The Use of Satellite Imagery and Digital Image Processing in Landscape Archaeology. A Case Study from the Island of Mallorca, Spain

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The aim of this research was to assess the potential use of satellite imagery and digital image processing for the detection and surveying of ancient land-use patterns. The rural land-use patterns in the southeastern region of Mallorca (Spain) were investigated in order to locate traces of the Roman field-division system. A satellite scene was analyzed using ground control for field observations to determine the rural patterns observed in the contemporary landscape and to identify the possible remains of centuriated systems. Digital image processing involved image rectification, georeferencing, and spatial enhancement using high-pass and directional filtering. While no incontrovertible evidence of centuriation was located, satellite data proved to be of use in surveying medium-scale rural patterns.

INTRODUCTION

The study of ancient landscapes constitutes an important issue in contemporary archaeology. Since the late 1950s, archaeologists have become more concerned with the study of ancient landscapes, their morphology, and their preservation within modern contexts. Remote sensing is highly useful in landscape archaeology; aerial photography and, more recently, satellite imagery have been used to detect the traces of ancient landscapes preserved or fossilized in the contemporary landscape. This article presents the results of an attempt to locate vestiges of the Roman system of cadastration known as centuriation, using digital image processing of satellite data.

Archaeological Remote Sensing

Aerial and satellite remote sensing concerns the use of reflected or emitted electromagnetic radiation in order to gain information about the Earth's features. Consequently, with this broad definition, remote sensing includes a wide range of techniques to obtain information by devices ranging from simple aerial photography to spaceborne multispectral imagery.

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For many years the use of remote sensing techniques in archaeology was restricted to the often successful use of aerial photography and visual interpretation to locate traces of archaeological sites.

The development of imaging systems, such as the Multi-Spectral Scanner (MSS) on Landsat satellites, made possible the first attempts at using satellite imagery for archaeological purposes in the late 1970s and early 1980s (Cook and Stringer, 1975; Brown and Ebert, 1978; Ebert, 1980; Findlow and Confeld, 1980). The spatial resolution of Landsat MSS images was too coarse to locate individual archaeological remains, and attempts to locate individual sites failed (Madry, 1984). However, large-scale cultural features such as irrigation systems were detected on MSS images (Ebert and Lyons, 1980).

From a wider perspective, the bandbreadth and comprehensive overview of satellite imagery proved to be useful in locating areas that were likely to contain archaeological sites. In analyses of this type, the study area is spatially stratified in environmentally homogeneous land units, and, thus, those which are most likely to have been settled in the past can be identified; the application of the methods of landscape analysis to satellite data provided a sound basis for archaeological survey (Wells et al., 1981; Allan and Richards, 1982; Camilli, 1983).

The availability of Landsat Thematic Mapper (TM) and SPOT imagery, providing spatial resolution improved up to 10 m in the case of SPOT panchromatic imagery, has lead archaeological remote sensing to greater development, although the possibility of locating unknown individual sites is still very much dependent on factors such as image spatial resolution, extent of the site, and ground conditions. Landscape analyses, as previously described, are still the widest application of satellite remote sensing in archaeology (Custer et al., 1986; Barisano et al., 1988; Dorsett et al., 1984; Dorsett and Graham, 1988; Ammerman, 1989; Ebert, 1989; Madry and Crumley, 1990; Joyce et al., 1992; Sinclair et al., 1992; Parmegiani and Poscolieri, 1995; Montufo, in press).

A more restrictive issue is the use of satellite imagery for detecting and mapping large-scale cultural features such as ancient land-use patterns (Guy, 1987; Marcolongo, 1988; Coudoux, 1988; Delezir and Guy, 1992; Montufo, 1993), roads (Debaine et al., 1989), and irrigation networks (Ebert, 1987; Showalter, 1993). The value of using satellite imagery for surveying ancient land-use patterns is discussed in detail below.

