

AIRBORNE DIGITAL IMAGING TECHNOLOGY: A NEW OVERVIEW

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Abstract

This paper presents an overview of current developments in the airborne digital imaging technologies—including both digital frame cameras and pushbroom line scanners—and analyses them in the context of their applications to digital photogrammetry.

KEYWORDS: airborne digital cameras, airborne pushbroom scanners,
digital photogrammetry, imaging sensors

INTRODUCTION

THIS PAPER CONCENTRATES on the developments in airborne digital imaging systems that have taken place in the 3-year period since the ISPRS Congress was held in Istanbul, rather than claiming to be a review of those that were already well established in the market. It provides a coherent narrative follow-up to the authors' invited presentation (Petrie and Walker, 2006) to the ISPRS Commission I Symposium at Marne-la-Vallée, France in July 2006, as already briefly reported to readers of *The Photogrammetric Record* by Mills and Cracknell (2006). In the first part of the paper, the significant advances that have taken place in the sensor technologies used in airborne imaging will be reviewed. The second part of the paper covers the developments that have occurred in airborne digital frame cameras, including small-format airborne cameras and systems as well as the medium- and large-format systems that are of most importance to photogrammetrists. The third part of the paper covers airborne pushbroom scanners. Besides the well-established Leica ADS40, the current state of development with the several other pushbroom scanners is discussed. The final part of the paper analyses the present situation in airborne digital imaging including technical, commercial and operational aspects of this rapidly developing field of activity.

SENSOR TECHNOLOGIES

Area Arrays

Over the past 2 years or so, there have been several important advances in the two main semiconductor technologies—charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS)—that are used in airborne imaging. In particular, the introduction of

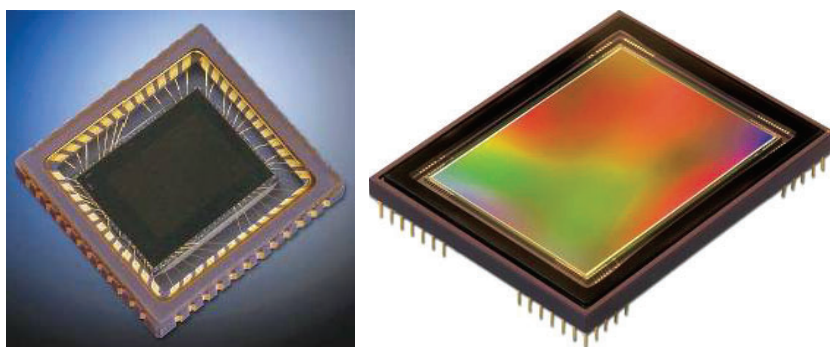


FIG. 1. (a) Typical CMOS area array illustrating the trend to smaller pixel sizes and to larger pixel counts and image sizes. (b) Dalsa CCD area array with 22 megapixels used in medium-format airborne digital cameras (source: Dalsa).

area arrays that offer larger format sizes (in terms of numbers of pixels) has had a major impact on airborne digital imagers, which can now produce images that are substantially larger in terms of their format size.

CMOS Arrays. CMOS arrays (Fig. 1(a)) are mass produced in large numbers by the manufacturers relatively easily and cheaply. So, until recently, they have been used mainly in document and bar code scanners, fax machines and cell phones, for example, where the demands for radiometric quality are not as high as are required in both professional studio photography and airborne imaging. However, the situation has now changed quite dramatically. First Kodak introduced a CMOS area array with 14 megapixels that has been used to power its range of Kodak Pro SLR cameras. Then Canon introduced its CMOS area array sensors for its EOS range of cameras, the latest in the series reaching 16.7 megapixels in size. Its Japanese rival, Nikon, has adopted the CMOS area arrays made by Sony that are 12.7 megapixels in size and used in its D2X range of cameras. All of these CMOS devices are now found in airborne digital cameras. Indeed it can be said that the previously dominant CCD-based technology used in small-format cameras has quite suddenly been replaced by CMOS devices. At the same time, the previous figure of 6 to 8 megapixels as the typical format size for the small-format SLR cameras being used in airborne imaging has been doubled to 12 to 16 megapixels.

CCD Arrays. In the field of medium-format area arrays that can be used for airborne imaging, a similar transformation has also taken place in terms of the number of pixels that are now available within the resulting image. However, within this category, CCD arrays (Fig. 1(b)) remain the dominant imaging technology, though once again there has been a huge stride forward with a doubling of the number of available pixels—from typically 16 megapixels to between 30 and 40 megapixels. Thus Kodak, for example, first increased the maximum size of its KAF series of CCD arrays from 16 to 22 megapixels and has now increased the maximum size to 31 and 39 megapixels, respectively. Similarly Dalsa has introduced CCD arrays that are 33 megapixels in size and are available in two different forms to generate monochrome and colour images, respectively. In turn, these developments on the part of the chip manufacturers have had a dramatic effect on the capacity of the digital backs used to convert film cameras—such as those from Rollei, Hasselblad, Mamiya and Contax—to produce digital images and use them for the acquisition of airborne digital frame imagery.

In the case of large-format digital cameras, the overwhelming majority of those being used for airborne imaging by non-military organisations use multiple cameras and lenses in conjunction with medium-format CCD arrays—as in the case of the Microsoft (formerly Vexcel) UltraCam and Intergraph DMC camera systems. Thus the increase in the size of medium-format CCD arrays has had its effect on this area too. This can be seen in the introduction of the new model of the Microsoft camera—the UltraCam-X—with the increase in the overall size of the final panchromatic image from 86 to 133 megapixels.

It is interesting to note that the increase in the number of pixels in the images being generated by these new CCD arrays is being achieved through the use of individual detectors that are smaller in size than before— $6.8\text{ }\mu\text{m}$ in the case of the Kodak arrays and $7.2\text{ }\mu\text{m}$ in the case of those from Dalsa. When applied to a standard size of chip—for example, $36\text{ mm} \times 48\text{ mm}$ in size—this creates a much larger number of pixels while improvements in the technology have ensured that the radiometric quality (sensitivity, dynamic range and so forth) of the previous larger-sized detectors, which were usually between 9 and $12\text{ }\mu\text{m}$ in size, has been retained.

Colour: Since both CMOS and CCD detectors are inherently monochromatic, a major concern is the provision of a capability to generate colour images. This adds considerably to the complications and expense of the resulting systems—certainly as compared with film cameras, where it is simply a matter of changing the film from monochromatic to colour or false-colour. As is well known, various different approaches can be taken to overcome this limitation:

- (i) the use of Bayer or some other interpolation scheme to generate colour or false-colour images with single CCD or CMOS arrays (Fig. 2(a));
- (ii) the use of multiple cameras (and arrays), each equipped with different filters, to collect images in different spectral bands with the later fusion of the individual spectrally separated images to form the final composite colour image;
- (iii) the use of beamsplitters to separate the different spectral bands within a single camera and the use of multiple area arrays within the camera to record the colour separated images, which are combined later to form the final colour image (Fig. 2(b)).

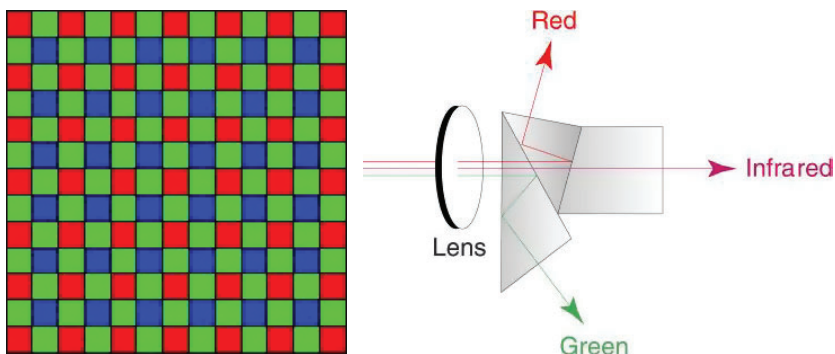


FIG. 2. (a) Bayer interpolation. A mosaic of tiny filters is placed over the array of detectors. Each pixel receives red, green or blue light in the pattern shown. For each pixel in the output image, one of the three bands is received directly while the other two are interpolated from the surrounding pixels. (b) Beamsplitter. This device is placed between the lens and the three separate image planes, each with its own area array and spectral filter.

