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Integration of aerial and satellite remote sensing for archaeological investigations: a case study of the Etruscan site of San Giovenale

R Lasaponara¹, N Masini², ⁵, R Holmgren³ and Y Backe Forsberg⁴

¹ CNR-IMAA (Istituto di Metodologie di Analisi Ambientale), Cda SLoja, 85050 Tito Scalo, PZ, Italy
² CNR-IBAM (Istituto per i Beni Archeologici e Monumentali), Cda SLoja, 85050 Tito Scalo, PZ, Italy
³ ARDOC—Archaeological Documentation, Djurgårdsagasatan 38, 582 29 Linköping, Sweden
⁴ The Swedish Institute of Classic Studies in Rome, Via Omero 14, I-0019 Rome, Italy

E-mail: n.masini@ibam.cnr.it and arcdoc@me.com

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Abstract
The objective of this research is to detect and extract traces of past human activities on the Etruscan site of San Giovenale (Blera) in Northern Lazio, Italy. Investigations have been conducted by integrating high-resolution satellite data with digital models derived from LiDAR survey and multisensory aerial prospection (traditional, thermal and near infrared pictures). The use of different sensor technologies is requested to cope with (i) different types of surface covers, i.e. vegetated and non-vegetated areas (trees, bushes, agricultural uses, etc), (ii) variety of archaeological marks (micro-relief, crop marks, etc) and (iii) different types of expected spatial/spectral feature patterns linked to past human activities (urban necropoleis, palaeorivers, etc). Field surveys enabled us to confirm remotely sensed features which were detected in both densely and sparsely vegetated areas, thus revealing a large variety of cultural transformations, ritual and infrastructural remains such as roads, tombs and water installations. Our findings clearly point out a connection between the Vignale plateau and the main acropolis (San Giovenale) as well as with the surrounding burial grounds. Our results suggest that the synergic use of multisensory/multisource data sets, including ancillary information, provides a comprehensive overview of new findings. This facilitates the interpretation of various results obtained from different sensors when studied in a larger prospective.

Keywords: remote sensing, archaeology, satellite data, LiDAR, aerial prospection, Etruscan civilization, San Giovenale

(Some figures may appear in colour only in the online journal)

1. Introduction
Over the last decades, some very important innovations have occurred in archaeological research, among them the wider use of (i) advanced technologies and ‘hard sciences’ for site discovery and cultural heritage monitoring and (ii) multidisciplinary approaches often oriented towards non-destructive techniques.

Great new potential developments for inter-site and intra-site analysis have come to light in this fervid scientific and cultural ambit. Both space and airborne sensors are ideal for providing synoptic views and multispectral capabilities, which enable us to go beyond what humans can visually detect.
Earth observation technologies provide data at different spatial, temporal and spectral resolutions from both active and passive sensors covering different ranges of the electromagnetic spectrum. Data from very high-resolution (VHR) satellite and airborne sensors provide high information content which unfortunately can only be extracted if complex scientific and technological challenges are resolved. VHR data pose serious challenges for data processing and interpretation because the features of interest are generally not isolated, but mixed with others and may also appear quite different within the same image due to their diverse physical characteristics. Moreover, regarding archaeological features, it must be considered that they typically do not exhibit clear and clean patterns and/or edges even in high-resolution data sets acquired from both active and passive sensors. This is due to the fact that archaeological marks are characterized by small spatial/spectral signals. Moreover, there are numerous factors that tend to distort their subtle edges and feature patterns.

To face these challenges and collect as much information as possible, the integration of different techniques and sensors is required. This may enable us to identify and extract subtle changes in the reflectance of various vegetation and soil types, as well as small micro-relief linked to outcrop remains.

This paper deals with multidisciplinary investigations carried out since 2007 in San Giovenale, an Etruscan site in Northern Lazio (see figures 1 and 2), by the institutes IMAA and IBAM of the Italian Consiglio Nazione delle Ricerche (CNR) and the Swedish Institute of Classic Studies in Rome. The investigated area has been affected by human activities from the remote past to the present, especially during the Etruscan period, i.e. eight to third centuries BC. The aims of the Swedish–Italian project are to verify, locate and spatially document ancient remains on the Vignale plateau within the area of San Giovenale in order to study them in a landscape-archaeological perspective.

