Airborne Pushbroom Line Scan

An Alternative to Digital Frame Cameras

My article on Airborne Digital Frame Cameras that was published in the October 2003 issue of GeoInformatics gave an overview of the principal technology that is being used currently to acquire digital images directly from an airborne platform. As the name suggests, these frame cameras use areal (square or rectangular) arrays of CCD or CMOS detectors to record individual frame images of the ground for mapping purposes. The main alternative airborne digital imaging technology uses linear arrays of detectors allied to a pushbroom mode of operation that utilizes the forward motion of the airborne platform to sweep out a continuous strip image of the ground. The aim of this new article is to present an overview of this alternative digital imaging technology.

by Prof. Gordon Petrie

A - Introduction - Heritage & Development

Film-Based Line Scanners

As mentioned in a previous article published in the July/August 2000 issue of GeoInformatics, the basic idea of an airborne line scanner is not new. One can trace its ancestry back to the shutterless airborne film-based strip cameras of the 1930s, known (after the inventor's name) as ***Sonne cameras***. These were used mainly for high-speed low-level reconnaissance flights over the ground during World War-II and the Korean War of the early 1950s. A 3D-stereo version of the Sonne camera was produced with two lenses that were offset relative to the exposure slit over which the film was being passed continuously to produce the strip images of the ground as the aircraft flew forward. This resulted in a pair of overlapping (forward and backward pointing) strip images that could be used to form a 3D stereo-model of the ground.

Airborne Pushbroom Line Scanners

Coming into the era of digital line scanners, the use of a linear CCD array in combination with a suitable lens to sweep out a single continuous strip image of the ground was applied first in the 1970s to airborne linescan imagers mounted on military reconnaissance aircraft. The more advanced concept of having a 3-line pushbroom scanner with forward/nadir/backward pointing of the three linear arrays to allow digital 3D stereo-imagery to be acquired from space was proposed in the Mapsat (USGS) and Stereosat (JPL) projects of the late 1970s. However these simply remained proposals; they were not built. At around the same time, Dr. Otto Hofmann of Messerschmidt-Bolkow-Blohm (MBB) made similar proposals for an airborne 3-line pushbroom scanner. The concept was nurtured and developed by the ***German Aerospace Center (DLR)*** together with the associated commercial companies (MBB, DASA, etc.) that have built several of the scanners constructed during this development period. This resulted in the construction of a series of airborne pushbroom line scanners in Germany over a 25 year period. The first of these was the Electro-Optical System (EOS) from the late 1970s that was funded by the Federal Research Ministry. After this, the Modular Opto-electronic Multispectral Scanner (MOMS) and the Monocular Electro-Optical Stereo-Scanner (MEOSS) were developed during the 1980s by DLR, principally with a view to them being operated from space. Various models of the MEOSS scanner were operated from airborne platforms to develop and prove the technology prior to them being mounted on the Indian SROSS-2 and IRS-1E satellites. Unfortunately both of these satellites were lost during launch in 1988 and 1993 respectively. During the early 1990s, DLR also sponsored the construction of the Wide Angle Airborne Camera (WAAC) and the High-Resolution Stereo Camera-Airborne (HRSC-A). These acted as prototypes for the similar imagers that were mounted on the Russian Mars-96, mission which also failed due to problems with its launcher. The Digital Photogrammetric Assembly (DPA) was another airborne pushbroom scanner built by

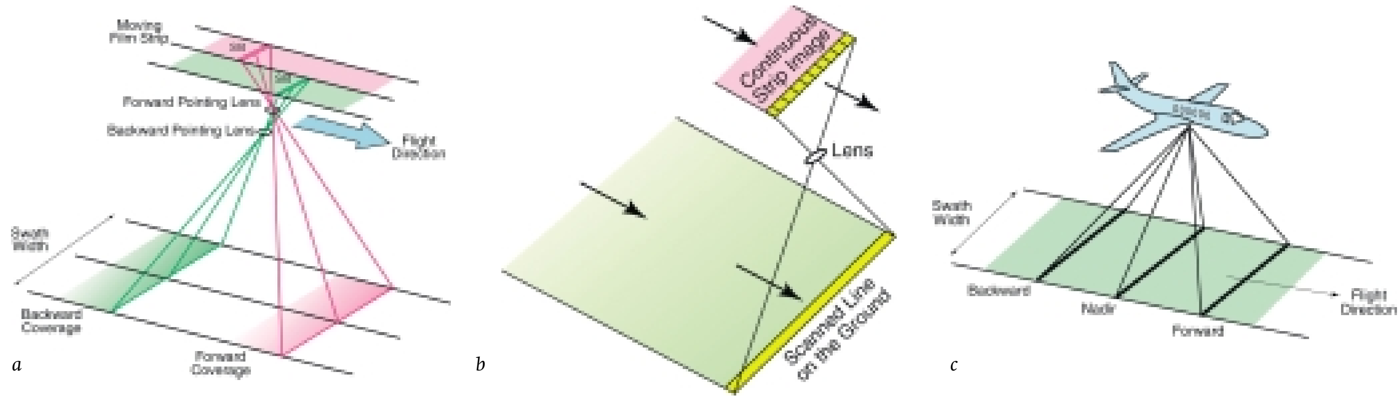

Fig. 1 - (a) The concept of the original shutterless pushbroom scanner (the Sonne camera) providing stereo-coverage of the ground via overlapping strip images recorded on film. (b) A simple pushbroom line scanner using a single CCD linear array to generate a continuous strip image in digital form. (c) The concept of the 3-line digital pushbroom scanner producing overlapping stereo strip images. (Drawn by Mike Shand)

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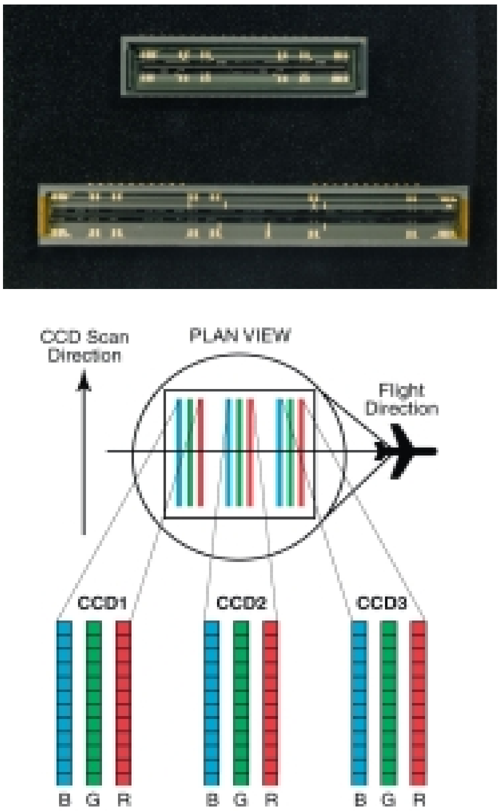


