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Evaluation of DTP Scanners - a Case Study with Agfa Horizon

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ABSTRACT

Scanners are an essential part of softcopy photogrammetric systems. 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. The main use of scanners today is definitely in the digitisation of aerial images, particularly for digital ortho-image and DTM generation, and integration of image data in GIS. So called photogrammetric scanners are in most cases very expensive, while at the same time they may exhibit significant errors, particularly in radiometry. DTP scanners have low price, and may have a good performance and sufficient resolution. Their main disadvantage is the lack of geometric accuracy and stability. By using calibration techniques, the geometric errors can be kept to less than 0.5 pixel of the highest geometric resolution, making thus such scanners suitable for most photogrammetric applications. This paper presents a short overview of scanners, a description of the 1200 dpi scanner Agfa Horizon, and finally test procedures and results of the radiometric and geometric quality of the scanner.

1. INTRODUCTION

Scanners are an essential part of softcopy photogrammetric systems. 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 close-range applications many metric, semi-metric and amateur cameras still use films. The reasons are the high film resolution, and low costs, ease-of-use and availability of amateur and semi-metric cameras. In aerial photogrammetry film-based systems will provide the main data input for many years to come. Film-based satellite images are provided by many Russian sensors, while also in USA companies, previously active in military applications, want to launch film-based high resolution commercial systems. The main use of scanners today is definitely in the digitisation of aerial images. The main applications that increase the need for digital aerial data are (i) the digital ortho-image generation, (ii) the automatic DTM generation, and (iii) the integration of digital data, particularly ortho-images and derived products, in GIS.

The aim of this paper is to look into more detail into DTP scanners, and especially the Agfa Horizon, and present their major characteristics and problems. The here presented work will
also include preliminary studies on specific important questions, like: how good are DTP scanners for photogrammetric tasks?, can their errors be corrected by calibration procedures?, at what costs?, what accuracy can be achieved after calibration?

1.1. SCANNER CLASSIFICATION

Scanners of documents (reflective and/or transparent) can be classified according to their function in the following categories:

1. photogrammetric scanners
2. modified analytical plotters or monocomparators
3. scanners of large documents
4. microdensitometers
5. DeskTop Publishing (DTP) scanners
6. scanners of documents and 3-D objects
7. slide scanners
8. document scanners (with OCR software)
9. multiple purpose scanners (scanner/copier/colour printer, similar to DTP scanners but more expensive and with a typical resolution of 400 dpi; scan/edit/fax scanners)
10. other specialised scanners (hand-held scanners, engineering document scanners, roentgen-image scanners, microfiche digitisers, barcode scanners)

Assuming that for photogrammetric applications, a scanner should be able to scan aerial images (23 x 23 cm) with a minimum optical resolution of 600 dpi and sufficient radiometric and geometric accuracy, only scanners of the first five categories should be addressed.

Photogrammetric scanners are produced by companies involved in photogrammetry, have a high geometric accuracy (typically 2 - 4 µm), sometimes software for interior orientation and epipolar transformation, but the majority of them are very expensive (300,000 - 400,000 SFr.). In the opinion of the author the most expensive photogrammetric scanners are sold at excessive prices, while there is a convergence between the lower priced ones and the top DTP scanners (see below). Expensive photogrammetric scanners may exhibit considerable errors particularly in radiometry. Figure 1 shows a part of an image of the OEEPE test on digital aerial triangulation, stretched with a gamma of 3. The images were scanned with a Zeiss/Intergraph PS1 using a 2048 element linear CCD which scans the image in swaths. As it is seen at the center of Figure 1 the border line between neighbouring swaths is clearly visible. The grey level differences between neighbouring pixels on either side of the line in the original image were up to 55 grey values. The pixels that had grey value 0 are displayed in white. As it can be seen, the image is completely saturated and the signal is lost. This may be due to various reasons: wrong setting (automatic or manual) of the density range during scanning, insufficient dynamic range of the CCD, wrong exposure...
of the film, drop-off of the illumination at the border of the scan area (notice the film border at the right of Figure 1; it is not however saturated, so this reason is not very probable). Figure 2 shows another example of the same problem, and additionally vertical dark stripes which must be either due to defective sensor elements or wrong radiometric calibration of the individual sensor elements (see also Colomer, 1993). Geometric errors may also occur with photogrammetric scanners. Images scanned with the Leica-Helawa DSW 100 for our Institute exhibited misregistration errors of the individual CCD frames from which the image consists of more than 5 pixels, while in other cases no error was observed. Putting together the individual CCD frames in a correct radiometric and geometric way is also a problem for the Signum HIRES scanner.

Figure 1. Part of an image of the OEEPE test on digital aerial triangulation digitised with
a Zeiss/Intergraph PS 1; a) radiometric differences between neighbouring swaths scanned by the linear CCD, b) pixels displayed in white have grey value 0 (saturation).

Figure 2. Same data set as in Figure 1. Vertical dark stripes are visible at positions a) and b).

Scanning by using analytical plotters equipped with CCD cameras never became popular, and it is very unlikely that this will change. Analytical plotters are widespread, have a high geometric accuracy, and are equipped with photogrammetric software. However, installation of CCDs at analytical plotters require modifications, that are very often expensive, the costs of the hardware (cameras, framegrabbers, monitors) and the necessary
calibration software is not inexpensive either, the scanning process is slow, and the radiometric quality suffers because illumination, optics, filters etc. are not optimised for scanning. Additionally, the concept of a scanner does not fit very well to analytical plotters which, by their very nature, are operator driven, and apart from that scanning would obstruct the normal work at the analytical plotter.

Scanners of large documents are in most cases drum scanners, and thus their geometric accuracy is generally less than that of flatbed scanners. They may have a high radiometric resolution, but often they do not scan transparencies. Often they can also plot, and thus are quite expensive. Their main application is in scanning of large format plans and maps, and less in scanning of films.

Conventional microdensitometers (Perkin-Elmer, Joyce-Loebl) have a very high geometric resolution (up to 2 µm), a very good geometric accuracy and radiometric quality (12 - 16 bit) but they are not very widespread, are generally very expensive, slow, quite complicated to calibrate, and less flexible both hardware- and software-wise. They are important for analysis of micro-image properties and specific applications where radiometric resolution and accuracy are of major concern (astronomy, medicine, image quality determination).

DTP scanners have been developed for applications totally different than the photogrammetric ones. However, since they constitute the largest sector in the scanner market, they are subject to rapid developments and improvements. The consultancy BIS Strategic Decisions (Norwell, MA) forecasts that the colour flatbed DTP scanner market will grow 39 % annually over the next five years (Holch, 1993). DTP scanners are usually flatbed employing linear CCD sensors, but there are also a few drum scanners using photodiodes or PMTs. Their geometric resolution is constantly increasing and today there are scanners with 1200 dpi resolution (this refers to flatbed scanners, drum scanners can have a resolution of up to 4,000 dpi), capable of scanning aerial image formats in both reflective and transparency modes, in B/W or colour. Their radiometric resolution and quality, and scanning speed can be comparable or even exceed that of the much more expensive photogrammetric scanners. They are supported by many computer platforms and sophisticated software for setting the scanning parameters, image processing and editing, and colour editing. Their price is generally in the 1,000 - 50,000 SFr. range, whereby scanners with a true (optical) resolution of 1200 dpi, and especially with a scanning format larger than A4 are towards the high end of the price range. Scanners with a 11 by 17 inches format, a resolution of 600-1200 dpi, and in most cases transparency options are offered by Agfa (Horizon, ACS-100), Howtek (Scanmaster), Pixel-Craft, Sharp (JX-600), Imagpro (QCS-2400), Truvel (TZ-3BWC), ANA Tech (Eagle 1760), and Scitex (Smart). For more details on DTP scanners see Holch, 1993. Good drum scanners (the ScanMate magic of the danish firm ScanView and the Howtek Scanmaster D4000) with a resolution of 2,000 - 4,000 dpi, and A4 or 25 x 25 cm format cost 25,000 - 80,000 SFr. respectively. The main disadvantage of DTP scanners is the insufficient geometric accuracy, caused mainly by mechanical positioning errors and instabilities, large lens distortions, and lack of geometric calibration software. Further improvements in the previous topics from the side of the manufacturers can not be excluded, and even now a user can develop own calibration software and by using appropriate test patterns and test procedures, a geometric
accuracy of less than 0.5 pixel can be achieved. For these reasons and because of their attractive characteristics and low price, the DTP scanners should be analysed more carefully.