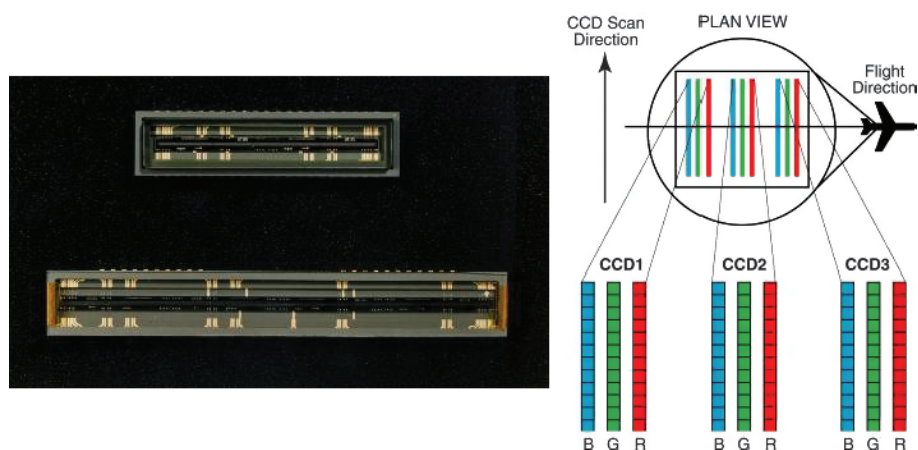


FIG. 3. (a) CCD linear arrays from e2v (UK). The upper photo shows a 4k pixel array; the lower photo shows a 12k pixel array (source: e2v). (b) Colour images are produced using trilinear arrays deployed in airborne pushbroom scanners such as the Wehrli 3-DAS-1 and 3-OC.

Linear Arrays

Linear arrays are, of course, the basic building blocks for airborne pushbroom scanners producing continuous strip images of the terrain. The ground coverage of these scanners is dependent on the length of the linear array that is fitted to the scanner. Airborne pushbroom scanners use linear arrays with between 4000 and 14 000 detectors (Fig. 3(a)). Invariably these use CCD detectors. At the top end, the major suppliers are Atmel (France), e2v (UK), Kodak (USA) and Fairchild (USA). There appears to be little new development to report in this particular field. The large-format pushbroom scanners are still equipped with arrays having 12 000 to 14 000 detectors as the longest available product. Attempts to use multiple arrays to widen the coverage run into difficulties with stepped arrays since the individual linear arrays cannot be butted together. So the separate images produced using such an arrangement would then have to be stitched together. Although this stepped arrangement has been used with the pushbroom scanners deployed in certain satellites—for example, in the IRS-1C/D series and in DigitalGlobe's QuickBird—so far it has not been employed in airborne pushbroom scanners, except for the panchromatic lines in the Digitale Photogrammetrie-Ausstattung (DPA) developed in Germany by Messerschmidt-Bölkow-Blohm (Hofmann et al., 1993).

As with area arrays, the requirement to generate colour images using linear arrays leads to complications. For the acquisition of simple colour strip images, multiple linear arrays equipped with different filters are set parallel to one another—as, for example, in the Kodak and the Sony trilinear arrays (Fig. 3(b)). Offsets are created with this arrangement—which results in different lines on the ground being imaged on the various linear arrays at the same instant of time. This needs to be compensated for during subsequent image processing.

AIRBORNE DIGITAL FRAME CAMERAS

The main developments in these frame cameras over the few years since a previous overview (Petrie, 2003) will be reviewed on the basis of the format size of the resulting images:

- (i) small format (up to 16 megapixels);
- (ii) medium format (from 16 up to 50 megapixels);
- (iii) large format (greater than 50 megapixels).

Small-Format Frame Cameras

As discussed above, there has been a very big change in this area with the introduction of single cameras equipped with CMOS arrays that can generate much larger images (with a greater number of pixels) than before. Besides this, there has been a very substantial rise in the number of imaging systems based on the use of multiple small-format frame cameras acquiring vertical and oblique images simultaneously.

Single Lens Monochrome Cameras. An example of a purpose-built small-format airborne digital frame camera that produces monochrome images is the Carl Zeiss VOS 40 series, which is designed specifically for use in military reconnaissance aircraft. The format size is quite small— $2k \times 2k$ —producing a 4 megapixel monochrome image. Each camera, however, is equipped with a powerful zoom lens with folded optics having maximum focal lengths of 270 mm for the VOS 40/270 model and 500 mm for the VOS 40/500 model. These cameras are designed to operate with electronic shutters giving rapid frame acquisition rates of up to 15 frames per second with the VOS 40/270 and up to 3 frames per second with the VOS 4/500.

Single Lens Colour Cameras with Mosaic Filters. Most of these small-format cameras produce colour images using mosaic filters and Bayer interpolation. Numerous examples of airborne cameras using various models from the Kodak DCS 460/560/660/760 range (equipped with CCD arrays) have been deployed in the past and many are still in widespread use. In 2003, Kodak introduced its DCS Pro 14n camera with its 14 megapixel CMOS area array. This was replaced soon afterwards, in 2004, by its slightly improved DCS SLR/c (= Canon) and SLR/n (= Nikon) models. These were of great interest to airborne digital camera operators and several systems based on the Pro SLR cameras were announced by airborne system suppliers. However, the Kodak DCS Pro cameras did not sell well in their main market of professional photography. Thus, in May 2005, Kodak withdrew completely from this whole area. This has left the field open to other suppliers of digital SLR cameras—in particular, to the two major Japanese companies, Canon with its EOS-1Ds Mk. II camera producing images with 16.7 megapixel images (Fig. 4(a)), and Nikon with its D2X camera with its 12.4 megapixel images. There is a very substantial price differential between these two cameras in favour of the D2X, but the EOS-1Ds Mk. II does of course generate images with a larger number of pixels.

As noted above, almost all the airborne digital cameras falling within this category are based on SLR cameras aimed at the professional photography market. For airborne use, they are then fitted to a simple anti-vibration mount equipped with shock absorbers, together with (i) an electronic unit that controls the timing and exposure of the image; and (ii) a GPS set used for flight navigation and georeferencing purposes (Fig. 4(b)). Usually the system is interfaced to a small laptop computer that is used both for flight planning and navigation purposes and for storage of the digital images acquired in-flight. In a few cases, a simple, relatively inexpensive, lower performance inertial measurement unit (IMU) may be used to generate tilt data to help carry out the rectification of the images. Many examples of these small-format systems based on professional SLR cameras have been supplied, for example, by the GeoTechnologies consultancy based in the UK.



FIG. 4. (a) The Canon EOS-1Ds Mk. II camera, based on a CMOS area array, acquires images with 16.7 megapixels. This camera produces its colour images using a mosaic filter and Bayer interpolation (*source*: Canon). (b) GeoTechnologies' SF-DMC small-format digital camera with an anti-vibration mount based on shock absorbers and an electronic control box (*source*: GeoTechnologies).

Besides all the many airborne digital camera systems that make use of professional cameras, there do exist single cameras that have been designed and built specifically for airborne use. A recent example is the ADC Air from Tetracam in California (Fig. 5(a)). This small and inexpensive camera is designed specifically for the agricultural monitoring market and features a CMOS chip from OmniVision that can generate either colour or false-colour images that are 3.2 megapixels in size. These cameras have come into fairly extensive worldwide use by farmers, crop consultants, agronomists and the like.