Fig. 2 - (a) CCD linear arrays with 4,096 (upper) and 12,288 detectors (lower) respectively manufactured by E2V. (Source: Thales Optronics) (b) The arrangement of the three sets of Kodak Tri-linear CCD linear arrays that produce RGB colour images in a 3-line scanner. (Drawn by Mike Shand)

DASA for the German Ministry of Defence. It became operational in 1995.

Besides these various German examples, in a similar manner, NASA sponsored the construction of an airborne pushbroom scanner, called Air-MISR. This acted as the development prototype for the MISR scanner operated from the Terra satellite.

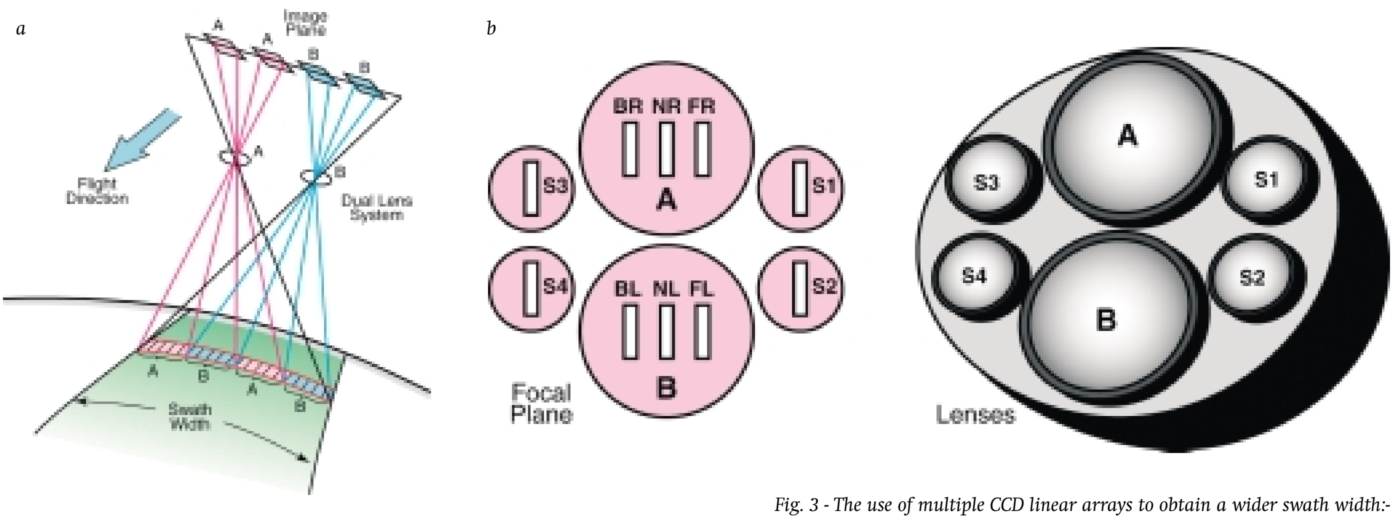
Spaceborne Pushbroom Line Scanners
As noted above, the development of these airborne pushbroom line scanners took place largely with a view to their operation from spaceborne platforms. While DLR had bad luck with the relevant satellites, it had a much better experience with pushbroom scanners on manned space platforms. Thus the MOMS-01 scanner was operated successfully from the Space Shuttle in 1983 and 1984. The 3-line stereo version of this scanner was also operated successfully both on the Space Shuttle in 1993 (as MOMS-02) and from the Russian MIR station (as MOMS-2P) between 1996 and 1998. Most recently, during 2004, an example of the HRSC pushbroom scanner has been operated from the ESA Mars Express mission producing the spectacular 3D images of the surface of Mars that currently excite us. Of course, line scanners that are similar to the pioneering German examples have been adopted widely elsewhere for use on satellites. These include the pushbroom scanners used (i) in the SPOT series since 1986; (ii) the Indian IRS-1C and -1D satellites launched during the 1990s; (iii) the Japanese OPS (on JERS-1) and ASTER (on Terra); and (iv) the American commercial high-resolution IKONOS, QuickBird and OrbView-3 satellites. Indeed, over the last 15 years, pushbroom scanners have become one of the two main optical imaging technologies being used from space - the rotating optical-mechanical scanners used in the American Landsat/TM, NOAA/AVHRR and Terra/MODIS satellites being the other. In summary, one can say that airborne and spaceborne pushbroom line scanners have developed in parallel - though the spaceborne examples reached production status first. Only in the last two or three years have the airborne 3-line pushbroom scanners used for mapping reached a similar status.

Airborne v. Spaceborne Platforms
The reason for the relative popularity of pushbroom line scanner technology on spaceborne platforms as compared with its relative lack of use on airborne platforms in the past is that all line scanners need to be operated from a very stable imaging platform that is not changing its attitude and altitude during flight. Otherwise gaps and double imaging will occur in the continuous strip image of the ground that is being produced by a pushbroom line scanner. In this respect, an airborne platform will be subjected to atmospheric turbulence to a smaller or greater degree. This produces sharp and unpredictable changes in the attitude and altitude of the platform with consequent effects on the coverage of the imaging scanner. Even with the use of gyro-stabilized mounts, the images produced by airborne pushbroom line scanners exhibit substantial geometric displacements. Whereas the flight of a spaceborne platform equipped with suitable stabilizing devices is, by comparison, quite stable. Furthermore those changes in the attitude and altitude of such a platform that do occur are quite small and change slowly in the near-vacuum of space by comparison with those experienced with an airborne platform. These small changes can be modelled and coped with relatively easily in the subsequent image data processing.