The Use of Remote Sensing To Study Ancient Land-Use Patterns

Aerial photography has been used since the late 1920s to survey rural landscapes with the aim of locating ancient land-use patterns. The most spectacular results were obtained in North Africa, especially in Tunisia, where the abandonment of large areas in a desert environment allowed the preservation of almost intact centuriation systems (Caillemer and Chevallier, 1956). The merits of applying aerial photographic survey to the study of ancient rural patterns are well known; they provide more quantitative information than do maps, and such information is not affected by the selection processes involved in cartogaphy. As Bradford (1957) stated: “these centuriae, where preserved skeletally, will normally stand out distinctly from the heterogeneous details of the modern field pattern . . . . A comparison of air photographs with most ordinary 1 : 25,000 scale maps will show that an infinitely greater number of mini boundaries appear on the air photographs of the same scale. . . .” Initially, aerial photographs were analyzed visually; more recently, different procedures based on the application of optical filtering have been developed, particularly at the University of Besançon (Favory, 1980; Chouquer and Favory, 1991).

Further development involves the use of satellite imagery for the detection of former quadriculate land-use patterns. Compared to aerial photography, satellite imagery allows the relatively inexpensive study of larger areas providing a wider spectral range. Furthermore, digital image processing can be applied to satellite images in digital format, providing a wide range of tools for enhancing the image.

Research around the world has shown the usefulness of applying digital image processing of satellite imagery to the study of ancient land-use patterns. Landsat MSS and TM data and SPOT imagery have been used to locate ancient patterns preserved on contemporary landscapes; these include centuriation systems in Italy (Marcolongo, 1988), prehispanic patterns in Mexico (Guy, 1987), and mediaeval land divisions in France (Coudoux, 1988). An ancient landscape with parcel divisions now covered by sand dunes was located in Ning Xia (China) using directional filtering of SPOT imagery (Delezir and Guy, 1992).

The Roman Centuriation

Many states and civilisations of the ancient world developed cadastration systems. The Roman system of cadastration, known as centuriation, constitutes the most important of these systems; the remains of centuriation systems appear in many areas of the Mediterranean world such as North Africa, the Iberian Peninsula, Italy, and France. Extensive research on centuriation has been conducted in the last decade using field survey, cartography, and aerial photographic survey (Bussi, 1983; Chouquer et al., 1987; Chouquer and Favory, 1991, 1992).

Centuriation can be thought of as a large-scale civil engineering and planning project with the aim of dividing and assigning parcels of land, especially in newly established rural communities. Three aspects determined the implementation of centuriation:

1. A survey operation to map new territories.
2. A state fiscal operation to fix the taxes of each parcel.
3. A legal operation to define the legal status of the land.

Usually constructed on an open landscape, centuriation produced a pattern of square fields with a regular size, shape, and orientation. Paths, walls, and ditches separated different parcels, producing a grid pattern in the landscape. The most common pattern determined parcels with a length of 710 m, although the size of the parcels changed over time.

The oldest Roman cadastration systems appeared in the second half of the 4th century B.C. (Chouquer et al., 1987) and their origin was closely related to military purposes. In newly conquered territories "colonies were established as agricultural settlements as well as bulwarks of Rome's defence" (Dilke, 1971:133). The expansion of the Roman Republic and the conquest of new territories in Italy, North Africa, the Iberian Peninsula, and France during the 2nd and 1st centuries B.C. allowed the development of centuriation systems. The earlier centuriation systems were characterized by square parcels of a length of 13, 14 of 15 *actus.** However, the classic format of square parcels of 20 × 20 *actus* (equivalent to 710 m) became established during the 1st century B.C., the century that saw the greatest development of centuriated systems. Under the Roman Empire, other formats of smaller size were used together with the classic one.

The centuriation system produced "one of the most profound, widespread and sudden changes which our western European landscape has ever undergone before the industrial revolution . . . " (Van der Leeuw, 1994:461). In fact, the grids produced by centuriation remain in many landscapes of the Roman world, especially in Italy and North Africa. Patterns have been maintained by successive farmers keeping the Roman boundaries; the stagnation of some agricultural societies has helped to maintain the Roman pattern. Although modern boundaries are not always the Roman originals, the shape and size of centuriation remain in many contemporary landscapes as a testament of the Roman heritage. Furthermore, the abandonment of large areas of agricultural land in North Africa has fossilized the Roman landscape.

A SURVEY OF CENTURIATION IN S.E. MALLORCA USING LANDSAT THEMATIC MAPPER IMAGERY

The Study Area

Mallorca (see Figure 1), the largest of the Balearic Islands, lies in the western Mediterranean some 180 km from mainland Spain. Different natural regions can be distinguished on the island. The northwestern side is dominated by the mountain range known as Serra de Tramuntana, while on the eastern coast stands a lower mountain range known as Serres de Llevant. The central part of the island is a undulating plateau formed of Miocene limestones and covered by Mediterranean red soils.

