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On the performance of photogrammetric scanners

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ABSTRACT

Scanners are necessary for retrieving digital information from analogue imagery. This paper discusses their geometric and radiometric performance, as input devices for softcopy photogrammetric systems. A classification and overview of scanners, their major technical characteristics, and their development over the last years are given. Some important scanner aspects, including illumination, dynamic range and quantisation bits, colour scanning, use of linear versus area CCDs, subsampling methods, scanning throughput and speed, and geometric and radiometric calibrations are presented. Thereby, different technological alternatives, their advantages and disadvantages are discussed.

1. INTRODUCTION

Scanners are an essential part of softcopy photogrammetric systems. The main use of scanners today is definitely in the digitisation of aerial images. Although there are developments aiming at the development of a digital aerial camera (using area, linear or 3-line CCDs), a digital substitute of the film-based photogrammetric aerial camera having its format and resolution, and with the spectral properties of film and its huge storage capacity, will not be easy. The whole production chain, the available hardware and software are currently geared towards processing of 23 x 23 cm frame aerial imagery. Even if digital cameras could be produced soon, there is a lot of time needed until appropriate and proven software for their data processing is developed, if the cameras are based on linear CCDs. Apart from that, today nobody will throw away the existing aerial cameras, or analytical plotters which need film.

The main applications that increase the need for digital aerial data are (i) orthoimage generation, (ii) automated aerial triangulation (AT) (iii) automated DTM generation, (iv) generation and update of digital feature databases, and (v) the integration of digital data, particularly DTMs, orthoimages and derived products, in GIS. A secondary application, which would remain even if digital aerial cameras were available, is the digitisation of existing films and image archives, to secure their existence and restoration. Photogrammetric film scanners are and in the near future will be even more used for producing digital aerial data. The author estimates that over 500 photogrammetric scanners should have been sold by now. Since every subsequent processing step builds upon the scanned imagery, the analysis of scanner accuracy and performance is of fundamental importance. Several problems that have been observed in digital photogrammetric procedures, like poor interior orientation and aerotriangulation results, as compared to results with analytical plotters, errors in DTMs (stripes etc.), and various radiometric artifacts and poor image quality, are occasionally (especially in the past) caused by insufficient geometric and radiometric scanner performance. Scanning, being the birth of the digital data, is probably the most critical procedure in the digital photogrammetric processing chain, and maybe one of the most underestimated ones. Unfortunately, many users take for granted that all photogrammetric scanners perform well. However, experiences with several scanners have shown that many problems of geometric and radiometric nature may occur.

An older overview of photogrammetric scanners is given in Baltsavias and Bill, 1994. Related work on test procedures for evaluation of photogrammetric film scanners is reported in Baltsavias, 1994, Baltsavias et al., 1997, Baltsavias and Kaeser, 1998, 1999, Bethel, 1994, 1995, Bolte et al., 1996, Gruen and Slater, 1983, Jakobsen and Gaffga, 1998, Koelbl and Bach, 1996, Koelbl, 1999, Leberl et al., 1992, Miller and Dam, 1994, Roos, 1993, Seywald et al., 1994, Seywald, 1996, 1997, Waegli, 1998. Out of the photogrammetric scanners that are available today, the ones that are used more extensively include: LH Systems DSW200/300, Vexcel VX 3000+/4000, Wehrli RM-1/2, ISM XL-10 (previously sold as OrthoVision by the firm XL-Vision), Zeiss/Intergraph PS1, Zeiss SCAI/Intergraph TD. However, for some of them published reports on their performance are not based on extensive tests. Fortunately, a significant increase of research activities has been observed after 1994, especially since 1996. Such publications include geometric and radiometric evaluation of the RM-1 (Bethel, 1994, 1995, Bolte et al., 1996, Jakobsen and Gaffga, 1998), DSW200 (Miller and Dam, 1994, Baltsavias et al., 1997), DSW300 (Baltsavias et al., 1998), Zeiss SCAI (Baltsavias and Kaeser, 1998), OrthoVision (Honkavaara et al., 1999, Baltsavias and Kaeser, 1999), radiometric characteristics of SCAI (Waegli, 1998, Baltsavias and Kaeser, 1999), image noise and sensitivity analysis of PS1, VX3000 and RM-1 (Koelbl and Bach, 1996), colour reproduction and image sharpness of various scanners (Koelbl, 1999), and limited tests on the geometric accuracy, MTF and noise level of VX3000 (Leberl et al., 1992, Seywald et al., 1994, Seywald, 1996) and on the geometric accuracy of PS1 (although the model was not explicitly named) (Seywald, 1996).

2. OVERVIEW AND MAJOR TECHNICAL CHARACTERISTICS

An overview of photogrammetric scanners is given in Table 1. The main scanners are listed on the first page of the table, while on the second one, not widely used scanners or ones not more in production are mentioned. Latter is done for reasons of completeness, but also because the market of older second-hand scanners, e.g. in USA, is not insignificant. The Kodak sensor of the SCAI has been used since autumn 1998. The old SCAI models were using a Thomson THX7821 3-linear colour CCD with 8640 elements, which was replaced by the Kodak sensor due to various problems (see Baltsavias and Kaeser, 1998). More details can be found for the DSW300 in Dam and Walker (1996), LHS (1999), the SCAI in Mehlo (1995), Vogelsang (1997) and Zeiss (1999), the VX scanners in Vexcel (1999), the XL-10 in ISM (1999), the RM-2 in CGI Systems (1999) and the UltraScan 5000 in Vexcel Imaging GmbH (1999). UltraScan 5000 has been announced recently and very little is known about its performance. Although the producing firm claims excellent results in all aspects, there are open questions, especially with respect to its dynamic range (claimed to be 3.6D with 4D maximum density) and geometric accuracy, since it uses for an on-line geometric calibration reference patterns on a "job-sheet" (film?) and stitching of overlapping scan swaths. In the sequel, only the five scanners on the first page of Table 1 and UltraScan will be treated. DSW300 and SCAI are tightly coupled to complete digital photogrammetric systems of the firms LHS, and Zeiss, Intergraph respectively, while XL-10 is coupled to ISM’s DIAP but also sold with Autometric’s Softplotter, and VX is used with Vexcel’s IDAS digital AT system. They can be divided into two groups based on price: the higher priced (LHS DSW300, Zeiss SCAI), and the lower priced ones (Vexcel VX, Wehrli’s RM-1/2, UltraScan), with XL-10 between these two groups.

Photogrammetric scanners are mainly produced by companies involved in photogrammetry, are flatbed and employ linear or area CCDs. With respect to sensors the following classification can be made:

- line sensors (used in the majority of scanners)
  Linear sensors with 2,048 to 10,200 pixels are used (although sometimes the number of active pixels is less). A clear tendency the last years, not only with photogrammetric scanners, is to use trilinear colour CCDs. XL-10 uses 3 optically butted trilinear CCDs to scan the whole image in one swath. A Time Delay and Integration (TDI) CCD, averaging 96 lines, with optional Peltier cooling is used in RM-1/2.

- area sensors
  They consist of CCD chips with a resolution ranging from 512 x 512 to 2000 x 2000 pixels. While sensors with 7000 x 9000 12 µm elements have been produced already in early 1995, use in scanners of CCDs with more than 4K x 4K pixels should not be expected in the near future.