Military Requirements
A further point is that an aircraft has to be flown in a straight line and at a fixed and level altitude to ensure continuous strip coverage of the ground using a line scanner. This resulted in a relative lack of interest in line scanner technology by many military organisations - since such a flight pattern made the aircraft a comparatively easy target for anti-aircraft defences. Give the highly manoeuvrable flight patterns that are often needed to carry out reconnaissance and damage assessment missions, frame cameras offered a much better prospect of a successful mission and of aircraft and crew survival. Thus many military organisations have tended to be much more supportive of digital frame camera technology. However it should be noted that the length of a flight over a specific target is often quite short - typically in the order of 20 seconds maximum. In which case, the image can be acquired successfully by a line scanner in a short burst with the aid of a stabilized mount. Thus certain air forces, e.g. the British RAF, do operate pushbroom line scanners extensively.

B - Imaging Technology

Detector Technology
Linear arrays are manufactured in very large quantities for use as imagers in document scanners, fax machines, bar code readers, hand-held scanners, etc. For these high-volume applications where image quality requirements are relatively undemanding and low cost is a major consideration, the linear arrays that are being employed are usually based on ***CMOS*** technology. Where image quality requirements are very high - as is the case with airborne and spaceborne scanner imagery - ***CCD detectors*** remain the most suitable imaging technology. Their spectral



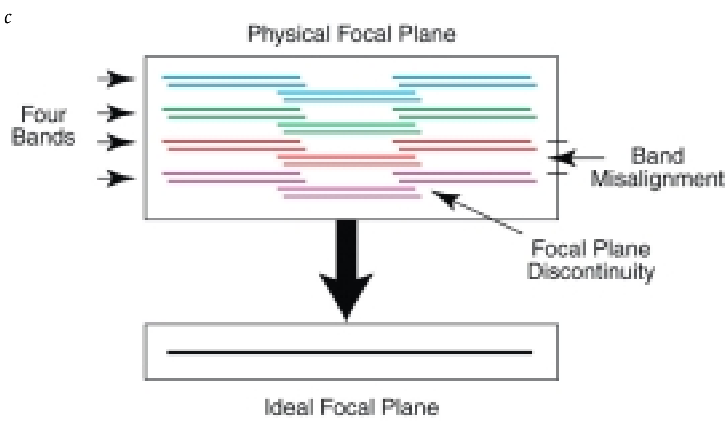


Fig. 3 - The use of multiple CCD linear arrays to obtain a wider swath width:-
(a) Using twin lenses (A & B) to generate a single line cross-track from four linear arrays as in MOMS-01.
(b) Using twin lenses (A & B) to give a 3-line panchromatic configuration (each with two linear arrays L and R in the cross-track direction) as used in the DPA pushbroom scanner: the other four lenses (S1 to S4) record the RGB and NIR line images needed to generate colour and false-colour strip images.
(c) The stepped arrangement of the multiple linear arrays used in the QuickBird pushbroom scanner to produce both a wider swath and multi-spectral images. Note the resulting offset positions and the discontinuities between the lines in the focal plane of the scanner. (Drawn by Mike Shand)

sensitivity is confined to the visible and near-IR parts of the spectrum - which satisfies the needs of most users. However if coverage is required in the medium-IR and/or the thermal-IR parts of the spectrum - e.g. using Infra Red Line Scanners (IRLS) to detect hot objects or to operate during darkness, then the detectors need to be made from exotic materials such as indium antimonide (InSb) or cadmium mercury telluride (CMT). Furthermore the familiar silicon-based optical glass elements have to be replaced by optical elements made from germanium, since the former type will not transmit radiation at MWIR or LWIR wavelengths. Recently CCD linear arrays that can operate in very low level light have been developed. Pushbroom scanners fitted with these arrays produce good quality imagery even under starlight conditions. This has important implications for military reconnaissance operations.

Array Lengths

In most cases, there is a need for a long ***length*** to the linear arrays used in airborne or spaceborne pushbroom scanners in order to ensure the coverage of a wide swath over the ground. As with areal arrays, larger sizes of linear arrays mean much higher cost - resulting from the manufacturing process with its lower yields. A linear array of 6,000 pixels - as used in the HRSC-A scanner - was typical in the mid-1990s. However nowadays scanners can make use of much longer linear arrays, e.g. those used in the Leica ADS40 are 12,000 pixels in length. At the very top end of the scale, a linear array of 14,400 pixels is now on offer. These longer CCD arrays are supplied by various specialist manufacturers such as Kodak, Fairchild Imaging and Perkin-Elmer in the U.S.A.; E2V in the U.K.; Atmel with a large factory in Grenoble, France (formerly owned by Thomson CSF) besides various facilities in the U.S.A.; Dalsa with manufacturing facilities in Canada and in the Netherlands, the latter formerly owned by Philips; and Sony in Japan.

CCD Detector Sizes

The size of the individual ***detector elements*** (pixels) used in the CCD linear arrays utilized in airborne and spaceborne scanners lies in the range 5 to 14μm - similar to those used in the areal arrays utilized in airborne digital frame cameras. In the case of the Kodak Tri-linear arrays, the manufacturer produces these in a standard length - with a trade-off between detector size and the number of detectors in the array. Thus the linear array with 14,400 detectors has CCD detector elements that are 5μm in size; 7μm detectors are used in the 10,200 detector linear array; the 8,000 detector array has 9μm detectors; and the 6,000 pixel array, 12μm detectors. The smaller-sized detectors have a smaller surface area available for collection of the radiation coming from the ground and this may require the use of larger aperture lenses to ensure a sufficient exposure. In order to increase the image ***resolution***, sometimes paired linear arrays are used, with each array offset laterally by half-a-pixel relative to the other. The mean values of the measured intensities are then adopted as the output values. This arrangement has been utilized both in the Leica ADS40 airborne pushbroom scanner as well as by CNES on the HRG (High Resolution Geometry) pushbroom scanner mounted on the SPOT-5 satellite - where it is termed "Supermode". If an Infra Red Line Scanner (IRLS) is being considered, then the detector sizes will be much larger - 20 to 40μm is typical - since there are much lower levels of radiation being reflected or emitted from the ground at MWIR and LWIR wavelengths. So a much larger surface area is needed for each detector to record a useful image.