Single Lens Colour Cameras with Multiple Arrays. Recently two digital frame cameras have appeared that are designed specifically for airborne use and feature multiple area arrays and a highly rectangular image format. The first of these is the New Metric Camera (NMC), which has been developed by a consortium of six European companies and research institutes supported by funding from the European Union (Mayr and Ohlhof, 2004). The camera was built by the VTT research institute in Finland. The NMC employs nine inexpensive CCD area



FIG. 5. (a) Tetracam ADC Air camera. This is an inexpensive small-format camera designed specifically for use in airborne agricultural and environmental monitoring based on a 3.2 megapixel CMOS area array. Once again, the colour images are produced using a mosaic filter and Bayer interpolation (*source*: Tetracam). (b) Redlake MS4100 camera. This is based on the use of three CCD area arrays, each with a $1\text{k} \times 1.9\text{k}$ pixel format, and a beamsplitter placed between the lens and the three arrays. Each array has its own spectral filter (*source*: Redlake).

arrays in its focal plane, each having detector elements that are $4\text{ }\mu\text{m}$ in size. The individual images produced by the nine arrays are optically butted within the camera to form a single rectangular image that is approximately $10\,000$ pixels (cross-track) $\times$ 1600 pixels (along-track) in size. The second camera in this category is the G2010 series developed by Global Imaging Technologies based in Baltimore in the USA. These also make use of multiple inexpensive area arrays to produce a rectangular image that is 7880×1020 pixels in size. However, the G2010 cameras use multiple lenses (one per array) instead of the single lens used in the NMC. Therefore, the optical butting and merging of the component images takes place on the object side of the lenses, rather than on the image side (inside the camera) as is done with the NMC. The company also makes the ARDIS II, which produces an image that is 7020×1030 pixels in size.

Single Lens Colour Cameras with Beamsplitters. A small number of single lens cameras make use of three separate CCD area arrays in conjunction with a beamsplitter to produce colour or false-colour images. These are produced by a single supplier, Redlake, from California (Fig. 5(b)). The company's MS3100 and MS4100 cameras are then sold to system integrators and suppliers such as Airborne Data Systems (ADS) in Minnesota and Integrated Spectronics (IS) in Australia. These add a suitable mount, control unit and GPS/IMU to create the final operational system—called AgriView by ADS and ISAACS by IS.

Multiple Cameras Generating Colour Images. Yet another approach within the small-format category is the use of multiple CCD cameras. Many of the resulting systems use this configuration to produce colour or false-colour frame images. Usually three or four of these monochrome cameras are coupled together with their optical axes set precisely parallel to one another and their shutters synchronised to operate simultaneously in order to ensure the coverage of exactly the same piece of ground by all the cameras. Each camera is fitted with the spectral filter (RGB or NIR) needed to capture the appropriate band image from which the final colour or false-colour image will be generated by image fusion. It will be seen that this arrangement allows each image to be recorded at its full radiometric resolution; thus there is no interpolation involved in the procedure.

This multispectral approach is extremely popular in the USA. For example, the GeoVantage company based in Massachusetts operates 22 of its multi-camera systems worldwide. Each system is based on the use of four tiny and inexpensive CCD cameras made by Sony, each with a format of 920×1280 pixels (Fig. 6(a)). Each system also incorporates an integrated GPS/IMU unit to measure the position and attitude data in-flight for each frame image. This data is then used to carry out the georeferencing and orthorectification of the numerous tiny frame images that are generated by the imaging system. The overall system is quite small and portable and can easily be shipped abroad from the USA and operated from a rented light plane such as a Cessna 172. The main target areas are agricultural monitoring and forestry—as confirmed by the recent takeover of GeoVantage by the John Deere company, which is a major manufacturer and supplier of agricultural machinery. Another similar multi-camera system is the SpectraView (Fig. 6(b)), which has been built in some numbers by ADS. This uses the same basic arrangement but with somewhat larger format (6 megapixel) digital cameras.

Multiple Cameras Generating Oblique Images. Another quite different development using multiple small-format digital cameras that has come to the fore recently acquires one vertical and four oblique colour photos simultaneously (Fig. 7(a)). This configuration was introduced some years ago by several different companies—Pictometry in the USA and the Idan and Ofek companies based in Israel. Recently it has also been adopted by several service providers in Europe. The five-camera arrangement is the same as that used by the Fairchild T5A film cameras



FIG. 6. (a) The GeoVantage multiple camera system features four small-format cameras, in this case from Sony. The photo shows the airborne control and data storage units on either side of the white external data pod containing the four cameras, together with the operator's display screen (*source*: GeoVantage). (b) The SpectraView multiple camera system from Airborne Data Systems. This produces its colour and false-colour images using four small-format digital cameras in a rigid mount, with each camera having a different spectral filter (*source*: Airborne Data Systems).

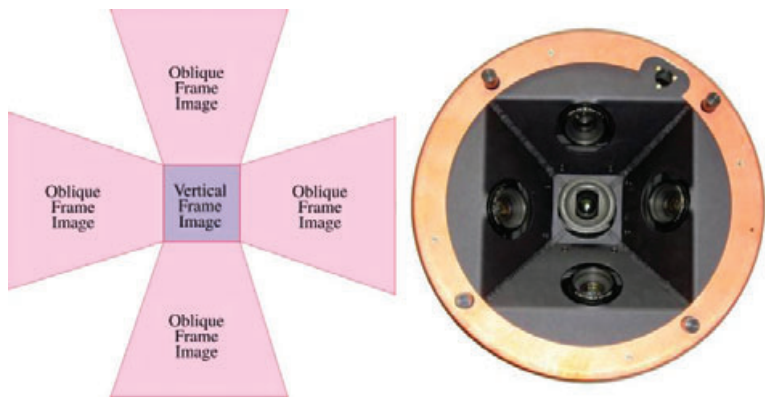


FIG. 7. (a) Coverage diagram for a multiple camera system consisting of five small-format digital frame cameras acquiring one vertical and four oblique colour images. (b) The MIDAS multiple digital camera system from Track'Air employs five Canon EOS-1Ds Mk. II small-format digital cameras in a custom-built mount (*source*: Track'Air).

deployed extensively for mapping in the USA during the 1930s. In this current revival of the old idea, now implemented using digital instead of film cameras, the target markets are law enforcement agencies and emergency (fire, ambulance) services. Apparently these organisations have found that oblique images are much more easily interpreted by non-expert users, who also consider the information about building use and structure offered by the oblique images to be useful for their operations. A representative camera of this type is the MIDAS system recently introduced by Track'Air from the Netherlands (Petrie, 2006). This makes use of five of the Canon EOS-1Ds Mk. II CMOS-based small-format cameras already mentioned (Fig. 7(b)).

Summary. Many small-format airborne digital cameras are currently in operational use and many more can be expected to come into use in the future. Indeed, it can be said that the technology is now well established. Up till now, the main emphasis has been on the production of colour and false-colour images for environmental monitoring and agricultural applications over

relatively small areas. However, the latest development is the introduction and extensive use of small-format oblique frame images taken in a systematic pattern to provide multiple images of the same area from different directions. Whichever of the several approaches described here is used, given the small formats, very large numbers of images have to be handled and processed if any substantial area of ground is to be covered. A high degree of automation in the subsequent processing of the images is required for this type of imaging to be successful, so GPS/IMU systems are highly desirable, either to obviate the need for aerial triangulation or to automate it by giving the image matching algorithm for tie point measurement good starting values.

Medium-Format Frame Cameras

The vast majority of medium-format frame cameras that are in current use for the acquisition of airborne digital imagery have been modified from existing film cameras built by Hasselblad, Rollei, Mamiya and Contax with the film magazine replaced by a digital back. Only a very few medium-format frame cameras have been purpose-built for operation from an airborne platform.

Modified Film Cameras. Suitable digital backs have already been developed by various suppliers for fitting to high-quality film cameras with 6 cm × 4.5 cm, 6 cm × 6 cm or 6 cm × 7 cm formats, as used by professional photographers both in their studios and in the air. These digital backs have been developed by MegaVision (USA), Phase One (Denmark), Sinar (Switzerland), Imacon (Sweden) and Jenoptik (Germany). Most of these devices have used Kodak's ITO-based 4k × 4k pixel (= 16 megapixel) CCD area array, which uses Bayer interpolation to generate colour images. Over the past 2 years, digital backs with a slightly larger version of this Kodak array with 4 k × 5.4 k pixels (= 22 megapixels) have come into widespread use. However, as discussed in the introductory section on sensor technologies, the latest development in this area is to make use of the still higher density CCD area arrays that have just become available and produce images that are 30 to 40 megapixels in size.

