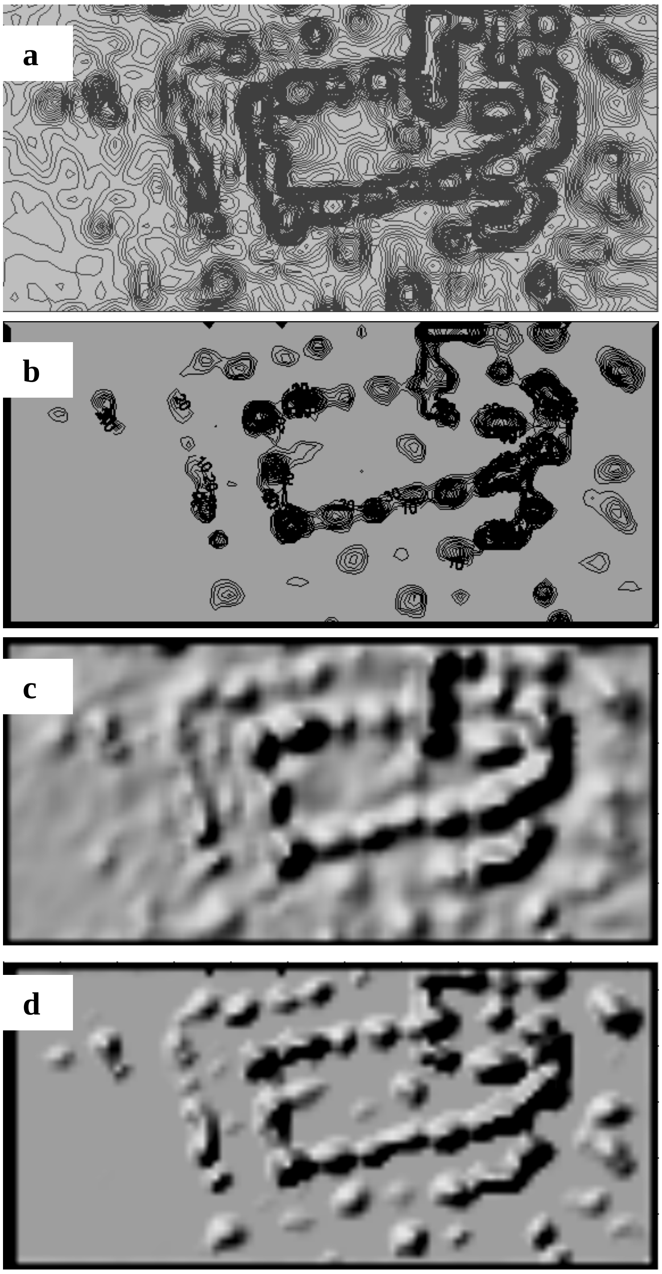

Fig.7. Raw ERT2 data and denoised results: a) Contour map of original ERT2 data and b) denoised data, c) Shaded relief map of original ERT2 data and d) denoised data.

The quality of the denoised images was evaluated through the computation of the normalized mean squared error (MSE), which is defined as follows [10]:

$$MSE_n = \frac{\sum_{i=1}^{N}\sum_{J=1}^{M}(X_{ij} - \bar{X}_{IJ})^2}{\sum_{i=1}^{N}\sum_{j=1}^{M}(X_{ij})^2} \qquad (1)$$

Where, parameters M and N denote the original image's size, X and $\bar{X}$ denote respectively the input data set and its mean matrix. Using Equation (1) the calculated MSE_n of ERT2, ERT3, magnetic and resistivity images are 0.31, 0.42, 0.24 and 0.23 respectively.

5. Discussion & Conclusions

According to the experimental results, it can be suggested that the denoising and fusion method combining the wavelet transform with image classification is of practical use in outlining shallow depth geophysical targets. Integrating multiple geophysical data sets offers an increased potential for improving our understanding of the subsurface.