Multiple Arrays

A consequence of the practical limits to the length of the linear CCD array is that ***multiple linear arrays*** have been used to enable a still wider swath to be swept out by the pushbroom scanner. However the use of this solution does have its consequences, since the linear arrays cannot be butted together to form an unbroken line. Different solutions have been adopted to get over this problem.

In the case of the DPA (airborne) and MOMS-01 (spaceborne) scanners, a dual-lens arrangement was used to implement the wider swath resulting from their use of multiple linear arrays. In the case of the pushbroom scanners that have been operated from Indian IRS-1C/D satellites, the individual linear arrays have been placed in a staggered but overlapping position to give the required wider coverage but still using a single optical mirror. A similar arrangement has been used in the pushbroom scanner operated on board the QuickBird satellite with its swath width of 27,000 pixels. Allowance then has to be made for these stepped arrangements of the linear arrays in the subsequent image processing in order to synthesize a single common line from the images produced by the component linear arrays.

Multi-Spectral Imaging
CCD detectors are inherently monochromatic with a spectral range covering the visible and near-IR parts of the spectrum. So ***filters*** need to be used in combination with ***multiple linear arrays*** to record images in specific spectral bands - e.g. as required to produce colour or false-colour images. The Kodak Tri-linear arrays that are used in the Wehrli and Starlabo airborne pushbroom scanners feature three linear arrays set in parallel cross-track very close together. Three sets of these Tri-linear arrays are placed in the forward, nadir and backward pointing positions within the focal plane of the scanner. This results in a slight problem in that the individual linear arrays in each Tri-linear set are again offset from each other - since they cannot be superimposed on each other. The effect of this offset is that, at any specific moment of time, each of the multiple linear arrays needed to produce the colour, false-colour or multi-spectral strip image is, in fact, imaging a slightly different line on the ground. So the individual spectral lines making up a single line on the ground are acquired at a very slightly different time and could even have slightly different attitude (tilt) values. This further accentuates the need for the scanner to be mounted on a very stable platform. In some cases, e.g. with the DPA pushbroom scanner, each of the four linear arrays recording the RGB and near-IR components of the colour and false-colour images has its own individual lens (all pointing in the nadir direction). The Wehrli 3-DAS-1 scanner also utilizes a separate lens for each of the tri-linear arrays used in its 3-line configuration. However, with the HRSC-A, ADS40 and Starimager scanners, only a single lens is used with the numerous linear arrays used in these scanners, but account still needs to be taken of their offset positions.

C - Geo-referencing of Pushbroom Scanner Images

With airborne film or digital ***frame cameras***, the procedures to ensure that the resulting frame images or their products are fitted to the terrain coordinate reference system are comparatively straightforward and well understood. Using either a photogrammetric bundle procedure or an orientation procedure, a 3D stereo-model can be formed from a pair of overlapping frame images. This stereo-model can then be fitted to the terrain reference system using a set of suitably positioned ground control points (GCPs). Often, the required number of control points can be cut down drastically using an aerial triangulation procedure that links the stereo-models together within a block.

With ***line scanner images***, the situation is very different. A single scanner image comprises many hundreds or thousands of discrete lines,that abut on one another. Each line is imaged at a different moment of time. Essentially this means that a single pushbroom scanner image comprises hundreds or thousands of discrete lines. Each of these lines has been exposed from a different position in the air and may have a different set of attitude (tilt) values resulting from the effects of atmospheric turbulence. This situation is in complete contrast to the situation that exists with a frame image - which has a single projection centre and a single set of tilt values that apply to the whole of the frame image.

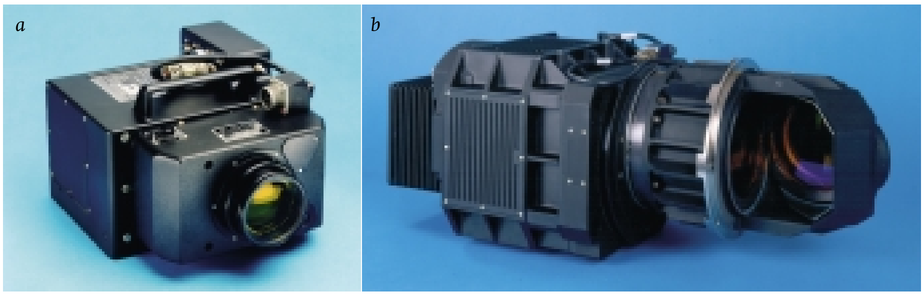


Fig. 4 - Two pushbroom line scanners from Thales Optronics - (a) the Type 8010 producing a strip image 4,096 pixels wide; and (b) the Type 8042 producing a 12,288 pixel wide strip image: both scanners generate monochrome (black-and-white) VNIR images. (Source: Thales Optronics)

It is quite impracticable to supply GCPs for each line of a scanner image. Thus it is necessary to to measure or derive very good estimates of the position of the projection centre and the corresponding set of attitude (tilt) values for every line in the pushbroom scanner image. This data is provided by an integrated ***DGPS/IMU system***, which forms an essential component of a pushbroom line scanner system. In fact, it would be true to say that airborne scanner systems could not have been developed as alternative imaging systems to airborne frame cameras without the recent developments in high-quality GPS sets and IMU units. By contrast, the use of a DGPS/IMU unit is not essential to the operation of an airborne frame camera - although they may well be used in conjunction with them to provide valuable auxiliary data for control and geo-referencing purposes.

The obligatory use of a DGPS/IMU system with a pushbroom line scanner adds considerably to the cost of the overall scanner system. A sum of between $30,000 and $200,000 is needed to cover the cost of the DGPS/IMU component of a single system. Currently the Canadian ***Applanix*** company (now owned by Trimble) is the dominant supplier of the high-quality DGPS/IMU units that are required to carry out high-precision photogrammetric work with pushbroom scanner images. These lie at the top end of the price range. However some multi-spectral and hyperspectral pushbroom scanners have used lower performance systems that lie at the lower end of the price range such as the C-MIGITS-III system from BEI Systron Donner - since the images are mainly used for thematic mapping where the requirements for geo-referencing will often be lower.