The geomorphology of the southeastern region is characterised by the Migjorn, a low limestone plateau, and the Campos basin (Butzer, 1963). This low-

* The *actus* was the metric unit used by Roman land surveyors and it was equivalent to 35.5 m.

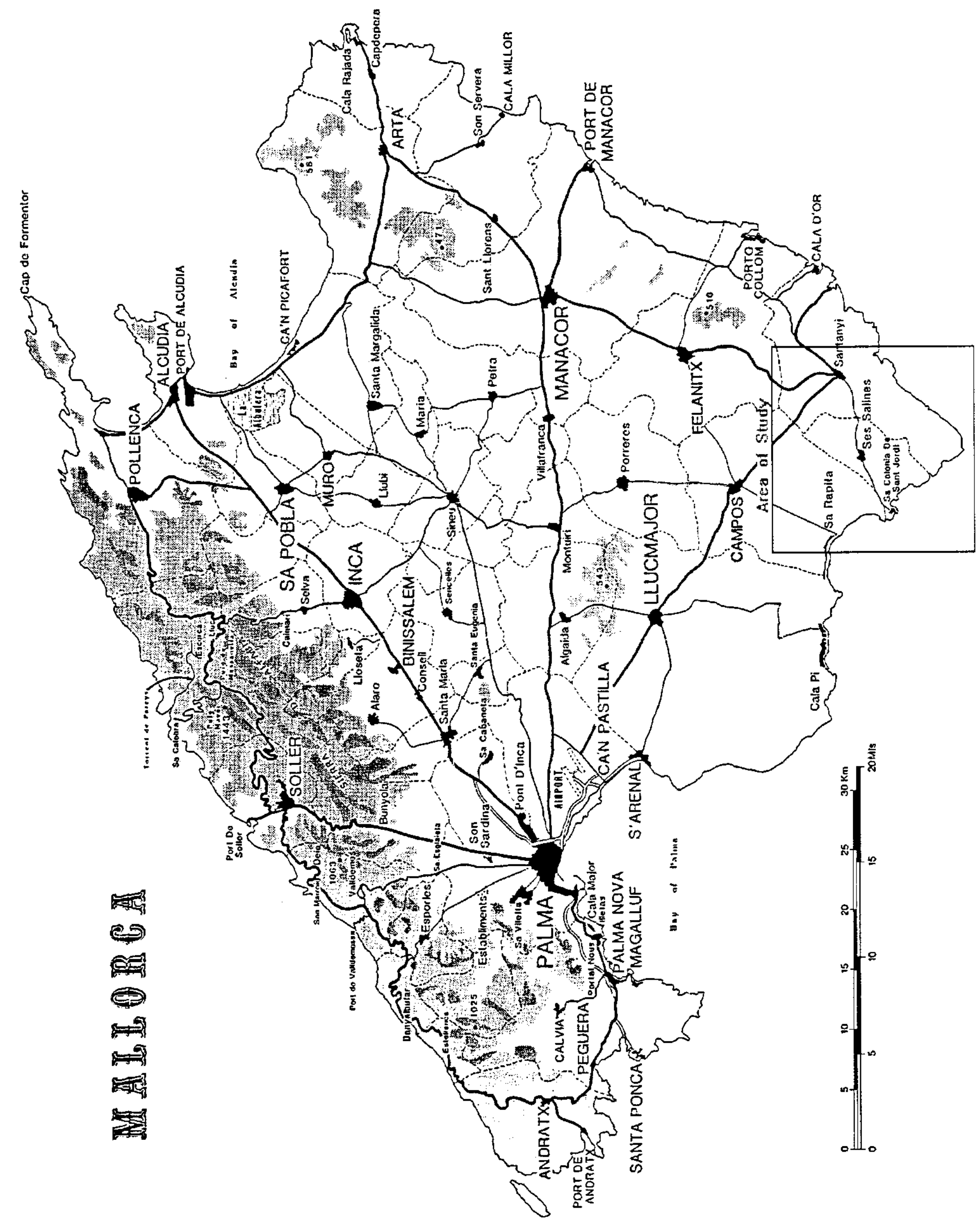

Figure 1. Location of the study area in the Mallorca island.

