Fusion of Geophysical Images in the Study of Archaeological Sites

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# Abstract

In the last few years, the idea of combining images, called image fusion, appeared and it has become a critical area of research and development. Image fusion can be defined as the process of combining images, taken from the same scene and create one single image containing all the essential information of the original images. A single sensor is not always sufficient. Different sensors, effective in different environmental conditions, provide different information of a scene. The underlying idea in this paper is to combine geophysical images taken with different sensors, from the same location, aiming to improve the detectability of possible archaeological targets. Three different fusion approaches were used: fusion by calculating the average of the individual images, and through the use of wavelet and curvelet transforms. Furthermore, taking advantage of the curvelet domain we exploit possible prior angle information to enhance the angles where the remnants are expected. We applied the methods in seven different pairs of geophysical images taken from two different archaeological areas. In all cases the fused images produced significantly better results than each of the original geophysical images separately.

**Keywords**: image fusion, archaeology, geophysics, wavelets, curvelets

# Introduction

Over the last two decades, geophysical methods have become a crucial part of archaeological research as they can accurately map near surface submerged structures of archaeological interest (e.g., Atkinson 1953; Weymouth 1986; Brizzolari, Ermolli, Orlando, Piro, & Versino, 1992a; Tsokas et al., 1997; Gaffney & Gater, 2003). The most commonly applied techniques in archaeological surveys include the use of magnetometers and gradiometers (e.g. Weymouth, 1986; Brizzolari, Piro, & Versino, 1992b; Clark, 1996; Tsokas et al., 1997; Kvamme et al., 2006), the measurement of soil resistivity or conductivity (e.g. Noel & Xu, 1991; Weymouth, 1986; Mauriello, 1998; Savvaidis, Tsokas, Liritzis, & Apotolou, 1999; Kvamme et al., 2006, Papadopoulos, Tsourlos, Tsokas, & Sarris, 2006), ground penetrating radar (e.g., Malagodi et al., 1996; Savvaidis et al., 1999; Kvamme et al., 2006; Ernenwein & Kvamme, 2008; Goodman & Piro, 2013), and magnetic susceptibility (e.g., Kvamme et al., 2006; Ernenwein & Kvamme, 2008).

The effectiveness of each method depends upon the physical properties of the target, which are related to the material, its history and its current condition, as well as its geometrical shape, size and burial depth. Moreover, target contrast with surrounding material (type of soil and rocks) and surface conditions play an important role. Often both the targets’ and the background properties vary spatially. For example, a ceramic oven may be next to remains of a limestone wall. Likewise, microtopography can cause changes in soil moisture. Considering that each geophysical method is sensitive to only a small subset of the target’s properties at best, such spatial changes, will cause the effectiveness of each technique to vary spatially as well.

Most frequently the use of two or more geophysical techniques is necessary to reveal the full matrix of archaeological sites. Nevertheless, even in these cases the analysis is performed by processing separately the individual datasets and the person doing the interpretation typically compares the products of this analysis i.e., the geophysical images by visual inspection, with some few yet notable exceptions (Kvame et al., 2006; Kvame, 2006; Ernenwein & Kvamme, 2008, Kvamme et al., 2019).

Over the last years there has been a growing interest in the use of multiple sensor fusion; hence, the single representation of different sources of sensory information is called multi-sensor fusion. Consequently, multi-sensor fusion became an area of many research activities and various applications (military, medical, remote sensing etc.) (Muller & Narayanan, 2009; James & Dasarathy, 2014; Simonea, Farinab, Morabitoa, Serpicoc, & Bruzzoned, 2002). Data fusion techniques take advantage of the complementary spatial and spectral resolution characteristics while at the same time they allow the integration of different information sources. For example, measurements of the local magnetic field and its gradients aim to detect changes in magnetic susceptibility and remanence, while electrical surveys attempt to detect variations of the resistivity. Image fusion can combine all the information from all sensors in one single image removing at the same time the background noise. In this work, we compare the results of three fusion methods, average method (Reiser & Lavenberg, 1980), wavelet (Mallat, 1989) and curvelet (Candes, 1998; Candes & Donoho, 1999) and try to find the appropriate one for fusing geophysical images together. Each geophysical image was created using different surveying methods. We propose a transformed curvelet algorithm that takes advantage of the angle information which is important in detecting archaeological targets. Finally, we compare the results with the methods mentioned above (average method, wavelet and curvelet). The data used in this study are from two different sites, one located in Greece and the other one in USA, corresponding to a variety of environmental and geological conditions, soil and archaeological targets.