All scanners employ a mechanical movement. Two cases can be distinguished:

- stationary stage/moving sensor (SCAI, VX, UltraScan)
- moving stage/stationary sensor (all other scanners)

The first alternative has the advantage that with roll film scanning the heavy roll film support and film do not have to move with the stage, reducing the danger of geometric inaccuracies, vibrations, and faster wear-out of the stage. It also leads, although not necessarily so, to smaller footprint scanners. The second case has the advantage that important and sensitive parts like sensor, optics, and illumination remain stable. Modifications of these components, especially the rapidly changing sensors, are also easier, without having to interfere or influence the mechanical positioning part. In addition, scanners with moving sensor and illumination only for the IFOV sometimes need to provide a separate mechanical movement for the illumination (and very well synchronised to the movement of the sensor). However, this aspect is not decisive in scanner evaluation and good scanners employing both mechanical movement alternatives have been produced. The stage/sensor movement can be in one or two directions. Movement in two directions can be realised by all type of sensors, movement in one direction only by optically butted linear CCDs. The disadvantage of the first case is that it requires high geometric accuracy in two directions. In addition, there may be clearly visible radiometric differences along the seam lines of neighbouring line swaths or area patches due to illumination instabilities and different sensor element response (not a serious problem with new generation scanners, see Baltsavias and Kaeser, 1998, Baltsavias et al., 1998). However, different sensor element response can also occur with optically butted CCDs, which in addition require very precise mounting and calibration, high bandwidth for the A/D converter (ADC) and electronics or slower scan speed (if one ADC is used) or alternatively more electronic components (if multiplexing of the signal from the CCDs is to be avoided), and very good image focusing and quality optics. The light source either illuminates the whole object to be scanned (VX) or only the portion that is scanned each time. Latter results in more stable and uniform illumination with higher power.

Photogrammetric scanners have a high geometric accuracy (nominally 2 - 4 µm RMS, real accuracy with some scanners may be worse), high geometric resolution (4 - 12.5 µm minimum pixel size), and sometimes photogrammetric software (e.g. interior orientation, image pyramid generation). Unix and Windows NT with standard interfaces dominate. For colour scanning, all but RM-1/2, use one scan pass. All use diffuse illumination, and most transfer the light from the source which is positioned far away from the sensor with fiber or liquid pipe optics. Typical current scan throughput rates are about 1 MB/s. A clear tendency is to use more quantisation bits (10-12) but this (a) does not necessarily mean major radiometric improvement, and (b) is anyway almost always reduced, for practical reasons, to 8-bit. The declared density range is sometimes incorrect (in many tests with various scanners the maximum density was 1.5-2.3D). Radiometric accuracy of 1-2 grey levels is specified, but in reality there are cases where much higher values and many artifacts occur, while dust, partly due to bad scanner design, is often one of the major problems. Radiometric quality of negatives, especially colour ones, may still be poor. Although radiometric aspects, which were

Table 1: Photogrammetric Scanners (for the newest status, especially on throughput, host computer and price, please consult a scanner vendor).

Brand / Model	LH Systems / DSW 300 [1]	Zeiss / SCAI [2]	ISM / XL-10 [3]	Vexcel Imaging Corp. / VX 4000HT [4]	Wehrli and Assoc. Inc. / RM-2 Rastermaster [5]
Mechanical movement	flatbed, moving stage	flatbed, stationary stage	flatbed, 1-D moving stage	vertical back-lit stage, moving sensor/optics invisible réseau	flatbed, moving stage
Sensor type	digital Kodak Megaplus 4.1I 2029x2044 CCD (960^2 - 1984^2 active)	Kodak trilinear colour CCD, 10200 pixels (5632 active)	Kodak trilinear colour CCDs, 3 optically butted 3 x 8,000 pixels	area CCD 1024 x 1024	Dalsa TDI linear CCD, 96 x 2048 pixels (1024 active) (option, Peltier cooling)
Scanning format x/y (mm)	265 / 265	275 / 250	254 / 254	508 / 254	250 / 250
Roll film width/length (mm/m) Motorised transport	35 - 241 / 152 manual, automatic	245 / 150 manual, automatic	241 manual, automatic	70 - 241 / 305 manual, automatic	No support
Scan pixel size (µm)	4 - 20 base resolution (and multiples of 2, other in software)	7 - 224 (in multiples of two, and 21 µm)	10 - 320 (in multiples of two)	7.5 - 210, continuously variable	10 - 80 or 12 - 96 (in multiples of two, other in software)
Radiometric resolution (bit) (internal/output)	10 / 8 or 10	10 / 8	10 / 8	8 / 8	12 / 8
Illumination	Xenon arc, liquid pipe optic, integrating sphere	Fan-cooled, halogen, 250 W, diffuse, fiber optic	daylight, fluorescent lamp	cold cathode, variable intensity	stabilised, high frequency, fluorescent, variable intensity
Colour scan passes RGB simultaneously?	1 no	1 yes	1 yes	1 no	3 no
Density range	3D	0 - 3D	0.1 - 2.4D	0.2 - 2D	0.2D-2.D
Geometric accuracy (µm)	2	2	< 3	4 - 5 or 1/3 of scan pixel size	< 4
Radiometric accuracy (DN)	1 - 2	±1.5		±2	
Scanning throughput [6] and/or speed	1.7 MB/s (12.5 µm, colour) 1.3 MB/s (12.5 µm, B/W) max. 100 mm/s	0.45 MB/s (14 µm, B/W) max. 4 MB/s (7 µm, colour) max. 38 mm/s	0.73 MB/s (20 µm, colour) 0.37 MB/s (20 µm, B/W) max. 35 mm/s	0.35 MB/s	1.2 MB/s (B/W) 0.5 MB/s (colour)
Host computer/ Interface	Sun Ultra 10, 30, 60 / fast 32-bit wide SCSI-2	UNIX SGI /fast SCSI-2 Pentium II, Windows NT/SCSI	Dual Pentium, Windows NT	Windows NT and X-Windows PCs required / RS 232 and 422	Pentium PC, Windows NT, PCI bus / SCSI
Approximate price [7] (US$)	145,000 / 125,000 with / without roll film	138,000 incl. roll film	95,000 incl. roll film	60,000 (for VX4000DT) excl. roll film	55,000

1 DSW 300, apart from enabling roll film scanning, is similar to the older DSW 200 with differences in scanning stage and electronics, and more precise servos.

2 Scanner also sold by Intergraph under the name PhotoScan TD. Differences to SCAI are the host computer (Intergraph TDZ 2000 with Pentium III, only Windows NT), softwaree JPEG compression and the scanner software. A ScanServer with dual processors and RAID disk subsystem is also offered.

3 Scanner previously produced by XL-Vision under the name OrthoVision; scanner division of XL-Vision bought in autumn 97 by ISM, which sells the scanner under the name XL-10.

4 VX4000DT is like VX 4000HT but with 768 x 494 CCD, lower scanning throughput, 8.5 - 120 µm scan pixel size. Option to scan 30 cm x 30 cm Russian satellite imagery (VX3000E).

