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Ikonos-2 multispectral satellite imagery to the study of archaeological landscapes: An integrated multi-sensor approach in combination with "traditional" methods

Stefano Campana

Department of Archaeology and History of Arts, Section of Medieval Archaeology - University of Siena
Via Roma 56, 53100 Siena, Italy
campana@unisi.it

Abstract. The experience of the Area of Medieval Archaeology at University of Siena on Ikonos-2 multispectral data has been developed in two substantial sample areas. In recent years both areas have been subject to multi-temporal analysis of vertical aerial photographs, to intensive field and aerial surveys. They therefore present an excellent opportunity for testing the potential of multistage remote sensing in combination with "traditional" methodologies for landscape analysis. In the absence of past experiences with Ikonos imagery we have used several processing routines whose effectiveness and response is well known. The results have been integrated in the archaeological GIS system where we collected most of the available data of the area: technical, thematic, historical maps, archaeological survey data, geological research, remote sensed data (vertical and oblique photography, Landsat TM), etc. The first results are definitely encouraging. Particularly, numerous traces indicated do not result visible in vertical and oblique aerial photographs.

Keywords. Multistage Remote sensing, high-resolution satellite imagery, multi-spectral analysis, visual analysis, sources integration, GIS based interpretation, field verification.

1 Introduction

There is increased interest today in making scientific progress through the use of remotely sensed data in social science research. On this topic it is important to remember that remote sensing is not a new technology. Archaeological studies have a long tradition of aerial photography application, from the earliest air photographs taken from balloons at the end of XIXth century to the crucial works of O.G.S. Crawford and many others aerial archaeologists, until the actually National Mapping Programmes. What has changed in recent years about remote sensing application it is the development of new sensors (in particular multi-spectral, hyper-spectral, microwave) and the availability of new tools for the management and integration of spatial information.

The Department of Medieval Archaeology at the University of Siena has long experience in programmes of landscape archaeology. Territorial studies have been based for the most part on three methodologies of investigation: field survey in sample areas; field examination to assess the significance of individual monuments; and analysis of vertical air photos combined with selective ground-truthing.[1]

Since the end of 1998 we tried the attention to increase our experience in remote sensing techniques.[2] Within the Department of Medieval Archaeology, the Laboratory of Aerial Photographic Interpretation has been active since 1984. The Laboratory is dedicated to the stereoscopic examination of vertical aerial photographs and in twenty years it has carried out numerous research projects, leading to the identification of over 5000 air-photo anomalies in Tuscany alone.[3] The photographs at our disposal belong to Regional Mapping Office or to Military Institute for Cartography. Despite good archaeological results, we have been conscious of the inherent limitations of this method of survey. The main problem is the cartographic nature of the data and the impossibility of planning the flights to coincide with "time windows" when conditions for the detection of archaeological features are at their best.

To try to and overcome these limitations in pursuit of our own objectives we have changed our focus to the experimental application and evaluation of new techniques in the study of the Tuscan landscape. This is the reason why we turned to oblique aerial photography, to the latest generation of multi-spectral high-resolution satellite imagery, to geophysical survey and to micro-digital terrain modelling using differential GPS.

The evaluation and use of Ikonos-2 imagery as oblique aerial photography and geophysics forms part of a wider strategy aimed at understanding the peculiarity of every single source so that we can on each occasion employ the appropriate combination of remote sensing techniques to maximize our understanding of the ancient landscape.

2 The project and its setting

2.1 Objectives

The central question was to establish whether Ikonos-2 imagery could be useful in the identification of archaeological sites and heritage resources in an area like Tuscany. In the past the successes achieved through the use of satellite imagery have usually been obtained in desert landscapes or in areas where such imagery represents the only available source of

[1] VALENTI 1999, pp.10-14; FRANCOVICH-VALENTI 2001, pp.83-116; CAMPANA 2001, pp. 47-71. A detailed introduction on the research programme can also be found on the Siena University Internet Site (Webmaster: L. Isabella, A. Mignani): <http://archeologiamedievale.unisi.it>.

[2] CAMPANA-FORTE 2001.