Scanners can be classified according to different criteria:

A. Dimensionality of simultaneously sensed elements

• point sensors (one pixel scanned at a time)

They are often used in microdensitometers and drum scanners for high geometric and radiometric resolution. Generally each pixel is illuminated by a laser beam and the sensor consists of a photomultiplier tube (PMT). PMTs have a very high speed and very high dynamic range. Microdensitometers and some drum scanners have a great flexibility in selecting different pixel sizes and forms and x-, y-spacing between pixels. DTP drum scanners use cheaper illumination/sensor systems, e.g. halogen lamps and usually photodiodes (their dynamic range is less than that of PMTs but higher and with a more linear response than that of CCDs).

• line sensors

The line usually consists of CCD elements but also photodiodes or charge-coupled photodiodes. There might be one linear CCD, or more, whereby in the latter case the linear CCDs are optically butted using beam splitting prisms or rotating mirrors. For colour scanning one or multiple 3-chip linear CCDs may be used.

• area sensors

They consist of CCD chips with a resolution ranging from 512 x 512 to 3000 x 2300 pixels.

B. Scanning pattern/movement

• drum scanners

Generally both stage and sensor are moving.

• flatbed scanners

The following cases can be distinguished: moving stage/stationary sensor, stationary stage/moving sensor, both sensor and stage stationary. To achieve high geometric resolution either the stage or the sensor is moving, whereby the movement can be in two or one direction. Movement in two directions can be realised by all type of sensors (point, line, area), movement in one direction only by linear CCDs with many sensor elements. The disadvantage of the first case is that it requires high geometric accuracy in two directions. In addition, in the case of line and area sensors there are often clearly visible radiometric differences along the seam lines of neighbouring line stripes or area patches due to illumination instabilities and different sensor element response. The a posteriori correction of this problem requires scanning of neighbouring lines/patches with overlap and application of a radiometric equalisation procedure as in mosaicking. The documents are usually scanned by a mechanical movement, however, electronic deflection of the beam or optical scanning (oscillating
mirrors, rotating prisms) can also be used. The light source either illuminates the whole object to be scanned or only the portion that it is scanned each time (thus, if the sensor is moving the light source must also move synchronously).

C. Other characteristics

Various other properties like format, resolution, reflective/transparent originals, binary-B/W-colour could be used for a scanner classification.

1.2. SOME SCANNER ASPECTS

1.2.1 Illumination

The illumination must be high in order to achieve a better radiometric quality and higher SNR. The higher the scanning speed, the higher the illumination should be since the dwelling time (integration time for CCD sensors) is reduced. On the other hand, high power light sources generate heat, which must be treated appropriately (cooling, use of cold light, placement of the light source away from the sensitive scanner parts), in order to minimise the influence on the mechanical parts and the electronics. The spectral properties of the light source and its temporal stability (related also to the power supply stability) are important factors. Light sources usually include halogen and fluorescent lamps (often over 100 W), as well as laser beams.

1.2.2 Dynamic range and quantisation bits

The dynamic range of films can be in extreme cases very high (e.g. 16,000:1). To capture this information a quantisation up to 16-bit would be necessary. Apart from microdensitometers, there are photogrammetric, drum and DTP scanners that have A/D converters 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 reduced to 8-bit. The user often has no influence and no information on how this reduction is made. If this is done properly, then the result will be a radiometrically better image with higher SNR. However, 10 or 12 bit quantisation can lead to an improvement only for low noise levels. This is not always the case, particularly with CCD based scanners. Parameters like cooling, maximum charge storage capacity, integration time, smearing etc. are not optimised to allow a truly beneficial 12-bit quantisation. The 12-bits are used as a selling argument but often they do not reflect an essential quality difference to 8-bit scanning.

1.2.3 Gamma correction

Often users apply a gamma correction during or after scanning. This is particularly the case with aerial films that appear relatively dark, especially at the borders. Thus, a gamma of 1.5 - 2 is often used to make these regions better visible. Some scanner vendors also use internally a gamma correction. This processing is appropriate if the image will be subsequently used only for visualisation purposes. Any other use for geometric or semantic information extraction will be negatively influenced by the gamma correction, since the dark grey levels will be stretched, but without occupying a larger number of grey values, and the
bright grey values will be compressed, thus resulting in information loss (or the opposite if negative films are used). A better way to improve the contrast is to use off-line after scanning another algorithm that does not result in less grey values or even better a locally adaptive algorithm that leads in a larger number of grey values. A local gamma correction is acceptable if it is applied locally to very dark fiducial marks (using ROI processing), in order to improve their visualisation for subsequent manual or semi-automated measurement.

1.2.4 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)
- use of 3-chip CCDs (linear or area arrays)
- rapidly strobing fluorescent lamps and dichroic filters
- use of a rotating filter wheel before the sensor (RGB and neutral filters) or rotating lamps

The first three approaches require one scan, while the last 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). The second is the best approach but also most expensive. Although many claim that the third approach is faster than the fourth, the scanning time is similar, if the same integration time for each colour is required. Another general belief that, the third approach often leads to smearing, while the fourth might suffer from misregistration of the three channels, is also not always correct.

1.2.5 Linear versus area CCDs

Among the sensors, the most promising and widely used are linear CCDs. Today there are various linear CCDs with 5,000 to 10,000 elements (the MN3666 from Matsushita with 7,500 elements, a 3-chip colour CCD from Kodak with 2,000 - 8,000 elements, TCD 141 from Toshiba with 5,000 elements, the firm Technolink (Americas) sells linear chips with 10,000 elements, Thomson has linear arrays with 5184 elements, Dalsa with up to 6,000 elements, and the list is continuously growing). With current technology multiple linear CCDs can be optically butted with high precision to result in a line with sufficient elements for a high resolution scan of close to 10 µm. Although area CCDs have a larger number of elements and theoretically should lead to a faster scanning, they have several disadvantages. Large area CCDs are very expensive and have blemishes, and standard CCDs need a lot of frames (and time) to cover the whole image and a precise positioning in two directions as compared to a long linear CCD which can scan the whole image in one swath. Radiometric differences along the seam lines of the frames can occur as explained above. Linear CCDs provide a better radiometric quality, need less integration time, have higher charge transfer efficiency, and suffer less from electronic noise (smearing, blooming etc.) than area CCDs. Linear CCDs have higher speed (pixel rates of up to 120 MHz) than standard area CCDs, and higher dynamic range (10,000:1 is possible, compared to 1,000:1 of a very good CCD). Area CCDs are designed to maximize the gain (the output signal) which also increases the noise, while linear
CCDs are designed to maximize the dynamic range, so they have less noise and therefore respond to less input light and due to the higher dynamic range they will respond to higher light levels as well. Compared to area CCDs they have much lower noise because they have fewer clock signals, so the latter can be better isolated from the video. They have adjustable integration time while area CCDs are usually locked to the RS170 or CCIR specifications (33 or 40 ms respectively). Parallel output for high data rates is easier with linear CCDs. Each line can be accessed immediately after integration, while with area CCDs all preceding lines must be first read out, and they are usually interlaced (so the first even line can be output only after all odd lines have been read out). Since a line contains a single row of pixels, the uniformity can be held much tighter than in an area array with several hundred-thousand pixels. They also have a more precise geometric centring. In very high precision imaging applications, contrast correction hardware and software algorithms are more easily implemented over a single line of pixels. Antiblooming drains which are important with high contrast objects are easier to implement with linear CCDs.

Linear CCDs also have some disadvantages. Normal operation of linear CCDs results in much shorter integration times than that of area CCDs, and therefore a much greater light intensity is required. Linear CCDs due to their long length 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. When applying subsampling, linear CCDs have a worse behaviour than area CCDs due to gaps in the scanning direction (see also subsampling errors in section 3.1.).

