ARTICLE IN PRESS

ELSEVIER

Computers and Electronics in Agriculture 00 (2002) 1–24

Computers and electronics in agriculture

www.elsevier.com/locate/compag

Reducing the cost of multi-spectral remote sensing: combining near-infrared video imagery with colour aerial photography

G.G. Wright [a], K.B. Matthews [a,*], W.M. Cadell [a], R. Milne [b,1]

[a] Land Use Systems, Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen AB15 8QH, UK

[b] Department of Engineering, The Robert Gordon University, Schoolhill, Aberdeen AB10 1FR, UK

Received 24 April 2002; received in revised form 19 August 2002; accepted 26 September 2002

Abstract

Land managers are often confronted with management problems that could be addressed using decision support or management information systems. The use of such tools, however, depends on the availability of appropriately resolved spatial data. One source of such data is multi-spectral remotely sensed imagery. The cost of such imagery, particularly where environmental goals are most important, is often prohibitive. Even when the cost of such imagery can be met, other factors, such as cloud cover for satellite-based systems or sensor scheduling for sophisticated airborne systems, may mean that imagery is not available. This paper investigates the utility of a system that combines near-infrared imagery from a video camera with conventional medium-format aerial photography deployed in a light aircraft platform. Previously, imagery obtained from video cameras has suffered from limited spectral range and from significant image motion effects. These problems were eliminated by the use of an electronic-shutter charge-coupled device video camera with a strong IR response. The systems components and the approach to their operational deployment are described and the options for transforming the raw imagery into survey coverage discussed. The image quality and cost is presented for a site characterisation application where the aim is the generation of normalised difference vegetation index values. It is concluded that the system has significant potential utility for decision support and land-management applications.

UNCORRECTED PROOF

* Corresponding author. Tel.: +44-1224-498200; fax: +44-1224-311556

E-mail address: k.matthews@macaulay.ac.uk (K.B. Matthews).

[1] Tel.: +44-1224-262400; fax: +44-1224-262444.

0168-1699/02/$ - see front matter © 2002 Published by Elsevier Science B.V.

PII: S0168-1699(02)00141-2

Y:/Elsevier Science/Shannon/Compag/articles/Compag1692/
ARTICLE IN PRESS

© 2002 Published by Elsevier Science B.V.

Keywords: Videography; Multi-spectral; Metric; Survey; NDVI

1. Introduction

1.1. Context

Developers of computer-based decision support and management information systems have sought to assist land managers making a wide range of increasingly complex decisions (Matthews et al., 1999). Management objectives include increasing efficiency, minimising environmental impact or achieving an acceptable balance between multiple objectives. Whatever the goal of such systems, their operational success depends on the provision of appropriately resolved spatial data within acceptable cost. Insufficiently resolved data produces unacceptable uncertainty in prediction whilst excessive cost prohibits employing such data at all. This paper presents an approach to reducing the cost of gathering high-resolution multi-spectral spatial data, suitable for a wide range of land-management applications, using off-the-shelf sensors deployed on a light aircraft platform.

1.2. Rationale

Spatial data may be acquired with the intention of characterising a site at a single date or the intention may be to monitor the site to observe the nature and degree of change. Achieving the required coverage and accuracy for either application using conventional ground-based survey methods alone is often either impractical or excessively expensive particularly in heterogeneous environments (Um and Wright, 1996). Remotely sensed, multi-spectral imagery (typically imagery with four or more bands, for example blue, green, red and near-infrared (NIR)) can significantly improve the quality or reduce the cost of site characterisation and monitoring. Multi-spectral imagery can be used as a primary data source, for example in vegetation surveys or as a secondary source to structure the pattern of ground-based surveys maximising the benefit of the sampling. Multi-spectral data may also be usefully employed as 'carrier surfaces' for the spatial interpolation of point survey data to give mapped coverage (Wright and Birnie, 1986; Leone et al., 1995).

The market for remotely sensed data and services has grown approximately 6% per annum between 1994 and 1997 (Olby, 1999). The rate of growth it is, however, lower than had been predicted given the increasing number and sophistication of the sensors available (ESA-ESRIN, 2002). The importance is recognised of spatial data for planning the management of environmentally sensitive areas (Wascher, 2000). For such applications, however, the take-up of remotely sensed data is hampered by the lack of clear financial benefits to offset against the costs of a monitoring programme. There remains an unfulfilled requirement for a sensor system that can

UNCORRECTED PROOF

be inexpensively purchased, deployed and analysed (Tarussov et al., 1996; Thomas, 1997).

1.3. Multi-spectral imagery sources

The most ubiquitous sources of multi-spectral imagery are satellite-based sensors (Moran et al., 1997). Such sensors are capable of capturing imagery across a wide spectrum (from ultra-violet to mid-infrared, 450–1500 nm) and have steadily increased their spatial resolution (for example the IKONOS satellite with a spatial resolution of 1 m). Limitations of satellite systems include the fixed schedule of coverage that may not allow imagery of specific events to be captured and the significant cost of geometrically corrected data for the sensors with the best resolution. The principal limitations of such systems for applications in western Europe and other areas prone to cloud cover is, however, the lack of days on which cloud free imagery can be obtained (Legg, 1991). Using airborne systems, it is possible to obtain imagery from below high-level, evenly distributed cloud cover with acceptable image quality degradation. Indeed depending on the season, image quality may be improved by eliminating harsh shadowing.

A number of airborne multi- and hyper-spectral imaging systems have been developed and tested during the last decade (Moran et al., 1997; Denniss and Bunn, 2000). The cost of these instruments and the commissioning costs of the aircraft in which they are installed means that they can only be deployed by most land managers on a contractual rather than an ownership basis. Even if the commissioning cost can be met, limits on the schedule of availability can mean the sensor has to be deployed in less than ideal conditions. The quality of results from these systems is impressive but the cost is prohibitive for most land managers.

Conventional aerial photography is one of the oldest and most widely-applied forms of sensors, capable of providing information in the visible and NIR spectrum. For multi-spectral imaging using conventional aerial photography two cameras are usually required. The first captures images with the three visible bands (red, green and blue) and the second either monochrome NIR or false-colour NIR (KODAK, 2001). Conventional photography provides a high quality product that is compatible with analysis by digital photogrammetry. For NIR photography optimising negative exposures, maintaining stocks of IR film and the availability of processing facilities can be problematic. The need for a second camera increases the capital cost and potentially makes operational deployment more difficult.

An alternative to conventional aerial photography as a source of imagery is the video camera. Off-the-shelf video cameras are commonly used by video survey companies, but mainly to give a visual check of ground conditions. Mass production of video cameras has reduced their capital cost, they are simple to operate and, since 25 frames are captured every second, it is possible to extract stereo coverage without the need to explicitly capture overlapping images using an intervalometer (Vlcek, 1983). The utility of video cameras for airborne remote sensing can be limited by their image capture process, with images blurred or smeared due to the movement of the sensor platform. Video cameras' spectral sensitivity is in many cases permanently

UNCORRECTED PROOF

limited to the visible spectrum. Frame selection and capture from video tape can be time consuming and geometric rectification may be hampered by lower quality camera optics.

1.4. Approach adopted

This paper describes a multi-spectral imaging system using NIR imagery, captured by an improved video camera, merged with conventional metric aerial photography. The imaging system is suitable for deployment on a light aircraft platform. All the components of the imaging system and the process used to convert the imagery into geo-referenced data use off-the-shelf technology with the aim of minimising all costs while achieving an acceptable image quality.

