The Analog-to-Digital Transition and Implications for Operational Use of Airborne Videography

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Abstract

Recent advances in domestic consumer video technology and improvements in computing power indicate possibilities for overcoming the limitations of analog video. This has prompted a re-evaluation of the potential of airborne video as an operational digital remote sensing tool. First, in retrospect, the difficulties of applying digital analysis to video are explained, based on four major links for image quality degradation. To exemplify the importance of technological advance in improving analog video digitization, a comparison is made of synchronization fidelity between older and newer model frame-grabbers. Recent developments in custom-built digital video cameras and PC video are explained, to highlight the important technological advance of "off-the-shelf" digital video. Finally, the "digital revolution" from the commercial video and computer markets is discussed in terms of the significance for the practicality of digital video remote sensing. In conclusion, from the perspective of past limitations, it is asserted that the "digital revolution" will lead to significant benefits for routine use of operational digital video remote sensing.

Introduction

Airborne videography provides a suitable means of cost-effective acquisition of imagery for a very long and narrow strip target by narrow-view-angle/dynamic stereo coverage. Examples of applications include pipelines, powerlines, highways, and coastlines. However, for display and digital analysis of video imagery, it is necessary to convert the analog signal to digital values. Furthermore, it is necessary to mosaic individual video frames together to provide complete cover of a site for computer-based classification. The time consuming process of digitization and mosaic creation have delayed widespread acceptance of the video technique. Furthermore, bad synchronization occurring during transmission is regarded as a major limiting factor of the precision attainable with digitized video. Such limitations have made it difficult for digital video remote sensing to become a routine operational technique. For this reason, the technique has often been used with a focus mainly on screen visual interpretation, such as pipeline route survey by visual sketch mapping (Sky Vision International UK Ltd., 1995; Cooper *et al.*, 1995; Campanella *et al.*, 1995).

Although in many previous applications video has been used successfully with visual analysis, many applications could be improved, in terms of information extraction, by adopting a digital approach. Many of the limitations inherent in the current practice of "digital" videography could be reduced or overcome by fuller use of current technology. Recent developments in computer technology and the emergence of "off-the-shelf" digital video (DV) cameras have reduced the time-consuming digitization process and have provided improved image quality by removing digitization noise and loss of image quality caused by "analog-to-digital" (A/D) conversion.

The main purpose of this paper is to consider how digital video remote sensing might realistically become operational in the context of the latest technology and of near-future technology development.

The Analog Era

Analog Video Remote Sensing and Degradation of Image Quality

A video remote sensing "system" contains a number of hardware components, including a camera, video cassette recorder (VCR), frame-grabber, and monitor. Three major steps affect the image quality of video remote sensing, in moving from an analog to a digital environment, as shown in Figure 1 (based on equipment used in a recent research project (Um, 1997)).

Any electrical communication system (e.g., TV, radio, telephone) uses a similar principle to define the performance of the system (frequency/noise: channel bandwidth/signal power). An electro-optical imaging system uses these two parameters as indicators of the radiometric and spatial resolution. Similarly, the horizontal resolution and signal-to-noise (S/N) ratio of the equipment constitute the main factors influencing the degradation of image quality. The signal-to-noise ratio for video cameras governs the ability of the camera to resolve slight differences in intensity. Briefly, the operational guideline is that the spatial resolution and signal-to-noise ratio of the entire system cannot exceed that of the weakest component.

Professional grade video cameras, as the first link, use three-chip CCD arrays of about 540 lines resolution to capture visible light. The video recording tape and Video Cassette Recorder (VCR), as the second step, is the weak link in the video "system." The spatial resolution of common VHS recording tape is 230 horizontal lines (regardless of how many lines the video camera is capable of resolving). Concerning radiometric sensitivity, the video camera typically may have a signal-to-noise ratio of about 59dB. When the signal is recorded on a standard VCR, however, the S/N ratio drops to 45dB.

