EVALUATION AND TESTING OF THE ZEISS SCAI ROLL FILM SCANNER

Emmanuel P. Baltsaviasa, Christoph Käserb

aInstitute of Geodesy and Photogrammetry, ETH-Hoenggerberg, CH-8093 Zurich, Switzerland, manos@geod.ethz.ch
bSwiss Federal Office of Topography, Seftigenstr. 264, CH-3084 Wabern, Switzerland, Christoph.Kaeser@lt.admin.ch

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ABSTRACT

In the summer of 1996 the Swiss Federal Office of Topography (L+T) performed in cooperation with ETH benchmark tests at different companies in order to evaluate three photogrammetric film scanners. After the tests a Zeiss SCAI scanner was acquired, installed, and tested in spring 1997 as to whether it fulfils the contract specifications. In this paper the results of these two tests performed with the SCAI, and in particular geometric and radiometric investigations, are presented. Good quality test patterns and accurate processing methods for the performance evaluation have been employed. The geometric tests include geometric errors, misregistration between colour channels, geometric repeatability, and determination of the geometric resolution. The radiometric tests include investigations on noise, linearity, dynamic range, spectral variation of noise, and artifacts. After a brief description of the scanner, details on the above investigations, including test patterns, processing methods, results and analysis are presented. Regarding the geometric accuracy the RMS was 2.0-2.3 µm and the mean maximum absolute error 6.0-8.1 µm. The errors are bounded, i.e. the maximum absolute error is 2.7-3.6 RMS. Systematic co-registration errors in scan direction between the colour channels of up to ca. 2.5 µm have been observed. The short term repeatability was very high. The radiometric noise level is 1-1.6 and 0.9-1.3 grey values for 7 and 14 µm scan pixel size respectively. The dynamic range is 1.6-1.9D and 1.75-2.05D for 7 and 14 µm respectively with a good linear response up to this value. Quite some artifacts and electronic noise up to 5 grey values were observed. There were no significant differences between R, G, B channels with respect to geometry but the B channel exhibits more radiometric noise and less dynamic range than the R and G. The effective y-pixel size can be smaller than the nominal one by 10% (exposure times > 4.5 ms) and up to 50% (exposure times < 4.5 ms). This reduction can be negatively influenced by inappropriate selection of exposure time and scan speed by the user. The software is generally positive but improvements, especially regarding automatic density determination and automatic setting of the scan parameters including scan speed and exposure time, are needed. Latter improvements have been partly implemented in the new software version PSC 3.0 which was not available to us at the time of these investigations.