This paper is organized as follows: in section 2 we present the fusion methods used in this work. In section 3 we describe the data while in section 4 we present the results. Conclusions are drawn in section 5.

# 2. Fusion Methods

Multi-sensor fusion can occur at three different levels: pixel, feature and decision level. This paper deals with the images at pixel level, where fusion between different images produces a final fused image in which each pixel is determined from a set of pixels in each original (input) image. Pixel level fusion increases the useful information content of an image so that the performance of tasks, such as the feature detection, can be further improved. Over the last years a lot of image fusion techniques have been proposed for various applications. During these years some of them were improved while some new techniques appeared in order to solve the existing problems. In this work we present three different fusion techniques: fusion with the average method (Reiser & Lavenberg, 1980), wavelet (Mallat, 1989), curvelet (Candes, 1998; Candes & Donoho, 1999) and we introduce a new approach of the curvelet method which we consider best for geophysical data. The target is to compare the results between each method and find the appropriate one for fusing geophysical images together in order to find possible archaeological remnants. Following, there is a brief description of each of the methods mentioned above.

# Average method

The simplest method to fuse two images, A and B, is to create an image where each pixel is derived as the average of the intensity of the corresponding pixels of the two original images, assuming that the images are already registered so each pixel of each image depicts the same pixel of the other image (Reiser & Lavenberg, 1980),

. (1)

Where is the intensity of the pixel of the fused image with coordinates in the image coordinate system, is the intensity of the corresponding pixel in image A, and is the intensity of the corresponding pixel in image B. The scalars and control the importance of each individual image during the averaging procedure. In the simplest form , and eq. (1) calculates the mean of the two original intensities, which is also the way it is used in this work.

# Fusion with Wavelets

The discrete wavelet transform was first introduced in the field of image processing with Mallat’s algorithm (Mallat, 1989). In one dimension, a wavelet , is a finite function in time and frequency of zero average (Meyer, 1992; Mallat, 1999),

. (2)

The initial wavelet function, also known as the *mother wavelet*, is then dilated with a scale parameter and translated by ,

. (3)

The wavelet transform of a signal at scale and position is defined through the correlation of with the specific wavelet,

(4)

where indicates the complex conjugate operation. Following, Eq. (4) an equally spaced, finite sequence signal can be decomposed in its wavelet coefficients by calculating a series of cross-correlations between and at different scales and relative positions. It should be noted that although the wavelets are not necessarily orthogonal, several wavelet families satisfy the orthogonality criterion, as for instance the “Daubechies” wavelets (Daubechies, 1988). The localization of the wavelet in time and scale determines the resolution of the wavelet transform in time and frequency. Practically the Discrete Wavelet Transform (DWT) is computed by successive lowpass and highpass filtering of the discrete signal, followed by down-sampling by the factor 2, which produces the two subband signals, called the approximations and the details, respectively. Depending of the length of the original signal, this procedure can be repeated starting with the approximations subband several times, producing multi-level wavelet decomposition. For two-dimensional signals such as images, the algorithm is similar to the one-dimensional case (e.g., Mallat 1999). The products of the decomposition of an image at level j produces four components: the approximation at level j + 1, and the details in three orientations; horizontal, vertical, and diagonal. The DWT is invertible hence, one can reconstruct the signal from the DWT coefficients with the inverse DWT, which is implemented in a similar way by cascading synthesis filter banks. An obvious advantage of the multilevel decomposition of an image is that it decomposes the contained information across different wavelength bands, allowing the details of each scale to be handled separately.