5 RM-1 like RM-2 except: price 45,000 US$, throughput half of RM-2, 8-bit A/D converter, DOS.

6 In all scanners the throughput also depends on the host (which changes frequently), the scanner/host interface and the output image format.

7 Prices are approximate and depend among other factors on included options and whether the host computer is included in the price or not.

Table 1: Photogrammetric Scanners (continued).

Brand **Model**	**Zeiss/Intergraph** **PhotoScan 1** [8]	**Int'l Systemap Corp.** **DiSC** [8]	**Lenzar** **Lenzpro 2000** [8,9] **Multimedia**	**Vexcel Imaging GmbH** **UltraScan 5000**	**GeoSystem** **Delta-Scan** [10]
Mechanical movement	flatbed, moving stage	flatbed, stationary stage	Flatbed, moving stage	flatbed, stationary stage	flatbed, moving stage
Sensor type	Fairchild linear CCD, 2048 pixels	Kodak trilinear colour CCD, 8,000 pixels	area CCD 1000 x 1000 2000 x 2000 (option)	Trilinear colour CCD, 6000 pixels, Peltier cooling	Toshiba linear CCD, 2048 pixels (5000 pixels planned end 96)
Scanning format x/y (mm)	260 / 260	320 / 320	559 / 889 (refl.) 406 / 610 (transp.)	280 / 440 (5 µm base resolution) 330 / 440 (29 µm base resolution) 280 / 260 roll film	250 / 250 or 300 / 300
Roll film width (mm) **Motorised transport**	No support	Roll film support	16 - 305 manual, automatic	Roll film support (option)	No support
Scan pixel size (µm)	7.5 - 120 (in multiples of 2) 4 µm base resolution option	10, 20, 40	3 - 254 continuously variable	5 and 29 base resolution (other freely selectable, 2.5 - 2,500)	7 or 14 - 112 (in multiples of 2)
Radiometric resolution (bit) **(internal/output)**	10 / 8	10 / 8	10 / 10 or 8	12? / 16 or 8	8 / 8
Illumination	halogen, 100W, fiber optic	halogen, fiber optic	Halogen, fiber optic	stabilised illumination	6 halogen lamps(15 W each), diffuse
Colour scan passes **RGB simultaneously?**	3 no	1 (colour is optional) yes	1 no	1 yes	colour filter planned for 1997
Density range	0 - 2.7D		0.2 - 2.2D	3.6D, 4D maximum	0.2 - 2D
Geometric accuracy (µm)	< 2	5	< 3 or 0.1 pixel	2	3
Radiometric accuracy (DN)	±2		±2.5	< 1 (for 8 bits)	
Scanning throughput [6] **and/or speed**	variable, 2 MB/s (7.5 µm) 1 MB/s (15 µm)	0.25 - 2.5 Mpixel/s	1.05 or 1.3 MB/s (10 or 8-bit)	0.45/0.37 MB/sec (B/W, 10/20 µm) 0.83/0.74 MB/sec (colour, 10/20 µm)	0.13 MB/s
Host computer/ **Interface**	Intergraph UNIX workstation / custom interface	PC-DOS / SCSI-2	Sun, SGI / SCSI-2	Windows NT/ SCSI-2, Unix (without GUI)	PC 486 DX4-100, Pentium-133 (option)
Approximate price [7] **(US$)**	147,000	75,000	165,000	39,500	25,000 incl. PC 486 host and software

[8] Scanners not produced anymore.

[9] Lenzpro 2001 is identical to Lenzpro 2000 with the exception of the platen size, which is 305 x 305 mm, and its price (150,000 US$).

[10] Very little known system introduced in the ISPRS Congress in Vienna, July 1996, by the Ukranian company GeoSystem.

previously underestimated in favour of the geometric ones, were paid more attention to, further developments are needed to decrease the radiometric noise and extend the dynamic range beyond the current limits. Some scanners (RM-2, UltraScan use cooling with Peltier elements to reduce noise. Colour accuracy, and especially balance, is not a major issue yet, one reason being that many subsequent photogrammetric operations do not use colour, but in the opinion of the author should be paid more attention to, especially for colour orthoimages and use of colour in automated object extraction. Some of the problems in the radiometric and geometric performance, especially related to calibrations, were, and maybe still are, to a certain extent due to poor algorithms and software errors.

Software has improved and hardware LookUp Tables (LUTs) employing real-time transformations are provided. Automatic density control, a very important feature, especially for unattended roll film scanning, is not provided by any photogrammetric scanner. Some scanners provide an online visualisation in a prescan of the effects of changing the scanner parameter settings, and visualisation of the histogram. Others provide on-the-fly image processing, like sharpening, flipping and rotation of the image etc. Digital dodging and treatment of hot spots are sometimes integrated in the scanner functionality or offered by separate packages. “Standard” image formats like untiled TIFF or GEOTIFF can not be always scanned directly, although often (time- and disk- consuming) conversion routines are provided. Increased attention is paid to geometric and radiometric calibration, although the potential and the need to further decrease the size of the maximum, often local and systematic, geometric errors is not always recognised. Modules for colour balancing exist in most scanners. Parameters like illumination intensity, scan speed, exposure time can be freely selected in some scanners, depending also on the sensor type that is employed. Subsampling at any pixel size is offered by some scanners through software interpolation. Generally, there is a tendency to perform more and more functions in software. This provides flexibility, speed increase with each new computer generation and avoidance of expensive and complicated and/or error prone hardware. Roll film scanning has become an issue the last few years and thus almost all scanners (except RM 1/2) offer such possibility aiming at large agencies and private companies that do heavy production work. Important aspects and parameters of roll film scanning include: good radiometric performance to be able to scan negatives, automatic density control, automatic coarse and fine film detection (latter even in case of big gaps, and allowing a user defined area to be scanned, e.g. including film border information or not), automatic re-orientation of images (flipping etc.), user-defined selection of images to be scanned, i.e. skipping every second image, automatic detection of beginning and end of the film, proper design to avoid damaging the film, film width and length, reel diameter, and rewinding speed. A problem when scanning roll film is sometimes the necessity with hot spots to set the scan parameters such that the contrast is improved. This, however, leads to saturation of the fiducials. The fiducials generally (including positives) have the lowest or highest (sometimes even both) grey values as compared to the grey values of the image (excluding film border). This might be good for manual processing but for digital processing, including automatic interior orientation, their contrast, colour, size, and shape including coding could be optimised, without causing any problems for manual processing. This is one more case, like the too thin lines of the calibration grid plates, where developments in digital photogrammetry did not lead to an appropriate rethinking of the old analytical/analogue ways.

3. SUMMARY OF GEOMETRIC AND RADIOMETRIC TESTS

In the following, a summary of performed geometric and radiometric tests will be given. More details can be found in the respective references of Section 1. For each scanner multiple results are presented, using the same scanner model but different scanners, or the same scanner under varying conditions, in order to check variations in their performance. The same scanner was used only with RM-1, where scanner 2 was as scanner 1 but after changing the friction drive, and scanner 3 as

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scanner 2 but after cleaning some lubricant on the reference rod of the stage movement in x. In all tests, except the ones referring to the RM-1 and the OrthoVision 2, the same test patterns, scan options and analysis methods have been used. In all results, except for the RM-1, the individual results are mean values of up to 29 scans. The geometric errors have been estimated using an affine transformation between measured and reference values of calibrated glass plates having an accuracy of 1 - 2 µm and a grid spacing of 2 or 10 mm, using all grid points as control. The pixel coordinates were measured automatically, e.g. with Least Squares Template Matching. When only 4 or 8 points are used as control (as with the image fiducials), the geometric errors increase.

