The Agfa Horizon scanner
characteristics, testing and evaluation

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THE AGFA HORIZON SCANNER - CHARACTERISTICS, TESTING AND EVALUATION

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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. Photogrammetric scanners are in most cases expensive, while at the same time they may exhibit significant radiometric errors. DeskTop Publishing (DTP) scanners have low price, and may have a good performance and sufficient resolution for photogrammetric applications. 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 many photogrammetric applications. This paper presents 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

Film scanning is an operation that is necessary in all fields of photogrammetry and particularly in aerial photogrammetry. This necessity will stay for quite some time because currently the production of digital aerial cameras is difficult and expensive. Photogrammetric scanners are still expensive and thus, users and researchers have considered the possibility of using other cheaper alternatives. 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, some flatbed DTP scanners could be considered for such applications. A review of different scanner types, including DTP scanners, and a literature overview is given in Baltsavias and Bill, 1994. The aim of this paper is to examine in more detail the DTP scanners, and especially the Agfa Horizon, and present its major characteristics and problems.

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 (the Unix-based scanner 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: 10 bit (according to Agfa the quantisation accuracy is 12 bit)
- Internal image memory: 8 Mb, optionally 32 Mb
- Originals: reflective (any thickness, 297 x 419 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 (Photolook running within Photoshop, Letraset ColorStudio, QuarkXPress ; with a Desk Accessory scanning can be started from any Macintosh programme), PC (PC View Color), Sun (PRESS View Color), Unix workstations (Pixel!FM of Mentalix, Cameleo of Caldera Systems)
- Scanning time: scanning speed 5 - 100 mm/s (in our UNIX-based system the minimum speed is 2 mm/s for the blue channel and 1200 dpi, and the maximum realisable scanning speed is ca. 80 mm/s for grey level, red or green channel

with 50 dpi) ; integration time 1 ms (see also Table 1)

- 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.

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.

Table 1 shows the scanning times for different resolutions and subtasks. The times refer to a Sparc 2 (64 Mb), a SCSI-2 interface to the scanner, and transfer of the data to the user disk space at a Sun Server via Ethernet. The radiometric calibration (black and white shading corrections) are performed before the scan of each colour channel and before every low resolution scan for automatic density control. The scan time is the time required to physically move the sensor over the scan area. A A3 preview (always at 50 dpi) needs 18 sec, and the setting of the scanning parameters 30 sec. For colour images, the red and green channels need the same scan time as grey level, the blue one needs five times more scan time to account for the low quantum efficiency of the CCD in the blue region. When the image exceeds the 32 Mb image buffer, the total scan time increases because the data transfer to the host becomes for unknown reasons very slow, e.g. a 116 mm x 116 mm image should be scanned with 1200 dpi in colour in 10 min but it needs 19 instead.

Figure 1 shows the main components of the Horizon. The beam splitter is a firm hybrid component consisting of 3 CCDs and a beam splitting prism. The beam splitting prism provides an identical image in two perpendicular planes. According to Agfa the CCDs are glued to the beam splitter with high accuracy (± 2 µm).

A mechanical transport system is used to move the zoombox. The zoombox is one large optical block weighting ca. 10 kg, which can be moved over the total A3 length (see Figure 1). 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 a 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. Agfa specifies that the scan to scan positioning error should be less than 20 µm.

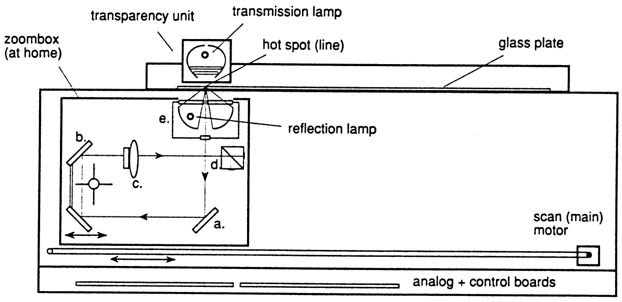


Figure 1. Horizon main components (front view): a. adjustable mirror, b. mirror carriage, c. lens and diaphragm, d. beam splitter with three CCDs, e. lighting unit.