The image quality in the third step (Figure 1) is determined by the sampling frequency and radiometric linearity of the digitizing device. Spatial resolution of a digitized frame is expressed as a matrix: the number of pixels (columns) per line by the number of lines (rows) into which the image is divided. The frame-grabber card used in this project

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STEP 1

In Flight: Video Camera (540 lines, 59dB) → Video Tape (420 lines) and VCR Recording (400 lines, 45dB)

STEP 2

In Playback: S-VHS VCR playback (400 lines, 45dB) → 21 inch Colour TV Monitor Display (550 TV lines/15.625kHz horizontal frequency-50Hz vertical frequency)*

STEP 3

In Digitization: VCR (400 lines)→ Frame-grabber (768 by 576 pixel) → 20 inch Display connected to Sun workstation (1280 *1024 lines/81.1kHz horizontal frequency-76Hz vertical frequency)

* The manufacturers of the TV monitor and workstation monitor do not specify the S/N ratio in the manual.

Figure 1. Image quality degradation link in video remote sensing.

digitized the incoming signal to produce an array of 768 by 576 pixels. This is well above the resolution of both the video camera and the VCR. Bandwidth (which controls the number of horizontal lines) and signal-to-noise ratio are also used to evaluate the resolution performance of the monitor. Most current monitors are capable of displaying more than 500 horizontal lines [Standard Video Graphics Array (VGA): 640 by 480 pixels; Super VGA: 800 by 600 pixels]. High-end graphics adaptors, introduced for professional workstations, currently (1997) offer top resolutions from 1280 by 1024 to 1600 by 1280 horizontal line frequencies. In summary, therefore, the present limitations of spatial resolution are set by the performance of the VCR, as the weakest link in the total video remote sensing system.

Technological Improvement of Synchronization Performance

An analog video signal comprises both the picture itself (analog video information) and timing information. Each complete picture is called a "frame," and each frame is built up of horizontal lines which contain picture information. For displaying the image on a monitor, each frame consists of two "fields" (ODD and EVEN), involving a double pass down the screen to display each frame. This can produce problems with images taken from a moving platform. This so-called "field displacement" problem, in which platform movement and sensor mechanics affect the synchronization, has been comprehensively investigated by Pickup *et al.* (1995) and Neale *et al.* (1994). The timing information is present between each horizontal scan line and is used to align the picture correctly (a sync pulse called the "horizontal sync"). These lines are transmitted sequentially, starting at the top left of the picture (Data Cell Ltd., 1991). During the digitization process, the frame-grabber generates its own pixel clock, and locks this clock to the sync signals provided by the input device, such as a VCR or video camera, to avoid bad synchronization.

"Pixel jitter" occurs when the frame-grabber fails to make its free-running pixel clock change instantly to synchronise with the horizontal sync signal that starts the digitization of a new line, thus reducing line-to-line consistency. By the very nature of the pixel clock recovery process, there is always a certain amount of pixel jitter or uncertainty in the clock transitions. Pixel jitter is a problem for all standard analog video sources, including cameras and VCRs (Data Translation Inc., 1994). This uncertainty of synchronization is undesirable in any application where the video data are used to extract information in a digital environment.

Figure 2 shows digitized images from the Matrox and Data Cell frame-grabbers[1] for the same video frame (the Data Cell frame-grabber had been purchased at a price of around $6400 in 1991 while a new Matrox frame-grabber was acquired at price of around $900 at the end of 1996). The two frame-grabbers have generally similar performances in the manufacturers' specifications: sampling frequency (768 by 576) and gray level (8-bit color depth). With the Data Cell product (the more expensive older model), the quality of frame-grabbed images showed a considerable synchronization error. The newer technology is cheaper and delivers better performance.

