Quality analysis and calibration of DTP Scanners

QUALITY ANALYSIS AND CALIBRATION OF DTP SCANNERS

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ABSTRACT

Scanners have been used as input devices in photogrammetric and cartographic applications mainly for digitisation of aerial images and maps. This paper deals with the use and applicability of DeskTop Publishing (DTP) scanners for photogrammetric/cartographic applications, their quality analysis and calibration. The motivation of the paper is the investigation as to what extent low-priced DTP scanners, which are rapidly improving during the few last years, can be used for such applications. The paper will mainly concentrate on flatbed scanners with aim the scanning of films. However, many of the topics mentioned in the paper are also valid for drum scanners. The paper gives a review of recent technological developments with respect to these scanners, describes advantages and disadvantages, presents characteristics and problems of such scanners, and investigations on their geometric and radiometric accuracy. Test patterns for calibration of such scanners and a novel, simple and generic geometric calibration method are presented. Results using five different scanners show that a geometric accuracy of 4 - 7 µm can be achieved.

1. INTRODUCTION

Scanners are an essential component in photogrammetric and cartographic applications. They have been used for scanning of aerial and satellite images, as well as digitisation of topographic and thematic maps, plans, charts and atlases. Aerial and satellite imagery has been used to derive Digital Terrain Models, orthoimages, and for digital mapping (new generation or update of existing map data). A trend is the use of digital orthoimages for generation and update of databases, generation of orthoimage maps, integration with other raster and vector data and visualisation. Although the developments in direct digital data acquisition have been enormous in the last decade, film-based systems are used in all fields of photogrammetry. In aerial photogrammetry film-based systems will provide the main data input for many years to come.

The scanning requirements depend on the document to be scanned and the application. Aerial images are scanned in grey levels or colour, require a format of 25 x 25 cm, a geometric resolution of at least 600 - 1200 dpi, a geometric accuracy of 2 - 5 µm (for high accuracy applications), a radiometric resolution of 10 - 12 bit and a density range of 2.5 D (panchromatic images) to 3.5 D (colour images). Satellite images often require a larger scan format (up to 30 x 45 cm). Maps/plans pose some additional requirements: opaque scanning, large scan format (e.g. A1), bilevel and multilevel (usually 1 - 4 bit) and halftone scanning. There is no single scanner, that can fulfil all these requirements. High-end, A3 DTP scanners come close to fulfilling these requirements with the main problems being in the geometric accuracy and resolution, and the scan format.

A classification of scanners is given in Baltsavias and Bill, 1994. DTP scanners can be divided in flatbed and drum scanners, or low (1,000 - 20,000 SFr. with few exceptions) and high cost (> 50,000 SFr.). Although drum scanners have a high geometric resolution (2000 - 4000 dpi), and high density range (3D - 4D), they are generally more expensive than their flatbed counterparts, and most importantly they have low geometric accuracy due to drum inaccuracies, unflatness of film on drum etc. and because of the same problems and the inability to scan glass plates an accurate geometric calibration is not feasible. Here, mainly only lost cost flatbed scanners will be treated.

2. OVERVIEW OF DTP SCANNERS

DTP scanners have been developed for applications totally different than the photogrammetric/cartographic ones. However, since they constitute the largest sector in the scanner market, they are subject to rapid developments and improvements. Flatbed scanners typically employ one or more linear CCDs, and move in direction vertical to the CCD to scan a document in one swath. Usually the stage is stationary, and the sensor/optics/illumination move. They can scan binary, halftone, grey level and colour data (with one or three passes), may have good and cheap software for setting the scanner parameters, image processing and editing, and can be connected to many computer platforms (mainly Macs and PCs, but also Unix workstations) via standard interfaces. They can usually scan A4 format, but some can scan up to A3 or even more. Some do not scan transparencies, others do so but only of smaller format (for A4 scanners the maximum transparency scan width is 8´´- 8.5´´). Such a width suffices to scan aerial films with 8 fiducials (5 fiducials are visible).