Figure 2 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. 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. Other causes of this error may be illumination nonuniformity and instability, and dust. The order of magnitude of this error is ca. 10% and it is visible as vertical stripes in the low and medium density ranges

Table 1: Scanning times (116 x 116 mm, grey level, reflective image) for the Horizon and different subtasks (in sec)

resolution (dpi)/ image size (Mb)	300/1.88	600/7.5	1200/30
memory allocation	4	4	15 - 30
radiometric calibration	2	3	3
scan time/ speed (mm/s)	2.5/50	5/25	9.5/12.5
transfer and save on swap disk space	5	11	48
display	0	0	0
other mechanical movements	1	2	3
total scan time ; throughput	14.5 ; 0.13 Mb/s	25 ; 0.3 Mb/s	78.5-93.5 ; 0.35 Mb/s
save on user disk space (0.1 Mb/s)	18.8	75	300

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. Unsharp masking (USM) for edge sharpening can be applied in real time by using a 3 x 3 filter mask and adding the inverted second derivatives of the grey levels to the original signal. 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).

In late spring 1994 the Horizon Plus was introduced. It has same price and similar characteristics as the Horizon. The main differences to Horizon include: the black and white shading corrections are applied digitally after the A/D conversion which is now 12-bit ; 3.2D density range and 3.4D maximum density ; transparent documents up to 24 x 34 cm are scanned by default ; new slide holders for 35 mm film roll, 24 x 34 cm, and batch scanning ; 1800 dpi interpolated resolution for grey scale and colour images ; preview with variable zoom ; CMYK scanning.

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 (but does not function for colour images), 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 or because the illumination is automatically turned-off to avoid overheating (inexplicably, sometimes this happens even if there is no overheating or only for colour but not grey level scanning). The processing routines are rather basic and include sharpening, smoothing, noise removal and edge enhancement. Their effect is coarse, and the edge enhancement (USM) creates artifacts at the edges (Figure 3). 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. 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.

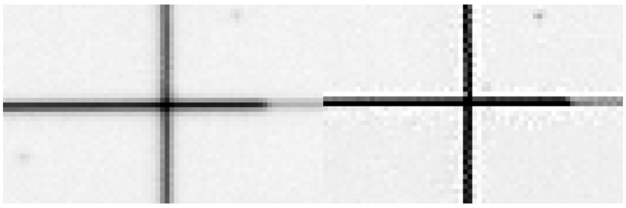


Figure 3. Left: original image. Right: after edge enhancement (USM).

After many years of development Agfa does not support any more PRESS View Color. Thus, the Pixel!FM software was installed and tested on the Sun. However, important scanner functions were not supported and the scanned images always had large artifacts, so we continued using PRESS View Color. The Photolook scanning software within Photoshop was tested with a Mac-based Horizon. The software is much cheaper than the UNIX-based software, has a good performance and has been newly ported on the new faster Macs with the Power PC

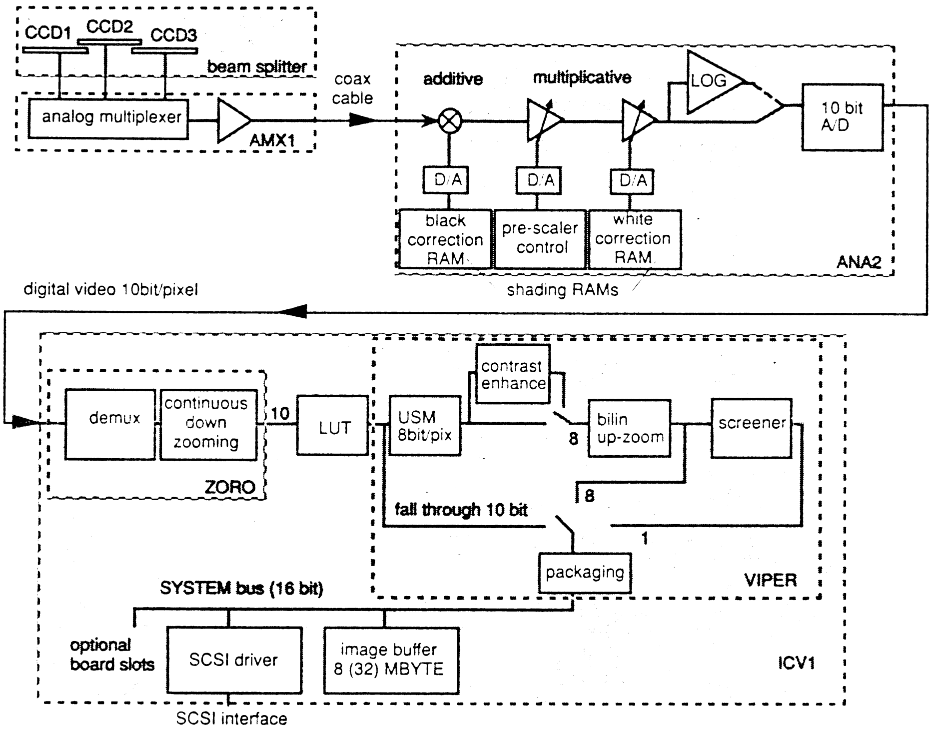
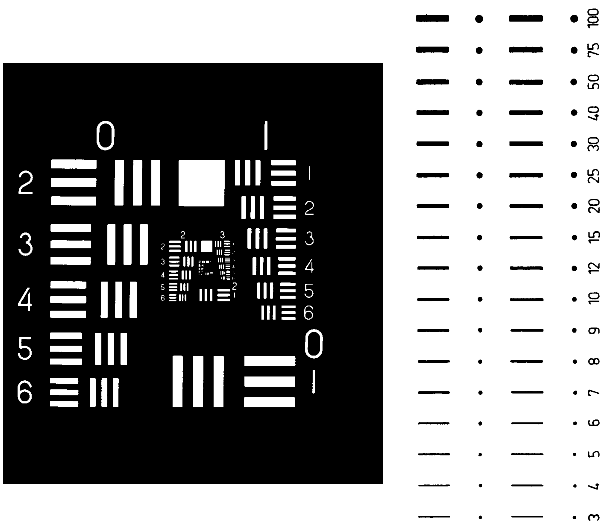