The largest suppliers of medium-format airborne digital frame cameras based on modified film cameras are Applanix and Rollei, who reportedly have supplied over 70 and 60 examples of each of their airborne camera systems, respectively. The Applanix product is its Digital Sensor System (DSS), based on the Contax 645 film camera, which has been modified to accept the MegaVision digital back (Fig. 8(a)). A choice of Zeiss lenses with focal lengths of $f=35$, 45 and 80 mm is available for use with this camera. As befits the world's leading



FIG. 8. (a) Applanix DSS medium-format camera system with, from left to right, the hardware control and data storage unit; operator monitoring screen; and camera unit with an embedded GPS/IMU unit mounted on a platform with a heading rotation movement. (b) The Rollei AIC (Aerial Industrial Camera) medium-format camera is fitted with a Phase One digital back producing a 22 or 39 megapixel colour image using a mosaic filter and Bayer interpolation (source: Rollei).

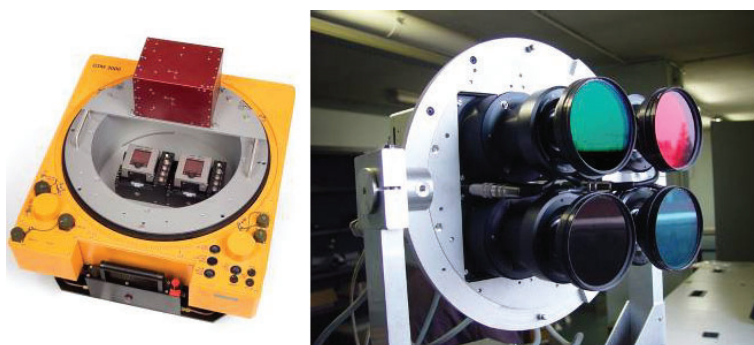


FIG. 9. (a) The IGI DigiCAM medium-format cameras use Hasselblad cameras equipped with Imacon digital backs. Two DigiCAM cameras are shown, together with an AEROcontrol GPS/IMU, mounted in a cylindrical aluminium box within a SOMAG GSM 3000 gyro-stabilised mount (*source*: IGI). (b) The IGN Quadricam uses four medium-format (16 megapixel) cameras, each with a different spectral filter. The four multi-band images are later merged to form the final colour or false-colour image—without interpolation (*source*: IGN).

supplier of high-quality GPS/IMU systems for airborne use, Applanix offers the DSS digital frame camera system integrated with its own POS/AV system. The DSS camera system has recently received a Type Certification from USGS. Rollei offers its Aerial Industrial Camera (AIC) based on cameras of its own manufacture and using digital backs with either 22 or 39 megapixel arrays made by Phase One (Fig. 8(b)). A third, rather smaller supplier until now has been IGI, whose DigiCAM unit is based on Hasselblad film cameras equipped with Imacon digital backs (Fig. 9(a)). The current model of the DigiCAM uses the 22 megapixel back; a new model equipped with the 39 megapixel back became available in autumn 2006.

Many of the medium-format digital cameras from these three suppliers have been integrated with airborne lidar systems. Thus Optech is an official reseller and supplier of the Rollei AIC camera for use with its ALTM airborne lidars; the Applanix DSS is integrated with the TopoSys Harrier lidar; while IGI can supply its DigiCAM camera integrated with its own LiteMapper lidar. With each of these integrated systems, the digital elevation model (DEM) generated by the lidar can be used, together with the GPS/IMU data, to orthorectify the medium-format digital frame images.

Multiple Cameras Generating Colour Images. The French national mapping organisation, IGN, has developed its own Quadricam multiple camera system in-house (Fig. 9(b)). This uses four cameras equipped with Kodak medium-format $4k \times 4k$ pixel CCD area arrays; $f=28$ or 50 mm Digitar lenses from Schneider Kreuznach; and Zeiss RGB + Schneider NIR filters to produce multi-band images from which medium-format colour and false-colour frame images can be constructed. Essentially this system has much the same basic arrangement as the GeoVantage and ADS small-format multi-band systems described above: each camera is fitted with the appropriate filter to record the required colour-separated RGB and NIR images needed to generate the final colour and false-colour images. Indeed, IGN built a multi-band system equipped with three small-format cameras before constructing this larger format system.

Large-Format Frame Cameras

Large-format cameras produce digital frame images with image sizes of 50 megapixels or more. They can be divided into two quite distinct categories:

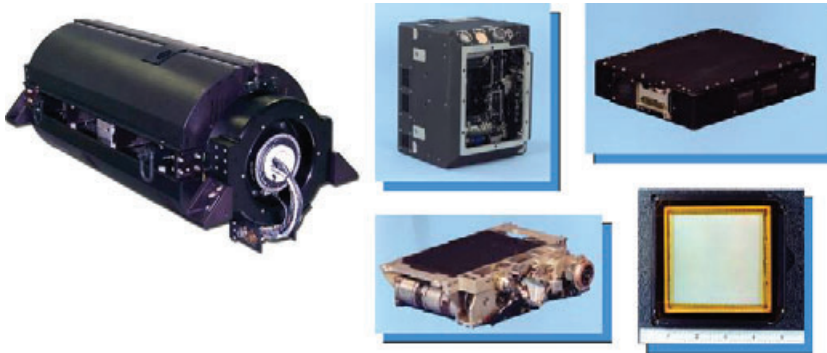


FIG. 10. (a) The Recon/Optical CA-270 camera produces large-format panchromatic and infrared monochromatic images simultaneously (source: Recon/Optical). (b) Components of the BAE Systems single-lens large-format camera, in this case providing a digital back for conversion of a KS-87 film camera to digital operation. Clockwise from top left are the camera body; the imaging electronics unit; the $9.2\text{k} \times 9.2\text{k}$ CCD area array; and the modified focal plane shutter (source: BAE Systems).

- (i) individual cameras equipped with individual large-format area arrays producing monochrome (black-and-white) frame images;
- (ii) systems employing multiple medium-format frame cameras which produce sub-images that are combined later using image processing techniques to form a single composite large-format digital frame image.

Single Cameras. The large-format single frame cameras use the largest CCD area arrays that are commercially available. Since these arrays are very difficult to manufacture and have low yields, they are extremely expensive. This has restricted their use to reconnaissance cameras built for defence forces. Recon/Optical is a major supplier of large-format digital frame cameras to government agencies and air forces. These include the CA-260/50 model, which is equipped with a $5\text{k} \times 10\text{k}$ ($= 50$ megapixel) CCD array supplied by Dalsa. Another model is the “dual-spectrum” CA-270 (Fig. 10(a)), which allows images to be acquired simultaneously in both the visible and infrared parts of the spectrum, enabling day and night acquisition of digital image data from airborne platforms. There is also the CA-295 high-altitude version. Another supplier is BAE Systems, which has built several examples of its “Ultra High Resolution Reconnaissance Camera” for the US Navy. This camera uses a $9.2\text{k} \times 9.2\text{k}$ ($= 85$ megapixel) CCD area array fabricated by Fairchild Imaging (Fig. 10(b)). This array also provides a read-out rate of 2 frames per second, as required for use with high-speed military reconnaissance aircraft flying at low altitudes.

Multiple Cameras. The approach taken by commercial suppliers of large-format digital frame cameras to the civilian market has been very different. They have all been employing sets of multiple medium-format cameras coupled together to form an integrated unit. The resulting images or sub-images are then rectified and stitched together—mosaicked—to form a single large-format digital monochromatic image. In the specific cases of the Intergraph and Microsoft cameras, which are the two major products falling into this category, these images can then be converted to colour by using the spectral data acquired by a second set of small-format multispectral cameras that has also been integrated into the overall camera system.