1. INTRODUCTION

PHODIS SC is part of the PHODIS family of digital photogrammetric products by Zeiss. It consists of three main modules: scanner, roll film attachment, and user interface. A description of PHODIS SC is given in Mehlo, 1995 and Roth, 1996. Here, only its main characteristics are given. The scanner is flatbed with stationary stage and moving sensor, optics and illumination and can scan colour in one pass. The sensor is a Thomson THX7821 CCC trilinear colour CCD with 8640 elements, out of which only the 5632 central are used (all 8640 elements are read out but only the 5632 are A/D converted), while the sensor element size is 7 µm. The pairwise distance between the single CCDs is known with an accuracy of < 1 µm and is 294 µm (i.e. corresponds to 42 pixels with 7 µm scan pixel size) and the sequence of the scan is B, G, R. Monochrome scans can be scanned as B/W with various predefined or user-definable weighted combinations of the R, G, B values. Films are scanned combwise in swaths (for an aerial image 6 swaths are needed). The swaths are not overlapping, and no radiometric feathering across seam lines of neighbouring swaths is performed. The maximum scan format is 250 (y) x 275 (x) mm. The scanning mechanism has a primary (x) and a secondary (y) carriage. The optics consists of a lightweight achromatic mirror lens with zero distortion. The light source is a stabilised 250 W halogen lamp positioned away from the scanner stage and the CCD. The light is conducted over the scanner stage with fiber glass optics and then diffused before illuminating the film. The light intensity cannot be changed, i.e. is the same for all scan pixel sizes. The scan speed range is from 0.35 mm/s to 38 mm/s, and the exposure (CCD integration) time (ET) 0.2-25.5 ms (default 2 ms). The scanner throughput is ca. 1 MB/s for 14 µm scans, while with 7 µm and colour scans ca. 3.8 MB/s can be generated. The internal image buffer is only 4 MB, thus the data must be transferred to host and saved on disk fast enough, so that no data losses occur. The scan pixel size is 7, 14, 28, ...224 µm. Scanning with 21 µm is also possible (but not with 35 or 42 µm which could be useful for certain applications). The generation of pixel sizes other than 7 µm is achieved, in the scan direction by increasing appropriately the scan speed and in the CCD line by pixel averaging which occurs in hardware after the A/D conversion. However, the effective pixel size in scan direction (= scan speed x exposure time) is less than the nominal one (for the base resolution of 7 µm, effective and nominal pixel sizes are always identical : by decreasing scan speed or ET, the scan time or the radiometric noise increase respectively). According to the manufacturer this pixel size reduction can be up to 50% for small ETs, while for ETs > 4.5 ms it is just 10% (note also that ET changes do not influence the scan speed, if they are < 4.5 ms). The image signal is A/D converted in 10-bit, normalisation corrections, see below) are applied, pixels are averaged in CCD line direction (for scan pixel size > 7 µm), and then transformed to 12-bit (justified according to the manufacturer due to less signal noise because of averaging and the two radiometric corrections, see below). Finally, the 12-bit data is stored with 8-bit through transformation with a linear or user-defined LUT (an option to store 12-bit data is planned for autumn 1998). For
The scanner performs for each element of each CCD two radiometric calibrations. The so called normalisation (or white adjustment) uses a special slit which is illuminated and a close-by opaque position to ensure that all sensor elements produce same grey values for a homogeneous dark and bright surface. From the two measurements, 16-bit gain and offset correction factors are computed for each CCD sensor element such that their responses become equal and applied after the A/D conversion. If the calibration slit is not homogeneous and absolutely clean or there is temporally varying dirt in other parts of the optical path, then the corrections are wrong. This calibration can optionally be performed before each scan, however at L+T it is not performed frequently. The so called black adjustment uses the values of light-protected sensor elements each to the left and right of the central 5632 elements and it aims again at correcting response nonuniformities of the CCD sensor elements due to dark current noise (particularly important to avoid radiometric differences between neighbouring scan swaths). These corrections are applied to the analogue image signal before offset and gain. To balance colour channels due to the different sensitivity of the CCDs in the visible spectrum, an appropriate gain of the analogue signal is also applied, e.g. for blue it is ca. 2-4 times more than for red (balance could technically be implemented by using different ETs, but with trilinear CCDs this would lead to different effective pixel sizes in scan direction). Two geometric calibrations can be performed. Their aim is to determine (a) the rotation between CCD lines and scanner stage coordinate system as well as nonorthogonality between the x and y stage coordinate system by scanning a horizontal line in two swaths (note that nonparallelism between the 3 CCDs can not be accounted for by this calibration), and (b) overlaps or gaps in the x-direction between two neighbouring scan swaths by determining the x-pixel size, though scanning of a diagonal line in two neighbouring swaths. In the first calibration, the errors (rotation between CCD lines and stage coordinates, nonorthogonality of x and y stage coordinate system) are corrected through virtual change of the stage coordinate system by applying for each scan swath an appropriate shift in scan direction. In the second calibration, it is assumed that the first one has already been accurately performed. In both calibrations it is assumed that the scanner has an accurate positioning in x and y. The measurements for the calibrations are manual or semiautomated and with the new software even fully automated. Finally, a grid plate up to 4.5 mm thickness can be used for evaluation of the geometric accuracy. With the new software version the grid line intersections can be determined automatically, and a visual control and correction of individual measurements is facilitated. 

The documentation does not mention how often the geometric calibrations should be performed but the manufacturer suggests once per year (except of change of scanner location, significant temperature and humidity variations, and vibrations/floor instabilities).