Table 2: Mean geometric errors of various scanner models and scanners.

Scanner model / scanner	RMS x (µm)	RMS y (µm)	Max. absolute x (µm)	Max. absolute y (µm)
DSW200 / 1	3.4	5.1	9.7	16.6
DSW200 / 2	1.8	2.5	6.8	8.7
DSW300 / 1	1.8	1.4	7.0	5.3
DSW300 / 2	1.3	1.4	5.3	5.2
SCAI / 1	2.2	2.1	6.1	7.4
SCAI / 2	2.3	2.1	8.1	6.6
OrthoVision / 1	7.5	7.0	26.8	17.9
OrthoVision / 2	1.3	2.2 [1]	4.1	7.6
RM-1 / 1	4.7		11.7 [2]	
RM-1 / 2	6.8		22.6 [2]	
RM-1 / 3	3.3			

[1] In the first 6 scans, the RMS in scan (y) direction was higher, between 3.2 and 4.3 µm, and the maximum absolute errors too. Then, a second scanner calibration led to improved results.
[2] Estimated from a plot of the residuals.

As it can be seen from Table 2, the differences between scanner models are significant. Differences between scanners of the same model or the same scanner under different conditions can also be substantial, as the results of DSW200, OrthoVision and RM-1 reveal. Newer, more mature scanners like the DSW300 and the SCAI show a better homogeneity.
Table 3 gives a summary regarding the dynamic range and the noise (standard deviation of homogeneous areas). In all cases, except of DSW200 / 1 the results are mean values of multiple scans, sometimes in colour. In all tests, a Kodak CAT grey level wedge on film with 21 densities from 0.05D to 3.05D and 0.15D density steps was used. It is unknown whether this grey level wedge was calibrated for the OrthoVision / 2 and the RM-1 tests. For OrthoVision / 2 only the densities 0.05D to 1.7D were checked. In this test, the noise is given as % of deviation from the average grey value of each density. 33 scans were performed with two different program versions. For both program versions the low densities (0.05-0.35D) showed a deviation of 2%-6% from the average value. For the higher densities (1.4D-1.7D), the deviation was 6%-14% for the old program and 8%-17% for the new one. The average deviation for all densities was ca. 6% and 7% with the old and the new programs, respectively. Although the average grey values of each density were not published, it is obvious that the low densities have too high noise. All tests of Table 3 are from different scanners except DSW200 / 2 and / 3, DSW300 / 1 and / 2, and SCAI / 3 and / 4, which were identical but using different LUTs. SCAI / 3 was the same scanner as SCAI / 2 but with the new Kodak sensor, instead the Thomson linear CCD. In SCAI / 1 and SCAI / 3 scans with both 7 and 14 µm scan pixel size, the low densities appeared with a lot of corn, which increased the noise and decreased the dynamic range. This corn really exists in the film, but it is peculiar that it did not

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appear in the SCAI / 2 scans or the ones of the other scanners (with the exception of OrthoVision / 1, but to a lesser extent). All DSW scanners used the Kodak KFA 2000 x 2000 pixel sensor, but however different versions of it (at least 3 different ones). The results of DSW 200 /2 and / 3 were very atypical among the four DSW200 scanners that we have tested, but are listed here, to indicate the differences that can occur. Apart from the sensor, some differences among the same scanner models were due to software changes, especially regarding the radiometric calibration. In most of the tests, the lowest density (0.05D) was to a large extent saturated but not totally. The performance (noise, dynamic range) was generally better for the R, then B/W, then G, and then the B channel, whereby the difference between the first three was often small. The average grey values of each density and the linearity were similar for the R,G,B channels, with the exception of OrthoVision 1. Use of a logarithmic LUT increases the maximum detectable density and the dynamic range, but at the expense of losing grey values in the bright areas and increasing the noise significantly.

Table 3: Radiometric performance of various scanner models and scanners.

Scanner model / scanner	Dynamic range	Mean noise (DN)	Scan pixel size (μm)	Type of used LUT
DSW200 / 1	0.05D-1.9D	1.1	12.5	linear
DSW200 / 2	0.05D-1.44D / 0.05D-1.75D	2.9 / 1.9	12.5 / 25	linear
DSW200 / 3	0.05D-2.2D	1.9	12.5	logarithmic
DSW300 / 1	0.05D - 1.95D	1.2 / 0.9	12.5 / 25	linear
DSW300 / 2	0.05D-2.16D	4.3	12.5	logarithmic
SCAI / 1	0.2D-1.28D / 0.35D-1.75D	2.3 / 2	7 / 14	linear
SCAI / 2	0.05D-1.75D / 0.05D-1.95D	1.3 / 1.1	7 / 14	linear
SCAI / 3	0.2D-1.58D / 0.2D - 1.75D	2.2 / 2	7 / 14	linear
SCAI / 4	0.2D-1.66D / 0.2D-1.83D	3.8 / 3.2	7 / 14	logarithmic
OrthoVision / 1	0.2D-1.44D	1.6 [1]	10	linear
OrthoVision / 2	-	6%-7% of mean grey value	20	linear?
RM-1	0.05D - 1.5D	ca. 1.5	12 ?	linear

[1] In the 0.2D to 1.7D range that was unsaturated, the mean noise was 2.5 grey values.

4. SCANNER ASPECTS AND TECHNOLOGICAL ALTERNATIVES

Different scanner aspects and necessary requirements for photogrammetric tasks, as well as various implementation options and technological alternatives are presented below.

4.1. Illumination

The illumination must be high in order to achieve a better radiometric quality and higher signal-to-noise ratio (SNR). This is due to the high scan speed and the light intensity loss in the parts of the

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optical path (e.g. in a concrete scanner with complex optical path only the equivalent of 1/ 4000 of the illumination reaches the CCD surface). The higher the scan speed, the higher the illumination should be, since the integration[1] (exposure) time is reduced. On the other hand, high power light sources generate heat, which must be treated appropriately, in order to minimise the influence on the mechanical parts and the electronics (cooling, use of cold light, placement of the light source away from the sensitive scanner parts and use of e.g. fiber optics for light transfer). The spectral properties of the light source and its temporal stability (related also to the power supply stability) are important factors. The spectral properties of the light should also "fit" to the spectral properties of the filters (for an example see Jakobsen and Gaffga, 1998) and the spectral sensitivity of the sensor, such that an optimised colour CCD response is achieved. In some scanners the light source has variable intensity in order to obtain balanced colour scanning: highest intensity used for blue channel, lowest for red. Alternatively, instead of increasing the illumination, the integration time could be increased. Note that variable illumination/integration time can/should not be used with trilinear CCDs (see an explanation in Section 2.3). With both increase of exposure time or illumination intensity, care must be taken to avoid saturation of low film densities and blooming. Some sensors provide anti-blooming devices, but for area CCDs these result in reduction of the fill factor (photosensitive area of the sensor element), e.g. for full-frame transfer CCDs from 100% to 70%, thus resulting in lower sensitivity. The illumination should be uniform over the whole field of view of the sensor and preferably diffuse (not directed). Diffuse illumination can be accomplished by use of fluorescent lamps, diffuser plates in front of the light source, diffuse reflectors, and integrating spheres. Light sources mostly include halogen lamps (often over 100 W), while xenon and fluorescent lamps are also being used.

