ELSEVIER

Journal of Archaeological Science 34 (2007) 214–221

Journal of Archaeological SCIENCE

http://www.elsevier.com/locate/jas

Detection of archaeological crop marks by using satellite QuickBird multispectral imagery

Rosa Lasaponara [a,*], Nicola Masini [b,1]

[a] *Istituto di Metodologie per l'Analisi Ambientale, IMAA-CNR, C.da S.Loja – 85050 Tito Sc. (PZ), Italy*
[b] *Istituto Beni Archeologici e Monumentali, IBAM-CNR, Sezione di Potenza, Via Federico II, 85020 Lagopesole (PZ), Italy*

Received 4 January 2006; received in revised form 31 March 2006; accepted 21 April 2006

Abstract

The capability of satellite QuickBird imagery for the identification of archaeological crop marks is herein presented and discussed for two test sites located in the South of Italy. The selected sites, dating back to Middle Ages, were buried under surfaces covered by herbaceous plants characterized by a different phenological status (dry/green) when the satellite data were acquired.

The methodological approach adopted for the enhancement and extraction of crop marks is mainly based on the use of data fusion and edge detection algorithm. The main remarkable differences found for the two archaeological sites can be suitably linked to the different state of vegetation that caused a different spectral response. In particular, near infrared (NIR) spectral channel was able to better enhance crop marks observed for dry vegetation; whereas, Normalized Difference Vegetation Index (NDVI) was found to be more capable to better enhance crop marks observed for green vegetation.

Keywords: Aerial archaeology; Satellite remote sensing; Crop marks; NDVI; QuickBird; Multispectral imagery

1. Introduction

During the last century, aerial photos have been the most common remote sensing data source used in the field of archaeological investigations. Both oblique and vertical aerial photography have been used extensively for the identification of marks linked to the presence of buried archaeological remains [4–7,26]. The different marks are generally known as soil, shadow and crop marks. Their characteristics strongly depend on vegetation cover and/or soil types. As an example, soil marks can appear as changes of color or texture; whereas shadow marks can be seen in the presence of micro-topographic relief variations that can be made visible by shadowing in low sunlight angle conditions. For crop areas, soil and moisture changes within near-surface archaeological deposits can influence surface vegetation patterns creating marks of various kinds. They can appear as differences of height or color in crops which are under stress due to lack of water or deficiencies in other nutrients. Crop marks can be formed both as negative marks above wall foundations and as positive marks above damp and nutritious soil of buried pits and ditches [7,26].

Crop and soil marks are more difficult to detect with certainty on the basis of aerial photography [8]. In particular, the visibility of crop marks often depends on many factors, such as, vegetation type and status, soil conditions, sun-sensor geometry and film sensitivity. So, it is really difficult to obtain photographs taken under optimal conditions. Satellite multispectral data can address some of these problems. In fact, satellite sensors provide information at a wide range of different wavelengths, many of which are more sensitive to vegetation status and soil compositions [1,10]. Nevertheless, the low spatial resolution of early satellite sensors, such as Landsat Tematic Mapper (30 m), pancromathic Spot (10 m), ASTER (from 15 m for VNIR channels to 90 m of thermal channels) did not provide sufficient

---

* Corresponding author. Tel.: +39 0971 427 214; fax: +39 0971 427 217.
E-mail addresses: lasaponara@imaa.cnr.it (R. Lasaponara), n.masini@ibam.cnr.it (N. Masini).

[1] Tel.: +39 0971 865918; fax: +39 0971 865947.

0305-4403/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2006.04.014

precision for the identification and inspection of archaeological sites. Thus, restricting the application of satellite imagery to paleogeographic environment studies [9,18,19,25] or to human ecology and landscape archaeology investigations [5,21,22].

The recent availability of Very High Resolution (VHR) satellite images, such as IKONOS (1999) and QuickBird (2001), may be able to furnish a valuable data source for archaeological investigations [13].

This paper presents and discusses the results obtained from the processing of satellite QuickBird imagery performed for two archaeological sites, dating back to Middle Ages, buried under surfaces covered by herbaceous plants characterized by a different status of the vegetation (dry/green) when the satellite data were acquired.

2. QuickBird satellite data

QuickBird offers panchromatic and multispectral imagery with the highest spatial resolution currently available within the satellite sensors. The QuickBird satellite has panchromatic and multispectral sensors with resolutions at 61–72 cm and 2.44–2.88 m, respectively, depending upon the off-nadir viewing angle (0–25°).

The sensor has a coverage of 16.5–19 km in the across-track direction. In addition, the along-track and across-track capabilities provide a good stereo geometry and a high revisit frequency of 1–3.5 days depending on latitude. The reader is referred to technical notes available on line at the web site http://www.digitalglobe.com/product/product_docs.shtml.

The panchromatic sensor collects information at the visible and near infrared wavelengths and has a bandwidth of 450–900 nm. The multispectral sensor acquires data in four spectral bands from blue to near infrared (NIR). Both panchromatic and multispectral sensors offer 11 bit (2,048 grey levels) resolution. The QuickBird imagery products are available at different processing levels (basic, standard, and ortho) serving the needs of different users.

The QuickBird data used for this study are listed in Table 1.