2. TEST PROCEDURES AND TEST PATTERNS

The geometric and radiometric investigations were performed with two SCAI scanners, one at Zeiss Oberkochen during the benchmark test (called SCAI1 thereafter) and one at L+T after delivery and installation (called SCAI2). In both cases all necessary scanner calibration procedures were performed in advance. The host computer was a Silicon Graphics Indy. Both scanners were equipped with a roll film transport system but no roll film was mounted on it.

The geometric performance was tested by scanning with 14 µm a custom-made glass grid plate, produced by a Swiss company specialising in high precision optical components (IMT) with a 1 cm grid spacing and 187.5 µm line width (25 x 25 lines, their intersections will be called crosses thereafter). The coordinates of the crosses were known with an accuracy of 2 - 3 µm. To determine the scanner resolution a standard USAF resolution pattern on glass produced by Heidenhain was scanned with 7 µm. The radiometric performance was mainly checked by scanning a calibrated Kodak CAT grey level wedge on film (21 densities with density step of approximately 0.15D ; density range 0.05D-3.09D). The densities were determined by repeated measurements using a Gretag D200 microdensitometer with 0.01D resolution. In addition, a B/W and a colour (only for SCAI1) aerial image were scanned with 14 µm in order to check the visual quality and possible radiometric artifacts. The grid plate was scanned in colour, once with SCAI1 and three times with SCAI2, to check the misregistration between the colour channels as well as the short term geometric repeatability. The grey level wedge was scanned in colour, with 7 and 14 µm pixel size to check differences between colour channels and the effect of pixel size on the radiometric performance. With SCAI1 the 7 µm scan was additionally subsampled to 14 µm by averaging 2 x 2 pixels (called version 2) and compared to the original 14 µm scan (version 1). With SCAI2 the 14 µm scan was done twice by using ETs of 1.7 and 0.6 ms.

The pixel coordinates of the grid crosses were measured by Least Squares Template Matching (LSTM) using a 27x27 pixel template. This algorithm is described in Gruen, 1985 and details can be found in Baltsavias, 1991. The accuracy of LSTM, as indicated by the standard deviations of the shifts, was for these targets 0.01 - 0.03 pixels. Matching results with bad quality criteria (low crosscorrelation coefficient etc.) were excluded from any further analysis. In addition, the matching results of all crosses with large errors were interactively controlled.

The geometric tests performed include:

1. Geometric tests

   For this purpose an affine transformation between the pixel and the reference coordinates of all crosses was computed with three versions of control points (all crosses, 8 and 4, the latter two versions simulating the fiducial marks used in the interior orientation of aerial images).

2. Misregistration errors between the channels

   Such errors were checked by comparing pairwise the pixel coordinates of each channel (R-G, R-B, G-B).
3. Evaluation of Geometric Performance

3.1. Geometric Accuracy and Repeatability

In all geometric tests x is the direction of the CCD line, y the scan direction. The results of this evaluation are shown in Table 1 and some examples are illustrated in Figure 1. The transformation with 8 control points (CP) was left out from the table to make it more readable. Generally, they were slightly better than the results with 4 CP (for SCAI2 2% higher RMS in x and 27% lower RMS in y, for SCAI9 9% lower RMS in x and same RMS in y).

First, the results using all crosses as control points are examined. The differences in accuracy between R, G, B is negligible. This means that the optical system has good achromatic properties. It is also due to the fact that the 3 channels are acquired quasi simultaneously (there is only an offset of 42 pixels between CCD-lines in scan direction). With both scanners RMS values are similar in x- and y-direction and vary between 2 and 2.3 µm. However, the maximum absolute errors are higher in y than in x for SCAI1 (which is what was expected since the geometry in scan direction should be less stable) but higher in x for SCAI2. Otherwise, both scanners show very similar RMS values and also range of maximum absolute errors. Latter are bounded and the average for all channels in x/y is 2.7/3.6 RMS (SCAI1) and 3.5/3.2 RMS (SCAI2). The short term repeatability, as indicated by the difference between minimum and maximum values of the 3 scans with SCAI2 (see Table 1), is very good. Figure 1 shows the residual plots for some scans. There were very little differences in the error patterns between the 3 channels and also between the 3 scans (SCAI2, compare middle and right plot of Figure 1). As it can be seen, the error patterns differ from scanner to scanner, from one scan swath to another, and even within one scan swath. Thus, it is difficult to interpret them and relate them to specific error sources, e.g. vibrations, mechanical positioning, calibration errors etc. However, in both scans the different error patterns for each swath are in most cases well visible, at swath borders x-errors are generally larger, and local systematic error patterns can be observed (e.g. in the lower right of the left plot in Figure 1), as well as slightly increasing errors in the lower half of the scans, i.e. away from the home position of the scanner. Distortion could not cause such errors, and since there were no major differences between the 3 scans of SCAI2 vibrations should not have a major contribution. The local systematic errors may primarily be due to temporally stable x-, y-positioning errors but also calibration errors.

