# AIRBORNE MULTISPECTRAL DIGITAL CAMERA AND VIDEO SENSORS: A CRITICAL REVIEW OF SYSTEM DESIGNS AND APPLICATIONS

**Canadian Journal of Remote Sensing, Special Issue on Aerial Optical Remote Sensing**
**21: 245-273.**

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## SUMMARY

Airborne multispectral remote sensor development based on low cost solid-state video and digital cameras has proceeded rapidly in the past ten years to a level where such sensors now compete with larger more sophisticated sensors in the commercial mapping and scientific research contract marketplace. For many organizations, development or leasing of such sensors is a cost-effective and advantageous alternative to buying data. The objective of this paper is to review the state-of-the-art in multispectral video/digital camera sensor design, the benefits and limitations of these designs, the types of applications in which they have been most commonly used, and some potential new applications. The paper demonstrates that low cost custom sensor design is currently viable, that the field of applications is very diverse, both in type and in level of scientific sophistication, and that many of these applications are operational, having been integrated into routine mapping/monitoring programs.

## 1. INTRODUCTION

In the past decade, airborne videography (in this paper, the term videography will be meant to include digital cameras unless otherwise stated) has developed rapidly from small individual research projects by less than five groups in the United States and Canada to very diverse research and commercial application by hundreds of users today. In 1994, for the first time to the author's knowledge, a contract was awarded by a major mapping user (the U.S. Army Corps of Engineers) for a project to map land cover in a 36,850ha area of Mississippi using airborne multispectral videography as the primary image data source (Gress, 1994). This development and acceptance of videography has been based primarily on the low cost of the sensor components which has allowed many research groups and mapping firms to design and construct their own sensors, or to have data acquired at minimal cost. Advances in technology have increased camera spatial and radiometric quality to a level where it is now possible to build a digital camera-based multispectral sensor for under $50,000 CAN which can be used in many of the same applications that were previously the domain of multispectral scanners an order of magnitude more costly. In the author's opinion, digital cameras developed to be compatible with high definition television (HDTV) formats will become the standard consumer imaging device and costs of utilizing them in remote sensing will decrease even further. Adaptation of sophisticated remote sensing techniques such as imaging spectrometry into low cost imaging will also continue as new designs based on video cameras emerge and as more advanced systems embrace higher spatial resolution digital camera developments.

## 1.1 The Airborne Videography Approach to Remote Sensing

In addition to the technological aspects described above, a distinct approach or paradigm has developed within the videography community which is very much in evidence at conferences and professional meetings. The approach can be summarized as applications-driven sensor and technique development with the constraint of cost-effectiveness. It is the author's opinion that the major deficiencies of much of the larger government-sponsored remote sensor development programs have been: a) applications' needs have often been developed after a commitment has been made to an expensive technology, and b) sensor design has not been conducted in the context of optimization of cost-effectiveness for those applications (although this is changing in Canada with re-organization and reduction of government funding). In the videography approach, existing research and operational mapping problems are addressed by determining the best sensor/platform configuration for the least cost. For example, King (1994a) conducted research to determine the most appropriate sensor configuration to be used by a non-governmental environmental organization in monitoring and mapping of a variety of resource industry activities. In such a needs assessment approach, many of the sensor solutions found to be optimal include video or digital cameras incorporating simplifications of techniques used with larger, more sophisticated sensors. This approach is not without limitations as data are generally of lower quality than one would expect from an expensive government-sponsored sensor. In fact, in the author's experience, a major criticism of the videography approach is that it often lacks the scientific rigour of methods and techniques developed in the remote sensing research community in the past twenty years. Such criticisms often have justification from the perspective of remote sensing as a research tool but they have not affected the progress of airborne videography development and acceptance in cost-effective operational mapping.

The applications in which airborne videography has found a niche tend to be those where relatively large scale imaging with ground pixel sizes in the range of 0.1m to 3m are required, and spatial coverage of individual images ranges between 100m and 3km. The vast majority of operational applications use some form of multispectral information but often for qualitative visual analysis, and not for quantitative analysis using automated computer-based techniques. Only a few researchers have developed and applied calibration techniques (as discussed later in this paper), although such techniques will increase in importance as their applicability increases and their cost of implementation decreases.

## 1.2 A Brief History of Airborne Videography and Digital Camera Remote Sensing

Early attempts to develop multispectral airborne video sensors (e.g., Robinove and Skibitzke, 1967 (this 3-camera sensor had mid-IR (1-5µm as used in this paper) imaging capabilities to 2.2µm); Mozer and Seige, 1971; Roberts, 1973) demonstrated that such analog electronic imaging systems were feasible, and that high spatial and spectral resolution were attainable but that the equipment was very bulky and generally fragile (being based on broadcast quality tube cameras). Development of video-based sensors was sporadic until the late 1970s and early 1980s when the first consumer-grade tube and solid-state cameras became available. Of the four systems developed in the early 1980s, two used tube based cameras and two used solid-state CCD (charge coupled device) sensors. By 1986, all new video sensors being developed were solid-state. The earliest solid-state sensor developed for airborne remote sensing incorporated a 100 x 100 CCD imager (Hodgson et al., 1981). It was followed by a four CCD camera multispectral sensor developed at the University of Toronto between 1983 and 1985 (Vlcek and King, 1985; King, 1988; King and Vlcek, 1990). During the same mid-1980s period a four camera tube-based sensor was developed at the United States Dept. of Agriculture, Weslaco TX research station (Nixon et al., 1985), a rotating filter wheel solid-state system was developed by Xybion Electronics of New Jersey (Niedrauer and Paul, 1985), and a beamsplitting three band (green, red, and near-IR (750 - 1000nm as used in this paper) tube-based camera was developed at the University of Minnesota (Meisner and Lindstrom, 1985). These three designs of multiple cameras, filter wheel, and beamsplitting comprise the principal approaches to multispectral imaging using video and digital cameras which are still being pursued today. They will be described in detail with additional examples of sensors developed subsequently.

Since the early 1990s the developments in low cost videography have been in three primary domains: i) integration of global positioning systems (GPS), ii) development of radiometric calibration capabilities, and iii) development of digital camera sensors. In addition, specialized capabilities such as distance/height measurement with laser altimeters, photogrammetric mapping, and low cost imaging spectrometry have been evaluated by a limited number of users. Each of these will be discussed with reference to the appropriate research and/or applications.

The diverse applications domains which have embraced video and digital camera technology are difficult to classify for summary discussion. In this paper, a classification by spatial format or geographic entity has been used in which most applications can be placed. The classification reviews applications as point (including site specific applications), line or corridor, and area-based (including multi-scene thematic mapping) in order to evaluate the utility of current technology and methods. The results of various researchers and operational organizations which are referenced in this paper are either from very recent or ongoing (and in some cases unpublished) work. They demonstrate the level of expertise and sophistication which currently exists in airborne video/digital camera imaging, and the direction this technique is heading in the near future.

### 1.3 Objectives of this Paper

The primary objective of this paper is to critically review the state-of-the-art of airborne videography and digital camera sensor designs and their associated imaging/mapping methods. This review is presented in the context of applications needs, that is, with reference to the relative success or utility of these designs and methods in providing cost-effective spatial information for given applications.

This article is intended to be both an update of previous 'review' articles on videography (Wright, 1993; Mausel et al., 1992a; Everitt and Escobar, 1989) and to provide a more indepth discussion of elements of sensor design and their relation to applications.

## 2. SOLID-STATE VIDEO AND DIGITAL CAMERAS

The following discussion of video and digital cameras is limited to solid-state imaging techniques and characteristics. It is intended as an overview of aspects important to applications remote sensing and development of low cost sensors and is not intended to be a rigorous technical discussion. The reader should refer to the many electronics signal generation and digital imaging texts or journals such as the IEEE or SPIE for more details. The term digital camera is used to refer to solid-state arrays which produce a digital two dimensional frame image. The author has evaluated and discussed their use in remote sensing in several articles (e.g., King, 1995; Lévesque and King, 1995; King et al., 1994; King, 1994b; King, 1993; King, 1992b; Mausel et al., 1992a). Discussion of linear arrays is beyond the scope of this article.

### 2.1 Charge Generation

Solid-state array imaging sensors consist of wafers (chips) of specific composition which absorb incident photons into their internal structure and release a proportionate amount of free charge carriers. The basic mechanism of charge generation consists of photons arriving at individual potential wells or photosites (arranged in a raster array), a certain proportion being absorbed, and those absorbed photons causing electrons in the chip material to become excited and jump to outer shells. Once in the outer shells, the electrons are less bound to the atomic nuclei and they can be held in electrodes embedded in the substrate by application of a potential voltage. They can then be transferred from electrode to electrode to the side of the chip (or to points within the chip) by varying the potential at each electrode. This potential is gated or timed, so that the sensor chip can be exposed to incident energy for a given time interval, and the generated free charge carriers are drawn off to form an analog electric signal. To-date no purely digital camera with a binary output signal from each photosite exists; the analog signal must be converted to digital either within the camera (hence the term digital camera) or using a frame grabbing device exterior to the camera.

### 2.2 Charge Readout

There are different techniques of charge accumulation in the chip which have resulted in various types of sensors such as CCD, CID (charge injection device) etc. Each has slightly different signal generation or processing features which are beyond the scope of this article but which result in slightly different sensor response and spatial resolution. CCDs have become the most common and least costly, and are used in most commercial or research multispectral video systems. There are also several types of charge transfer techniques out of the photosites. Most cameras use 'interline' transfer techniques which means that the photosites do not touch each other in the raster grid but that there are column or row spaces between them. The charge from each photosite is read off to the adjacent space (called a shift register) and then down the spaces (usually columns) to the edge of the chip. Other sensors use 'frame' transfer techniques where the charge for the whole frame is transferred to a buffer of the same size and then read out from that, or where the charge is attracted through adjacent photosites to the edge of the chip. Frame transfer techniques allow the photosites to be very close to each other (and sometimes touch). This closeness, called the 'fill factor', is important in terms of spatial resolution because it is inversely related to aliasing, the false resolution of spatial frequencies above the Nyquist limit (Barbe and Campana, 1976). Some recent digital frame transfer cameras have 100% fill and minimize the effects of aliasing. An added detrimental effect which occurs when charges are transferred through adjacent photosites is that charge errors such as saturation or lack of signal in a photosite(s) can sometimes spread through the transfer area. Saturation causes 'blooming', a transfer of high voltage which appears white in the image. A dead photosite may transfer a zero signal level resulting in a black column in the image. Most solid-state chips have several 'blemishes' of either individual photosites or columns. Some manufacturers have tiered pricing for individual camera models which reflect the number of blemishes in the chip and their location in the field of view.

### 2.3 Image Formation

The analog output signal from the sensor usually consists of a specific voltage (often 0-1V) where the maximum voltage represents photosite saturation, and the minimum image signal voltage represents no incident radiation to the photosite (the black level). Another portion of the voltage range below the black level is used for signal timing and blanking in video systems. The analog voltage can be displayed directly by modulating electron guns of a monitor in proportion to the voltage level, or it can be recorded directly using analog recording techniques such as a video tape recorder. Alternatively, this small voltage range can be sampled digitally at a given spatial frequency to produce a digital image. Typically, digitization is conducted at the same number of rows and columns as are present on the chip. Current video sensors with approximately 780 x 512 photosites on the chip are usually coupled to frame grabbers with the same sampling frequency. Digital cameras, typically with more than 1024 x 1024 photosites, utilize an in-camera A/D converter but the signal must still be formatted into a raster grid for subsequent computer display. This is accomplished either within the camera (typically in field-portable models) or using a computer frame grabber. Frame grabbing in the same format as the imaging chip does not mean, however, that spatial resolution is not degraded in the digitization process as all signal processing steps contribute to spatial resolution degradation (e.g., see Slater, 1980; King, 1992a). Unlike video, there are no current standards for spatial format of digital camera sensors. Sensor chips in the 1k x 1k range have most commonly been developed with a 1280 x 1024 format, but recently, a format of approximately 1500 x 1024 has become common. At higher resolutions, sensors with formats such as 2k x 2k, 3k x 2k, 4.4k x 3.4k, 4k x 4k and 5k x 5k have been developed. The 3k x 2k sensors are becoming common as alternatives to 35mm film. The most significant milestone of these increases in numbers of photosites will probably be the development of a sensor with enough photosites and angle of view to match the resolution of standard large format (23cm x 23cm) aerial photography.

Radiometrically, digital sampling has commonly been 8-bit, that is, the sensor output voltage is divided into 256 possible grey levels. However, current digital cameras generally provide for 10, 12, 14, or 16-bit digitization providing up to 64,000 grey levels at correspondingly greater costs. Such advanced sensors with pixel formats above 2k x 2k are currently too costly (about $40,000

CAN) to utilize operationally by most videography users. However, there is much interest in such cameras by remote sensing firms and government agencies involved in research and development in order to replace the multispectral line scanners which were most common through the 1980s. With the constant cost decreases of imaging technology predicted for the near future, advanced capabilities beyond 8-bit, 1k x 1k sensing will soon be feasible for most users.