The project is strongly based on remotely sensed data contributions, such as (i) satellite imagery; (ii) digital terrain models (DTMs) derived from LiDAR survey; (iii) aerial infrared thermographic images; (iv) near infrared and conventional photographs; (v) historic archive of aerial photographs.

In particular, a LiDAR survey was carried out in order to overcome the limits of optical imagery, such as the dense vegetation which covers a large area of the Vignale plateau, preventing investigations solely based on satellite and aerial photography. The availability of an ultralight plane allowed us to capture numerous images from different heights and viewing angles, hereby using the on-board infrared thermo-camera and digital photographic equipment. This allowed us to take near infrared and conventional photographs.

The rationale of our investigations is based on the consideration that the full exploitation of multisource data sets can offer a comprehensive overview by combining information obtained from sensors with different technological characteristics. This allowed us to better depict the Earth surface area and collect more detailed information on the study site, facilitating the classification and interpretation. As expected, the integration of the various data sets enabled the identification of a number of unknown features of cultural interest, which were verified and confirmed by conventional archaeological field surveys.

2. Study area and identification of archaeological features

Vignale, a tufa plateau, is a result of a pyroclastic flow of ignimbrite, approx. 1200 m in length measured from the furthest western tip to the main road of Civitella Cesi-Blera in the province of Viterbo. The area is found about 60 km NW of Rome (figure 1).

The plateau measures 78–420 m in width and rises 175–180 m above sea level, delimited to the north by the Fosso del Pietrisco brook and to the south by the Vesca river (figure 2). Vignale is located opposite the sister plateau consisting of the main acropolis and the Borgo area excavated by the Swedish Institute of Classical Studies in Rome from 1956 to 1965 (Boethius et al 1962, Thomasson 1972, Pohl 1980, 1985, 2012, Karlsson 2006). The archaeologically studied remains of San Giovenale show evidence of human occupation from the proto-Villanovan culture up to the medieval period. In particular, the main acropolis of San Giovenale is characterized by human settlements from proto-Villanovan to Etruscan period (13th–3rd centuries BC) in various parts of the site (such as a–c in figure 2). A ditch running North–South (see f in figure 2) separates the plateau.

Features similar to those discovered at this site can also be detected by applying remote sensing techniques to the Vignale plateau (figure 2). As on the main acropolis, archaeological remains are also found to the East on a possible ancient ditch, in the western part of the plateau, also indicate Etruscan presence. The latter is attested to by covered architectural remains (see h and g in figure 2) adjacent to previously documented wells and cisterns dating back to the sixth century BC (Boethius et al 1962). San Giovenale is surrounded
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Figure 2. Aerial photograph of San Giovenale and its surroundings in 1960 (taken by the Italian Airforce in 1960; courtesy: Swedish Institute of Classical Studies in Rome). Aerial photos from historical archives have been valuable in identifying early shafts and trial soundings on Vignale—later compared to data obtained at the site from the more recent remote sensing techniques.

by several necropoleis such as Porzarago and Casale Vignale (figure 2), which indicate the periods of the habitation remains.

The main archaeological finding was an Etruscan bridge with stone abutments on either side of the Pietrisco brook, unearthed and investigated in 1959–63 (Forsberg and Thomasson 1984). This feature was the starting point of the entire investigation of the Vignale plateau aiming to further the understanding of the connection between the main plateaus of the San Giovenale area. An analysis of the bridge complex and the results from further investigations carried out by the team in 1999 was studied in a doctoral thesis by Backe-Forsberg (2005).

These investigations and the results from field surveys in 2006 urged the necessity to expand knowledge of the Etruscan presence on the Vignale plateau. Therefore, the Vignale archaeological project (VAP) was founded in 2006 with the aim of studying the available archaeological record and to acquire new information using different remote sensing techniques. For this reason, since 2007, the two institutes IMAA and IBAM of the Italian CNR have been involved in the VAP by the Swedish Institute of Classic Studies in Rome.