The results using only 4 control points were, as expected, worse but in accordance with the above statements. The RMS in x/y are (2.2 - 2.3)/(2.9 - 3.3) for SCAI1 and (2.4 - 3.2)/(2.2 - 2.4) for SCAI2. The mean maximum absolute errors in x/y were (5.9 - 6.0)/(6.9 - 8.0) for SCAI1 and (7.5 - 7.8)/(6.4 - 6.5) for SCAI2. A problem is the high mean y value for SCAI1 and mean x value for SCAI2 showing a systematic bias, for SCAI1 even larger than half the RMS.

The blue channel of the grid plate, the B/W aerial film and the blue channel of the colour aerial film (latter only for SCAI1) were subsampled and strongly contrast-enhanced by Wallis filtering. Then, the borders between scan swaths were visually controlled to detect geometric shifts and radiometric differences between the swaths. However, no such problems could be observed.

2. Artifacts

Some of the above mentioned scanned patterns as well as the aerial films were very strongly contrast-enhanced by Wallis filtering (Baltsavias, 1991). This permits the visual detection of various possible artifacts like radiometric differences between neighbouring swaths, electronic noise, etc. However, the quantification of radiometric errors is always performed using the original images.
Table 1. Statistics of differences between pixel and reference coordinates after an affine transformation (in μm)

<table>
<thead>
<tr>
<th>Scan version, # of control/check points</th>
<th>Statistics(^1)</th>
<th>Red channel</th>
<th>Green channel</th>
<th>Blue channel</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>SCAI1, one scan, 625/0</td>
<td>RMS x</td>
<td>2.2</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>RMS y</td>
<td>2.0</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>max abs. x</td>
<td>6.1</td>
<td>6.0</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>max abs. y</td>
<td>7.5</td>
<td>7.6</td>
<td>7.1</td>
</tr>
<tr>
<td>SCAI1, one scan, 4/621</td>
<td>RMS x</td>
<td>2.2</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>RMS y</td>
<td>2.9</td>
<td>2.9</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>mean x</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>mean y</td>
<td>2.0</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>max abs. x</td>
<td>6.0</td>
<td>5.9</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>max abs. y</td>
<td>6.9</td>
<td>7.3</td>
<td>8.0</td>
</tr>
<tr>
<td>SCAI2, three scans, 625/0</td>
<td>RMS x</td>
<td>2.3</td>
<td>2.1</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>RMS y</td>
<td>2.0</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>max abs. x</td>
<td>8.1</td>
<td>7.7</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>max abs. y</td>
<td>6.3</td>
<td>6.1</td>
<td>6.7</td>
</tr>
<tr>
<td>SCAI2, three scans, 4/621</td>
<td>RMS x</td>
<td>2.8</td>
<td>2.4</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>RMS y</td>
<td>2.3</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>mean x</td>
<td>-1.2</td>
<td>-1.6</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>mean y</td>
<td>0.2</td>
<td>0.4</td>
<td>1.0</td>
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<tr>
<td></td>
<td>max abs. x</td>
<td>7.5</td>
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<tr>
<td></td>
<td>max abs. y</td>
<td>6.5</td>
<td>6.0</td>
<td>6.7</td>
</tr>
</tbody>
</table>

\(^1\) When all points are used as control points, the mean values are zero and thus not listed.