[3] COSCI 2001, pp.55-64.

remotely sensed data.[4] In Italy, for instance, there have been relatively few studies using satellite imagery, and these have been mainly restricted to Roman centuriation and geomorphological or paleoenvironmental analyses.[5] Two factors have been in operation here: on the one side low resolution of Landsat and Spot imagery, on the other the principal advantages of satellite imagery, its capacity to capture large section of the landscape and to record these at a number of different wavelengths in the visible, reflected or emitted infrared parts of the electromagnetic spectrum. In addition, computer enhancement of the digital data places less dependence on the time of year for revealing archaeological features. It is possible to identify the main differences between Landsat and Ikonos-2 as being that Ikonos-2 imagery has a higher ground resolution but a lower number of bands, including the complete absence of medium and thermal infrared.

The continuing improvement in the resolving power of the last generation of satellites is changing the possible uses of satellite imagery so that in the right circumstances the information drawn from Ikonos-2 imagery is beginning to stand comparison with that of vertical air photography. Theoretically the level of detail visible in Ikonos-2 imagery allows the identification of line features 3-4 meters in width and of area features within the range of 1000-2500 sq m. In archaeological terms, Etruscan-Hellenistic *oppida*, Roman villas, churches, monasteries, medieval castles and villages are all types of remains that would potentially be visible on the last generation of satellite imagery.

Before starting the evaluation of Ikonos-2 imagery along the lines of our general approach to archaeological landscapes we identified a number of problems that we wanted to understand and that we thought capable of at least partial resolution.

Overall, we wanted to understand:

- Firstly, why should we use high-cost satellite imagery, in Tuscany or more generally in Italy, if other sources such as multi-temporal vertical aerial photographs and oblique photographs are already available or can be obtained at lower cost?
- Is the level of detail available on satellite imagery useful for archaeological interpretation?
- What kinds of archaeological features can we perceive, and by what means?
- What are the relationships and the possible benefits of integration between aerial photographs and high-resolution multispectral satellite imagery?
- When is the use of multispectral satellite imagery helpful?
- Finally, what is the particular contribution of multi-spectral data to the discovery of archaeological sites and the better understanding of the ancient landscape?

2.2 The areas of study

We identified two sample areas representative of the landscape complexities and settlement patterns of Tuscany.

The first, consisting of primarily flat land, is situated in the province of Livorno and includes the coastal strip between Populonia, Campiglia Marittima and Donoratico. The second area is situated in the south of Siena province. This geo-morphologically hilly countryside is representative of considerable stretches of Siena province.

The total extent of these sample areas is around 470 sq km. Both areas have recently been the subject of numerous socio-archaeological studies, field-walking surveys, excavations, vertical air-photo interpretation and geological and geomorphological analyses. Presently there are in our RDBMS more than 1800 archaeological sites, from Palaeolithic to Middle Age.[6]

At the outset we focused on a number of long-standing archaeological problems that seemed capable of resolution, or which could benefit from our study. They included the following.

- Communication networks, with particular attention to the Via Consolare Aurelia and the Via Maremma. The growth or contractionof lake areas.
- Focuses of economic resources: swamp and mining areas.
- The urban topography of Populonia.
- The identification of castles and monasteries (in particular *Castrum Porto* Baractoli, the settlement of San Pietro ad Asso), Roman villas, medieval villas and changes in settlement distribution over time in the territory of Val di Cornia and Val d'Orcia.
- Principal and secondary sea landing-places (Baratti and Piombino).

2.3 Background data entry and its management

When setting up the research project we paid particularly close attention to the systematic collection of data. The first objective of the operation is close to the aim of this paper. We acquire as many individual pieces of information as possible for comparison and for evaluation of Ikonos-2 imagery. At a second stage we will aim to integrate and reinterpret the whole body of information using GIS based technology, and from this to postulate new settlement patterns.

To manage all the related documentation we have designed an archaeological GIS system which uses a data model that combines base maps, digital elevation models, remotely-sensed data, alphanumeric and multimedia spatial databases. At the same time, we have designed an ArcView GIS extension for the better management of the raster and vector data.[7] The basic concept of the extension is to use a friendly wizard to select the source-material that we want to present visually - Ikonos-2, vertical photographs from 1954, vector data, TIN data, or any other kind of data - and then to add automatically the data corresponding to the area that we are looking at on-screen. This utility allows us to organise and manage - without the need for grids or other reference tools – very large numbers of datasets, thereby reducing dead time and giving other researchers easy access to the data.

[4] We are thinking for instance of the pioneering work of the NASA Space Centre in south America, see <http://www.ghcc.msfc.nasa.gov/archeology/archeology.html>.