In this work, we perform the image fusion starting by applying a multilevel DWT to the input images. The maximum useful level of the decomposition can be readily calculated (e.g., Mallat, 1999; Kanagaraj, Arumuga, & Arulmozhi 2010). After the decomposition of the two initial images, the fused image is formed in the wavelet domain after comparing and selecting the best between the corresponding coefficients of each input image. Although many different fusion rules can be applied, in this work the *maximum frequency rule* is used. This method selects the coefficient with the highest absolute value. Higher absolute coefficient in one image over the other means that the specific feature is represented in a higher contrast, in this particular image, and subsequently it should be used in the final fused image. When all coefficients of the fused image are selected then the inverse DWT is performed and the fused image in the spatial domain is retrieved (Figure 1).

# Fusion with curvelets

The curvelet transform is based upon two more elementary decompositions, the ridgelet and the radon transform. The ridge function was first introduced by Logan and Shepp (1975) in connection with the mathematics of computed tomography. Assuming a univariate function , the bivariate function is defined as (Candes, 1998; Candes & Donoho, 1999),

, (4)

where , and , indexes the scale of the ridgelet, its location and its orientation. The function remains constant along the “ridges”,

The ridgelet coefficients of an image are then defined as,

(5)

The exact reconstruction is performed as,

. (6)

In 2-D, points and lines are related through the radon transform. The radon transform of a function of two variables is a function defined (Asano, 2002) on a family of straight lines over various radial directions. On any given straight line, the value of the equals the integral of along this line. Thus, the Radon transform for a 2-D mapping  is the gathering of line integrals indexed by and is described by,

(7)

where is the Dirac delta function (Dirac, 1984). Essentially, the radon operator, maps the spatial domain into the projection domain . In this domain, each point corresponds to a straight line in the spatial domain; conversely, each point converts to a sine curve in the projection domain (Averbunch et al., 2001). Using (5) and (7) we can express the ridgelet transform as the application of a 1D-wavelet transform to the slices of the radon transform, where the angular variable is constant and is varying:

, *(8)*

where . A schematic representation of the ridgelet transform can be seen in Figure 2. The ridgelet transform is suitable for the efficient representation of linear features of various scales but it fails to do the same for curves. Candes and Donoho (2000) resolved this issue by introducing the curvelet transform. The latter essentially divides the image into small block partitions (tiles), where the small portions of the curved features can be approximated sufficiently as straight lines. Next, ridgelet transform is applied to the partitioned sub-images. One of the important characteristics of curvelet transform is that introduces a variable degree of discretization of the orientation as a function of scale, with the angular resolution to be doubled every other scale.

To fuse the images with the curvelet transform we work in a similar manner as with the wavelet transform. In this case, both images are initially decomposed into subbands by means of the 2-D discrete wavelet transform (Figure 3). Afterwards, the details of each subband are divided into small tiles, and the curvelet coefficients are obtained by applying the ridgelet transform to each tile, of each subband. The advantage of the curvelet transform is that the image is expressed as a function of the scale (wavelet transform), orientation (ridgelet transform) and the spatial location (tiling) of its features. For this procedure we used the CurveLab 2.1.2 (Candes, Demanet, Donoho, & Ying 2005; available online from [www.curvelet.org](http://www.curvelet.org), last accessed on July, 2019). The next step is to combine the curvelet coefficients of the initial images and create the fused image in the curvelet domain. As in the case of the wavelets-based fusion we apply the maximum frequency rule to select the features with the best representation among the initial images. Finally, with the inverse of the above procedure (i.e., inverse curvelet transform) the final fused image is extracted (Figure 3).