Table I. Spectral bands of the Landsat Thematic Mapper.

Band	Wavelength (μm)	Wavelength
TM1	0.45–0.52 μm	Blue
TM2	0.52–0.60 μm	Green
TM3	0.63–0.69 μm	Red
TM4	0.76–0.90 μm	Near-infrared
TM5	1.55–1.74 μm	Mid-infrared
TM6	10.40–12.50 μm	Thermal infrared
TM7	2.08–2.35 μm	Mid-infrared

lying area is covered mainly by Mediterranean red soils that constitute the best agricultural zones. The settlement of the area is characterised by small villages scattered around Campos and Santayı, the two most important settlements of the region. Isolated settlement is quite common.

Mallorca was conquered by Rome in 123 B.C. with the purpose of controlling the island and obtaining new lands to be settled by Roman citizens. Archaeological evidence reveals the presence of a substantial population in the southeastern region during Roman times (Orfila, 1988). Within this context, centuriation would have been implemented; in fact, various authors have proposed the existence of centuriation systems on the island, especially in the central region (Gurt et al., 1991; Cardell and Orfila, in press) and in the southeastern region (Rossello-Verger, 1974), although no substantial evidence has yet been located.

Methodology

The methodology was designed placing great emphasis on digital image processing of satellite images. Digital image processing was undertaken using the ERDAS 7.5 software (ERDAS, 1990) running on a PC-based system equipped with a truevision ATVista display adapter of 1024 × 1024 pixels and 32 bits connected to a Mitsubishi color monitor, a Cypher M990 tape drive, and a Calcomp 9100 digitizer.

The selected image was obtained by Landsat 5 Thematic Mapper rotating mirror scanner on August 15, 1988 (path 196, row 033 quadrant 1). Data are gathered by the Thematic Mapper in seven spectral bands providing a spatial resolution of 30 m in all bands except for Band 6, the resolution of which is of 120 m (see Table I).

Digital image processing involves different procedures to extract the maximum information from the electromagnetic values obtained by the satellite and present this information in a comprehensible form. Image rectification was used to achieve geometric accuracy. The main analyses were based on spatial convolution filtering; hence, different high-pass and directional kernels were applied to enhance linear features. The value of using spatial filtering to detect large-scale archaeological features such as land-use patterns and irrigation or communication systems has been identified by different researchers: biassed kernels were used to detect irrigation networks on an MSS image in India (Debaine et al., 1989) and square land patterns in China (Delezir and Guy, 1992); Thematic Mapper images have also been analyzed using spatial filtering to detect prehistoric canal systems in USA (Showalter, 1993).

Further cartographic study was carried out to provide an accurate map of relevant linear features, removing irrelevant background data. Cartography used was maps at scale of 1 : 25,000 produced in the 1960s. They were selected first because they were produced before the process of urban development and rural patterns were still well perserved; in addition, they provide great detail about rural patterns because they record not only roads and rural tracks but also many stone walls forming field division.

Field work was carried out for 2 weeks, with the aim of acquiring direct knowledge about the study area, including an assessment of land cover to ensure the correct identification of features on the image. Special attention was given to the study of field boundaries, as they are the physical manifestation of the pattern. Field boundaries consist mainly of tracks, paths, and stone walls. Stone walls are a typical element in Mediterranean landscapes; in the context of Mallorca, they divide fields, but apart from this primary role they also prevent damage from water erosion (Butzer, 1963). Furthermore, archaeological reconnaissance was also conducted to provide data about the archaeological setting on the island, especially during the Roman period.

Figure 2† displays the raw image of the study area combining three spectral bands (TM 7, TM 5, and TM 1) as a false color composite. This band combination was selected because it displays all areas of vegetation in different green tones; however, the combination of the red band (TM3) and the near-infrared band (TM4) displayed irrigated fields as extremely bright parcels, and this was deemed unsatisfactory.