Flatbed scanners have a resolution of up to 1200 dpi (21 µm pixel size) over the whole scan width. Few scanners offer the option to increase the resolution by projecting a document portion (smaller than the full width) on the CCD. Their price range, with few exceptions, is 1,000 - 20,000 SFr. The big price jump occurs when going from A4 to A3 format. The transition from 600 dpi to 1200 dpi costs less. A3 scanners with 600 x 1200 dpi start at ca. 19,000 SFr. A4 scanners with 600 x 1200 dpi and transparency options cost much less (2,000 - 5,000 SFr.). Their radiometric resolution and quality, and scanning speed can be comparable to or even exceed that of the more expensive photogrammetric film

Table 1. Specifications of some DTP scanners.

Model	Agfa Horizon Plus	Agfa Arcus II	UMAX Mirage D-16L	UMAX PowerLook II	Sharp JX-610	Scitex Smart 340 L
Mechanical movement	stationary stage	stationary stage	stationary stage	stationary stage	moving stage	stationary stage
Sensor type	3 butted CCDs 3 x 5,000 pixels	trilinear CCD 5000 pixels	colour CCD[1] 5000 pixels	trilinear CCD 5000 pixels	linear CCD 7500 pixels	linear CCD
Scanning format (mm)	A3 (refl.) 240 x 340 (transp.)	210 x 355 (refl.) 203 x 254 (transp.)	305 x 452	212 x 297 (refl.) 212 x 254 (transp.)	305 x 432	A3 (refl.) 262 x 420 (transp.)
Geometric resolution (µm) vertical x horizontal[2]	21.2 x 21.2	21.2 x 42.3	31.75 x 63.5 (A3) 15.9 x 31.75 (half width)	21.2 x 42.3	21.2 x 42.3	21.2 x 21.2
Density: range/max.	3.2/3.4	3.1/3.2	3.0/3.2	3.3/	3.3/	
Radiometric resolution (bits) internal/output	12/12 or 8	12/12 or 8	10/10 or 8	12/12 or 8	12/8	/8
Illumination	halogen, 400 W	fluorescent, 8 W	halogen	cold cathode, 3 W	3 RGB strobing fluorescent	
Colour passes	3	1	1	1	1	
Geometric accuracy[3] (µm) x/y	92/47	63/41	18/19	52/43	56/28	
Scanning throughput[4] and/or scanning speed (ms/line)	0.35 Mb/s (1200 dpi) 1.7 (B/W)	4 - 15	5.4 (B/W), 9.9 (colour)	ca. 5 (B/W), 9.4 (colour)	0.62 Mb/s (A3) 12 (B/W), 35 (colour)	0.48 Mb/s (A4) 0.68 Mb/s (A3)
Internal image buffer	8 Mb (32 Mb option)	1 Mb (2 Mb option)	2 Mb	2 Mb		
Host computer/ interface	Mac, PC, Unix/ SCSI-2	Mac, PC/ SCSI-2	Mac, PC, Unix/ SCSI-2	Mac, PC/ SCSI-2	Mac, PC, Unix/ GPIB, SCSI-2	Mac
Software[5]	FotoLook, FotoTune Light, Photoshop	FotoLook, FotoTune Light, Photoshop	MagicScan, MagicMatch, Photoshop, Binuscan ColorPro, Live Picture	MagicScan, MagicMatch, Photoshop, Binuscan ColorPro, Live Picture	Scan JX, Photoshop, ColorSync	
Approximate price (SFr.)	40,000	4,500	12,000	4,500	19,000	65,000

[1] The manufacturer does not specify whether colour is achieved by a trilinear CCD or colour filter multiplexing on the elements of one CCD. Patterns occurring in colour images scanned with Mirage indicate that the scanner uses colour filter multiplexing.
[2] Horizontal is in CCD direction, vertical in scanning direction.
[3] Average values estimated by using 525-625 grid crosses as control points and an affine transformation (see Table 2). Higher order transformations lead for some scanners in smaller geometric errors.
[4] Scanning throughput depends mainly on data transfer rate to host, and speed of writing data on disk.
[5] Other optional packages and third party software also available.