# Fusion with curvelets using prior information

As mentioned above, curvelet domain provides numerous advantages. This is mostly because, in curvelet domain the image is expressed in terms of different wavelengths and different orientations as well. In archaeological applications there is usually a large amount of prior information available, about various properties of the expected targets. In this work we take advantage of the two more robust prior information; the expected dimensions and the orientation of the targets.

The knowledge of the size of the relics can be readily exploited in the case of multiscale transformations as those presented in this work. For example, it is safe to assume that the details of the highest level subband in curvelet transform are unlikely to correspond to any archaeological feature but instead they represent the noise, which is typically abundant in all geophysical measurements. Similarly, the longest wavelength signal is also probably not related with features of archaeological interest, but can be attributed to other causes, such as topographic variations for instance in the case of electrical resistivity surveys, and spatial changes in the levels of soil moisture. Such signal is expected to be mapped on the approximations subband. On the contrary, signals of intermediate wavelengths are usually the most interesting ones, as they include those produced by archaeological targets. Such signals will be imaged in the details subbands of the levels in between. Following this reasoning, we amplify signals that are expected to represent the useful information and suppress the ones that are expected to map the noise.

The expected orientation of the targets is another piece of information that can be used as commonly as the archaeological features all aligned to specific orientations rather being arbitrary placed in space. Often, the orientation of the features can help distinguish relics associated with different periods of occupation. In most of the cases, the expected orientation is known prior the geophysical investigation, for example based upon previous findings in the area; hence it can be used as a-priori information to improve the results of fusion, utilizing the advances of curvelet domain. To include the orientation information, after the curvelet decomposition of the original images the fusion of the coefficients is performed as described in the previous section. Then we chose the bands that represent wavelengths similar with the potential targets. For these bands we select the coefficients that correspond to orientations parallel with the expected targets based on the a-priori information. We amplify the fused coefficients by multiplying them with a positive number . This procedure should be done gradually considering that the operations in curvelet domain are highly non-linear and could produce significant artifacts to the fused image. The optimum amplification factor should ideally highlight the features along the preferred orientations and at the same time maintain the potential artifacts to a minimum. We perform a “trial and error” search for each case to conclude to the optimum value. In most of the cases this value doesn’t exceed 1.5.

# Application with real data

Next, we demonstrate the aforementioned methods in two different real-data cases. The first area is from Maronia, Greece and the second from the Army City in Kansas, USA. For the first case we present in detail the results from all methods, but in the second case we focus on the curvelets technique which showed the best performance in both cases. Results from the rest of the techniques can be found in the supplementary material

# Maronia

The first dataset is from the archaeological area of Kampana, situated near Maronia city in north-eastern Greece (Figure 4, right image) a municipality in the Rhodope Prefecture. It has been inhabited since the Neolithic age around 3rd millenium B.C. Up to the 2nd millennium B.C. the area was inhabitant by at least seven settlements mostly by Thracian tribes. It is situated on the south-west slopes of Ismaros, about midway between the mouths of the Hebrus and the Nestus and named after Maron, son of Euanthes, a priest of Apollo, who in the Odyssey gives Odysseus the wine with which he afterwards intoxicates Polyphemos.

Excavations of the site, started ain 1969 (Tsokas et al., 2004), have brought to light many important monuments such as a theatre (323-146 B.C), a sanctuary, probably dedicated to Dionysos (323-146 B.C), parts of the fortification wall of the Classical city and the House of the mosaic (323-146 B.C). Byzantine monuments have also been revealed, such as the atrium of the early Christian Basilica (6th century A.D), a Byzantine monastery and a part of a bath installation dated to the period of Justinian A'. The archaeological area of Kampana, which is the one that interest this paper, was discovered in 1905 when the citizens were using the docks to build an elementary school. It was constructed in the Hellenistic period and remodeled in Roman times. It preserved three rows of stone seats of the cavea, the central and the horseshoe-shaped conduit of the orchestra, and the building of the Roman skene. During the classical period the city had a rectangular fortification wall with a perimeter of 10,4km extending from the coast up to the top of Ismaros, part of which remained unbuilt and was used as shelter in case of emergency. Constructed with curved stones (gneiss and granite) from the surrounding area, the fortification remains intact today and in some points it reaches the height of two meters and a thickness of 2.30-3 meters, showing some rectangular and semicircular towers.