## 2.4 Spectral Response

Materials used in solid-state sensors have differing spectral sensitivities. The most common chip material is silicon. It has been mass manufactured and integrated into optical cameras since about 1975. Others, such as PtSi, InSb, and HgCdTe are more expensive to manufacture but respond to different wavelengths in the mid-IR and thermal-IR and generally not with the same quantum efficiency (the efficiency in conversion of incident photons to image signal). For CCDs the quantum efficiency is typically about 10% in the blue (380-430nm), about 40-60% in the far red/beginning of the near-IR (680-800nm), and then about 10% again in the near-IR at 900-1000nm. The shape of the response curve is almost Gaussian. An important point is that almost one-half the response is in the near-IR, providing excellent potential for Colour Infrared (CIR) composite imaging and vegetation studies, while blue response is very poor. The low signal-to-noise ratio in the blue reduces the clarity of images and often necessitates a wider bandwidth filter, larger aperture, or increased gain (which also adds noise). Some camera manufacturers have recognized the need for greater blue response in certain applications and have intensified the signal level through electronic or optical means.

The response of typical CCDs allows use of filters of bandwidths as small as 10nm except in the blue where 25nm or more is required. Use of interference filters less than 10nm in bandwidth is not recommended because the shift in the wavelength of transmission with increasing view angle can become a significant proportion of the bandwidth. With view angles of greater than 30 , the wavelength of transmission at the edge of the field of view may be outside the stated filter bandwidth if such narrowband filters are used. This shift is towards the blue end of the spectrum and can be estimated using standard formulas often given in optical products catalogues (e.g., Melles Griot, 1993). It was corrected for using curved filters in the MEIS II linear array sensor at some expense.

Silicon sensor response is very linear (Neale and Crowther, 1994; King, 1992a; Crowther, 1992) in all spectral bands, that is, the analog voltage amplitude and/or the digital grey level is directly proportional to the target radiance. This permits fairly simplified radiometric calibration of video and digital cameras, although, as discussed later, the two-dimensional format of the sensor presents some difficulties.

## 2.5 Spatial Resolution

The brief overview of spatial resolution given below summarizes typical ranges of resolution for video and digital cameras in the common units of line pairs per millimetre on the sensor surface. This is the most common and easiest method of evaluating resolution and can be carried out effectively using bar targets in the lab or from the air. The modulation transfer function (MTF) is a more rigorous measure of optical-electronic image formation capabilities and has been described in many papers on solid-state imaging (e.g., Neville, 1993; Schroeder, 1992; Jensen, 1968). Silicon-based solid-state imaging sensors have variable spatial resolution depending on the number and size of the photosites on the sensor chip. A discussion of the relationships between photosite size, spatial resolution, and view angle is presented in Sections 5.1.1 and 5.1.2. The approximate maximum spatial resolution for a high contrast, well illuminated target imaged using common video techniques, digital cameras, and standard 35mm film cameras is given in Table 1. Note from Table 1 that video resolution in the vertical image direction is always less than in the horizontal image direction because of the requirements for a limited number of scan lines (480 image lines) by television standards. Even when the signal is digitized directly and not recorded on a video cassette recorder (VCR), the vertical resolution is less than the horizontal due to interlacing overlap (see section 2.6.1). In digital cameras, the resolution is essentially the same in both directions if the photosites are square.

The maximum spatial resolutions listed in Table 1 are rarely achieved as resolution is a function of target contrast, illumination, lens aperture, and spectral band. King (1992a, 1988) evaluated the spatial resolution of a multispectral video sensor while varying these parameters. It was found that spatial resolution decreased linearly but not significantly with target contrast to a contrast of about 20% where it fell rapidly. Resolution also varied significantly with spectral band, being lower in the blue due to poor signal-to-noise ratio and lower in the near-IR due to crosstalk between photosites by photons absorbed deeper in the sensor substrate at these wavelengths (Purll, 1983). The lower near-IR resolution tends to cause blurring so manufacturers generally place a near-IR cut-off filter in front of the lens which must be removed for near-IR imaging.

Table 1. Maximum approximate spatial resolution for video, low cost digital cameras, and 35mm film imaging in the horizontal and vertical image directions (H,V respectively) in line pairs per millimetre (lp/mm).

| Data Acquisition Format | | H resolution | V resolution |
|---|---|---|---|
| Video: | 792 x 480 photosites,<br>6.4 x 4.8mm sensor,<br>Super VHS recording. | 25 | 20 |
| Video: | 792 x 480 photosites,<br>6.4 x 4.8mm sensor,<br>digitized directly. | 40 | 30 |

| | | | |
|---|---|---|---|
| Digital Camera: | 1280 x 1024 photosites, 9 x 7mm | 55 | 55 |
| Digital Camera: | 1280 x 1024 photosites, 21mm x 16.8mm | 24 | 24 |
| 35mm film: | standard | 80 | 80 |

Also evident in this research on spatial resolution was that specification of the nominal ground pixel size as the defining resolution element is convenient but useful only for generalized application. It overestimates by a significant amount the size of an object which can actually be resolved, (ie. detected, identified, and measured). The spatial resolution measure of lp/mm from empirical tests is much more accurate in flight planning related to object detection.

### 2.6 Image Scan Formats

The two most important aspects of image scan format related to system design are whether the generated image is line-interlacing and the read-out rate of the sensor.

#### 2.6.1 Interlaced vs. non-interlaced imaging

The output signal from a solid-state sensor can be formatted to match television scanning standards or as a raster image read row by row. The term 'video' has been generally applied to those imaging signals which include, amongst other specifications, a specific number of scan lines where the odd numbered lines are scanned from top to bottom of the display first, followed by the even numbered lines. In North America the NTSC (National Television Standards Committee) system specifies 525 total lines per video frame with the odd 262.5 and even 262.5 lines termed 'fields' (in Europe and elsewhere there are other numbers of lines and scan frequencies). Each field is scanned in 1/60 sec with a complete 'interlaced' frame being scanned in 1/30s. This makes use of the retention time of the eye and avoids flicker while allowing for a lower bandwidth signal to be broadcast. In airborne imaging with a constantly moving platform, the time between successive video fields presents some problems and any sampled frame must be reconstructed using post-processing algorithms (see Section 5.1.2).

Digital cameras are generally non-interlaced; each image is read out row by row. They are termed full frame, non-interlaced, or progressive scan imagers. Some cameras with video range formats have been developed which are full frame. They provide a full 484 lines of vertical resolution per shuttered image (some in 1/60s) whereas only 244 image lines are produced per interlaced video field. For example, Kestral Corp. of Albuquerque, New Mexico has incorporated a full frame camera into their multispectral sensor called 'AirCam' (Butler and Otten III, 1994). If future HDTV standards are full frame, the term 'video', with its interlacing connotation, should probably be discarded. However, this will not likely happen because high resolution digital consumer imaging devices of the future will still be called video cameras even if they are non-interlaced. The term 'videography' (first proposed by Vlcek, 1983) as used in this paper will probably not disappear and will be applied to digital camera imaging using HDTV components.

One specific type of high resolution digital camera consists of a low resolution standard video CCD chip (e.g., 768 x 525) which is quickly moved along one or two axes a distance of 1/3 to 1/2 pixel to create a higher resolution image. This type of design basically serves to fill in the spaces between photosites in a low cost interline transfer CCD. It is very useful in still imaging but is not suitable for airborne imaging due to aircraft movement during the time of CCD shifting.

#### 2.6.2 Read-out rates

As stated above, NTSC video imaging rates are 1/60s per field, 1/30s per frame. This produces a large amount of imagery and typically results in over 95% forward overlap. One under-utilized benefit of such data redundancy is that objects can be viewed as they pass across the vertical field of view. Illumination/view angle effects can be evaluated by sampling the same objects in several sequential images (King, 1991). More detail is given on this in Section 5.1.1. Another benefit is that the redundant information in multiple images acquired at the video rate (1/60s per field) can be used to significantly improve the spatial resolution of video images (Verreault et al., 1995; Verreault and Gagnon, 1993). The major disadvantage of the high frequency of image generation in video systems is that data volumes are high for all but the shortest of missions. Recording such large quantities of data in analog format on a VCR is simple because of its high bandwidth/storage capabilities. However, digital storage must be at slower rates and is only possible for reduced overlap when several spectral bands are being acquired. Currently, many digital video systems utilize low cost 8mm storage devices with storage rates of approximately 0.5 Mbyte/sec (Mb/s). This impacts the design of flight parameters. As an example, for a typical digital video format of 792 x 480, four bands of 8-bit imagery (1.52 Mb) can be stored in about 3 seconds. For aircraft speeds typically about 50m/s, the required forward advance of 150m between multispectral datasets is fine for 60% stereo overlap as the resulting coverage in the vertical image direction will be 375m. Such a coverage could be obtained with 1/2" video cameras (6.4 (H) x 4.8mm (V) sensor) using a 16mm focal length lens at about 1250m altitude above ground level. The ground pixel size would be on the order of 0.75m in the vertical direction. This represents about the minimum coverage and smallest pixel size possible for this imaging configuration with the storage rate constraint. If smaller pixels were desired, it would be necessary to reduce forward image overlap, reduce the aircraft velocity, and/or acquire fewer spectral bands. Progress is also being made in recording rates as new tape devices in the lower cost range capable of sustaining 2-4Mb/s, and high capacity (> 9Gb) hard drives with writing speeds between 10 and 20Mb/s are developed.

Digital cameras in the 1000 x 1000 to 2000 x 2000 range typically have flexible readout rates between about 10 and 30 frames per second, although almost any read-out rate is possible given the trade-off with number of pixels. Some cameras with smaller formats in the 256 x 256 range can output up to 1,000 frames/s while even smaller format cameras down to 64 x 64 can achieve read-out rates up to 15,000 frames/s (Maas, 1992). Low cost storage at 0.5 Mb/s is often too slow for remote sensing using large sensors and/or fast image generation rates. For full resolution storage of four or more 1k x 1k spectral bands, means of higher speed (and generally higher cost) storage such as high speed frame grabbing boards with large amounts of local bus memory are required. This type of storage may be suitable for many applications and is being integrated into the system under development by the author (described in Section 3.2).

## 2.7 Computer Controlled vs. Manual or Autonomous Imagers

Most standard industrial video cameras are designed to operate remotely and autonomously. For such cameras, the aperture is generally set when the camera is positioned, and the shutter speed or gain is allowed to vary automatically in response to varied illumination or target brightness. Such automatic exposure control optimizes overall image contrast and the brightness over which sensor response is linear (Richardson et al., 1992), but it presents problems if used in continuous airborne imaging where feature image brightness from scene to scene may vary due to internal camera adjustments. Consequently, most sensor developers disable the automatic gain control (AGC) (e.g., Neale and Crowther, 1994; Mao et al. 1994). In recent developments of both analog and digital sensors, electronic or computer control of the shutter speed has been included. This allows the shutter speed to be remotely adjusted for optimum exposure. The optimum exposure is usually determined by viewing images/histograms of each spectral band in-flight. Another benefit of a user-controlled shutter speed which is becoming increasingly important with advances and greater interest in calibration is that the shutter speed of each spectral band can be set in an inverse relation to the camera's spectral response curve. This aids in analysis of feature spectral reflectance by flattening out the camera spectral response and eliminating camera induced spectral variations, although image exposure may not be optimized.

Complete computer control is becoming more common in digital cameras. They typically allow flexibility of camera readout rates, shuttering, gain, image size, format, location on the display, text/graphics applications, and real-time processing (sometimes termed DSP - digital signal processing) of the imagery. If at all possible, a system which will be flexible for many applications should be computer controlled in as many ways as possible. Specific details of imaging parameter control in the multispectral digital camera sensor developed by the author are described in Section 3.2.

Some digital cameras allow manual triggering by the operator. They have been developed primarily for consumer and photojournalism and consequently have been designed to take the 35mm photography approach into the realm of digital imaging. Most consist of video (approximately 780 x 512) or non-video (usually more than 1,000 x 1,000) format CCD chips housed in a hand-held 35mm camera body with a small hard disc either attached to the camera or housed in a separate portable casing. Some of these cameras allow operator viewing and editing of images on a small display monitor as well as some control of imaging parameters (e.g., electronic zoom, white balance etc.) through a keyboard housed in the casing. Although such cameras are more difficult to adapt to flight mission data acquisition requirements, they can be useful in reconnaissance, or they can be interfaced with an external computer or GPS.

# 3. MULTISPECTRAL VIDEO AND DIGITAL CAMERA DESIGNS

Multispectral airborne video and digital camera sensor development has generally been based on perceived needs for four spectral bands between the blue and near-IR. Studies of multispectral video to determine the intrinsic dimensionality (the number of spectral bands accounting for 95% of the data variance in principal components analysis) were conducted by the author (King and Vlcek, 1990). The data consisted of varied land cover types (forest, soil, grass, road) imaged in 11 bands, each 40nm in bandwidths centred every 50nm from 400nm to 900nm. The dimensionality was consistently five for all sets of imagery acquired during the growing season. Evaluation of band contributions on these components showed that the same four bands consistently contributed most to the data variance. They were the blue-green (430-470nm), green-yellow (530-570nm), deep red (680-720nm) and near-IR (780-820nm). Thus, four bands is a suitable number. However, correlation analysis (King, 1988) showed adjacent bands to be very highly correlated, so a smaller number of bands could feasibly be used for certain applications. Under read-out and storage rate constraints, some 3 band systems have been developed which generally acquire images in the green, red, and near-IR. Two band systems have also been developed for red/near-IR ratioing in vegetation studies. Most systems have capability for changing filters so spectral bands can be tailored to specific applications. A few researchers have integrated mid-IR or thermal-IR sensors into their video systems for specific projects (e.g., Benkelman and Behrendt (1992) using a solid-state thermal sensor; the Weslaco group incorporating mid-IR tube cameras beginning in the mid-1980s (Everitt et al. 1986)).

