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Remote Sensing in Archaeological Research

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Summary. The adoption of remote-sensing data and their analysis within archaeological research has been significantly less than in other environmental sciences. Although some applications are limited by the nominal ground resolution of the sensors, multi-spectral remote sensing data from satellite platforms, mainly Landsat TM and SPOT, and the NERC airborne campaigns have been used successfully for archaeological applications. The vast reduction in hardware and software costs and the large archive of data available combine to provide a potential major archaeological archive. Such data can then be used for a range of investigations, at varying spatial scales, and also provide the foundation for comprehensive, cost efficient monitoring programmes. There are further archaeological applications in non-northwest European environments. Recent developments of new sensors and image analysis software also offer new archaeological applications.

1. Introduction

Remote sensing techniques, the imaging of phenomena from a distance, have long been a research tool in archaeology. Aerial photography is probably the most widely used of such techniques, and at the scale of individual site investigations various forms of geophysical and seismic survey can be applied. The methods to be discussed in this paper involve multispectral imagery from scanners mounted on aircraft and satellites to identify archaeological features represented by soil and crop marks. These methods should not be viewed as a replacement for other techniques, but as adding to a range which in certain circumstances will enhance the information available

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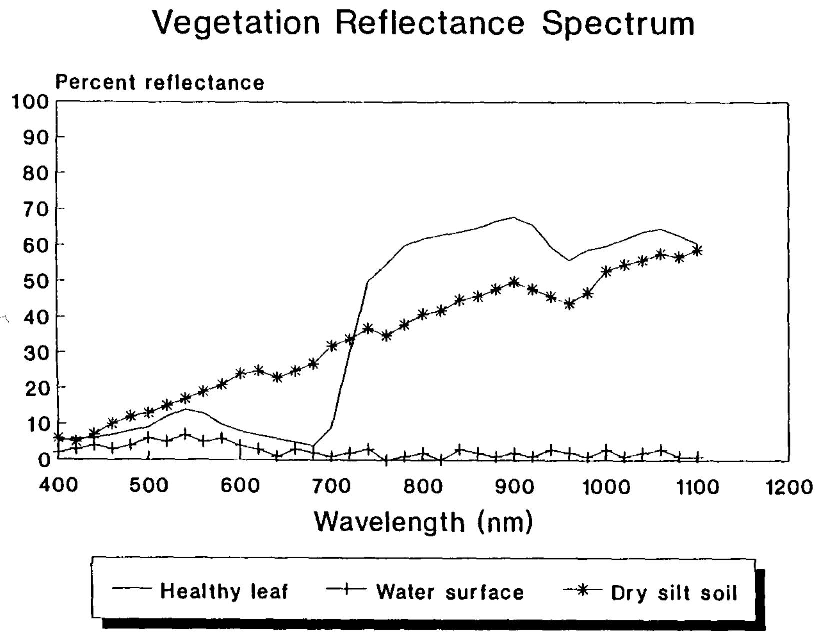

Figure 1. A typical reflectance spectrum for green vegetation, bare soil, and water in the range 400–1200 nanometres. The discrete bandwidths of the various sensors, Table 1, are used either individually or in combination to discriminate between such surfaces according to the reflectance characteristics.

for archaeological applications. In the wider context multispectral data can be integrated with any other form of spatially referenced information, particularly within a Geographic Information System, and many of the image enhancement methods applied to multispectral data can be used with suitably transformed, i.e., digitised, conventional air photography. Therefore multispectral remote sensing has the potential to become a fully integrated and routine technique in archaeological research. At present it is neither.

2. Background

Multispectral scanners, mounted on aircraft or satellites, measure the amount of light reflected from vegetated, ground and water surfaces in discrete parts of the electromagnetic spectrum (Figure 1 and Table 1). Different scanners employ different numbers of spectral channels and band-

Table 1. Summary of sensor specifications. Wavelength units are in nanometres.