The intentions of the Swedish–Italian scientific research project are to answer several questions amongst which appear the following: (1) What was the function of this direct connection between the main acropolis and the Vignale plateau?—if it were direct at all? (2) What was the extension and importance of a presumed habitation site on Vignale? (3) Could the archaeological pattern of San Giovenale be a model for understanding Vignale itself?

In this paper we try to address some of these questions by investigating three selected test sites TS1, TS2 and TS3 (figure 3).

TS1 is a wooded area located on the northern slope of the Vignale plateau facing the monumental Etruscan bridge. This was a good starting point for understanding any connection between the bridge and TS2. The latter constitutes the western part of the Vignale plateau where trenches and field survey campaigns suggest a habitation site.

TS3 is located on the eastern part of the Vignale hill (figure 3), partly known as the necropolis of Fosso del Pietrisco, where three pozzi-tombs from c. 700 BC were excavated in the 1960s (Gierow 1969). All the selected test sites, many hidden under the vegetation cover, may be helpful in understanding the correlation between the test sites themselves.

3. Remote sensing data set and methodologies

3.1. Satellite data set and data processing

In the last decade, VHR commercial satellite data, such as IKONOS (1999) and QuickBird (2001), have become widely
used data sets for archaeological applications. A number of archaeological investigations profitably adopted them to carry out analyses and to detect unknown features/sites, etc (see Lasaponara and Masini 2011 and references therein).

VHR satellites offer data acquired by both panchromatic and multispectral sensors with a current spatial resolution less than 0.5 m (GeoEye). The satellites provide good stereo geometry and a high time revisit frequency of 1–3.5 days depending on latitude.

The data processing chain was mainly based on (i) pansharpening, (ii) convolution filtering and (iii) geo-statistics.

Pansharpening enables us to merge the higher spectral information content of multispectral channels with the higher spatial detail of panchromatic pictures.

To further enhance edges of both surface and subsurface archaeological features, some convolution filters, including high pass, Laplacian, directional, Gaussian high pass and Sobel and Robert filters, have been used (for additional information on spatial filtering, see Lasaponara and Masini 2012).

The use of convolution filters highlights geometric spatial detail in a digital scene linked to changes in brightness values which are generally influenced by the surrounding pixels. The use of filtering determines variations in the geometric detail at both local (contextual) and global (whole image) levels in the perception of the information content.

A further approach adopted for Vignale to extract information content from the digital image is the spatial analyses, which enable us to capture features, patterns and trends using distance and spatial relationships, in particular: (i) measuring the interdependence of brightness values, (ii) quantifying spatial distribution and (iii) describing spatial clustering or random distribution of features. The spatial autocorrelation statistics measure the degree of dependence among pixels, considering their similarity and their distance relationships. The output is a new image, which contains a measure of autocorrelation for each pixel produced by computing global and local indicators. Global indicators measure, with one summarizing value, if and how much the data set is autocorrelated. Local indicators inform us about pixel clusterization, by measuring the amount of homogeneous features inside the given window.

In this study, we used three local indicators: Moran’s I (Anselin 1995), Geary’s C (Cliff and Ord 1981) and Getis–Ord Gi (Illian et al 2008). The local Moran’s I identifies clustering, Getis and Ord’s Gi extracts hotspots and finally, the local Geary’s C detects areas of dissimilarity between pixels.

3.2. Multisensor aerial prospection from the ultralight plane

In the framework of the VAP, an investment in an ultralight plane was considered very effective to gain complementary visual and photographic information from the air in different seasons and illumination conditions. The hiring of any flying vehicle, including pilot, is a costly venture. But, by having the archaeologists fly their own machine, we could exclude this service (pilot and archaeologist, Richard Holmgren, figure 4, left).

The ultralight plane is a DTA-combo version, able to start and land from the fields nearby. Equipped with two seats and stripped of all its side sections, the photographer in the back seat had a clear photographing view in using three various types of digital cameras: (i) conventional, (ii) near infrared and (iii) thermo-camera. The use of traditional aerial photography for archaeological investigation is well known and documented. In
this study, coupled with the traditional aerial photography, we also used NIR and thermo-cameras, for the reason explained below.