Figure 2. Main circuit boards and video data stream.

processor. Since most Horizon users have Macs and there is a guarantee that Agfa will continue to support this package, we plan to buy a Power Mac with the Photolook software.

3. TESTS OF AGFA HORIZON

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.



a) b)

Figure 4. Test plates from Heidenhain.

For testing we used aerial films of high dynamic range (both grey level and colour), some self-made test patterns (see Figure 13), and the following 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 4). The plate in Figure 4 a) was mainly used to check the geometric resolution. The plate in Figure 4 b) 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.

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. In the figures of this section the errors have been intentionally amplified in order to make them more visible. 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 5). 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 (shading correction) which is also performed before every scan for 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 5). 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. Other causes of stripes are blemishes, dark current noise, different light sensitivity and wrong calibration of the individual sensor elements, and illumination nonuniformity or instabilities.

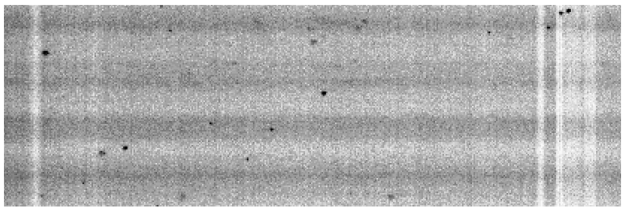


Figure 5. Vertical stripes and horizontal banding.

3. Horizontal banding

This error is again visible in uniform areas (see Figure 5) 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 6.

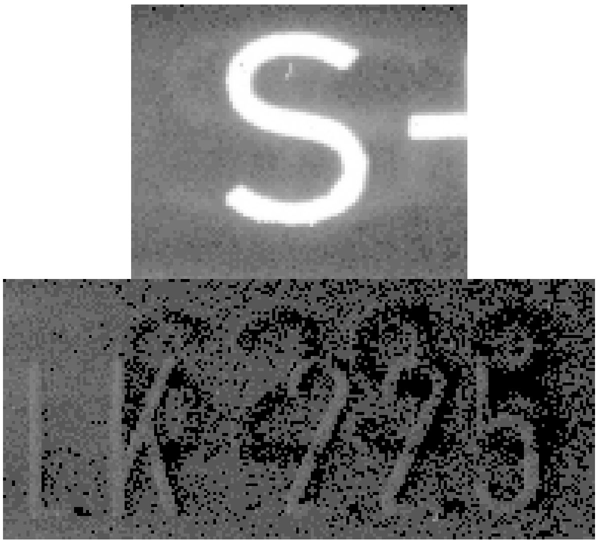


Figure 6. Echoes. Top: the letter S is repeated to the left and right of its position (error due to secondary reflections). Bottom: LK 225 and 6298 coming from the 1st and 2nd linear CCD are repeated in the 3rd CCD (error due to multiplexing). The grey level error is ca. 1-2 grey levels.

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 (see point 4. in section 3.2.).

