Optical Imagery from Airborne &

Comparisons of Resolution, Coverage & Geometry for a Gi

As discussed in my article on imagers published in the April/May 2000 issue of GeoInformatics, over the last two or three years, the previous rather simple distinction between (i) analogue film cameras producing very high-resolution frame images from airborne platforms; and (ii) digital line scanners producing continuous strips of linescan imagery of a markedly lower resolution from spaceborne platforms, is being replaced by a much more complex scenario. This is based on the very varied mixtures of technologies, geometries and platforms that are now becoming available through the introduction of the new types of digital imagers capable of being operated both from airborne and spaceborne platforms.

By Prof. Gordon Petrie

The New Digital Images

(a) Pushbroom Scanners. With the successful launch of the IKONOS, EROS-1A and QuickBird satellites in September 1999, December 2000 and October 2001 respectively, **spaceborne pushbroom scanners** now produce much higher resolution imagery from satellites than before. Furthermore the corresponding **airborne pushbroom scanners** are now reaching an operational and production status. They include DLR's HRSC-A/AX/AXW series of imagers and the forthcoming ADS40 imager from LH Systems - which is based on the same basic pushbroom scanner technology and has been produced with the cooperation and assistance of DLR.

(b) Frame Cameras. At the same time, **frame-type imagers** have gone from being purely film-based to becoming producers of digital imagery as well. These digital frame cameras have been mounted on **airborne platforms** - as in the case of the Z/I Imaging DMC 2001 digital modular camera and the several other multi-spectral digital frame cameras from Airborne Data Systems, Terra Systems and Duncan Technologies that have been developed in the U.S.A. Others have been operated from **spaceborne platforms** - e.g. the use of simple low-cost digital frame cameras mounted on the micro-satellites built by Surrey Space Technology (SSTL).

The Past

As a result of this rapid development and introduction of digital imagers, the high walls existing between photogrammetrists and remote sensing specialists - which previously had only a few very narrow doors opening between them - are beginning to crumble.

(a) Photogrammetry. Up till now, most photogrammetrists have been quite comfortable working with high-resolution frame-type photographic imagery with its stable and well-understood geometry. This produces 3D stereo-models that can be precisely measured to produce high-quality 3D coordinate data or detailed topographic maps. Only a very few photogrammetrists endeavoured to cope with the overlapping space linescan images produced by the pushbroom scanners mounted on the SPOT, MOMS and IRS satellites. These displayed a much more complex and rather unstable geometry with positional and attitude values that are ever changing on a line-by-line basis along each continuous strip image. However, during the 1990s, photogrammetric solutions have been developed that resulted in the production of DEMs and orthoimages from this type of overlapping 3D space linescan imagery.

(b) Remote Sensing. By the same token, most remote sensing practitioners were equally happy with their use of much lower-resolution, monoscopic, space linescan imagery to help solve their own specific application problems in the field and environmental sciences. Furthermore, they seldom rose above the use of fairly crude 2D "rubber-sheeting" methods when carrying out their so-called "geo-referencing" operations - i.e. fitting their space scanner images to ground control points and maps. The formation and use of 3D stereo-models was (and is) unknown to the vast majority of these practitioners. The matter of flight planning was also largely unknown to the remote sensing community, given the fact that the satellites from which their images were mostly being acquired were being operated within a pre-defined orbit and ground track, producing linescan imagery with a fixed and pre-determined ground resolu-