FIG. 11. (a) Concept of the Microsoft UltraCam large-format digital camera—showing the arrangement of the four lenses mounted along the flight direction and the multiple CCD area arrays that are used to generate the final panchromatic image. (b) The principal components of the Microsoft UltraCam-X model with (from left to right) the camera unit with its recessed handles; data storage unit; and user display screen (*source*: Microsoft).

The main development with Microsoft's UltraCam large-format digital frame camera is a new model called the UltraCam-X (UC-X), which was introduced at the ASPRS 2006 Annual Conference in Reno (Petrie, 2006). Fundamentally, the UC-X retains the same basic design characteristics as the previous UltraCam_D (UC-D) model. This comprises the distinctive four-in-line lens arrangement used in conjunction with multiple CCD area arrays and the combining of the resulting nine individual images to form a single composite panchromatic image (Fig. 11(a)). This merging process is followed by the "colourising" of the pan image using the data from the four additional small-format multispectral images that are also collected by the camera system. However, there are several major changes in the new UC-X (Fig. 11(b)). The most important one lies in the use of higher density CCD area arrays having pixels that are $7.2\ \mu\text{m}$ in size instead of the $9\ \mu\text{m}$ size used before in the UC-D. The result of this change is that the final composite pan image of the UC-X is $14\,430 \times 9420$ pixels (= 133 megapixels) in size as against the $11\,500 \times 7500$ pixels (= 84 megapixels) of the UC-D, giving a 60% increase in the pixel count. Similarly, the size of each of the four multispectral images in the UC-X has been increased to 4992×3328 pixels (= 16.6 megapixels) instead of the 4008×2572 pixels size (= 10.3 megapixels) used in the UC-D. The UC-X also has a re-designed external casing, including recessed handles at each corner, with a view to a reduction in the space requirements of the camera on board a survey aircraft.

The other leading supplier of large-format digital frame cameras to the commercial market is Intergraph with its DMC (Fig. 12(a)). Though major new developments in the DMC may be in the offing, so far only incremental modifications have been revealed publicly. Intergraph announced at the ASPRS Conference in Reno (Petrie, 2006) that it had received a Type Certification from USGS in respect of the DMC camera (Fig. 12(b)), the first large-format airborne digital imager to achieve this status. To obtain this, it had to undergo extensive reviews of its design by USGS, which also carried out detailed inspections of Intergraph's manufacturing, testing and calibration facilities and procedures to ensure that they met the required standards (USGS, 2007). Presumably the considerable effort and expense involved in achieving this certification will be beneficial both to Intergraph in terms of sales and to the American users of its DMC camera in terms of them bidding for aerial photography contracts. In spring 2007 refinements were announced to reduce weight and cost and thus increase the range of aircraft capable of accommodating the DMC. The SSD solid state disc storage system slots into the main housing of the camera,

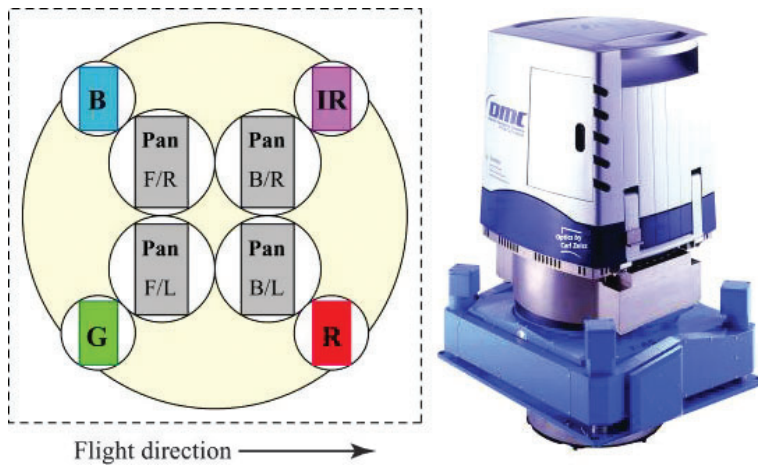


FIG. 12. (a) Principle of the Intergraph DMC large-format digital camera system comprising four medium-format pan images pointing obliquely outwards in a star-like configuration; and four vertical pointing small-format cameras, each of the latter covering a different spectral band. (b) The Intergraph DMC camera in its current configuration mounted in a T-AS gyro-stabilised mount (*source*: Intergraph).

has a capacity of 1000 images and can be exchanged in flight. Users choosing this option need not purchase the large, heavy Flight Data Storage (FDS) units. For customers who prefer the latter, however, the capacity of the FDS has been increased so that the DMC is supplied with two rather than three of them. Further reductions in weight and footprint have been achieved through the Inflight control computer and displays, for which a separate laptop is no longer required.

Another company to have constructed large-format digital frame cameras is DIMAC Systems based in Luxembourg. The original configuration of this DiMAC camera comprised between one and four separate cameras (modules) that could be set in either a vertical or an oblique configuration within a cylindrical drum casing. When used in its full four-camera configuration with each camera set to point obliquely towards the ground, the DiMAC was not greatly dissimilar to the Intergraph DMC. The use of a Phase One digital back, however, produced colour images directly by interpolation, which dispensed with the need for the additional group of multi-band small-format cameras that are a feature of the DMC and UltraCam camera systems. Until now, these DiMAC cameras have been prototypes operated by its sister mapping company, CICADE, based in Belgium.

More recently, with the introduction of the new 39 megapixel digital backs and a new partnership with VX Services from Colorado, the company has decided to reconfigure the DiMAC camera completely (Petrie, 2006). The new arrangement is to use two of the cameras (modules), both equipped with the new 39 megapixel digital back from Phase One (Fig. 13(a)). These two cameras sit side by side in the cylindrical drum case, each with its optical axis vertical (Fig. 13(b)). The CCD area arrays are then offset with respect to the optical axes so that they cover the areas to the left and right of the flight line. In this way, the individual images acquired by each camera do not need to be rectified as they did with the previous oblique configuration. Instead, the two vertical images will be merged using in-house software (DiMerge) to produce a colour image that is $10\,500 \times 7200$ pixels (= 75.6 megapixels) in size.

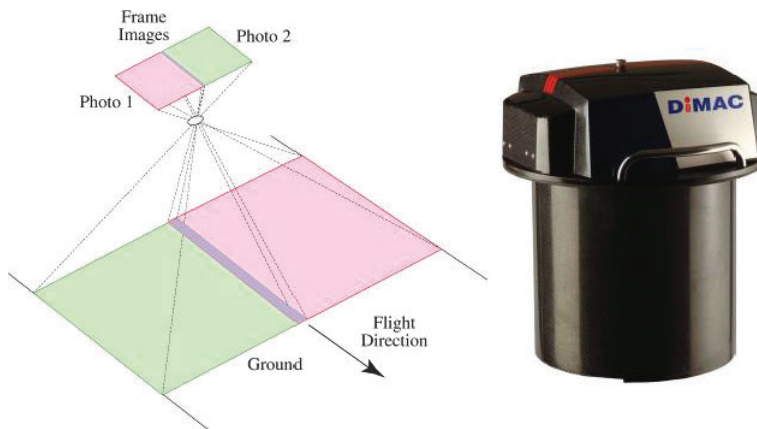


FIG. 13. (a) Concept of DiMAC 2.0 large-format digital camera with two vertical pointing camera modules mounted side by side, covering the areas to the left and right of the flight line, respectively. (b) The cylindrical outer case of the DiMAC 2.0 camera with its carrying handles: the camera modules are mounted inside the case (source: DIMAC Systems).

AIRBORNE PUSHBROOM LINE SCANNERS

Leaving aside the very specialised hyperspectral scanners, which will not be covered in this paper, three main groups of airborne pushbroom line scanners are left (Petrie, 2005):

- (i) simple monochrome scanners equipped with a single CCD linear array producing a continuous strip image of the terrain and used mainly for military reconnaissance;
- (ii) simple colour scanners equipped with trilinear CCD arrays to produce continuous colour strip images (as discussed earlier), again used primarily for military reconnaissance purposes;
- (iii) three-line scanners that generate overlapping forward-, nadir- and backward-pointing strip images that allow the production of 3D stereomodels, DEMs and orthorectified images for mapping purposes.