The paper sets out the salient features of video cameras for airborne imaging applications, in particular the recent improvements in spectral response, resolution and image capture. The components of the imaging system are then detailed, with particular focus on the characteristics of the video camera employed. Issues of operational deployment, data processing and digital image processing are also presented. The results of tests comparing the image quality of conventional and the improved video camera are given. Examples of the initial airborne testing of the system are also presented. The aim for this testing was to examine the practicality and cost of combining imagery from the metric camera with the IR video data, in particular the creation of false-colour IR composites for visual interpretation and vegetation indices suitable for use in quantitative analyses.

2. Video image gathering

Several developments in the field of videography are relevant to the development of an airborne multi-spectral site characterisation system, in particular the control of exposure using automatic gain control (AGC), the alternative image capture strategies and electronic shuttering.

2.1. Automatic gain control

Effective imaging of varied terrain requires a camera capable of capturing a wide range of feature brightness across its spectral range. The AGC compensates for changes in light intensity. AGC means that in all but exceptional circumstances the video camera can cope with the range of lighting conditions experienced during the mission without the need to vary the aperture setting of the lens. This is particularly useful for airborne applications as it eliminates the need for powered, auto-iris lenses which add to the cost, bulk and power requirements of any system. AGC simplifies the task of processing imagery into a single mosaic by reducing differences in exposure between individual images and between flight lines. AGC also improves the quality of the imagery achieved by increasing the digital number (DN) range of values (Richardson et al., 1992).

UNCORRECTED PROOF

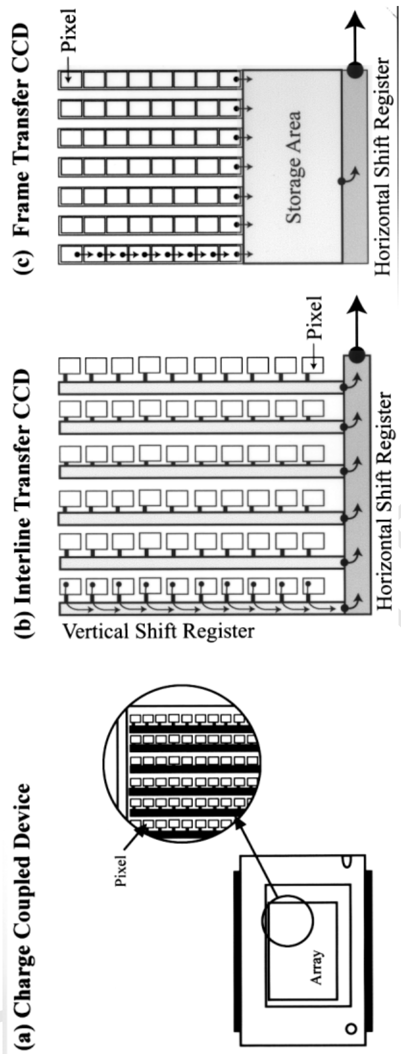


Fig. 1. Frame and interline-transfer CCDs (after MacDonald, 2001).

UNCORRECTED PROOF

2.2. Image capture

Images are captured in video cameras using charge-coupled devices (CCDs) (Fig. 1(a)). Progressive-scan CCDs capture a whole image simultaneously with full vertical and horizontal resolution. In contrast, interlace CCDs capture an image in two half resolution phases. The delay between these image capture events can lead to blurring of objects moving across the field of view. Two types of CCD support full frame capture, interline-transfer and frame-transfer (MacDonald, 2001). These CCDs differ in their approach to translating the charges from the pixels into a video signal. After transfering the pixel charges to the vertical shift registers, the interline-transfer CCD passes the charges to a horizontal shift register to form a single line of the video image, Fig. 1(b). These lines are integrated by the cameras electronics to form a standard video signal. Frame-transfer, by contrast, transfers charges vertically within the CCD, in effect the CCD acts as its own vertical shift register, Fig. 1(c). In addition to the horizontal register the frame capture CCD has a storage area where charges from the CCD are accumulated before they are passed to the horizontal register. The significant difference between interline and frame-transfer CCDs for airborne imaging is that frame-transfer CCDs require additional mechanical rather than integrated electronic shuttering to eliminate image motion. Mechanical shuttering increases the cost and weight of the lenses required and decreases reliability.

2.3. Electronic shuttering

The quality of images captured by progressive-scan, interline-transfer CCDs is improved by the incorporation of an electronic-shutter mechanism. The duration of the charge accumulation, (effectively the duration that the CCD is exposed for), is fixed and set manually, with a range typically between 1/50 and 1/16 000 of a second. The very short exposure times can be achieved without increased bulk or loss of reliability since the shutter employed is electronic rather than mechanical.

The time taken to capture an image is independent of that required for data processing. The CCD still captures a standard 25 frames every second but each image can be the product of an exposure lasting 1/16 000 of a second. The video signal from the CCD is usually adjusted by an AGC within the camera to give best possible image quality within the constraints of the shutter speed and lens aperture chosen.

The electronic shuttering combined with AGC and lens aperture settings give a wide range of options for ensuring optimal picture quality. The benefits of the progressive-scan CCD with electronic-shutter and AGC are particularly noticeable in the reduction of image motion, discussed in the following section.

2.4. Image motion, shutter speed, and ground resolution cell

Image motion, seen as blurring or smearing, occurs due to aircraft forward motion, roll, pitch, yaw and as a response to various frequencies of vibration while

UNCORRECTED PROOF

the shutter is open. The degree to which the image is degraded is determined to a great extent by the duration over which the image is obtained. In videography, this is determined by either the shutter speed or the scan rate depending on the CCD employed.

Even for short exposure or scan times, there will always be image motion due to the continuous movement of the platform. Tolerable image motion may be usefully determined by calculating the ground resolution cell (GRC) for the sensor and relating this to the speed of movement of the platform. The GRC is the size of the minimum resolvable target for the combination of: ground clearance; resolution and dimensions of the CCD and the focal-length of lens used. The relationship between these factors can be formulated as follows:

$$\mathrm{GRC} = GS/LR$$

where G is the ground clearance (m), S is the size of the CCD array across the swath (m) (for CCDs with rectangular rather than square elements the GRC will be orientation specific), L is the lens focal-length (m), R is the resolution (the number of CCD pixels across the swath). Fig. 2 shows the relationship of ground clearance to ground resolution for three lenses (8, 16 and 25 mm) deployed on a generic CCD.