Table 2. Statistics of pairwise differences between pixel coordinates of the colour channels (in μm)

<table>
<thead>
<tr>
<th>Scan version, # of comparison points</th>
<th>Statistics</th>
<th>Green - Red channel</th>
<th>Blue - Red channel</th>
<th>Blue - Green channel</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>SCAI1, one scan, 625</td>
<td>RMS x</td>
<td>0.2</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMS y</td>
<td>1.4</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean x</td>
<td>0.0</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean y</td>
<td>1.3</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>max abs. x</td>
<td>0.8</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>max abs. y</td>
<td>2.7</td>
<td>4.3</td>
<td></td>
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<tr>
<td>SCAI2, three scans, 625</td>
<td>RMS x</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>RMS y</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>mean x</td>
<td>0.2</td>
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</tr>
<tr>
<td></td>
<td>mean y</td>
<td>0.9</td>
<td>0.8</td>
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<tr>
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<td>max abs. x</td>
<td>0.8</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>max abs. y</td>
<td>2.1</td>
<td>2.0</td>
<td>2.1</td>
</tr>
</tbody>
</table>
3.2. Misregistration between Colour Channels

The results are summarised in Table 2 and one example is given in Figure 2. The errors are much larger in y than in x. The differences between the 3 scans (SCAI2) are very small. Generally the differences between the channels R, G, B are similar for G-R and B-G but quite larger for B-R (ca. the sum of G-R and B-G differences). The y-differences had always the same sign. This and also the large values of mean y (very similar to RMS y) show systematic errors in the scan direction. These errors are due to inaccurate mounting of the 3 CCD-lines on the CCD chip, i.e. the distance between the CCD lines is not exactly 294 µm. The error is larger between R and B and it becomes clearly visible when scanning with small pixel size sharp edges. As a test, a razor blade parallel to the CCD lines was scanned with 7 µm. The upper edge was blueish and the lower one reddish over the whole edge width of 5 pixels, and the differences between R and B were up to 40 grey values. This misregistration will also slightly influence the geometric measuring accuracy in scan direction. The shift between the CCD lines can be accommodated by an appropriate time offset (depending on the scan speed) between the integration times for each CCD line.

3.3. Geometric Resolution

The smallest line group that could be sufficiently detected for both scanners had a line width of 7 µm (see Figure 3). Contrary to what would be expected with linear CCDs, the contrast of vertical lines (vertical was the scan direction) was clearly worse than that of the horizontal ones. Since the fast CCD sensor movement results in a smear and contrast loss, it was expected that the horizontal lines (i.e. parallel to the CCD) would have less contrast. However, this did not occur in this case because the effective ET is less than the nominal one.
4. EVALUATION OF RADIOMETRIC PERFORMANCE

4.1. Noise, Linearity, Dynamic Range and Spectral Variation of Noise

The results from the grey scale wedge are shown in Table 3. With SCAI1 two problems occurred. Firstly, a very large number of pixels were rejected by the blunder test which excludes dust and corn, due to the very corny appearance of the scanned images. The number of rejected pixels was higher for the lower densities and reached up to ca. 50% (in comparison with SCAI2 0.6% of the pixels were rejected the most). Secondly, the scan parameters were not appropriately set and thus, the first two densities were saturated. Hence, the analysis will concentrate on the results of SCAI2. With SCAI2 the 14 µm version with ET 0.6 was of little use. The scanner does not adjust the analogue or digital gain automatically when the ET is changed, and thus, due to the lower ET, the density range 0.05-3.09D was mapped to grey values 3-122, making a direct comparison to the version with ET 1.7 difficult. However, if the grey value range of the latter version is compressed to 3-122, then its noise is 32%-41% less than the noise of the version with ET 0.6, which makes clear the benefit of lower noise with longer ET. An example of the histogram of the grey scale for the red channel and 14 µm is shown in Figure 4.