A general assessment of land cover in the area can be made from this image. Various nucleated settlements appear, Campos being the most important, located in the upper left corner of the image. Santanyı and Ses Salines lie further southwards, and Colonia Sant Jordi is located on the coast. The area is predominantly rural with the majority of the land being cultivated, but because the image was obtained in summer, only the irrigated fields with growing vegetation stand out in the image as dark green fields, while the remaining fields, where the crops have been harvested, appear as bare soils in pale yellow, pale blue, or reddish tones. Many areas are covered by the *garriga,* a typical Mediterranean formation composed of low shrubs; moreover, some woodlands are still found in the zone, these areas appearing in the image in dark grey and brown tones.

† The photographs presented in this article are directly obtained from the computer display.

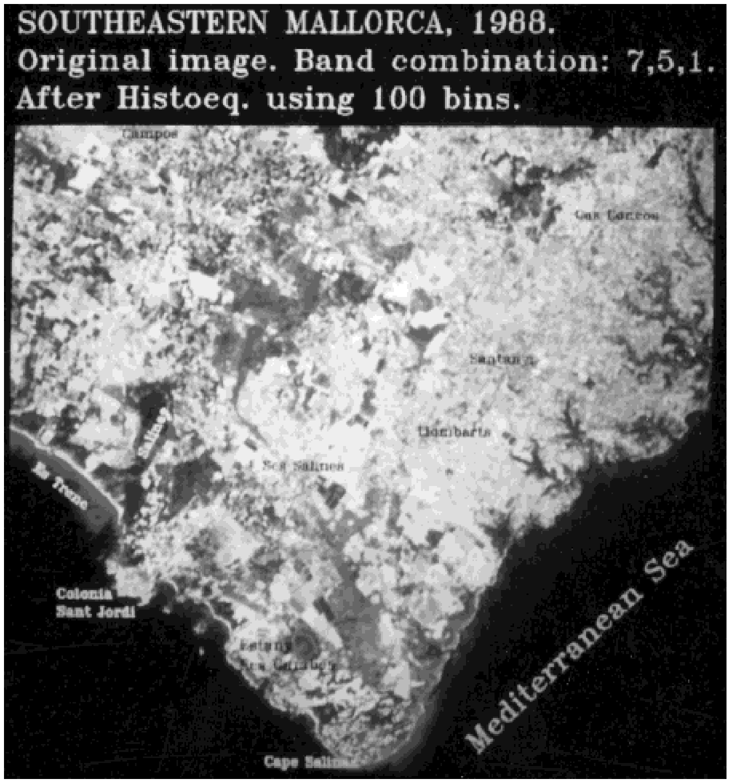

Figure 2. Southeastern Mallorca (Spain). Original image after histogram equalization.

The first step when analyzing the image was to carry out a preliminary assessment of rural land-use patterns present in the contemporary landscape was made. In consideration of the results of such assessment as well as relevant background knowledge, two smaller sites having regular land-use patterns were chosen for a more detailed study. The first one was located around the village of Santanyı, the second one between Colonia Sant Jordi and Ses Salines.

Visual analysis of the Santanyı area showed poor definition and fuzziness in the image. Consequently, a preliminary attempt was made to improve spatial definition, considering that the application of a high-pass filter would provide a reasonable increase of definition and detail on the image. High-pass filters increase the contrast between edges and their surroundings, causing the image to appear with sharper edges; hence a 3 × 3 high-pass kernel was applied over the image.

Further analysis was carried out by applying biassed kernels. Figure 3 shows the resulting image after the application of a 3 × 3 compass northeast

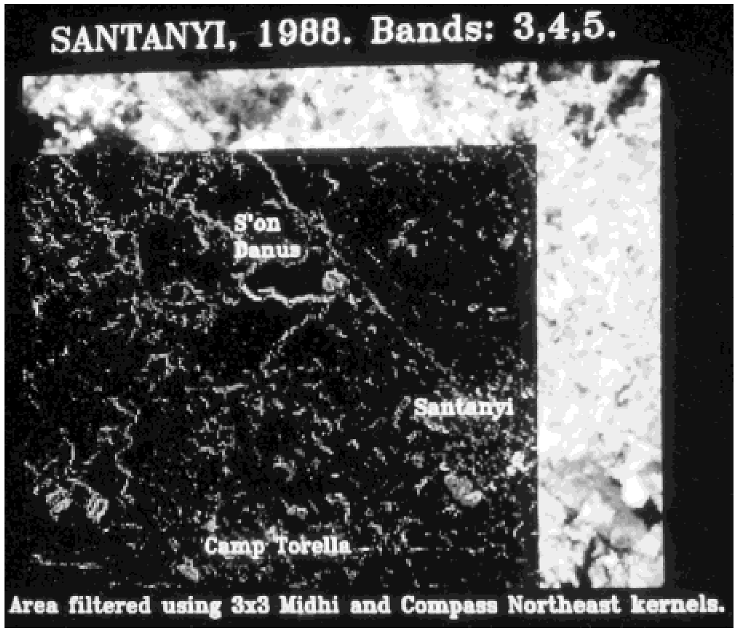

Figure 3. Area of Santanyí. The image displays the results after directional filtering.