1.2.6 Scanning speed

High or low scanning speed? Many users are fascinated by high speed, and vendors of high speed scanners use this as a selling argument. First of all, the total time for a successful scan should be taken into account. As an example, the Agfa Horizon needs 2 min to scan, transfer to swap disk space of the host computer and display in a window, a 30 Mb image. The scanner can mechanically move the 15,000 linear CCDs at up to 100mm/s, which means for a 1200 dpi resolution a grey level image of 15,000 x 4724 pixels could be scanned in 1 sec., i.e. a 71 MHz bandwidth. The electronics of the scanner have however a maximum bandwidth of 15 MHz, so the maximum scanning speed that can be realised in this case is 21 mm/sec. The same realisable maximum scanning speed is enforced because of the signal integration time of 1 ms, i.e. in one second 1000 pixels with 21.17 μm pixel size can be scanned. With 15 MHz bandwidth the 30 Mb image can be scanned in 2 sec. The majority of the required 2 min is for transfer of the data via the SCSI interface (max transfer rate 1.5 Mb/sec) to the host and for saving the data on disk. That means that the physical scanning process could be much slower without increasing considerably the overall time, i.e. with a 30 times slower scanning rate (0.5 MHz) the overall time would be 3 instead of 2 min (actually Horizon permits only a 4 times slowing scanning rate as the minimum scanning speed is 5 mm/s). This is still not the total time needed for a successful scan. The time needed to set and optimise the scanning parameters can be much more than the time required to do the final scan (it has been reported that a very expensive photogrammetric scanner needed 0.5 h for a high resolution scan of an aerial image, but 1 h was needed to set the appropriate scanning parameters, see also Colomer, 1993). In
certain cases, as with the Agfa Horizon, a successfully scanned image must be transferred from
the swap disk space to the disk space allocated to the users. For the Agfa Horizon this
procedure needs 6 min for a 30 Mb image, so it is 3 times more than the time required for a
successful scan. The digitisation of the image is just one part in the processing chain. Usually
other processes follow, like ortho-image and DTM generation, mapping etc., i.e. procedures
that require much more time than the scanning itself. As a conclusion, the scanning speed
could be much slower without any significant reduction in production throughput. The
reduction of the scanning speed would have several advantages: the scanning mechanism
(mechanical, optical, etc.) could be slower which means simpler, cheaper and stabler
components; the integration time could be increased which means higher signal to noise ratio,
and no need for powerful illumination which is expensive and generates a lot of heat,
influencing the optomechanical and electronic parts, and requiring expensive and dust inducing
cooling mechanisms; vibrations in the scanning direction could be avoided or reduced; the
smear in the moving direction depends on the product (scanning speed * integration time), so it
could be decreased if the integration time is increased less than the scanning speed is
decreased; 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 image buffers in the
scanner that are 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.

1.2.7 The question of required geometric resolution

The required geometric resolution clearly depends on the application and the user
requirements. For DTM generation, there are many published good results that were achieved
with pixel sizes of 10 - 30 μm. Krzystek, 1992 reports accuracy comparisons for DTM
generation between images scanned with 15 and 30 μm at a Zeiss/Integraph PS 1. The
accuracy difference between the two versions was small and the 30 μm version had an
accuracy of ca. 0.1 ‰ of the flying height. For measurement of fiducials which can be
measured with least squares matching with an accuracy of less than 0.1 pixel, a resolution of
1200 dpi completely suffices, 600 dpi is also adequate. Problems may occur with signalised
control points. With their standard size (optimised for the measuring mark of an analytical
plotter) a 1200 dpi resolution is almost the minimum for their accurate measurement. For
ortho-image generation many people claim that the resolution can be fairly low, e.g. 20-40 μm
or even lower. The argument they use is that for creating a sufficient quality hardcopy with
accuracy similar to those of printed maps or even lower this resolution suffices (Leberl,
1992b). However, the digital ortho-images can be used, and there lies their value, in
applications that require higher resolution and accuracy, as in updating of topographic maps.
For high geometric accuracy, a 600 - 1200 dpi resolution may be sufficient but for visual
interpretation an even higher resolution might be desirable especially in urban and forested
areas. Ideally the full resolution of the film should be reproduced, which given that high
resolution films and aerial cameras with forward motion compensation can result in 60 Lp/mm
(Meier, 1984) and assuming that to resolve a linepair ca. 3 pixels are required due to phase
differences, this would require a pixel size of 5.5 μm and an image size of 1714 MB. However,
the visual interpretation can also be improved by other means than resolution, as digital image enhancement, use of colour, oversampling, and stereo viewing. In addition, the overall image quality does not only depend on pixel size. The quality depends on the characteristics of the whole imaging system including illumination, optics, filters, sensor, A/D converter, hardware and software processing etc. and to overestimate the importance of pixel size would be wrong. Although there are rapid developments in computer technology, huge data sets resulting from a very high scanning resolution (with 8 μm pixel size an aerial image would require 827 Mb) can still not be handled conveniently or not at all. For this reason, owners of high resolution scanners often do not use the highest resolution but a lower one that produces less data (Colomer, 1993, Kiefer, 1993). From a practical point of view, today the limit for a practical handling and interactive work seems to be around 15 - 20 μm. In the opinion of the author a resolution of 1200 dpi is sufficient for almost all measurement purposes. The main limitation is the interpretation of fine details, and the signalisation of control points especially for high altitude flights, but with the help of GPS this problem can be circumvented, or the orientation can be performed at an analytical plotter. Le Poole, 1992 claims that the MTF of films is rather the same for different emulsions (grain sizes) with a value of around 50 % or less at 40 Lp/mm. Thus, he concludes that for a faithful digitisation a 10 μm pixel size is needed. Leberl, 1992a also presents different arguments regarding the optimal pixel size and in Leberl, 1992b a slightly different opinion. Baehr, 1992 discusses the appropriate pixel size for ortho-images and proposes the use of variable pixel size within the same image and depending on the application. Diehl, 1990, discusses the effect of graininess on the radiometric noise in digitised images. He states that for 7.5 μm pixel sizes the radiometric noise due to graininess can amount to more than 20 % of the signal, while for larger pixel sizes it is much less. Hempenius and Xuan, 1986 report on optimal parameters for digitising aerial images. Trinder, 1987 mentions that a pixel size of 25 μm is adequate for pointing and interpretation, but systematic measuring errors of 0.2 pixels (however with manual pointing) require a pixel size of 10 μm in order to preserve the precision of the image geometry. Trinder, 1989 uses synthetic images and reports tests on the influence of image quality, quantisation level, target size in pixels, and SNR on the precision of target location. Systematic errors can be significant if there is substantial asymmetry in the target intensity profile.

1.2.8 Literature overview

It is surprising how little has been reported up to now about the performance of scanners. As an example, although the Zeiss/Intergraph PS 1 was introduced in 1989 and Helava’s HAI 100 (DSW 100) even earlier, there is no published independent report on the performance of these scanners as far as the author knows (with the exception of a very recent and brief report in Colomer, 1993). This is even more surprising since the cost of such scanners is enormous, while for other much cheaper input devices, like CCD cameras, there are hundreds if not thousands of published papers. In the following an overview of publications on scanners and related subjects will be given.

A survey of scanners (but with incomplete data and omitting many scanners) is published in Geodetic Information magazine, January 1993. Aslund et al., 1977 describe the IRIS comparator/scanner, and Hanf and Deter, 1983 the FEAG scanner/plotter, Brown, 1987 reports

Accuracy analysis of scanners are published by Johannsen, 1976, and Lichtner, 1981. Boochs, 1984 reports on tests and accuracy analysis of drum scanners mentioning that they exhibit significant geometric errors. A comparison of flatted DTP scanners is given by Matazzoni, 1991, Diehl and Edwards, 1992, and Seiter, 1993. Bosma et al., 1989 give an evaluation of low-cost scanners, Steiger, 1991 make a quality comparison between colour DeskTop Reproduction and Electronic Image Processing scanners. Sarjakoski, 1992 reports on the Sharp JX 600 DTP scanner and the development of a calibration procedure with an accuracy of 0.2 pixel (8 \( \mu \text{m} \)) - he also reports in other tests an accuracy of 0.1 pixel. His results are too optimistic because all blunders larger than 30 \( \mu \text{m} \) had been removed (actually often errors of +/- 60 \( \mu \text{m} \) occurred). Klaver and Walker, 1992 report that the same scanner without calibration has sometimes local errors up to 170 \( \mu \text{m} \). Chen and Schenk, 1992 present a low-cost transparency scanner made from off-the-self components, its calibration and its accuracy.

Guelch, 1986, Baltavias, 1988, Wilkins 1990, Fuchs and Ruwiedel, 1992, deal with CCDs mounted at analytical plotters, their use as scanners, and their calibration.

Thompson and Quellette, 1972 discuss the accuracy requirements of scanners. Makarovic and Tempfli, 1979 report on image digitisation for automatic photogrammetric processing. Gruen and Slater, 1983 present a strategy for testing the radiometric and geometric performance of high resolution scanners. Ehlers, 1991 reports on digitising and photogrammetric requirements. Diehl, 1992, discusses the optimal digitisation steps for usual films. Boberg, 1992 presents results from a subjective evaluation of image quality, and reports that image sharpness had the largest influence on quality assessment, while mean density, contrast and granularity had a smaller influence. Schroeder, 1992 discusses the spatial resolution of a linear CCD in terms of the optical transfer theory. Baehr, 1988 presents different methods for measuring the geometric resolution of digital cameras in general and in relation to specific applications. There are hundreds of papers on geometric and radiometric analysis of CCDs and many of them are useful, as most scanners employ linear or area CCDs. Because of space limitations we will restrict ourselves to Beyer, 1992 where many radiometric and geometric tests are presented, as well as a large reference list.