Since the NIR spectral band enhances changes in the chlorophyll reflectance, we expected that NIR photography should enable us to detect anomalies and any other notable cultural patterns in the low vegetation, such as crop or herbaceous cover. However, mostly the NIR images were used as an intermediate analysing tool between conventional photography and thermal image. Since aerial colour and monochromatic photography do not reveal any hidden feature, but thermal photography does, the NIR images pinpointed a match between the visible landscape and the more abstract and low-resolution thermal imagery. NIR scenes have been elaborated using geo-statistics and convolution filtering as have been the satellite pictures, as described in section 3.1, to enhance the subtle spectral/spatial features of potential archaeological remains.

The thermo-camera provides a thermal map showing warmer or colder regions depending on the surface type and is affected by the presence and discontinuity of structures hidden beneath.

Features such as masonry or wells would be characterized by temperature variations resulting in a measurable value (increasing or decreasing) depending on target emissivity and acquisition time (early morning or late afternoon).

The interpretation of thermographic maps depends on the radiation wavelength, temperature and characteristic of surface properties (emission, reflection and absorption components). In order to perform thermal data analysis, the primary component to be taken into account is the emissivity, which is dependent on surface temperature. To improve the analysis, the reflection component should be minimized as much as possible. In the current survey, to minimize the reflected components and maximize thermal emission, the flight survey of May 2007 was taken close to sunset, thus facilitating the identification of potential hidden archaeological remains.

Data processing for the whole optical data set including NIR and thermo pictures was performed using filtering and geospatial statistical analyses as for the satellite data and described in section 3.1.

3.3. Aerial LiDAR and data processing

Aerial LiDAR is an active remote sensing technique that provides direct range measurements between a laser scanner and Earth’s topography, mapped into 3D cloud points.

There are two different types of scanner: (i) conventional scanners, which detect a representative trigger signal for each laser beam; (ii) full waveform (FW), which digitizes the complete waveform of each backscattered pulse.

In the presence of micro-relief, the use of airborne laser scanning (ALS) is more suitable than optical data to identify and map traces of past human activities, even under vegetation cover. Recently, this technology has been successfully used in archaeology within a number of applications ranging from geology, urban, vegetation and water (see for example Doneus et al. 2008, Gallagher and Josephs 2008, Lasaponara et al. 2011, Masini et al. 2011 and references therein). Using ALS, both anthropogenic (including railways, electrical cables, etc) and natural targets can be captured and monitored even if the large volume of high density LiDAR data makes analysis and interpretation difficult.

All the possible applications of LiDAR in archaeology imply and require the extraction of a very accurate DTM from which it is also possible to detect micro-relief linked to outcrop archaeological features for both bare and densely vegetated areas. To this aim, it is crucial to carry out a reliable processing of cloud points to discriminate between terrain and off-terrain points/objects by applying reliable filtering methods.

In the Vignale area, we adopted the progressive triangulation irregular network densification method by Axelsing (2000), which is also embedded in Terrasolid’s Terrascan commercial software (http://www.terrasolid.fi/en/products/terrascan). The discrimination of vegetation from soil, carried out in order to obtain the DTM, was performed using a classification procedure already applied by the same authors in previous papers (see for example Lasaponara et al. 2011).
and Masini 2009). This is a fundamental step of LiDAR data processing, which is regarded as the most complex for archaeological investigation which requires a high-quality DTM. This imposes a detailed and reliable separation of terrain and off-terrain points while maintaining a high point density. The separation of terrain and off-terrain points, generally called classification, can be obtained using (i) height (obtained from the 3D point clouds); (ii) intensity; (iii) RGB colours (if available); (iv) and echo width. Herein, the analysis was carried out using both height and orthophoto acquired at the same time as ALS survey.

To analyse and interpret the DTM in order to extract micro-relief of cultural interest, further data manipulations such as hill shading and principal component analysis (PCA) are required.