[5] In particular we would point to the experience of MARCOLONGO-MASCELLARI 1978, pp.131ss.; BARISANO *et al.* 1984 ; PIERI-PRANZINI 1989, pp.1385-1388; ALESSANDRO *et al.* 1992, pp.547-551; COSTI *et al.* 1992; DICEGLIE 1992, pp.421-439; COLOSI *et al.* 1996 ; BAGGIO *et al.* 1998; FORTE *et al.* 1998, pp. 291-304; CREMASCHI-FORTE 1999, pp.207-226; PRANZINI-SANTINI 1999, pp. 283-291; MARCHISIO et *et al.* 2000.

[6] CORTEMIGLIA *et al.* 1983, pp. 148-173; FEDELI *et al.* 1993; MAZZANTI 1995; CECCARELLI LEMUT-GARZELLA 1996; BIANCHI *et al.* 1997; COSCI 2001, pp.55-64.

[7] Lorenzo Bianchini, of the Department of Engineering at the University of Florence, wrote the programme for the extension in ESRI AVENUE language.

The RDBMS has been developed from 1996 by the Laboratory of Information Technology Applied to Medieval Archaeology (LIAAM – University of Siena). We have extended it with the addition of new modules for remotely sensed data, GPS data and ground-truth check data.[8]

3 Analysis of high-resolution satellite imagery (HRSI) *Ikonos-2*

The two images we used in our study were captured on 10th July 2000 at 10.05 in the morning by the multispectral sensor of Ikonos-2 satellite.

Some technical data of Ikonos multispectral imagery are:

- *Geometric resolution:*	4m
- *Spectral bands:*	4
- *Spectral bandwidth:*	450-880 nm
Blue	450-530 nm
Green	520-610 nm
Red	640-720 nm
Near Infrared	770-880 nm
- *Dynamic range:*	11 bit

The first imagery, on the Livorno coastline, is characterised by excellent quality, very good visibility and a total absence of cloud and haze. The second imagery, in the province of Siena, is of low quality, showing evidence of clouds and of degradation by haze.

3.1 Image processing and interpretation of archaeological features

Our methodological approach to Ikonos-2 imagery has been focused on 2D visual interpretation and the exploration of 3D representations.[9] The procedure followed in processing the Ikonos-2 imagery falls into two main phases, both taking into consideration the existing remote sensing techniques.

The first phase consists of a series of standard transformations of the whole image. In this stage of the processing some of the most commonly used techniques have been contrast stretching, density slicing, RGB colour composites of the original bands (3-2-1; 4-3-2; 4-2-1; 3-4-1) and arithmetic manipulation, in particular averaging (to reduce the noise component) and rationing (especially Normalized Difference Vegetation Index). This phase plays a central role in the identification of archaeological features.

At the moment there is relatively little useful literature on the archaeological interpretation of Ikonos-2 imagery.[10] It is widely recognised that the successful interpretation of aerial photographs is based on twin foundations, a good understanding of the mechanisms whereby archaeological sites are made visible and a detailed familiarity with the traces created by archaeological and other features.[11] Visual analysis of Ikonos-2 imagery has much in common with the analysis of aerial photographs. The main variations, in our experience, lie in the different ground resolutions of the two media. The ground resolution of the Ikonos-2 imagery is adequate to distinguish features, though sometimes small shapes can be misinterpreted. Bearing in mind this problem, the first phase of our approach has been to note any suspected feature. Between the first and second phase of processing and visual interpretation we use the GIS system to make comparisons with the features identified in various GIS layers. This step has been extremely useful in preventing other kinds of misidentification, for instance of non-archaeological features. In all, we have recognized in our satellite imagery 104 anomalies, of which 45 had already been identified through the analysis of air photography. The GIS based comparison reduced the number of probable archaeological features to eighty-four.

At the second phase of image processing, the focus of view was narrowed in order to isolate homogeneous textures around individual anomalies. The processing was carried out using Principle Component Analysis (PCA), Tasselled Cap Transformation (TCT), Decorrelation Stretch (DS) and RGB colour composites of the results of the various transformations. The filters, when applied - whether in the first or second phase - were primarily constituted of 3 by 3 matrices, for the most part confined to sharpening, smoothing, edge enhancement.[12]

On completion of the image processing we are able to recognize some trends. As we expected the best results come from transformations in which the near infrared band plays a primary role, especially in NDVI, Principal Component Analiysis, brightness and Wetness Transformation and relative colour composites.[13] Certainly there is no single ideal technique, but rather a spectrum of techniques producing variable results. An approach based on visual detection is affected by subjectivity, and the perception of anomalies varies from individual to individual.