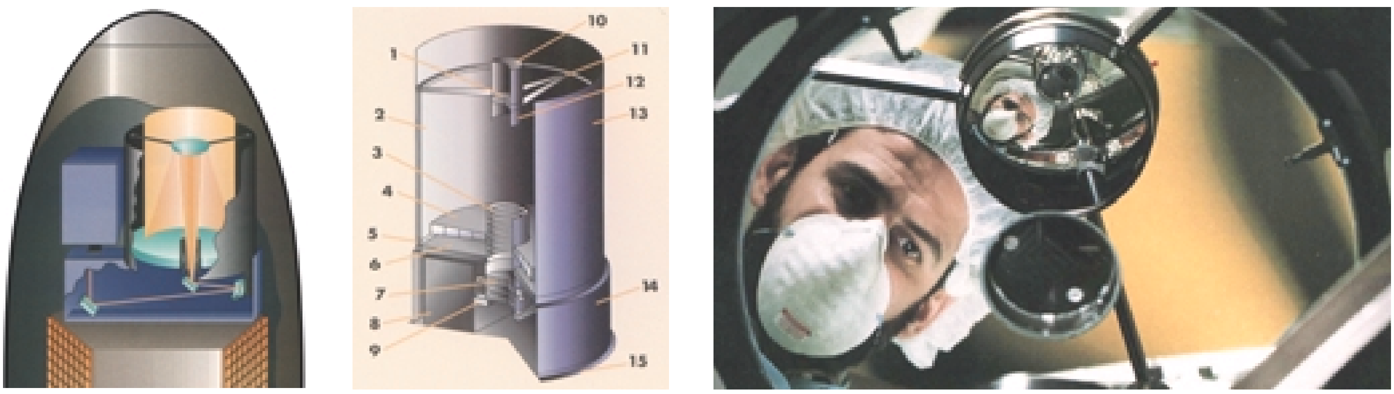

Figure 1:
(a) Diagram of the Kodak Model 1000 space imaging system - which is similar to the design of the Kodak-built pushbroom scanner used in the IKONOS satellite. The folded mirror optics comprise three focusing mirrors and two plane flat mirrors. The focal plane with its CCD linear arrays (having 12 μm pixels for the Pan imager) and the associated electronics are accommodated in the case to the left of the main barrel of the optical telescope.
(b) Diagram of the main features of a Kodak-built mirror optical telescope used for space remote sensing. Individual features are as follows: 1 - Secondary Mirror Assembly; 2 - Metering Structure; 3 - Primary Mirror Baffle; 4 - Primary Mirror Assembly; 5 - Interface Ring; 6 - Primary Mirror Reaction Structure; 7 - Corrector Lens Assembly; 8 - Focal Plane Electronics; 9 - Detector Assembly; 10 - Secondary Mirror Thermal Isolation Shroud; 11 - Secondary Mirror Spider Assembly; 12 - Secondary Mirror Baffle; 13 - Outer Barrel/Sunshade; 14 - AFT Cover Assembly; 15 - AFT Access Plate
(c) View of the IKONOS primary mirror, looking into the forward end of the main barrel of the telescope. (Source: Kodak Commercial & Government Systems)

& Spaceborne Platforms

ven Ground Pixel Size

tion. Obviously this rather cosy situation will change radically with the flexibility and the alternative solutions offered through the introduction of airborne pushbroom scanners. These can be flown over a wide range of flying heights; with lenses of different focal length and angular coverage; and giving different ground resolutions - just like airborne frame cameras.

The Present & Future

With the advent of the new airborne and spaceborne digital imagers using both framing and pushbroom line scanning techniques, photogrammetrists and remote sensing specialists are going to have to look in a totally different manner at the very many different types of digital imagery having different geometries that will be coming their way in the future. A massive shift in thinking will be needed: one can even forecast that many users will need a substantial re-education. Besides which, as far as one can judge at the present time, notwithstanding its requirements for chemical processing and high precision scanning before it can be used in image processing systems or DPWs, the "old-fashioned" **photographic film camera technology** still has a long life ahead of it. Indeed, for many applications, it is still extremely competitive with the new digital imaging technologies both in terms of cost and coverage - especially when really high resolution imagery is required.

Aims & Objectives

This article attempts to set out and compare the geometry, resolution and coverage of the main types of optical imaging technologies - whether new or old. This comparison will be carried out within the specific context or framework of imagery having a **ground pixel size** in the range 0.5 to 2m - since this resolution can now be obtained from all of these different types of imager, whether operated from airborne or spaceborne platforms. It is interesting to note that, while this is regarded as "high resolution" imagery when acquired from a spaceborne platform, it is regarded as "small-scale, low resolution" imagery when acquired from an airborne platform! In this particular context, imagery having much smaller ground pixel sizes - in the range 0.1 to 0.5m - can rather readily be obtained from an airborne platform, but not so readily from a spaceborne platform. Only military reconnaissance satellites such as the American KH-11/KH-12 series operated by NRO can reach this ground resolution from space - and this needs a large imager similar to the Hubble Space Telescope to do so. The size and cost of such devices precludes their use for civilian purposes.

1 - IMAGERY FROM SPACEBORNE PLATFORMS

A) Spaceborne Pushbroom Scanners

An obvious starting point in this discussion is to analyze the most significant parameters of the existing (IKONOS, EROS-A1 and QuickBird) and the forthcoming (OrbView-3 and EROS-B) commercial "high-resolution" satellites. All of these satellites feature pushbroom scanners equipped with linear CCD arrays; flexible off-nadir pointing towards targeted areas; and an along-track stereo-imaging capability. Table I summarizes their main orbital parameters and those of their respective Pan imaging sensors.

• Orbital Inclinations & Altitudes
Most commentators tend to lump all of these commercial "high resolution" satellites together as a common group providing images with around 1m ground pixel size. However Table I shows that, from the technical standpoint, there are some quite significant differences between them. Thus IKONOS has been placed in an orbit having a much greater altitude (680km) as compared with the others, which have been (or will be) flown at a much lower altitude (450 to 470km). This means that the Kodak-built telescope used on IKONOS is employing a focal length of 10m to allow images with 1m ground pixel size to be acquired. This has meant that folded mirror optics - utilizing three focusing mirrors and two plane flat mirrors - have been used to accommodate this within a 2m length inside the IKONOS satellite (Figure 1). The greater altitude also means that the orbital inclination value (i) of IKONOS is somewhat different to the others in order to achieve the Sun-synchronous orbit that is used by all of these near-polar orbiting satellites.

• Swath Width
However the most striking difference lies in the respective swath widths covered by these satellites (Figure 2a). While the IKONOS, EROS-A1 and OrbView-3 satellites provide images with swath widths in the range 8 to 12.5km, the QuickBird satellites have been designed from the outset to cover a much wider swath from a single orbit. In the case of the failed QuickBird-1, this was to have been 22km. To achieve such a wide coverage using a 1m (actually 0.82m) ground pixel, it must utilize a linear array of 27,000 pixels. Since currently the longest available linear CCD array is in the region of 12,000 to 13,000 pixels, **multiple linear arrays** have to be used to get this coverage. Of course, this type of solution has been used previously with the medium-resolution Pan imagers deployed on the Indian IRS-1C and -1D satellites launched in 1995 and 1997 respectively. At that time, the available linear arrays were much shorter. So each of these IRS satellites is equipped with three linear CCD arrays of 4,096 pixels giving a total length of 12,000 pixels. However it has been found in practice that these three arrays had not been aligned perfectly within the focal planes of their imagers. The result has been that the three separate sub-scenes or strips that are produced by the IRS-1C and -1D imagers have had small discontinuities or mismatches between them. Therefore the sub-scenes need to be transformed and stitched together via a preliminary processing stage using common points in the small overlaps between them in order to achieve a single homogeneous image. Obviously a similar procedure will be required for the QuickBird images.