scanners. DTP scanners with automatic density control and user definable tone curves that can be applied during scanning need for the setting of the scan parameters a few minutes as compared to much more time required by most photogrammetric scanners. In particular, the sensor chip and the electronics of DTP scanners are updated faster and are in most cases more modern that the respective parts of photogrammetric scanners. New generation DTP scanners employ 10 - 12 bit digitisation and have a density range of up to 3.4D (some manufacturers of high-cost flatbed scanners claim a density range of 3.7D, 4.0D maximum density, and 16-bit quantisation, which are difficult to believe - see also section 6.5). Some scanners employ modern trilinear colour CCDs and scan colour documents in one pass. Functions that can be encountered in DTP scanners include sharpening, noise removal, automatic brightness and contrast adjustment, manual and automatic thresholding, white and colour balancing, black/ white point setting, negative scanning, automatic colour calibration, self-defined screens for scanning halftone documents and printing images, multiple self-defined thresholding for each colour channel to scan multi-colour documents, preview (sometimes with variable zoom) and scan area selection, CMYK scanning, colour correction, integrated JPEG compression, and batch processing. The scanners can be bundled with other packages for image processing, editing, and retouching, colour management and calibration, image management etc. Their quality is rising while their price drops (especially for the A4 format scanners). The main disadvantage of DTP scanners is the insufficient geometric accuracy and stability, caused mainly by mechanical positioning errors and instabilities, large lens distortions, and lack of geometric calibration software, and to a lesser degree the geometric resolution and the small scan format. For scanning maps the geometric accuracy may be sufficient but the format is limited to A3.

Table 1 shows the major features of scanners, that can scan 23 cm x 23 cm aerial films, and some A4 scanners that were tested. Other A4 scanners with resolution of 600 x 1200 dpi and transparency options include among others: Agfa DuoScan (1000x2000 dpi), Epson ES1200C, HP Scanjet 4c, LaCie Silverscanner III, Linotype-Hell Saphir, Mustek Paragon 1200, Nikon Scantouch AX1200, Tamarack's Artiscan 12000C, Ricoh FS2, Microtek ScanMaker III, Sharp JX-330M, Relisys 9624, Mirror Color Scanner 1200, Spectrum Scan III. Other A3 scanners include: Linotype-Hell Topaz (variable resolution/500 dpi over 30.5 cm width, 203 x 457 mm transparencies), Scitex Smart 320 (variable resolution/500 dpi over A3 width, 260 x 434 mm transparencies), Pixelcraft's ProImager 8000 (400 x 1400 dpi, transparency option in preparation), and the older models Imapro QCS-2400 (600 x 1200 dpi, 5´´ x 7´´ transparencies), Howtek Scanmaster 3+ (400 x 1200 dpi, A3 transparencies), Anatech Eagle 1760 (600 dpi, 419 x 610 mm format).

Details on different scanner aspects and necessary requirements, and different implementation options and technological alternatives are presented in Baltsavias and Bill, 1994. Knowledge on these topics allows users to better understand and evaluate scanners or appropriately set the scanning parameters.

3. ERROR TYPES AND TEST PATTERNS

Geometric and radiometric calibration procedures are usually applied by all DTP scanner vendors but in all cases they are incomplete, or not accurate enough. In DTP scanners geometric calibration is not implemented, or if it is, patterns and procedures of low geometric accuracy are used. Calibration and test procedures can and should also be applied by the user periodically. For such calibration procedures software and test patterns should ideally be supplied by the scanner vendors but this is unfortunately a rare case. In addition, the scanner vendors rarely provide the users with all relevant technical specifications of the scanner and with error specifications, e.g. tolerances for the RMS and maximum error that can occur in different cases.

Error types can be classified according to different criteria, e.g. geometric and radiometric errors, or slowly and frequently varying errors. In the following the second classification will be used. The main slow varying or constant errors are lens distortions, defect pixels, CCD misalignment errors, subsampling errors, smearing due to defocusing and high speed, colour channel misregistration etc. The main frequently varying errors are mechanical positioning, illumination instabilities, stripes, vibrations, electronic noise, dust etc. As it can be seen from the above, the frequently varying errors mainly refer to the radiometry, whereby frequently geometric errors refer to mechanical positioning and vibrations. For a detailed description of possible errors see Baltsavias, 1994b and the description of a high-end DTP scanner (Agfa Horizon) and the errors it exhibits see Baltsavias, 1994a. The major errors are geometric positioning inaccuracies, lens distortions, electronic noise and small dynamic range, colour balance and colour misregistration. Other errors can occur depending on the design, construction, and parts of each individual scanner. Whether some errors are slowly or frequently varying depends on the quality and stability of the scanner, e.g. in DTP scanners the positioning errors vary from scan to scan or even within one scan. In DTP scanners the geometric errors in CCD direction considerably increase towards the borders of the scanner stage, and in scanning direction they may slightly increase towards the end of the scan.