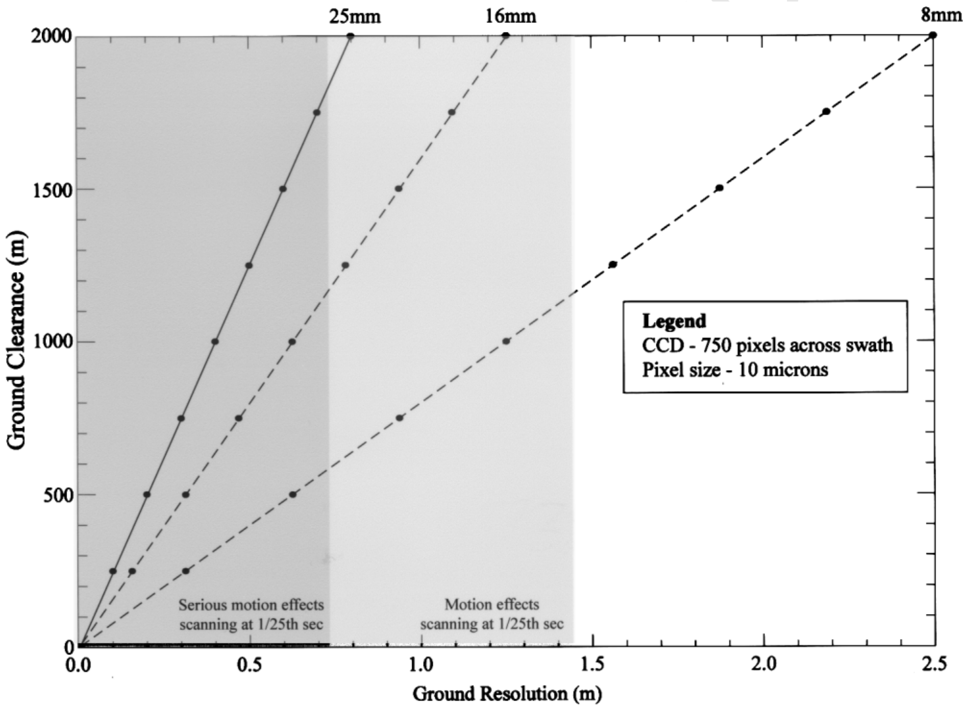


Fig. 2. Relationship of ground resolution and ground clearance for three lens sizes using a generic CCD specified in the legend.

A heuristic for tolerable image motion is that less than half a pixel is acceptable. Assuming a typical light aircraft travelling at around 130 km h^{-1} (or 36 ms^{-1}) and a period of 1/25 of a second to capture the image, then the distance travelled by the aircraft is 1.44 m. The shaded zone of the graph in Fig. 2 shows the 1.44 m zone with the darker shading showing the half distance of 0.72 m. As the practical ground clearance is 2000 m, in all but cloud free conditions, it is clear that conventional interlaced CCD cameras, operating at 1/25 of a second, can suffer significant image motion. Electronic-shutter CCDs taking images in 1/2000 of a second will, in contrast, experience negligible image motion. This makes them highly suitable components of an airborne imaging system.

3. Image analysis

3.1. Data fusion

Data fusion typically involves combining remotely sensed imagery from different portions of the electromagnetic spectrum or imagery with other data sources such as digital elevation data (Guneriussen et al., 1996). Data fusion may also combine data with different spatial or temporal resolutions linking them to a common map base, and if necessary re-sampling them to a common spatial representation (Chavez, 1991). The aim of this process is to combine images in such a way that resulting outputs provide either improved visualisation of the phenomena being investigated or allow the integrated analysis of both datasets to improve the results achieved. The fusion process does not create new information but rather arranges data such that its information content can be more easily accessed. When sources of visible spectrum data and NIR can be brought together then it is possible to consider, for example, using a range of vegetation indices for site characterisation purposes.

3.2. Site characterisation with vegetation indices

Remote sensing has long been used for estimating vegetation attributes, a strong correlation existing between the ratio of NIR to red reflectance (IR/R) and the vegetation's leaf area or biomass (Kanemasu et al., 1974). The more robust vegetation index is the normalised difference (spectral) vegetation index (NDVI). A number of formulations exist for calculating NDVI but generically

$$\mathrm{NDVI} = ((\mathrm{InfraRed} - \mathrm{Red})/(\mathrm{InfraRed} + \mathrm{Red}))\mathrm{SF},$$

where InfraRed and Red are the infrared and red image values and SF is a scaling factor used to convert the floating-point ratio values into integers between 0 and 255 for display. The ratio has a range of values from −1.0 to +1.0. Higher NDVI values indicate larger quantities of plant biomass. The transition from vegetated to bare soil conditions occurs around the zero NDVI value but is dependent on the DN range of the sensor(s) employed.

UNCORRECTED PROOF

NDVI is strongly correlated with the fraction of photosynthetically active radiation intercepted by the canopy (Hatfield et al., 1984) and a near linear relationship exists between NDVI and both leaf area and biomass. The index has been used as an input to a rangeland-management tool to assist the setting of appropriate stocking densities to preserve the vegetative diversity of a rangeland (Wright et al., 1997).

4. Materials and methods

4.1. The CCD video camera

The CCD camera system used was the monochrome PULNiX TM765i[2], shown with the other components of the system in Fig. 3. The TM765i is typical of CCD cameras developed by PULNiX and other manufacturers to meet the needs of the industrial-vision and surveillance markets. These instruments, available off-the-shelf, are ideal components for a reduced-cost imaging system.

The video camera has an electronic-shutter mechanism, providing a sharp picture at speeds (between 1/50 and 1/16 000 s) without smearing or blurring. In order to maintain an acceptably bright image, a shutter speed of 1/2000 was used with optimum exposure maintained by the AGC.

The TM765i CCD has a resolution of 756x581 pixels and was deployed with a Pentax 8.5 mm CCTV lens at a ground clearance of 1000 m giving a GRC of 0.38 m. The CCD has a strong response across a wide wavelength spectrum. This is illustrated in Fig. 4 showing that for NIR radiation the CCD has a 50% response when compared to the potential for visible light. This is a significant improvement on previously available CCDs which typically had a 10–20% relative response. For the purposes of the development study, a visually opaque 750 nm NIR filter (Kodak Wratten 88A) was used to isolate the NIR band.

The TM765i is $42 \times 32 \times 130$ mm^3 and weighs 190 g. This compactness simplifies the operational deployment of the camera on a light aircraft platform since structural modification is not required. The small size and weight of the camera also makes it possible to consider deploying the camera from even lower cost platforms such as blimps, kites and model aircraft with limited payloads (Silbernagel et al., 1998; Benton, 2001; Cousins, 2001).

4.2. Operational deployment

The video camera was paired with a medium-format (120/220) metric camera, a Rolleiflex 6006[3] fitted with a Zeiss Planar f2.8/80 mm lens. This allowed the capture

[2] PULNiX America, Inc. http://www.pulnix.com.
[3] RolleiMetric http://www.rolleimetric.de.