• QuickBird-2
With QuickBird-2, the telescope with its mirror optics has been built by Ball Aerospace (which has also built the satellite bus), while the focal plane, comprising the CCD linear arrays, image compression facilities and associated electronics, have been supplied by Kodak. In a paper presented at the ASPRS 2001 Conference by Hargreaves & Robertson of the Canadian MDA company - which has supplied the product generation system for the QuickBird-2 imagery to Digital Globe (nee EarthWatch) - such an arrangement of multiple linear arrays is described (Figure 3). For a 27,000 pixel width, this would comprise three linear arrays, each of 9,000 pixels. This would be well within the state-of-the-art in CCD linear array technology during the period

Table I - Characteristics of Space Scanner Imagery - Pan Sensors Only

Space Platform	Sensor Array Type	Orbital Height (km)	Swath Width (km)	Linear Array (pixels)	Ground Pixel (m)	Pointing Along Track	Pointing Cross Track	Orbital Inclin-ation	B:Ht. Ratio
QuickBird	Linear	450	16.5	27,000	0.6	±30°	±30°	98°	Variable
IKONOS	Linear	680	11	13,500	1	±45°	±45°	98.1°	Variable
EROS-A1	Linear	480	12.5	7,800	1.8	Yes	±45°	98°	Variable
OrbView3*	Linear	460	8	8,000	1	±45°	±45°	97.3°	Variable
EROS-B*	Linear	600	16	20,000	1	Yes	±45°	98°	Variable

* = Forthcoming

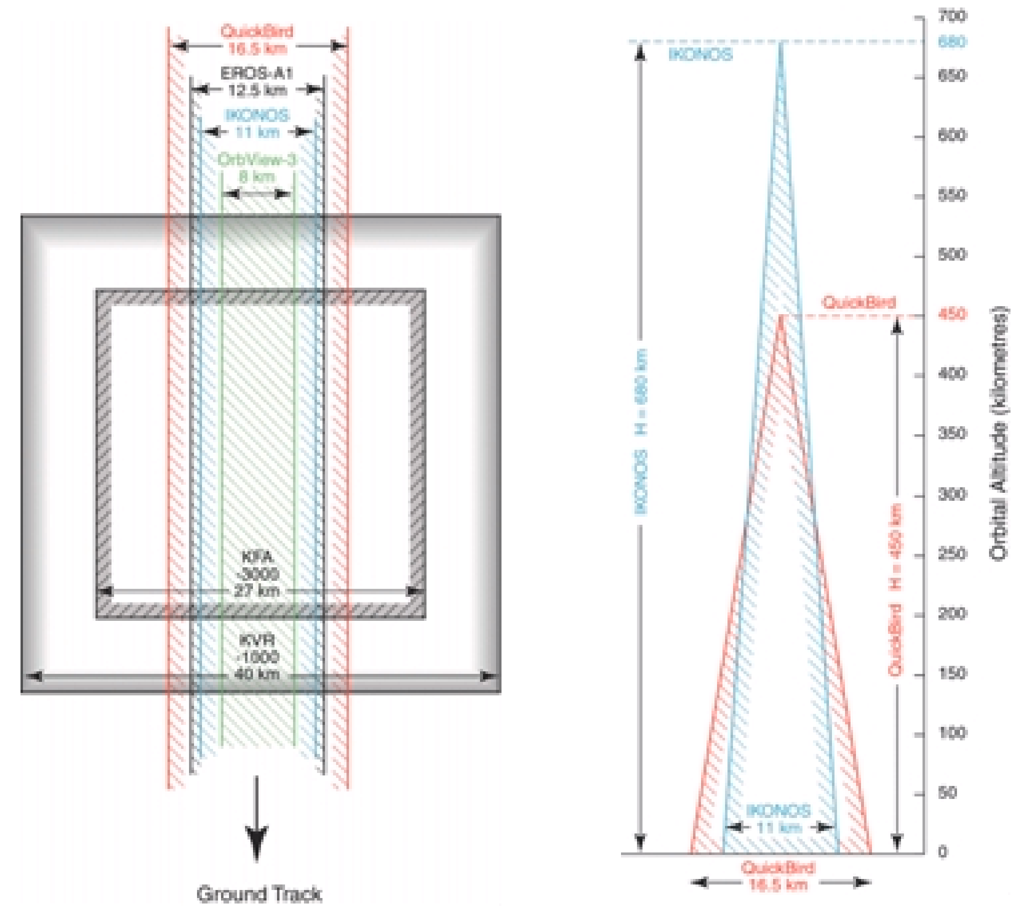

Figure 2:
(a) The respective ground coverages and swath widths of the spaceborne pushbroom scanners (QuickBird, IKONOS, OrbView-3 & EROS-A1) and frame film cameras (KFA-3000 & KVR-1000). The corresponding ground pixel sizes of the resulting images are 0.6m (QuickBird), 0.8m (IKONOS), 1m (OrbView-3) and 1.8m (EROS-A1) for the pushbroom scanners and 2m for the KFA-3000 and KVR-1000 film cameras.
(b) Diagrammatic comparison of the respective orbital heights and swath widths (ground coverage) of the IKONOS and QuickBird satellites and their pushbroom scanner imagers. (Drawn by M. Shand)