Tsokas et al. (2004) performed magnetic measurements (vertical gradient of the local magnetic field; from hereafter referred to and as magnetic method) in an area of 11200 m2 and electrical measurements of the apparent resistivity (hereafter referred to and as electrical method) in an area of 5500 m2, part of the previous area (Figure 5). Τhe area was first divided into 20mx20m square cells. Magnetic measurements were performed with a step in both directions and a few months later the electric measurements took place keeping a 1m step. Since the original raw data were not available, we used 8-bit, grayscale images of dimension that both correspond to theoretical image resolution of 0 per pixel side. These images were created from the original data after applying typical processing routines (e.g., Scollar, Weidner, & Segeth 1986; Tsokas, Bargiemezis, Stampolidis, & Kurgiakidou 2004), which include correction for temporal changes in the readings, converting readings to estimated values at regular and fixed intervals of distance, checking for unusual one-point errors, distinguishing heading errors and positional errors (destagger etc), despiking and interpolation using the sin method and finally, smoothing of the data using the median method with a moving rectangular window of 1 meter. For the magnetic data, the MagPick software (Tchernychev, 2009) was used to reduce the dipolar anomalies (e.g., Blakely 1995; Tchernychev, 2009; Montaj Geosoft, 2010).

# Army-City

The second dataset is from Army City which is situated in Riley County, Kansas, USA, owned by the U.S. Army (Figure 4, left image). The city was built in 1917 for the needs of Camp Funston, which was one of sixteen “Divisional Cantonment Training Camps” established during World War I. It extended 92,400m2 and included large theaters, the Orpheum, a Hippodrome and organizations such as the YMCA and YWCA (Young Men's and Women’s Christian Association). The population of Army City was about 3,000 people, among them were businessmen and their families, men working either in Army City or Camp Funston as well as families of officers. A flood in 1919 followed by a fire in 1920 destroyed the entire city. Presently, it remains buried under a hay field with very limited surface indication of its existence while it is assumed that the maximum depth of the buried relics is around 30cm.

During July 8-18, 2002, the University of Arkansas with the support of the U.S. Department of Defense, through the Strategic Environmental Research and Development Program (SERDP-CS1263) performed five different geophysical methods in the broader area of Army City (Figure 6): earth resistance, magnetic gradiometer, ground penetrating radar (GPR), electromagnetic (EM) conductivity and magnetic susceptibility derived from the same EM measurements in a surveyed area of about 16,000 m2 (Ernenwein & Kvamme 2008; Kvamme, 2006), (Figure 7). For each method, common processing procedures were applied as described in Ernenwein and Kvamme (2008) and Kvamme (2006). For the first four methods the area was divided into 20×20 m2 square grids with steps of 0.5 m (Figure 6 top right). For the magnetic gradiometer survey the sampling interval was 0.25 m. In the case of GPR, the area was divided into 4 grids of 50×50 m2 and 4 grids of 50×30 m2. Even though data were collected for different depths, we used the results from the depth range of 0.25 to 0.5 m, (Figure 6 top left). Figure 7a shows the results of the earth resistance measurements after been fully processed (survey defects removal, despiking, high-pass filter and low-pass filter) and local contrast enhancement and improvement of brightness and contrast was applied. On the top left corner, walls and rooms are revealed composing a part of the Hippodrome. The building on the north part of the image appears to be a part of the “Orpheum Theater” while the northwest-southeast street between these two buildings is “Washington Avenue.” The perpendicular road to Washington Avenue is General Street and on the right side of the first was an open area/park. The white dots south of the image are indicated as building footers. One interesting thing is that vegetation marks on the surface coincide with most anomalies in the resistivity image.