3.2 Ground-truth reconnaissance and results

Altogether, our present processing of the Ikonos-2 imagery has allowed us to identify 84 archaeological features. Firstly, we may note that 82% of these are in the coastal strip (sample area 1). We think that the reasons for this situation are to be found in the different qualities of imagery in the two sample areas, and above all in the differences of morphology and land cover. In the first stage of analysis we interpreted features as enclosures, mounds, roads, ancient riverbeds and some not-identified. Aware of the need of ground truthing for validating remote observations, during the winter of 2001/2002 we checked in the field, mainly through traditional field survey, a sample of 40% of the features.

The results confirmed the presence of archaeological finds or features in 59% of the cases. In the 18% anomalies were the consequence of modern activities. In the 23% where we found no archaeological artefacts or structural remains there was also no modern activity that might have revealed such evidence.

The anomalies varied widely in size, from 200 sq m to 100,000 sq m (Fig.1). Clearly, Ikonos-2 imagery allows us to recognize quite small objects, beginning from 200 sq m.

[8] For the characteristics of the DBMS see FRONZA 2000, pp. 125-137; for the new modules see CAMPANA 2001, pp.61-63.

[9] As software we used mainly ERMAPPER, ERDAS Imagine, ENVI and ArcView 3D analyst (ESRI).

[10] PAVLIDIS *et al.* 2001, pp.393-400.

[11] WILSON 2000.

[12] CAMPANA-PRANZINI 2001, pp.17-62.

[13] On account of the very similar spectral ranges of bands 1-2-3-4 of Ikonos with Landsat TM in the first approximation we used the algorithm developed by CRIST-CICONE 1984.

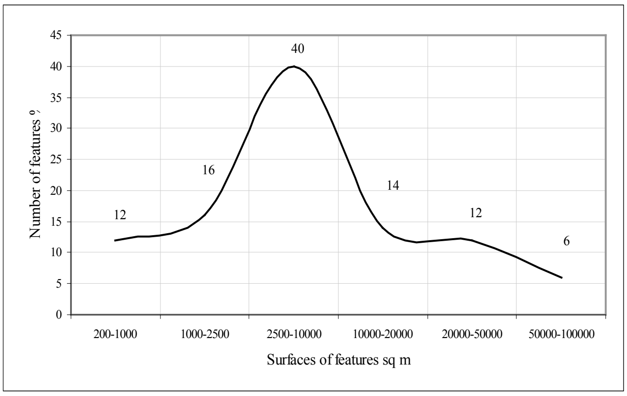

Fig.1. *Trend of size range of archaeological features.*

In figure 2 an example is shown from the Necropolis of San Cerbone (sample area 1), which has been well known since the end of the XIXth century. Even without the aid of special processing, using simply the true colour composite, we can easily make out on the satellite imagery the burial mounds of "Flabelli di Bronzo" and "Letti funebri", circular features with a diameter of 30 and 20 m respectively. The principal component analysis, especially PC1-PC2-PC3, and the related colour composite also enable us to identify another funeral monument, the "tomba delle pissidi cilindriche". From the point of view of geometric resolution, the Ikonos-2 imagery can therefore clearly show structures with surface areas of about 20 to 30 m. Of course we have to acknowledge that the identification is aided in this case by the presence around the mounds of stone pathways that emphasize the different spectral responses of the various surfaces.

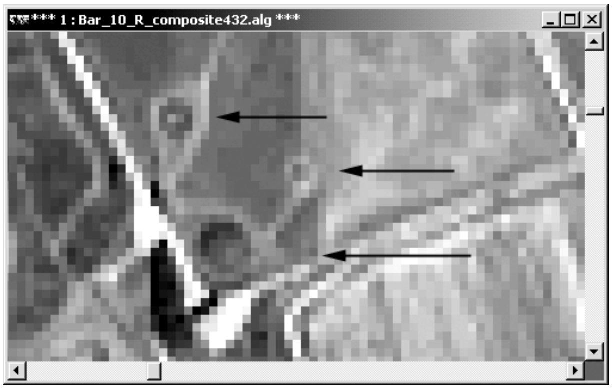

Fig.2. *True colour composite of the Etruscan necropolis of San Cerbone (Baratti - sample area 1).*

However, cases like this must be considered rare (only 12% in our sample), being related to particular situations on the ground. Most of the archaeological sites which we detected (70%) had a bigger surface area, between 1,000 and 20,000 sq m.