Current video and digital camera system configurations can be categorized by the way in which the spectrum is divided for multispectral imaging. Additional components such as GPS, laser altimetry, and radiometric instrumentation are discussed after these basic imaging configurations. In discussion of sensor designs below, direct reference to camera manufacturers has been intentionally avoided because the number of manufacturers is very large and each offers different features which may be suitable for given applications' needs. However, some multispectral systems designed for remote sensing and sold by commercial enterprises are referred to by name along with the university and government systems discussed.

## 3.1 Multiple Camera Systems

The most common and easiest configuration to conceptually design is a multiple camera system where each camera is equipped with an appropriate interference filter and the image signals are recorded on VCRs or digitized in a frame grabber and stored digitally on disk or tape.

### 3.1.1 Multiple camera mounting

The cameras must be boresighted in a sturdy mount that can be adjusted easily by the user. Such mounts should be constructed of a material which is rigid and can dampen or eliminate vibrations. Early mounts were constructed of aluminum with rubber or some other dampening material (e.g., Nixon et al., 1985). King and Vlcek (1990) used an aluminum plate and brackets which fit directly into a Wild RC-8 or RC-10 aerial photographic mount to make use of their capabilities for dampening and in-flight adjustment of crab angle but had difficulty with aluminum relaxation causing the cameras to move out of alignment. Anderson (1994) has used wood for mounting small video cameras. Neale and Crowther (1994) have constructed a mount of graphite carbon composite which slides into a teflon coated ring mounted on rubber shock absorbers which can rotate for crab adjustment.

While a mount must be sturdy, it must also allow fine adjustment of the cameras in all three axes of rotation with the capability of locking the setting once achieved. Camera alignment is generally conducted outdoors while viewing objects at infinity (with infinity focus) (e.g., Neale et al., 1994; Nixon et al., 1985). This can be a difficult procedure because the cameras must be aligned with the filters in place, and differences between bright sky and dark land targets such as buildings or mountains can cause some blooming of the bright signal into the dark signal displacing the boundary between the two. This effect varies with camera aperture so if conducted, it is best to keep the same aperture for data acquisition. If zoom lenses are used, the alignment procedure must be repeated for any change in focal length setting (Everitt et al., 1991). King (1988) developed a procedure for aligning cameras in the lab based on relative orientation methods in photogrammetry. A pair of circular and cross targets are placed at a distance of about 10m on a wall in each image corner while a single horizontal line is placed across the centre of the field of view. The targets are separated by a distance equal to the lens centre separations of the pair of cameras being registered. Each camera is registered one at a time to a master camera by switching between the two cameras rapidly (at the video frame rate of 1/30s) or overlaying them directly using digital or analog overlay electronics. On a monitor, both targets imaged by both cameras (ie. two circles and two crosses in each corner) and two horizontal lines are visible. The yaw is eliminated first by adjusting the cameras to make the horizontal lines parallel. Then progressively, the pitch and roll are eliminated at the upper left and bottom right, respectively. The upper right and bottom left are used as check targets. The process is iteratively repeated until the cross target representing one camera is positioned in the centre of the circular target representing the other camera in all image corners and the two horizontal lines are parallel.

Despite efforts to develop precise and stable mounts for multiple camera systems, the author and Neale (1995) have noted that most users must conduct post-flight band registration anyways. It is very difficult to perfectly align cameras for a given flight altitude and most mounts tend to relax with time or are subject to vibration. Neale et al. (1994) simply conduct a rough registration and then apply post-flight automated band registration software based on maximization of the correlation between bands given various possible image shifts.

A recent addition to camera mounting developments is a two axis gyro for measurement of pitch and roll and an electric compass for yaw measurement incorporated in the Kestral AirCam multi-camera system (Butler and Otten III, 1994). This data is used in post-processing of the imagery to obtain vertical perspective. Linden et al. (1995) have incorporated a solid-state gyro parallel to the camera focal plane for pitch and roll measurements to a precision of 1/10 every 0.1s. Poole (1994), although not currently conducting multispectral video data acquisition, will incorporate a multispectral system (in collaboration with the author) in his gyro-stabilized mount which currently houses two calibrated 35mm cameras and a single colour video camera. Evans (1992) has developed a gyro-stabilized mount for his single camera-GPS-laser altimeter system. Such mounts are essential if airborne video imagery is to be used in area mapping and mosaicking. They are currently costly (greater than $18,000), however, and can represent a large proportion of total system costs.

3.1.2 Data acquisition

In a multiple camera system, the cameras must be synchronized so that they acquire images of the same area at the same time (to make real use of the alignment). Early analog systems stored images on VHS, Super VHS or 3/4" U-format VCRs. The systems developed by the USDA-ARS at Weslaco which have been adapted and modified by others (e.g., Neale and Crowther (1994) at Utah State University) utilized the same number of VCRs as cameras. Currently in these systems, synchronization supplied by a master camera is sent to an SMPTE (Society of Motion Picture and Television Engineers) time code generator and encoded on the audio track of each spectral band. When digitizing later, the frame grabber can select specific frames from the SMPTE time code. King (1988) reduced the bulk of multiple VCRs and synchronization requirements by sending four camera signals through a switcher operating at field or frame rate. In this way, each successive video field or frame was from a different camera (spectral band) and the signal could be recorded on one VCR. This technique suffered the limitation of post-flight band registration as the aircraft translation from frame to frame resulted in shifts of up to five lines. Although the registration procedure simply involved digitally overlaying one band in green over another band in red to determine the required image shift, this technique was only suitable for research and registration of a few scenes; it is not recommended for production mapping from many scenes. Ehlers et al. (1989) used high speed recording on video tape and then storage on optical disk in their 3-camera CCD system, thus improving the spatial resolution from a maximum of about 400 lines (as with Super VHS) to 700 lines. Current multiple camera digital video sensors send the camera images directly to a single multi-channel frame grabber (e.g., the Specterra Inc. (Perth, Australia) Digital Multispectral Video (DMSV) system (Lyon et al., 1994), the Airborne Data Acquisition and Registration (ADAR) 5000 of Positive Systems Inc., Whitefish Montana (Benkelman and Behrendt, 1992), the system recently developed by the Weslaco group (Everitt et al., 1995), and the new version of the Utah State 3-camera system (Neale et al., 1995)), or to multiple frame grabbers where one frame camera acts as the 'master' controlling timing and synchronization and the others are 'slaves' (e.g., the Stennis Space Center (Mississippi) Real Time Digital Airborne Camera System (RDACS) (Mao et al., 1994); the Kestral Corp. AirCam system (Butler and Otten III, 1994)). Digital images produced by these systems are generally routed immediately to a digital tape device or hard drive (often through a SCSI interface). However, Pickup et al. (1995a) store images more quickly using the 64Mb of RAM in their personal computer. This allows up to 37, 1.7Mb 4-band scenes to be acquired with greater overlap (up to 40% with 18cm pixels and aircraft velocity of 50m/s) than is possible using direct storage to tape or hard drive.

Since 1985, the system developed by the author (e.g., King, 1988) and the Weslaco group (e.g., Everitt et al., 1991) have also had capability for real-time colour/false colour imaging through incorporation of a colour encoder. The encoder processed input signals from any three of the cameras to produce analog colour output imagery which was recorded on a VCR for visual analysis. Capability for assigning of any filtered camera to red, green, and blue, respectively allowed for any false colour combination depending on the filters being used.

Currently, there are differences in filter mounting position in multi-camera systems. Some systems have the filters mounted in front of the lens, while others have them mounted behind the lens. When the latter is conducted using interference filters, separate focus for each filter is required because the rays are converging in a very short distance. A small change in convergence due to wavelength or filter optical properties will change the focus. Mounting filters behind the lens is therefore suitable for multiple camera systems where separate focusing for each camera is possible (Verreault, 1995; Slater, 1992). However, good near-IR focus is often 'beyond infinity' and is thus difficult to achieve. Mounting filters behind the lens has also been shown to reduce vignetting and associated decrease in image quality attributed to the filters (Mao et al., 1994). However, filters mounted in front of the lens can be more easily exchanged.

The cost of multiple camera systems is higher than the single camera systems discussed below simply because of the extra cameras, lenses, synchronization electronics, and larger mount. Commercial multiple camera video systems range in price between $30,000 CAN and $75,000 CAN for the camera/storage system alone, however, a system can be developed for a little as $15,000 CAN. A multiple digital camera system costs greater than $90,000 CAN for three to four 1,000 x 1,000 cameras and the associated computer hardware and software. GPS and other component integration presents additional costs which are not discussed in this paper.

Besides those multi-camera analog and digital video systems referred to above, a sample of others which are currently operational includes the following. The Weslaco group (Escobar et al., 1995) have extended their multispectral system to nine cameras including ultraviolet (300-400nm) and thermal-IR (8-14μm) sensing capabilities. This system incorporates four red/green/blue (RGB) frame grabbers with 512 x 512 pixel format, 64Mb of buffer memory, and four RGB displays for various false colour composite combinations. Digitization of a subset of the total video data is conducted in-flight while the complete data are recorded on S-VHS recorders. The University of Munich (Pellikka, 1994) have developed a four camera system with data recording of three channels as RGB on S-VHS tape. Simon Fraser University (Roberts et al., 1992; Roberts and Evans, 1986) has a three camera sensor coupled with a colour video camera, each camera being recorded on a separate 8mm VCR and then digitized post-flight. Colour and colour-IR photography are acquired simultaneously. Wrightson (1994) assembled a three camera digital video sensor in a period of one weekend for reconnaissance and imagery evaluation in a time-critical rivers mapping project. The University of Arizona has developed a two camera sensor primarily for red/near-IR sensing of vegetation (Marsh et al., 1991). The University of Nevada (Tueller, 1994; Nowling and Tueller, 1994) is in the process of testing a recently developed four camera video sensor with a custom-designed frame grabber for in-flight digitization of all bands simultaneously in 512 x 512 format and storage on the computer's hard drive. GPS positions are tagged to each multispectral scene. Eoscan Inc. have developed a 12-channel combined video/photography system due to be reported on in 1995 (Mueksch, 1995). There is one digital camera system using multiple cameras which is currently operational while others are under development. The Positive Systems ADAR 5500 (Benkelman, 1994) incorporates four 1500 x 1000 cameras each imaging in a 39 angle of view. Data can be acquired in single band format, and delivered as mosaics of several images or as ortho-rectified mosaics. Two other systems are known to be under development. The Stennis Space Centre is developing a three camera sensor, each being 1280 x 1024 in format with images routed to three 4Mb frame grabbers at rates of about 1 frame every 2s (Gress, 1994). Specterra Inc. is currently converting their 4-camera system to digital cameras in the 1280 x 1024 format range (Honey, 1995). Daedalus Inc. of Ann Arbor MI is currently in development stages of a 2k x 2k multiple camera sensor (Ory, 1995).

### 3.2 Band-sequential Imaging: Filter Wheels and Tunable Filters

A lower cost alternative to multiple camera systems is a single camera with capability for changing the spectral band-pass. Mechanical filter wheels mounted in front of, or behind the lens are the most common means to accomplish this. Xybion Electronics Corp. produced the first video-based filter wheel camera in 1985 (Niedrauer and Paul, 1985), and has subsequently produced a line of such cameras, each with different optical-electronic features. These cameras are capable of acquiring up to six spectral bands at a rate of one band per video field or frame. The filter wheel is mounted between the lens and the CCD. It normally houses filters with 70nm bandwidth but the wheel has been designed to be accessible for exchange of filters. The shutter speed is adjustable up to 1/10,000s. The camera sensor is part of an integrated system which includes post-processing software for registration of the sequentially acquired spectral bands. Fouche and Booysen (1994) have developed a filter wheel-based video system with seven filters for use in drone aircraft. The drones and image acquisition (including filter selection) are radio controlled from the ground while the image signals are transmitted to the ground and then recorded on VCR tape. The drones are typically flown at low altitude in the range of 100-200m for large scale assessment of agricultural crop condition.

King (1992b, 1995) has developed a digital camera sensor using a rotating filter wheel. A schematic of the sensor is shown in Figure 1.