The enlarged features (Figures 2A and 2B) are presented

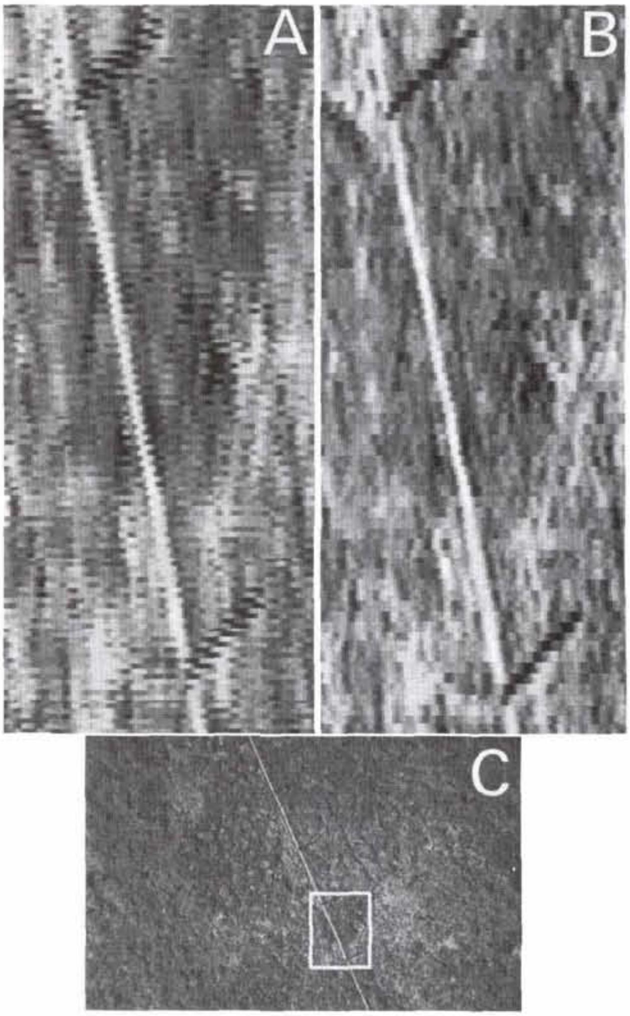

Figure 2. Illustrative comparison for images digitized from different frame grabbers, A: Data Cell, B: Matrox, C: Full frame [Rectangle = Upper video coverage].

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[1] Use of trade names in this paper is for the benefit of the reader and does not imply any product endorsement.

to highlight the field displacement problem during digitization. To demonstrate clearly the "line jitter" problem, an image with a very narrow swath (20m) was used for this experiment because this image is more prone to synchronization error, due to the small ground resolution cell (GRC). The pipeline boundary fence (a linear feature) shows the contrast between the two frame-grabbers. The Data Cell image did not resolve the fence pole orientated horizontally, whereas the image from the Matrox frame-grabber did not appear to be artificially degraded, showing the fenceline clearly. The Matrox images displayed better synchronization of the same scene features. The Data Cell image has lower contrast and is less distinctive due to poor synchronization (however, it should be emphasized that only one example of each digitizing board was used for this observation). Synchronization errors in Figure 2 caused displacements of the entire frame of around 15 pixels vertically (V) and 9 pixels horizontally (H)[2]. Recent developments in synchronization performance of new frame-grabbers show promise for overcoming this limitation of analog video. However, there is still room for improvement in the quality of the video image digitized from such analog recording. An approach based on A/D conversion is limited because there are still several image quality degradation links before the video data can be used in a digital environment.

Correction of Synchronization Error

The issue of compensation for synchronization errors has been extensively researched in TV engineering. One method for correcting synchronization errors is time-base correction (TBC). TBC was developed principally to deal with imperfections in broadcast quality video for television. Initially, during this process, an analog video signal is converted to digital form, so that the re-alignment of horizontal scan lines can be made to remove synchronization and timing errors, caused principally by the mechanical imperfections of analog video recorders. Some recent video camera models include the function of "on-board TBC" (Sony Ltd., 1995).