Monochrome Pushbroom Line Scanners. Most of the scanners in this category are of a relatively simple design producing monochrome linescan images in the visible and near infrared (VIS/NIR) parts of the spectrum. In the UK, Thales Optronics offers two different models of pushbroom line scanner. The Model 8010 uses a single linear array with 4096 CCD detectors and a fast data acquisition rate of 1800 lines per second allows the scanner to be used for low-level imaging by reconnaissance aircraft (Fig. 14(a)). A range of interchangeable lenses with focal length values of 152, 76 and 38 mm is available for use in different operational situations. By contrast, the Model 8040 is optimised for the acquisition of continuous strip imagery from high altitudes (Fig. 14(b)). Thus it features a long focus lens with $f = 450$ mm; a linear array of 12 288 CCD detectors; and the high scan rate of 1800 lines per second. The Model 8040 is normally operated from a rotatable pod fitted to the underside of the aircraft. This allows it to be pointed obliquely to the side of the aircraft to acquire imagery in a stand-off mode as well as in the vertical (nadir) orientation.

Colour Pushbroom Line Scanners. These scanners are of a similar design to those of the previous category, but each is equipped with a single trilinear array that is used to produce

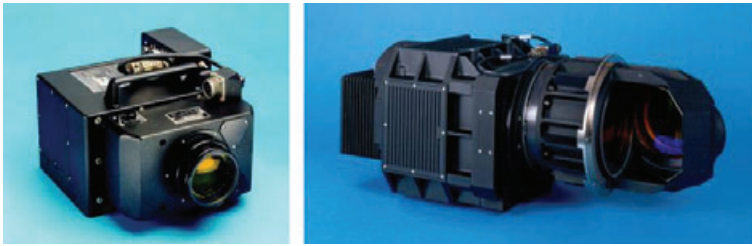


FIG. 14. (a) Thales Optronics (Vinten) 8010 single-line pushbroom scanner produces monochromatic linescan images with a 4k pixel swath width. (b) The Thales Optronics 8040 single-line scanner is equipped with a pentaprism that can be rotated to point in the cross-track direction to acquire oblique linescan imagery (source: Thales Optronics).

continuous colour strip images instead of monochrome images. Examples are the Carl Zeiss VOS 60 and VOS 80 scanners, both featuring a single Kodak trilinear array of 3×6000 CCD detector elements and equipped with lenses of $f = 60$ and 80 mm, respectively. The linescan image data can be acquired at rates up to 1600 lines per second. These scanners have been used extensively in German military reconnaissance aircraft. A second German example is the optional pushbroom line scanner that can form part of the Falcon airborne laser scanning systems produced by TopoSys. The Falcon II pushbroom scanner features four parallel linear arrays, each generating images that are 682 pixels wide and capturing their images in the red, green, blue and infrared (RGB + NIR) channels, respectively. The new Falcon III system also has four linear arrays, but each has an increased length of 2048 pixels.

Three-Line Stereo Pushbroom Scanners. The three-line scanners produce three overlapping strip images from which 3D stereomodels can be formed. Additional linear arrays can also be incorporated into the scanner focal plane to allow multispectral, colour and false-colour images to be generated. As is well known, over a period of 25 years, the German Aerospace Center (DLR) has been in the forefront of developing this particular imaging technology (Figs. 15(a) and (b)). Parallel developments in Germany included the DPA mentioned above.

In the late 1990s, Leica Geosystems licensed the technology and used the experience gained by DLR to build its own ADS40 three-line pushbroom scanner (Fig. 16(a)). Each of the three (backward-, nadir- and forward-pointing) lines comprises a pair of CCD linear arrays



FIG. 15. (a) The DLR HRSC three-line stereo pushbroom scanner was developed originally for the Russian Mars96 mission. It is now being used on the ESA Mars Express mission. (b) The HRSC-AX (Airborne Extended) version of the HRSC scanner is equipped with a narrow-angle lens and an integrated GPS/IMU unit (source: DLR).

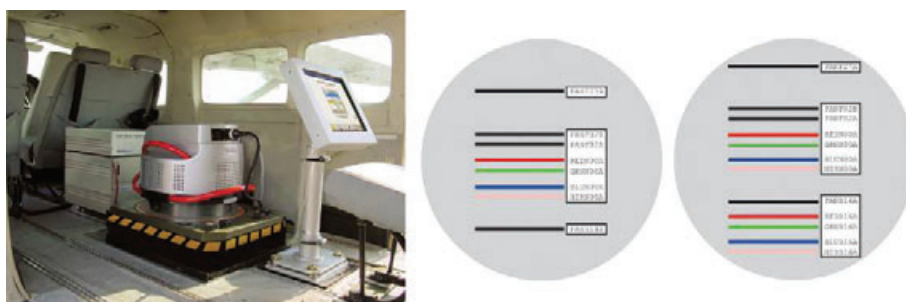


FIG. 16. (a) This Leica Geosystems ADS40 three-line stereo pushbroom scanner is mounted on a PAV30 gyro-controlled mount installed in a Cessna Caravan aircraft of PASCO, Japan. (b) The alternative focal plates of the latest second-generation version of the ADS40 pushbroom line scanner (*source*: Leica Geosystems).

linked together in parallel, with each of the arrays being shifted laterally—“staggered”—by half a pixel with respect to the other. Also mounted in the focal plane are the four additional single (not paired) 12 000 pixel CCD linear arrays that record the ground images in the individual RGB and near-IR spectral bands. A “trichroid” beamsplitter ensures that the RGB radiation from the ground passing through the main lens of the ADS40 reaches the appropriate linear arrays, which are of course physically separated on the focal plane. It is interesting to note that, in order to satisfy different user requirements, four quite different positions of the linear arrays within the focal plane have been supplied to different users. More recently, new sensor heads SH51 and SH52 have been added, resulting in still more configurations, though the staggered lines are placed in the nadir position only (Fig. 16(b)). Interestingly, these new sub-systems now include a “tetrachroid”, a four-way beamsplitter which causes the radiation from a single line on the ground to be recorded by the correct RGB and NIR linear arrays.

Another major change to the ADS40 that has taken place recently is the move away from complete reliance on the Applanix POS/AV system for the supply of the GPS/IMU components that form a fundamental part of any airborne pushbroom line scanner. This move appeared inevitable once the Applanix company had been bought by Trimble, one of Leica Geosystems’ main competitors in the surveying instrumentation field. So the 2006 ASPRS Conference saw the introduction of the IPAS10 (Inertial Position & Attitude System) that had originally been developed by the small Canadian company, Terramatics, whose acquisition by Leica Geosystems had been announced at the Photogrammetric Week in 2005. The IPAS10 system has now been integrated into the ADS40 pushbroom line scanner. Another disadvantage of the Applanix POS/AV system from Leica Geosystems’ point of view was that it uses inertial system components from the Litton company that are subject to stringent export licensing and controls by the appropriate US government authorities. So Leica Geosystems has also decided to change the suppliers of the inertial components used in the ADS40 for some markets and will now source these from iMAR (Germany), Sagem (France) and other European suppliers, who, apparently, operate under a different and rather more liberal licensing regime. This will allow the ADS40 to become more competitive in markets such as China where the US controls have previously inhibited sales, resulting in a business advantage for the DMC and the UltraCam, which can be operated quite efficiently without an IMU.

Another three-line pushbroom line scanner with a rather different design from that of the ADS40 was introduced by Wehrli & Associates at the ISPRS Congress held in Istanbul in July



FIG. 17. (a) The 3-DAS-1 three-line pushbroom scanner produced jointly by Wehrli & Associates and Geosystems features three Kodak trilinear arrays, each with a separate lens, to produce continuous colour linescan imagery (source: Wehrli & Associates). (b) The Jena-Optronik JAS 150 three-line pushbroom scanner (source: Jena-Optronik).