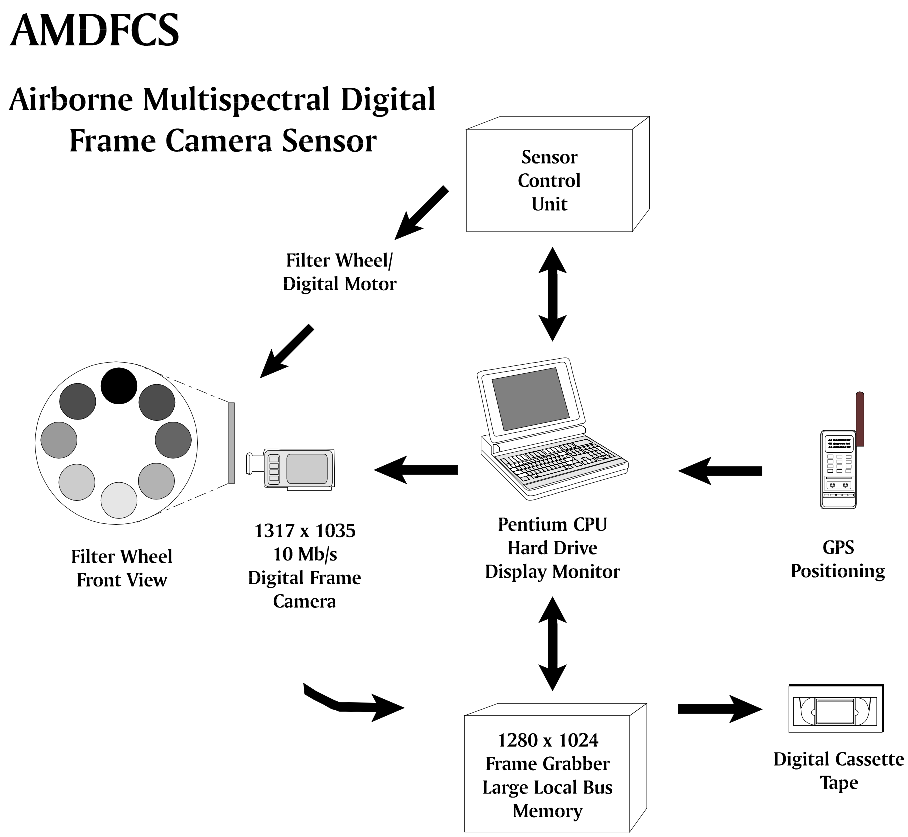


Figure 1. Airborne multispectral digital frame camera sensor (AMDFCS) design configuration.

The sensor produces 1280 x 1024, 8-bit images in up to eight bands in less than 1.2 seconds. Filters are mounted in front of the lens to avoid differences in focus as discussed in 3.1.2. Each image is 1.33 Mbytes so personal computer (PC) bus and 8mm tape storage rates are not adequate. To acquire up to 10 Mb/s of data, the images are routed from the camera to a local bus frame grabber with up to 256 Mb of on-board memory. This allows up to 40, 4-band datasets or 20, 8-band datasets to be acquired and stored before downloading (as the aircraft turns around). New low cost, high speed, large capacity hard drives are currently being investigated as an alternative to the on-board memory for direct storage of larger volumes of data. Image acquisition in this system is completely computer controlled. The user inputs the number of spectral bands (1-8), the exposure time for each spectral band, the number of multispectral datasets to acquire, and the time between each dataset. Time between datasets will be replaced by GPS positional control of exposure locations (see GPS discussion in Section 4.1). The sensor is designed for both multispectral and photogrammetric mapping (elevation modelling/ortho-imaging). The first application of the camera was in digital elevation modelling (see Section 6.4.2) in 1990; prototype multispectral imagery was acquired for forest damage assessment (see Section 6.1) in 1993; system development was completed to an operational level in 1995. Other filter wheel CCD-based cameras do exist which are designed more for medical or astronomy use. They often have slow read-out rates in the order of 25-100s or are moving sensor cameras such as described previously and are thus not suitable for airborne imaging.

A recent development in sequential filtering which may eliminate the need for a rotating wheel is the tunable filter. This is a single filter whose wavelength of transmission can be varied electronically (often with an acoustic pulse) at speeds as fast as about 50ms. Bandwidths as small as 0.1nm can be utilized. The view angle of such filters can be as much as +20 . Currently, the major limitations of these filters are low transmission (less than 30%), and separate filters must be used for the visible and near-IR spectrum.

The principal advantage of a single camera band-sequential system is that it has one optical axis. Consequently, no pre-flight alignment is necessary and optical problems such as differential spatial illumination are simplified. It is smaller and lighter for installation in small aircraft. The cost of filter wheel cameras is also lower than multiple camera systems, being in the $20,000-30,000 CAN range for commercial video-based cameras and about $30,000 CAN for the development of the imaging components of the digital camera sensor described above. Tunable filters typically cost in the range of $7,000 - $25,000 CAN.

The band-sequential imaging approach has not achieved the popularity of multi-camera sensors because of the inherent requirement for post-processing band registration. The larger the number of bands and the slower the data acquisition time, the greater the aircraft movement from the first to last spectral band. For low altitude flying with small coverage and small pixels, aircraft rotations can become significant and post-flight band registration becomes more difficult. For short time intervals, however, aircraft rotations are generally negligible and only translations are required to register images. The Xybion sensors use automated registration software which produces aligned multispectral datasets given input parameters such aircraft velocity. Shifts in video systems are typically 1-3 lines between bands with a loss of 4-12 total lines of data from the top and bottom of imagery in 4-band multispectral scenes. In the author's digital camera system described above, the aircraft will advance about 30m in the 0.6s required for a 4-band dataset. For imagery with 1m pixels, this translates into a loss of 30 lines from the top and bottom of the 1280 x 1024 imagery. It has yet to be determined whether this limitation outweighs the limitations of cost, timing/synchronization, mounting, alignment, and post-flight registration required with a multiple camera system.

### 3.3 Beamsplitting Systems

Beamsplitting cameras pass incident radiation through a system of dichroic mirrors and split the signal into three bands, each band directed to a separate CCD. The most common of these camera types today is the 3 CCD colour video camera which divides the radiation into B/G/R, each with bandwidth of about 100nm. However, 3 CCD higher resolution digital cameras (in the order of 1500 x 1024) are now available. Some of these cameras have separate RGB analog or digital outputs which can be fed to a computer and used in simplified spectral analysis.

The only beamsplitting system using video cameras and incorporating near-IR spectral sensitivity was the Biovision camera (Meisner and Lindstrom, 1985), subsequently commercialized by E. Coyote Enterprises of Norman Wells OK. The original camera was tube-based and the blue tube was replaced by a near-IR sensitive tube. The system suffered from poor resolution and image lag (smear due to retention on the tubes) but it was very compact and easy to install in aircraft. The latest version incorporates three CCDs (Anderson, 1994).

The principal advantage of beamsplitting is that there is only one optical axis and that axis is precisely positioned so there are no alignment problems. However, the disadvantage is that sensor modification by an applications user is difficult since optical modifications are required. The bandwidth in most commercial systems with three CCDs is wide and changing it requires some form of filtering mechanism in the optical path after the dichroic mirrors. This reduces the flexibility of variable filtering which is a part of other designs. Related to this, the exposure cannot be varied for each spectral band, except through internal filtering. Imaging of varied terrain therefore requires an aperture which can accommodate the wide dynamic range of feature brightness across all bands, resulting in reduced dynamic range in any single band.

### 3.4 Striping Filter Systems

Some colour cameras, using a single sensor chip, place a visible spectrum striping filter over the chip which essentially transmits a single colour (band) to each photosite. In visible-range cameras, the filter typically consists of more green than red or blue to match the eye's spectral sensitivity. Adjacent photosites of varying colour are then mixed (by a weighted average) to derive an RGB signal for every photosite. Averaging tends to reduce the spatial resolution somewhat. For example, a 1280 x 1024 colour digital camera with such a striping filter typically has maximum spatial resolution of about 800 lines compared with 1000 lines for its black and white counterpart (Richardson, 1992). Such cameras generally have RGB digital output and can be used effectively in some reconnaissance remote sensing. Like beamsplitting systems, the spectral bandwidths are about 100nm and as such these cameras are not suited to precise quantitative spectral information extraction. The author compared one of these cameras to 70mm colour photography and standard VHS video for spatial resolution and image contrast rendition (in Mausel et al., 1992a). The digital camera produced a much higher image contrast than the film and as a result the spatial resolution appeared similar (at equal contrasts, the 70mm film would normally produce higher resolution). The digital camera imagery also provided much higher resolution and contrast than the video imagery (demonstrating the potential improvement in low cost imaging capabilities over videography). Digital cameras which produce a standard CIR composite image using striping filters have recently been developed (e.g. see Bobbe and Zigadlo, 1995).

There has not been much research conducted into the spectral information content for remote sensing of such standard colour cameras with separate RGB filtering. Although the bandwidths are wide, there is still potential for quantified discrimination of land and water features. One research group (Lee and Chao, 1992) who are interested in developing a visible range multispectral video sensor as an alternative to colour photography, studied the statistical properties of three primary colour filters placed over a video camera under different illumination conditions. They found that the blue response was very weak, that most bands are highly correlated, and that the hardcopy output needed for visual interpretation was quite different in tonal and contrast rendition than the monitor images and photographs. McCreight et al. (1994) regularly use the RGB output from a video camera installed on their ultralight platform in broad spectral analysis.

The use of wide spectral bands in beamsplitting and striping filter cameras poses and important question in videography applications. The most common remote sensing approach has been to minimize spectral bandwidth in order to isolate and detect small variations in target spectral reflectance in response to some physical characteristics. However, as narrowband imaging has become the standard, the need for sophisticated sensor design, precise calibration, and analysis of environmental effects such as bi-directional reflectance and atmospheric effects has increased. Consequently, the costs to conduct rigorous quantitative remote sensing are very high. In the author's opinion, if the whole spectrum of potential applications of remote sensing worldwide is considered, the vast majority do not require, and the users cannot afford, the level of sophistication common in scientific research. Low cost cameras such as standard off-the-shelf beamsplitting or striping filter cameras which have some capability for separate imaging of various regions of the spectrum are suitable for many applications with commercial potential.

### 3.5 Frame Format Imaging Spectrometry

A recent development of imaging spectrometry capabilities using a low cost video camera is the Variable Interference Filter Imaging Spectrometer (VIFIS) system of Sun and Anderson (1994; 1993). An interference filter with continuously varying spectral transmission across the field of view is placed in front of a CCD video array. Currently, three video cameras are utilized, one with a visible range filter, the second with a near-IR range filter, and the third with no filter. Frame images are acquired in-flight at the standard video rate and recorded on a VCR. The images are digitized post-flight using an RGB frame grabber. Each image contains all spectral bands (up to about 60), arranged in the image columns. Data acquisition is synchronized with the aircraft velocity so each successive frame is translated one band's spatial width from the previous frame. Post-processing software is used to extract the columns corresponding to each spectral band from a series of frames. These columns are concatenated to construct an image for each band. The system was developed for about $20,000 which is an order of magnitude less than any imaging spectrometer. The primary advantage of the sensor over imaging spectrometers with a one-dimensional field of view is that it acquires a full frame of imagery in each exposure. Thus, a recognizable image is produced which can be immediately viewed and interpreted. The principal disadvantage of the sensor is that each spectral band has a different view angle, ie. for the visible-range camera, the blue bands are always viewing forwards while the red bands are always viewing backwards within the 31.5 angle of view. This severely complicates the analysis of features with strong bi-directional reflectance distributions across the view angle. In addition, as with a one dimensional field of view imaging spectrometer, the aircraft must remain stable during image acquisition for the spectral columns to be easily aligned in post-processing. Current research is being conducted to address these limitations and conduct radiometric calibration of the sensor.

## 4. ADDITIONAL SYSTEM INSTRUMENTATION

Several video and digital camera sensors incorporate additional components for specific applications' needs. This section will consider three of the most common, although there are others.

4.1 Global Positioning Systems (GPS)

GPS has become a standard component of airborne video systems in the past five years. It is used at various levels of sophistication and precision. The following description classifies these levels from simple to advanced.

1. A single GPS is used alongside the video system. The time or coordinates of the GPS and the video frame count are noted manually at certain points along flight lines. This method can be used effectively in quick-look studies or where system development/integration is time-constrained. Wrightson (1994) used this method in a contract where a multispectral system was developed in a few days for some time-critical mapping. 2. At a higher level, the GPS coordinates of the signal closest to the exposure time are encoded in the header of the digital image or on the audio track of VCR tape and displayed in video frames. The multispectral system developed by Everitt et al. (1991) was one of the first to have this capability. 3. The GPS time code is matched post-flight to an encoded time code on the video. The Stennis Space Center has adapted this system (Mao et al., 1994), because through interpolation between each GPS signal, a much more precise position for each frame can be determined than for the methods above. 4. The GPS signal is used to trigger the camera. Where the time interval between GPS signals is not too large for a given application, this technique can be used to reference each multispectral dataset directly to geographic coordinates from the flight planning stage on. King and Chichagov (1993) triggered a digital camera from a differential GPS. The image positions are much more precise than if a time interval between images is used because data acquisition is not dependent on the aircraft velocity. However, for precise positioning requirements, it should be noted that there is a small delay of about 5ms from the reception of the GPS signal to the triggering of the camera (Novak, 1992). Also, Evans (1992), in studies to compare actual image centre track on the ground with GPS readings, found that they differed by 1-3% of the total field of view due to aircraft rotations (under light winds). Thus, for precise mapping using GPS, camera orientation must be known or a gyro-stabilized mount must be used. 5. Use of GPS in an integrated flight planning, navigation, and data acquisition program. The flight lines and image centres can be plotted on a digital map in a Geographic Information System (GIS). The output file can then be used to navigate the aircraft using a moving map display or through the autopilot, and the GPS can be used to trigger the cameras at the specified image centres. This capability is not yet incorporated into any systems but it should be possible in the near future.