2. DESCRIPTION OF AGFA HORIZON

The basic characteristics of Agfa Horizon are:

- Scanning system: 3 optically butted linear CCDs Toshiba TCD 141 (3 x 5,000 pixels)
- Scan mode: colour (3 x 8 or 10 bit/pixel), grey level (8 or 10 bit/pixel), line-art (1 bit/pixel), halftone (Unix software supports only 8 bit/pixel for colour and grey level)
- Scan resolution: 20 (50 for the Unix-based system) - 1200 dpi, interpolated 2400 dpi for line-art and grey level (latter case not implemented in the Unix-based system)
- A/D conversion: 12 bit
- Internal image memory: 8 Mb, optionally 32 Mb
- Originals: reflective (any thickness, 297 x 420 mm), transparent (217 x 340 mm, with firmware change 242 x 360 mm)
- Illumination: 2 halogen lamps, 400 W
- Lens (Agfa made): 3/1 object magnification, 107 mm focal length
- Density: range 3D, maximum density detected 3.3D ; auto density control, set black and white point, editable tone curves
- Interface: SCSI-2 ; image passing modes to the host: FIFO or start/stop/transfer mode with multiple partial scans
- Computer support (incl. software): Mac (Photoshop, Letraset ColorStudio, QuarkX-Press, with a Desk Accessory scanning can be started from any Macintosh programme), PC (PC View Color), Sun (PRESS View Color, Pixel!FM)
- Scanning time: 2 min (real time) for 30 Mb for scanning, transfer, storage on swap disk space and display (on Sun Sparc 2); scanning speed 5 - 100 mm/s (max speed that can be realised for grey level images is ca. 20 mm/s); integration time 1 ms
- Driving system: 400 step stepping motor
- Colour scanning: 3 passes, dichroic filters with > 75% transmission
- Other characteristics: calibration of the illumination before each scan ; user-defined tone curves and unsharp masking in real time ; lifespan 7 years ; IR, IR/UV filters ; preview and scan area selection ; TIFF, Sunraster, EPS, Icon file formats ; descreening ; two optional slide holders (24 x 35 mm, 6 x 6 cm etc.)
- Price: 41,500 SFr. + 3,700 SFr. for software + 6,000 SFr. for 32 Mb memory option.

The software related characteristics are applicable for the PRESS View Color Sun-based software, driver and firmware. There are some other functions that can be executed via existing hardware in real-time but they have not been implemented yet, e.g. horizontal and vertical flip, reverse video etc. After many years of development Agfa does not support any more PRESS View Color. As alternative software package for Unix-based systems, Pixel!FM of the company Mentalix can be used. It may even support workstations other than Sun.

Figure 3 shows the main components of the Horizon.
Figure 3. Horizon main components (front view): a. adjustable mirror, b. mirror carriage, c. lens and diaphragm, d. beam splitter with three CCDs, e. lighting unit.

Figure 4 shows the beam splitter. It is a firm hybrid component consisting of 3 CCDs and a beam splitting mirror. The beam splitting mirror provides an identical image in two perpendicular planes. The CCDs are glued to the beam splitter with high accuracy ($\pm 2$ $\mu$m).

Figure 4. Beam splitter.

Figure 5 shows the main components of the zoombox transport system (the main steel cable and the return wheel are not shown). The zoombox is one large optical block weighting ca. 10 kg, which can be moved over the total A3 length. It contains a lighting unit,
mirrors, a colour filter wheel, a lens plus diaphragm, the beam splitter, one analogue video board, motors, sensors and one motor control board. The zoombox glides through the main housing on two skates, which are guided by the gliding bar and are driven by a stepper motor and a cable system. Positioning is controlled by the motor steps. The positioning accuracy is ca. 10 μm. The steel cable is tensioned by a spring and twisted around the motor axis. The zoombox skates are two large blade springs that press the zoombox against the glass plate in order to obtain a uniformly focused image across the scan area. The friction blocks of the skates glide at the bottom of the scanner housing over two guiding strips with a minimum of erosion. At the top, wheels attached to the zoombox ride against the glass plate.

Figure 5. Zoombox transport components: a. zoombox carriage, b. linear ball bearing, c. gliding bar, d. cable bearing wheel, e. main drive spring, f. horizontal return wheel, g. main motor.
Figure 6. Main circuit boards and video data stream.

Figure 6 shows the main circuit boards and the video data stream. The analogue video signals from the 3 CCDs are multiplexed and amplified on the AMX board, which is attached to the zoombox. Six daughter boards (for even and odd sensor elements of the 3 CCDs) monitor the video signal quality for dark signal drift and noise reduction. A video coax cable transports the video signal at a rate of 15 MHz to the ANA board in the lower section of the Horizon. The black and white corrections are applied using information from the shading RAMs. The correction values are stored in the RAMs by a calibration procedure which is executed before each scan. They are read during each scan line and are added to the analogue video signal after 12-bit D/A conversion. The black correction is related to the dark current and dark current differences among the sensor elements. The order of magnitude of this error is ca. 1%. It is visible as vertical stripes in the dark shades of an image and depends on the amount of exposure. The white correction relates to the different light sensitivities (gain) of the sensor elements. In addition, the illumination is never 100% uniformly spread over the total scan line. Dust may also be a cause. The order of magnitude of this error is ca. 10% and it is visible as vertical stripes in the low and medium density ranges of the image.
The pre-scaler multiplication controls the necessary amplification of the video signal, and is a function of lamp intensity, scanning speed etc. After a 10 bit A/D conversion, the ASIC ZORO demultiplexes the video signal and performs down-zooming of the image to a coarser resolution. Electronic zooming is an alternative to optical zooming and has the advantage that the lens - CCD distance remains fixed. It has however other disadvantages as it will be shown in point 7 of section 3.1.) Unsharp masking (USM) for edge sharpening can be applied in real time by using a $3 \times 3$ filter mask and adding the inverted second derivatives of the grey levels to the original signal. USM is locally adaptive and proportional to the contrast over grain ratio. The contrast enhancement is applied by amplifying the high frequencies of the signal more than the lower ones. Through bilinear interpolation a higher resolution can be achieved. The screener can convert the image to a 1-bit halftone image for printing purposes. The digital video signal is clocked at 15Mpixels/s (without processing).

![Figure 7. Left: original image. Middle: after edge enhancement (USM). Right: after more edge enhancement.](image)

The existing software (PRESS View Color) is generally positive. It is easy to use, has the basic modules for input/output of images, scanning, image handling and display, processing, and image and colour editing. Scanning is performed easily and fast. The automatic density control works very well, and user-definable tone curves (including inversion and binarisation) can be downloaded to the scanner and applied in real time. The only problem in scanning is that it may be interrupted either by an inexplicable error message (which occurred seldomly) or because the illumination is automatically turned-off to avoid overheating. The processing routines are rather primitive and include sharpening, smoothing, noise removal and edge enhancement. Their effect is coarse, and the edge enhancement (USM) creates a lot of artifacts at the edges (Figure 7). A positive aspect of these routines is that they can be applied to ROIs (closed contour with an arbitrary shape) with an undo possibility. Gamma corrections, inversion and binarisation can also be applied.
a posteriori. Software for vectorisation of contours and lines using a Bezier or linear approximation exists, but preliminary tests showed a poor performance, slow execution and often execution failure. Basic, very useful features that are missing include histogram calculations and measurement of pixel coordinates. Image handling and display are convenient with the exception of the zoom factor which is limited when a maximum image size is reached, i.e. one can not zoom a lot with large images. The memory management is not efficient. After scanning and display, the images are stored in the swap disk space. Since this is limited (in our case 320 Mb), one can not scan continuously images because even if the images are in between stored on the user disk space, their space in swap disk space is not freed. Thus, in order to continue scanning one has to exit the program, the swap space is cleared (a very slow process with this software), and the program has to be started again. A last problem is the fact that the image storage is very slow. The storage rate on a Sun Sparc 2 (scanner host) over the network to the Sun server is 5 Mb/min, slower than our own programs by a factor of ca. 10.