2004. This 3-DAS-1 scanner was built in collaboration with the Geosystem company from the Ukraine that has previously built many of the film scanners sold by Wehrli. The 3-DAS-1 scanner is equipped with three of Kodak's trilinear arrays which acquire their RGB strip images in the forward, nadir and backward directions, respectively (Fig. 17(a)). The prototype instrument shown in Istanbul was fitted with the 8000 pixel version of the trilinear array with CCD detectors that are $9\text{ }\mu\text{m}$ in size. Unlike the ADS40, which uses a single lens, the 3-DAS-1 employs three separate lenses, one for each of the trilinear arrays. Integral to the design and practical operation of the 3-DAS-1 scanner is its new ASP-1 stabilised mount, though one of the well-established Leica or Zeiss mounts may also be used. The ASP-1 is a simple kinematic design with the pitch and roll motors tilting the scanner's adaptor plate under direct command from the IMU module, which uses fibre-optic gyros. In 2005, a second prototype of the 3-DAS-1 was shown, but, so far, the scanner has not been sold commercially.

The ASPRS 2006 Conference saw the introduction of a completely new design of three-line pushbroom scanner, called the 3-OC, which has been developed by the Wehrli/Geosystem partnership specifically for an American mapping company (Petrie, 2006). Like the 3-DAS-1, the new 3-OC pushbroom scanner uses three Kodak trilinear arrays, each with 8000 pixels, pointing in the forward, nadir and backward directions. However, in this new instrument, the forward and backward arrays are both pointing at an angle of 45° to the vertical, instead of the 26° forward- and 16° backward-pointing arrangement of the 3-DAS-1. Within this new 3-OC scanner, the three lenses are placed in a line parallel to the flight direction with their optical axes all pointing downwards in the vertical direction. The 45° forward and backward pointings are achieved by placing suitable prisms in front of the two outer lenses of the three used in the scanner. It would appear that the configuration of this new 3-OC scanner is designed specifically to produce continuous oblique linescan coverage of the ground with a view to satisfying the growing oblique imagery market discussed earlier in the context of multiple digital airborne frame camera systems.

The resources required to design, build, test and market any large-format airborne imager are considerable. Moreover, with the pushbroom scanner approach, it requires the very close integration of the GPS/IMU system into the design for the imager to function at all. Obviously Leica Geosystems has had the financial, technical and human resources to be able to do this successfully. However, all the other companies in this area are finding it hard to make progress in terms of being able to bring pushbroom scanner products on to the market, for a variety of different political, financial, business and technical reasons. For example, the Jena-Optronik

company had been expected to show its new JAS 150 (Jena Airborne Scanner) at the ASPRS 2006 Conference through its American agent, E. Coyote Enterprises (Fig. 17(b)), but the introduction was delayed through the bankruptcy of the company supplying the electronics boards for the JAS. Besides this, it has to be added the quite unrelated but sad news that the Japanese Starlabo company, which had been building the StarImager series of airborne three-line pushbroom scanners, has gone out of business.

OVERVIEW AND CURRENT TRENDS

The remarkable range of hardware developments described above has been accompanied by incremental developments on the software side. As they are purchased and deployed, the airborne digital imagers are currently reshaping production photogrammetry. Several characteristics and trends can be discerned.

Aerial Film Imagery versus Airborne Digital Imagery

Though airborne digital imagers attract widespread interest, it should be remembered that compared with the employment of high-performance, expensive airborne digital imagers, several times as many film cameras still remain in use (Cramer, 2005b). Workflows based on film cameras, chemical film processing and high-speed film scanning still dominate the industry. Moreover, the headlines grabbed by these new large-format imagers, especially the ADS40, DMC and UltraCam, tend to leave in the shadows the fact that more units of medium-format digital frame cameras are already in operation.

The suppliers of aerial film cameras are selling out the remaining units, so this revenue stream has dwindled. Similarly, photogrammetric film scanners continue to be produced by a handful of manufacturers and units already in use are being upgraded to increase performance. The number of units being sold is clearly decreasing.

Of course, airborne digital imagers eliminate the need for chemical film processing or scanning. This not only saves time and simplifies the workflow, but also goes a considerable way towards closing the price gap between the technologies: high-performance airborne digital imagers command a price from 50% to more than 200% higher than film cameras, before the addition of GPS/IMU is considered. The latter is an expensive sub-system, though the emergence of competition in the marketplace will reduce price levels.

GPS/IMU Sub-systems

In most cases, the airborne digital imagers have narrower swath widths than aerial film cameras, necessitating more flight lines. With GPS/IMU estimates of position and orientation, together with modern, highly automated triangulation, this is less problematic than may at first be thought. Secondly, many of the users of the medium-format frame cameras are supplying image products to markets for which orthorectification based on GPS/IMU data and off-the-shelf digital terrain models suffices: in this case, triangulation is unnecessary.

Airborne digital imagers are usually equipped with an IMU, whereas the majority of film cameras are not. Line scanners require GPS/IMU units so that the scan lines can be approximately rectified for comfortable viewing and for the extraction of tie points, a requirement that does not arise with film cameras. Small- and medium-format frame cameras perform best with GPS/IMU, because the very large numbers of images that these sensors need to acquire to cover blocks of comparable size to the high-performance imagers or aerial film cameras must be processed using automatic tie point matching, which works much better if

initial approximations are available. GPS/IMU data processing has, however, created another learning curve, involving calibration issues, map projections, spheroids and so on.

Calibration

Camera calibration and system calibration offer further challenges: it is unreasonable to expect end users to calibrate their own cameras (Cramer, 2005a, b). This is a demanding procedure, especially for multiple digital frame camera systems and pushbroom line scanners. For the former, first the individual cameras are calibrated, after which the whole system is calibrated as a unit. Airborne digital imagers require careful radiometric, as well as geometric and optical, calibration. The complexities of calibration are likely to lead to certification by national bodies of the hardware suppliers' calibration information, which represents, for a few countries at least, a major change from the policy used for decades with film cameras. The recent certification of the DSS and DMC cameras by USGS is an example. It has been suggested that the stability and reliability of the multiple digital camera systems that rely on integrating multiple frame camera images into a single, synthetic image need everything in a photo mission to be working perfectly, though any worries about perfect synchronisation of the shutter times of the various sensors within the system seem to have been dispelled. Recent tests with the analysis of DMC and UC-D images have revealed remaining systematic errors in imagery, perhaps due to imagery from non-optimally corrected individual sensor heads being used in the image stitching process. A pushbroom line scanner, on the other hand, needs very good system calibration, which is difficult. Users have experienced failures that do not occur with film cameras. Nevertheless, it is likely that these are no more than the teething troubles often encountered with innovative products throughout industry, and certainly the failure rate has fallen dramatically compared to 5 years ago.

Software

There are numerous small differences in the processing chains of the various imagers. The high-performance airborne digital imagers are delivered with special airborne storage units, on which the imagery and metadata are written in flight and from which it is downloaded, often in special formats, using ground-station hardware (cables, power supply and so on) and software designed specially for the purpose. Film cameras, of course, have no such requirement and the medium-format digital frame cameras typically write imagery on rather standard, albeit ruggedised, hard drives in popular formats, so downloading to a workstation is straightforward. Furthermore, the data from the high-performance imagers typically requires special processing, including low-level radiometric corrections, reformatting and, in the case of the high-performance imagers with multiple frame cameras, the weaving together of the raw frames into synthetic single central perspective images. These processes are performed by special software supplied with the imager, but once the images have been created they can be used by the digital photogrammetric workstation software which has been in use with scanned film images for years. Indeed, ready availability of software that required only modest enhancement has been a selling point for the DMC and UltraCam, as users are able to commence work immediately, using familiar software, whereas for the pushbroom line scanners considerable software development has been required. In particular, the standard mathematical or "sensor" model provided in most digital photogrammetric workstations, based on the collinearity equations, is insufficient and a time-dependent model has to be added. As a result, many software vendors handle triangulated imagery from these imagers for the generation of terrain models, orthorectified imagery and feature databases, but rather few offer rigorous triangulation.

Computation times for the pushbroom line scanners make many operations, for example, vector superimposition, slower. Heavy users of line-scanner imagery have installed impressive racks of computers, each typically a high-end PC with multiple CPUs.