kernel, the aim of which is to maximize discrimination of linear features that lie orthogonal to an NE–SW line. The filtered area is depicted in black and different linear features and boundaries are noticeable within this area. Linear elements located between Santanyı, Camp Torella, and S' on Danus denote a square pattern due to regular trends having an NE–SW direction while others have a perpendicular orientation NW–SE; together, these seem to produce a grid pattern in the landscape. Conversely, surrounding areas such as Camp Torella shows a far more heterogeneous pattern due to the irregular field division.

Figure 4 shows the area between Colonia Sant Jordi and Ses Salines. Edges between features denote a quadriculate pattern composed of linear elements having an NE–SW direction while others have a perpendicular orientation; these include roads, paths, and field boundaries. The image was considered to provide good definition of features, and therefore no high-pass filtering was applied. Directional filtering was used, although no features of interest were enhanced.

RESULTS AND DISCUSSION

The rural patterns present in the contemporary landscape of southeastern Mallorca over an area of some 150 sq km were studied with the purpose of

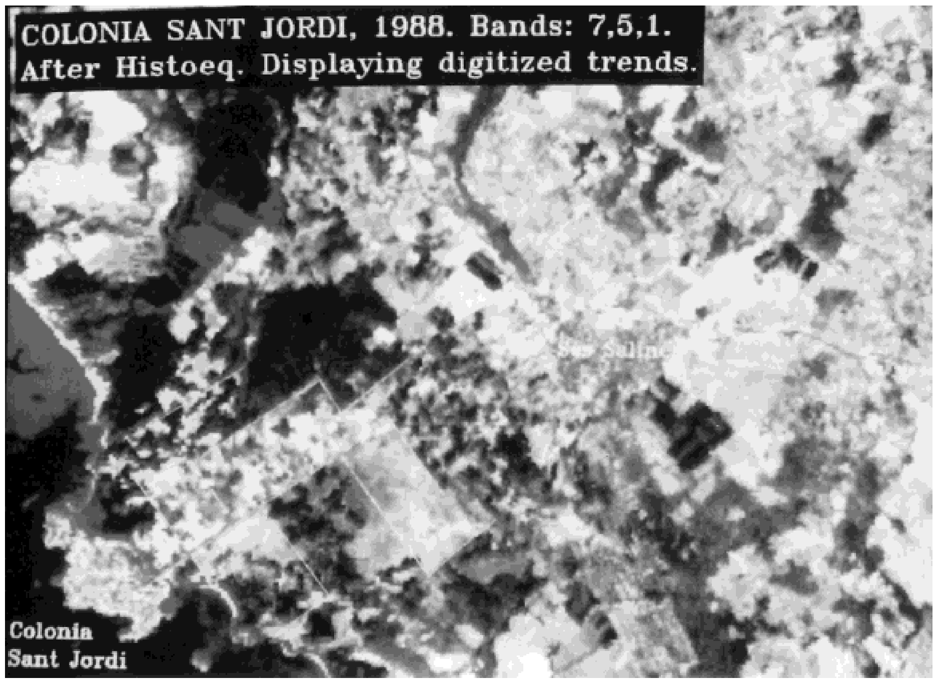

Figure 4. Area of Colonia Sant Jordi. Field divisions denote the quadriculate pattern.

locating the remains of centuriated patterns. After the initial analysis of the whole region, two sites were selected for further study. They included the area around Santanyı, where previous research suggested the presence of centuriated patterns, and the area of Colonia Sant Jordi, where traces of a quadriculate pattern were located.