3. TESTS OF AGFA HORIZON

Scanners, even DTP ones, are extremely complex and sensitive devices. Different sources like radio frequencies, magnetic fields that cause electrical noise, power supply etc. can have a great influence on the scanner performance. Even if these possible error sources are ignored, there are still a lot of components to be checked and calibrated. In the case of Horizon different calibrations are performed: automatic calibrations in factory, service calibrations (start-up or periodic), and calibrations before each scan. Each one of them consists of several calibration procedures, e.g. in service calibration twelve different components are tested and calibrated. Both hardware and software calibrations are executed. All software calibration results are stored and the corrections are performed before or during scanning, i.e. no software postprocessing of the images is performed. Some calibration procedures are not supported for transparent material. For calibration Agfa is using scan patterns, patterns that are permanently within the scanner, and different calibration devices. The calibration patterns are in certain cases not stable or accurate enough, particularly for an accurate geometric calibration. To give an idea of the possible amount of errors it is enough to mention that Agfa lists 29 topics under service trouble shooting, and 14 under image trouble shooting, most of them with many possible causes and correction measures. This number may be frightening but it also shows that Agfa paid attention to calibration, and at least the possible errors are known, even if they are not always corrected. This is also proven by image quality specifications and tolerances given by Agfa on 19 topics. In our experience most of these tolerances are met.

The tests were performed in 3 stages. Firstly, before buying the scanner by using the scanner of the Agfa office in Zurich. Unfortunately, due to limited swap disk space, large images and test patterns could not be scanned with 1200 dpi. Thus, some errors were not detected at this stage. The second and most extensive test was after buying the scanner. Some of the occurring errors were, according to Agfa, due to this specific scanner that was bought, so the scanner was replaced and the tests were repeated. The type of errors remained the same. Their magnitude, however, was different but their variations were not large. These variations
are due to scanner instabilities and fabrication tolerances. No specific tests were performed in order to check the repeatability of the errors, but since the tests were extensive, were performed at least twice and extended over a period of several months some conclusions on error repeatability can be drawn. The tests concentrated on scanning transparent material, mainly grey level, and to a much lesser extent colour. The tests will be divided in radiometric, and geometric tests.

Figure 8. Test plates from Heidenhain.

For testing we used aerial films of high dynamic range (both B/W and colour), some self-produced test patterns (see Figure 19), and the following commercially available test plates. A test plate of a Wild STK comparator with 23 x 23 grid lines with 1 cm interval and a thickness of ca. 40 µm was the main test pattern. The coordinates of the grid nodes were measured at a Wild AC3 analytical plotter. High quality test plates from Heidenhain (Dr. Johannes Heidenhain GmbH, Dr.-Johannes-Heidenhain-Str. 5, D-8225, Traunreut, Germany) were also used (see Figure 8). Plates 7 a) and 7 b) were used mainly to check the geometric resolution, so their use is partly overlapping. Plate 7 c) is useful to check the visual appearance of important features like lines and dots, in relation to the feature size. Some other test patterns to check the radiometric quality and colour quality were available but were used to a limited extent (see point 11. in section 3.1.). Finally, some of the tests were performed without any material, i.e. just the scanner glass plate was scanned. Other companies that sell different test patterns, even custom-tailored are Teledyne Gurley (514
Fulton St., Troy, NY 12181, USA) and Max Levy Autograph Inc. (220 West Roberts Ave., Philadelphia, PA 19144-4298, USA).

In scanner tests the highest possible true geometric resolution should be used, otherwise some errors are not visible, or can not be quantified precisely. Additionally, for radiometric tests it is useful (i) to choose the density range of the scanner such that errors are amplified, and (ii) use postprocessing functions (gamma corrections, contrast enhancement) again in order to amplify the errors and make them visible. After the errors are detected, their quantification can be based on images scanned under “normal” operational conditions.

3.1. RADIOMETRIC TESTS

Radiometry is often underestimated in scanner testing, especially in the photogrammetric community. However, good radiometric performance is of major concern even for expensive photogrammetric scanners as Figure 1 and Figure 2 show. The here presented tests are not complete and include the following.

1. Photo Response Non-Uniformity (PRNU)

It was tested by scanning homogeneous areas (the scanner glass plate, or the test grid plate). In these uniform areas the standard deviation of the grey levels was computed and found to be 1.5 - 2 grey levels. Care was taken to avoid areas including dust etc.

2. Vertical stripes

In uniform areas, black and particular bright vertical stripes can occur (see left part of Figure 9). The grey level difference of these stripes from the neighbourhood is however very small, in the order of 2-3 grey levels. More serious problems can occur, if dust exists on the calibration slit. This slit is used for a pre-scan calibration and automatic density control. If dust exists on the slit, then wrong correction values are computed for the underlying sensor elements, and very noticeable vertical stripes occur, having a width proportional to the width of the dust particles (see right part of Figure 9). The slit can be cleaned from above, but dust can be deposited in the lower part of the calibration slit (interior of the scanner), because the
scanner has openings for the cooling fans. The same error will clearly occur if dust exists on other parts like sensor elements, mirrors or lens.

Figure 9. Vertical stripes and horizontal banding (exaggerated for better visualisation).

3. Horizontal banding

This error is again visible in uniform areas (see Figure 9) but has a small magnitude. Agfa mentions as probable cause of this error, the lack of installation of a “power π” filter, but it is unknown to us what this means.

4. Echoes

Echo or ghost images are parts of an image that are repeated in another part of the image. This error is mainly due to the multiplexed read-out of the signal, i.e. the sequence of the pixels is pixel 1 of CCD1, pixel 1 of CCD2, pixel 1 of CCD3, pixel 2 of CCD1, pixel 2 of CCD2 etc. This means that adjacent information in the video signal does not refer to adjacent elements in the original image. This may cause sharp transitions in the analogue signal. When electronic circuits begin to fail, echo problems may occur. Another cause maybe the unwanted reflection of light in the optical path (secondary reflections). Echoes may be visible and occur at sharp edges. In the case of multiplexing, the edge will be repeated in all three partial images (one from each CCD). The error will be particularly
visible when a bright object in one CCD falls on a dark area in the other two CCDs and vice versa. Examples of such errors are shown in Figure 10.

![Echoes](image)

Figure 10. Echoes. Top: border of a scanned aerial film (full width covering all 3 linear CCDs). Middle left: the letter S is repeated to the left and right of its position (error due to secondary reflections). Middle right: LK 225 and 6298 coming from the 1st and 2nd linear CCD are repeated in the 3rd CCD (error due to multiplexing). Bottom: the multiplexing error occurs even if a bright object falls onto bright background (here the image is stretched with a gamma of 0.05 for visualisation purposes; the multiplexing error in the original image was ca. 1 grey level).

5. Dynamic range

As a test, films with high dynamic range were scanned. The films included the snow-covered Alps, shadow areas, dark forested areas all in the same image simultaneously. In addition, the very dark border of the film was also scanned. Automatic density control was used and the result was checked visually and for saturation. By changing the LUT of individual grey levels, e.g. 0 and 255, and displaying them in color saturated areas can be easily detected. However, Horizon gave very good quality images without saturation, for images with a density range of over 2D.

6. Radiometric differences along the borders of partial scans
This error is related to a geometric error and will be treated in the section on geometric tests.