For the magnetic gradiometer survey the sampling interval was 0.25m and the maximum accessible depth was less than 1,5m. The instrument used for the measurements was a Geoscan Research FM-36 fluxgate gradiometer. Figure 7b shows the measurements after been processed (survey defects removal, despiking, high-pass filter and low-pass filter, local contrast enhancement and improvement of brightness and contrast). Magnetic measurements reveal the materials that contain iron or steel such as building materials (nails, nuts), concrete foundations and pipelines. Positive and negative magnetic values appear in the image (e.g. left and right corner) where they possible indicate pipe joints. Magnetometry is also sensitive to burned materials and since Army City was burned from the 1921 fire some burned materials might also have been sensed.

For the ground penetrating radar (GPR) in order to take the measurements, the area was divided into 4 grids of 50x50m and 4 grids of 50x30m. The instrument used was a Geophysical Survey Systems, Inc. SIR-2000 with 400 MHz transducer and survey wheel. The vertical low pass filter was 800MHz, the vertical high pass filter was 200MHz and the vertical resolution was 512 samples per trace. Figure 7c shows the result of the 25-50m depth, selected as the image with the maximum useful information, after been processed (survey defects removal, despiking, high-pass filter, low-pass filter, local contrast enhancement and improvement of brightness and contrast).

To perform the electromagnetic induction survey, the Geonics EM38 instrument was used in Quadrature mode keeping the sensor in a vertical orientation to achieve the deepest subsurface penetration. Measurements were taken every 0,5m. Figure 7d shows the image after despiking to remove some of the low-level metallic noise, a high-pass filter for trend removal and a low-pass filter for further noise suppression. Some basic processing was also applied (survey defects removal, low-pass filtered, smoothed and/or interpolated, local contrast enhancement and an improvement of brightness and contrast). In the final image with the white color we can distinguish some buried pipes.

The instrument used for the magnetic susceptibility survey is the Geonics, Ltd. EM-38, positioned at the in-phase mode while the measurements step was 0.5m. Figure 7e illustrates the resulted image after been processed (despiking, a high-pass filter to eliminate large zones of high measurement and a low-pass filter for further noise suppression, local contrast enhancement and improvement of brightness and contrast). The magnetic susceptibility data appear more sensitive to the burned materials than iron or steel.

# Results

Next, we present and compare the results from the three different methods discussed above for each pair of images. It should be noted that all pairs of geophysical images, were finely co-registered using the semi-stochastic method described in Karamitrou et al., (2011; 2017) to mitigate possible local arbitrary offsets from the theoretical grid, that are typically introduced during the measurements with handheld devices.

# Maronia

The apparent resistivity and magnetic images from Maronia are partially overlapped and both show interesting features that can be attributed to archeological structures. The two images are characterized from different histograms, with the magnetic image to be of low contrast, while the electric image has gray values at the edges of the histogram, i.e., either very bright or very dark.

The results of the fusion are shown in Figure 8. We can see some rectangular features that appear clearer (NE and SW of the image) than in the two original images separately. However, one apparent problem with this approach is that the fused image suffers from lower contrast and it is generally smoother, compared to the original images. Also, the bright regions of the electrical image contaminate the fused image as well decreasing the amount of visible structures in these regions.