The green channel has slightly more noise that the red one, and the blue one significantly more. The noise level is 1-1.6 and 0.9-1.3 for the 7 and 14 µm scans respectively. The 14 µm scans have slightly less noise than the 7 µm ones (11%-23% less noise), but still more than theoretically expected (if the ET is kept constant for all scan pixel sizes, then with larger pixel sizes, signal and noise in scan direction should remain the same, with the exception of averaging of film corn noise and dust, and with the averaging in CCD line direction less noise by a factor of ca. 1.4 (=√2), i.e. 29% less, should be expected). The noise is decreasing from low to high densities, but beyond the maximum detectable density even a slight increase can be observed. For high densities beyond 2D the standard deviation is higher than expected and observed with other scanners, but this also shows that even for the highest densities the signal is not saturated. The dynamic range, according to the criteria listed in section 2, is 1.6-1.9D and 1.75-2.05D for the 7 and 14 µm scans respectively, whereby R has a higher dynamic range than G and this than B. The plots in Figure 5 are in accordance with the above stated maximum detectable densities and show a good linear behaviour up to these densities. There are some differences between the 3 spectral scans, especially between B and the other two channels. All mean grey values were nicely monotonically decreasing even for the highest densities. The mean values are similar for all spectral channels, indicating a good colour balance. The biggest differences are between R and B and reach 7 grey values the most. The mean values are also similar between the 7 and 14 µm scans. The grey value range slightly decreases from R to G to B channels.

A final note on some results of SCAI1 (see Table 3). There, it can be noticed that the 14 µm scan (version 1) had almost as much noise as the 7 µm scan which was contrary to what was expected. Also a visual comparison for low densities with a lot of corn did not show any difference. Thus, the 7 µm scan was subsampled by 2 x 2 averaging and “14 µm version 2” was created. This version does show, as expected, a significant decrease in noise. The explanation for the high noise of 14 µm version 1 is that the effective y pixel size is less than the nominal one, i.e. there is less averaging than it should be in the scan direction.

4.2. Artifacts and Radiometric Problems

To detect artifacts visually the contrast of the scanned test patterns and the aerial films was strongly enhanced by Wallis filtering. For large images, first a subsampling by factor 2 has been performed. However, the quantification of radiometric errors always occurred in the original images. Figure 6 shows...
<table>
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<tr>
<th>Density</th>
<th>Red channel, SCAI2 Mean</th>
<th>St. D.</th>
<th>Mean</th>
<th>St. D.</th>
<th>Blue channel, SCAI2 Mean</th>
<th>St. D.</th>
<th>Mean</th>
<th>St. D.</th>
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Table 3: Radiometric tests with grey scale wedge. Mean and standard deviation of grey values. Maximum density that can be detected shown in bold.
The distance between the echoes is 294 µm. Since the internal image buffer is small, if the data cannot be written to the host disk at this throughput rate data will be lost. Note that, in both cases, the data loss influenced 31 lines. Figure 6 f) shows also vertical stripes due to different CCD sensor element response. The mean difference of stripes to the background was up to 5 grey values. With both scanners, especially SCAI2, horizontal stripes were observed. Concluding, quite some radiometric problems and artifacts could be observed. They have a local influence but can not be neglected as they cause errors higher that the noise level of the scanner. These problems can become more grave, if the image contrast is strongly enhanced, as this is sometimes done in order to generate more texture for matching in DTM generation and automatic point measurement in aerial triangulation.