D - Pushbroom Scanners

The various types of airborne pushbroom scanners that are currently in operational use will be considered under the following headings:-
(i) Monochromatic scanners usually equipped with a single linear array;
(ii) Multi-spectral scanners employing multiple linear arrays designed to produce colour or false-colour images;
(iii) Hyperspectral scanners that employ imaging spectrometers to create a large number of images simultaneously in contiguous narrow spectral bands; and
(iv) 3-line scanners generating overlapping forward, nadir and backward pointing

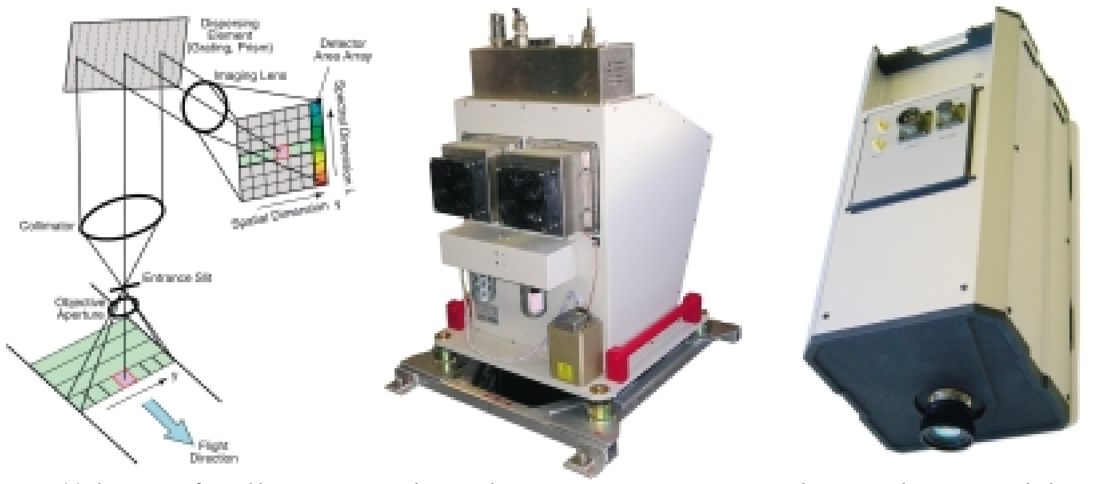


Fig. 5 - (a) The concept of a pushbroom scanner employing a dispersive grating or prism to generate hyperspectral images. N.B. The hyperspectral images will form a stacked 3D cube in the focal plane of the scanner. (Drawn by Mike Shand)
(b) The ITRES Research SASI-640 pushbroom scanner producing hyperspectral images in the short-wave-IR (SWIR) region. N.B. The new model of SASI will be much smaller in size. (Source: ITRES Research) (c) The Specim AISA+ pushbroom scanner producing hyperspectral images in the VNIR wavelength region. (Source: Specim)

images to produce 3D stereo-models: most scanners of this type also produce multi-spectral images simultaneously.

D.1 Monochrome Pushbroom Scanners

Into this category fall several of the pushbroom line scanners fitted to military reconnaissance aircraft. In general, colour or false-colour is not regarded as an essential feature in the imagery needed for military interpretative purposes. Instead the rapid data acquisition, processing and interpretation of the imagery in digital form is regarded as the primary requirement by military users. So most of the pushbroom scanners operated by military organisations generate monochrome (black-and-white) images. Usually the main scanner image will be nadir pointing. However sometimes this will be supplemented by side-pointing (i.e. tilted or oblique) scanner images.

(a) Thales Optronics
Taking the pushbroom line scanners offered by ***Thales Optronics*** (formerly Vinten) in the U.K. as an example, these have been produced since 1992. Currently two substantially different models are offered by the company. The Type 8010 scanner is intended for low-altitude reconnaissance operations. It features a 4,096 detector linear array supplied by E2V with each detector being 12µm in size. This sensor records digital monochromatic image data over the wavelength range 500 to 950µm, i.e. from green to near-IR, at a scan rate of 1,800 lines per second. Interchangeable lenses with focal length (f) values of 6 inches (152mm); 3 inches (76mm) and 1.5 inches (38mmm) are available to satisfy different operational requirements. At the other end of the operational range is the Type 8042 scanner which is optimised for high-altitude or long-range reconnaissance imaging. It features a linear array with 12,288 detectors, each 8µm in size, again supplied by E2V. Like its smaller brother (the Type 8010), it records its image data over the same spectral range (500 to 950µm) and at the same rate (1,800 lines per second) with a 12-bit image depth. Given its intended high-altitude operation, the Type 8042 scanner is equipped with a long-focus f = 18 inch (450mm) lens. When installed in a pod fitted below the reconnaissance aircraft and having a rotation mechanism fitted to the pod, the instrument can be pointed well to the side of the aircraft to acquire its imagery obliquely in a "stand-off" mode as well as in the nadir position.

(b) COSE
Another example of a European pushbroom line scanner falling into this category is the GlobalScan imager manufactured by ***COSE*** in France. This features a 6,000 pixel linear array and can be equipped with a range of lenses for operation at low- and medium altitudes. The scanner can be fitted in a pod which transmits its image data in real time to a ground station, which records and displays the acquired data also in real time.

D.2 Multi-Spectral Pushbroom Scanners

It must be said that most airborne multi-spectral line scanners, such as the well-known Daedalus (later SenSyTech, now Argon) series, continue to use rotating optical-mechanical scan heads to scan the terrain. Only a few are pushbroom line scanners. An important early airborne pushbroom scanner was the Multi-spectral Electro-optical Imaging Spectrometer (MEIS) constructed by ***Macdonald Dettwiler Associates (MDA)*** in the mid-1980s. The MEIS scanner featured eight nadir-pointing CCD linear arrays, each with 1,728 detectors placed in parallel with one another in the cross-track direction. Each linear array was fronted by an interchangeable optical filter. These allowed different optical channels to be selected over the visible and near-IR parts of the spectrum. The MEIS scan rate could be varied according to the speed of the airborne platform. MEIS also featured interchangeable lenses to allow a choice of coverage (i.e. swath width) and ground resolution. The MEIS scanner was operated commercially by the Moniteq company in the late 1980s and early 1990s. A MEIS-II was constructed for and operated by the Canadian Centre for Remote Sensing (CCRS).