In all of the above, differential GPS gives much greater precision and accuracy. In photogrammetry and digital camera imaging, it is now common to position principal points to within 10cm (Merchant and Tudhope, 1994; Novak, 1992). Use of the OmniStar system, a group of baystations located around the continent, allows differential GPS and automated mapping to be done without ground survey. In the author's digital camera mapping research (e.g., see King and Chichagov, 1995), the next phase will be to photogrammetrically calibrate the camera for principal point position, focal length, and radial/tangential distortions, then, with differential GPS, position the principal point of each exposure precisely. Using the distortion information and aircraft attitude measurements, other control points can be selected and used in mapping procedures such as bundle block adjustments for Digital Elevation Model (DEM) derivation (see discussion of potential applications in Section 6.4.2). The need for field survey of control points will be eliminated.

### 4.2 Radiometric Measurement Instrumentation

Few video-based sensors have included radiometric measurement instrumentation in their designs. Such instrumentation is sometimes used in attempts to calibrate the imagery, and sometimes as an additional measurement technique. Utah State University (Neale and Crowther, 1994; Crowther, 1992) have had the most experience in incorporating a visible/near-IR radiometer and a thermal radiometer into a multispectral video system. The former is a four band 1 angle of view radiometer with bands designed to match the Landsat Thematic Mapper bands 1-4 while the latter operates in the 8-14 μm range and has a 2 angle of view. The radiometers are aligned with the centre of the video field of view. The visible/near-IR radiometer is also used in sensor calibration (see discussion on calibration in Section 5.2). Fouche and Booysen (1994) have incorporated a thermal-IR radiometer into their drone platform for combined imaging/temperature measurement of agricultural crops. The monitor display of the radiometer is viewed in-flight by a miniature video camera and the images are transmitted to the ground. The Kestral AirCam system (Butler and Otten III, 1994) includes two radiometers, one for upwelling spectral radiance across the whole visible/near-IR in 4nm bandwidths, and the other for downwelling solar irradiance. McKenzie et al. (1992) use a 512 channel radiometer in test flights over agricultural fields to determine the best spectral filters to use in growth and health studies with their four camera digital video sensor (the Specterra Inc. DMSV). Other research using radiometers at large scale with light aircraft are described in Section 6.4.1.

### 4.3 Laser Altimetry

Some video sensors designed more for positional measurement than multispectral analysis incorporate height determination using a laser altimeter as an integral component. The Southern Forest Experiment Station of the USDA Forest Service has for some time been developing capability for measurement of tree height, along with other forest inventory parameters such as species, density, crown and canopy closure, etc. Jacobs et al. (1993) describe the use of a laser altimeter which is bore sighted to a fiducial mark at the centre of the field of view of a solid-state video camera. The system is generally flown at altitudes of about 250m. Such an altitude results in a laser instantaneous field of view (IFOV) of 0.25m while the video IFOV is 0.21m. Laser pulses and readings are generated every 2cm advance of the aircraft while a video image is generated every 2-2.4m. The video imagery is used primarily to aid interpretation of the laser readings and to make other forest measurements. The precision of tree height determination is typically 5cm. Capability for stereo anaglyphic display of the video imagery has also been incorporated for such interpretation (Corbley, 1994a). Geomatics Info Inc. of Boulder CO has developed a system called ACCUDAT for helicopter surveys (Corbley, 1994b). It incorporates a laser rangefinder, differential GPS/moving map navigation, and a stabilized platform-mounted colour video camera. The camera has a fixed 71 angle of view for oblique imaging along transects.

## 5. APPLICATIONS ISSUES RELATED TO SENSOR DESIGN

The vast majority of operational and commercial applications of videography have emphasized visual analysis of multispectral composite imagery. However, as interest in quantitative analysis grows, many spectral and spatial issues arise. The issues described in the following section are particularly critical in sensor design and data analysis for quantitative information extraction.

### 5.1 Inter-relationships amongst Sensor Design Parameters, Environmental Variables and Applications

In designing a video or digital camera system there are many options which have impacts on the quality of the data which can be acquired. Sensor chip size, photosite size on the chip, exposure time (may include both sensor integration time and shutter speed), lens focal length, and filter bandwidth are usually selected in relation to view angle, ground pixel size, or target spectral detection requirements. Sections 5.1.1 and 5.1.2 summarize the more important relations between them and the trade-offs that must be dealt with.

#### 5.1.1 Sensor size, lens focal length and view angle

In terms of the sensor size, as sensor size increases, so does view angle for a given lens. Sensor sizes in solid-state video cameras are usually 6.4 x 4.8mm (corresponding to a 1/2" tube size), however, 4 x 3mm and 8.8 x 6.6mm (corresponding to 1/3" and 2/3" tubes, respectively) are also common. All of these sensors require small focal length lenses in order to produce a view angle adequate for area-based coverage. Focal lengths commonly used are 6mm, 8mm, 12mm, 16mm, and 25mm, while longer focal lengths are used for very narrow or small targets. Digital cameras sensors are generally larger, ranging from 9 x 7mm to about 21x 16mm for sensors with formats of about 1280 x 1024 photosites. The larger of these sensors produce a view angle of about 1/2 that of 35 mm photography. In higher cost digital cameras, such as 3,000 x 2,000 cameras, the sensors are larger still (about 28 x 18mm) and the angle of view is very close to that for 35mm photography. Lenses commonly used with digital cameras have focal lengths of 15-50mm. For area-based mapping, large sensors with small focal length lenses are best. However, the principal limitation is that as sensor size increases, if the number of photosites is constant, spatial resolution decreases. A 21 x 16mm sensor flown at the same altitude, with the same lens as a 9 x 7mm sensor will have a much greater view angle, but the ground pixel size will be much larger. This is the standard trade-off in flight planning: coverage vs. spatial resolution.

There are several optical view angle effects on radiometric quality which must also be considered. As view angle increases, radiation incident to the sensor surface decreases theoretically as a function of $\cos^4$ or $\cos^3$ of the view angle (Slater, 1980). This variable is often termed 'shading' or '$\cos^4$ fall-off'. For a typical 30 angle of view, the incident radiance at the edge of the sensor is reduced to 87% of the nadir value if the $\cos^4$ rule applies. However, actual fall-off in many modern lenses is less than this and may be in the order of $\cos^1$ (Pellikka, 1994). In addition to shading, as the lens aperture is opened, more radiation is absorbed and blocked by the lens walls, thus decreasing the radiation reaching the sensor (Slater, 1980). This effect, called 'vignetting', normally combines with shading to produce significantly decreased image brightness towards the corners of images. Discussion on correcting these effects is given in Section 5.2. Another problem with wider angles of view is the blue shift with view angle in interference filter transmission as discussed previously in section 2.4.

Spatial variation in feature brightness can also be due to environmental effects such as those of the atmosphere (particularly in higher altitude imaging above approx. 1000m), the bi-directional reflectance distribution function (BRDF), and topography. The literature on each of these is extensive so the discussion given here will be limited to empirical studies using video imagery. Quantitative information extraction from multispectral video has often been conducted without addressing such spatial variations in feature brightness. In the author's experience, angles greater than about +10 cause significant problems in routines such as statistical classification and consequently some processing should be conducted to reduce their effects. One of the unique aspects of analog video imaging is the high degree of data redundancy since images are acquired every 1/30s. This allows features to be tracked as they cross the field of view. King (1991) sampled many two dimensional features (flat agricultural fields, water, open areas) and three dimensional features (trees, forests) at five locations as they passed across a 33 view angle. Mean and variance in feature brightness at each position was determined for green, red, and near-IR spectral bands from several months (June-August), several times of day (9:30-14:30), two flight directions (north-south, east-west) and three flight altitudes (304m, 608m, and 1220m). Without correcting for the shading/vignetting effects described above (ie. the net feature brightness variation was studied), it was found that there was a linear relationship between feature brightness and view angle. Features were brighter than the nadir value on the side of the image further from the sun and darker on the side of the image closer to the sun. The variation was about +12% of the nadir value on average at +13 view angle. The effects were the same in each spectral band allowing ratioing to be effective and reduce the spatial variations to about +5%. The ratioing method ($Band_i/\Sigma Band_i$) was then applied to land cover classification with the result that a class of mixed deciduous forest, which was distributed spatially across the field of view, and which had been identified as three spectrally distinct clusters by an unsupervised classification, was assigned to one class only. Pickup et al. (1995a,b) have found that for their system (the Specterra Inc. DMSV) and rangeland applications, there is less similarity in feature brightness with view angle across spectral bands as King had found and the ratioing techniques did not perform adequately. Consequently, they developed a different empirical method based on previous techniques for line scanners (Royer et al., 1985) but adapted to the two-dimensional array image format. In this approach the scattering angle is calculated for all pixel coordinates within the image based on a specific formula which incorporates the solar and viewing zenith angles and the relative angle between the incident radiation and the observation plane. The inclusion of the angle of the observation plane accounts for aircraft rotation. If this can't be measured an estimate can be made from the difference between the observed location of the zone of maximum backscatter (Pickup et al. use the term the 'hot spot') and where it should be based on the scattering angle image. The brightness mean, standard deviation, and percentile values for all scattering angles in a series of 20-30 frames are calculated. They are plotted against scattering angle and $\cos^4$ of the view angle to account for shading effects. A linear or quadratic function is fitted which is inverted to derive the normalized brightness values at each pixel. In classification tests they found that this method performed much better than ratioing for spatially large classes. Qi et al. (1995) have used standard bi-directional reflectance models to normalize their multispectral video data (from the Utah State system). Vegetation indices calculated from the normalized data are used to estimate leaf area index (LAI) of agricultural targets.

5.1.2 Photosite size, exposure time, and image motion

In terms of photosite size, as the sensor size increases, the photosite size tends to be larger. Photosites typically range in size from about 7μm to about 21μm so there is a wide variability in sensitivity per photosite between sensors. The primary limitation of large photosites is reduced spatial resolution as noted above, while the primary benefit is increased radiometric sensitivity. This allows more precise radiometric imaging as the spectral bandwidth can be decreased, the shutter speed increased (decreasing image motion effects during sensor exposure), the aperture decreased (decreasing vignetting effects), or the gain decreased (decreasing electronic noise). Shutter speeds in the range of 1/500 s to 1/1000s are required for small ground pixel size imaging at typical aircraft velocities to keep image motion below the pixel level.

In applications and flight planning there is another trade-off between image motion and spectral bandwidth. For a given ground pixel size requirement, the shutter speed necessary for the given aircraft velocity to produce 1/2 pixel image motion (a common upper limit on acceptable image motion) can be calculated. This shutter speed may pose a limit on the bandwidth of the filter depending on the region of the spectrum and the camera's spectral sensitivity. For example, for most CCD cameras, and typical shutter speeds of faster than 1/500s, bandwidths of less than 10-20nm are not possible in the blue region because of reduced camera sensitivity. For the small 9 x 7mm sensor chip in the author's system, bandwidths of greater than 25nm must be used in the blue while bandwidths as small as 6nm are feasible in the red/near-IR.

Image motion between video fields in interlaced cameras is a separate issue that has been addressed by several researchers. This image motion is generally seen as a blocky striping effect in images. Approaches to correct or reduce it vary in sophistication. Lyon et al. (1994) use post-processing consisting of a shift of the second field by one row (their flight conditions are generally consistent) to bring it into correct alignment with the first field. This approach of shifting lines horizontally or vertically has also been adopted by Neale et al. (1994) using the correlation between pixels that would be adjacent for a given shift in lines or columns, by the Stennis Space Remote Sensing Centre (Mao et al., 1994), and by Mitchell et al. (1995) with precision of less than one row or column. Bakker et al. (1993) (as cited in Pellikka, 1994) use only one image field and interpolate an average value between the lines, thus maintaining geometric quality while compromising radiometric quality. Pellikka (1994) evaluate the bottom of video frames to determine where the image information in the even and odd fields ends (when grey values fall below a given threshold). The difference in number of rows between the end of the even and odd fields is the required translation to restore their geometry. Pickup et al. (1995a,b) evaluate the spatial autocorrelation of the odd and even fields with varying lag distance. If there is displacement between the fields, the autocorrelation function doesn't decrease gradually after the required lag of 1 row and zero columns as expected but is more varied due to the blocky/striping effect. The cross-correlation between the fields is evaluated to determine the lag at which it is maximum, this being the displacement which must be corrected for. This method works well for both aircraft translation and rotation between fields but it must be applied to images acquired with a fast shutter speed where image motion within the exposure is negligible. The best solution which eliminates the need for any post-processing or analysis is to use full frame non-interlaced cameras. Such cameras are now common in video formats and are incorporated into the Kestral Inc. AirCam (Butler and Otten III, 1994) and the Positive Systems Inc. ADAR 5000 (Benkelman and Behrendt, 1992).

### 5.2 Radiometric Calibration

Radiometric calibration of a sensor involves determining the relationship between image brightness as measured in digital image units (often called digital numbers - dn), and the actual radiance or reflectance of the target. Silicon-based sensors are linear in their response so calibration relations can be simple. However, array sensors such as video or digital frame cameras are two dimensional so the calibration must be done across the whole frame.