4.2. Quantisation bits and dynamic range

Some scanners have ADCs with 10 - 12 bit quantisation, but since almost all software and hardware supports only 8-bit/pixel and to avoid problems with excessive amount of data and image display, the data is usually reduced to 8-bit. The user can often influence this conversion through a LUT (usually linear, sometimes logarithmic). Assuming that for aerial images a maximum density of 2.5D (B/ W) to 3.5D (colour) is required, theoretically a quantisation with 316 ($10^{2.5}$) and 3,162 ($10^{3.5}$) steps (grey values) would be sufficient. Such a statement is, however, very misleading. It is unfortunately used even by some manufacturers that use the bits of the ADC to give the specification for the maximum density of the scanner, e.g. if using 10-bit (=1024) grey values, the maximum density is given as 3D (=log(1023)). Stretching this naive belief, one could claim that by using e.g. a 16-bit ADC (and leaving sensor and overall noise the same), a maximum density of 4.8D could be achieved! Thus, the 10-12 bit are sometimes used just as a selling argument but they do not necessarily reflect an essential quality difference to 8-bit quantisation.

The number of required bits depends on the noise level and the input signal range (i.e. possible range of electrons generated in each sensor element). For a given input signal range, the number of necessary bits mainly depends on the noise level of the system. To allow a reasonable discrimination between neighbouring integer grey levels, we propose that the noise (standard deviation) should be less than half grey level, or the opposite, the quantisation step should not be finer than twice the noise. One could argue that this is a too strict criterion, but at least the quantisation step should not be finer than the noise level. Since the noise varies with density, the lowest noise (usually for the highest densities, but densities should not be saturated!) should be taken into account. If the lowest noise with an 8-bit digitisation is e.g. 0.5 grey levels (a realistic

[1] Integration and exposure time are not necessarily identical. This can make a difference, especially for linear CCDs. For scan pixel sizes, other than the base (optical) resolution, the pixel size in the scan direction (y) depends on scan speed and exposure time. The integration time, i.e. the effective exposure time, may however be smaller, resulting in a smaller effective pixel size in y and systematic loss of film information.

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example), then the quantisation step should be 2 ∗ 0.5 (i.e. 8-bit suffice) or 0.5 (i.e. 9-bit are needed) according to the two criteria listed above. Quantisation with more bits than that can have some advantages. It reduces the quantisation noise (theoretically, ca. 0.3 of quantisation step), i.e. an image scanned with 12-bit and then scaled to 8-bit has 16 times less quantisation noise. Another advantage is that the effective number of bits decreases with increasing signal frequency input to the ADC, e.g. with 10MHz frequency the effective number of bits of a 10-bit ADC can be 6 bits and 3 bits less than that with 1 MHz. Thus, the rule of thumb "buy 1-2 bits more than what you need" has a validity, especially for scanners with fast ADCs. With more bits, finer digital radiometric corrections (e.g. coming from the sensor normalisation, i.e. enforcement of uniform response of all sensor elements), if they are estimated with the necessary accuracy, can be applied. However, it is better to apply such corrections to the analogue signal before A/D conversion, i.e. improve the signal before stretching it. A final advantage could be that through an appropriate reduction of 10-12 bit to 8-bit a better signal could be obtained. Very little investigations have been performed on such an appropriate reduction. Diehl, 1992 for example proposed to use quantisation steps such that the noise level is the same for all densities. Another criterion could be the following. Based on the image histogram acquired by a prescan, the quantisation steps could be selected such that the noise is minimised in the most important regions, e.g. there where many grey values occur. Even nonequidistant quantisation steps could be used, allowing a denser sampling (i.e. higher contrast) in the important regions. This, however, could mean different treatment (and radiometric differences) between overlapping images.

Alternatively, for a given noise level more bits can be used, if the input signal range increases appropriately. Assuming that integration time is long enough to just avoid saturation and that, apart from the shot noise, the other noise sources are grey level independent (i.e. additive), then for a given noise level a finer quantisation makes sense, only if the value range of the original input signal also increases, i.e. the maximum charge storage capacity of the sensor elements increases by e.g. using larger sensor elements. As an example, consider a CCD with 50,000 electrons maximum charge storage capacity and 100 electrons noise, and quantisation in 250 grey levels, i.e. one grey level corresponds to 200 electrons. To meaningfully increase the quantisation levels to 1000, would require a maximum charge storage capacity of 200,000 electrons.

There is no clear-cut definition of the maximum detectable density. In Baltsavias et al., 1998 reasonable rules for its definition and methods for its detection are given, based on the minimum and maximum detectable density. The minimum detectable density is not necessarily 0D. Many scanners have problems with very low densities, i.e. are saturated for densities less than 0.2D, which may occur with aerial films and do occur with glass plates used for calibration purposes. To increase the maximum detectable density, the signal must be increased and the noise decreased. The number of quantisation bits play thereby a role, but a minor one, and only as long as the noise level is less than 0.5 quantisation level. To increase the signal, the following can be done: increase of illumination power, longer integration time, better focusing of the illumination on each sensor element (e.g. by use of microlenses), use of CCDs with high quantum efficiency (e.g. thinned and back illuminated), increase of maximum charge storage capacity, i.e. use of larger pixels. Noise can be reduced by averaging of multiple scans, slow scan, cooling and stabilised environmental conditions, and appropriate choice of sensor and electronics (avoidance of multiplexed read-out, good isolation of neighbouring sensor elements and CCD lines (no optical and electronic crosstalk), avoidance of blooming and smear, low output amplifier noise, short and isolated cables from sensor to ADC etc.). However, even with almost perfect sensors, the noise due to film granularity still remains.

Diehl, 1990 discusses the effect of granularity on the radiometric noise of scanned images and states that for 7.5 μm pixel size the radiometric noise due to granularity can amount to more than 20% of the signal. For typical films, this noise (RMS granularity) is about 0.008-0.033D for density 1D and

48 µm round aperture (corresponds to a 38 µm quadratic one). Using the empirical formula (Diehl, 1992)

$$RMS(D) = RMS(\text{for } 1D) * (D+1.5)/2.5 \ ,$$

the RMS for 2.5D would be 0.013-0.053D and for 12.5 µm aperture (pixel size) ca. 3 times more (0.039-0.161D). Latter values are theoretical and a bit pessimistic (relation between RMS and pixel size is not linear, due to correlation of the samples, i.e. film grains) but still show that the film itself might ultimately be the main limiting factor in radiometric scanner performance and higher dynamic range (and an argument in favour of digital aerial cameras!). Another report which compares film and electronic image sensors with respect to sensitivity, linearity, noise, signal to noise ratio, dynamic range, MTF and image sharpness is given by Dierickx (1999). A possible way of improving the radiometric and colour performance of the scans may be to predefine optimal scan parameters and LUTs for different common B/W and colour films, which are made available to the user.