7. Subsampling errors

The horizontal scanning always occurs at 1200 dpi. For down-zooming (subsampling) the signal is first low-pass filtered and then resampled (fast interpolation in hardware). In vertical direction, down-zooming is obtained by speed control of the zoombox. Scanners that do not have an optical zoom facility (with the exception of scanners employing microscanning) use similar procedures for subsampling, whereby the area based CCDs use low-pass filtering and resampling in both directions. This way of subsampling creates different problems. Horizontal lines may totally disappear if they lie in the gap between two consecutive positions of the CCD lines. Since low-pass filtering and resampling occurs only in horizontal direction, the two directions are treated differently. To check these problems the test plate of Figure 8 c) was used. The plate has 17 lines/dots of width/diameter from 100 to 3 µm. The distance between the lines and their length is 2 mm. Figure 11 shows the plate with the lines in horizontal direction (the displayed images has been rotated by 90 degrees) and a scanning resolution of 600 dpi. The top image of the Figure shows a grey level profile along the middle of the lines. Since the lines are of decreasing width, the contrast of the lines should monotonically decrease. This is not exactly the case, but approximately so. This can also be observed in Figure 14 that shows the modulation M of the lines \( M = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \). The bottom image of Figure 10 shows a profile along a line with a uniform grey level distribution along the line. So, when subsampling by factor two, no significant errors occur. All lines are visible, although with a continuously decreasing contrast as the line thickness decreases. The dots are visible up to 20 µm size. Figure 12 and Figure 13 show similar results for a scanning resolution of 150 dpi and horizontal and vertical lines respectively. In Figure 12 some horizontal lines almost disappear, as it was expected, since they lie in the gap of 148 µm between two consecutive positions of the CCD lines. As Figure 14 shows the modulation is not monotonically decreasing with decreasing line width. The 50 µm thick line has a higher contrast than the 100 µm line, while the 10 µm line has a similar contrast as the same line scanned with 600 dpi! Thin lines of even 3 µm width are visible because the contrast of the lines of the glass plate is high and the effective pixel dimension in the scanning direction is 21.2 µm (1200 dpi). The grey level profile along a line is homogeneous as it can be seen in the right image of Figure 12. The dots are visible up to 30 µm size. The results of Figure 13 are unexpected and difficult to explain. The top image of the Figure as well as Figure 14 show a very nonmonotonic modulation. The 20 µm thick line has a similar contrast as the 100 µm line, and a much higher contrast than the same line scanned with 600 dpi! Many lines are hardly visible (actually the horizontal lines of Figure 12 are better visible, contrary to the expectations). There is no explanation for this other than that the low-pass filtering and resampling have not been implemented properly. The bottom image of Figure 13 also shows that the grey level profile along a line has many discontinuities. This may be due to the fact that neighbouring pixels along the line are actually 169 µm apart due to the gap between two consecutive positions of the CCD lines. Only the dots of 100, 30, 25, and 20 µm size are visible.
As a conclusion subsampling by a factor more than 2 should be avoided. Actually, the ideal solution is to always scan with full resolution and then use an image pyramid generation algorithm for a proper subsampling.

Figure 11. Top: grey level profile along horizontal lines (displayed image has been rotated by 90 degrees) of different thickness scanned with 600 dpi. Bottom: grey level profile along one line.
Figure 12. Left: grey level profile along horizontal lines of different thickness scanned with 150 dpi. Right: grey level profile along one line.
Figure 13. Top: grey level profile along vertical lines of different thickness scanned with 150 dpi. Bottom: grey level profile along one line.
Figure 14. Modulation (contrast) for lines of different width and different scanning resolutions. Top left: horizontal lines (in CCD direction) with 600 dpi. Top right: horizontal lines with 150 dpi. Bottom: vertical lines (in scanning direction) with 150 dpi.

8. Oversampling errors

Oversampling should theoretically be possible for B/W and grey level images. With PRESS View Color however it can be performed only for B/W images. Even this operation does not function properly as Figure 15 shows. There are vertical streaks every two lines, and the lines with the error in the upper part of the thick black line of the right image of Figure 15 are shifted in x-direction by 1 pixel in comparison to the lines with the error at the lower part.
9. Smear

It is caused by the movement of the zoombox in vertical direction and it is proportional to the scanning speed. Thus, sharp edges are defocused, i.e. their contrast is decreased and they become wider (Figure 16). Agfa mentions a 20% loss of focus in the scanning direction, whereby in our results with the grid test plate, the vertical lines were 2 pixels wide, but the horizontal lines 2.5 - 3 pixels. This smearing also decreases the resolution in the scanning direction.

![Figure 16. Smear of horizontal lines](image)

10. Different noise patterns between the 3 CCDs
This effect has been observed, e.g. in the 4 linear CCDs of SPOT. For this purpose a horizontal stripe of the grid test plate was scanned. A low-passed filtered version of this image was subtracted from the original to detect the noise, and the result was normalised. The noise pattern in the vertical swath of each CCD was visually inspected but no difference among the 3 CCDs was found.

11. Other image quality tests

For this purpose different test patterns can be used. The UGRA/FOGRA (UGRA/FOGGRA, 1988) reproduction test chart is a 20 x 27 cm photograph (cost 250 SFr.) which can be used for control of tonal rendering, colour rendering, gray balance, image reproduction, and image quality, e.g. defects such as dominant colour casts, improper grey balance, graininess etc. Kodak sells photographic step tablets (transparencies) with up to 21 density steps in 0.15 spacing and a 250 mm length, and colour separation guides and gray scales. A gray scale with 20 density steps with 0.1 spacing (0 - 1.9D) was scanned with the Horizon. The results are not conclusive because the grey scale was old and partly dirty and because for a good test of the radiometric quality much more than 20 density steps are needed. In any case, the automatic density control determined almost exactly the minimum and maximum density and the density difference between neighbouring steps was generally correct.

Concluding, Horizon has a pretty good radiometric performance with the main errors being the echoes due to multiplexing, the smear in the scanning direction (not a radiometric problem in principle) and the dust problems which are however a problem common for most scanners.

3.2. GEOMETRIC TESTS

The following geometric tests were performed.

1. Nonalignment of the 3 CCDs

For this purpose the horizontal lines of the grid test plate were used (actually one line suffices) and scanned over the whole possible width. Knowing the approximate position of the transition from one CCD to the other the horizontal line was checked for discontinuities. If a discontinuity was visually detected, then the vertical position of the line on either side of the discontinuity was determined using least squares template matching and the misalignment error was quantified. In the old scanner, the error between two of the CCDs was 0.3 pixels (Figure 17), in the new scanner no error was observed. This type of error is more or less constant over time. It can not be corrected so easily in real time using hardware because it requires transformation and resampling in both CCD and scanning directions. The same test pattern can be used to detect more general errors caused by noncolinear CCDs. However, overlap errors can not be detected by this pattern. Only about 4,777 sensor elements from each CCD are used for the image composition. An error in the correct detection of the last active pixel of one CCD and the first one of the next CCD will lead to gaps or overlaps, i.e. global shifts of all elements of the next CCD, and scale differences. For calibration, patterns
similar to those mentioned in 4. below (i.e. inclined lines) or two known distances (e.g. 3 crosses, one for each CCD) can be used.

![Figure 17. Misalignment between two linear CCDs.](image)

2. Vibrations

Vibrations in horizontal directions were detected using the grid test plate. The vibration (shift) was constant within each scanline. The vibrations caused the straight lines to be imaged as a sine curve (Figure 18). The vibrations do not occur continuously along the scan direction and they tend to be more frequent and pronounced towards the end of the scan. In the old scanner the maximum amplitude of the sine function was ca. 0.5 pixels, in the new scanner 0.1 - 0.2 pixels. This error is particularly disturbing because it is not stable, so it must be corrected for each scanning. As test pattern a thin line in the vertical direction along the image border can be scanned (see Figure 19). The line must not be known, but it must have high contrast and must be straight. Using image processing the edge points can be detected, a straight line fit can be computed, and the residuals from this fit will give the position and the amount of the errors. These errors can be corrected a posteriori by a linear transformation and resampling in the horizontal direction only for the lines where such vibrations occur.

![Figure 18. Vibrations in horizontal (CCD) direction (displayed image has been rotated by 90 degrees).](image)

Agfa mentions also vibrations in the vertical direction. We could not detect such vibrations. Possible reasons for that are: (i) the smear in the vertical direction which could mask the vibrations, and especially (ii) the fact that the spacing between the horizontal lines of the grid test plate was too large (1 cm), so vibrations which could have occurred between the lines can not be detected with this test pattern. Vertical vibrations cause nonuniform movement in the scanning direction, effect which can also be caused by a poor mechanical positioning mechanism.
3. Lens distortion and scale differences in horizontal direction

To check this, the grid test plate was scanned. The distances between the grid nodes at
the left and right border, and at the center of the grid plate were computed after estimating
the grid node position by least squares template matching. At the borders a distance of 1 cm
was 469.5 - 470 pixels, while at the center 475 pixels. This corresponds to pixel sizes of
21.30 - 21.28 µm, and 21.05 µm respectively, while with a 1200 dpi scanning a pixel size of
21.17 µm should be expected. These errors although large, are relatively stable over time,
and in theory they could be corrected in real-time by using the Horizon hardware. After a
calibration, correction values (horizontal shifts) could be saved in a LUT and a linear
transformation and resampling could be performed.

Figure 19. Self-made test patterns used for correction of vibration and partial image scan-
ingen errors (displayed image has been rotated by 90 degrees).