Figure 9 shows the results of the wavelet-based fusion approach. In this case, wavelets provided the ability to amplify the scales where we had the most useful information by a factor of 1.5x and suppress in a similar way the scales that correspond to high or low frequency noise during the fusion process. To identify the scales corresponding to noisy features, we selectively amplified one scale at a time, and we measured the average size of the enhanced features. Scales that correspond to features of similar size as the expected targets (meter-scale objects) were enhanced, while the rest were suppressed. In the resulted image (Figure 9C), the contrast has been improved between some features and the background area, compared with the average method. However, the contamination from the bright regions of the electrical image is worse in this case, which was to be expected from the maximum frequency rule that was used for the fusion. It should be noted that the wavelength of the bright regions is not significantly different from the wavelength of the structures that appear on the NE part of the image, thus the noise suppression at the lower scales could not filter out this problem.

This is not the case when the fusion is performed in the curvelet domain (Figure 10), as the coefficients that are to be fused include also the orientation information. Therefore, a bright region without any clearly oriented features (e.g., lines, curves) will be expressed with low curvelet coefficients despite its brightness, as opposed to a less bright feature with clear orientation that will have a high curvelet coefficient respectively. In this case, the maximum frequency rule successfully selects the most informative features between the two original images, and as it is apparent in Figure 10, succeeds to filter out the bright uninformative region of the electrical image, without however removing possible features, even within this problematic region. Furthermore, in the rest of the image the results are also better than the previous methods, showing clear lines, rectangles and curved features that can correspond to possible archaeological structures. It should be noted that we enhanced the scales where the useful information is expected and suppressed those corresponding to noise, by the same factors as with the wavelet based fusion. Again, to separate the scales with the useful signal from those with the noise we followed the same trial and error approach as with the wavelet fusion, mentioned above.

Finally, we investigated how we can further improve the curvelet-based fusion by incorporating the prior information about the expected orientation of the buried structures as it was described earlier. From previous nearby excavated archaeological structures it is apparent that the general orientation of the ruins follows a NE or NW orientation. This can be confirmed also from the features that are imaged in the two separate geophysical images. Figure 11 shows the fusion results when this information is taken into consideration. The fused image appears even clearer, and the last regions of contamination from the bright region of the electrical image are not present. Furthermore, there is a significant improvement in imaging of the features along the expected orientation. It is worth noting that the features shown in the fused part of the image, i.e., the overlapping part of the images seem to continue smoothly in the regions of the magnetic image that are not taking part in the fusion process, suggesting that such features are non artefacts of the fusion process or the angle enhancement. Figure 12A shows the relative difference between the fused image without the angle enhancement and the fused image after enhancing the north-east to north-west orientation. We note that the differences are not dominated by the features along these angles. Some features that could correspond to possible archaeological targets are shown in greater detail in Figure 12. One of these possible targets is an ellipsoidal feature at the center of the image. Half of this feature is shown on the fused part of the image and it continues smoothly without discontinuities in the non-fused part of the magnetic image. It is worth mentioning that this feature is faint in the magnetic image and it is not distinguishable in the electric resistance image.

At the top of the fused image we can recognize two curved features, one next to the other (Figure 12, feature 2). In the original images we can see some part of the features appearing in the magnetic image (A) and some other parts in the electric resistivity image (B) but in the fused image it is easily recognizable almost the complete feature, which was fully formed by the combination of the two original images. Figure 12 (second row) is a zoomed version of this feature for all three images.

Another interesting example is a rectangular target near the bottom of the images (Figure 12-feature 3) which is clearly visible in the fused image but not so clear in the magnetic or in the apparent resistivity image (Figure 12-third row).

To confirm that the linear features that appear in the last image were not artifacts of the fusion technique, we repeated the fusion by enhancing features at angles of 450 degrees with respect to the expected ones. The result is shown in Figure 13. In this case we do not observe similar linear features along the new preferred orientation, but instead, this new image looks more similar with the result of the curvelet method without incorporating the orientation information.

# Army-City

Following the results of the previous test case, we focus here only in the curvelet method with the incorporation of the prior information about the orientation of the features, since it seems to produce the best fused image in all cases. Nevertheless, results from other methods can be found in the supplementary material. In the Army City dataset we use five images from different geophysical methods and a total of seven combinations. The combinations are such that every time at least one high-resolution method (electrical or magnetic) was included.