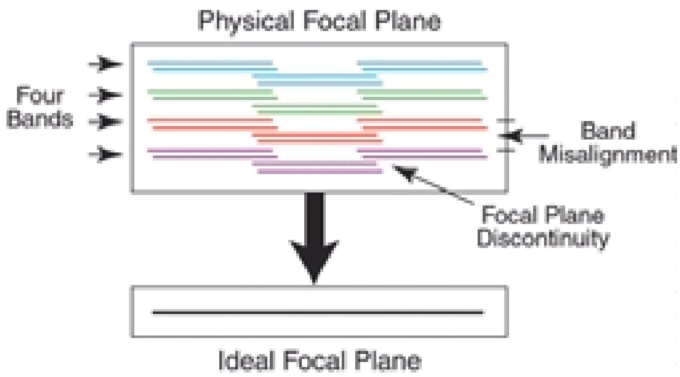

Figure3:
The arrangement of multiple linear arrays as described by Hargreaves & Robertson (2001) of MDA. The physical focal plane discontinuities and the offset positions of the linear arrays covering different spectral bands need to be corrected to produce a single (ideal) final image line. (Drawn by M. Shand)

when the QuickBird satellites were being built. It may well be that the multiple arrays that are being used with the QuickBird imagers will be better aligned than those used in the IRS-1C/D satellites. Nevertheless it will still be necessary during image pre-processing to synthesize a single common line from the sub-images produced by the component linear arrays in order to eliminate any potential physical focal plane discontinuities. Be that as it may, the wide swath width of the QuickBird optical imaging system has been the essential feature behind the changes to the orbital parameters that EarthWatch (now Digital Globe) were able to make when it received its licence from the U.S. Department of Commerce in December 2000 allowing it to operate satellites capable of acquiring imagery with a 0.5 ground pixel size. The availability of this comparatively large angular coverage and swath width allowed EarthWatch/Digital Globe to re-design and re-configure the QuickBird-2 satellite orbit. Instead of the originally planned orbital altitude of 600km, a new lower altitude of 450km was chosen. From this altitude, QuickBird-2 will still produce images having a swath width (16.5km) that is greater than those of its commercial satellite competitors, while also having a superior ground pixel size of 0.6m (Figure 2b).

• Geometry

It is also worth noting some of the geometric aspects of these different spaceborne pushbroom scanners. Judging from the characteristics of many of the published IKONOS images - as evidenced by the highly displaced buildings - many are acquired in an off-nadir (oblique) configuration. Thus the flexible off-nadir pointing capability of the imagers is a vital point in their successful operation. Interestingly this is mostly achieved by altering the pointing of the satellite as a whole, rather than using a rotating mirror in front of the imager's main telescope. However it should be recognised that this off-nadir pointing also results in a reduced ground resolution in the area imaged by the scanner as well as increasing the areas that are "dead". With regard to the along-track stereo configuration, since Space Imaging has refused to supply stereo-imagery to non-government agencies and to release the calibration data for the IKONOS pushbroom scanner, it is difficult to judge whether this stereo-capability has been used to any great extent. Once the EROS-A1 imagery becomes more widely available and the QuickBird-2 imager comes into operation, a better judgement can be made about this particular matter. In the meantime, it is worth noting that the EROS-A1 satellite consistently changes its pointing in the along-track direction while carrying out its imaging of the ground (Figure 5). This has been done to ensure a longer dwell time to allow more light to reach the CCD linear array sensor of the imager - so improving the quality of the image. It will be very interesting to learn, in due course, if this continuous change in the direction of its pointing during image acquisition is executed in a smooth manner to allow the accurate modelling of the resulting image or whether it gives rise to geometric discontinuities.

Table II - Characteristics of Russian Space Frame Cameras & Frame Photography

Film Camera Type	Format (cm)	Focal Length (m)	Angular Coverage	Flying Height (km)	Ground Coverage (km)	Photo Scale	Ground Resol. (m)	Orbital Inclin--ation	B:Ht. Ratio
KVR-1000	18x18	1.00	8.5°x8.5°	220	40x40	1:220,000	2	67°	-
KFA-3000	30x30	3.00	6°x6°	270	27x27	1:90,000	2	83°	0.04

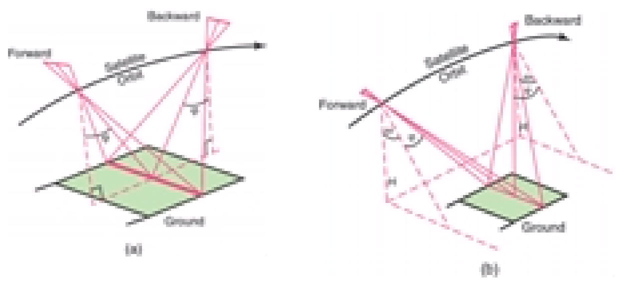

Figure 4:
(a) Overlapping stereo-images obtained in simple along-track mode from a space-borne pushbroom scanner using forward- and backward-pointing CCD linear arrays.
(b) Flexible pointing towards a targeted area employing both the along-track and cross track pointing capabilities of a spaceborne pushbroom scanner imager, in combination with forward- and backward-pointing CCD linear arrays. (Drawn by M. Shand)