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 increasing the scanning speed by the same factor as the resolution decreases. This way of subsampling of the linear CCDs may cause some slight problems. Since low-pass filtering and resampling occurs only in horizontal direction, the two directions are treated differently. In horizontal direction each of the sensor elements has an integration time of 1 ms, and then these pixels are numerically combined to larger ones by a weighted averaging. In vertical direction the larger (subsampled) pixels are created by implicit averaging (unweighted) through the faster scanning movement, whereby for every large pixel there is again an integration time of 1 ms. As a result we would expect horizontal lines to be better defined than vertical ones. This may seem contradictory to the fact that the horizontal lines are smeared due to motion (see point 9. below).

To check these problems the test plate of Figure 4 b) was used. The plate has 17 lines/dots of width/diameter from 100 to 3 µm. The plate with the lines in horizontal direction was scanned with 600 dpi, and grey level profiles across all lines and along the middle of each line were computed. All lines were visible, although with a continuously decreasing contrast as the line thickness decreases. Horizontal and vertical dots were visible up to 20 or 30 µm size respectively. Figure 8 shows the modulation (contrast) M of the lines (whereby M is computed by $M = [I_{max}-I_{min}]/[I_{max}+I_{min}]$). Since the lines are of decreasing width, the contrast of the lines should monotonically decrease. This is not exactly the case, but approximately so. The profiles along the lines had a uniform grey level distribution, whereby with vertical lines the grey levels were slightly nonuniform. So, when subsampling by factor two, no significant errors occur. The same procedure was repeated for 300 dpi. All lines were visible. The dots were visible up to 30 - 40 µm size. The modulation naturally drops in comparison to the 600 dpi scanning, and is generally decreasing monotonically with decreasing line width. Again it was observed that grey levels are less uniform along vertical lines than along horizontal ones.

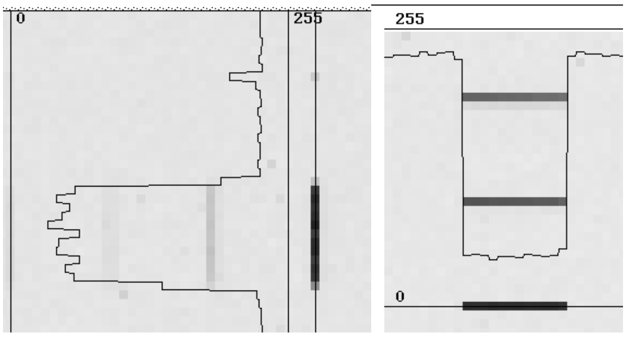


Figure 7. Scan with 150 dpi. Left: grey level profile along the 100 µm vertical line. Right: grey level profile along the 50 µm horizontal line.

The last test was with 150 dpi. As Figure 8 shows some horizontal lines almost disappear, and 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. The grey level profile along a horizontal line is homogeneous as it can be seen in the right image of Figure 7. The dots were visible up to 30 µm size. Vertical lines, as Figure 8 shows, have 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. The left image of Figure 7 also shows that the grey level profile along a line has many discontinuities. Only the dots of 100, 30, 25, and 20 µm size were visible. The results with 150 dpi were initially partly unexpected and difficult to explain. The horizontal lines are again better defined than the vertical ones, but the overall modulation is nonmonotonic. A possible reason for this behaviour is that the scanning speed for 150 dpi is the same as for 300 dpi, i.e. the speed was not increased by factor two as it should because it would exceed the maximum speed of the motor. Thus, in scanning direction the pixels incorporate radiometric information only from half of the area that they