Component of electromagnetic spectrum	Daedalus 1268 airborne scanner	Landsat 4 & 5 Thematic Mapper	SPOT Image MSS sensor	SPOT Image panchromatic sensor
visible	420–450			
visible	450–520	450–520		
visible	520–605	520–600	500–590	510–730
visible	605–625			
visible	630–690	630–690	610–680	
short wave IR	695–750			
short wave IR	760–900	760–900	790–890	
short wave IR	910–1050			
short wave IR	1550–1750	1550–1750		
short wave IR	2080–2350	2080–2350		
middle IR	8500–13000	10400–12500		
Sensor resolution	altitude dependent	30 m	20 m	10 m
No. of spectral channels	11	7	3	1

widths. The first major satellite borne sensor was the Landsat Multispectral Scanner, first carried on Landsat 1 in 1972, but with a nominal ground resolution too coarse to be considered for most archaeological applications. The Thematic Mapper (TM), carried first on Landsat 4 in 1982 and still operational on Landsat 5, has a ground resolution of 30 m and is capable of providing much valuable data for a wide range of environmental science applications. Within the United Kingdom these applications have developed alongside airborne and ground-based experiments, for example to evaluate the spatial resolution possible at which different types of feature can be identified.

In order to promote such remote sensing research one of the programmes sponsored by NERC was an airborne remote sensing campaign which has taken place annually since 1982. NERC funded the flying of a Daedalus 11 channel Airborne Thematic Mapper (ATM) together with black and white photography. Such scanners were first constructed in order to simulate satellite sensors such as Landsat TM and were initially experimental instruments. However they can now be used for general applications following radiometric and atmospheric correction (see Donoghue and Shennan 1988a). For mapping and overlay applications geometric correction is necessary, although this results in spectral degradation because of the re-sampling of data elements.

The Landsat TM has seven discrete spectral channels, three within the visible spectrum, and four infrared channels (Table 1). The eleven channels of the Daedalus scanner include seven which are very close to the specifications of Landsat TM. Since 1986 the SPOT Image satellites have been operational, with fewer channels than Landsat TM, but a finer ground resolution (Table 1). These three families of sensors are currently the major ones to be considered for archaeological applications. The discrete channels of the multispectral sensors are used in combination, for example as ratios or composites, to enhance features of interest identified as a result of the surface reflection and absorption characteristics (Figure 1).

3. Trial investigation

In 1985 a three year project was initiated to evaluate the capability of multispectral remote sensing data for detecting and mapping archaeological features manifest as crop and soil marks. The chosen test site was Morton Fen, located at the western margins of the Fenlands of eastern England.

The area consists of marine and freshwater sediments deposited at or near the coast over the last 6500 years. The fen is traversed by ancient drainage channels, now sediment-filled, equivalent to creeks on modern salt marshes and the spatial pattern of these former channels reflect the changing environmental conditions prevailing at the coastal margin due to man and to changing land-sea level relationships. Morton Fen has been investigated in detail on two occasions, between 1951–52, and between 1984-present. The former study involved a comprehensive regional survey of crop and soil marks and was published by Hallam in 1970. The latter study formed part of the Fenland Project (e.g., Lane 1988) which seeks to re-assess the archaeology and environmental history of the entire Fenland region surrounding the Wash estuary. During this study close links were forged with members of the Fenland Project who mapped Morton and surrounding fens and who provided advice on interpretation of the imagery and assistance with palaeoenvironmental reconstruction. We in turn provided new data on crop and soil marks as well as maps and dates of the sedimentary sequence.

The area was considered particularly suitable for remote sensing survey because its flat terrain simplifies spectral analysis yet it incorporates a wide variety of crop types and farming practices. In addition, land drainage and deep ploughing have caused changes in the surface soil due to peat oxidation and wind erosion. Consequently, there has been an overall reduction in altitude of the land surface and, with time, features once at depth are liable to be revealed at the surface. Thus, there is an urgent need for survey and monitoring of the wide areas so affected, lest archaeological information be lost.