UNCORRECTED PROOF

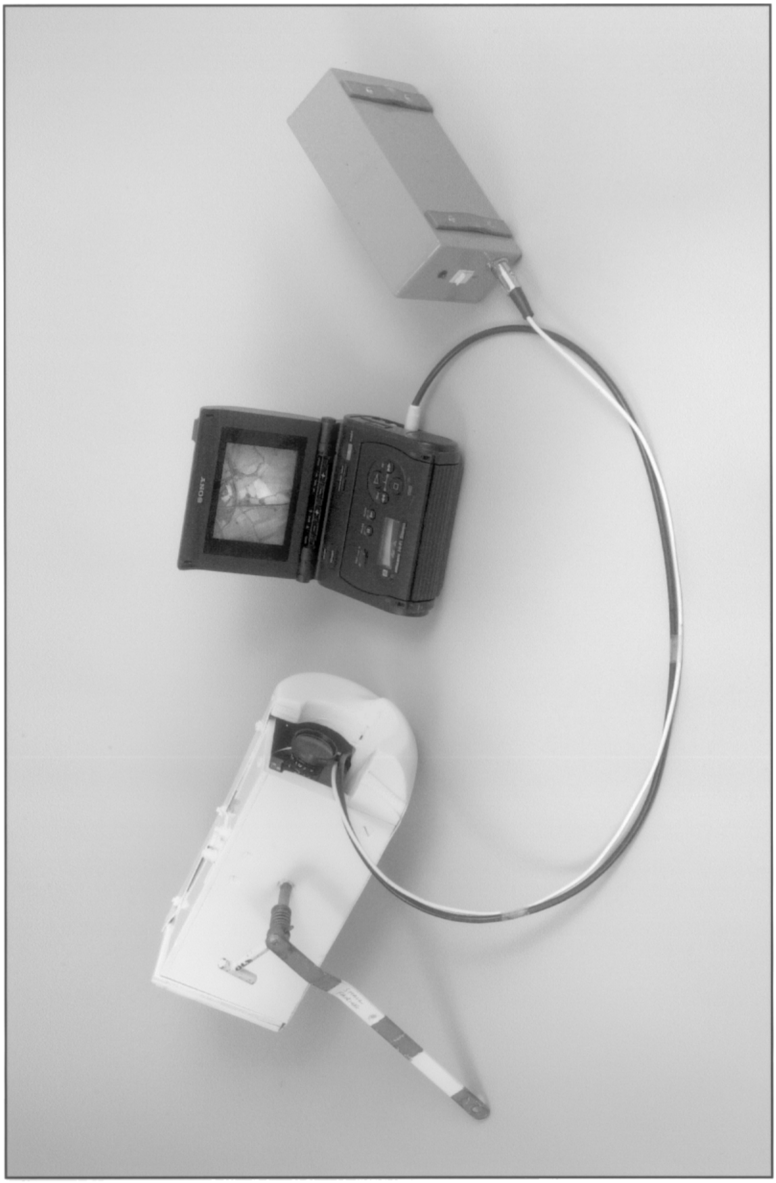


Fig. 3. Camera within the pod, power pack and recorder.

ARTICLE IN PRESS

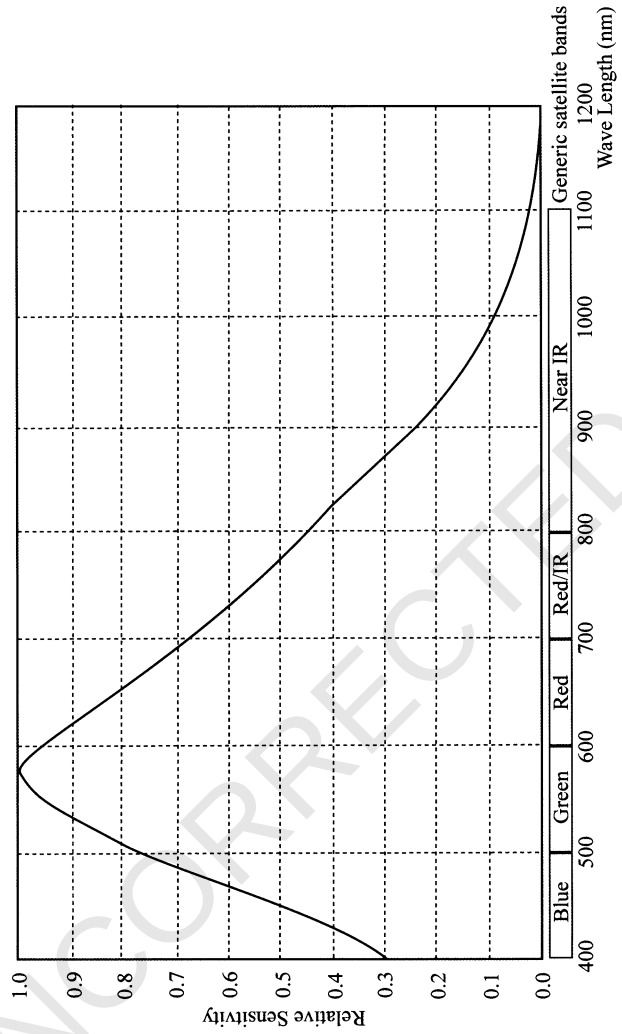


Fig. 4. Relative response of PULNiX TM765i CCD.

UNCORRECTED PROOF

of four bands of information: red, green and blue from conventional colour film and NIR from the video camera.

For the metric camera system, a rig had been designed that attaches to the front seat rails of a Cessna 172 (Ekin and Deans, 1986; Ekin, 1987). When over the target this carriage is moved out through a window fitted into the base of the door. The rig is required to be retractable as when deployed it introduces significant drag to the aircraft. The rig for the video camera is a pod attached to the aircraft door so as to be in-line with the conventional camera when it has been deployed. From the pod, a power cable runs to a high capacity (3–4 h) 12 V battery pack within the aircraft. A second cable runs from the TM765i to a Sony portable Hi8 Video Walkman. Battery power was used for both video camera and recorder since fluctuations in the power from the aircraft tended to reduce the image quality achieved.

Fig. 5 shows external and internal views of the camera rigs. The external views show the metric camera rig deployed as it would be during image capture and the pod used to house the video camera. The internal view shows the controls for the metric camera (on a single board near the camera) and the video recorder/monitor. Simultaneous operation of the metric and video camera only requires the pilot to power on the video camera and recorder to begin recording and then concentrate on the operation of the metric camera.

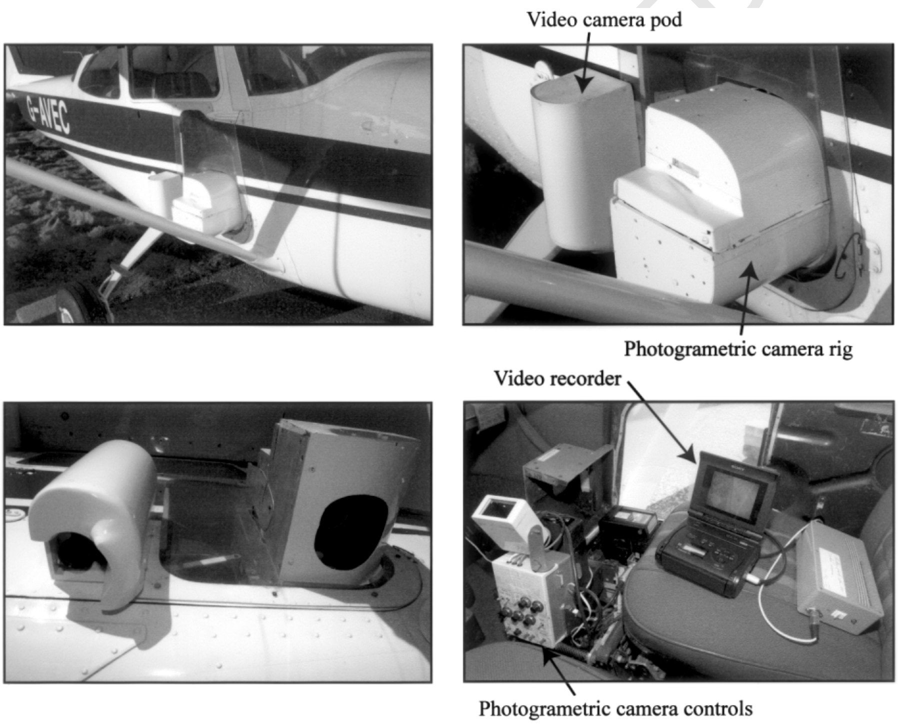


Fig. 5. External and internal views of the camera rigs.

Flight lines are pre-planned to give the desired stereo coverage with the metric camera, (approximately 60% overlap-lap and 10% side-lap). The video recorder is left running continuously during the course of the flight lines with individual frames captured on return to base. The coordinates for the start-, way- and end-points of the flight lines are stored in the GPS based navigational system. Once the aircraft is set on the required heading the metric camera is triggered at fixed time intervals by an intervalometer along the flight line (Ekin, 1994).