Hill shading enhances elevation values as shaded relief using loaded elevations by lighting the DTM with a hypothetical light source (Masini et al 2011). The selection of the direction parameters (zenith and azimuth angles) depends on the difference in height and orientation of archaeological micro-relief. Single shading is not the most effective method to visualize and detect micro-relief. If features and/or objects are parallel to the azimuth angle, they will not create a shadow and as a result it would not be possible to distinguish them. The problem could be solved by observing and comparing DTM scenes and shading them by using different angles of lighting. To capture the key meaningful features, the visual analysis of multiple shading maps can be improved by statistical enhancement using PCA, as for example in Masini et al (2011). The PCA is a linear transformation which decorrelates multivariate data by translating and/or rotating the axes of the original feature space, so that the data can be represented without correlation in a new component space (see figure 11).

In order to do this, it is first computed: (i) the covariance matrix ($S$) among all input spectral bands, then (ii) eigenvalues and eigenvectors of $S$ in order to obtain the new feature components.

The PCA transforms the input multispectral bands into new components that should be able to make the identification of distinct features and surface types easier. This is a direct result of two facts: (i) the high correlation existing among channels for areas that do not change significantly over the space; and (ii) the expected low correlation associated with higher presence of noise.

The major portion of the variance in a multispectral data set is associated with homogeneous areas, whereas localized surface anomalies will be enhanced in later components. In particular, each successive component contains less of the total data set variance. In other words, the first component contains the major portion of the variance, whereas later components contain a very low proportion of the total data set variance. Thus, they may represent information for a small area or essentially disregarded as noise.

### 4. Results

#### 4.1. Results from satellite data

The satellite images used for this study were acquired by QuickBird (catalogue no. 90100100132D8200) on 12 July 2003, at around 9:52 am with an off nadir view of 1.44.

Satellite data provide a global overview and a useful landscape perspective. As an example, figure 5 shows transformation of the landscape occurred from 1961 to 2010, using a 3D visualization to facilitate the data interpretation. In particular, figure 5(a) shows the DTM derived from 2010 LiDAR survey; figures 5(b)–(d) display the 1961 aerial photo, 2003 QuickBird false colour composite and 2010 aerial photo, respectively, in 3D visualization obtained draping optical pictures over the DTM (derived from LiDAR survey).

Regarding the specific test areas, we only focus on TS2 test site characterized by the presence of sparse vegetation because both TS1 and TS3 are covered by trees and dense vegetation and, therefore, optical and thermal data could not provide any information regarding features under canopy. The TS2 test site was selected because it is characterized by the presence of wells already surveyed on the site during the 2007 field survey (Backe Forsberg et al 2008). Figure 6(a) shows test site TS2 observed through a QuickBird panchromatic image.

The satellite data were processed as described in section 3.1 to enhance the subtle spectral/spatial features of potential archaeological remains. The best results in terms of edge enhancement were obtained by using the geo-statistic analyses based on both global and local spatial autocorrelation indices. Each local index and its relative result emphasize a particular information content. To facilitate the data interpretation, we visualized them all together, using the RGB composition as shown in figure 6(b), such as (i) R: Moran, (ii) Geary and (iii) B: Geary. Satellite pictures emphasize the presence of linear anomalies (indicated by red arrows in figures 6(a) and (b)) and also show (figures 6(a) and (b)) a number of punctiform anomalies, which are more emphasized using geospatial statistics (figure 6(b)). These anomalies are related to wells, some of which perfectly matched with already studied wells and features. All the identified anomalies have been confirmed by aerial survey and ground truth. Satellite data processing, herein described, enabled us to detect nine wells previously unknown. As a whole, the wells follow a linear pattern oriented in N-S, E-W directions. This is very important and may suggest an ancient plan of potential buried habitations. Moreover, these wells are located in an area characterized by dense remains of building debris and Shards. Finally, an oblique linear anomaly (indicated by red arrows in figure 6(b)) was also identified and it may be related to a long defensive/transhumance wall, running in N-S, E-W directions of the Vignale plateau.