3. Rational basis and tools

3.1. Parameter selection

In order to experience the multispectral capability of QuickBird imagery for the identification of archaeological marks all the four bands (blue, green, red and near infrared) have to be considered. Of these four bands, the near infrared (NIR) should be the most useful for the detection of crop marks [10,11] as shown by Fig. 1, that draws the spectral signatures observed for three different status of a given type of vegetation. In particular, green and healthy plants tend to exhibit the spectral behaviour drawn by the green line. Whereas, vegetation under stress, due to lack of water or nutrient deficiencies, is generally characterized by different patterns depending on the level of disease. As an example, yellow and brown curves, drawn in the left part of Fig. 1, are related to stressed and severely stressed plants, respectively. The QuickBird Red and NIR bands are indicated by vertical red lines; thus, showing that the NIR offers a larger spectral separability than Red band. This should make the NIR band ideal for identifying archaeological crop marks linked to variations in vegetation growth and/or color in comparison to the surrounding area (see, right part of Fig. 1). Additionally, on the basis of remotely sensed data, crop marks may be suitably identified by exploiting vegetation indices that are spectral combinations of different bands. Such indices are quantitative measures, based on vegetation spectral properties, that attempt to measure biomass or vegetative vigor. Vegetation indices are mainly derived from reflectance data from the Red and near infrared (NIR) bands. They operate by contrasting intense chlorophyll pigment absorption in the red against the high reflectance of leaf mesophyll in the near infrared. The simplest form of vegetation index is the ratio between two digital values from the red and near infrared spectral bands. The most widely used index is the well-known Normalized Difference Vegetation Index (NDVI) obtained by using the following formula:

$$\mathrm{NDVI} = [\mathrm{NIR} - \mathrm{Red}]/[\mathrm{NIR} + \mathrm{Red}]$$

The normalization of the NDVI reduces the effects of variations caused by atmospheric contaminations. NDVI is indicative of plant photosynthetic activity and has been found to be related to the green leaf area index and the fraction of photosynthetically active radiation absorbed by vegetation. High (low) values of the vegetation index identify pixels covered by substantial proportions of healthy (disease or stressed) vegetation. It is expected that crop marks created by vegetation patterns should be emphasized by using NDVI.

Table 1
Image metadata of Iure Vetere and Irsi

Site	Iure Vetere	Irsi
Acquisition date	2004-06-11	2004-07-04
Acquisition time	9:38.49	9:45:06
Cloud cover	5%	2%
Catalog id	1010010003025A01	101001000313CA02
Pan resolution	0.64 m	0.61 m
Multi resolution	2.56 m	2.46 m
Environmental quality	70 – good	90 – excellent
Off-nadir	14°	0°

3.2. Satellite data processing

3.2.1. Data fusion

The idea underlying our analysis is that archaeological features could be enhanced and efficiently studied by exploiting the high spatial resolution of satellite QuickBird panchromatic data and the multispectral properties of the four spectral channels. The methodological approach (shown in Fig. 2) adopted for the enhancement and extraction of crop marks is mainly based on the use of data fusion and edge detection algorithms.

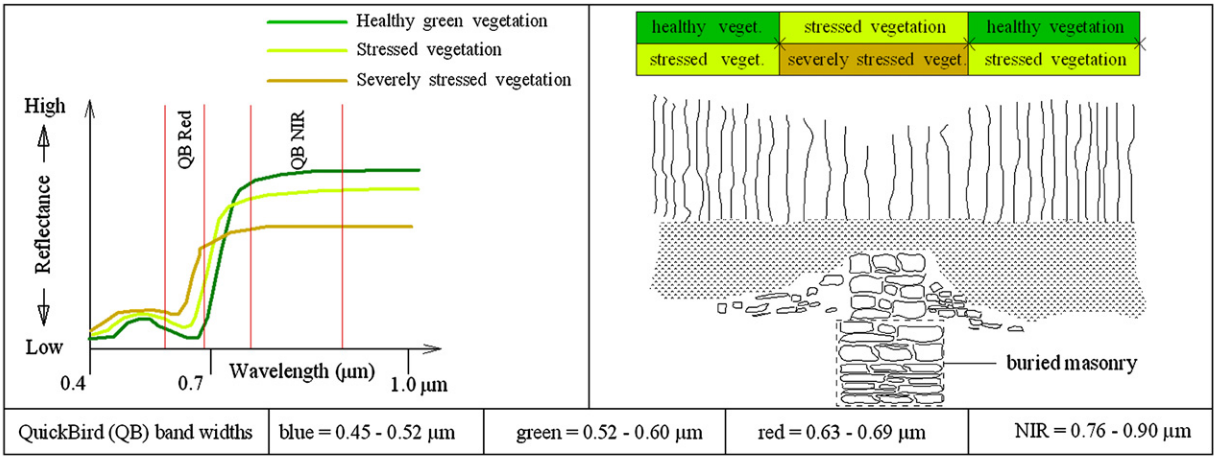

Fig. 1. On the left of the figure spectral reflectances observed for different status of a given vegetation type; red lines indicate QuickBird band widths for Red and NIR channels. On the right a detail of the typical crop marks caused by the presence of buried structures.