The use of wavelet transform only, without the classification technique, does not lead to a satisfactory removal of the noise signal (Fig. 5). This result could not be achieved by standard filtering technique such as Fourier methods, which have good frequency resolution, but lack spatial resolution [11]. In contrast, the decomposition and reconstruction of geophysical datasets by wavelet techniques exploit fully the different directional and spatial attributes of the geophysical signals resulting to a more efficient extraction of the useful signals [12].

Moreover, integrated data may simultaneously show relationships between the conductive, magnetic and electromagnetic properties of the underground targets, improving our knowledge of the features, exploiting multiple sensor attributes and enhancing overall interpretation. The advantage of the method is based on the fact that the wavelet decomposition, reconstruction and image classification as an intermediate step of processing, retains the useful information within both spatial and spectral domains. It exploits fully the information context of multiple geophysical datasets and provides a significant suppression of the white noise and the coherent one caused by the systematic undulations of the ground surface. Image processing with wavelet transform was easily implemented and performed in Matlab. The suitable mother wavelet has to be chosen at the onset of the procedure, which is based to the user's experience and level of training with the process. Further evaluation of the above process is under way and is based on different datasets from various archaeological sites that contain targets of different attributes (dimensions, depth extent, a.o.).

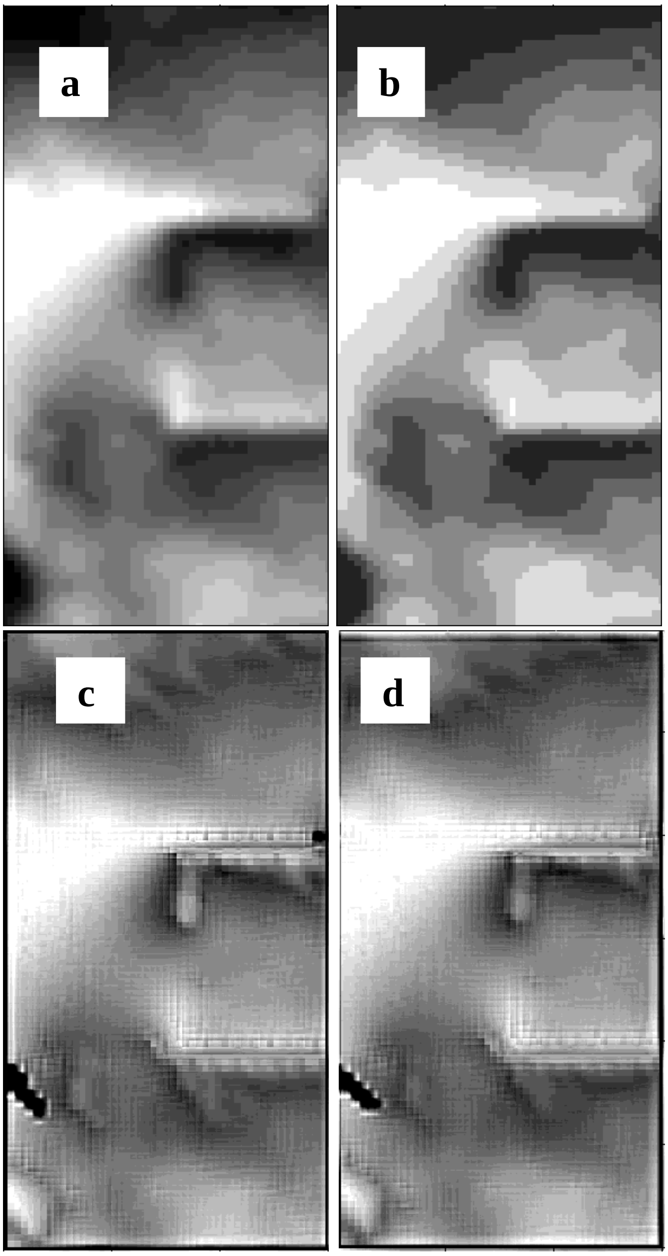

Fig. 8. Original data and processing results from Istron (archaeological site of Priniatikos Pyrgos). a) original conductivity data, b) classified conductivity image, c) and d) reconstructed image of the difference between the approximated image of the classified data and the original image fused with its directional derivatives in 30^0 and 45^0 respectively.

Acknowledgements：

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