A typical anomaly is represented for instance by Montegemoli in sample area 1 (Fig.3).

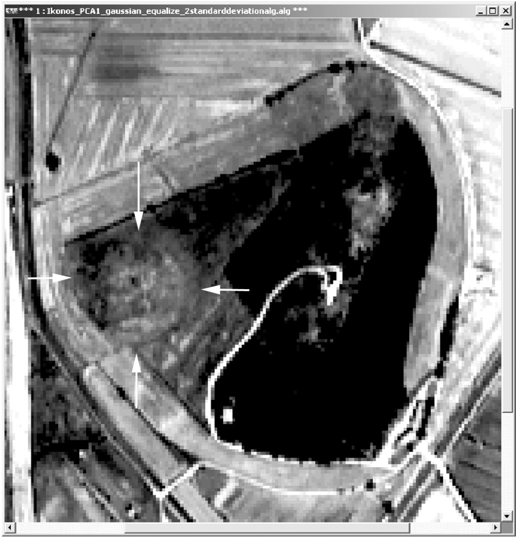

Fig.3. *First principal component of the Montegemoli hill-country (Piombino - sample area 1). On the western side of the area it is possible to observe a round-shaped anomaly.*

The Ikonos-2 satellite imagery enables us to recognise a circular anomaly on the western side of the area in question. This anomaly can be detected in a colour composite 4-3-2 and is clear in the first principal component. This anomaly was not seen during vertical air photo interpretation, and non of the three photographs that we used for comparative purposes - an excellent frame from a flight taken in 1938, a low-class photograph from 1954 and a recent ortho-photo map of good quality with 1m resolution - show this anomaly. The generation of a DTM enables us to relate the anomaly to the morphology, and to recognize the existence of a ditch surrounding the hilltop. This feature was not detected in any earlier researches but recent examination on the ground attests to the occupation of the area from Late Antiquity to the late Middle Ages. For the detection of linear features Ikonos-2 imagery is very effective, with a minimum range between 2-4 m. The most distinguishing characteristic, however, is the straightness or linearity of these features and the orientation, parallel or perpendicular. The topography of the landscape of sample area 1 also reveals linear geologic fault and fractures that can be confused with causeways. Anyway a successful example is represented by the identification of numerous linear features, which we have interpreted as parts of the road system of the ancient Via Consolare Aurelia. In the imagery it is possible to recognize several wide-spaced parallel segments that in one case lead from the main road to the swamp area and then on to Populonia. Other anomalies appear to be related to the Via Aurelia but have still to be checked on the ground (Fig.4).

Turning attention now to the near infrared wavelength and multispectral imagery, the last example highlights the possibility of identifying features in conditions of broken morphology and heterogeneous land cover (Fig. 5). The site in this case is in the district of Montalcino (sample area 2), a zone in which, according to documentary sources, stood from the middle of VIIth century the medieval monastery of San Pietro ad Asso. Before our research the monastery was identified with the farm of San Pietro, which contains the still visible remains of a Romanesque building: a small church tower and several pieces of decorative stonework. All of the documentary sources, from the second half of the XIIIth century onwards, refer to a village that must have been present in the same area.

The identification of the monastery was determined through the use of 3D landscape models generated from isolines drawn from technical maps and differential GPS data collected during ground survey. This permitted the recognition of an abnormal hill form only 200 m from the abandoned farm of San Pietro. The ground survey produced clear evidence for shaping of the hill's profile, with terracing along the slopes as well as round the crest of the hill. In particular, on the topmost part on the northern side there is a considerable spread of walling, perhaps attributable to fortification works.