Data fusion refers the process of combining multiple images of a scene to obtain a single composite image. The different images to be fused can come from different sensors of the same basic type or they may come from different types of sensors. The composite image should contain a more useful description of the scene than provided by any of the individual source images. In the current cases under investigations the QuickBird panchromatic and multispectral images were fused by using a data fusion algorithm that was specifically developed for VHR satellite images [27]. This algorithm was adopted by Digital Globe [http://www.pcigeomatics.com/support_center/tech_papers/techpapers_main.php] and it is also available in a PCI-Geomatica routine.

3.2.2. Edge detection

In order to emphasize the marks arising from the presence of buried structures, an edge detection algorithm was applied to both QuickBird single images and data fusion products. Among the traditional edge detection procedures we selected a multiscale algorithm for its versatility and reliability [15,16]. The edge detection was performed by applying a multiscale approach based on the scale-space theory [14] that uses

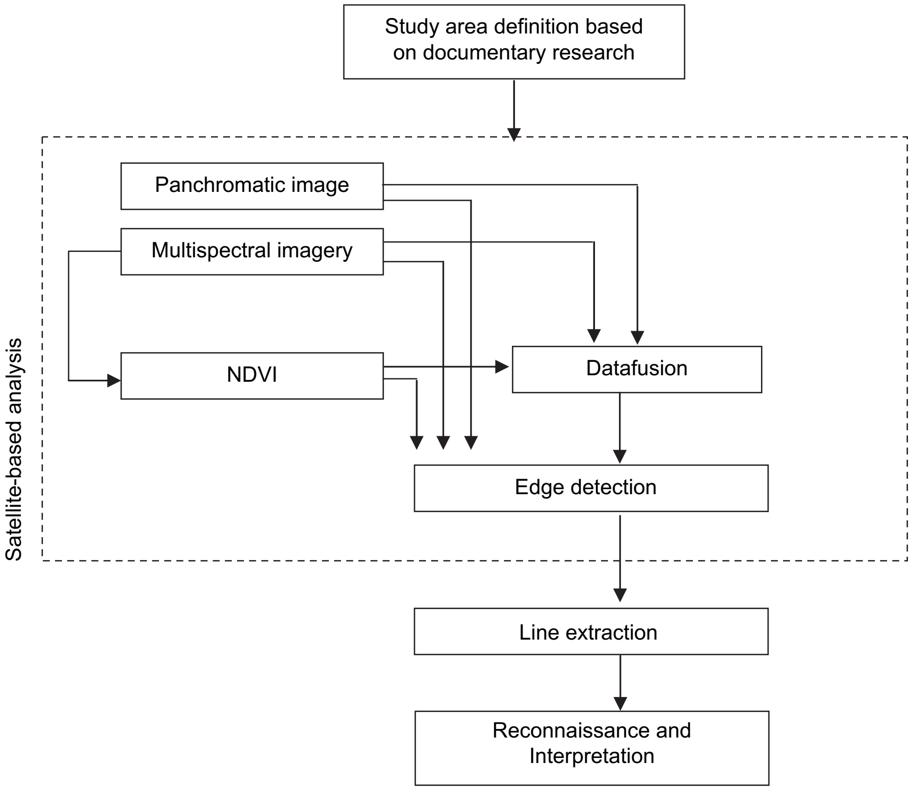

Fig. 2. Flow chart of the procedure adopted for the identification of archaeological marks.

Gaussian smoothing kernels. The selection of scale was performed by keeping in mind that, in our case it was necessary to focus on structures having small sizes and signal amplitudes as expected in the case of crop marks due to buried structures.

3.2.3. Line extraction

Using visual inspection, only features with regular patterns were considered. This choice was performed mainly because the presence of geometric features, being quite rare in nature, generally provides useful information for the identification of signs indicating ancient human activities.

Finally, the last step of the adopted procedure is the reconnaissance and interpretation of marks. This is a very important task that is performed also using ancillary information, such as the traditional cartography, field surveys, geophysical prospections, etc. This allows for eliminating or at least reducing the potential coarse errors linked to modern human activity, such as, the presence of road networks, bridges, pipeline, etc. that can be selected by the edge identification procedure.

4. Reconnaissance of archaeological crop marks: results and discussion

The investigations were performed for two archaeological sites, Monte Irsi and Iure Vetere, dating back to Middle Ages, located in the South of Italy (Fig. 3). These test sites are characterized by a different status of vegetation when the satellite data were acquired. For the first site (Monte Irsi) the vegetation cover was completely dry; whereas, for the second (Iure Vetere) the vegetation cover was green and healthy.