Different test patterns, test and calibration procedures are given in Baltsavias, 1994b. The most important test patterns are grid plates for the geometry, resolution charts for determination of the MTF, grey scale wedges for determination of the density range, grey level linearity and noise level, and colour charts for colour reproduction and purity. The test patterns that were used in our tests were the following:

- Resolution chart

  A USAF resolution 3-bar chart on glass plate produced by Heidenhain.

- Gray scale wedges

  A transparent Kodak grey scale wedge with 2.5 x 14 cm size. The grey scale was measured repeatedly with a Gretag D200 densitometer and the 21 densities with an approximate step of 0.15 D were found to cover the range 0.05 - 3.09 D.

- Grid plates

  Two plates were used (see Figure 1). The left one (off-line) is used to model the slow varying errors (lens distortion). The right one (on-line) is scanned together with the film and is used to model the frequently varying errors (mechanical positioning). The left plate has 25 x 25 grid crosses with a grid spacing of 1 cm, the right one 237 crosses at each border (left and right) with a spacing of ca. 1 mm. The plates were custom-made with thick lines (ca. 190 µm) and a small white square at the center of each cross. The squares were measured repeatedly at a Wild AC1 analytical plotter with an estimated accuracy of 2 - 3 µm.

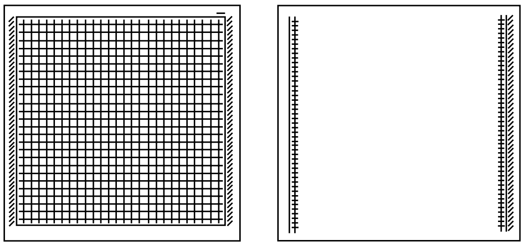

Figure 1. Grid plates for geometric tests and calibration.

4. TESTS AND CALIBRATION OF DTP SCANNERS

Using the above test patterns the following five scanners were tested: Agfa Horizon, Agfa Arcus II, UMAX Mirage D-16L, UMAX PowerLook, Sharp JX-610. The first scanner belongs to our Institute and was tested over a few years, the remaining ones were tested at companies or were lent. In all tests a resolution of 600 dpi was used (exception: 400 dpi for Mirage). The same test patterns, data measurement and analysis, and calibration procedures were used for all scanners. A difference exists for the grid plates. The 25.4 cm wide plates could not be put flat on the A4 scanners (Arcus II and PowerLook) and a part of the plates could not be imaged. Latter is important for the on-line plate because one of the border lines was totally missing. This plate positioning (one side of the plates was lying on the scanner frame around the scanner glass plate, less than 1 mm higher than the scanner glass plate) caused imaging displacements which could not be modelled by an affine transformation (as used in the interior orientation). For all geometric tests Least Squares Template Matching (LSTM) was used to measure the grid crosses. The standard deviation of the matched positions was 0.03 - 0.04 pixels, i.e. 1.3 - 2.6 µm, for the 600 dpi and the 400 dpi scans respectively. In the following x-direction is the direction of the CCD line (horizontal), y-direction is the direction of the scanning movement (vertical).

4.1. Geometric accuracy without calibration

Table 2 shows the geometric accuracy of the scanners. For all scanners, except the Arcus, two scans were made. The results were similar for both scans, however here the worst of the two results is shown. For this test all grid lines were measured by LSTM and an affine transformation was computed between these values and the reference values (as measured at the analytical plotter). As control points either all points were used, or four corner or eight points. In the last two cases the remaining points were serving as check points and their errors are shown in Table 2. The versions with all points as control show the global geometric accuracy of the scanners. Only for Horizon the accuracy is worse than 60 µm, for the Mirage it is even close to 20 µm! The maximum errors are bounded and correspond to ca. 2.5 - 3.5 RMS. The errors are generally larger in x, indicating large lens distortions. Using only 4 control points the errors of the check points increase. This is natural because the corner points have larger errors than points, let's say in the middle of the scanner stage, and thus the estimated affine parameters have larger errors. The big systematic errors introduced by the errors of the corner points are also indicated by the large mean errors, which ideally should be zero. A version with 8 control points (4 corners and 4 points at the middle of the borderlines) was also tested. The results were better, in some cases significantly.