Since then, much of the attention of the airborne remote sensing community has been focused on the development of hyperspectral imagers that produce images over a much greater number of spectral bands. However a few multi-spectral pushbroom scanners continue to be built and operated. Examples are those that have been produced in Germany during the 1990s for the ***Alfred Wegener Institute (AWI)*** for Polar & Marine Research based in Bremerhaven. In fact, a family of three scanners have been built and operated by the Institute:- (i) a Vertical Line Scanner (VLS); an Infra-Red Line Scanner (IRLS); and (iii) a Colour Line Scanner (CLS). The IRLS has a single thermal-IR detector and a rotating scan head. However the other two instruments are pushbroom line scanners. The VLS uses a single linear array with 1,024 detectors producing a 8-bit monochrome images. So it really belongs to group D.1 in this present classification. However the CLS is a multi-spectral pushbroom scanner equipped with three CCD linear arrays, each having 2,048 detectors. These generate 8-bit images in the wavelength ranges 0.40 to 0.48µm (blue); 0.48 to 0.58µm (blue/green); and 0.58 to 1.00µm (red/near-IR). The AWI aircraft that operate these scanners are equipped with a Honeywell INS and a GPS unit. These give the attitude and positional data required for the georeferencing and rectification of the

Fig. 6 - (a) DLR's HRSC 3-line pushbroom scanner as deployed on the Mars Express mission.
(b) The HRSC-AX airborne version of the HRSC 3-line pushbroom scanner. (Source: DLR)

imagery. The IRLS and CLS scanners have also been operated by the ***Airborne Research Australia (ARA)*** based in South Australia. Most recently, imagery produced by the IRLS and CLS is being offered as a commercial service by ***Hansa Luftbild*** based in Munster, Germany.

D.3 Hyperspectral Pushbroom Scanners

Instead of the relatively small number of spectral bands (<10) used in multi-spectral scanners, hyperspectral scanners allow the acquisition of images on hundreds of narrow spectral bands simultaneously. These scanners use dispersive gratings or prisms to separate the incoming radiation from the ground into distinctive angles according to their wavelengths. Thus the spatially separated rays from each ground pixel within the scanned line will be imaged at a different position on the detector array. As the diagram shows, an areal array of CCD detectors is used to record the ground position of each pixel in the scanned line in one direction on the array. In essence, this acts as a linear array in the cross-track direction. In the other direction of the 2D areal array, the detectors measure and record the intensity of the radiation in each narrow spectral band produced by the grating. In fact, many well known airborne hyperspectral scanners - e.g. the models from GER and Daedalus in the U.S.A.; NASA's AVIRIS; and the HyMap from Integrated Spectronics in Australia - all use rotating optical-mechanical elements to scan the ground in the cross-track direction. However several airborne hyperspectral scanners are configured as pushbroom line scanners. Three will be discussed here as examples.

(a) ITRES Research

ITRES Research is based in Calgary, Canada. The company produced its first Compact Airborne Spectrographic Imager (CASI) in 1989. The ***CASI*** generates 288 individual spectral images simultaneously over the wavelength range 400nm to $1\mu m$ with a swath width of 550 pixels. Over 20 of these systems have been produced and they remain in widespread use in North America, Western Europe, Japan and Australia. In the late 1990s, a second-generation CASI-2 was produced with improved electronics. The latest model in the series - the CASI-3 from 2002 (now renamed the CASI-1500) - has a much longer swath width of 1,500 pixels, while still retaining the 288 spectral channels. Moreover the CASI-3 images have a 14-bit depth instead of the 12-bits used in the earlier models. The CCD areal arrays (used as linear arrays in the spatial dimension) are supplied by E2V in the U.K. During 2002, ITRES also introduced two new pushbroom scanners. The first was the ***SASI*** (Short-wave infrared Airborne Spectrographic Imager). This produces images with 160 separate spectral channels in the near-IR and SWIR regions covering the wavelength range between 900nm and $2.5\mu m$, again with a 14-bit depth. The swath width of the SASI is 640 pixels. Also during 2002, ITRES introduced its ***TABI*** (Thermal Airborne Broadband Imager). This pushbroom line scanner - which with its monochrome images really falls into Group D.1 above - operates over the thermal-IR (LWIR) region, i.e. over the wavelength range 8 to $14\ \mu m$ - producing a 320 pixel wide image swath.

Fig. 7 - The Leica Geosystems ADS40 airborne 3-line pushbroom scanner as deployed operationally in an aircraft. (Source: Leica Geosystems)

The ITRES range of scanners all utilize the Canadian Applanix POS/AV system to produce the IMU and DGPS data needed to carry out the later rectification and georeferencing of the images.

(b) Specim

The AISA range of hyperspectral pushbroom scanners is produced by Spectral Imaging (Specim) Ltd., based in Oulu, Finland. The company's range of AISA scanners is not too dissimilar to the CASI and SASI range from ITRES. The ***AISA+*** model covers the VNIR wavelength range in 244 spectral bands with an image depth of 12-bits and a swath width of 500 pixels. The ***AISA Eagle*** also operates in the VNIR region with 244 spectral channels and a 12-bit output, but with an increased swath width of 1,000 pixels. Finally Specim has also produced its ***AISA Hawk*** pushbroom scanner that operates in the SWIR (1 to $2.5\mu m$) wavelength region producing images with a 320 pixel swath, 244 spectral channels and an image depth of 14-bits. The AISA scanners have used a Boeing/Rockwell C-MIGITS-II integrated DGPS/IMU unit to provide the positional and attitude data required for the geo-referencing of their image data.

(c) APEX

As a final example of a hyperspectral pushbroom scanner, it may be worthwhile to mention the APEX (Airborne Prism EXperiment). This instrument is being developed on behalf of ESA by a large Swiss-Belgian consortium, headed by VITO (Belgium) and RSL (Switzerland). The instrument will be used as a prototype and validation device for future spaceborne hyperspectral scanners. The APEX scanner will produce its 1,000 pixel wide imagery in 300 spectral bands covering both the VNIR and SWIR wavelength range using dispersive prisms to create the spectrally separated imagery. It is scheduled to become operational later this year (2005).

D.4 Three-Line Pushbroom Scanners

As discussed in the Introduction to this article, these devices produce overlapping strip images that allow 3D stereo-models to be formed. Often however they will produce multi-spectral, colour or false-colour images as a secondary product - or even as the primary product.