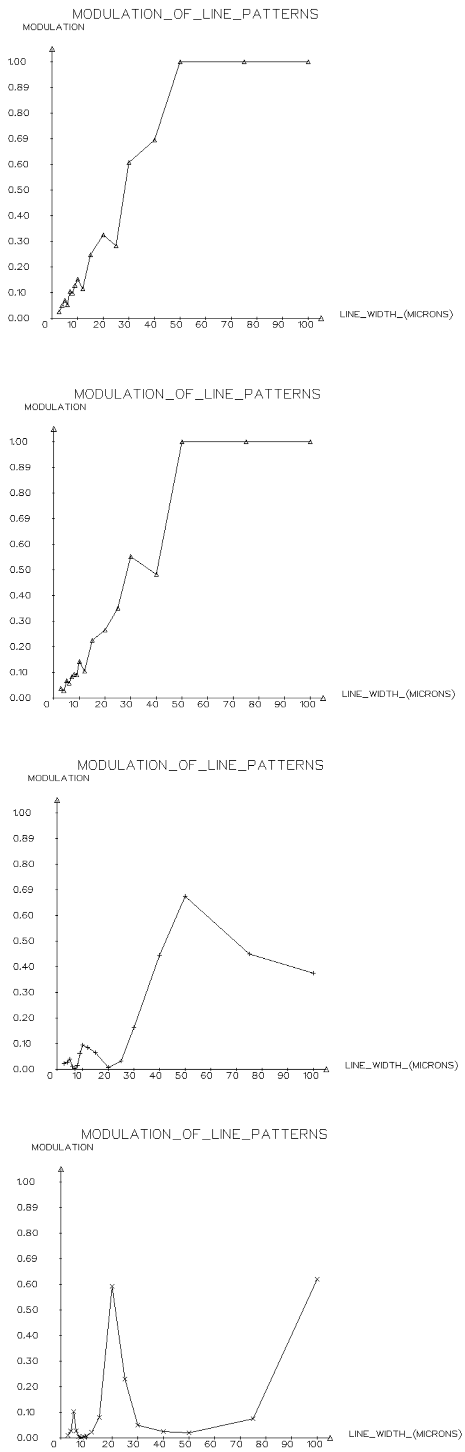


Figure 8. Modulation (contrast) for lines of different width and scanning resolutions. From top to bottom: horizontal lines (CCD direction) with 600 dpi, vertical lines (scanning direction) with 600 dpi, horizontal lines with 150 dpi, vertical lines with 150 dpi.

should cover (this is not the case if the integration time for 150 dpi has been increased by factor two).

As a conclusion subsampling by a certain factor must be accommodated by a respective scanning speed increase (or integration time increase), otherwise it should be avoided. To avoid degrading the modulation of vertical lines as compared to horizontal ones, scanning can be performed with full resolution in both directions and by use of hardware a correct subsampling can be implemented in video rate.

8. Oversampling errors

Oversampling is implemented in CCD direction by the scanner hardware and in scanning direction by decreasing the scanning speed by the same factor as the resolution increases. With PRESS View Color oversampling can be performed only for binary scans. Even this operation does not function properly as Figure 9 shows.

Figure 9. Left: binary image scanned with 1200 dpi (twice enlarged). Right: binary image scanned with 2400 dpi. Note the vertical streaks every two

9. Smear

It is caused by the movement of the zoombox in vertical direction and is proportional to the scanning speed. Thus, sharp edges are defocused, i.e. their contrast is decreased and they become wider (Figure 10). 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.

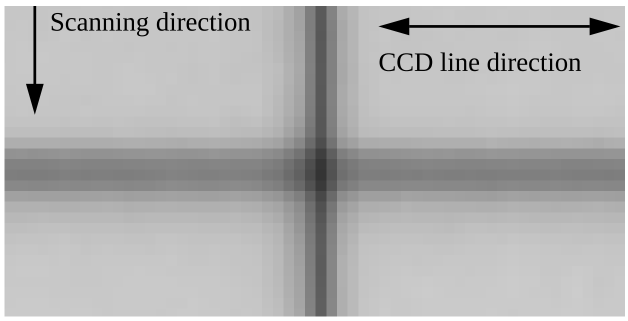


Figure 10. Smear of horizontal lines

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. Kodak sells photographic step tablets (transparencies) with up to 34 density steps in 0.1D spacing (0.0D-3.4D range), and colour separation guides and gray scales. A Kodak grey scale with 20 density steps with 0.1D 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 found 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 to 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 lest 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 11), in the new scanner no error was observed. This type of error is 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.

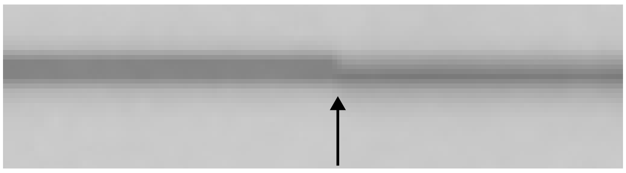


Figure 11. Misalignment between two linear CCDs.

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 12). 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 channel of a scanned image. As test pattern, a thin line in the vertical direction along the image border can be scanned (see Figure 13). 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.

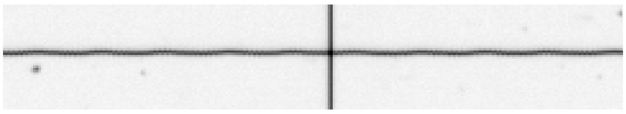


Figure 12. Vibrations in horizontal (CCD) direction (displayed image has been rotated by 90 degrees).