The above mentioned scanner accuracy may be sufficient for some applications. Consider for example a scanner with 100 microns geometric error, used to generate hardcopies of digital orthoimages in scales 1:24,000 and 1:12,000, using 1:40,000 scale input imagery scanned with 25 microns, and an orthoimage pixel size of 1 m (equal to the footprint of the scan pixel size). The scanner error translates to a planimetric error of 4 m in the digital orthoimage, and 0.17 mm and 0.34 mm in the 1:24,000 and 1:12,000 hardcopies. This approximates the measuring accuracy in topographic maps, and may be acceptable for many users.

Table 2. Statistical values (in µm) of geometric accuracy without calibration. Errors (residuals) after an affine transformation.

Scanner	Control/ check points	RMS		Mean		Max absolute	
		x	y	x	y	x	y
Horizon	4/621	146	71	-5	-26	224	151
	8/617	147	67	-4	-13	223	139
	625/0	92	54	0	0	220	159
JX-610	4/621	106	51	67	-39	214	117
	8/617	91	42	45	-26	182	105
	625/0	56	29	0	0	182	91
Mirage D-16L	4/621	35	20	24	-4	73	56
	8/617	32	20	20	-7	67	54
	625/0	18	19	0	0	56	51
Arcus II	4/521	85	81	51	-69	199	151
	8/517	76	62	36	-46	180	129
	525/0	63	41	0	0	216	122
Power-Look	4/546	101	112	-66	103	181	177
	8/542	87	77	-45	65	158	138
	550/0	52	43	0	0	185	114

4.2. The geometric calibration procedure

The calibration consisted of two stages. In the first stage the effects of the lens distortion were modelled. Radial lens distortion caused large displacements in x-direction, and the tangential lens distortion smaller but significant displacements in y-direction. The off-line plate was scanned, all points were measured by LSTM and an affine transformation between these measurements and the reference values using all points as control points was computed. The residuals of this transformation were indicating the occurring errors. These errors were transferred from the pixel to the scanner coordinate system. There an x-correction regular grid was interpolated based on the residuals.

The same procedure was repeated many times and the correction grids were averaged to reduce temporal noise, especially due to vibrations. For the Horizon four scans were averaged, for the other scanners two, except for the Arcus where only one scan was available. For the y-correction grid (modelling of tangential lens distortion) a similar procedure was used. In this case once an affine transformation and once a 7 parameter transformation (affine plus an x^2 term in y) was used. The x^2 term in y corresponds to the second order tangential distortion. By subtracting the residuals from the two transformations, we were left with the errors modelled by the x^2 term in y, and subsequently a y-correction grid in the scanner system was computed as for x. The x-grid was always used, the y-grid (called y-precorrection) is optional. Errors due to lens distortion are stable, so these correction grids do not need to be computed often (for the Horizon we applied the calibration using correction grids that were computed one year in advance).

For the second stage of the calibration the crosses of the two border lines of the on-line plate were measured by LSTM and an affine transformation between these values and the reference values using all points as control points was computed. The y-residuals of this transformation were indicating the occurring errors at the two border lines. For the A4 scanners only one border line was imaged, so a similarity instead of an affine transformation was used. Since scanning is performed in one swath we can assume that no errors can suddenly occur in the interior of the CCD. Thus, the error at any point in the interior of the image can be bilinearly interpolated using the errors at the borders. This calibration stage is used to model the y-errors. They are mainly due to mechanical positioning. The part coming due to the tangential lens distortion can either be excluded by using the y-precorrection grid, or it can be modelled by using a transformation higher than the affine in the interior orientation. We used just a 7 parameter transformation (affine plus an x^2 term in y). This was sufficient for all scanners. The seventh parameter can be only determined, if 8 control points (fiducials) can be used.