(a) DLR HRSC-A, -AX & -AXW Scanners

As noted above in the Introduction, the High Resolution Stereo Camera (HRSC) was devised by DLR's Institute of Planetary Exploration based in Berlin with a view to its

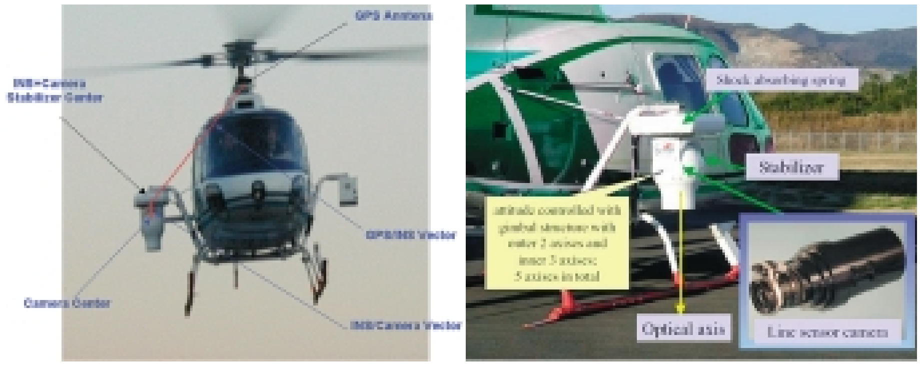


Fig. 8 - (a) The Starimager system mounted on a helicopter, showing the positions of the various system components on the aircraft. (b) A close-up view of the Starimager 3-line pushbroom scanner on its stabilized gimbal mount attached to the side of its helicopter platform. (Source: Inst. of Geodesy & Photogrammetry, ETH, Zürich)

operation over Mars on the Mars96 mission. The instrument was developed and proven via an airborne prototype - the ***HRSC-A*** (= Airborne) model. It was then developed further and its performance enhanced through the construction of a new model - the ***HRSC-AX***. This utilized much longer linear arrays (with 12,172 v 5,272 detectors) producing images greater radiometric depth (12 v 8 bits). Yet another model - the ***HRSC-AXW*** - was built. This also featured these higher performance linear arrays which were used in combination with a much wider-angle lens. The first two of these instruments, the HRSC-A and -AX, are both fitted with nine linear arrays. Five of these - two pointing forward; two backward and the fifth pointing in the nadir direction - produce overlapping panchromatic strip images. The remaining four arrays have RGB and near-IR filters placed over them to acquire the data needed to generate colour and false-colour strip images. The third instrument - the HRSC-AXW - has five linear arrays. Three of these are mounted in the forward, nadir and backward pointing positions needed to generate overlapping 3D panchromatic stereo-coverage, the remaining two being colour lines. All three airborne models of the HRSC scanner are mounted on Zeiss T-AS gyro-controlled mounts. Each is interfaced to an Applanix POS-AV system that generates the positional and attitude data required for the geo-referencing of each image line using its DGPS/IMU combination.

Initially, from 1997 onwards, a number of scientific projects were undertaken using the HRSC-A scanner. These included environmental monitoring projects covering volcanos, open-cast mines, forests and coastal areas. Later all three models of the HRSC-A scanner were used extensively for commercial imaging and mapping work, carried out in collaboration with the French ISTAR company. This resulted in the coverage and ortho-image mapping of many cities in France and Germany and later numerous cities in the U.S.A. This provided DLR and ISTAR with extensive operational experience of the different airborne versions of the HRSC scanner and of the complex processing of the resulting image data.

(b) DLR WAAC Scanner

The Wide Angle Airborne Camera (WAAC) is the airborne derivative of the Wide Angle Opto-electronic Stereo Scanner (WAOSS) that was also developed for the Mars96 mission. While the HRSC instrument was designed to produce high-resolution imagery, the WAOSS was designed to provide wide-angle (80°) coverage of large areas at a reduced ground resolution. Thus, while both scanners had similar CCD linear arrays of 5,000 detectors, the WAOSS scanner featured an f = 21.7mm lens and the HRSC, an f = 75mm lens. Both the WAOSS and the HRSC are 3-line scanners, which allowed them to generate DEMs. However the WAOSS did not possess the multi-spectral capability of the HRSC. The airborne WAAC scanner became operational in 1995 and has been used for the acquisition of imagery for various scientific research projects, e.g. of volcanos in Italy. The spare flight model of the WAOSS was finally orbited in 2001 as part of the payload of DLR's small BIRD satellite. This remained operational until the satellite lost its attitude control in February 2004.

(c) Leica ADS40 Scanner

Early in 1997, Leica Geosystems and DLR signed an agreement to cooperate in the design and production of a new airborne pushbroom line scanner designed specifically for commercial imaging and mapping purposes. Obviously the new design took into account the considerable experience gained with the various HRSC-A and WAAC scanners. The engineering model of the new instrument was first flown in late 1998; the prototype was then flown in January 2000; and finally the production version of the ADS40 was formally launched and displayed at the ISPRS Congress held in Amsterdam in July 2000. The first deliveries of the ADS40 took place in late 2001. Since then, its North American user community has expanded to include EarthData (now with 2 units), Horizons Inc.; 3001 Inc.; DeLorme; and Digital Aerial Solutions Inc. in the U.S.A. and North West Geomatics Ltd. (2 units) in Canada. In Europe, two ADS40s have been supplied to the Russian LARIS cadastral mapping project; while two others are operated by CGR in Italy and Terra Digital in Germany. The largest single operator with three units is PASCO in Japan, which was indeed the first customer for the ADS40.

With regard to the layout of the focal plane, the forward-pointing CCD linear array is set at an angle of 28.4° to the nadir, while the backward pointing array is set at 14.2° to the nadir - giving an angle of 42.6° between the forward and backward rays. As mentioned above, all three arrays comprise pairs of CCD linear array detectors, each shifted laterally from the other by half-a-pixel (3.25µm). These paired arrays produce the three overlapping panchromatic strip images. 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 RGB and near-IR spectral bands. A beam splitter (trichoid) ensures that the radiation from the ground passing through the main lens of the ADS40 reaches the appropriate linear array, 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. Two of these arrangements have been adopted as standard offerings; the other two are regarded as bespoke items. The ADS40 also features a specially designed telecentric lens which ensures that all the radiation from the ground reaches the focal plane at right angles, irrespective of the angles at which the object rays from the ground entered the lens. The inertial measurement unit (IMU) of the Applanix POS/AV system is mounted rigidly to the focal plane. Thus it is fully integrated into the ADS40 scanner, rather than simply being attached to it. The ADS40 is mounted on the same PAV30 gyro-stabilised mount that is used with the Leica RC30 film frame camera.