Pickup *et al.* (1995) carried out an investigation to match the displacement between "odd" and "even" fields in airborne video. However, their observations were largely based on video imagery acquired from an unshuttered video camera. This problem has largely been solved by the use of a shuttered video camera. Neale *et al.* (1994) developed a software package ("Lineshift") to shift the even or odd scan line using a certain correlation algorithm. This program can correct two types of errors: (1) inherent deficiencies in video recording due to horizontal camera movement in the airplane and capture process and (2) bad synchronization between VCR and frame-grabber. Their application has been based on video imagery acquired with a custom-built multi-spectral video camera, which necessitates post-registration of the individual channels.

To avoid the "field displacement" problem, some industrial television systems have used a non-interlaced video camera. These non-interlaced systems transmit the 625 scan lines progressively in each full-frame, and there are no half-frame fields. The frame rate must then be increased to 50 frames per second. Vertical resolution is improved, but the bandwidth required to transmit the signal is doubled compared with conventional interlaced television (Noll, 1988). Additionally, some video cameras can operate in either "field" or "frame" mode (interlaced or non-interlaced). If frame mode is selected, then the resultant images will not be subject to field displacement problems. However, the image quality will not give the best image spatial resolution relative to ground conditions (Sony Ltd., 1995).

With current technology, it is still difficult to obtain frame-grabbing devices free of blemishes or additional noise without a large capital expenditure. The TBC and Lineshift software might be the solution to this problem. The TBC approach requires additional hardware and the line-shift technique also requires additional software. Such a process for correction of synchronization error would take a long time for many individual frames, and it is unlikely that this approach could be conducted on a routine basis in an operational environment.

Limitations of Computer Specification

Unlike airborne scanners, imaging spectrometers, or aerial photography, airborne video can generate dynamic stereo coverage in each single flight line, by recording a very large number of individual frames within a very short time (operational rate of 25 frames/s in the European PAL television system and 30 frames/s in the American NTSC system). Video allows flexible post-flight selection of the overlap percentage whereas photography, for example, has a fixed overlap percentage at the moment of exposure. Such dynamic stereo coverage makes video the best means of recording a large number of ground features over a given time interval, which is a main requirement in the case of monitoring a long narrow corridor (e.g., a pipeline or road).

Such dynamic stereo coverage allows approximately 99 percent overlap between sequential frames. Theoretically, there should be less geometric and radiometric difference among closely adjacent sequential frames because they have more similarity in imaging conditions. As a result, mosaicking of video frames with abundant overlap could be a significant advantage because it would show better geometric and radiometric fidelity than with the standard 60 percent overlap of aerial photography. Dynamic stereo coverage (achieved by high frame rates in analog or digital-recorded video) is not achieved with any other remote sensing system, including digital camera systems.

For the overlap redundancy to be useful in digital stereo mosaicking, it should be possible to control precisely the required overlap percentage for individual frames during the digitization process, in accordance with user requirements. The ideal way of achieving a precise overlap percentage is one in which the frame interval can be controlled directly from the digitization process, so that multiple frames can be digitized with a precise overlap percentage. For operational application, several thousand frames may need to be digitized. The file size of data produced per color image, in interlaced frame mode, is around 1.3 megabytes in the CCIR (International Radio Consultative Committee) video standard digitization (768 by 576 pixels), assuming a byte of storage per pixel. This totals around 4.5 Gb for 3472 frames taken with a 28.8-m along-track net gain on a 100-km length of pipeline. As a further step, the digitized frames should be mosaicked together for further digital analysis, and the classified mosaicked data should be stored in a GIS database. For a change-detection study, such video should be acquired on a time-sequential basis (say, annually for five years). Such a process requires a total storage space of approximately 50Gb (as estimated in Table 1).

In a real operational environment, much more random access memory (RAM) and hard-disk storage space will be required than estimated here because the operator will always want to process the data at much faster speeds and have more spare storage space than in a research environment. Due to such reasons, many previous researchers had concluded that the advantage of video as a real-time remote sensing tool was not sustainable due to the required time

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[2] The difference in V and H synchronization error is believed to be caused by resolving power differences in the scan direction of the video sensor.