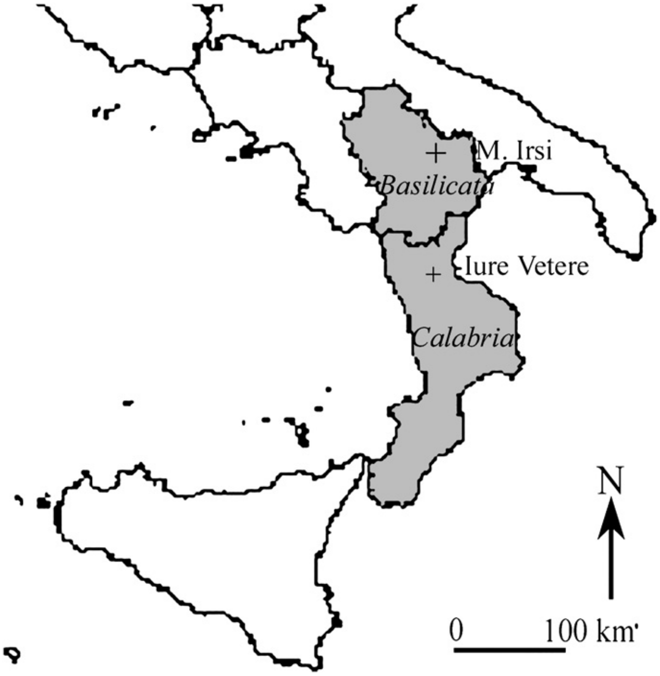

Fig. 3. Location in the Southern Italy of the two archaeological sites.

4.1. Monte Irsi study case

4.1.1. Study site description

The first test site is located close to the border between the Basilicata and Apulia Regions (see Fig. 3). Monte Irsi is a hilly plateau (Fig. 4a), near the confluence of the Bradano and Basentello rivers. The investigated area is characterized by the presence of vegetation made up of herbaceous plants that were dry when the satellite data were acquired.

The strategic location of Monte Irsi favored a long and intensive human activity from Paleolithic to Middle Ages, as testified by archaeological remains [23,24]. As regards the Middle Ages, documentary sources state the existence of a village (Yrsum) and a monastery [12]. The village achieved its maximum expansion between the 12th and 13th centuries and was abandoned in the 15th century, whereas the monastery was destroyed around 1370 [12].

Today, the only building preserved is a church belonging to the monastery (see letter a in Fig. 5). Archaeological remains referable to a roman villa (letter b in Fig. 5) are visible near to the church. At the highest part of the hill, a buried medieval settlement, built on preexistent structures dating back to the Late Iron Age, was found by Small [24]. Just the medieval settlement is the object of our investigation.

4.1.2. Satellite-based identification of crop marks

The reconnaissance of marks referable to buried structures was performed by analyzing the results obtained from the edge detection algorithm applied both to single channel and data fusion products.

The single channel processed at their own spatial resolution (2.80 m) did not allow to detect marks linked to buried remains. This fact was mainly due to their low spatial resolution. Better results were obtained from the processing of data fusion products (0.70 m). In particular, a small number of geometric features was visible from blue, green and red (Fig. 6c). Improved results were obtained from NDVI map (Fig. 6f). Nevertheless, a more detailed morphological reconstruction of the medieval buried remains was obtained from the processing of panchromatic image and NIR data fusion product (see Fig. 6b and f).

The fact that, in this case, the NIR channel is more capable than other spectral channels to better enhance the surface anomalies is mainly due to the sensitiveness of the NIR band to the vegetation status. In fact, vegetation reflectance is a function of a number of bio-parameters such as density, height, biomass, leaf area, chlorophyll, water content, etc. Variations in plant parameters cause reflectance spectra changes. Stress factors, such as lack of nutrient and/or water, cause significant variations of plant reflectance [17] because of their affect on chlorophyll content, biomass amount, etc. Shortage of nutrition and/or water causes an immediate change in both leave signatures and vegetation structure. In particular, variations in vegetation water content further influence the overall heights of response curves beyond the chlorophyll absorption band at 0.65 μm [2]. Therefore, on the basis of QuickBird spectral channels, the crop marks observed in presence of dry vegetation are strongly enhanced by the NIR spectral band.

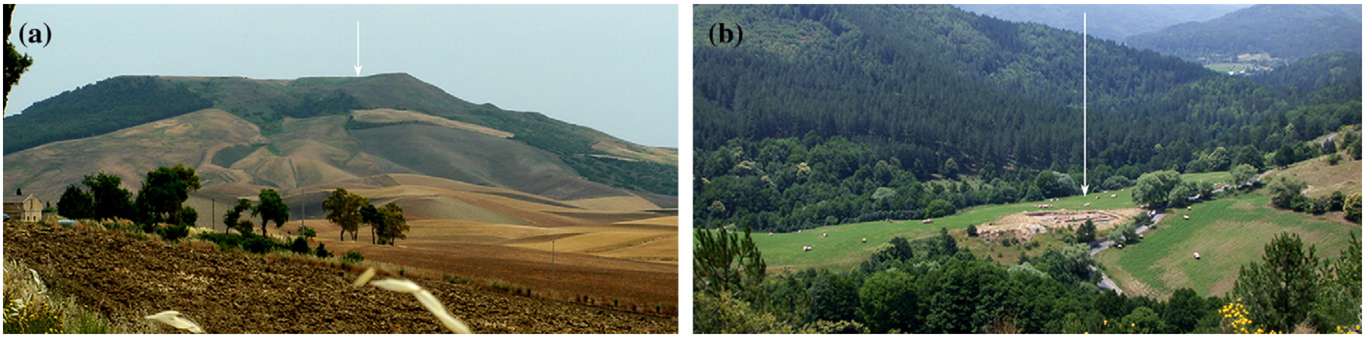

Fig. 4. Panoramic views of Monte Irsi (a) and Iure Vetere (b). The arrows indicate the location of the study areas.