4.3. Data processing

The land-management application may require real-time monitoring, simple visual identification of phenomena, field-map navigation in collaboration with other media or a fully map-referenced product. Fig. 6 shows the process used to turn the raw data from the metric- and video-cameras into digital images suitable for manipulation by photogrammetric and image processing software.

4.3.1. Image capture

The medium-format metric camera films were developed and printed. The prints were then scanned on a HP 7440c flatbed scanner giving raw full-colour images of 900×900 pixels with 24 bits per pixel (2.43 Mb per image).

The data processing of the video camera data is a two-stage process, identifying the frames required and then capturing them as digital images. Frame identification requires the replay of the video tape to identify the frames required. This means the matching of the features on the video tape either with existing imagery or baseline mapping. Individual frames are converted from analogue (on the video tape) to digital format (on the PC hard-drive) using a frame-grabber; in this case the Quantum Snapmagic[4]. The images captured are single-band (8-bit) with the full sensor resolution (0.44 Mb). This low-cost unit can capture up to one frame every 2 s. To achieve the appropriate image overlap, a frame is grabbed once every 5–10 s depending on the aircraft ground speed.

4.3.2. Digital image processing

Two software packages were used for creating site coverage, ImageAssembler[5] and Orthobase[6]. ImageAssembler is a share-ware package for creating composite images, typically from sets of digital photographs. It mosaics images together by rubber sheeting the images, using two tie points per image. This mosaicing operation does not create a geo-referenced image.

Orthobase was also used to create a seamless mosaic using the more sophisticated ortho-rectification process. Ortho-rectification is similar to rubber sheeting but also removes distortions in the imagery introduced by the sensor's lens, platform attitude

UNCORRECTED PROOF

[4] Quantum Leap Software Ltd http://www.quanleap.co.uk.
[5] PanaVue http://www.panavue.com.
[6] Leica Geosystems http://www.erdas.com.

Y:/Elsevier Science/Shannon/Compag/articles/Compag1692/
ARTICLE IN PRESS

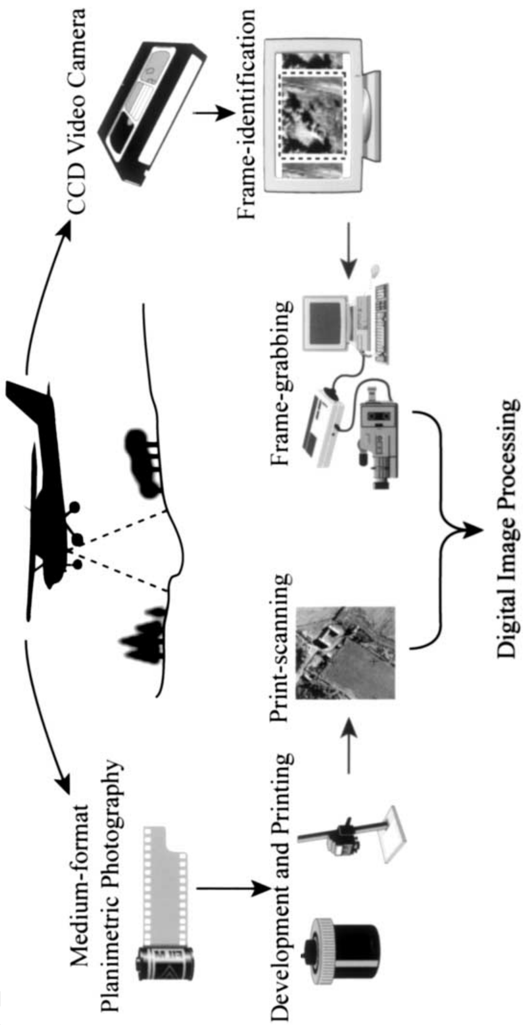


Fig. 6. Data processing.

and terrain. Removal of lens distortions uses data provided by metric-lens calibration. Lacking such data for the TM765i lens, partial data (focal-length and radial distortion) for a generic lens was used when rectifying the video-imagery[7]. Removing terrain and attitude distortions uses: ground control points (GCPs), features identified in the imagery with known x, y and z coordinates; tie points that record the location of features between pairs of images and a digital elevation model (DEM). Both the aerial photographs and the video camera images were linked to the Ordnance Survey (OS) map base and with a DEM derived from the (OS) 5 m contours dataset.

Once linked to the common map base and mosaiced, the RGB and NIR images are brought together in a multi-spectral image stack within Erdas Imagine. This enables the visualisation of false-colour composites (green, red and NIR mimicking false-colour IR film), and allows the calculation of per pixel NDVI values using the red and NIR bands.

5. Results

5.1. Ground-based testing

The series of images in Fig. 7 illustrate the reduction in blurring from image motion achieved by the TM765i compared to a conventional video camera. The pairs of images were taken from a moving vehicle (85 km h^{-1}) using a conventional shutterless video camera with an interlaced CCD (1a and 2a) and the TM765i (1b and 2b), the TM765i images are NIR. The increased sharpness of the TM765i imagery is particularly obvious for the near subjects (1a and 1b) though still significant for the more distant scenes (2a and 2b).

5.2. Airborne testing

The images presented in this section are for an area of farmland and woodland in North East Scotland, obtained on 15th September 1999 at midday, with a variety of land covers identifiable.

Fig. 8 is a seamless mosaic of 11 TM765i images. The resulting image is not referenced to a map base and retains distortions introduced by the terrain and the camera optics. This means it is not possible to combine this TM765i image with those from the metric camera. ImageAssembler does, however, allow the rapid creation of site coverage that may be used to visually identify features of interest; the 11 image mosaic was created in only 15 min. This approach is potentially of use for reconnaissance or as a secondary data source when used in conjunction with other data referenced to a map-base.

[7] Pentax http://pentax.co.uk.