4.3. Effective Pixel Size in Scan Direction

As explained above, for pixel sizes larger than the base resolution the effective y pixel size is smaller than the nominal one. According to the manufacturer a size reduction up to 50% should not pose any problem. Actually, a smaller y pixel size results in less averaging in scan direction, a sharper image, less smear and higher contrast, thus also higher MTF, for lines parallel to the CCD, and in some cases recognition (but also total loss) of objects smaller in y than the nominal pixel size. On the other hand, the radiometric noise is higher, the sensitivity lower, a part of the film area is systematically not used, and aliasing, contaminating high frequencies, is increasing (Moiré, artifacts). A pixel size reduction of 10% is probably not relevant, but more investigations should be undertaken to study the effect of a 50% reduction. Since the maximum transfer rate is 3.8 MB/s, the maximum number of scan lines, e.g. for 7 µm, should be 3800000/(3*5632) = 225 lines/s, i.e. the minimum ET should be 4.4 ms. For 14 and 28 µm, the minimum ETs are 2.2 and 1.1 ms respectively. However, the user can set the ET down to 0.2 ms (and the default ET is 2 ms). A smaller ET than the minimum one would lead to a data loss during the transfer, which however does not occur. Thus, the nominal ET remains, e.g. for 7 µm 4.4 ms. For 7 µm by selecting effectively a smaller ET, only the SNR would drop. For 14 and 28 µm nominal pixel size and 0.2 / 2 ms ET, the effective y pixel size is reduced by 91% / 9% and 45.5% / 0% respectively. Thus, an inappropriate selection of ET by the user could lead to information loss. It would be better, if the scanner would automatically set the minimum ET depending on the maximum transfer rate, the nominal scan pixel size, the maximum scan speed, and the bandwidth of the electronics (A/D converter and ALUs). Based on the previous parameters (assuming an electronics bandwidth of 5-10 MHz) and aiming at keeping the ET same for all scan pixel sizes, it was estimated that all scan pixel sizes (7-224 µm) could be scanned with ET = 5.9 ms and scan speed 1.2 - 38 mm/s, up to ET = 20 ms and speed 0.35 - 11.2 mm/s (naturally the illumination power must be such that low densities are not saturated with this ET). The first case (ET = 5.9 ms) would also allow the possibility to increase the ET by a factor of ca. 4, in case it is necessary, e.g. with dark or old films. An additional problem is that the user can change through editing of a file the scan speed (25%-100% of predefined speed values for each scan pixel size ; latter are unknown but we assume that they correspond to the respective minimum ET).

Figure 6. Artifacts and radiometric problems in contrast enhanced images (except d): a) vertical stripes (red channel, SCAI2) ; b) vertical black and white stripes (blue channel, SCAI1) ; c) inverse echoes due to cross-talk (blue channel, patterns at border of aerial film, SCAI1, scan direction is from top to bottom) ; d) grey region with height of 31 pixel in the scanned grey scale which did not physically exist. Presumably it is due to data losses during data transfer from scanner to host (red channel, 7 µm scan, SCAI1) ; e) sudden occurrence of a dark vertical line segment that does not physically exist with width of 2 pixels and height of 31 pixels. After this vertical line all pixels of these lines are shifted by two as the broken vertical stripes in f) clearly show. Again presumably due to data losses during data transfer (red channel, 7 µm scan, SCAI1) ; f) vertical dark stripes due to different response of the CCD sensor elements.
Since scan pixel size and ET are fixed, a reduction of the speed leads again to a smaller y pixel size.

5. SUMMARY AND CONCLUSIONS

Regarding the geometric accuracy the RMS was 2-2.3 \( \mu \text{m} \) and the mean maximum absolute error 6-8.1 \( \mu \text{m} \). The errors are bounded, i.e. the maximum absolute error is 2.7-3.6 RMS. Local systematic errors were observed with both scanners probably mainly due to temporarily stable x-, y-positioning errors and to a lesser degree calibration errors and vibrations. The co-registration of colour channels is very good in x, but in scan direction there is a constant shift from one CCD line to the next one of ca. 1 \( \mu \text{m} \) due to fabrication inaccuracies. The shift between R and B channels is ca. 2.5 \( \mu \text{m} \), i.e. more than the geometric accuracy of the scanner, and with high resolution scans creates wrong colours at sharp edges. The short term repeatability was very high. Both scanners had similar geometric accuracy values but one was better in x-direction, the other one in y. The use of a denser and more accurate grid plate will allow a better modelling and understanding of the magnitude and distribution of the errors. An effort to use a 1 cm thick plate with 2 mm grid spacing and 1 \( \mu \text{m} \) accuracy was not possible because SCAI can use plates only up to 4.5 mm thickness.