#### 4.2. Results from NIR photography

NIR photography (wave lengths ranging from 700 to 900 nm) was utilized in using an ordinary digital single-lens reflex camera modified for this specific purpose. The hot mirror
Figure 5. The transformation of the landscape from 1961 to 2010. (a) DTM derived from 2010 LiDAR survey. (b)–(d) 3D visualization obtained by DTM derived from LiDAR survey of 1961 aerial photo, 2003 QuickBird false colour composite, and 2010 aerial photo, respectively.

filter in front of the sensor that blocks the infrared part of the spectrum was removed and replaced with an infrared filter. This gives much faster exposures, which is essential in an often unsteady and small plane. The images were taken parallel to the conventional aerial colour and b/w photos shot over the area.
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Figure 6. Test site TS2 observed from (a) QuickBird panchromatic image and (b) RGB composition of Moran, Geary and Getis indices. White arrows indicate punctual anomalies related to wells, whereas red arrows indicate linear and areal anomalies corresponding to the depression further confirmed, measured and visualized by DTM derived from LiDAR survey.

Figure 7. Test site TS2 observed from (a) NIR image captured from ultralight plane and (b) the resulting RGB composition (R = NIR image; G = results of Moran index; B = product of convolution directional filtering). Red and yellow arrows indicate punctual anomalies related to wells: most of them are visible from VHR satellite images.

To enhance the subtle spectral/spatial features of potential archaeological remains, NIR scenes were elaborated using geo-statistics and convolution filtering as described in section 3.1 for the satellite pictures. The best results in terms of edge enhancement were obtained by using both spatial autocorrelation and convolution directional filter angle. The latter was based on the first derivative that selectively enhances image features having specific directional components (gradients). Each data processing method and relative result emphasize a particular information content. In order to visualize them all together, we used the RGB composition, such as (i) R: convolution filtered picture, (ii) G: product of spatial autocorrelation and (iii) B: the satellite panchromatic scene.

Figure 7 shows test site TS2 observed from NIR image (figure 7(a)) captured from ultralight plane and the result from the RGB (figure 7(b)) composition (R = NIR image; G = results of Moran index; B = product of convolution directional filtering). Red and yellow arrows indicate punctual anomalies related to 13 wells: most of them (9) are also visible from VHR satellite images. In pinpointing the most distinctive of these wells, the distance between these features suggests a distribution resembling that of a habitation area such as those found on the main acropolis in San Giovenale (Karlsson 2006, Pohl 2009, 2011, 2012 forthcoming). Scattered debris in the area suggests a settlement through at least three centuries starting from the sixth century BC.
μ is naturally emitted from a body in the thermal infrared field. IRT is a technique that allows us to estimate the energy that is naturally emitted from a body in the thermal infrared field (between 4 and 20 μm) when its temperature is greater than 0 °C.

In Vignale the thermal pictures were taken from the ultralight plane by using a thermo-camera AVIO TVS 600 microbolometric. It works in the electromagnetic spectrum, between 8 and 14 μm, and is equipped with a 35 mm lens. The resolution is 1.4 mrad. The camera provides a thermal mapping that in our case was used primarily over the flat areas of the Vignale plateau. The latter delivered an even surface where the distribution of thermal radiation was without any interference by shadows and geological features that could disturb the layout.

The anomalies obtained for TS2 were also captured by thermographic images. Results from thermal images are shown in Figure 8. The thermal anomalies enable us to identify a higher number of possible wells, which well fits with those previously obtained from both satellite (9) and aerial NIR pictures (13). The layout of the additional wells detected only using the IRT pictures further confirms the hypothesis of potential buried habitation, distributed over the entire western point of the plateau (Backe-Forsberg et al. 2008). In sum, for test site TS2, all the remote sensing data sets indicate the presence of wells whose spatial pattern may suggest a layout related to a potential buried habitation site.

TS3 site, related to a necropolis in Fosso del Pietrisco, has been investigated using both digital models derived from LiDAR and IRT images. Figure 9 shows test site TS3 (necropolis of Fosso Pietrisco) as obtained from aerial photo taken in 2010 (figure 9(a)); digital surface model (DSM) and DTM derived from 2010 LiDAR survey (figures 9(b) and (c), respectively) and thermal infrared picture taken in June 2007 (figure 9(d)).