UNCORRECTED PROOF

Y:/Elsevier Science/Shannon/Compag/articles/Compag1692/

ARTICLE IN PRESS

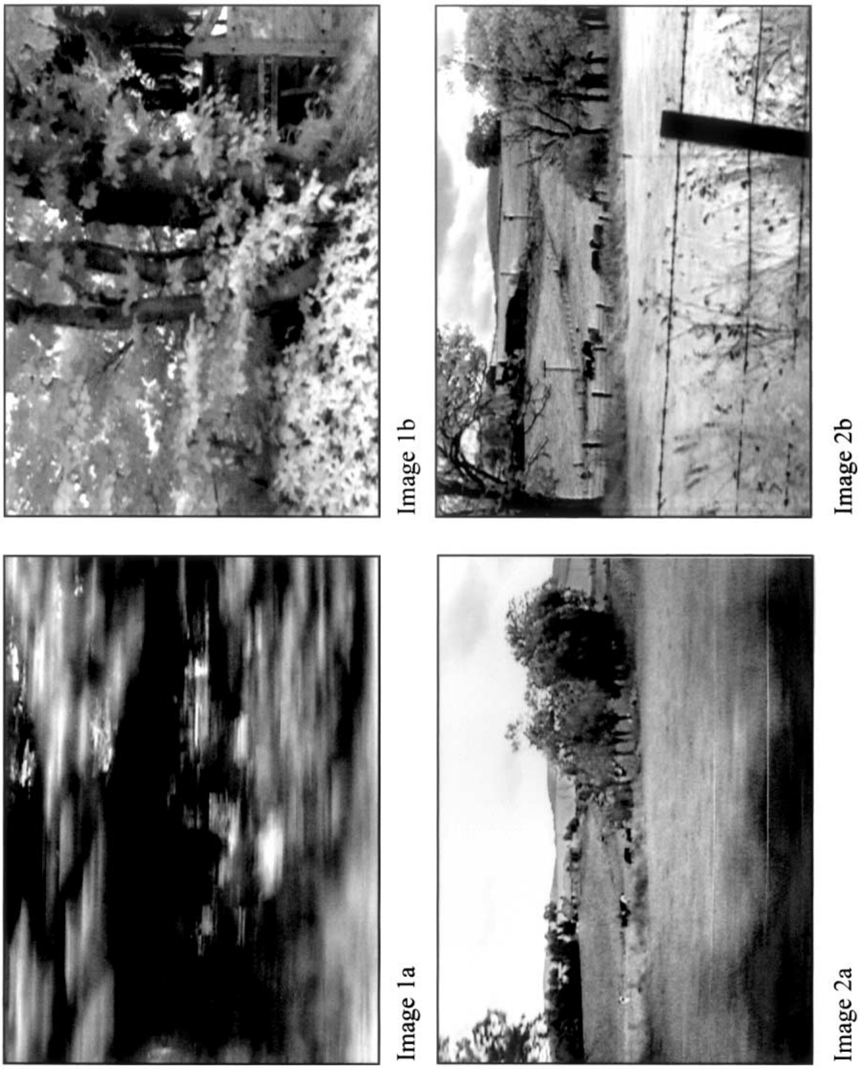
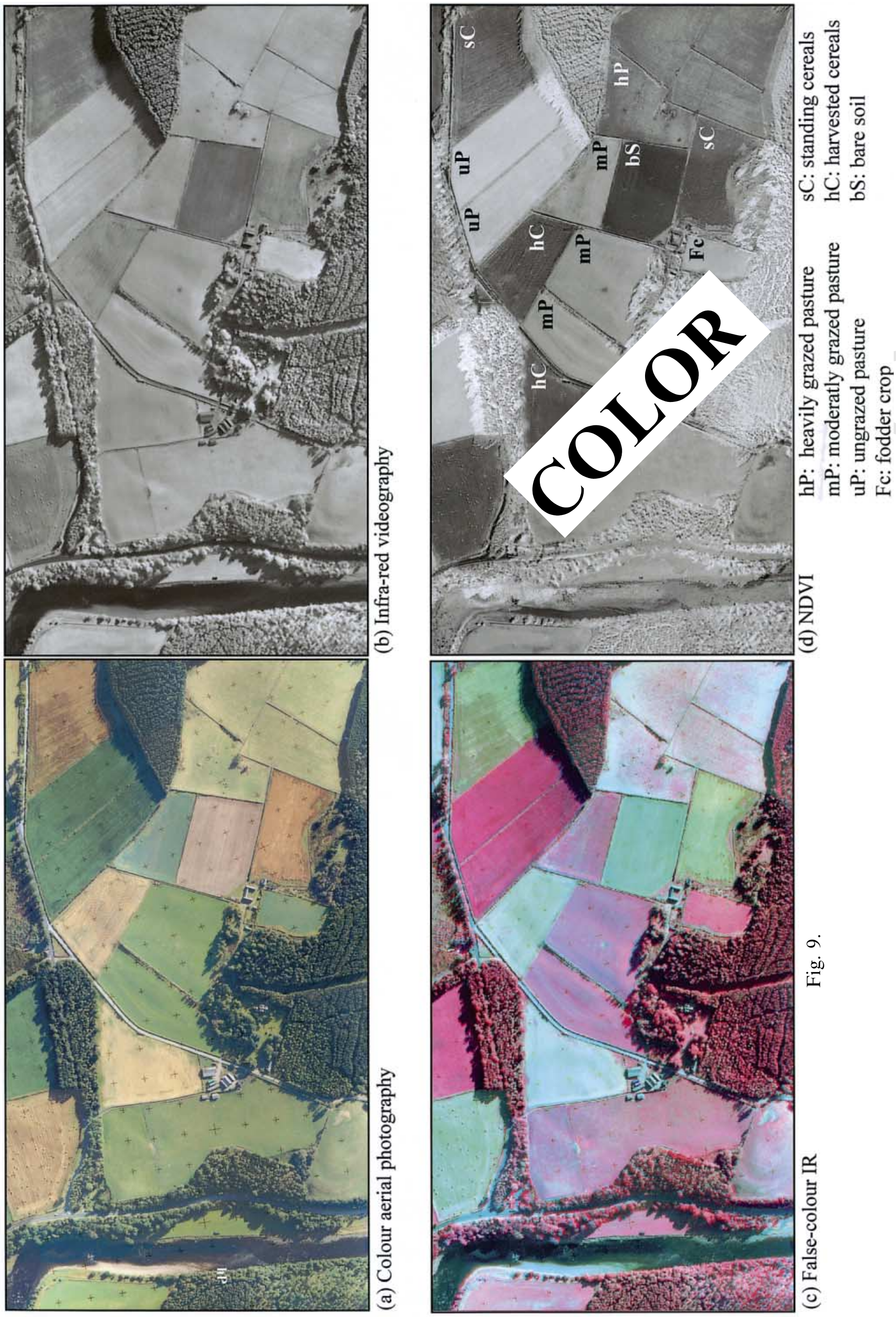


Fig. 7. Near and distant scenes captured with a conventional video camera (1a and 2a) and the TM765i (1b and 2b), from a moving vehicle.

Fig. 8. ImageAssembler mosaic.



(a) Colour aerial photography

(b) Infra-red videography

(c) False-colour IR

(d) NDVI

Fig. 9.

Fig. 9 shows examples of the ortho-rectified metric and TM765i imagery. Fig. 9(a) shows the medium-format metric colour-photography. Fig. 9(b) shows the NIR imagery from the TM765i for the same site. It is noticeable that the TM765i imagery appears less sharp than the metric colour-photography despite their identical 1 m resolution. This is probably because the metric colour-photography was re-sampled from a higher resolution. The DN range for the NIR imagery is 17–246; this results in a more than adequate level of contrast across the image.

Fig. 9(c) shows a false-colour composite of the metric and TM765i images. The match for images shows no bleeding of colours characteristic of mis-registration.

Fig. 9(d) presents the NDVI image. For the fields identified in Fig. 9(d), histograms are presented showing the proportion of each field with particular NDVI values, Fig. 10(a–d). Fig. 10(a) shows eight pasture fields, Fig. 10(b) two fields with standing cereals, Fig. 10(c) three fields with bare soil or recently harvested cereals and Fig. 10(d) a single fodder crop field. It is possible both from Fig. 10(a) and visually in Plate 1(d) to contrast the degree of grazing of the pastures from heavily grazed to ungrazed.

6. Discussion

The success or failure of an imaging system can depend less on the capital cost of the equipment and more on the recurrent costs of data processing. Capital costs can be amortised over the lifetime of the sensor. The costs of processing the raw imagery into the form required for analysis has an immediate impact on individual projects. Of particular significance is the amount of labour required.

Table 1 presents the costs of the two sensors deployed. The relative effort required for ortho-rectification and two measures of the data quality, the maximum ground resolution and the residual errors are also presented for the two sensors.

6.1. Capital costs

It is clear from Table 1 that the metric camera represents a large capital investment and has higher calibration and consumables cost than the video camera. The expense, weight and mechanical nature of the metric camera also means that it is unsuitable for use in any platform less expensive than a light aircraft. The higher capital, calibration and consumables costs must, however, be set against the lower cost of processing the imagery to create survey coverage. The software required to create geo-referenced maps is also significantly more expensive than that needed create a photo-mosaic.

UNCORRECTED PROOF

Fig. 9. Examples of the imagery.