The radiometric noise level is 1-1.6 and 0.9-1.3 grey values for 7 and 14 \( \mu \text{m} \) scans respectively. The dynamic range is 1.6-1.9D and 1.75-2.05D for 7 and 14 \( \mu \text{m} \) scans respectively with a good linear response up to these values. There were no significant differences between R, G, B channels with respect to geometry but their radiometric noise and dynamic range was different with B clearly showing a poorer quality, and G being only slightly worse than R. Quite some artifacts and electronic noise problems causing systematic local errors larger that the accuracy values but one was better in x-direction, the other one in y. The use of a denser and more accurate grid plate will allow a better modelling and understanding of the magnitude and distribution of the errors. An effort to use a 1 cm thick plate with 2 mm grid spacing and 1 \( \mu \text{m} \) accuracy was not possible because SCAI can use plates only up to 4.5 mm thickness. The radiometric noise level is 1-1.6 and 0.9-1.3 grey values for 7 and 14 \( \mu \text{m} \) scan pixel size respectively. The dynamic range is 1.6-1.9D and 1.75-2.05D for 7 and 14 \( \mu \text{m} \) respectively with a good linear response up to these values. There were no significant differences between R, G, B channels with respect to geometry but their radiometric noise and dynamic range was different with B clearly showing a poorer quality, and G being only slightly worse than R. Quite some artifacts and electronic noise problems causing systematic local errors larger that the noise level of the scanner were observed. The most important are vertical stripes due to different CCD sensor element response because of inaccurate radiometric calibration, and echoes due to cross-talk between the 3 CCDs. Data losses depend on the data transfer rate of the scanner/host interface as well as the host configuration and its simultaneous use by other programs. Tests at L+T with 7 \( \mu \text{m} \) scans of colour aerial images (host was a 180 MHz O2, RS5000 processor, 128 MB RAM) did not show any such data losses, although the worst possible case has not been checked yet.

The software is generally positive and easy to handle. One major weakness of our older software version was the lack of the ability to find automatically the darkest and lightest regions in an image and set appropriately the scan parameters (setting of analogue offset, ET and scan speed is to be preferred over simple offset and gain changes which just enhance the noise). This feature is very important, especially for good quality unattended roll film scanning. According to the manufacturer, the new software version PSC 3.0 uses the prescan image and its histogram information to determine semi-automatically the minimum and maximum density and set appropriately the scan parameters. Colour corrections are also possible. The user can select a ROI in the prescan image, change brightness or make colour corrections, check the effect of the changes on-line, and after being satisfied, use them for the full resolution scan. The unattended roll film scanning has been tested by scanning 400 images with different distances between the images particularly between flight strips. For all images the scanner software was able to detect automatically the area to be scanned. Automatic interior orientation works nicely, but, due to a bug, with TIFF images the film orientation (i.e. fiducial numbering) must be manually given. Images can be scanned in TIFF format but only in the tiled option (software conversion to untitled TIFF is possible). In RGB to B/W scans, user-definable LUTs for each colour channel can not be used, although they would allow a variable (grey value dependent) weighted averaging. An excessive reduction of the nominal y pixel size should be avoided. Users should not be permitted to make unreasonable selections of scan speed and/or ET. An option “adjust” which suggests to the user an ET does not function well. The documentation needs improvement. It gives a function by function description. What is missing is an overview and flowchart of the operations, especially in the complex part of roll film scanning. Partially more explanations are needed, e.g. regarding the calibrations or how are the three colour CCDs used with B/W scans etc. A better and more frequent (e.g. once per month) geometric calibration could improve the accuracy, especially if inaccuracies due to ageing effects start occurring. In particular, the calibration measurements should not be allowed to be manual and nonredundant, since this may lead to less robust and accurate calibration and geometric positioning. A compulsory radiometric normalisation before each scan could lead to less vertical stripes. Although not necessary for scanning per se, good quality and possibly automated software modules for correction of vignetting and hot spots is very important in production environments, especially when scanning negatives. A thorough control of the functionality and performance of the new software version is planned.

Summarising, SCAI is a good quality scanner. Improvements, especially in close cooperation with users and researchers, can be made and thus lead to an even better performance.

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REFERENCES