4. Partial image scanning

This is a peculiarity of Horizon. When the image to be scanned is larger than the image
buffer of the scanner (32 Mb in our case), then a partial image with size equal to the frame
buffer is first scanned, the zoombox moves to the start position, the image data are
transferred to the host, the zoombox is positioned after the end of the previous partial scan,
the next partial image is scanned, and the procedure is repeated until the whole image is
scanned. These partial images have an overlap. To scan an aerial image with 1200 dpi 4-5
partial images are needed. The overlap error was quantified by using a self-made pattern
consisting of high contrast lines, approximately straight, with an inclination of 45 degrees
with respect to the horizontal direction (see Figure 19). At the position of the overlap error
the lines were broken (see Figure 20), and by using again least squares template matching
(other image processing procedures could also have been used) the error could be quantified.
The error was typically 2 pixels between 1st and 2nd partial image, 3 pixels between 2nd
and 3rd partial image, and 3.5 pixels between 3rd and 4th partial image.
Figure 20. Test pattern and overlap error. From left to right between 1st and 2nd, 2nd and 3rd, 3rd and 4th partial images.

Although there were small variations the error magnitude was fairly constant in both old and new scanner, and was always increasing towards the end of the scan. Apart from the geometric error there were also small, but in many cases visible, radiometric differences at the border between two partial images, due to illumination instabilities. Our interpretation was that the scanner had not a precise enough positioning system, and such errors are known to increase with increasing distance from the zero point of the transport mechanism. After months of discussions with Agfa, and possible explanations from their side which were all wrong, we were informed that this problem occurs only with the Unix-based systems and is due to the driver. To test this, a grid test plate was scanned at a Mac-based Horizon with 8 Mb image buffer at the Federal Office of Topography in Bern. With 8 Mb image buffer, there are a lot of partial images, and the overlap error between neighbouring images may not be visible. However, if this error would have occurred, then distances between an increasing number of partial images would have been shorter and shorter. A comparison of the known distances between grid nodes in the vertical direction, with the distances measured in the image, indicated that no overlap error occurred. Whether this statement can be generalised, is unknown.

5. Colour misregistration

To test the colour registration between the R,G,B channels high contrast B/W edges in vertical and horizontal direction are useful. Thus, the test plate of Figure 8 a) was used. In the old scanner the misregistration was clearly larger in vertical direction, due to mechanical positioning errors. Although Agfa gives a tolerance of 1 pixel, the error in vertical direction was ca. 2 pixels. A quantification of the error is possible with visual, manual measurements and even better by separating the three channels in 3 files and then measuring corresponding features, e.g. corners, in all three channels. In the new scanner, the situation was opposite. The error in the vertical direction was in the 1 pixel range, but in the horizontal direction it was ca. 2 pixels. Possible error sources include the lens (unknown whether it is apochromatical) or differences in the colour filters, each of which acts as a lens.

The test plate of Figure 8 a) was visually inspected and the smallest group of 3 line pairs that could be discerned was detected. This corresponded to 17 Lp/mm (i.e. 29.4 µm line width) for the vertical lines and 20 Lp/mm (25 µm line width) for the horizontal ones, while after unsharp masking it was increased by factor 1.12 or 1.26. Our expectation was that due to smear the resolution would be better for the vertical lines. The plate of Figure 8 b) was also used to determine visually the resolution in the vertical direction, and in this case it was found to be 16.67 Lp/mm (i.e. 30 µm line width). This result, that to resolve a certain signal frequency ca. 50% higher sampling frequency is needed, is in accordance with the expectations and is due to phase differences that may occur between signal and sampling frequency.

7. Deformations

This effect was observed only once, when scanning a poor quality aerial film. At certain regions of the image large deformations were observed. After a slight movement of the film and rescanning, the deformations still existed, but they were different (see Figure 21). There is no clear explanation of this error. However, since at the regions where the deformations occurred, the lines of the grid test plate that was covering the film were not deformed, it seems that the error was due to film deformation.
Figure 21. Top: deformations (probably due to film deformation). Bottom: same as top but after slightly moving the film and rescanning. Deformations still exist but are different. Note that the lines of the grid test plate are not deformed.

8. Global geometric errors

For this purpose, all grid nodes of the grid test plate scanned with 600 dpi was determined by least squares template matching and compared to the known values. In total 492 visible crosses were used. An affine transformation between the two data sets, using all crosses as control points gave an a posteriori standard deviation of unit weight of 52 µm. A quadratic transformation gave a respective value of 47 µm, and the $x^2$, $xy$, and $y^2$ terms in horizontal direction were not significant. This indicates that an increase of the degree of the polynomial does not necessarily lead to large error reductions, and that in scanning direction higher order terms are required. The same procedure was repeated by leaving out the three border columns of the crosses (both left and right). In this case the a posteriori standard
deviation of unit weight was reduced significantly to 31.5 µm and 24.4 µm for the affine and quadratic transformation respectively. This indicates significant errors due to lens distortion.

To simulate a realistic situation of aerial image scanning where only the fiducial marks are used for the interior orientation, we computed an affine and a bilinear transformation, using as control points the 4 corner crosses. The results of the two transformations were very similar, whereby the xy term of the bilinear transformation in the horizontal direction was not significant. Two cases were compared. One by using the 4 corner crosses, most of which were poorly imaged (case A), and a second one by using other better defined crosses in the neighbourhood of the corners (case B). In case A the RMS error was 100 µm in x and 84 µm in y, and in case B 87 µm in x and 78 µm in y. This error magnitude is what should be expected from Horizon without any geometric calibration. With 1200 dpi scanning the error would decrease only insignificantly because the error sources and magnitude remain the same. With a higher scanning resolution, only the matching accuracy could be possibly improved but this gain would be very small compared to the whole error budget. In both cases the residuals of the remaining 488 check points showed very strong systematic patterns, particularly the x-residuals. Figure 22 shows the pattern of the residuals for the first two grid lines. For the other lines similar patterns were observed alternating from line to line. The magnitude of the x-residuals remained nearly constant from line to line, while for the y-residuals it was increasing towards the center of the image.

![Figure 22. Systematic pattern of residuals of check points along horizontal grid lines.](image)

No calibration software has been written yet for the Horizon. It is expected that after calibration the RMS errors will be reduced to under 10 µm. The errors in the CCD direction are relatively stable over time with the exception of the vibrations. The errors that are frequently variable and thus difficult and time consuming to correct are in the scanning direction. The overlap error is fairly simply to detect. The most difficult errors are due to mechanical positioning errors and vibrations that can cause local systematic errors like overlaps, gaps, different pixel sizes and scale differences. These errors are constant within
each scan line, and thus for their detection test patterns on either or both sides of the image could be scanned. These test patterns should include a vertical line for the detection of vibrations and crosses in vertical direction with a small spacing. Only the second pattern must be geometrically precisely known.

4. SCANNER SPECIFICATIONS FOR PHOTOGRAMMETRIC TASKS

An optimal photogrammetric scanner should have the following characteristics:

- Flatbed stage (high geometric accuracy, scanning of rigid documents).
- Optically butted linear CCDs.
  
  many elements per CCD, butted precisely, 3-chip CCD wished, low noise (dark current, fixed pattern, reduced smearing and blooming), no defect pixels, uniform response, high maximum charge storage capacity, read-out without multiplexing of the butted CCDs (i.e. single readout register per CCD array), individual exposure control for each colour channel. An interesting technology is also Time Delay and Integration (TDI) scanning which permits a higher scanning speed or a higher SNR (such a technique is employed e.g. in the Polaroid CS 500 scanner).
- Calibration (radiometric and possibly geometric before each scan), corrections implemented in hardware as much as possible, calibration software and test patterns provided, geometric errors constant over a long time period.
- Variable geometric resolution (with optical zoom or electronic zoom with correct subsampling), highest resolution of at least 1200 dpi.
- 12-bit quantisation with freely definable reduction to 8-bit, density range greater than 2.5D.
- Powerful, uniform, and stable, white illumination, preferably cold light. Avoidance of flare light particularly when scanning transparencies.
- Clean and stable power supply.
- Scan speed not very relevant (10 - 30 min for a 1200 dpi B/W scan) ; user definable.
- Preferably movable stage with all electronics, optics and illumination stationary.
- Flat, anti-Newton glass plates, help to position approximately the document on the glass plate, flat and stable cover.
- Simple optics (mainly filters and lens between illumination and sensor with minimisation of mirrors).
- Software (free setting of scanning parameters, editable tone curves, automatic density control, basic measurement, editing and image processing routines, support of various image formats incl. TIFF).
- Support by various computers, no need of large image buffer, no writing on swap but directly on user disk space, standard interface (SCSI).
• Accurate mechanical positioning in scanning direction (RMS = 0.25 - 0.33 pixel of highest geometric resolution, i.e. smallest pixel size).

• Chromatically corrected lens with low lens distortion (latter not so important, can be corrected by calibration, using hardware eventually in real time).

• No mechanical oscillations.

• Packaging such to avoid dust.