ARTICLE IN PRESS

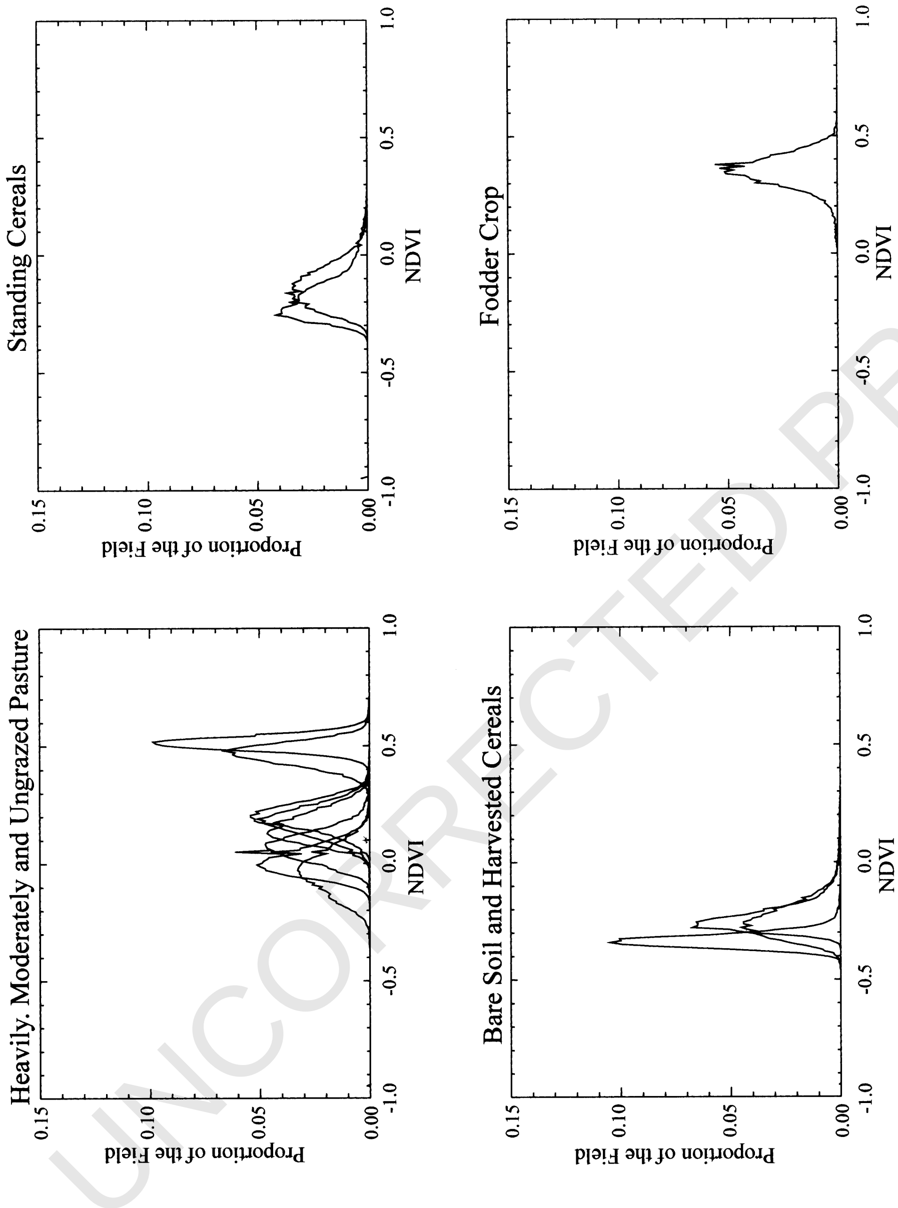


Fig. 10. Histograms of NDVI values for selected fields.

UNCORRECTED PROOF

Table 1
Costs and features of the imaging system

Item	Capital cost ($US)	Depreciation period/straight-line cost per annum ($US)
CCD camera, lens, video recorder, peripherals	2250	5/450
Metric camera, lens, peripherals	12 900	5/2500
ImageAssembler software	66	3/20
Orthobase software	3000	3/1000
Survey costs	*CCD camera* ($US)	*Metric Camera* ($US)
Calibration (per annum)	n/a	300
Consumables (per flight)	15	150
Commissioning (per flight)	450	
Survey (per hour)	150	
Data processing costs	*CCD camera*	*Metric camera*
Ground control (h km^{-2})	c.18	c.7
Mosaicing (h km^{-2})	c.6	c.4
Images (km^{-2})	27	18
GCP (pts. per image)	3.7	2.2
Data required	DEM, Base-map, dGPS(?)	DEM, base-map
Image analysis (h km^{-2})	2	
Data quality	*CCD camera*	*Metric Camera*
Maximum ground resolution	1.0 m	>0.25 m
Rectification errors (*xyz* in m)	1.1, 1.1, 2.4	0.5, 0.5, 1.0

6.2. Cost and quality of survey coverage

While the costs of commissioning and flying a light aircraft based survey are not inconsiderable, they are significantly outweighed by those of the labour-intensive data processing of the imagery. Ortho-rectification is faster for the imagery obtained with the metric camera firstly since fewer images per unit area are required. Secondly, fewer GCPs are required to achieve a given level of accuracy as the internal geometry of the metric lens is more accurately known, and since the metric camera lens has less distortion. Distortions in the video camera imagery were only eliminated by increasing the overlap between adjacent images, thereby utilising only the central portions of each frame. The labour required to ground control and mosaic the metric camera imagery is thus significantly less than that required for the video camera imagery.

The need for larger numbers of GCPs may be difficult to meet in areas such as semi-natural rangeland, where there are limited numbers of mapped features available. In such areas, it may be necessary to collect additional ground control information for features that are visible on the imagery but not mapped on the base-mapping. This can be accomplished using differential GPS but does significantly increases the cost of the final imagery.

UNCORRECTED PROOF

For ground resolution, the metric photography is limited not by the resolution of the sensor but by the accuracy of ground control. Where accurate ground control is available, particularly feature elevation values, imagery from the metric camera with 0.25 m resolution has been rectified successfully (Miller et al., 1994). For the metric imagery used here, the mean errors in x- and y-axes were acceptable, being half the resolution of the rectified imagery. For the video camera imagery, despite the additional ground control used, the errors were approximately double the metric photography. Developments of the video camera component of the system will focus on reducing these errors by using lenses with improved optics and if necessary calibrated lenses.

6.3. Alternative tools and methodologies

Alternatives to the data capture methods used here are possible depending on equipment available. In particular professional quality digital stills cameras are becoming avaliable with sufficient resolution (for example the Nikon D1x, with 5 megapixel resolution). These have the advantage of maintaining an entirely digital workflow, eliminating the processing and printing phases that are time consuming and potentially introduce additional distortions to the imagery. Digital stills cameras eliminate: the need for access to a professional quality photographic processing laboratory, the delay between capture and analysis that can be unacceptable for real-time monitoring applications and the risk of in-transit risk of damage to light-sensitive media. Such cameras, do however, represent a substantial investment (6750 $US) and the workflow benefits may not outweigh the costs of replacing existing equipment. If required, film-based medium-format metric cameras can still deliver image resolution significantly greater than even the best digital stills cameras.