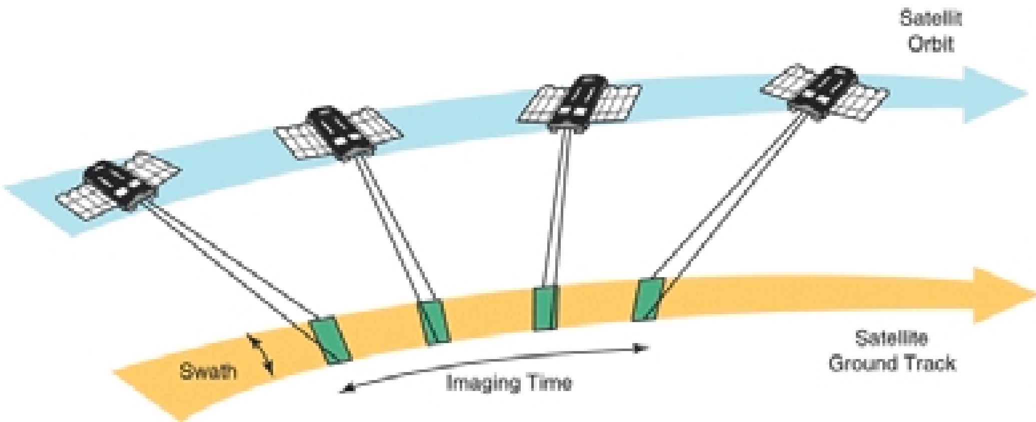

Figure 5:
The EROS-A1 imaging concept by which the space linescan image is acquired. The orientation or direction of the satellite and its linear array sensor are changed continuously as the satellite travels forward over the Earth. This gives the linear array sensor a longer dwell time, thus allowing more light to reach it and so improving the quality of the image. (Drawn by M. Shand)

B) Spaceborne Photographic Frame Cameras

As with the spaceborne pushbroom scanners, it is necessary to use optical systems with very long focal lengths to obtain images with ground resolutions in the range 0.5 to 2m from space using photographic frame cameras. Only Russian agencies have made extensive use of such imagers. This contrasts with the Western space film cameras - NASA's LFC and ESA's MC - that were operated from manned Space Shuttle missions during the early 1980s. These were used to give large area coverage - 170 x 340km (LFC) and 190 x 190km (MC) respectively - at the relatively moderate resolution values of 10m (LFC) and 18m (MC) respectively. The two main Russian film cameras that have been used to produce imagery from space within the range being discussed here are the KA-3000 and the KVR-1000. Both use classical refractive lenses rather than the reflective mirror optics used with the spaceborne pushbroom scanners described above. Both of the Russian cameras have been operated during quite short duration missions so that the film can be returned and developed within a useful time period. So these missions can be flown at much lower orbital altitudes than those used by the long-lived satellites equipped with scanner imagers that transmit their images to ground stations. From altitudes of 270km (KA-3000) and 220km (KVR-1000) respectively, they produce images with a ground resolution of around 2m.

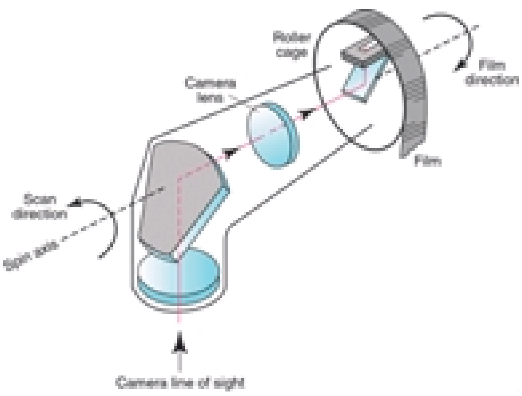

Figure 6:
Rotating optical bar concept as used in the KVR-1000 panoramic film camera. (Drawn by M. Shand)

• Swath Width & Coverage
In the case of the **KA-3000**, which is a classical type of frame camera using photographic film equipped with lens having a 3m focal length, the ground area covered from the 270km orbital altitude is 27 x 27km. The **KVR-1000** panoramic film camera is altogether different in terms of its basic design and operation since it gives a sequential line-by-line exposure of the frame cross-track using a mirror rotating in front of the lens and film (Figure 6). So the scale and resolution vary greatly across the large-format (18 x 72cm) image, which covers an area of 40km (along-track) x 160km (cross-track). While the ground resolution may be 2m at the centre of the frame, it becomes poorer as one moves outwards from the centre cross-track towards the sides of the frame. Thus the format size of the images that are actually supplied to users covers only the central part (18 x 18cm) of the exposed frame. This gives a ground coverage of 39.6 x 39.6km and a swath width of 39.6km. This still provides by far the greatest swath width of all the imagers being considered in this account (Figure 2a), but with a reduction in the ground resolution as one moves from the centre of the image out to its sides in the cross-track direction. From the KVR-1000's photo scale of 1:220,000, 1mm on the photo is equivalent to 220m on the ground. Using a 10μm pixel size in a photogrammetric film scanner, this gives a ground pixel value of 2.2m.