The first complete calibration of a multispectral video sensor was conducted by King (1992a, 1988) using the 4-camera sensor developed at the University of Toronto (King and Vlcek, 1990; King, 1988). Response linearity was evaluated for each spectral band by viewing a uniformly illuminated calibrated grey step wedge in the centre of the field of view. Relations between digital image brightness and radiance were established. The effect of increasing the aperture to levels where saturation of the brighter grey wedges occurred was also studied. From saturation and dark level signals, the dynamic range of the system was determined. The dark current noise was evaluated by digitizing images while the lens caps were in place. Noise variations with signal level were evaluated by analyzing spatial variation in pixel values in the uniform grey wedges. The root mean squared (RMS) noise was divided into the dynamic range to give a signal-to-noise ratio of 41.1 Using simple probability estimates for assignment of grey values to a given pixel based on the RMS noise (one standard deviation), it was determined that the 95% probability level for separation of targets occurred at 2.9% reflectance. This measure could be used as a measure of radiometric precision of a sensor. Noise reduction is an important aspect of image generation and processing which significantly improves data quality for quantitative information extraction. Noise reduction can be accomplished with some effectiveness through post-image generation filtering. For example, Mao et al. (1995a) conduct a fast fourier transformation of their data to isolate and adaptively remove noise in small windows. King and Vlcek (1990) found that moving window low-pass filtering significantly improved land classification accuracy of variable targets such as forest types. The best method for noise reduction is through cooling of the detector using air, water, liquid nitrogen or electronic means to reduce the number of thermally generated electrons to a negligible amount. Every 7.05 C of cooling reduces the thermal noise by one half (Hodgson et al., 1981) so cooling to less than -30 is commonly applied to CCD type imagers to reduce noise to a negligible level (although it increases camera cost significantly). Spatial non-uniformity in response (shading, vignetting) was evaluated in King (1992a) for two lenses, eleven spectral bands, and all apertures by viewing a large uniformly illuminated grey target with a diffuser over the lens. The relations found varied from band to band principally because of the transmission differences between filters. Also, the experiments were conducted in a lab setting with an illumination level and spectrum different than that typical of outdoors. Consequently, it was decided that the lab calibration could not be used to correct airborne imagery. Neale and Crowther (1994) and Crowther (1992) used similar methods but narrowed the requirements by using just the spectral bands and apertures used in their system and by conducting the calibration outdoors under typical sunny flight conditions. They have been able to produce both spectral response curves and grey level images for the uniform target for each spectral band/aperture combination which show the brightness fall-off with view angle. These uniform target images are inverted and multiplied by airborne images to flatten out the optical non-uniformity. Subsequently, the camera calibration spectral response relationships are applied to derive radiance from image digital grey numbers. Pellikka (1994) carried out similar shading/vignetting correction procedures and found between 0-9% decrease from nadir depending on spectral band and aperture. The exponent to apply to the cosine of the view angle was determined for each pixel, aperture, and spectral band. The relationships are used to correct airborne imagery. Mao et al. (1995b) have also developed methods for vignetting (and shading) correction. Beyer (1992a,b) conducted a complete lab calibration of a 1280 x 1024 digital sensor for close-range photogrammetry. Thom and Jurvillier (1994) describe a calibration of noise and spatial response non-uniformity for a 4,000 x 4,000 digital camera. Other research groups (e.g., Pickup, 1994; Louis, 1994; Lévesque and King, 1995) are currently, or will soon be pursuing such radiometric calibration.

An alternative to pre-flight calibration which is more precise but also more costly is in-flight acquisition of calibration data. This requires field personnel, a portable spectrometer, and targets which are large enough to occupy several image pixels. Mao et al. (1994) have used large calibrated targets placed at the mid-point of flight lines in agricultural studies. Regression equations are used to related spectral radiance measured at the time of flyover to image brightness. Neale et al. (1995) have tested in-flight calibration in addition to their lab-based studies. The average of the centre pixels in the video imagery is related to the radiometer readings and a formulation reconciling the differences in spectral bandwidths between the video filters and the radiometer is applied. Artan and Neale (1992) compared airborne video with 0.25-0.4m ground pixel sizes in spectral bands similar to Landsat TM bands 2-4 with ground-based radiometer measurements in the same spectral bands. They found very strong relations ($r^2$: 0.903 - 0.996) between video image-based vegetation indices (such as the normalized difference index (NDVI = (near IR - red)/(near IR + red)) and field measures of alfalfa leaf area index, %shading, plant height, and above ground biomass. The USDA Weslaco group have conducted many studies of agricultural target reflectance relationships with multispectral video image brightness. Their general approach has been to measure reflectance in pre-flight tests to determine the statistically most significant spectral bands to use and then to measure reflectance in-flight for calibration of those bands. Example studies include: weed spectral reflectance determination and mapping (Everitt et al., 1994a), wheat and corn growth studies (Wiegand et al., 1992), and ground vegetation cover mapping in rangelands (Everitt et al., 1992). In aquatic studies, Bagheri and Stein (1994) obtained images of calibrated halon panels using the Xybion MSC-02 filter wheel camera before and after flights to map near shore depths and water conditions. They converted the image data to reflectance for regression against the various water variables.

There have not been enough attempts as of yet to reduce spatial variations in image brightness in multispectral video/digital camera images due to topography. One example is Pellikka (1994) who used a (DEM) with 10m horizontal resolution and 0.5m vertical resolution. An irradiance surface was generated for the given sun illumination angle at the time of imaging for both the actual pixel orientation (slope and aspect) and a flat plane at the same elevation. The ratio of these was applied as a correction factor to each pixel to remove the effects of topography on image brightness.

## 5.3 Geometric Calibration

Geometric calibration has not generally been attempted by users of airborne multispectral videography because the relatively poor spatial resolution, has, until recently, limited the capabilities of video for mapping. However, a great amount of research in geometric calibration has been conducted in the field of close-range photogrammetry using both video and digital cameras. Much of the methods developed can be adapted for airborne mapping purposes. Detailed analysis of these studies is beyond the scope of this paper. Good complete references are El Hakim et al. (1989) for video CCDs, Beyer (1992a,b) for a 1280 x 1024 digital camera, and Thom and Jurvillier (1994) for a 4,000 x 4,000 digital camera; some other sample references will be given to highlight the types of activities being pursued. Studies conducted in the 1980s on CCD sensors to determine pointing accuracy (the accuracy with which a point can be located in image coordinates) found accuracies of 0.1 times the pixel size possible (e.g., El Hakim, 1986) while more recently image coordinates have been determined to within 0.01-0.02 pixels (Beyer, 1992a,b). Calibration for focal length, principal point position, and spatial distortions is required for mapping purposes. Standard methods used in photogrammetry can generally be applied to solid-state array images. For example, Ehlers et al. (1989) calibrated their high resolution analog system using methods given in Fryer and Mason (1989). Novak (1992) determined these geometric parameters for a 1280 x 1024 digital camera using an outdoor 3-dimensional target before integrating the camera with a GPS system for airborne mapping. In the absence of camera calibration parameters, King et al. (1994) conducted a sensitivity analysis by varying the focal length and principal point position within a reasonable range and analyzing the change in the bundle adjustment solution for x,y,z coordinates in stereo digital camera imagery. This served as a useful surrogate since the camera had been leased and a calibration was not possible. The CSIRO group (Pickup, 1994) have determined appropriate geometric lens corrections to improve their mapping capabilities with the Specterra DMSV system.

# 6. COMMON CURRENT AND POTENTIAL APPLICATIONS OF AIRBORNE VIDEOGRAPHY AND DIGITAL CAMERA IMAGING

Applications of videography are too diverse to describe by domain and too many to provide a complete listing and summary in one review article. Videography is now applied in the resource domains of forestry, rangeland, agriculture, water, geology, and environment in a variety of ways, as well as in urban and demographic analysis. For this paper, a classification by geographic coverage has been selected in order to make specific points about the suitability or lack of suitability of video and digital camera imaging. Methods using both imaging types continue to be developed in research and the primary applications tend to be site specific with success demonstrated at given test sites but not often beyond in operational applications. In recent years some users have begun to carry out larger projects for government mapping programs. The most recent of each of these types of projects will be highlighted in the discussion below.

The analytical methods used with video/digital camera data can also be categorized. There is a relation between the level of sophistication of analytical methods and the number of applications in which they are used. The most common analysis applied operationally by many commercial enterprises is visual interpretation of colour/CIR imagery, generally within a digital/GIS environment where features or conditions are identified by eye and the analyst transfers this information into a database. Kettler et al. (1992) compared visual interpretation of airborne CIR video acquired with 9-12nm spectral bandwidths to 70mm Kodak Aerochrome 2443 CIR film. Not surprisingly, for both forest and agricultural targets, the video provided better spectral definition while the photography provided better image texture related to vegetation species differences. In multispectral videography, the next level of sophistication is the analysis of several spectral bands (usually statistically) to identify one best band for mapping the feature of interest. This methodology has been applied quite successfully by the Weslaco group for the past ten years in detection of rangeland and crop damage, insect infestation, crop growth stages, and environmental problems such as soil salinity (e.g., Everitt et al. (1991) gives a summary of five such applications). More sophisticated analysis has generally made use of multiple spectral bands in statistical analysis. Classifications using standard techniques such as maximum likelihood (e.g., King and Vlcek, 1990) or band ratioing (e.g., Lyon et al., 1994) for land and aquatic vegetation mapping are common. However, not enough research has been conducted with more advanced spectral information extraction techniques. An analytical domain that should also receive more attention but which has not yet been adequately studied is the spatial information content of high resolution video and digital camera imagery. Other sensors are now being routinely evaluated for image texture (e.g., Roach and Fung (1994) using the MEIS II airborne pushbroom scanner and LANDSAT TM; Bowers et al. (1994) using SPOT). Airborne videography offers a lower cost method to acquire and analyze image texture and structure than other multispectral scanners and imaging spectrometers. Research in evaluation of first and second order texture measures, the fractal dimension, and image semi-variance in video and digital camera imagery is being conducted in forestry applications by the author and his colleagues (e.g., Lévesque and King, 1995; Yuan et al., 1991; King, 1988) and by Mausel (1994). This type of information will be integrated more often with multispectral information as the techniques are proven in a variety of situations and as the complexity of the analysis becomes more de-mystified.

### 6.1 Point/Site Mapping

Airborne videography is well suited to point or site specific studies where the coverage of individual frames is limited but the area must be imaged with high resolution (e.g., less than 3m pixels). The small sensors in video/digital cameras provide view angles which are always less than photography for any given lens and as a result they can only compete on a cost basis with photography in such localized studies. A specific advantage of video sensors in such studies is the electronic shuttering which is standard in most cameras today. This allows faster exposure times than are typically used in photography (because CCD sensors have greater sensitivity than standard film) and low altitude imaging with small pixel sizes to be conducted without noticeable image motion effects during sensor exposure. Some applications at these scales have been successful enough that they are now operationally. However, this category must also include the many applications which have been developed through research which have not yet been proven to be applicable spatially or temporally beyond the specific study areas.

In forestry, at large scale, Yuan et al. (1991), King et al. (1992) and Lévesque and King (1995) have been studying spectral and textural characteristics of individual deciduous trees with varying amounts of pollution related damage. Imagery is generally acquired with 0.3-0.5m pixels and a field of view of less than 500m. Models have been developed which produce an index of damage analogous to those used in field assessment but with better accuracy because many of the damage symptoms are exhibited in the upper parts of the tree crown which are not easily viewed from the ground. The airborne data in these studies is sampled from plots as small as 20m square in the middle of forested areas. If navigation can be accomplished well and the small plots can be imaged near the centre of the field of view, statistical information extraction can be carried out without the need for image data processing to reduce view angle effects as discussed previously. Verreault et al. (1993) have used the Xybion MSC-02 filter wheel video system with a ground pixel size of 17 x 19cm for evaluation of forest regeneration. Of six bands tested at 500nm, 600nm, 700nm, 750nm, 850nm, and 950nm in March flights, they found that subtraction of the 600nm images from the 750nm images eliminated the background snow effects and permitted accurate counts of regenerating conifers greater than 10 years old.

The Weslaco group regularly fly at altitudes below 1000m with pixel sizes less than 1m for site specific mapping or object detection. For example, Everitt et al. (1991) used 0.9m pixel CIR composite video in comparison to 70mm CIR photography to map harvester ant mounds in cotton fields in CIR composite imagery. This video resolution was just enough to detect the mounds which were very bright white against the surrounding red vegetation. In such cases where spectral discrimination is quite easy, the additional spatial resolution of photography is not needed. Also in the domain of agriculture/rangelands, Brown et al. (1994) developed methods for identification of various species of weeds in individual fields using multispectral videography with a pixel size of 15cm. They selected appropriate spectral bands based on statistical analysis of spectro-radiometer data. The bands which best discriminated the weed species being studied were centred at 440nm, 530nm, 650nm, and 730nm. The weeds are mapped at critical times in their growth cycles and a digital file is produced for the farmer to input to a computer controlled herbicide sprayer. Case study evaluations have found that herbicide use can be reduced by up to 40% from the blanket spraying methods commonly used. Pickup et al. (1994) have begun to apply the Specterra Inc. DMSV video sensor with their geometric and radiometric corrections (described previously) in classification of rangeland vegetation. In large scale, 18cm pixel imagery, they were able to produce classifications of per cent total vegetation cover vs. soil or litter cover, as well as individual shrub per cent cover, which matched those produced by ground-based quadrat sampling methods. The next step will be to evaluate the video methods in larger area mapping. Louis (1994) is determining if radiometrically calibrated large scale multispectral video can be related to neutron probe soil moisture readings to allow the video to be used for spatial mapping of soil moisture in individual fields at large scale. Palacio-Prieto et al. (1994) used a colour video camera suspended from a tethered helium balloon at altitudes of 20-100m above ground to image gully erosion in central Mexico with pixel sizes of 4-15cm. By acquiring images before and after the rainy season, they were able to measure gully growth in an area of 700m$^2$ to within 10% of field measures.