4.3. Colour scanning

Colour scanning can be implemented by:

- primary or complementary colour filters spatially multiplexed on the sensor elements (1-chip colour linear or area CCD, not used in photogrammetric scanners)
- use of 3-chip CCDs (linear or area arrays with RGB filters usually on the sensor elements ; used in SCAI, XL-10, UltraScan)
- use of filters (RGB and neutral) sequentially for each IFOV (can be implemented only for area CCDs ; used in DSW300 and VX ; scan in B/W performed by selecting one spectral channel or a combination thereof)
- use of filters sequentially for the whole image (can be used for both linear and area CCDs, but for latter it does not make sense ; used in RM-1/2)
- very fast, computer-controlled LCD filters (new technology, preliminary results not very good, however fast developments expected)
- use of three colour LEDs (single pass scan, advancement of older technology using white lamp and switchable colour filters, use of an RGB LED strobe with a single CCD, up to now used in DTP scanners only, e.g. Nikon and Cannon)

The first three and the last two approaches require one scan, while the fourth one three. The first approach leads to reduced spatial resolution and sometimes pattern noise in the image, and it lacks the ability to colour balance (blue in particular, where CCDs have a much lower sensitivity). The second one is advocated as the best approach but is also the most expensive. In reality, use of 3 area CCDs does not bring any major advantages in comparison to the third case, except the possible avoidance of vibrations that may cause colour misregistration. On the other hand, it leads to less illumination for each colour channel, plus a change of filters (in order to optimise them), if they lie on the sensor elements as is the case with trilinear CCDs, is impossible. Filters on the sensor elements are not of top quality and their responsivity tolerances are quite high. In addition, some companies optimise these filters for applications other than film scanning (e.g. the Kodak KLI-10203 line sensors have filters optimised for reflective scanning, while the remaining line sensors have filters optimised for colour negative films). Trilinear CCDs may also have a disadvantage that since the pixel size in scan direction (except for the base resolution) is given by (scan speed x exposure time), the exposure time can not be changed for each channel to achieve a better colour balance. This is solved by some trilinear CCDs, like the ones from Kodak, by allowing

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independent electronic exposure control for each channel. Colour balance can be also achieved by analogue or digital gains but this increases the noise for the blue channel, and does not improve its SNR. 3-chip CCDs also do not allow variable illumination, but this could be partially circumvented by using directly before each chip neutral filters absorbing light at different degrees, thus having a constant but different illumination intensity for each channel. For 3-chip line and area CCDs, if the signal is multiplexed and one ADC is used, then electronic noise (echoes) can occur. Both third and fourth cases allow a better quality colour balance than the first two by varying integration time and/or illumination intensity. 3-chip approaches might also lead to geometric problems like slight differences in focal distance and pixel size from chip to chip, chips not lying on one focal plane, registration errors between the three sensors (e.g. for linear CCDs the lines must be parallel with distance an integer multiple of the minimum pixel size, and no offset along the CCD line direction). An example of a trilinear CCD where co-registration in CCD direction was excellent but constant errors between CCD lines have been observed is given in Baltsavias and Kaeser, 1998. With the third approach the danger of colour misregistration due to mechanical positioning errors is less than the fourth one. Note that misregistration between colour channels can also be caused by the lens and other components of the optical path (platen, mirrors) but also electronic problems (see random y-shift of some DSW200 sensor models in Baltsavias et al., 1997). With respect to speed, the second case is a bit faster than the third and this than the fourth one. However, the scan time is mainly due to setting and optimisation of scan parameters, transfer to host, saving on disk and display/visual control. Thus, all cases may lead more or less to similar throughput rates.
A rather new technological alternative is the use of liquid crystal technology that allows a fast electronic switching and selection of filters centred at freely selected wavelengths. As far as the author knows, for the moment they have certain limitations (low peak transmission, same bandpass width around the center wavelength) and first experiences with the CCDs of ADAM Technology's PROMAP analytical plotter were not positive (personal communication). However, these developments should be followed since they might permit a filter adaptation to varying film spectral properties and a quasi-simultaneous colour scan with one linear CCD.
Use of RGB LEDs offers certain advantages. Technological developments have improved the brightness of blue and green LEDs, only one CCD is needed, power consumption is greatly reduced, independent gain control is possible, while long life/high reliability, good colour purity, shock and vibration resistance, fast switch speed, small size, and low heat dissipation add to their attractiveness.

4.4. Linear versus area CCDs

Among the sensors, the most widely used are linear CCDs. Currently, there are various linear CCDs with up to 12,000 elements and trilinear CCDs with up to 10,000 elements (Kodak seems to be preparing a 14,000 element one). Main manufacturers include Kodak, EG&G, Fairchild, Dalsa, Toshiba, Matsushita, Thomson and Philips. With current technology, multiple linear CCDs can be optically butted to result in a line with sufficient elements for a high resolution scan of 10 µm or less in one swath. However, optical butting requires very precise CCD mounting such that one line on one focal plane is created and the overlap between the lines is an integer multiple of the minimum pixel size. 3-chip colour sensors are much easier and cheaper to fabricate with linear than with area CCDs but again their geometric mounting must be precise and their ability to colour balance, as mentioned above, is limited. In comparison to area CCDs, radiometric differences along the seam lines of the partial scans (swaths and tiles respectively), if they occur, they do so at less positions. Normalisation of the sensor elements is easier, but if errors occur, they influence much more pixels than in area CCDs. In addition, noise is more correlated, resulting e.g. in vertical stripes. Treatment of the two directions is unequal (e.g. lines parallel to the CCD are smoothed and loose contrast due to high scan speed. For scan pixel sizes, larger than the minimum one, the