4.3. Geometric accuracy after calibration

To check the validity of the calibration procedure we scanned the two plates simultaneously, i.e. the off-line plate was placed on top of the on-line and were fixed by tape to the scanner stage. This could be avoided, if we had designed the off-line plate such that it included the two border lines of the on-line plate with the dense crosses. Due to this procedure the crosses of the upper plate were naturally radially displaced, but this effect could be accommodated by the affine transformation. However, this could not happen with the two A4 scanners since the glass plates were not lying on the scanner stage and the radial x-displacement was asymmetric. The same problem occurred with the Mirage. This scanner has a dual lens system employing many mirrors (unfortunately the scanner representative did not want to or could not provide us with technical details). The x-residuals of the off-line plate revealed an asymmetry with respect to the centre of the scanner stage, thus indicating that the lens had an asymmetric position with respect to the CCD line. These x-errors for the three scanners could be reduced by using additional transformation terms (x^2 or xy) in the x-direction (see version 3 in Table 3). The scan of both plates was done twice except for the Arcus. The results of the two scans were similar and the average is shown in Table 3. Table 3 shows statistics of the residuals of the check points of the off-line plate after calibration.

Version 1 includes an affine transformation and y-precorrection. Version 2 includes the aforementioned 7 parameter transformation and no y-precorrection. Version 3 for the last three scanners is like version 2 but with an additional term (x^2 or xy) in the x-direction. The results of the three last scanners are not optimal due to the aforementioned problem with the positioning of the glass plate and the dual lens system of the Mirage. Still with version 3 we get an accuracy of 6 - 10 µm. This is remarkable especially for the Mirage, which had a scan pixel size of 63.5 µm. The results of the first two A3 scanners is more representative and show an accuracy of 4 - 7 µm. The JX-610 reaches an accuracy similar to that of many photogrammetric scanners. Version 2 is slightly better than version 1 and does not require y-precorrection, so it is faster. The errors in x- are slightly larger than in y-direction, and have a remaining systematic part. The maximum errors are equal to 2.5 - 3.5 RMS. The achieved geometric accuracy corresponds to 0.1 - 0.2 pixels. If 8 fiducials and a 7 parameter transformation can be used, then no y-precorrection is necessary, while in all other cases the y-precorrection brings substantial improvement.

Table 3. Statistical values (in µm) of geometric accuracy after calibration indicated by the residuals of the check points.

Scanner	Version[1]	Control points	RMS		Mean		Max absolute	
			x	y	x	y	x	y
Horizon	1	4	8	8	4	6	22	27
	2	8	7	6	3	0	20	20
JX-610	1	4	7	6	5	5	14	16
	2	8	5	4	4	1	14	15
Mirage D-16L	1	4	19	10	-15	2	40	23
	2	8	14	8	-9	1	30	22
	3	8	8	9	1	1	21	22
Arcus II	1	4	18	11	8	-5	45	25
	2	8	16	9	4	3	39	28
	3	8	10	9	4	3	22	28
Power-Look	1	4	12	6	-6	-1	32	15
	2	8	12	6	-5	1	33	16
	3	8	10	6	0	1	26	16

[1] See explanation in text.

Thus, calibration paves the way for use of DTP scanners in practically all photogrammetric applications, but at a cost: grid plates, development of calibration software, more computations for calibration and, if necessary, image resampling.

4.4. Colour misregistration

It was tested by scanning the resolution chart in colour and separating the R, G, B channels. Well defined points (e.g. corners) were selected in one channel and the same points were found by LSTM in the other two channels. The difference of the pixel coordinates of corresponding points gives the channel misregistration.

These errors are mainly due to the mechanical positioning inaccuracies (for 3 pass scanners), chromatic properties of the optical system (all scanners) and errors in the calibrated offset between the 3 colour CCDs (for trilinear CCDs). Table 4 gives some statistics of the misregistration errors. The mean difference shows that a large part of these errors is systematic. One pass scanners generally exhibit smaller errors than three pass scanners, although, as the case of Mirage shows, the errors can be large even for one pass scanners. The errors are larger in y-direction, influenced by mechanical positioning or offsets between the 3 colour CCDs. It must be noted that this test covers a small area (ca. 1 x 1 cm) at the centre of the scanner stage. Ideally, the whole stage should be covered. It should be expected that the misregistration errors increase towards the left and right borders due to the chromatic properties of the lens.

Table 4. Statistical values (in µm) of misregistration errors of the R, G, B channels.