Several studies have been carried out for research purposes using pixel sizes of 1m or greater where the objective is to develop methods which can be extended to site mapping (e.g., at the farm level) over larger areas. Pearson et al. (1994) applied the Stennis Space Center's RDACS 3-camera sensor in feasibility studies to determine what kinds of growth and damage assessment could be conducted in various agricultural situations in Wisconsin. Their methodology was developed through consultation with farmers and included criteria for very quick information turnaround, varied monitoring frequencies for different crops, and production of an information product which was cost-effective and practical to the farmer. The Weslaco group has developed methods for mapping soil salinity in sugar cane (Wiegand et al., 1994a) and cotton (Wiegand et al., 1994b) fields and have been able to determine losses in yield per hectare for each, relating these to reduced farmer income. Lyon et al. (1994) applied their Specterra Inc. DMSV four camera digital video sensor in growth studies related to irrigation of citrus orchards, and in evaluation of re-vegetation health after mining. Mausel et al. (1990) demonstrated that much more detail in soil classes could be obtained using multispectral video imagery than was traditionally available from standard county soil maps. They found strong correlations of soil chroma and organic matter with principal component transformed imagery, and lower, but significant, correlations of slope and elevation with the image variables. Mausel et al. (1992b) utilized a soil index which subtracts out the brightness of partial vegetation cover in the near-IR and visible to determine effectively soil organic matter content, and soil colour properties. In aquatic studies, Lyon et al. (1994) have imaged site specific areas of algal blooms and high sediment loads. In some cases, they used the CASI imaging spectrometer to help identify the best spectral bands for feature detection and then determined if the standard filter set of the Specterra Inc. DMSV video system would be suitable or if other filters should be selected. Mausel et al. (1991) found very strong relations between red and yellow/green band brightness in multispectral video and both secchi disk depth and turbidity in nine lakes of different characteristics. The results formed the basis for further investigation into quantitative modelling of silt load, chlorophyll, pH etc. Liedtke et al. (1995) found strong correlations between suspended sediment concentration and specific bands of their 4-band system (Roberts and Evans, 1986). In each of these studies, the imagery and spectral analysis demonstrated the utility of single or multi-band video in discrimination of these features but methods must be developed which will allow such mapping techniques to be applied spatially and temporally on an operational basis.

Some users have begun to apply the effectiveness of videography for site specific mapping on an operational basis, essentially sampling areas as large as counties at specific sites for analysis of certain ground features. For example, Everitt et al. (1994b) acquired multispectral imagery of citrus orchards in two counties in southern Texas. Using CIR composite and black and white near-IR imagery, they were able to correctly distinguish and map black fly infestations in 25 of 27 damaged orchards, the other two being a different pest which produces similar symptoms. Most of the infestations could be mapped using imagery with 1.8m pixels, however, detailed analysis of 0.6m pixel imagery was required for complete mapping of young trees within any given orchard. In this regional study they integrated GPS data which had been acquired simultaneously to provide ground position information which was matched with street addresses of affected orchards for follow-up survey and management activities. Hice and Young (1995) describe a real-time video acquisition and analysis system for forest fire monitoring and other applications requiring time-critical information. They transmit S-VHS resolution video to a ground receiver in the vicinity of the aircraft and then relay the signal to another receiving station at the management base. Images are quickly analyzed to help in decision making for fire fighting resource allocation.

### 6.2 Line/Corridor/Transect Mapping

Airborne videography is well suited to mapping of linear and curvilinear features or transects which generally require fairly narrow view angles and few adjacent flight lines. Most mapping of curvilinear targets consists of many short, straight flight lines and subsequent processing of imagery to produce a continuous mosaic, although with a gyro stabilized mount, a single flight line could be used within certain aircraft rotational limits. Analog airborne video, with image generation rates of 1/30s is ideally suited to continuous data acquisition along transects or corridors such rivers, coasts, hydro right-of-ways, and transportation routes. Visual interpretation of moving video, whether vertical or oblique, offers a perspective which can aid in understanding of spatial extent of features and relationships between features which is difficult to achieve through other means. Such visualization is one of the analysis techniques of airborne video which has not been well evaluated. An example of such visual analysis applied in a very time-critical situation is that of Tarussov (1994) where an ultralight platform housing a single video camera was flown over 30km of a river course to quickly identify and map ice jams at time intervals of 1 hour. Corbley (1994b) describes some of the visualization advantages of video over photography in pipeline monitoring. Pierce (1994) has used visual interpretation of oblique colour video and vertical photography for determining shoreline conditions such as erosion, condition of structures, water clarity, and near-shore topography. The data were primarily used in a GIS mapping system of a large utility company to monitor changes and deal with public concerns regarding waterway management. Continuous image acquisition at high frame rates such as that of analog recorded video is currently not possible with either low cost digital video or digital camera systems. However, such capabilities are possible at higher cost and will be integrated into future digital video systems as costs decline. For the moment, visual interpretation of digital imagery is most often conducted using mosaics of CIR imagery such as that shown on the cover of Photogrammetric Engineering and Remote Sensing 60(6), 1994 from the Utah State University multispectral video system (Neale and Crowther, 1994).

In quantitative analysis, the Utah State University and associated research groups have extensive experience in river/riparian analysis. In several research projects, they have used the Neale and Crowther (1994) multispectral video system with ground pixel sizes of less than 1m and spectral bands in the green, red and near-IR to evaluate conditions of the Green River and other rivers in Utah and Idaho. In the Green River, Redd et al. (1994) classified specific riparian vegetation cover types with mixed results. Species such as tamarisk and willow were quite separable while others such as cottonwood, grasses, Russian Olive, etc. could not be distinguished accurately. Snider et al. (1994) mapped effects of river damming on water habitat, riparian vegetation and river edge slopes under four levels of water flow. Anderson et al. (1994) were able to classify hydraulic features (e.g., run, shoal, turbulent, shallow, sand, etc.) and extract riverine depths in specific sections of the river which were relatively calm. Panja et al. (1994) conducted similar research in the Virgin River in southwest Utah. They were able to quantitatively determine changes in spatial extent of these hydraulic features with errors in linear measurements of 15%. In St. Charles Creek in Idaho near the Utah border, Bartz et al. (1994) classified riparian cover types into eight broad classes (deciduous, herbaceous, soil, water, etc.) with adequate accuracy (70-100%) when the imagery was corrected for vignetting effects. Several additional papers on these topics were presented by this group of researchers at the 15th Biennial Workshop on Color Photography and

Videography in Resource Assessment, May 2-3, 1995, Terre Haute IN (ASPRS, Bethesda MD, In Press). Other researchers have also been studying river and estuary environments using transects of airborne videography. Roberts et al. (1992) determined relationships between river water depth in very shallow areas suitable for salmon spawning habitat and spectral band brightness using their three band video sensor. In comparing the video to digitized colour and CIR photography, they found that the video data provided slightly better correlations with water depths, particularly in the green band but that the spatial resolution was much poorer. The operating costs of the video data acquisition were lower (about $120/hr) and the data was immediately available for analysis. The New Jersey Institute of Technology has been modelling water variables in estuarine and river environments using the Xybion MSC-02 6-band sensor for about eight years. For example, Bagheri and Stein (1992) flew transects of multispectral video just off the coast of New York to determine if it could be used as an alternative or complement to Landsat TM for determination of phytoplankton abundance. When the video data were corrected for sun glint effects, a strong relation between the two data types was found and reliable estimates of phytoplankton abundance could be derived. Recent work (e.g., Bagheri and Stein, 1994) is designed to determine the applicability and cost-effectiveness of video methods in relation to imaging spectrometry. They found that both data types can be well related to chlorophyll a and suspended sediments. The imaging spectrometer data was able to determine depth much better than the video (but the video had been acquired on a cloudy day) while the video data revealed some unexpected under surface pollution sources.

### 6.3 Area/Regional Thematic Mapping

To conduct regional mapping with coverage close to, or representative of the whole area, large image coverage is necessary to be cost-effective. In videography, with view angles generally less than 40 , it is difficult to achieve large coverage except from high altitude. Coverage equivalent to about 1:10,000 photography is possible with most video and digital cameras using common lenses from altitudes of about 3,000-4,000m. For example, for the horizontal image dimension, a 21mm digital camera sensor with a 28mm focal length lens would require an altitude of 3,066m, a 9mm digital camera with a 15mm lens would require an altitude of 3,833m, and a 1/2" video sensor (6.4mm) with an 8mm video lens would require an altitude of 2,875m. Wright (1993) provides some cost comparison analysis between 35mm, 70mm photography, and S-VHS video for area-based mapping. For an effective ground pixel size of 0.7m in all three media, the ratio of total raw data acquisition of video to 35mm photography to 70mm photography is about 1:2:3, respectively. However, video requires many more flight lines and about three times the total number of frames as the 70mm photography to cover the same area because of its smaller view angle. This impacts significantly the post-flight costs of geo-referencing, mosaicking, interpretation, etc. and generally outweighs the low data acquisition costs to make video more costly overall. In a specific empirical study, Everitt et al. (1994a) agree with these general findings in their comparison of CIR 70mm photography and multispectral video for identification and mapping of two specific rangeland weed species. They found that although the video imagery could distinguish the weed species well enough at in 1070m altitude, the coverage of each frame was only 5ha so data processing and interpretation were more costly than for the photography. Some progress has been towards addressing these problems in area-based mapping. Neale et al. (1994) have probably the most experience in developing automated mosaicking procedures for handling a large number of video frames in order to reduce the costs of post-flight analysis. Their applications have included wetland classification (Shoemaker et al., 1994) where mosaics of up to 34, 3-band scenes were produced to provide large area coverage, and Romney (1994) in mapping of abandoned mine sites within 74,500ha where 165 mosaics of 10 scenes each were created for multispectral classification. Other research includes Linden et al. (1995) who developed automated mosaicking software which incorporates attitude sensor and differential GPS measurements. The Weslaco group have taken a different approach in attempting to acquire large area imagery. Davis et al. (1995) have developed a 3-camera video system in which the two outside cameras are angled obliquely but with 10% overlap with the central camera. The total coverage at 3,500m altitude using 12.5mm focal length lenses is approximately equal to that of 23cm format photography using a 152.4mm focal length lens from the same altitude. The immediate problems to be dealt with are distortion correction and automated mosaicking of each 3-camera scene.

Visual analysis of large amounts of multispectral videography or standard colour/CIR videography in a digital mapping environment is relatively simple in concept and has a good record of success for operational replacement of photography and field surveys. In many cases, although the raw data acquisition costs may be greater than costs of photography, the advantages of real-time image viewing in-flight, direct mapping in a GIS, and visualization analysis of continuous video provide indirect benefits which may improve analytical results. For example, Lusch and Sapio (1987) developed a program to cover the whole of Michigan's forested areas with CIR composite imagery using the Biovision camera for mapping of gypsy moth defoliation. Visual interpretation of three damage classes and map production was conducted for the 816km$^2$ of the feasibility project in only six hours immediately following the flight. Thus, although the costs of the video method, estimated at about \$1.35US/km$^2$ were more than photography and sketch mapping, the maps were produced quicker than could be done with photography and the method was shown to be much more accurate than sketch mapping. This forest damage assessment methodology has since become an operational program with the Michigan Depts. of Natural Resources and Agriculture. Myhre (1995) and Linden et al. (1995) describe a low cost single colour camera system used by the U.S. Forest Service in several locations for forest pest damage assessment and other forest inventory activities. Jacobs and Eggen-McIntosh (1993) used two crews of two members each to visually interpret four tree damage classes in colour video of Louisiana immediately after Hurricane Andrew. An area of 1.7 x 10$^6$ha was sampled with flight lines 16km apart and images were analyzed every 800m along each line. Each image had a field of view of 92m and a 15cm ground pixel size. Eggen-McIntosh and Jacobs (1993) acquired and visually interpreted 700km of colour video flight lines in Mexico for verification of forest cover classes previously mapped from Landsat TM imagery for the United Nations Food and Agricultural Organization (FAO) Tropical Forest Resources Assessment Program. The video data were much less costly than field investigation and could be effectively used to find errors in the TM classification. Slaymaker et al. (1995) used GPS referenced airborne colour video to serve as site specific reference data for Landsat TM classification of deciduous forests in the northeastern United States. They acquired continuous imagery along 1500km of north-south and east-west transects spaced 15km apart in both the spring and fall. Two cameras were used: one with a wide angle lens providing a 500m swath and 1m ground pixel size, and the other with a 12x zoom lens providing a 30m swath and 6cm ground pixel size. Field verification of a subset of scenes was used to develop a visual interpretation key for 12 species groupings classes at Anderson et al. (1976) level III and 42 sub-classes of species proportions at Anderson et al. level IV. Interpretation of 17,836 sample points was used to provide training data for classification of the Landsat scene. Classification was conducted using a hybrid method which incorporated the spectral pixel values, the expected neighbourhood values for each forest type in a 5x5 window and the terrain slope from a DEM. Accuracy assessment of the level III classification revealed improvement to 89.2% from the 70% achieved using maximum likelihood classification of the pixel spectral values alone.