• Scanning of reflective and transparent, binary, B/W and colour documents.

• Scanning format (for aerial images 26 x 28 cm to allow scanning of calibration patterns at the film borders, to account for 30 x 30 and 23 x 46 cm satellite images the format should be 35 x 50 cm). The glass stage and the illuminated area larger by at least 1 cm on each side.

• Price below 100,000 SFr.

5. CONCLUSIONS

DTP scanners can be used for photogrammetric tasks, if they are calibrated, especially in geometry. Some of their components like sensors, electronics, computer platforms, software, and characteristics like radiometric performance and speed are partly equal or better than those of very expensive photogrammetric scanners. The main problems of DTP scanners are positional accuracy, uniformity and repeatability, mechanical instabilities (vibrations), and lens distortion or imperfections of other optical parts (mirrors, filters). Positional accuracy is necessary to avoid overlaps or gaps when scanning in multiple swaths or multiple CCD frames, and colour misregistration errors when scanning in 3 passes. A uniform movement in scanning direction is required to avoid local errors that result in gaps, overlaps and thus also scale differences. Nonuniformities can be caused not only by the positional mechanism but also vibrations in the scanning direction. Even if these requirements are fulfilled, systemic gaps or overlaps over the whole scan length can occur, if there is no exact synchronisation between scanning movement and signal integration/read-out. The previously mentioned problems can be severely reduced by employing better scanning mechanisms (usually mechanical) and lenses. However, even in this case a calibration will still be necessary, as it has been shown by the errors occurring with expensive photogrammetric scanners. The importance of high scanning speed is overestimated. High scanning speed leads to several negative or expensive consequences.

Calibration includes modelling and correction of errors that can generally be divided into two groups:

1. Slow varying errors

   These errors mainly occur in CCD direction and are related to lens distortion and scale differences. Other CCD sensor related errors like CCD misalignment and blemishes are also relatively stable. Calibration of this type of errors is easier as it can be
performed once every a long period of time. Some of the necessary corrections can be applied in real-time during scanning by using off-the-self hardware that read pre-saved correction values and perform 1-D geometric transformations and grey level interpolation. This is particularly the case with linear CCD based scanners. DTP scanners like the Horizon already have such hardware, but it is not used for geometric calibration.

2. Frequently varying errors

Such errors, like scale differences, mainly occur in scanning direction. Errors in CCD direction, like vibrations, also exist. Finally, radiometric errors, e.g. due to illumination instabilities, are in most cases frequently varying. This type of errors require a difficult and time consuming calibration, which must generally be performed for each scan. Thus, test patterns must be scanned together with the images, and the correction must be applied after scanning. The size of the test patterns, e.g. thickness of lines, must be chosen appropriately so that the patterns can be measured precisely for all geometric resolutions that are typically chosen by the user.

Such calibration procedures and test patterns should ideally be supplied by the scanner vendors but this is unfortunately a rare case. However, this task can also be performed by a user, if the necessary expertise and means are available. Calibration is also a way of reducing the scanner costs by avoiding expensive mechanical and optical parts, of course at a cost of a lower scanning throughput.

The geometric accuracy of Agfa Horizon without applying any geometric calibration is ca. 80 µm. This RMS error was estimated using 500 check points, four control points at the corners and an affine transformation. The geometric accuracy potential after calibration can be ca. 10 µm. It may be even lower, if the frequently varying errors are well modelled and corrected for. The errors in CCD direction considerably increase towards the borders of the glass plate, and in scanning direction they increase slightly towards the end of the scan. Surprisingly, the errors in scanning direction, which are more frequently varying and more difficult to correct are smaller than those in CCD direction. The type and the order magnitude of the occurring errors is quite stable.

No errors occur only in the interior of the image, which makes a calibration possible by using test patterns at the borders of the image. Actually, in most cases only one border in each direction (horizontal and vertical) need to be used. In some cases the test patterns can be self-made without requiring an exact knowledge of their geometric characteristics. Even if the latter is a necessity, the patterns can be self-made and measured, e.g. at an analytical plotter. If the base material is stable, e.g. film with thick Estar base, then this measurement procedure must not be repeated very often.

The emergence of several standards in DTP make a brand selection for the user much easier because more products are compatible with each other. Examples include file formats (like TIFF or Kodak Photo CD), compression, colour management (such as Apple’s ColorSync, interfaces (SCSI), and the relatively new TWAIN application program interface (API) which has been adopted by most scanning hardware and software vendors. The
TWAIN API aims to provide a seamless link between compatible products, meaning any TWAIN-compatible software will drive any TWAIN-compatible scanner. In DTP the computers that are mostly used are Macs and to a lesser extent PCs. For this reason when buying a DTP scanner it is worth considering connecting it to such a computer because they are supported more by the scanner vendors, and there are a lot of good and cheap programs related to the scanners.

DTP scanner vendors usually do not know, or if they know they do not care, about the requirements in the photogrammetric community. It is our task, and especially the task of international and national societies, to contact them and conceive them about the photogrammetric/cartographic/GIS market potential, so that they derive appropriate calibration software and also possibly modify the scanners in order to better meet our requirements and ease calibration. The author tried for several months to convince Agfa about the above necessity, unfortunately without success.

With the developments in the DTP scanner market and in low-cost photogrammetric scanners, it should be expected that several good quality scanners will soon be available at a price under 100,000 SFr. Today there are various scanners in this price range, that can or could be used for photogrammetric tasks. In the category of photogrammetric scanners the VX 3000 from Vexcel Imaging Corp., the RM-1 Rastermaster of Wehrli Inc., while International Systemap Corporation has announced the Digital image Scanner (DiSC), a scanner with very good specifications but still unknown performance. The Rollei RS1-C could theoretically also be employed as a scanner but this was very rarely the case. In the DTP category with a minimum resolution of 1200 dpi and sufficiently large format for scanning aerial images, apart from Agfa Horizon, there is the Howtek Scanmaster D4000, and the newly announced Smart 340L from Scitex. It is a 1200 dpi, A3 format, CCD-based flatbed scanner for the Macintosh which can scan reflective or transparent, B/W or colour documents. The Ricoh FS2 is a one-pass colour-CCD, 10-bit quantisation, 1200 dpi scanner of A4 format (according to another publication reflective documents of up to 23 x 37 cm can be scanned) with transparency option, costing 6,300 DM. In the opinion of the author the expensive photogrammetric scanners have no future. For photogrammetric tasks low-cost photogrammetric or DTP scanners will be used, whereby in the latter case the user should in most cases develop calibration software himself.

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Rollei, 1993. Rollei RS1-C. Product brochure, Rollei Fototechnic GmbH, PO Box 3245, 38022, Braunschweig, Germany
3-line color CCD from Dalsa (3 x 2098 contiguous pixels, 3 x 8-bit, 4kHz line rate, 30 MHz sensor data rate, 8 lines separation between the 3 lines, balance of each colour sensitivity independently for a given scanning speed and lighting conditions to achieve maximum dynamic range for all colours). 4096 pels, 7 µm, 60 MHz, 10 µm, 120 MHz sensor data rate, 6000 pels, 10 µm 60 MHz, Technolink (Americas), Cameras 10,000 pels, & MHz, 12,670 $, 5000, 20 MHz, 4775$S, 5000, 10 MHz, 3077$, 7500 10 MHz, 8334 $, Thomson 5184, 7 µm, 4000:1, maximum data rate 20 MHz, 4250 $

TDI technology for imaging in low light or high speed scanning conditions. Much improved sensitivity (noise floor) than comparable linear CCDs, 2048 pels, 13 µm, 120 MHz sensor data rate, 96 TDI stages, 6000 pels, 10 µm.

EG&G Reticon (all with antiblooming) 2048 13 µm, 13,000:1, 20 MHz data rate, TDI 2048 x 32,64,96, 13. µm, 1300:1 120 MHz or 2048 x 64, 27 µm 5500:1, 128 MHz

IDark Signal Non-Uniformity, Photo Response Non-Uniformity, MTF or CTF, Quantum Efficiency (or sensitivity), charge transfer efficiency, dark current noise, smear, blooming, dynamic range, linearity, saturation level, noise floor or Noise Equivalent Power, spectral responsivity, SNR, grey level resolution, maximum charge storage capacity, video data rate.

Joyce-Loebl 2605 drum scanner (12.5-1000 µm, maximum 1000 x 1200 mm, 1-10rev/s, refl and transm., 0-2D or 0-4D, Optronics 5040 drum scanner/laser plotter (12.5 - 200 µm, up to 1000 rev/sec maximum 1270 x 1016 mm only for reflective)