4.2. Iure Vetere study case

4.2.1. Study site description

The site is Iure Vetere where the first monastery of Florense Order was founded by Gioacchino da Fiore at the end of the 12th century. It is located on the ridge of a hilly plateau that faces the watershed between the basins of the Arco river and its affluent, in the Sila territory (Calabria Region) (see Figs. 3 and 4b). The archaeological area is characterized by the presence of vegetation composed of dense herbaceous plants that were green and healthy when the satellite data were acquired. From a geological point of view Iure Vetere is within the Monte Garigliano unit made up of igneous rocks, such as graniodiorites and magmatites. The soils are mainly composed of siliceous sands, products of the chemical and mechanical alteration of acid igneous rocks, with a minor part of clays made up of kaolins and vermiculites [20].

Before starting archaeological excavations (2002–2004) preliminary investigations based on aerial photos (1998–1999) and geophysical prospections (1999) were performed [19]. The results obtained allowed the identification of the highest probable location of buried remains.

Such results were confirmed by the excavation campaigns that unearthed a large structure related to a church; but the location of the rest of the medieval monastery was still unknown. For this reason, the archaeologists enlarged the study area to the whole plateau. This coupled with the physical characteristics of the area suggested the integration of the aerial photo data set with VHR and multispectral satellite imagery such as QuickBird.

4.2.2. Satellite-based identification of crop marks

The reconnaissance of crop marks was performed by analyzing the results obtained from the edge detection algorithm applied both to single channel and data fusion products.

Fig. 7a–f show the QuickBird imagery for the investigated area. A visual inspection of Fig. 7a–c, e) puts in evidence the presence of potential anomalies in the south part of the area. Such anomalies are more visible in the NIR (Fig. 7b) and NDVI (Fig. 7c, e) than panchromatic (Fig. 7a). Blue, green and red spectral channels are not shown because they did not exhibit any visible marks.

The processing of NDVI map showed the presence of crop marks having a rectilinear morphology (Fig. 7d) that compose a quadrangular shape of about 45 × 100 m. These features could be referable to underlying remains of the monastery as expected by the archaeologists [19].

In this case, the results obtained from the edge detection extraction applied to data fusion products (Fig. 7f) substantially agree with those found from the NDVI map at 2.80 m spatial resolution (Fig. 7d). The main advantage of using data fusion products was the increased spatial resolution that provided a more accurate localization of the crop marks. This was very helpful during the last geophysical prospection campaign (July 2005) which confirmed the presence of the linear features detected by using QuickBird data [3].

The capability of QuickBird NDVI to better enhance spatial anomalies for surfaces covered by green and healthy herbaceous plants is due to the fact that the NDVI is related to plant photosynthetic activity and to the green leaf area index. In Iure Vetere case, crop marks are highly visible in the NDVI map due to differential growth patterns caused by underlying archaeological deposits that tend to impede stunt or delay growth of vegetation. A growing plant lacking certain nutrients tends to produce less chlorophyll so causing decreases in NDVI values.

5. Final remarks

Satellite QuickBird imagery were used in order to assess their capability to detect crop marks. The analyses were

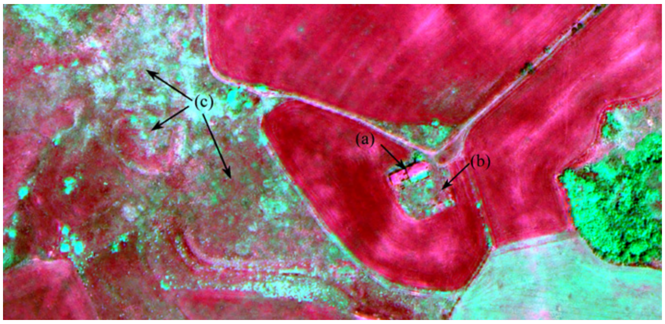

Fig. 5. Monte Irsi QuickBird RGB (R = red data fusion; G = NIR data fusion; B = panchromatic). Letters (a)–(c) denote the location of the church (a), archaeological remains of a roman villa (b), and the medieval settlement (c).

performed for two test cases, dating back to Middle Ages, buried under surfaces characterized by a different status of vegetation (dry/green) when the satellite data were acquired. Results from our investigations showed that the multispectral VHR satellite data provide valuable information for vegetated areas, where the use of aerial photos can be limited since the visibility of crop marks strongly depends on many factors such as, vegetation type and status, soil conditions, sun-sensor geometry and film sensitivity. So, it is really difficult to obtain photographs taken under optimal conditions. Satellite multispectral data can address some of these problems.

One of the main advantages of VHR satellite is the possibility of combining multispectral and pancromathic data to achieve improved accuracies and better inference about the surface characteristics of the single sensor. In particular, the data fusion allows the enhancement of spatial anomalies linked to the presence of archaeological marks; thus, making their recognition and extraction easier.

Compared to aerial photo the QuickBird imagery can be promptly geo-referenced and offer a very large coverage. This makes them ideal for investigations on regional scale as well as for researches performed in areas where aerial photography is restricted because of military or political reasons.