Specific details of much of the project have been published elsewhere (e.g., Donoghue and Shennan 1988a, 1988b), and only the major conclusions are summarised here.

i) Digital multispectral data were processed and enhanced to reveal successfully a range of features of archaeological significance, though Landsat TM data (30 m ground resolution) yielded little useful archaeological information. In contrast, airborne data collected at nominal ground (pixel) resolutions of 2, 5, and 10 m highlighted a considerable amount of palaeoenvironmental and archaeological detail (Plate 3(a), see also Shennan and Donoghue 1988a, 1988b; SERC 1988). Degradation of the 10 m data has indicated that features are also revealed at 20 m nominal pixel resolution. These results suggested that the SPOT-1 panchromatic and multispectral data (10 m and 20 m ground resolution respectively) have the potential to provide information on archaeological and palaeoenvironmental features for large areas at a comparatively low cost, since a single scene can be purchased for *ca.* £1500 and covers an area 60 by 60 km. The potential appears confirmed by Plates 3(b) and 3(c), although the full image has yet to be analysed.

ii) Airborne multispectral data collected during the early growing season, May, revealed more information than all the available conventional air photography. This was primarily due to crop marks being more apparent at a waveband in the near infrared (760–900 nm) and soil marks particularly well defined in the wavelength range 630–690 nm. These results emphasised the additional benefits of sensing in several discrete rather than one single waveband. The ability to enhance data for discrete wavebands reduces the dependence on the time of year for revealing archaeological features.

iii) Quantitative analysis of the eleven wavebands of the airborne Daedalus scanner to select the three bands which will optimise image contrast (Sheffield 1985) pick out, following calibration, combinations of three wavebands out of bands 3, 4, 5, 6 and 7 (Table 1, and Donoghue and Shennan 1988b). In comparison, qualitative processing for detecting features shows that bands 5, 7, 10 and 11 proved to contain most information. Bands 3, 5 and 7 of the Daedalus scanner have similar bandwidths to multispectral channels on the SPOT MSS sensor. Bands 10 and 11 only have similarities with bandwidths on Landsat.

iv) Analysis of the airborne data demonstrated a necessity for their calibration, and for the development and implementation of various image enhancement and feature extraction algorithms. Establishing a physical basis for their interpretation and an operational methodology for information extraction served as the basis for this work. Where possible, procedures have been developed that can be applied to the analysis and interpretation of satellite data.

v) Archaeological features such as artificial and natural watercourses, ditches, salterns, peat-cuttings and settlements have been identified using methods such as contrast stretching, spatial filtering (directional high pass or Prewitt spatial box-filter) and numerical transforms (e.g., the Karhunen-Loeve transform). A number of these, and others, were programmed and installed on an IBM PC system (the main image processing was carried out on an I^2S system).

vi) Multi-temporal coverage of the same site reveals extra information. For example a superficial crop mark revealed by seed germination patterns may not relate to the same feature that is revealed later in the year by a deeply rooting mature crop; overlaying (a technique common in Geographical Information Systems) eases such analyses.

vii) Considerable problems were encountered in relating the relative geometries of data from adjacent airborne flight lines. Similar difficulties arose in comparing and combining multi-temporal airborne data. These problems were attributed to the inherent instability of aircraft as data collection platforms, combined with the nature of the sensor used. Airborne linescan data commonly displays a varying geometry along and between flight lines. These variations are inconsistent, and unless detailed information on attitude changes for the platform are available, they cannot be fully compensated for. In contrast, satellite platforms are very stable thereby providing imagery with a consistent geometry which promotes both the comparison and combination of adjacent and overlapping data sets.

viii) Analysis of soil properties has led to a greater understanding of the physical processes that relate soil disturbance to spectral properties. Land drainage and farming methods in the Fenlands lead to changes in the surface due to peat oxidation, wind erosion and deep ploughing. Features once at depth become revealed as they begin to influence the rooting zone. A satellite-based monitoring system would be able to reveal these changes in a cost-effective manner and target smaller areas for specific study and possible conservation.

4. The current situation

Coles (1986) identified site preservation, display potential and cost effectiveness as particular problems facing current research in wetland archaeology. In the broader context site identification and management can be added. Survey using remote sensing data from aircraft or from high spatial resolution satellite data can provide detail of the context of sites and their landscapes, early detection of sites under threat and is rapid and repeatable. The techniques are particularly valuable in areas such as the English Fenland, the Humber estuary, north-west England and the Somerset levels and their hinterlands where previous survey work is fragmentary and the nature of the archaeology is difficult to convey to the public without the use of convincing maps and images of palaeoenvironments.

Though helpful to the Fenland Project it was apparent that the remote sensing programme could have been more useful if it had been coordinated with the Project. The two ran simultaneously rather by chance than due to pre-planning. If the remote sensing programme had been operational and available at the earliest stage of the Fenland Project the ability to survey rapidly a large area, *ca.* 4000 km^2, could have helped with the targeting of resources as well as providing significant environmental information.