Visual analysis of the Colonia Sant Jordi area revealed a quadriculate land-use pattern. Different filtering operations were carried out, although no features of interest were enhanced. Further study of the image and cartography at scale of 1 : 25,000 allowed the definition of the observed pattern in terms of distances and orientation. Some linear elements were recorded which had an orientation of 53°N and distant about 720 m from each other. In the NW–SE direction some linear features having an orientation of 143°N were mapped, but distances between them did not match with patterns similar to centuriation. These indicated that the morphology of the pattern was different from that produced by centuriation.

Rural land-use patterns in the Santanyı area were not clearly depicted on the image. However, filtering of the satellite image revealed a regular pattern different from that of the surrounding areas. Further study using cartography at a scale of 1 : 25,000 was used to determine accurately distances and orientation of the pattern. The results denote a pattern of linear features, including roads, tracks and stone walls, with an orientation of 137°N and some 710 m from each other. Together with other features having an orientation of 47°N and again 710 m away, they form a quadriculate pattern standing out distinctly within a general landscape characterised by small fields. These contemporary features (roads, tracks, stone walls) may be the remains of the centuriated systems, fossilized within the contemporary landscape. In fact, these trends form a grid similar to those produced by centuriation systems in other Mediterranean areas, but further conclusions await additional archaeological and historical analyses.

The regular field divisions present within the Santanyí area were not clearly depicted in the satellite image, due to factors on the ground affecting the visibility of the pattern. For example, the field divisions in Mallorca are composed mainly of gravel tracks, presenting essentially the same reflectance as the surrounding bare soils (a higher contrast will appear if surrounding fields are cultivated), and stone walls, too tiny to be recorded in a Landsat TM image. Another factor is that the image was obtained in summer, when only the irrigated parcels with growing vegetation stand out distinctly, while the remaining parcels with the crops having already been harvested are depicted as quite homogeneous areas.

Spatial resolution of TM data was another factor that interfered with a clear depiction of small-scale land-use patterns. Better results might arise if other satellite imagery providing better spatial resolution (e.g., SPOT images) is used. Digital image processing techniques can also be applied to increase spatial detail. For example, recent research has shown that the use of merging multitemporal satellite images offers better spatial resolution, the use of this technique provided a pixel size of 2 m in SPOT panchromatic images (Eriksson and Anderson, 1993).

CONCLUSIONS

The results obtained by using satellite imagery for a survey of ancient rural land-use patterns are highly dependent on three factors:

1. The existence of the remains of former land-use patterns in the study area.
2. The existence of other patterns that can be confused with ancient land-use patterns.
3. The ability of the system to record and discriminate between patterns.

Evidence of centuriation in Mallorca is limited and affected by post-Roman land-use patterns; together with factors on the ground affecting the visibility of land-use patterns, these prevented better results when analyzing the image. The ability of TM data to detect medium-scale land-use patterns was demonstrated. In the area of Colonia Sant Jordi a regular pattern was detected, although its morphology was different from centuriation. Rural patterns around Campos were also clearly visible, mainly due to the contrast between irrigated and nonirrigated fields. However, they were not of interest for this research because they also differ from centuriated patterns. On the other hand, rural patterns around Santanyı, where most consistent evidence of centuriation was located, were not clearly depicted on the image due to factors discussed above. The role of satellite imagery was not only limited to identifying areas likely to contain quadriculate patterns, but, in fact, medium-scale patterns were identified on the image.

The conjunction of extensive coverage and reasonable spatial resolution provided by satellite imagery renders its great potential for surveying rural land-use patterns. Research has shown that satellite images can be used to identify and map ancient land-use patterns in areas where they are not affected by modern intervention. In most cases, however, ancient patterns are not well preserved and further data are needed to define those forms.

For the particular case of the detection of centuariated patterns, satellite images would be of use to study large areas and determine those where square fields are present. Time and effort would be saved by identifying those areas most likely to contain remains of former quadriculate land patterns. Large-scale aerial photography, providing better spatial resolution than does satellite imagery, and cartography can best be used to determine accurately the morphology of observed land-use systems in terms of distances and orientation. In addition, Geographical Information Systems (GISs) can be used to model the evolution of land patterns over time, by integrating remotely sensed data, either satellite imagery and aerial photography, and other historical and archaeological data.

The integration of different data sources on a multiscalar approach will provide a better identification and discrimination of land-use patterns. Nevertheless, the determination of the origin of the land-use system is a different matter, a matter concerning history rather than remote sensing.

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