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effective pixel size in scan direction is generally smaller than the nominal one, and in some cases significantly less, thus resulting in loss of image information, see Baltsavias and Kaeser, 1998). Servo-controlled changes in the scan speed may cause, through respective changes of the integration time, higher or lower grey values (Jakobsen and Gaffga, 1998). Linear CCDs suffer less from electronic noise (smearing etc.) than area CCDs. Another reason for their lower noise is the fact that they have fewer clock signals, so the latter can be better isolated from the video. Antiblooming drains, which are important with high contrast objects, are easier to implement with linear CCDs. They have adjustable integration time while area CCDs are usually locked to the RS170 or CCIR specifications (33 or 40 ms respectively), although area CCDs with electronic or mechanical shutters or strobe lights can also control the integration time. Linear CCDs have higher speed (pixel rates of up to 200 MHz) but this characteristic is irrelevant for the current scan throughput rates or even negative (see Section 2.5). Normal operation of linear CCDs results in much shorter integration times than that of area CCDs (typically 1-2 ms), and therefore a much higher light intensity is required. Due to their long length (especially with optically butted linear CCDs), they place special demands upon lenses and associated optics. They usually have smaller pixel size than the area CCDs, thus usually smaller maximum charge storage capacity. Linear CCDs can not work in the stop-and-go mode, i.e. either a large internal image buffer is needed, or the data must be continuously transferred to host, but this is not a critical drawback. Summarising, apart from possibly less electronic noise, slightly higher scan rates, and under certain conditions better colour co-registration and possibility to scan in one swath, it seems that their disadvantages are more. In practise, good scanners have been and can be manufactured with both area and linear CCDs. Regarding TDI technology, although in theory it should lead to higher SNR and be particularly suitable for high speed or low light applications, investigations with the RM-1 (Bolte et al., 1996) showed that its density range is only 1.5D. In addition, when scanning a uniform surface the average of its 96 lines for each sensor element showed clear peaks, indicating that for some sensor elements systematic radiometric deviations occur (Jakobsen and Gaffga, 1998).
Area CCDs with a resolution of more than 4K x 4K are currently impractical for various reasons. With increasing number of elements the costs rise rapidly, geometric problems like deviation of the sensor from a plane are more likely, electronic noise is increasing, errors due to nonplanarity of the scanner glass plates (assuming same imaging scale factor) increase due to the larger opening angle, geometric and radiometric fit of the scanned image tiles to form a whole image gets more difficult (increasing effects of lens distortion, light fall-off and scale (pixel size) errors, normalisation of sensor element response more difficult), and the danger of blemishes (pixels whose grey values differ a lot from the grey values of their neighbours) increases. In this respect, the software option offered by DSW300 to use in scanning only 1/4 of the sensor area may be positive. The only advantages of large CCDs are a slightly faster scanning and in case radiometric differences between image tiles do occur, such problems occur in less positions. Summarising, even 500 x 500 CCDs could be used, while 2K x 2K resolutions seem fully sufficient. An advantage of area CCDs, which is not currently used in scanners, is the possibility to average multiple frames, thus reducing the noise. Area CCDs have usually larger pixel sizes than the linear ones. (e.g. for the Kodak sensors used in scanners, area CCDs have 9 µm pixel sizes (up to 24 µm available), while linear ones 7 µm, i.e. 65% larger pixel area). The pixel area is directly proportional to the responsivity of the sensor. A larger area leads to higher dynamic range due to higher charge storage capacity and saturation level and, keeping the other conditions same, higher frame rates. For same number of sensor pixels and scan area, it also leads to larger focal lengths in comparison to smaller pixel size, which results in more uniform imaging and less vignetting. With full-frame transfer CCDs, which are used in scanners, the gate electrodes are semitransparent in the visible range, thus reflecting some of the incoming light and reducing the sensor sensitivity. This can be improved by using thinned, back-illuminated sensors. However, these are more expensive and require cooling to reduce the excess noise. A new, cheaper alternative has been introduced by Kodak (the so-called Blue Plus sensors),

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making use of transparent gate electrodes. This results in much improved quantum efficiency in the blue and green range, e.g. for 450 nm the quantum increases from 10% to 40%.
Alternative technologies could/should be examined. CMOS sensors currently provide a lower resolution than CCDs and up to now lower image quality, due to higher noise and small fill factor (15%-40%). However, they have various advantages: no saturation and blooming, higher dynamic range, on-chip processing (ADC, automatic gain control etc.), fast read-out, less power requirements, random pixel access, high colour constancy, framegrabber or complex drivers and timers are not required. They do not allow as CCDs variable and long exposure times but this can be circumvented by fast acquisition and averaging of multiple frames. Some CMOS sensors employ a logarithmic conversion from light energy to voltage, leading to a huge dynamic range of 120dB, making them ideal for objects with high dynamic range. The developments with CMOS sensors are very rapid the last years with continuously improving performance and resolution up to 2000 x 2000 pixels. Another ad CID sensors have high dynamic range, superior anti-blooming as compared to CCDs, allow nondestructive read-out and adaptive exposure control, and random pixel access. The IEEE-1394 standard implemented by an increasing number of CCDs allows full camera control from a computer and direct digital image transfer from camera to computer without the need of a framegrabber with a transfer rate of 200Mb/s (expected to triple the next few years).

4.5. Scanning throughput and speed

High speed is sometimes overestimated by both users and manufacturers. First of all, the total time for a successful scan should be taken into account. This is composed of prescan and setting of scan parameters, mechanical scan time and integration time (for linear CCDs integration time takes place in parallel), transfer of data to ADC, AD conversion and other electronic processing, transfer to host, writing on disk, operations like subsampling (if done in software, usually only for area CCDs), mosaicking, image formatting and re-orientation, display, visual control and eventually reselection of scan parameters and rescan, and optionally compression. Currently, interactive operations take quite some time and these are not included in the scan times given by manufacturers, which are given for the scanner native image format (usually faster than other formats) and without image reorientation. From the remaining processes, the bottleneck currently lies rather in data transfer and disk save. Technological developments will soon shift the bottleneck to other factors like, bandwidth of electronics, maximum scan speed, and especially minimum integration time. However, geometric and radiometric quality should not be sacrificed in the name of faster scanning. Integration time must be long enough for high dynamic range and SNR, colour balance might require much slower scan for the blue channel, high bandwidth A/D conversion decreases the number of effective bits, too high scan speed can cause vibrations, while scanner stage settling with area CCDs should be long enough for accurate geometric positioning. As an example, with linear CCDs reasonable results can be achieved by using an integration time of 4 ms, i.e. 250 scan lines/s. For a 10,000 pixels long CCD this would require an A/D conversion with 2.5MHz, while the remaining operations can (or will soon be able to) be performed at this rate. This means that a B/W aerial image could be scanned with 14 µm (270 MB) in 1.8 min. This is good enough and a very small fraction of the time spent for further photogrammetric processing, where much more time can get lost due to poor scanning results. Even if the scanning time could be 10 times lower, i.e. 11 s, the gain would be minimal in comparison to image quality degradations.
Further advantages of slower scan speed include: slower scanning mechanism means simpler, cheaper and stabler components; longer integration time means no need for powerful illumination which is expensive and generates a lot of heat, influencing the optomechanical and electronic parts, and requiring mechanisms for controlling the heat dissipation; the smear in the scanning direction would decrease; noise like lag which is typical of high speed imagers could be decreased; the bandwidth and the price of the electronics could be decreased while more operations could be

applied in "real-time" using hardware processing capabilities; large internal image buffers that are sometimes required to store the data before transferring it to the host would not be necessary since the low data rate could be accommodated by the host/scanner interface or a small image buffer.

4.6. Optimal scan pixel size

There is no clear answer to the question of optimal scan pixel size, and no agreement exists among scientists and users, or scanner manufacturers. Decisive factors as to what is the optimal pixel size are the applications of the user, and the amount of data that can be handled. Although there are rapid developments in computer technology, large data sets resulting from high scanning resolution can still not be handled conveniently or not at all (e.g. for big blocks in AT). Today, the limit for practical handling and interactive work seems to be around 10 - 15 µm. Here, the topic of the optimal scan pixel size will be addressed from a practical and realistic point of view. Many empirical tests have proven that for certain tasks like DTM and orthoimage generation, and AT, good results can be achieved with 25 - 30 µm, while use of half the pixel size for DTM generation and AT leads to small gains, often only in the 10-20% range. For interpretation of fine details and mapping, and measurement of small signalised points, finer resolutions, in the 10 - 15 µm range, are used. Finally, to preserve the resolution of the original film and using 60-30 lp/mm film resolution and the Kell factor, scan pixel sizes of 6 - 12 µm would be needed.
Some investigations on the effect of pixel size (and also compression) on the metric quality of digitised images is given in Jaakkola and Orava (1994).