Certain practical aspects distinguish the processing of pushbroom line-scanner imagery from that for frame camera imagery. For example, since the line scanners have three or more lines that capture imagery of the same strip, there is scope for special multiple-image matching algorithms to provide more successful image matching for tie point measurement or generation of digital terrain models than would be the case for conventional stereopairs from either film or digital frame cameras. Despite considerable research efforts over many years, however, such approaches are only now entering production software. Secondly, it is obvious that pushbroom line scanners produce continuous strip imagery, so the production of orthorectified imagery of large areas requires mosaicking between strips but not along them, thus reducing computation and increasing the probability of deliverables being aesthetically pleasing.

Colourising

Colour and false-colour imagery are obtained in quite different ways with the different imagers. With film cameras, the use of colour or false-colour film meets the requirement and the colour bands are in virtually perfect registration. In the small- and medium-format digital frame cameras, Bayer interpolation plus a mosaic filter is the popular solution, usually resulting in 3×8 -bit colour or false-colour imagery. In the multiple large-format frame imagers, the issue is more complex. They achieve colour or false-colour images by using the system calibration and image matching of their panchromatic, RGB and NIR images and the “colourising” of the much higher resolution synthetic panchromatic images using the resulting colour or false-colour composites. Clearly, very precise image matching is essential whatever the flying height.

In the case of the pushbroom line scanners, there may be coincidence of the red, green and blue bands using an optical beamsplitter, for example, Leica Geosystems’ trichroid beamsplitter ensures perfect coincidence of red, green and blue. More recently, the tetrachroid beamsplitter has extended this coincidence to the NIR. However, unless all wavelengths are handled rigorously in this way, true co-registration cannot be achieved until the workflow reaches the generation of orthorectified imagery, and, even there, it is possible to see colour fringing in areas of steep slopes (or buildings and trees in the case of large-scale imagery) if the height information is not of high quality. In the case of the ADS40, the latest configurations enable colour and false-colour orthorectified imagery to be generated without use of the panchromatic bands, so this problem has been eliminated. On the other hand, the colourising challenge for pushbroom line scanners is less than for multiple frame-camera solutions, because the resolution of the colour linescan imagery is the same as that of the panchromatic, or it is lower only in the direction of flight. Nevertheless, conventional algorithms may be unsuitable for this predominantly along-track pan-sharpening. For the multiple large-format frame imagers, on the other hand, the resolution of the multispectral inputs is far below that of the panchromatic, putting effective yet fast algorithms at a premium.

Performance

There is a consensus that digital imagers provide superior radiometric content to film, in terms of signal-to-noise ratio and spectral resolution, such that map specifications can be met with a larger pixel size than would be required with scanned film (there is not space here to broach the issue of optimum scanning pixel size). The ratio of appropriate pixel sizes has been

suggested to be in the 1.4 to 2.0 range, but this is a supplier's estimate based on customers' feedback of an empirical or anecdotal nature. Nevertheless, film imagery is acknowledged to be capable of the very highest resolution, combined with the most advantageous geometry, so its accuracy remains the goal to which digital imagers aspire. For practical purposes digital imagers are demonstrably capable of meeting most specifications. The benefits of digital imagery in terms of improved performance in image matching for both tie point measurement and generation of digital terrain models, or of superior orthorectified imagery with easier mosaicking and image balancing, are acknowledged by many but not rigorously assessed or quantified. Perhaps Madani (2006, personal communication) puts it well, "Based on [*Intergraph's*] experience, you can fly higher with DMC than a film camera for a particular scale and ground sample distance. On the other hand, the number of models and strips can get higher due to focal length and digital footprints."

There is a host of practical performance issues on which evidence will emerge only as users accumulate experience with the digital imagers. These include stability, reliability, customer support, long-term costs and learning the types of projects to which the various solutions are best suited. It is interesting, too, that large parts of the photogrammetric community have overcome any innate conservatism in favour of frame cameras and have purchased pushbroom line scanners or imagery acquired with them. This is an unfamiliar technology to most practising photogrammetrists not regularly using satellite imagery, yet its acceptance is already widespread only 7 years after the ADS40 was introduced.

Applications

There has been some support for the opinion that the line scanners are best for very large projects with orthorectified imagery as the primary deliverable. However, this is perhaps more a result of the early success of ADS40 users in winning US government contracts on the National Agriculture Imagery Program (NAIP) (where GPS/IMU trajectories, triangulation with little ground control and the use of off-the-shelf DTMs enabled huge areas to be covered with orthorectified imagery of high radiometric quality) than of specific characteristics of the technology, though they do have the advantage noted above that no mosaicking is required in the along-strip direction. Indeed, the difference in resolution between panchromatic and colour lines with these imagers is much less than the high-performance multiple frame camera solutions. Furthermore, it is clear that when the nadir line image is used for orthorectification, the line-scanner solutions produce deliverables with little or no "building lean" in the along-strip direction. This effect can be achieved, to a limited extent, by flying very large forward overlaps with film and digital frame cameras, though this makes mosaicking more difficult.

Contrasting papers given at the 49th Photogrammetric Week (Fritsch, 2003) showed that both ADS40 and film imagery were well able to fulfil the NAIP requirements. Indeed, it can be argued that the very long strips from the ADS40, resulting in gigantic image files, reduce workstation performance. The frame imagers seem to have found their early use on a wider range of projects, including some that required imagery at very large scales. There has been some debate whether the pushbroom line scanners are useful mainly for medium- and small-scale work, whereas only frame cameras can provide imagery at high resolution. Nevertheless, ISTAR (now Infoterra) has successfully completed large-scale projects from HRSC-A imagery and both Leica Geosystems and Jena-Optronik have published many examples of very high-resolution imagery acquired with their scanners. Moreover, Leica Geosystems has increased the sensitivity of the RGB and NIR lines fourfold in the new SH51 and SH52 sensor heads, so there is no longer any question of the ADS40's resolution being limited owing to insufficient incidence of photons. Indeed, the restriction now is the cycling speed of 800 Hz. Intriguingly,

there is some evidence that users performing data collection for large-scale engineering maps or drawings still prefer scanned film: practitioners think that the work is more accurate, as well as easier for vector data collection.

To conclude, it is noteworthy that the diffusion of small- and medium-format frame cameras has been a response to, or been accompanied by, significant changes in applications. The popularity of integrating these cameras with airborne lidar systems has been mentioned. One radical change is the increasing popularity of “acquire once, sell many times” business models, in contrast to traditional photogrammetric projects for which imagery was commissioned specially for the project and not generally reused after delivery. Another is the frequent repetition of coverage of areas, for example, for agricultural purposes. The simpler, lighter solutions based on the small- and medium-format digital frame cameras, used in lower cost aircraft, have been well suited to these applications. Finally, users’ preferences have engendered a slightly unexpected growth in the popularity of oblique imagery, again typically acquired by these small-format digital frame camera systems. All of these trends are likely to be reinforced with the blooming of “Internet mapping”, as companies such as Google, Microsoft and Yahoo have elected to become geospatial players. Thus, a complex picture can be identified of a rapidly increasing number of airborne digital imagers being deployed on a broad range of applications, within which certain directions and relationships are beginning to become clearer.

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Résumé

On présente dans cet article un aperçu des développements actuels dans le domaine des technologies de l'imagerie numérique aéroportée, concernant à la fois les caméras matricielles et les capteurs à barrettes. On les analyse en regard de leurs applications en photogrammétrie numérique.

Zusammenfassung

Dieser Beitrag gibt einen Überblick über aktuelle Entwicklungen der flugzeuggestützten digitalen Bildaufnahme. Es werden sowohl digitale Flächenkameras, als auch digitale Zeilenkameras vorgestellt, und in Bezug auf ihre Anwendungen in der digitalen Photogrammetrie analysiert.

Resumen

Este artículo hace una revisión de los avances actuales de las tecnologías de obtención de imágenes digitales—incluyendo cámaras métricas digitales y sensores—de modo aerotransportado y las analiza en el contexto de su aplicación a la fotogrametría digital.