From the original images it was clear that the dominant orientations of the buried features are northwest-southeast and northeast-southwest. Therefore, for the curvelet based fusion we chose to enhance these angles ( from the vertical axis) exploiting the advantages that curvelet domain provides. As with in the previous case the fused images, regardless the combination, succeed to include most of the information available in the source images (Figure 14). For example, both the remains of the walls (e.g., upper left part of the image) that are clearly imaged with the electrical method and linear magnetic anomalies that possibly correspond to metallic pipes, are present in the fused image (Figure 14a), providing a complete representation of the building structures as well as the hydraulic system of the facilities.

Furthermore, structures in the center of the images that are not distinguishable in the electric image but are clearly visible in the rest of the methods are visible in all fused images. Similar to the Maronia case, features that are irrelevant with the archaeological structures such as the arbitrary shape bright anomalies in the electromagnetic conductivity, and especially the magnetic susceptibility images (Figure 7 and e) are not generally inherited in the fused images that they participate as they do not produce significant curvelet coefficients due to their random shape.

The fusion method can readily be generalized to consider more than two source images. Taking advantage of the multiple overlapping datasets in the region of Army City, we produced fused images of multiple images. Figure 14h, shows such an example with the fusion of all five geophysical images. The final fused image includes most of the features that are present in the initial images. In certain areas the buried structures have been enhanced and appear more complete. However, in many parts, the fused image presents overwhelming number of features, making it difficult for interpretation.

# Discussion and Conclusions

This paper investigates the applicability and usability of fusion of dissimilar geophysical images produced from various geophysical methods, examining different fusion methods. Although different images display the spatial distribution of different physical properties (ex. apparent resistivity, magnetic field gradient, electromagnetic reflections, etc.) they all can potentially detect and locate buried targets acting either additively or complementary to each other. Ideally, a fusion algorithm combines all the useful information of the initial images to one image and suppresses the background noise. The resulted fused image improves the interpretation capabilities with respect to the initial images.

We examined three different approaches of image fusion; the first simply averages the pixel values of the initial images. The second uses wavelet decomposition in 2-dimensions and then it selects the high energy coefficients to reconstruct one fused image. The third approach used curvelets instead of wavelets, which allow the decomposition of an image not just in different bands (i.e. wavelengths), but also along different angles. Fusing the corresponding curvelet coefficients of the decomposed initial images results in fused images with the maximum amount of information for each band and each orientation. Furthermore, in many archaeological applications of the geophysical methods the primary orientation of the potential targets is known (ex. from past excavations) or can be presumed (ex. historical evidence, geomorphology, etc.). Taking advantage of the curvelet decomposition, this orientation-information can be used as a-priori constraint to improve the results of fusion. We applied and compared the various fusion algorithms between geophysical images taken from two different areas with different geological and archaeological characteristics with various modalities each one sensitive into different physical properties.

As presented above, in almost every case the average method produces decent fused images that contain most of the information of the initial images. As expected, the contrast is reduced and, in some cases, the averaging process nearly eliminated targets that were already weak in the original images.

The method of wavelet fusion also gave overall good results. It performed well especially for point targets, but it didn’t provide the possibility to take advantage of the information about the expected general orientation of the targets and filter out large anomalies of arbitrary shapes that are not related with the targets.

Curvelet based fusion was significantly more effective in every case. The advantages of curvelet domain in representation of linear and curved features were apparent in almost all cases. Additionally, the curvelet domain allows the incorporation of the a-priori information that constrains the expected orientation of the targets. Based on this advantage, targets aligned with the preferred orientations were enhanced and became more detectable. Perturbations of the coefficients in the curvelet domain are highly nonlinear so a lot of effort and attention is required to keep artifacts as limited as possible.

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