Agfa mentions also vibrations in the vertical direction caused by the scan motor with a period of two pixels for 1200 dpi, and causing a maximum error of 10 µm. We could not detect such vibrations. The reason is 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 could not be detected with this test pattern.

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 position of the grid nodes 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 could be corrected in real-time by using the Horizon hardware, e. g. after a calibration, correction values (horizontal shifts) could be saved in a LUT and a linear transformation and resampling could be performed. As calibration patterns, crosses in horizontal direction with a regular spacing could be used.

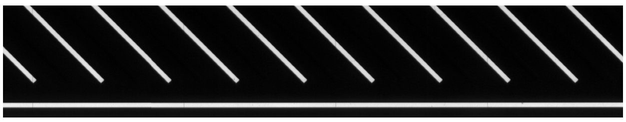


Figure 13. Self-made test patterns used for correction of vibrations and partial image scanning errors (displayed image has been rotated by 90 degrees).

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 is 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 13). At the position of the overlap error the lines were broken (see Figure 14), 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.

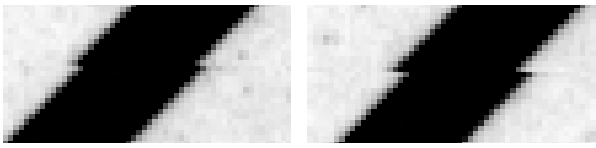


Figure 14. Test pattern and overlap error. From left to right between 1st and 2nd, and 3rd and 4th partial images.

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. Although Agfa mentioned that this problem occurs only with the Unix-based systems and is due to the driver, it was also observed with a Mac-based Horizon with 32 Mb image buffer.

5. Colour misregistration

To test the 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 4 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 geometric positioning inaccuracies, the lens (unknown whether it is apochromatical) or differences in the colour filters, each of which acts as a lens.

6. Geometric resolution.

The test plate of Figure 4 a) was visually inspected and the smallest group of three-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, contrary to our expectation that due to smear the resolution would be worse for the horizontal lines. One possible explanation is that the vertical edges are noisier than the horizontal ones, possibly due to vibrations in horizontal direction. The 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 15). No clear explanation for this error can be given. 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 15. 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 in the right image 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 were 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 (the overlap error, see point 4. above is not included in this error budget). 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 16 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 (the ratio [maximum error in y/maximum error in x] was 0.4-0.5 for the few first and last lines, while at the center it was 1.-1.1). There were no large local errors (random or systematic) and the maximum error was ca. 2 times the RMS error.

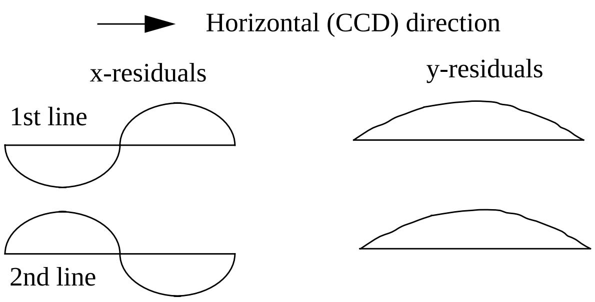


Figure 16. Systematic pattern of residuals of check points along horizontal grid lines.

We have not yet developed any calibration software for the Horizon. It is expected that after calibration the RMS errors will be reduced to ca. less than 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 (an advantage of scanning the whole image in one swath using butted linear CCDs is that calibration patterns are needed only at the image border).

4. CONCLUSIONS

The Agfa Horizon is one of the best, but also most expensive, flatbed DTP scanners. Its radiometric performance, and the scanner software are generally good. Its geometric accuracy without applying any geometric calibration is ca. 50 µm but when using 4 corner points as control points the error increases to 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. 0.5 pixel (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 of 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.

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 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). The previously mentioned problems can be severely reduced by employing better scanning mechanisms (usually mechanical) and lenses. An alternative is the development of calibration software. This software and test patterns should ideally be supplied by the scanner vendors. Due to the rapid developments in DTP, new, cheaper scanners with transparency option, 600-1200 dpi and A3 format will be produced. Any good DTP scanner (like the Horizon), if it is geometrically calibrated, can be used in many photogrammetric applications. Even without calibration these scanners can be used in photogrammetric and GIS-related applications that require a geometric accuracy of 0.1 - 0.2 mm or more.

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