TABLE 1. ESTIMATION OF DATA STORAGE REQUIREMENT

Initial Digitized Data	Mosaicked Data*	Processed Data*	Total for One Year/for Five Years
5 Gb	3 Gb	2 Gb	10 Gb/50 Gb

* The mosaicked data take less space than the initially digitized data due to overlap. The processed (classified) video takes less space than the mosaicked data because it does not have three different layers (red, green, and blue).

and labor, and the loss of image quality during digitizing and mosaicking. However, developments in software image compression techniques may lead to significant advances in storage and manipulation of images, provided that loss of image detail can be reduced.

Transition Period

Due to image quality degradation in the digitization of analog video, there have been several trials to introduce a custom-built digital video camera into video remote sensing. Relevant to the requirement for real-time digitization in video remote sensing is the recent emergence of "PC video." Due to the historical importance of the concept of "custom-built digital video" and "PC video" in validating the significance of an "off-the-shelf" digital video camera, much of this section examines previous efforts to acquire digital video and the possible computer digitization of the analog video signal by off-the-shelf "PC video."

Custom-Built Digital Video Camera

Due to the advantages of direct digitization, some recent multispectral video systems have a direct digitization function in-flight (Pearson *et al.*, 1994; Everitt *et al.*, 1996; Heitschmidt *et al.*, 1996; Mao and Kettler, 1996). Such custom-built digital video cameras were designed using the same approach as the custom-built analog video cameras which combine a multiple-camera analog system where each camera is equipped with an appropriate interference filter. The image signals are digitized in-flight by multiple frame-grabbers and stored digitally on disk or tape instead of analog recording. Although custom-built digital video avoids the degradation of image quality during A/D conversion, there are many disadvantages of the custom-built digital video camera compared with recently introduced "off-the-shelf" digital video (DV) cameras. Custom-built cameras are generally very expensive, which inhibits their practicality for routine operational use. For a fraction of the price, a similar performance can be achieved by using an off-the-shelf DV camera.

Everitt (1996) states that "the basic digital video system here can be assembled for about $18,000. Replacement of the system described here with a true digital system could result in a three-fold increase in cost." Another limitation is that different image bands of a multispectral digital airborne camera system are significantly misaligned with each other. The band-to-band misalignment includes band-to-band image rotation, shift, and scale variation. This has arisen due to a limitation of the system design and implementation using off-the-shelf components such as lens, filters, and cameras, which are originally manufactured for stand-alone use. Therefore, raw imagery usually cannot be directly used for multispectral analysis without band-to-band registration (Mao and Howard, 1996).

As for the mosaicking of images from custom-built digital video, Heitschmidt *et al.* (1996) state that "the most prominent problem faced in this project was the mosaicking of such a large set of images. Because the real-time digital airborne camera system (RDACS) records multispectral data, the mosaicking process was repeated for each spectral band. Transformations created while mosaicking the first band (here the red band) were saved for reapplication to the remaining green and infrared bands. This process involved simply swapping out files from one band to another band and reapplying the same transformation. In this way, it was expected, the finished mosaics would retain their band-to-band registration. Unfortunately, it was discovered that the output mosaics were not identical in file size and geometry. Repeated attempts to band-to-band register these mosaics failed to produce acceptable results and, due to time constraints, this process remains problematic, and much work remains to be done in this area to ensure accurate multispectral alignment."

As in the case of custom-built digital video, 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. Such custom-built cameras certainly have their own limited niche applications which require multispectral sensitivity and pure experimental precision. For the most part, however, they do not have operational performance due to cost and complicated post-processing requirements (King, 1995).