The situation has changed significantly since 1985. At that time major limitations on the use of remote sensing were the costs of equipment, software and data. The processing during the trial investigation were performed using an image analysis system installed on a minicomputer. The total outlay excluding data, estimated commercial prices, would have been in the order of £70k to £100k. A number of the image processing methods which were found most useful during the trial investigation were incorporated into a system which could run on a personal computer with high resolution colour graphics display. Although there are limitations regarding data storage and the requirement for a facility to pre-process the satellite data delivered on computer tapes, it is now possible to analyse and display ATM, Landsat TM and SPOT data on a PC system with a capital outlay, including software but not data, of less than £5k. This puts such methods within the reach of most levels of archaeological research, national through to the county unit.

Commercial data costs are in the region of £1500 for a 60 × 60 km image, approximately £0.41 per square kilometre, for satellite imagery. In addition there are existing archives held by NERC which could be useful for any hindcasting approach and for establishing any monitoring programme. Similarly there are over 100 different sites flown between 1982 and 1990 (Figure 2) during the NERC ATM campaigns. These provide a very valuable data source, with multispectral data at a fine ground resolution, in some cases 2 m. This archive has not been systematically evaluated for archaeological users. It should also be possible to envisage specific future airborne campaigns structured to support major archaeological programmes.

While hardware and software costs have decreased by at least a factor of ten over the past five years there remain potential limitations on the wide adoption of remote sensing in archaeological research. Two that are easily recognised are perception and personnel. The trial investigation using Morton Fen was possible because of the foresight of SBAC to support another project originating essentially from outside the discipline of arch-