(d) Starlabo Starimager

The Japanese Starimager-100 (SI-100) - which was originally called the TLS (= Three Line Scanner) - is a 3-line pushbroom scanner with the forward pointing linear array set at 17° to the nadir and the backward array at

Fig. 9 - (a) An overall view of the Wehrli 3-DAS-1 3-line pushbroom scanner sitting on its ASP-1 stabilized mount. (b) A close-up view of the underside of the Wehrli 3-DAS-1 pushbroom line scanner with its three lenses as seen from below. (Source: Wehrli Associates)

23° to the nadir - providing an angle of 40° between the forward and backward rays. Each of the three imaging positions is occupied by a Kodak Tri-linear array. Each of the three lines in the array is 10,200 pixels in length with each detector being 7μm in size. A later version of the scanner - called the Starimager-200 (or SI-200) - also features Tri-linear arrays but with 14,400 detectors, each 5μm in size. Also a Nikon lens with a very different focal length (f = 200mm) is fitted to the SI-200, instead of the Hasselblad f = 60mm lens used in the earlier SI-100 model. The SI-200 also has an additional linear array that generates a near-IR strip image. Yet another model, the SI-250, has the original Hasselblad f = 60mm lens, but is fitted with the 14,400 pixel Tri-linear arrays. The Starimager is mounted on a gyro-stabilized mount that is attached by an arm and brackets to the side of the main body of a helicopter. An IMU and a Trimble GPS provide the attitude and positional data required for the later photogrammetric processing of the scanner image data.

The basic concept of the original TLS was set out by Prof. Murai of the University of Tokyo in 1993. The patents were acquired by the Starlabo Corporation in 2000. This allowed the design and construction of the TLS to begin with cooperation from the University's Institute of Industrial Science. It would appear that, so far, the Starimager scanners have been used mainly to acquire imagery for a number of application projects concerned with environmental monitoring; the generation of 3D city models; and surveys of linear features such as roads, railways, power lines, rivers, shore lines, etc. at large scales.

A great deal of the application software for use with the Starimager scanner imagery has been developed by Prof. Gruen's group at the Institute of Geodesy & Photogrammetry at the ETH in Zürich. This development includes software for triangulation, point positioning, DTM generation, rectification and ortho-image generation. Processing of Starimager scanner imagery has also been carried out by ISTAR in France. Recently the Intergraph subsidiary, Z/I Imaging, announced its support for the exploitation of Starimager scanner imagery on its ImageStation DPW. This includes feature extraction and ortho-image generation. It will be most interesting to follow the development of the Starimager, especially if the scanner starts to be sold to and operated by commercial air survey companies and government mapping agencies world-wide, and not just the Starlabo organisation in Japan.

(e) Wehrli Associates 3-DAS-1 Scanner

This new 3-line airborne pushbroom scanner was introduced at the recent ISPRS Congress held in Istanbul in July 2004. The Wehrli company has been well known for many years as a supplier of photogrammetric film scanners. In recent years, these have been produced in association with the GeoSystem company from the Ukraine which manufactures the optical and mechanical components of the instruments and assembles and tests them. The same combination of companies has now produced this new airborne scanner with Dr. James Bethel of Purdue University acting as a design consultant.

Like the Starimager, the 3-DAS-1 scanner is equipped with three of Kodak's Tri-linear arrays which acquire their RGB strip images in the forward, nadir and backward directions respectively. The prototype instrument shown in Istanbul was fitted with the 8,000 pixel version of the Tri-linear array with detectors 9μm in size. However the use of the 10,200 pixel version of the Tri-linear array (as used in the Starimager SI-100) is under consideration. The forward pointing array is set at an angle of 26° to the nadir; the backward array points at 16° to the nadir. This gives an angle of 42° between the forward and backward pointing rays. Unlike all the other 3-line scanner instruments in this group that use a single lens, the 3-DAS-1 employs three separate lenses, one for each of the Tri-linear arrays. These are commercial-off-the-shelf (COTS) lenses sourced from Rodenstock with a focal length (f) of 100mm and an aperture of f/4. As an alternative, the use of wider aperture f/2.8 lenses is being considered. This would allow more radiation to pass through each lens and allow the use of the higher density Tri-linear arrays. Integral to the design and practical operation of the 3-DAS-1 scanner is its new ASP-1 stabilized mount which is used rather than one of the well-established Leica or Zeiss mounts. The ASP-1 is a simple kinematic design with the pitch and roll motors tilting the scanner's adapter plate under direct command from the IMU module which utilizes fibre-optic gyros. The prototype shown at Istanbul was designed to be attached to an Applanix DGPS/IMU unit, but once again, other suppliers are being considered. It will be interesting to see how this new pushbroom scanner design develops. Currently the prototype 3-DAS-1 pushbroom scanner is being operated by the Belgian Eurosense company.

Conclusion

In summary, airborne pushbroom line scanners do offer an alternative to the dominant digital frame camera technology. However, in the small- and medium-format sectors of the airborne imaging market, pushbroom scanners cannot compete strongly with the digital frame cameras that are supported by the very large consumer and commercial markets for such cameras. Instead pushbroom line scanners have found a number of specialist markets. These include (i) the monochrome pushbroom scanners used for military reconnaissance purposes; and (ii) hyperspectral scanners that produce multiple images in numerous narrow spectral bands for use by field and environmental scientists. Of most interest to the mapping community are the wide-swath 3-line pushbroom scanners that can generate overlapping stereo-imagery from which elevation and ortho-image data can be derived. So far, only the Leica ADS40 has established itself in the market as a competitor to the large-format digital frame cameras. However other similar 3-line pushbroom scanners have now been developed. It will be most interesting to see how they progress.

Professor G. Petrie (g.petrie@geog.gla.ac.uk),
Department of Geography & Geomatics,
University of Glasgow, Glasgow, G12 8QQ, Scotland, U.K.
Internet: www.geog.gla.ac.uk/~gpetrie