4.7. Subsampling

Different resolutions can be achieved by the following means:

- Optical zoom
  This also requires refocussing each time the resolution changes. It can be implemented either with very stable and precise optomechanical systems or by systems that can be self-calibrated, e.g. by means of a réseau (implemented in Vexcel VX). To avoid interference with the image the réseau is scanned separately from the image by using two illuminations, for each of which only the réseau or the image is visible. Spacing of the crosses must be sufficient and adapted to the smallest sensor IFOV, while lines should be wide enough to permit accurate measurements even with coarse pixel sizes.
- Electronic zoom (RM-1/2, SCAI, XL-10)
  Thereby, scans are always performed with the base resolution but the signal is low-pass filtered and resampled in both (area CCDs) or one (linear CCDs) direction. In the latter case, subsampling in scanning direction is accomplished by increasing the scan speed by the same factor as the resolution decreases. This type of subsampling of linear CCDs leads to the problems mentioned in Section 2.4. Some area CCDs also provide binning capabilities that allow direct scanning with coarser pixel sizes, usually only by a factor of two. However, this hardware binning may lead to saturation.
- Software zoom (DSW300)
  The scan is always performed in the base resolution and the image is subsequently subsampled to lower resolutions using software on the host computer.
- Use of dual or multiple lenses
  This technology has been used in DTP scanners with linear sensors. By using e.g. two lenses, the line can be projected on a varying film area, resulting in smaller scan pixel sizes at the expense of the scan swath width.

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- Hybrid approaches (UltraScan)
  UltraScan has two base resolutions of 5 and 29 µm, using optical zoom. Through electronic zoom some so-called native resolutions can be generated, e.g. from 5 µm, pixel sizes of 10, 20, 40 etc. µm. Using software interpolation, any pixel size can be generated. In addition, the scanner can oversample, option with questionable utility for film scanning. Thus, a pixel size of 2.5 µm can be generated, while e.g. a pixel size of 20 µm can be generated by scanning with 5 µm and electronic zoom, or by scanning with 29 µm and software interpolation.

Optical zoom using stable and precise optomechanical systems is faster than software zoom but also more expensive, and requires more careful calibration. Electronic zoom is simple, fast, and does not require complicated calibration or expensive optomechanical parts, but for linear CCDs requires accurate setting of the scan speed and leads to a smearing of horizontal lines and different resolution in horizontal and vertical direction.

4.8. Photogrammetric functions

Some photogrammetric scanners offer the possibility to perform certain photogrammetric tasks like measurement of fiducials (SCAI and DSW300 even fully automatic), and generation of image pyramids. The measurement of the fiducials does not have to be a part of the scanner software, i.e. it can be performed later by photogrammetric software, but some users find this scanner software option convenient. A possible use of the fiducial measurement during scanning, is when scanning only sections of the image.

4.9. Geometric and radiometric calibration

Geometric and radiometric calibration procedures are usually applied by all scanners but in some cases they are incomplete, slow, not performed often enough or with sufficient accuracy, and (referring to the geometric ones) do not cover the whole possible scan area. Robustness in presence of dust is not guaranteed, and manual measurements are sometimes required or allowed. Photogrammetric scanners are usually well calibrated with respect to geometry but some of them exhibit significant radiometric problems like stripes, visible interlacing of horizontal lines, echoes due to multiplexing, unsharpening or echoes due optical and electronic cross-talk, other noise patterns, saturation of grey levels (especially in images with high contrast), while problems with radiometric differences between neighbouring swaths have been reduced. In particular, the normalisation of the sensor element response and its robustness with respect to dust should be improved and performed more often. Algorithmic methods to detect and eliminate dust have been implemented in some scanners, but poorly, thus, leading to wrong corrections and introduction of bright "electronic" dust. Even with the most accurate scanners, the geometry could/should be improved. Investigations (Baltsavias and Kaeser, 1998, Baltsavias et al., 1998, Jakobsen and Gaffga, 1998) have shown that large local systematic still exist. These errors, even if they are in the range of 6 - 8 µm, do not permit full exploitation of the accuracy potential of digital photogrammetric procedures. In some cases, the major part of these errors is stable, so it is easy to correct them through calibration.
Calibration and test procedures can and should also be applied by the user periodically. For such calibration procedures software and test patterns are usually supplied by the scanner manufacturers but this is done only for some aspects of the geometric calibration. Manufacturers should also clearly indicate when and how often calibrations should be performed. The need to perform regularly the calibrations and keep the scanner in proper environmental and maintenance conditions should always be stressed to the customers. In addition, manufacturers should provide the users with all relevant technical specifications of the scanner and with error specifications, e.g. tolerances

for the RMS, maximum errors etc. that can occur in different cases. A quality assurance certificate delivered together with the scanner is a kind of guarantee for the customer, a measure against which he can compare the scanner performance after installation and periodic checks, and a useful document for the quality certification of his own production company.

5. CONCLUSIONS

The number of photogrammetric scanners, with the exception of the UltraScan, seems to have stabilised since 1996 with five main products sharing currently the market. No major newcomers should be expected, except maybe in the lower end of the spectrum. Since 1996 there were quite some changes and improvements with DSW300, SCAI and RM-2. Generally the scanner performance and functionality has improved, while their price has stabilised, unfortunately at still high levels. Major changes include roll film scanning, better software, faster scan throughput and some improvements in their radiometric quality. One can talk of second generation film scanners with more functionality, better performance, and less costs in comparison to their predecessors. Future developments should be expected in the sensors (more pixels, better radiometric performance), quantisation with more bits, faster scans, and extended software functionality (especially with respect to automation, speed and ease-of-use, e.g. automatic density control, on-line display in overview (prescan) image of effect of radiometric parameter settings, automatic film detection in roll film scanning, image processing like edge and contrast enhancement, digital dodging etc.). The radiometric performance and the dynamic range should be improved by a careful selection of sensor and electronics (especially large pixel size and blue-enhanced sensors), intelligent calibration but also slower scans, frame averaging and cooling. An optimal setting of the LUT and reduction from more to 8-bits will also lead to a better quality image.

Scanners are extremely sensitive and complex instruments, and a very high number of errors due to hardware, firmware or software parts may occur. Thus, topics like proper calibration, environmental and maintenance conditions, as well as careful and simple design, good quality components including those from third parties, and intelligent and robust image processing software are a must. Various scanner aspects with emphasis on geometric and radiometric quality issues have been discussed. They are important for both users and scanner manufacturers. Knowledge on these topics allows users to better understand and evaluate scanners, while vendors can use this information in the stage of design and construction of a scanner or the update of an existing model. Different implementation options and technological alternatives have been presented. New developments, particularly in sensor technology and colour scanning, should be examined and, if useful, integrated by scanner manufacturers.

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