Nevertheless, there are also some considerable drawbacks. Although, the use of data fusion allowed the identification of features with the spatial detail of pancromathic (0.6 m) instead

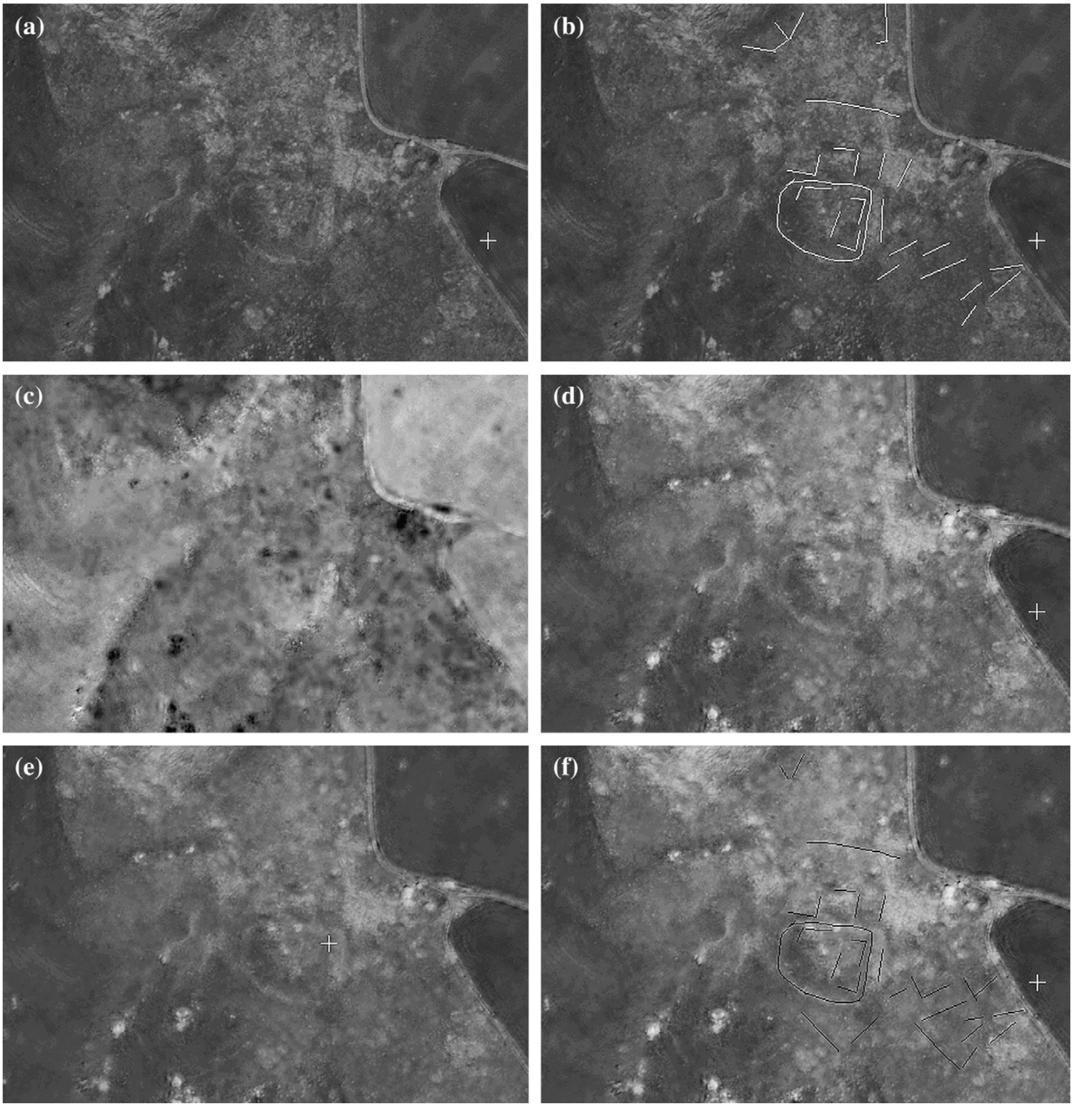

Fig. 6. Monte Irsi QuickBird images: (a) panchromatic; (b) panchromatic with location of marks of archaeological interest; (c) red channel data fusion product; (d) NIR channel data fusion product; (e) NDVI map; and (f) NIR channel data fusion product with location of marks of archaeological interest.