PC Video

As computer processing power increases and prices dramatically decrease, hardware and software tailored for video applications have begun to appear in general-purpose computers running in a multimedia environment. Such PCs help to solve the technical issues involved in integrating video with computers more easily than that of the "custom-built" approach, and will help to develop the practicality of airborne video systems. Previously, video frame-grabbers were in general designed for professional users (such as in television broadcasting), which resulted in the operating costs of this equipment being prohibitively expensive for remote sensing practitioners. "PC video" is manufactured in the context of optimizing cost-effectiveness for PC-based business communications, targeting a large mass market. Such a card for a personal computer is called a "CODEC" card, because the software or hardware performs compression (CO-) when recording video, and decompression (-DEC) for further display, e.g., from Avid, Data Translation, Radius, Truevision, Fast, and Matrox (McMullon, 1996; Doyle, 1997). The CODEC card can turn a computer into a possible tool for real-time digitization of video signals. This could permit direct input of video format to a computer in-flight, with much lower cost than with a custom-built digital video camera (discussed in the previous section).

The digitization function was initially designed to enhance business communications or to capture favorite TV programs of the domestic user, which may be used in pictures, presentations, and movies, increasingly in a multimedia environment. Many computers now come supplied with an analog video (AV) interface. Apple's Macintosh 7500 and 8500 have a Philips video digitizing chipset on the motherboard (Doyle, 1997). Toshiba portable computers have introduced the TECRA series (produced in mid-1996) which have a zoom-video (ZV) port to permit real-time acquisition and display of video imagery from a VCR or video camera. Many other PCs will soon be on the market with such a function.

The CODEC card uses the MPEG (motion picture expert group) compression function, and playback devices process 3 million bits of information per second with image quality comparable to VHS (while DV uses a digital video compression function that handles roughly 25 million bits per second, more than 8 times the resolution power of MPEG) (McCleskey, 1997). Video-capture cards have a technical complexity which ensures that the video signals remain synchronized during digitization and compression. A typical video-capture card that supports full-screen, full-motion video will likely cost more than $1,000, and a fully equipped system costs well in excess of $15,000 (Silver, 1996). As a result, such approaches are still primitive due to the cost, the analog-to-digital (A/D) conversion process, and the compression of MPEG format, because they are still being developed to be used with a video camera based on analog recording.

The Digital Era

Emergence of Off-the-Shelf Digital Video (DV) Camera

The ultimate solution is likely to be the off-the-shelf digital video (DV) camera. Lately, digital cameras have become the new phenomenon in the world of still photography. There are already relatively affordable still cameras that use CCD chips to convert light signals into digital signals. Moreover, full-motion video digital technology is already "on the street." "Digital Video" is a new video-compression and videotape format that is quickly becoming a global standard. DV is a worldwide unified format (decided in 1995) supported by 56 companies ranging from electronics to computer manufacturers (such as Apple and IBM) world-wide, assuring its future as the next standard in home video. In particular, the DV standard was decided in consideration of direct digital recording of future High Definition TV (HDTV) signals (Doyle, 1997).

This marks a turning point in the history of consumer video (including airborne videography), from analog toward digital and onward to High Definition video (HD video) (Table 2). In the past, high-quality digital video has meant that cameras were large in size and formed part of an expensive system which was solely available for broadcasting or other professional purposes. DV changes such a concept by being available at almost domestic consumer prices (Silver, 1996; Panasonic Ltd., 1997).

Working with digital video should avoid artifices such as "image quality degradation" that would otherwise be caused by repeated analog recording of video on tapes. There are no serious spatial resolution degradation links among the data acquisition systems because the data are initially stored in digital form, and the recent digital camera and tape have similar resolution (currently around 500 lines). With the advent of digital video, the progressive degradation of analog image quality could soon be of only historical significance, because DV will permit the direct digitization of the video signal from the sensor. In digital video, there is no need for "blanking" or "sync pulse," because a computer knows exactly where a new line starts as long as it knows the number of pixels per line (Murat, 1995). In contrast to the analog approach, the digital tape records the video signal as a long series of bits (zeroes and ones). This "bitstream" is much easier for a magnetic or optical storage medium to keep track of than a complex analog waveform (McCleskey, 1997).