In IRT image (figure 9(d)), circular thermal anomalies mark the positions of tombs. There are around 60 as confirmed by in situ analyses. Each spatial anomaly refers to multiple tombs, these being overlapped with each other. In this specific case, it is not the buried stone construction beneath that affects a heated soil layer above. It is rather the slight concave edges of the now sunken and compacted space beneath, which gets heated at a particular angle—leaving a semicircular warmer area.

4.4. Results from aerial LiDAR

On Vignale, the LiDAR survey was carried out by GEOCART s.r.l. in September 2010, over an area of around 6 sq km by using a FW scanner, the RIEGL LMS-Q560, on board a helicopter. The scanner acquired data in South–North and East–West directions, with a divergence of the radius of 0.5 mrad and a pulse repetition rate at 180.000 Hz. The average point density value of all the data sets is about 20 points m⁻². The accuracy is 25 cm in xy and 10 cm in z (altitude).

In order to emphasize archaeological features with particular reference to micro-relief in TS1 and TS3, we adopted shading procedures. We employed routines embedded in the ENVI and Global Mapper software to visualize elevations and slopes by using colour graduations.

Single shading is not the most effective method to visualize and detect micro-relief and therefore we used different angles of lighting and compared the different DTMs scenes. In addition, all the shaded DTM scenes were further processed by using the PCA (Masini et al. 2011) and convolution-filtering techniques (Laplacian, directional, Gaussian high pass) to emphasize the key meaningful features.

TS1 test site is characterized by the presence of dense vegetation and therefore optical or thermal data could not provide any useful information regarding potential features under the canopy. Therefore, for this area we only focused on the results obtained from LiDAR elaborations, which are shown in figure 10 as both DSM and DTM.

The DSM (figure 10(a)) provides the model of the surface including vegetation, whereas the DTM (figure 10(b)) is obtained by filtering the wood cover. The DTM allowed us to identify and map an Etruscan road on the northern slope (figure 10(b)). This was an important archaeological discovery. The road, well depicted in figure 10(c), clearly showed a connection between the Vignale plateau and the main acropolis as well as with the surrounding burial grounds. Moreover, an alternative route, connecting the Vignale plateau with the northern side of the Fosso del Pietrisco, has also been discovered further west of the bridge. These findings are very important, because previous assumptions did not show any clear connection to the western part of the Vignale plateau. Since detailed chronological data already exist on the different phases of the bridge complex (Backe-Forsberg 2005), a sequential route adjacent to the bridge delivers valuable information on the dating of infrastructure in relation to habitation remains in San Giovenale.

To emphasize archaeological features, linked to micro-relief, shading procedures and PCA were used, as shown in figure 11. Therein, hill shading procedures applied to the DTM of TS3 (necropolis of Fosso Pietrisco) are displayed for the following lighting angles: (figure 11(a)) zenith = 45°, azimuth = 0°; (figure 11(b)) zenith = 45°, azimuth = 90°;
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Figure 9. Test site TS3 (necropolis of Fosso Pietrisco): (a) aerial photo taken in 2010; (b), (c) DSM and DTM derived from 2010 LiDAR survey; (d) thermal infrared picture taken in June 2007.

Finally, regarding the TS3 site (a necropolis in Fosso del Pietrisco), the hill shading approach used for DTMs allowed us to identify and map the micro-relief related to the tombs previously discovered using IRT (see figure 9).

5. Discussion

In this study we investigated the Vignale plateau in San Giovenale (Blera). The selected area is particularly interesting from an historical and archaeological point of view, because of its long human frequentation, with particular reference to the presence of the Etruscan civilization from the sixth century BC onwards.
Figure 10. Digital models derived from LiDAR survey. The filtering of vegetation allowed us to identify and map a road connecting Vignale to the main acropolis by a bridge. (a) DSM of the plateau with the northern wooded slope of Vignale; (b) DTM; (c) 3D visualization of DTM. X-X' is the transversal section of the hill side road; Y-Y' is the section on TS2 test site thus revealing a difference in height which could divide the western part of the Vignale plateau into two different zones. Arrows in figure 7(b) denote a linear anomaly with potential cultural interest.
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Figure 11. Hill shading procedures applied to DTM of TS3 (necropolis of Fosso Pietrisco) with the following angles of lighting: (a) zenith = 45°, azimuth = 0°; (b) zenith = 45°, azimuth = 90°; (c) zenith = 45°, azimuth = 180°; (d) zenith = 45°, azimuth = 270°.