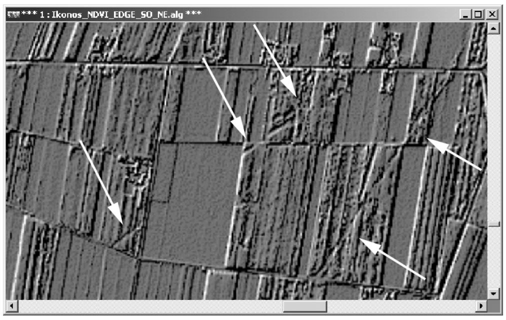

Fig.4. *NDVI and edge enhancement of zones showing linear features (sample area 1) interpreted in relationship to the Aurelia road system.*

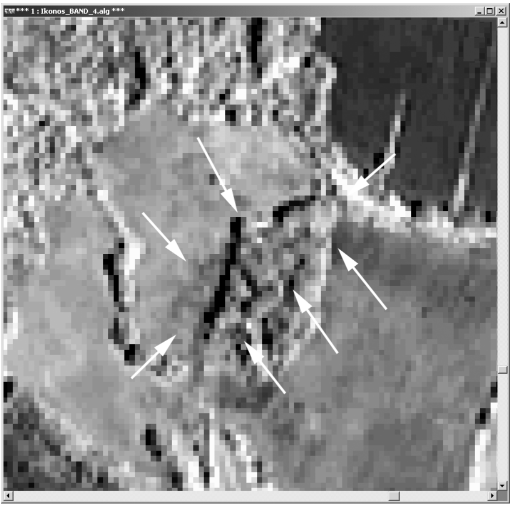

Fig.5. *The features are very clear on the near-infrared band. Early medieval Monastery of San Pietro ad Asso (sample area 2).*

3.3 Discussion of results

Positive results have been obtained using Ikonos-2 multispectral imagery, with the recording of 84 features in the sample areas, of which 39 are new sites. In fourteen cases where anomalies were identified previously through vertical or oblique photographs it was possible to add to the existing information. We should perhaps note one peculiarity of Ikonos-2 imagery. Through Ikonos-2 we can recognise many features that were visible in the early air photographs but which are no longer identifiable in those taken between 1976 and 1996. This situation perhaps derives from the inappropriate "time-window" in which the later photographs were taken, or alternatively from the higher sensitivity and computer enhancement capabilities of the Ikonos-2 data. If confirmed, however, this trend will indicate HRSI as an important tool for monitoring and exploring of the archaeological heritage (Table 1).

In conclusion, we believe that most of the results obtained from analysis of the Ikonos-2 imagery depend very much upon the multispectral properties of the sensor. In our study we concluded that bands 2 (green), but above all 3 (red) and 4 (near infrared), show the most potential for the identification of archaeological features.

Band 1, blue, suffers from atmospheric attenuation and scattering that degrades its definition. Red and near infrared images are less affected by haze and provide good definition for soil marks and crop marks. Despite these promising early results the true potential of this type of imagery is still not fully clear and needs to be further evaluated to test its responsiveness under a broad range of environmental conditions.

	Features in the two sample areas	*Features visible only through a single source single source*	*Increased information for features visible from two or more source*
Vertical aerial photographs 1938-1954	92	36	32
Vertical aerial photographs 1970-1996	22	6	2
Oblique aerial photographs 2001	14	3	4
Ikonos multispectral imagery July 2000	**84**	**39**	**14**

Table 1. *Relationship between remotely sensed techniques.*

4 Conclusions

Although this work is still in progress, with 60% of the features still to be confirmed in the field, our experience working with Ikonos-2 imagery has been, as a whole, positive. In relation to the questions that we posed at the beginning of our research we think that in general multispectral imagery has characteristics which are entirely compatible with the needs of archaeological landscape investigation.

The resolving power of the images allows us to identify a large range of archaeological sites. At the best, archaeological features are distinguishable at a size of 20 to 30 m across, and more commonly in the order of 50 to 60 m across. In this context it should be noted that a new satellite, QuickBird-2, has become available since October 2001. The sensor has almost the same spectral characteristics as Ikonos-2, apart from a geometric resolution of 2.5 m. Moreover there is the possibility of re-sampling the imagery as panchromatic data with a ground resolution of 0.6 m. This means that a pixel of Ikonos-2 data correspond to 43 pixels of Quickbird-2 pan-sharpened data.[14]

In summary, the particular contribution of Ikonos-2 imagery should be recognized as lying in its multispectral properties, in the near infrared band and in the possibility of recording the whole of the landscape at times when crop marks or soil marks

[14] See the Internet site: <http://www.eurimage.com/Products/product_pdf/qb.pdf>.

are at their best. Unfavourable aspects of recent satellite imagery remain substantially the same as for the preceding generation of satellites, in particular the impact of unfavourable morphology, the need for excellent atmospheric conditions, and the relatively high cost.

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