A DV camera incorporates analog-to-digital conversion into the camera (unlike the multiple frame grabber approach of the custom-built camera) and manages the digitization, compression, and synchronization processes simultaneously during video imaging. The sophisticated and expensive components found on current analog video capture cards are no longer needed because the video information on a DV cassette is already digital (a "pure digital signal" without going through the "digital-to-analog" and "analog-back-to-digital" conversion process), so all that is required is a means of copying the information onto the computer's hard disk (Silver, 1996). No conversion is required from analog to digital (as required with current Hi8 and S-VHS) and no additional compression is needed (such as MPEG or CODEC cards).

TABLE 2. TECHNICAL DEVELOPMENT HISTORY OF OFF-THE-SHELF DOMESTIC VIDEO CAMERA

Analogue Era			Digital Era	
Pre-1984 → Vidicon VHS	1984 → CCD VHS	1987 → S-VHS	1996 → Digital video	HD video
no shutter: freeze frame gave blurred image.	shutter (1/1000) 230 lines resolution	more than 400 lines resolution	more than 500 lines resolution	more than 1000 lines resolution

The resulting captured video is the original itself. Such a card for a personal computer should be a fraction of the cost of the existing video capture cards because the card will not need high-quality A/D converters and the encoding and decoding chips that digitize the video (McMullon, 1996; Doyle, 1997). With a digital video camera, it should be possible to connect to a computer using the new high speed data protocol. Transfer of digital video to computer should be faster than normal play-back because the design of the digital video camera has initially been made for digital storage.

With its advanced digital compression technology, the potential of DV surpasses all previous consumer video media. Because DV is a digital format, the recorded data are able to withstand long-term storage (Panasonic Ltd., 1997). Time-Base-Corrector (TBC) is a standard feature of the DV format which corrects timing error by binary signal sampling. This reduces horizontal jitter by compensating for any irregularities in the time axis. "Digital image stabilizer" is able to eliminate camera shake without affecting either resolution or image size. With such error correction features for picture stability, captured footage is free of both jitter and flicker. As for the picture quality, all variants of digital video are nearly broadcast quality. Morgan (1995) points out that picture quality is likely to be substantially more than a 25 percent improvement over the S-VHS and Hi8 performance. For remote sensing purposes, the resulting image is likely to be much better than S-VHS because there is no radiometric or spatial resolution loss due to data conversion. The quality should be more than adequate, especially considering that the analog S-VHS is still acceptable in many applications.

The cost of a digital video camera is reasonably affordable for the professional user (and still cheaper than conventional professional photography). The prices in July 1997 ranged from $1,700 to $4,300 (based on the retail price in the UK, converted to U.S. dollars; *Camcorder User*, July, 1997). Along with the digital video camera, a standard for the digital video cassette is also available. A 60- or 180-minute tape costs nearly two to four times more than for Hi8 and S-VHS. Although expensive compared to other consumer cassettes, the DV cassette's image quality, freedom from analog tape artefacts, and dropouts will lead to it supplanting the Hi8 and S-VHS analog formats (McMullon, 1996; Gadgetz, 1997; Doyle, 1997).

For computer storage of digital video, Sony's DV still-image capture board (DVBK-1000) enables users to transfer images from a digital video camera directly to a PC without the need for analog-to-digital conversion. It allows the computer to control video camera functions directly and display the time code on-screen (via DV interface), making it easy to identify virtually the exact frame of each image. It is also equipped with on-screen video camera control with point-and-click menus for functions, including play, pause, stop, fast forward, and rewind (Sony Electronics Inc., 1997). JVC have also announced a new terminal called Joint Level Interface Protocol (JLIP) which has been designed to facilitate easier integration of video systems with computer equipment. This allows the DV to be controlled from a computer. JLIP allows the interconnection and bi-directional control of DV equipment and computers. A typical master-slave system would link the serial interface of a personal computer to one or more JLIP-compatible DV devices (VCRs, DV camera, etc.) via a junction box using suitable software (JVC Ltd., 1997).