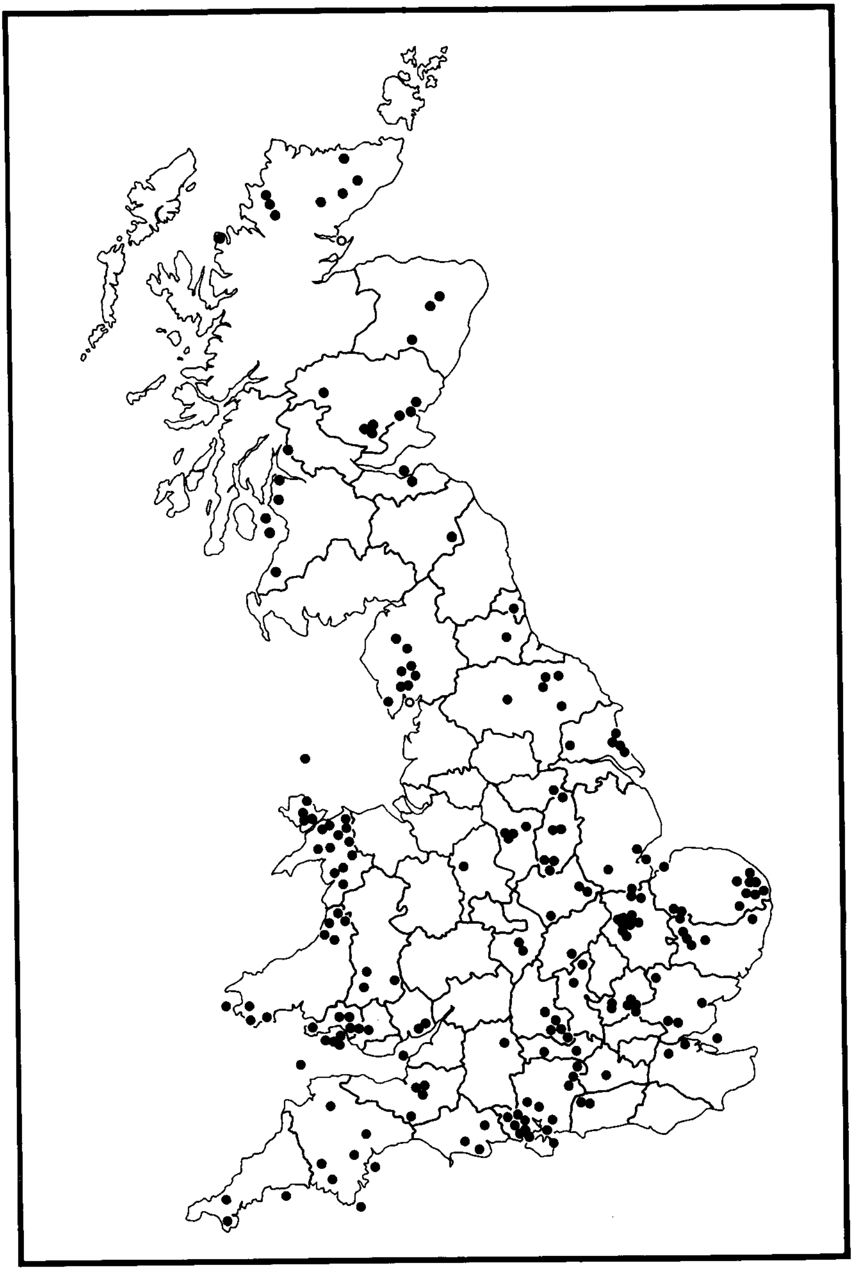

Figure 2. Location of sites flown during the NERC ATM campaigns 1982–89.

aeology. Only with similar open views will the methods become adopted. It is ironic that one comment which has subsequently been made about the project was that resources should not be committed to programming algorithms since they exist elsewhere. Yet it is precisely developments of such work which are now part of one of the commercially available software packages that allow processing to be carried out cheaply on a personal computer. The next stage is to view remote sensing as only one input into computer-based Geographic Information Systems, so that the results can be integrated with other archaeological data, both in a research and management role.

The second potential limitation is that of trained personnel. Remote sensing and image analysis is not a common part of archaeological training at present and it could take some years for this to take place. Furthermore, such skills are in short supply in the commercial sector, particularly environmental consultancy which is likely to be a growing field in the next decade. Given this situation the ability to attract and retain competent personnel may be a significant limitation.

5. Possible future developments

It would be optimistic to suggest that all of the following will occur, but the opportunity exists to employ satellite and airborne remotely sensed imagery in numerous archaeological applications. The NERC archive of satellite and ATM data should be routinely analysed; major archaeological projects should incorporate remotely sensed imagery at an early stage of project formulation in order to target ground resources; satellite data at 10 m and 20 m ground resolution could be used in initial surveys where an understanding of the large scale environmental context is lacking; annual monitoring programmes could become established within management strategies, since as soil changes occur due to drainage and agricultural activities existing information on both archaeological sites and environmental context may be destroyed while previously new information will be discovered. The ability to monitor large areas repeatedly using current technology is possible.

There are also continuing enhancements in sensor technology and image processing which have yet to be evaluated within an archaeological context. For example, archaeologically related crop marks are often associated with moisture or mineral stress of the vegetation canopy which may be observed as a systematic deviation in the reflectance curve from a that of healthy vegetation. Such features, which can be seen in laboratory measurements, require a spectral resolution of 10 nm or less in order to be resolved. Recent advances in instrument design have led to the use of imaging spectrometers with 10 nm spectral resolution in mineral exploration surveys. These data sets are likely to be of considerable value to archaeologists in the near future.

Another technique of major importance is the use of multispectral remote sensing at mid-infrared wavelengths for sediment mapping. In the mid-infrared many silicate, carbonate and sulphate minerals are characterised by their emittance variations in the 8000–12000 nm wavelength region. The strongest spectral features, known as the Reststrahlen band, are due to SiO_2 bending and stretching modes. The strengths and positions of absorptions at mid-infrared wavelengths give the potential for remote mapping quartz content in sedimentary facies. A preliminary investigation of this possibility is planned for the summer of 1991 using NASA's Thermal Infrared Multispectral Scanner (TIMS).

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References

Coles, J.M. 1986: Precision, purpose and priorities in wetland archaeology. *Antiquaries Journal* 66, 227–247

Donoghue, D.N.M. and Shennan, I. 1988a: The application of multispectral remote sensing techniques to wetland archaeology. In Murphy, P. and French, C. (editors), *The Exploitation of Wetlands* (Oxford, British Archaeological Reports British Series 186) 47–59.

Donoghue, D.N.M. and Shennan, I. 1988b: The application of remote sensing to environmental archaeology. *Geoarchaeology* 3, 275- 285.