If a film-based image is captured then negative scanning avoids the distortions introduced by printing and may also improve the dynamic range of colour values achieved. Negative scanners with sufficient resolution are becoming increasingly available at decreasing cost. The errors in geo-referencing introduced by flatbed scanning of a print are, however, in most cases negligible. With the limited numbers of GCPs available in rural imagery the residual errors from the ortho-rectification process are at least an order of magnitude larger than those introduced by flatbed scanning. Furthermore, clients frequently specify hard copy prints in addition to the digital products. Partly this is for convenience of use in field or office-based discussions, but is also a product of the aesthetic appeal of analogue prints with their sharp edges and ability to resolve very small features. This aesthetic appeal operates despite knowledge that the resolution of conventional photographic imagery is far greater than necessary to provide an adequate basis for most land-management decisions.

Video image capture may be significantly simplified by the use of a digital video recording device, again increasingly available at low-cost. Digital video recording means that individual video frames may simply be sampled direct from the recorder and used immediately within a digital image processing system. Data processing for digital video data simply becomes a matter of frame identification.

UNCORRECTED PROOF

The process of frame identification from video imagery can be time consuming, particularly with the less familiar NIR band. The use of contemporary stills imagery, in this case from the metric camera, while not essential, does significantly help in the identification of the start and end points of the flight lines. The success of fixed-interval frame-grabbing depends on the skill of the survey pilot in maintaining a steady rate of advance and the flight conditions being relatively calm or at least not gusty. The process of frame-grabbing could be semi-automated by tagging frames with GPS coordinates.

7. Conclusions

Combining video camera imagery with metric aerial photography has provided a method of collecting high-resolution, multi-spectral imagery with potential utility for decision support and land-management. The quality of imagery achieved to date has been evaluated as visually acceptable, with none of the characteristic blurring associated with earlier videography and achieving a good match between the two data sources and the map base features. Since the system can be implemented using off-the-self components it has a capital cost lower than comparable custom-built systems. The processing costs are principally defined by the labour required. The amount of labour required depends firstly on whether a geo-referenced product is needed and secondly on the accuracy required. Improvements to both image recording hardware and the software used to process imagery can, based on recent experience, be expected to reduce the labour required per unit area.

Acknowledgements

The research for this paper is funded by grant-in-aid from the Scottish Executive Environment and Rural Affairs Department and the Macaulay Development Trust. The authors also acknowledge the assistance provided by PULNiX (UK), Pentax (UK), Dr W.H. Ekin and Mr D. Riley.

References

Benton, C., 2001. Kite aerial photography (online). Available from: http://arch.ced.berkeley.edu/kap/, Aug, 2002.

Chavez, P., 1991. Comparison of three different methods to merge multi-resolution and multispectral data: Landsat TM and SPOT Panchromatic. Photogrammetric Engineering and Remote Sensing 57 (3), 295–303.

Cousins, D., 2001. Microlite offers true picture of crop condition. Farmers Weekly, 63.

Denniss, A., Bunn, A., 2000. SHAC UK's first SAR and hyperspectral airborne campaign. Geoinformatics 4, 12–15.

Ekin, W., 1987. A new lightweight camera rig. Photogrammetric Record 12 (69), 343–348.

UNCORRECTED PROOF

Ekin, W., 1994. The use of a low-cost GPS receiver for block aerial vertical photography. Photogrammetric Record 14 (84), 875–886.

Ekin, W., Deans, N., 1986. Further developments of an inexpensive retractable vertical camera rig for a light aircraft. Photogrammetric Record 12 (68), 227–236.

ESA-ESRIN, 2002. European EO Services: Activities, Achievements, Issues and Future Prospects, Summary Report of ESA-Industry Workshop: EO Market Development, ESAESRIN, Frascati, Italy.

Guneriussen, T., Johnson, H., Sand, K., 1996. DEM corrected ERS-1 SAR data for snow monitoring. International Journal of Remote Sensing 17 (1), 181–195.

Hatfield, J.L., Asrar, G., Kanemasu, E.T., 1984. Intercepted photosynthetically active radiation estimated by spectral reflectance. Remote Sensing of Environment 14, 65–75.

Kanemasu, E.T., Niblett, C.L., Manges, H., Lenhart, D., Newman, M.A., 1974. Wheat: its growth and disease severity as deduced from ETRS-1. Remote Sensing of Environment 3, 255–260.

KODAK, 2001. KODAK Aerial Imaging Products (online). Available from: http://www.kodak.com/US/en/government/aerial/products/index.shtml, Aug, 2001.

Legg, C., 1991. A review of Landsat MSS image acquisition over the United Kingdom, 1976–1988, and the implications for operational remote sensing. International Journal of Remote Sensing 12 (1), 93–106.

Leone, A., Wright, G., Corves, C., 1995. The application of satellite remote sensing for soil studies in upland areas of Southern Italy. International Journal of Remote Sensing 16 (6), 1087–1105.

MacDonald, K., 2001. Introduction to video 101 (online). Available from http://www.pulnix.com/imaging/pdfs/primer.pdf (Aug, 2002).

Matthews, K., Sibbald, A., Craw, S., 1999. Implementation of a spatial decision support system for rural land use planning: integrating GIS and environmental models with search and optimisation algorithms. Computers and Electronics in Agriculture 23, 9–26.

Miller, D., Finch, P., Fon, T., 1994. A model of DEM and orthophotograph quality using aerial photography. In: Pröbsting, T. (Ed.), Photogrammetrie and Forst. Albert-Ludwigs Universität Freiburg, Freiburg im Breisgau, pp. 227–239.

Moran, M., Inoue, Y., Barnes, E., 1997. Opportunities and limitations for image-based remote-sensing in precision crop management. Remote Sensing of the Environment 61, 319–346.

Olby, N., 1999. EOPOLE Newsletter, Earth Observation Data Policy and Europe, Issue 1, University College, London.

Richardson, A.J., Everitt, J.H., Escobar, D.E., 1992. Calibration of gain compensated aerial video remote sensing imagery using ground reflectance standards, Proceedings of the Thirteenth Biennial Workshop, American Society for Photogrammetry and Remote Sensing, Orlando, Florida, pp. 87–97.

Silbernagel, J., Lang, N., Wample, R., Smithyman, R., Hendrix, W., 1998. Geospatial analysis of blackleaf in vitis, In: Petoskey, B. (ed.), First International Conference, Geospatial Information in Agriculture and Forestry, Decision Support, Technology and Applications, vol. 1, ERIM International, Inc., Lake Buena Vista, Florida, pp. 1257–1264.

Tarussov, A., Dubois, J.M.M., Wenzl, M., 1996. Light airborne remote-detection systems for the earth sciences. International Journal of Remote Sensing 17, 2699–2718.

Thomas, M., 1997. DIY remote sensing. Mapping Awareness, 32–33.

Um, J., Wright, R., 1996. Pipeline construction and reinstatement monitoring: current practice, limitations and the value of airborne videography. The Science of the Total Environment 186, 221–230.

Vlcek, J., 1983. Videography: some remote sensing applications, Proceedings of the Fiftieth Meeting, American Society for Photogrammetry and Remote Sensing, Washington, D.C., 63–69.

Wascher, D. (ed.), 2000. The face of Europe-policy perspectives for European landscapes, ECNC Technical Report Series, European Centre for Nature Conservation, chapter 4, Methodological Approaches, 43–50.

Wright, G.G., Birnie, R., 1986. Detection of surface soil variation using high-resolution satellite: results from the UK SPOT simulation investigation. International Journal of Remote Sensing 7 (6), 757–766.

Wright, G.G., Sibbald, A.R., Allison, J., 1997. The integration of a satellite spectral analysis into a heather moorland management model (HGMM): the case of Moidach More, northeast Scotland. International Journal of Remote Sensing 18 (11), 2319–2336.

UNCORRECTED PROOF