Improvements in Computing Power

At present, the major limitation of digital video remote sensing in relation to computing is the digital transfer rate and storage for continuous digitization. The computing power problem, however, is likely to be eased significantly in the near future. It is difficult to predict even one snapshot in the burgeoning field of computer technology. For instance, at the start of this research project (1994), the specification of a standard PC included 640Kb memory and a 70Mb hard-disk. Currently (1997), a PC with multimedia function has at least 16 Mb of memory and a 1.5-Gb hard-disk, for a price similar to that of three years ago. In addition, advances in hard-disk drive technology are allowing disk drives of several gigabyte capacity to be used for image storage. Read/write optical disk drives allow not only high capacity storage (1Gb and up), but are also a very portable data medium. Digital Video Disk (DVD), new standard for high density CD, will also assist in ensuring the practicality of video imaging for operational use.

It is expected that the increasing volumes of data being generated by digital video frames may not be a major problem soon. If, due to computing power development, 20 or 30 video frames could be digitized within one minute, then digital video remote sensing would become quite a powerful tool for any linear remote sensing application. This process should be achieved much more easily with digital video, due to the "turnkey"-based digital interface of the camera. In the case of aerial photography, even as digital camera technology is developed, it will still entail digitizing frame by frame, which requires much time and labor. This limitation also applies to other remote sensing tools, such as line scanners and imaging spectrometers.

Another gain to be expected with the improvement of computing power is the practical potential of automated video mosaicking. Possibly the first fully automated digital mosaicking procedure has recently been developed for the U.S. Forest Service, based on operational use of an S-VHS camera with a GPS receiver, a tip/roll indicator, and an SMPTE Time Code Generator. A studio-quality computer-controlled tape deck accurately positions the video tape on the precise frames where GPS and aircraft attitude data are available, and a custom written software package, the Automated Video Toolkit (AVT), performs the automated mosaicking, 40 times faster than the existing Forest Service manual method (Linden *et al.*, 1996). The introduction of automated image matching techniques into video mosaicking would be very significant, bearing in mind that video would not be of much use in a digital environment without mosaicking. In particular, computing power has, until recently, been a primary factor hindering development of matching techniques that require extensive memory and high speed (Ventura *et al.*, 1990; Saleh and Scarpace, 1992). Also, high resolution digital video imagery will greatly contribute to automating the mosaicking process, due to strong signal and less noise in the image pattern matching process, without the loss of quality caused by A/D conversion. The digital revolution will affect the development of matching techniques which become attainable. In consideration of this, the routine "practicality" of digital video remote sensing should happen coincidentally with the requisite developments in computing performance.

Conclusions

Satisfactory data collection from an accurate measurement system is one of the most important concerns of any remote sensing project. Until now, video remote sensing in a digital environment has just been at the exploratory stage. Video remote sensing has invested heavily in research and development for digital imaging (as in the case of custom-built digital video cameras). The recent advent of off-the-shelf digital video (DV) cameras has significant implications for digital video remote sensing and will provide the capability to monitor the spatial distribution of ground features much more effectively.

The "digital revolution" is likely to change the general concept of airborne videography in the remote sensing discipline, by making it possible to acquire data sets with a radiometric or spatial precision of the original, depending on the capability of the computer in terms of power, memory, and extended storage. The multimedia computer and the DV could soon make present analog video remote sensing obsolete and will change the attitude of many remote sensing practitioners towards video as a practical tool for operational applications. The improved image quality and flexibility of data storage and processing will ultimately lead to the practicality of a linear "facilities GIS database."

Furthermore, there is much potential in the digital video camera in terms of cost and quality. With the declining cost of the DV, these types of systems will be available to broader markets, including video enthusiasts and home users in the not-so-distant future. Technological developments of the digital video cameras themselves will lead to improved performance, through better spatial resolution and increased sensitivity of detectors. In the near future, more research should be conducted with off-the-shelf digital video to assist the time-dependent user (although it may seem a little premature to think of introducing digital video strip mapping for routine applications). In view of the typical time lag for the new technology of "digital video" to be transferred to operational use, there is an opportunity for this overview to serve as a catalyst for further research in the context of the "analog-to-digital transition of airborne video."

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