• Russian DK-1 and DK-2 Imagery
Most recently, the Russian Sovinformsputnik organisation has been making available space imagery with 1m (DK-1) and 1.5m (DK-2) ground pixel sizes. This is being sold via the Land Info International company based in Colorado in the U.S.A. It is not too clear as yet as to whether this imagery has been taken with a film camera or an electro-optical scanner system (or both!).

Ground Resolution & Ground Pixel Size

Before dealing with airborne imagers and before any further comparisons are made, it would seem appropriate next to define the relationship between the **resolution** of the lens/film combination used with metric film cameras - which is normally expressed in line pairs per mm (lp/mm) - and the **pixel size** that is widely used with digital imagers. This relationship is normally given by the Kell factor - which states that 1 line pair (lp) is equivalent to $2\sqrt{2}$ pixels. To simplify matters, most practitioners adopt the easily remembered relationship that 1 line pair (lp) is equivalent to 2 pixels. Thus 1 pixel is equal to 0.5 line pair (lp). This relationship is, of course, referring to the situation that exists within the focal plane or image plane of the respective imagers. It can then be translated over to the corresponding terms - **ground resolution and ground pixel size** (or Ground Sampled Distance (GSD) in American usage) - that are widely used to express the equivalent values over the ground.

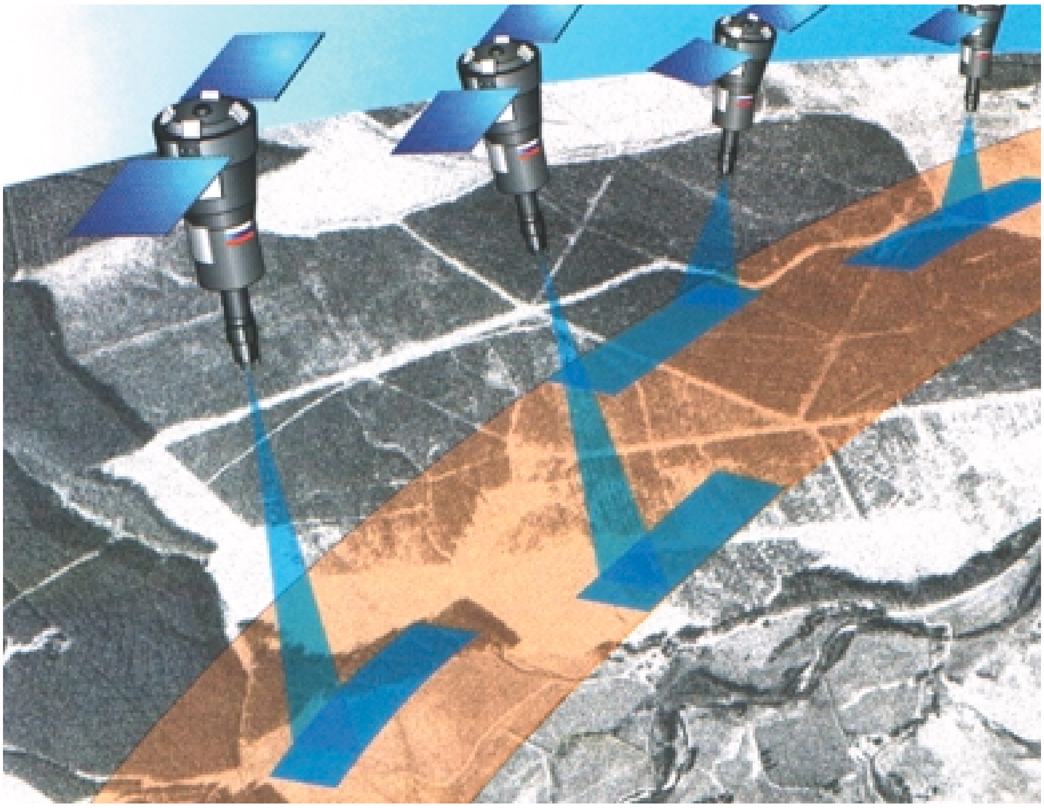

Figure 7:
The concept of the RESURS-DK space imaging system. The satellite appears to utilize body pointing to acquire off-nadir images using a pushbroom scanner imager. (Source: Sovinformsputnik)

According to the information provided by Sovinformsputnik at the ISPRS 2000 Congress in Amsterdam, the RESURS-DK satellite (which is thought to be the system acquiring the DK-1 and DK-2 imagery) has a projected life of three years. This points to the imager being a pushbroom scanner equipped with linear arrays (Figure 7). The RESURS-DK flies at an orbital height of 350km and produces imagery with a swath width of 28.3km. For a 1m ground pixel size for its pan imagery, this means that a single line will have 28,300 pixels - which would require the use of a very similar CCD linear array to that of QuickBird-2. Obviously given the current lack of any further information from the Russian agencies involved in the acquisition and marketing of the DK-1 and DK-2 imagery, it is difficult to go much further with this particular analysis. Otherwise one simply makes too many assumptions or presumptions - that, in total, may lead to quite erroneous conclusions! In due course, this particular matter will become clearer.