Attempts at thematic mapping of large areas using quantitative classification or analysis have not been very successful (if analyzed rigorously for accuracy), due either to the view angle/atmosphere problems discussed earlier which reduce mapping accuracy, or the poor spatial resolution which does not allow the same precision in land class attributes as can be obtained from photography. For example, tests to evaluate image processing techniques in standard classification of land cover types to a precision of vegetation species groupings were conducted using 4-band, 3m pixel multispectral video by King and Vlcek (1990). The classes were: hillside forest - maple/beech/ash, riverside forest - willow/ironwood etc., coniferous plantations - red pine and mixed conifers, bare soil, hay/open, and short grass. Through band ratioing to reduce view angle variations (see previous discussion), noise reduction, and post classification smoothing, the accuracy of maximum likelihood classification was improved from 57.4% to 70.6%. However, this is still much too low to be useful in operational mapping. An interpreter could do much better at this level of attribute precision by visually interpreting from the screen and outlining polygons within a GIS. Mausel and Kramber (1987) provide another rigorous accuracy assessment in thematic mapping using video. They found similar levels of accuracy for several specific agricultural classes. Attempts are being made to improve accuracy, however. For example, Qi et al. (1995) and Pickup et al. (1995b) are including BRDF/view angle normalization procedures and Pickup et al. (1995b) are transforming their spectral bands to canonical variates to plot data distributions and assign mixed pixels to proportions of each of the desired classes. Other researchers have simply decreased the precision of class attributes in order to provide suitable thematic map accuracy. Monday et al. (1994) mapped 280, 4-band scenes of 1m pixel ADAR5000 imagery over a 25.7km$^2$ test area in Irving, TX to determine the normalized difference vegetation index (NDVI). The NDVI was used to classify impermeable vs. permeable surfaces for use in run-off determination within each ownership land parcel for compliance with US water quality management guidelines. The images were rectified and an ortho-image mosaic was produced to use in a GIS. The results of classification correlated very well with expected values and project was completed in eight months instead of the three years expected using ortho-photography. The costs were 1/3 higher but the digital multispectral database is finding many other uses within the urban management department. The city of Irving has since mapped its whole 181km$^2$ area using the ADAR5500 digital camera system (Anon., 1995). Veregin et al. (1995) have achieved 93% accuracy in classification of impermeable/permeable surfaces by using detailed classes (asphalt, shingle roofs, etc.) which were later aggregated into the two broader classes. Lowe et al. (1995) also used a simplified classification scheme (coniferous, two deciduous classes, cloud, cloud shadows, road) in forest inventory in Alabama to compare the cost-effectiveness of Landsat TM, multispectral video (using the Weslaco 3-camera system) and ground sampling. They found no significant difference in accuracy amongst the three techniques and that the multispectral video was the least costly.

This trade-off between attribute precision and accuracy of classification is strongly related to the trade-off between spatial coverage (view angle) and spatial resolution and could really be applied to most multispectral airborne sensors. Despite their advanced spectral imaging capabilities, they generally do not provide a wide enough view angle with high enough spatial resolution to be considered as alternatives to visual interpretation of photography or videography in accurate mapping of detailed classes. Those that do provide such a view angle (e.g., the MEIS FM sensor (Neville, 1993) with 6000 pixels in a 70 angle of view) require so much data processing and correction for quantitative analysis that they are currently not cost-effective operational large area mapping.

### 6.4 Some Potential Applications Fields

As stated earlier, with advancements in sophistication of video and digital camera technology, more applications are developing which were once confined to the realm of expensive scanners or photographic systems. The discussion below concentrates on two of these which relate to the potential integration of multispectral and mapping activities using the same low cost sensor.

#### 6.4.1 Large scale radiometric data acquisition

One of the strongest areas for potential use of multispectral videography is in precise, very large scale imaging and radiometric measurement using light aircraft or drones. Fouche and Booysen (1994) have combined multispectral video, photography and thermal radiometry sensors in their drone platforms previously discussed in this article. The thermal radiometer, with a field of view of about 5m at 200m altitude, is used to compare crop and air temperature for determining moisture stress, while the video imagery and photography are used to match the ground cover spatial variation to the radiometer signal variation. Two ultralight systems which have emphasized radiometric measurement more than multispectral videography but which have capability to incorporate a light weight video sensor have been developed by the Université de Sherbrooke and Oregon State University. The Université de Sherbrooke system (Tarussov et al., 1993) currently consists of one video camera for continuous flight track monitoring, downwelling and upwelling spectro-radiometers, a photographic camera, and a GPS (a ground penetrating radar sensor has also been used on this platform). All down looking instruments are aligned and the photographic camera is triggered simultaneous with the radiometric measurements. The Oregon State Airborne Data Acquisition and Management System (ADAMS) incorporates two solid-state cameras with user selectable filters, an upwelling visible/near-IR radiometer, a thermal IR radiometer, an altimeter, and GPS (Chen et al., 1994; McCreight et al., 1994). The data management system allows flights to be planned and conducted in a portable PC-based Windows format with pen-based cursor control and written command input capability. It includes a moving map display and radio-frequency data download capabilities. Such developments should be integrated with small multispectral video/digital camera systems to help improve quantitative information extraction capabilities within the videography community. For example, the multispectral digital frame camera sensor of the author (see Section 3.2) will be installed in the Université de Sherbrooke ultralight aircraft in August 1995. Models are being developed which relate spectral, textural, and structural image measures to forest damage symptoms in individual trees. The increased interest in radiometric calibration and quantification of airborne videography will also aid in expanding its use in providing high resolution, large scale information for smaller scale mapping sensors such as imaging satellites. This multi-stage approach to collection of spatial data is becoming increasingly important in global studies which require high quality local information. Large projects such as the Boreal Ecosystem-Atmosphere Study (BOREAS) use a multi-stage data acquisition approach and would benefit from the low cost capabilities of multispectral videography as an intermediate data source between the ground and satellite sensors.

### 6.4.2 Positional mapping and elevation modelling

Another area-based mapping domain in which digital cameras are now finding application is positional mapping. As digital camera technology advances and resolutions approach photography, most topographic mapping will begin to use these cameras as the primary image source. Flying a digital frame camera and developing digital elevation models is a much simpler process than using photography because it avoids the scanning stage and computer control of digital cameras provides additional flexibility and accuracy in data acquisition. It is also much simpler than using an imaging spectrometer or line scanner which have a constantly varying geometry from line to line as the aircraft translates and rotates, so much of the methodology developed in analytical photogrammetry can be directly applied. For example, Ehlers et al. (1989) registered stereo imagery from their calibrated 3-camera video system to a base map and then produced orthoimages from the stereo pairs for use in polygon updating in a GIS. King et al. (1994) and King and Chichagov (1993) have evaluated a 1280 x 1024 digital camera in elevation modelling in an urban area using standard bundle adjustment techniques to determine point positions and interpolation techniques to determine the three dimensional terrain surface. DEM precision was consistently in the range of the pixel size even without camera calibration. King et al. (1995) used automated image matching and parallax measurement of matched points to determination a DEM in natural terrain where available control point distribution was poor. DEM precision was lower than in the previous urban study (about four times the pixel size) but compared favourably with a DEM of the same area derived from scanned aerial photography. Precision and accuracy would be expected to improve by including camera calibration parameters in the modelling process. Novak (1992) has included the integration of camera calibration data and precise measurement of the GPS antenna offset from the camera principal point in the Ohio State University MapCam system which is based on a 1280 x 1024 portable CCD digital camera. Results related to digital elevation modelling and ortho-imaging are not yet available. Jadkowski et al. (1994) have evaluated a 1280 x 1024 digital camera and are currently testing a 2048 x 2048 camera in pipeline right-of-way mapping. They acquired almost 2,000km of stereo data with 0.75m pixels, registered the images to existing digital maps of the pipeline and conducted map revision in an analogous fashion to previous photography-based methods, only at lower cost and in an entirely digital environment. Jurvillier and Thom (1993) tested the capabilities of a 4,000 x 4,000 in mapping by constructing a mosaic of 45 ortho-images. At very large scale, Merchant and Tudhope (1994), conducted tests of 1280 x 1024 digital cameras in precise mapping of hydro towers and lines. They mounted two calibrated cameras in the wing tips of a small aircraft for stereo imaging and acquired data at an altitude of 61m with 5cm pixels. All positioning of the aircraft and imagery was accomplished using differential GPS to an accuracy of 10cm. Through standard photogrammetric bundle adjustment techniques, they were able to position various components of the hydro line system to within 10-15cm, except for the main cables for which the accuracy was only 40-60cm. The authors feel that with a two fold increase in resolution (for example utilization of a newer 3000 x 2000 digital camera), a larger base-to-height ratio, and more stability within the optical system, such digital camera imaging techniques could completely replace the expensive ground survey and photographic methods currently in use.

## 7. SUMMARY DISCUSSION OF THE ROLE OF THE AIRBORNE VIDEOGRAPHY AND DIGITAL CAMERA APPROACH IN REMOTE SENSING AND MAPPING

From the previous description of characteristics, designs, and applications of airborne videography, it is evident that it is developing rapidly both in terms of technical capabilities and types of applications. It is becoming the technique of choice in a wide variety of operational mapping programs.

Videography is low cost and very simple to implement in reconnaissance remote sensing and can often serve as a cost-effective alternative to aerial photography. In-flight monitoring, quick imagery turn around time, simpler interfacing of GPS, and capability for real-time digitization are the most significant advantages of video and digital cameras over photography in visual interpretation-based reconnaissance and analysis. The principal need for development in videography which will contribute to its replacement of photography in most visual analysis applications is stereo viewing capability. Photographic interpretation depends very heavily on a three dimensional perspective of the landscape; as workstation capabilities for stereo display of digital camera and video imagery continue to develop and decrease in cost, the need for hardcopy photography will diminish.

In more sophisticated scientific studies, there is a trade-off between cost and measurement capability. Interest in radiometric measurement is steadily increasing and video/digital cameras are being integrated into airborne systems which include radiometers and common calibration procedures. However, a basic truth in system development is that the costs of instrumentation, measurement (sometimes including intense field measurement, calibration, and analysis) increase in proportion with the required level of measurement precision. In contrast, with continual component cost decreases, it is currently feasible to operationally apply videography at levels of sophistication which were beyond most users' means five years ago. For example, five years ago, only a few research systems incorporated GPS encoding directly into the video/digital camera signal generation because it was necessary to acquire custom-built devices at significant cost. Today all systems being developed incorporate this capability at a much lower cost. In an analogous way, two years ago only one research system integrated multispectral video with radiometer instrumentation. Today, many commercial systems are including this capability, at least as an option. Radiometric measurement, although currently not precisely integrated with video/digital camera imaging, will become a standard requirement of environmental researchers, non-governmental organizations, and government agencies as their desire for more quantitative and rigorous measurement increases. These developments must, however, take place from a needs driven perspective in order to be effectively transferred to operational environmental programs.

Finally, low cost digital cameras can serve as dual purpose sensors, providing simple means for both multispectral imaging and mapping. The combination of these activities will significantly improve the capabilities of resource and environmental spatial analysis in a GIS environment. Good geometric control using a medium-to-high resolution digital frame camera is beneficial in airborne remote sensing if the data are to be integrated into GIS. Although low cost sensor resolution is still much less than that of film, and the view angle of digital cameras is smaller than photography, they are very well suited to complete coverage mapping of areas up to about the size of small watersheds (e.g., for conservation authorities, private enterprise, environmental groups etc.) with precision in the order of 1-3m in areas of developed or natural terrain. This dual capability significantly enhances the appeal of digital cameras and provides an important advantage over higher cost imaging spectrometers and line scanners.

The limitations which restrict the effective use of videography are related to two fundamental characteristics: a) the small view angle does not allow cost-effective large area mapping (in relation to photography), and b) the two dimensional radiometric corrections/calibration required for effective quantitative thematic mapping are a significant part of the investment in the system. Consequently, few users have developed operational thematic mapping programs. Users should not be falsely led to believe that accurate automated thematic mapping of precise land cover types can be conducted on an operational basis. Too little rigorous study of mapping accuracy has been conducted to justify its widespread application. Extension of thematic mapping spatially to several scenes or temporally has also not been explored. Each must be accomplished before the technique can become operational.

## ACKNOWLEDGEMENTS

The author is grateful to the Natural Sciences and Engineering Research Council of Canada and the National Research Council for funding his research program as well as to the Canada Centre for Mapping, the Ontario Provincial Remote Sensing Office, GEOsurv Inc. of Ottawa, and Horler Information Inc. of Gatineau Quebec for flight, software, and personnel contributions. Appreciation is also extended to the many colleagues who sent their latest research methods and results, particularly to Chris Neale of Utah State University for a thorough review of the draft.

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