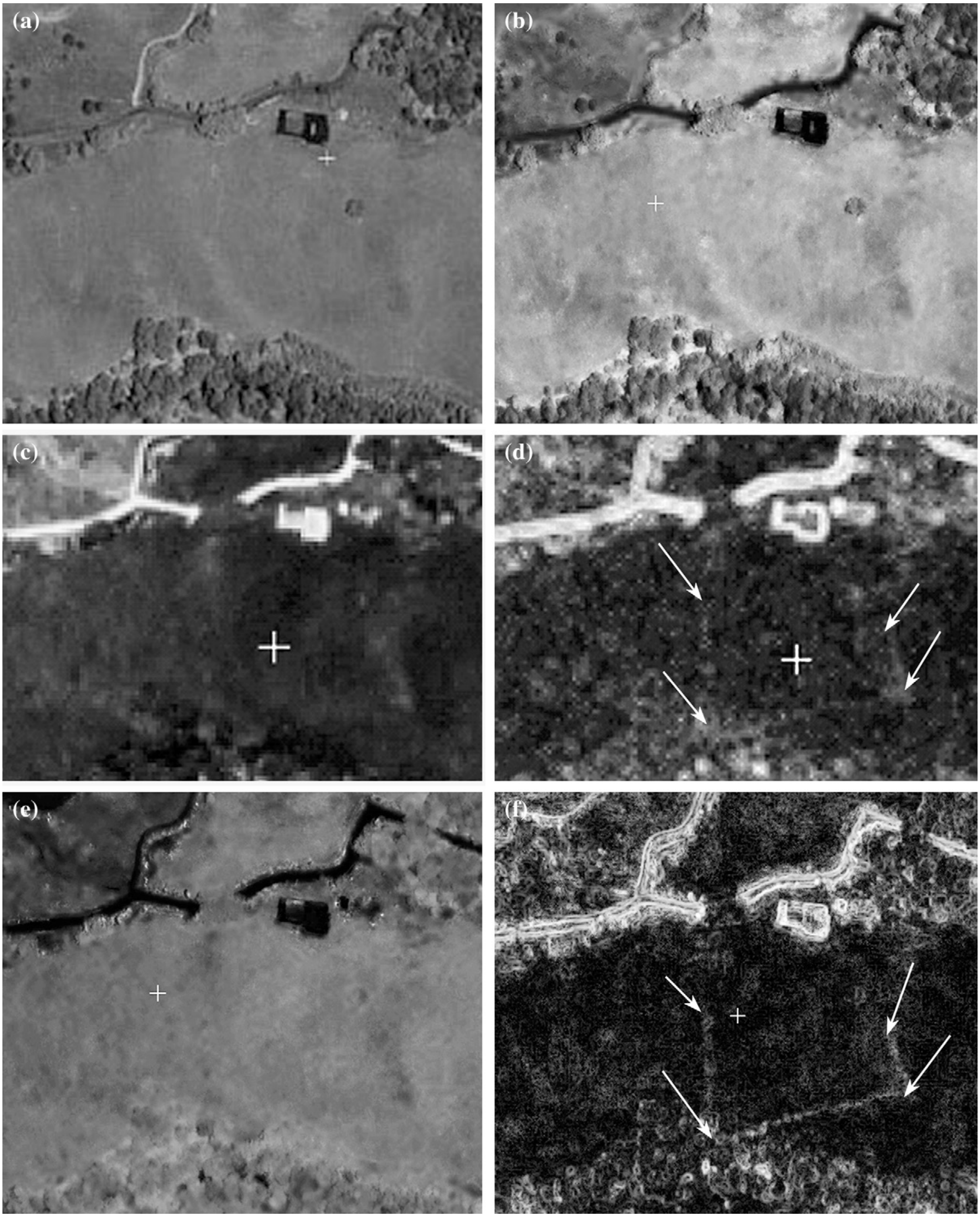

Fig. 7. Iure Vetere QuickBird images: (a) panchromatic image; (b) NIR channel data fusion product; (c) NDVI map (2.80 m); (d) results from NDVI map processed according to the flow chart in Fig. 2; (e) NDVI data fusion map; (f) results from NDVI data fusion map processed according to the flow chart in Fig. 2. The arrows in (d) and (f) denote the location of marks of archaeological interest.

of multispectral (2.40 m) this spatial resolution is still lower than those obtained from aerial photo. Thus could be a limitation for the identification of small features.

The current cost of archived satellite QuickBird pancromathic plus multispectral images data is 18.20 euro/km^2, whereas it is 22.75 euro/km^2 for new data acquisitions. Discounts at around 20% are generally offered for University and research Institution (the reader is referred to information available on line at the web site http://www.digitalglobe.com/product/product_docs.shtml). Currently, the cost of

QuickBird imagery is still higher than oblique aerial photos costs, but it is lower than the aerial photogrammetry.

In conclusion, the main findings of the performed investigation can be summarized as follows:

(1) the use of data fusion and edge detection procedures improves the identification of crop marks linked to the presence of buried archaeological remains;
(2) the integration of results obtained from panchromatic and image fusion products provides valuable information for a detailed physical and geometrical characterisation of the archaeological site, as required prior to any excavation work;
(3) the use of NDVI allowed to better enhance crop marks observed for surfaces covered by green and healthy herbaceous plants;
(4) the use of NIR channel was able to better enhance crop marks observed for surfaces covered by dry herbaceous plants;
(5) the QuickBird products are still more expensive than oblique aerial photos costs, but they are cheaper than aerial photogrammetric images;
(6) the spatial resolution of VHR satellite imagery is still lower than those obtained from aerial photo, thus should limit the identification of small features.

References

[1] M. Altaweel, The use of ASTER satellite imagery in archaeological contexts, Archaeological prospection 12 (2005) 151–166.

[2] E.C. Barrett, L.F. Curtis, Introduction to Environmental Remote Sensing, John Wiley and Sons, New York, 1976.