2 - IMAGERY FROM AIRBORNE PLATFORMS

A) Airborne Photographic Frame Cameras

(i) Typical of the older metric film cameras that are still in widespread use within the mapping industry are the Wild RC10 and Zeiss RMK-A models providing images with a resolution of 40 lp/mm (= 0.025mm on the film). For aerial photography taken with a metric camera @ 1:40,000 scale, 1mm on the image is equivalent to 40m on the ground. So, using one of these older film cameras (with a resolution of 40lp/mm), the resolution of 1lp (0.025mm) on the film is equivalent to 1m on the ground. The corresponding ground pixel size is 0.5m.
(ii) The newer generation of metric film cameras such as the Wild RC30 and the Zeiss RMK-TOP use gyro-controlled mounts in conjunction with forward motion compensation. In turn, this allows the use of fine-grained high-resolution films. Typically the resolution of the images delivered by current metric film cameras is 60 lp/mm (0.017mm on the film). Using the modern higher performance cameras (having a resolution of 60lp/mm), with photography @ 1:60,000 scale, 1mm on the image is equivalent to 60m on the ground. So 1lp (0.017mm) is again equivalent to 1m on the ground resulting in a ground pixel size of 0.5m.

• Swath Width & Ground Coverage
Metric film cameras have a standard format or frame size of 23 x 23cm. For various image scales, the corresponding ground coverages are as follows (see also Figure 8):

- **(i)** An image @ 1:40,000 scale will give a swath width of 23 x 400m = 9.2km and a ground coverage for a single frame of 9.2 x 9.2km.
- **(ii)** Similarly an image @ 1:60,000 scale gives a swath width of 13.8km and a ground coverage of 13.8. x 13.8km for a single frame.
- **(iii)** With a 1:80,000 scale image, a swath width of 18.4km and a single frame coverage of 18.4 x 18.4km results.
- **(iv)** A 1:100,000 scale frame image has a swath width of 23km and produces frame images that cover and area of 23 x 23km in ground terms.

(a) Equal Swath Widths. From this discussion, it can be seen that medium (1:40,000 to 1:60,000) scale aerial photography gives images with a swath width and ground coverage that is roughly in the same range (9.2 to 13.8km) as that offered by OrbView (8km), IKONOS (11km) and EROS-A1 (12.5km) respectively. However this imagery will have a superior resolution or ground pixel size of 0.4 to 0.6m versus the 0.8m of IKONOS & OrbView and 1.8m of EROS-A1. Only QuickBird-2 with its use of multiple linear arrays will give a superior swath width of 16.5km for roughly the same ground pixel size of 0.6m that will be provided by the aerial photography.

(b) Equal Ground Pixel Values
Making a second comparison, if a modern aerial camera (with its 23 x 23cm format) is flown to produce imagery @ 1:100,000 scale, then the swath width is 23km, while the resolution for 1lp/mm is equivalent to 1.7m on the ground. So the equivalent ground pixel size of the photography is 0.85m, the same as that of IKONOS and OrbView, but with a superior swath width of 23km.

B) Airborne Digital Frame Cameras

Currently there is much activity in the development of airborne digital frame cameras. At the one end of the scale is the quite extensive use of very small-format digital cameras such as the Kodak DCS 420 and 460 CIR models. These are mainly used on light aircraft from low altitudes for coverage of local areas where rapid response is the key issue. However the format size is very small - 2k x 3k = 6 Megapixels. Thus large numbers of the resulting frame images are needed to cover even a small area of ground. So they do not come into consideration within the remit of the present discussion. The use of larger CCD areal arrays to produce digital frame images is a matter that is being extensively pursued by a number of groups in several different countries. Typical examples are those frame cameras using 4k x 4k = 16 Megapixel arrays from Kodak and Dicomed. These include the digital frame cameras constructed by the French IGN national mapping agency; Ohio State University in the U.S.A. (the AIMS system); and the GeoTechnologies consultancy in the U.K. (with its MF-DMC camera). Even using a short focal length lens, the coverage for a ground pixel size of 0.5 to 0.6m will be in the order of 1km. So quite obviously the next stage in this development will be to utilize still larger arrays. Both 7k x 9k = 63 Megapixel arrays (from Philips) and 9k x 9k = 81 Megapixel arrays (from Lockheed) have been developed, but, up till now, they have only been available in very small (sample) quantities. None have appeared on an operational digital camera up till now.

• Z/I Imaging Digital Modular Camera
As is well known, an alternative route to overcoming the limited coverage of the currently avail-