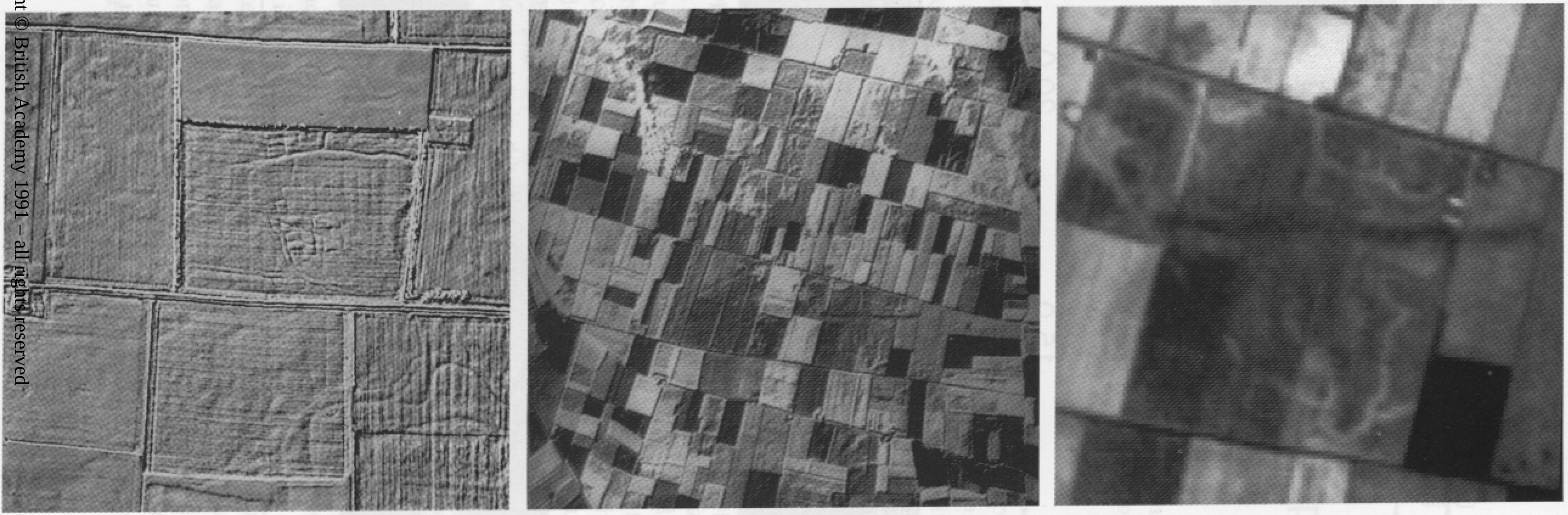
Hallam, S.J. 1970: Settlement around the Wash. In Phillips, C.W. (editor), *The Fenland in Roman Times: Studies of a Major Area of Peasant Colonisation with a Gazetteer Covering all Known Sites and Finds* (London, Royal Geographical Society Research Series 5) 22–113.

Lane, T. 1988: Pre-Roman origins for settlement on the Fens of south Lincolnshire. *Antiquity* 62, 314–321.

SERC 1988: *Science-based Archaeology Committee Report* 1985–88 (Swindon, Science and Engineering Research Council).

Sheffield, C. 1985: Selecting band combinations from multispectral data. *Photogrammetric Engineering and Remote Sensing* 51, 681–687.

PLATE 3



(a) (b) (c)

(a) Crop marks indicating a settlement site, and associated artificial and natural water courses. The data are from band 7 of the NERC ATM Daedalus scanner, Table 1, with a nominal ground resolution of 2m, and have undergone an edge enhancing procedure. (b) SPOT Image panchromatic image of Morton Fen, after edge enhancement. A series of features are visible, some of which are enlarged on Plate (c). The pixel resolution is 10m and the Plate shows an area ca. 10.2 km by 10.2 km. (c) SPOT Image panchromatic image of Morton Fen showing a medieval field boundary (T. Lane, pers. comm.), the dark horizontal line; a part of the 'Bourne-Morton Canal' (probable Romano-British age) running SW-NE on the right of the Plate; and various extinct, meandering tidal creeks.