[3] M. Bavusi, D. Chianese, V. Lapenna, Indagini geofisiche a Iure Vetere, IMAA-CNR, Tito Scalo (Potenza), 2005.

[4] R.H. Bewley, Aerial survey for archaeology, Photogrammetric Record 18 (104) (2003) 273–292.

[5] C.D. Clark, S.M. Garrod, M. Parker Pearson, Landscape archaeology and remote sensing in southern Madagascar, International Journal of Remote Sensing 19 (8) (1998) 1461–1477.

[6] O.G.S. Crawford, Air photography for archaeologists, Ordnance Survey Professional Papers, New Series, 12, HMSO, Southampton, 1929.

[7] J. Dassie, Manuel d'archeologie aerienne, Editions Technip, Paris, 1978.

[8] D.N.M. Donoghue, Multispectral remote sensing for archaeology, Archeologia Medievale 12 (2003) 1–10.

[9] D.A. Drake, Recent aeolian origin of superficial gypsum crusts in Southern Tunisia: geomorphological, archaeological and remote sensing evidence, Earth Surface Processes and Landforms 22 (1997) 641–656.

[10] M.J.F. Fowler, Satellite remote sensing and archaeology: a comparative study of satellite imagery of the environs of Figsbury Ring, Wiltshire, Archaeological prospection 9 (2002) 55–69.

[11] M.J.F. Fowler, Y. Fowler, Detection of archaeological crop marks on declassified CORONAKH-4B intelligence satellite photography of Southern England, Archaeological Prospection 11 (4) (2005) 237–246.

[12] M. Janora, Memorie storiche, critiche e diplomatiche della città di Montepeloso, La Bautta, Ferrara, 1987.

[13] R. Lasaponara, N. Masini, QuickBird-based analysis for the spatial characterization of archaeological sites: case study of the Monte Serico Medioeval village, Geophysical Research Letter 32 (12) (2005) L12313.

[14] T. Lindeberg, Feature detection with automatic scale selection, International Journal of Computer Vision 30 (2) (1998) 79–116.

[15] N. Masini, R. Lasaponara, Note sulle performance ottenute dalle tradizionali tecniche di edge detection per l'elaborazione dei dati satellitari Quickbird in ambito archeologico. Rapporto tecnico CNR-IBAM 2005/001.

[16] N. Masini, La fotointerpretazione aerea finalizzata allo studio morfologico dei siti urbani e fortificati medioevali della Basilicata, in: C.D. Fonseca (Ed.), "Castra ipsa possunt et debent reparari." Indagini conoscitive e metodologie di restauro delle strutture castellane normanno-sveve, Edizioni De Luca, Roma, 1998, pp. 205–250.

[17] J. McMurtey, E. Chappelle, M. Kim, J. Meisinger, L. Corp, Distinguishing nitrogen fertilization levels in field corn (*Zea mays* L.) with actively induced fluorescence and passive reflectance measurements, Remote Sensing Environment 47 (1994) 36–44.

[18] J.T. Parry, The investigative role of Landsat TM in the examination of pre-proto-historic water management sites in northeast Thailand, Geocarto International 4 (1992) 5–24.

[19] M.R. Potenza, La fotogrammetria come tecnica di supporto nelle indagini archeologiche ed architettoniche: il caso dell'insediamento florense di Jure Vetere e del complesso abbaziale di San Giovanni in Fiore, in: C.D. Fonseca (Eds.), I Luoghi di Gioacchino, S. Giovanni in F, 2005.

[20] D. Roubis, F. Sogliani, M. Lazzari, Ricerche archeologiche a Jure Vetere (S. Giovanni in Fiore): la campagna di scavo del 2002 e le indagini geopedologiche, Siris, Studi e Ricerche della Scuola di Specializzazione in Archeologia di Matera 4 (2003) 99–118.

[21] T.L. Sever, Validating prehistoric and current social phenomena upon the landscape of Peten, Guatemala, in: D. Liverman, E.F. Moran, R.R. Rinfuss, P.C. Stern (Eds.), People and Pixels: Linking Remote Sensing and Social Science, National Academy Press, Washington DC, 1998, pp. 145–163.

[22] P. Sheets, T.L. Sever, High tech wizardry, Archaeology 41 (6) (1988) 28–35.

[23] A. Small, The Iron Age and Roman Site of Monte Irsi, in: P.L. Shinnie, J.H. Robertson, F.J. Kense (Eds.), Canadian Archaeology Abroad, University of Calgary, Calgary, 1976, pp. 23–33.

[24] A. Small, C. Small, I. Campbell, M. MacKinnon, T. Prowse, C. Sipe, Field survey in the Basentello valley on the Basilicata–Puglia border, Echos du Monde Classique, Classical views 42 (1998) 337–371.

[25] K. White, H.M. El Asmar, Monitoring changing position of coastlines using Thematic Mapper imagery, an example from the Nile Delta, Geomorphology 29 (1999) 93–105.

[26] D.R. Wilson, Air Photo Interpretation for Archaeologists, St. Martin's Press, London, 1982.

[27] Y. Zhang, Understanding image fusion, Photogrammetric Engineering and Remote Sensing 70 (2004) 657–661.