Scanner	Colour channels	RMS		Mean		Max absolute	
		x	y	x	y	x	y
Horizon	R - G	18	29	17	28	33	41
	R - B	4	20	1	19	17	32
JX-610	B - G	7	4	-7	-3	14	7
	B - R	10	2	-9	2	14	4
Mirage D-16L	R - G	5	19	4	15	18	47
	R - B	10	16	9	-9	26	43
Arcus II	R - G	2	9	0	7	6	22
	R - B	4	10	-1	-6	13	23

4.5. Dynamic range, grey level linearity and noise

The grey scale wedge was scanned for this test. In all cases the scanning parameters (e.g. min and max density or equivalent measures) were set automatically by the scanners. A rectangle at the centre of each grey scale was cut out to avoid border effects. Each rectangle included ca. 16,000 pixels (for 600 dpi) or 7,000 pixels (for the Mirage). The influence of dust and similar noise was reduced by excluding all pixels outside the range [mean ± 3 standard deviation]. Thus, for each grey scale a mean and standard deviation was computed (see Table 5). Arcus II, Mirage and PowerLook are saturated for D = 0.05, as indicated by the very small standard deviation (e.g. Arcus II can accommodate a minimum density of 0.08D). In all cases the mean grey value is decreasing with increasing density. All scanners show similar noise, generally lower for high densities and higher for low ones. The Horizon shows the least noise for low densities but the highest noise for high ones. The low standard deviations of PowerLook for high densities is rather an inability of discriminating different densities than an indication of low noise. The bold numbers in Table 5 show the highest density D_i for which (mean + standard deviation) > mean of density D_{i-1}. As it can be seen, in all cases densities greater than ca. 2.5 D can not be meaningfully resolved (see also the near vertical curves for high densities in Figure 2). For the high densities, the differences between the means of neighbouring grey scales are larger for the Horizon and Arcus (7.5 grey levels range for the densities 1.9 - 3.09 D), while for the other scanners they are smaller (3 grey levels range for the densities 1.9 - 3.09 D). The big differences between the means of the five scanners for the same density (for D = 0.35 the maximum difference is 34 grey levels!) show that the grey levels have rather a relative value.

In a previous test larger rectangles within each grey scale were used. For medium and especially high densities variations within the grey levels of each grey scale were noted. The grey values were for all scanners higher towards the borders of the grey scale that were next to the scanner glass plate. The grey level differences between borders and centre reached up to ca. 20 grey values for the highest densities. For high densities all scanners showed higher mean and standard deviations than the ones in Table 5, especially Horizon and Sharp. For example Horizon had an average standard deviation of 3.6 for densities larger than 2.0D, as opposed to 1.1 in Table 5. It seems that the older generation sensors of Horizon and Sharp are more sensitive to overshoot from the neighbouring bright scanner glass plate.

The grey level linearity is checked by plotting the logarithm of the grey values versus density (see Figure 2). Ideally, these plots should be straight lines with equal distances between the means of neighbouring grey scales. The two models of UMAX show as expected a similar curve. The curve of JX-610 is the one with the largest deviation from a line. The two UMAX scanner curves can be approximated by a line with an inclination of less than 45 degrees. This implies a tone curve that stretches the bright areas. The results of all scanners (especially for high densities) depend on the form of the tone curve (LUT) that is used to reduce the 12 or 10 bits to 8, but the form of this LUT is unknown. A gamma larger than 1 will increase the noise for high densities and decrease it for low ones, while a gamma of less than 1 has the opposite effect. Given that the LUTs of the scanners are unknown the most objective comparison between the scanners is for the medium densities. In all cases the density range and maximum densities given by the manufacturers do not make much sense for high densities, as long as the noise level is too high to permit a meaningful discrimination between neighbouring densities.

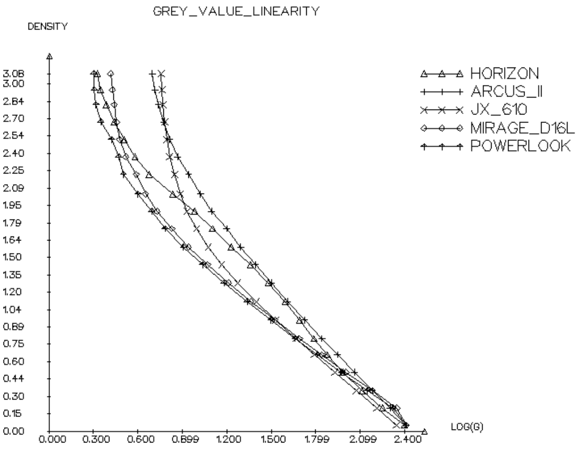

Figure 2. Grey level linearity for various scanners. Logarithm of grey values versus density.