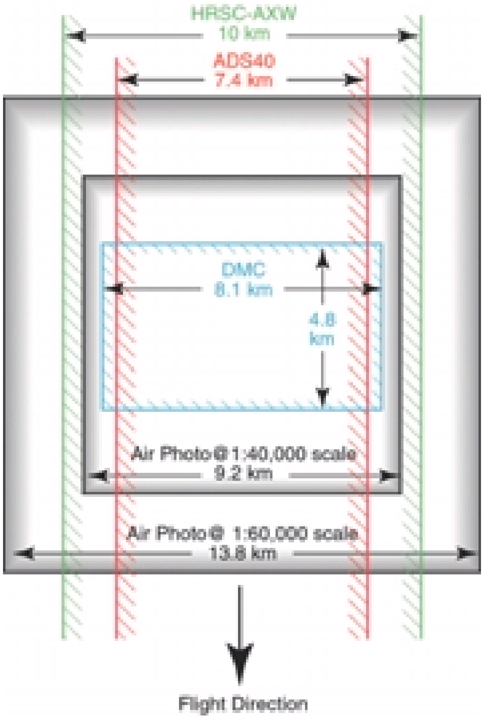

Figure 8:
The respective ground coverages and swath widths of the airborne pushbroom scanners (HRSC-AXW & ADS40), digital frame camera (DMC) and frame film cameras (RMK-TOP & RC30). (a) The coverages are those for a flying height of 6,000m (20,000ft) for the scanners, digital camera and the aerial film cameras (the last giving a photo scale of 1:40,000). The corresponding ground pixel values are 0.4m (film cameras), 0.6m (ADS40 & DMC) and 0.8m (HRSC-AXW).
(b) If the film cameras acquire data with 0.6m ground pixel size, the photo scale will be 1:60,000 and the ground coverage 13.8 x 13.8km. (Drawn by M. Shand)

able areal arrays is to use multiple cameras equipped with those areal arrays that are available in production quantities. Such a development is currently under way by Z/I Imaging in the form of its Digital Modular Camera (DMC). To generate pan (black-and-white) images, the DMC integrates four individual cameras arranged (i.e. tilted outwards) in a star-type configuration. The resulting four individual tilted images overlap slightly and are exposed simultaneously. They are then processed to form a single perspective image. Each of the four component cameras is fitted with a 7k x 4k CCD areal array manufactured by Philips. In combination, this configuration produces a 13.5k x 8k = 108 Megapixel image giving an angular coverage of 68° x 44° over the ground. With regard to the coverage of the DMC camera, from a flying height of 6,000m and using an f = 120mm lens, the ground covered by a single frame formed from the four component images will be 8.1 x 4.85km. The corresponding ground pixel size will be 0.6m. Obviously the ground coverage of a single composite frame image is considerably smaller than that of a standard metric film camera such as the RMK-TOP or RC30 producing images with a similar ground pixel size. The respective ground coverages of the DMC and the metric film frame cameras for the flying height of 6,000m are shown in diagrammatic form in Figure 8.

C) Airborne Pushbroom Scanners

The main characteristics of the new HRSC and ADS40 airborne pushbroom scanners are given in Table III. From this, it can be seen that the three different models of the HRSC imager built by DLR and the ADS40 built by LH Systems use CCD linear arrays of different lengths in conjunction with lenses of different focal length and angular coverage (- in exactly the same way as aerial frame cameras). The imagers can be viewed as having narrow (HRSC-A), normal (HRSC-AX), semi-wide (ADS40) and wide (HRSC-AXW) angular coverages.

• Swath Width & Coverage
Considering a common flying height of 6,000m results in imagery with ground pixel values of 0.24m (HRSC-A), 0.25m (HRSC-AX), 0.62m (ADS40) and 0.83m (HRSC-AXW) respectively. The corresponding swath widths are 1km (HRSC-A), 3km (HRSC-AX), 7.4km (ADS40) and 10km (HRSC-AXW) respectively. Obviously the ADS40 and HRSC-AXW are the two airborne pushbroom scanner imagers that fall into the category being discussed in the present article. Their respective ground coverages have also been included in Figure 8. Comparing these two imagers with the airborne film frame cameras, it is apparent that their current use of linear arrays with 12,000 pixels (having a 6.5 or 7µm pixel size) in pushbroom scanners does result in some limitations in the resulting swath width. They compare with the 30,000 pixels at 7 µm that can be obtained from the airborne metric frame camera with its 23cm format. For a ground pixel size of 0.8m, the wide-angle HRSC-AXW pushbroom scanner with its f = 47mm lens covers a swath that is 10km in width. Whereas, for the same ground pixel size, the metric frame camera with its f = 15cm lens would achieve a coverage of 21.8km. This comes as no surprise. It has been known for some time that the limitations in ground coverage for a given ground resolution from the present generation of digital imagers result from the current limitations in the sizes of the linear and areal CCD arrays that can be fabricated at the present time. Undoubtedly this situation will improve with time. The alternative at present is to use multiple linear arrays as is being done with the imager on-board the QuickBird-2 satellite.

Conclusion

As this article has endeavoured to show, with the advent of the various new types of digital imager, there is now a considerable area of overlap in terms of the imagery that can be obtained from both airborne and spaceborne platforms. Frame and linescan imagery having ground pixel values between 0.5 and 2m can be obtained from both types of platform. However there are still some obvious differences in terms of the resolution and coverage that can be obtained from different combinations of imager and platform. These need to be considered carefully by users. So does the economic side. At the present time, for most applications, airborne imagery will be considerably less expensive to acquire. However, for those areas where access to imagery is either restricted or forbidden, space imagery is really the only possible solution. But access to this imagery can only be gained by paying a premium price.

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Table III - Airborne Pushbroom Scanner Imagery - Flying Height 6,000m

Airborne Scanner Type	Focal Length (mm)	Swath Width (km)	Angular Coverage	Linear Array (pixels)	Pixel Size (_m)	Ground Pixel (m)	Pointing Along Track
HRSC-A	75	1	12°	5,272	7	0.24	±18.9°
HRSC-AX	151	3	29°	12,172	6.5	0.25	±20.5°
HRSC-AXW	47	10	79°	12,172	6.5	0.83	±20°
ADS40	63	7.3	64°	12,000	6.5	0.62	+28.4/-14.2°