Satellite, aerial LiDAR, NIR and IRT images acquired from an ultralight plane, along with historical photos, field surveys and ancillary information were combined to improve the current knowledge of the study area. The synergetic use of diverse remote sensing technologies was necessary and planned in order to conduct investigations in both densely and sparsely vegetated areas.

In particular, the VHR satellite imagery allowed us to analyse and identify potential features of archaeological interest for test site 2 (TS2) providing geo-referenced maps to locate ancient remains in a landscape prospective. In combining a range of digital photographic techniques such as thermo, near infrared and conventional photographs, an ultralight plane was used for the higher resolution they offer in both spatial and spectral domains. Finally, a LiDAR survey, conducted using a full-wave form scanner, was carried out to overcome the limits of optical imagery mainly due to the presence of dense vegetation that entirely covers the slopes surrounding the Vignale plateau. Moreover, the very high spatial resolution of DTMs, produced by the LiDAR survey, allowed us to better explore the available data set acquired from 1961 to 2010 in a 3D view.

The archaeological features were detected in both densely and sparsely vegetated areas, thus revealing a large variety of cultural transformations, ritual and infrastructural remains such as roads, tombs and water installations.

In more detail, satellite data enabled us to detect nine punctiform anomalies related to wells, as verified by ground truth. The above said anomalies are more emphasized using geospatial statistics. NIR and IRT serial images enabled us
to identify a higher number of anomalies related to wells, respectively, 13 from NIR and 20 from IRT.

As a whole, the wells follow a linear pattern oriented in N-S, E-W directions. This is very important and may suggest an ancient plan of potential buried habitations. Moreover, these wells are located in an area characterized by dense remains of building debris and shards. Finally, an oblique linear anomaly was also identified and confirmed by further analysis based on aerial data sets. These anomalies may be related to a long defensive/transhumance wall, running in N-S, E-W directions of the Vignale plateau.

Aerial photos acquired in IRT allowed us to discover a number of anomalies identified as tombs of Villanovan period, thus improving the current knowledge about the insulated necropoleis such as Fosso del Pietrisco on the eastern part of the Vignale hill.

LiDAR survey allowed us to provide the DSM of the necropoleis characterized by the presence of a complex pattern due to overlapped tombs.

The extended discovery of the Villanovan tombs is of utmost importance in the understanding of uncovered habitation remains of this period.

Moreover, data processing and analyses of the DTM obtained from LiDAR highlight the presence of traces and ancient remains under canopy (see figure 10). A road connecting the Vignale plateau and the main acropolis were detected and mapped. Moreover, an alternative route, connecting the Vignale plateau with the northern side of the Fosso del Pietrisco, has been also discovered further west of the bridge. These findings are very important because previous assumptions did not show any clear connection to the western part of this plateau.

6. Conclusions

This paper describes a synergetic application of satellite remote sensing, aerial LiDAR, NIR and IRT image acquired from an ultralight plane, historical photos, field surveys and ancillary information used for investigating the Vignale plateau in San Giovenale (Blera). The study area is characterized by complex morphological features and the presence of vegetation from sparsely spontaneous herbaceous to wood close canopy.

The ancient human presence and frequetation, recorded over the centuries in this area, causes the presence of diverse archaeological marks ranging from micro-relief, linked to shallow surface remains, to crop and soil marks for buried settlements. The complexity of vegetation cover types and morphological features imposed the synergetic use of both active and passive sensors, which enabled us to detect archaeological features in both densely and sparsely vegetated areas. The feature patterns of archaeological interest have revealed a large variety of cultural transformations of the investigated area with ritual and infrastructural remains such as roads, tombs and wells, which indicate the presence of necropolis and habitation areas.

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