Table 5. Radiometric test with grey scale wedge. Mean and standard deviation of grey values.[1]

Density	Agfa Horizon[2]		Agfa Arcus II		UMAX Mirage D-16L		UMAX PowerLook[3]		Sharp JX-610	
	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.
0.05	248.9	1.0	255.0	0.1	255.0	0.0	255.0	0.0	219.9	1.7
0.2	177.0	1.7	199.2	1.6	221.5	2.4	209.5	2.6	161.6	2.0
0.35	128.6	1.1	151.4	1.5	150.2	1.8	140.0	1.9	117.2	1.7
0.51	95.1	0.9	113.7	1.4	100.1	1.4	92.6	1.5	83.5	1.4
0.66	74.2	0.9	87.4	1.2	68.5	1.1	63.5	1.2	60.7	1.2
0.8	60.1	0.7	68.3	1.1	47.9	0.9	44.6	0.9	45.2	1.0
0.96	48.2	0.7	52.1	1.0	32.5	0.7	30.5	0.7	32.8	0.9
1.12	38.2	0.7	39.7	0.9	22.0	0.6	20.7	0.6	23.9	0.7
1.28	29.1	0.8	30.7	0.8	15.3	0.6	14.1	0.5	17.7	0.7
1.44	21.8	1.2	23.8	0.7	10.7	0.5	9.9	0.4	13.6	0.6
1.59	15.9	0.7	18.6	0.7	7.7	0.5	7.1	0.3	10.9	0.6
1.75	11.7	1.0	14.9	0.6	5.8	0.4	5.1	0.3	8.9	0.5
1.9	8.6	1.1	11.5	0.7	4.4	0.5	3.9	0.3	7.6	0.6
2.05	5.9	1.4	9.5	0.6	3.5	0.5	3.0	0.1	6.7	0.5
2.22	3.7	1.1	7.8	0.7	2.9	0.3	2.2	0.4	6.0	0.5
2.37	2.8	0.8	6.4	0.7	2.3	0.5	2.0	0.2	5.5	0.5
2.52	**2.2**	**0.9**	5.5	0.7	2.0	0.3	**1.6**	**0.5**	**5.2**	**0.5**
2.67	1.8	1.0	**4.9**	**0.7**	**1.9**	**0.4**	1.2	0.4	5.1	0.5
2.82	1.4	1.1	4.5	0.7	1.8	0.4	1.1	0.3	4.9	0.5
2.95	1.2	1.1	4.2	0.8	1.7	0.5	1.0	0.2	4.8	0.5
3.09	1.1	1.1	4.0	0.8	1.6	0.5	1.0	0.1	4.7	0.5
Mean St. D.[4]		1.0		0.9		0.7		0.7		0.8

[1] Scanning resolution 600 dpi (Mirage 400 dpi), transparency, all scan parameters set automatically.
[2] Density range = 3.0 D, maximum density = 3.3 D. Values slightly worse than those of Horizon Plus.
[3] Density range = 3.0 D, maximum density = 3.2 D. Values slightly worse than those of PowerLook II.
[4] Excluding lowest and highest density which are partly affected by saturation.

5. CONCLUSIONS

DTP scanners are the fastest growing segment in the scanner market. Improvements in their overall quality, scan format, geometric and radiometric resolution and lower prices should be expected. However, an improvement in the geometric accuracy of the DTP scanners, or the production by DTP scanner manufacturers of new scanners specifically for photogrammetric/cartographic applications is not probable. What could be done however, is the optional provision of customers with calibration patterns and software at an extra cost which could be around 4,000 to 6,000 SFr. Here we presented a general and simple geometric calibration procedure that has been used with various scanners and led to an accuracy of 4 - 7 µm. In their current state, DTP scanners can be used in some photogrammetric tasks. The important point is that the user must clearly define the application requirements and examine himself whether they (particularly the geometric accuracy) can be fulfilled by a given DTP scanner. The main problem of DTP scanners regarding image scanning is that they lack high geometric accuracy. Improvements on this topic will drastically increase the range of their application. For the above reasons the developments in the DTP scanners should be closely monitored.

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