

Description and evaluation of the high quality photogrammetric scanner UltraScan 5000

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Abstract

Scanning of analogue images has become a key hardware technology specific to modern digital photogrammetry. Since specialised photogrammetric scanners have been introduced in the late 1980s, a gradual development and improvement of their performance regarding hardware, software and functionality, and productivity has been observed. Originally, geometric accuracy of scanners was the overriding specification for scanners. This is increasingly being augmented by a concern for good colour and radiometric performance. This article describes the UltraScan 5000, a modern photogrammetric scanner manufactured by Vexcel Imaging Austria, and its features, assesses its radiometric and geometric performance with various well-founded tests, and discusses its versatility and use in production. The UltraScan 5000 was introduced in November 1998 and since then, a surprisingly large number of systems has been installed worldwide. Their successful operation illustrates on a daily basis the validity of the technical solution and tests at user sites have confirmed a good to excellent performance regarding geometric accuracy and resolution, radiometric performance (noise, dynamic range) and colour rendition. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Photogrammetric scanning has become of growing interest with the advent of softcopy photogrammetry. In the late 1980s, the then-existing scanning technology was of insufficient stability to transfer the geometric accuracy of photogrammetric film into

a digital format. Specialised photogrammetric flatbed scanners began to appear about 10 years ago, with the introduction of Zeiss/Intergraph PS1 in September 1989, Vexcel's VX3000² in October 1989 (Leberl et al., 1990a, 1990b, 1992) and HAI's DSW 100 also in 1989.

At that time electronic, low-cost drum scanners were still not introduced in the market; this began in February 1990 with the announcement of a new

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² In 1992, this product has been spun out into a separately funded US company, Vexcel Imaging Corporation.

Optronics scanner product. Low-cost electronic drum scanners then conquered the market in the graphic arts, with great radiometric abilities, but very poor geometric accuracies. While various attempts were made to use such scanners in photogrammetry, it turned out that not even low accuracy orthophoto production was feasible, given that geometric errors of up to $\pm 500 \mu\text{m}$, with typical values for high-end drum scanners of 25–50 μm , were reported, as a result of the inability to maintain tight contact of the film with the drum at all times and across the entire format of aerial photos (Thorpe, 1992).

This justified the development of photogrammetric flatbed scanners, with a large enough format to scan a full size aerial image and accurate enough to meet the photogrammetric requirements of about $\pm 2 \mu\text{m}$. Since 1991, a number of such flatbed scanners has appeared in the market, as discussed in the literature (Baltasvias, 1998, 1999). In spite of predictions that digital cameras will ultimately eliminate the need for film scanners, the need for scanners has been growing.

Scanners ideally should be capable of digitising a full-frame aerial photograph in one single shot and at a geometric resolution of at least 2000 dpi or 12.5 $\mu\text{m}/\text{pixel}$. However, such a capability does not exist at this time. Therefore, aerial photography is being scanned in parts, assembling a complete, large digital image from small tiles or swaths collected by moving the sensor head or scanner stage.

It is the sensor type—either a linear or an area detector array—which defines the type of subimages. The linear array produces swaths or image strips, the area array creates tiles. Both approaches to scanning result in a need for a high geometric stability to avoid geometric mismatches between subimages, and both need high radiometric repeatability to avoid visible seams where separately collected tiles or strips join.

Geometric stability needs to produce high geometric accuracy to support photogrammetric measurements, and photogrammetric scanners also have to meet excellent radiometric specifications. One obvious reason is the demand for high-quality image products in the form of orthophoto maps, which need to show interpretable details. A second reason is the need to resolve fine differences in image density in support of stereo matching, where a loss of texture

leads to a loss of correct matches. Thirdly, as one uses the digital images for image mensuration their value would get compromised, should details for ground control measurements not be identifiable, for example in high contrast environments where shadows exist.

We therefore argue strongly that a photogrammetric scanner needs to fully resolve the entire density range of any images it needs to process. We have found that in the case of monochrome (black and white, B/W) material a maximum density of up to 2.5 D is typically present in aerial photography, and that in the case of colour diapositive film, maximum densities may exceed values of 3.0 D. These ranges can be even larger in still photography with good illumination for close-range photogrammetry.

This paper will present some studies about the radiometric capabilities a scanner needs to have, and illustrates this with the UltraScan 5000.

2. Design concepts of photogrammetric scanners

2.1. Drum versus flatbed scanners

Photogrammetric scanners are of the so-called “flatbed” type. Drum scanners, for obvious reasons, cannot produce the high geometric accuracy needed for photogrammetry, holding a large format aerial photograph tight on the drum is practically impossible, and besides, the handling and workflow of drum scanners cannot compete with the convenience of operating with a flat scanner stage. This last fact is abundantly documented by the overwhelming acceptance of flatbed scanners in the graphic arts, since they came in the market about the end of 1996 and reduced dramatically the use for all types of drum scanners.

In the early years of photogrammetric softcopy photogrammetry, manufacturers of drum scanners made the argument that flatbed scanners would not be able to approach the radiometric performance that drum scanners routinely produce. This disadvantage of flatbed scanners has been overcome during the last few years by improved electronic linear and area array CCD sensors with better signal-to-noise characteristics and a greater number of pixels, making

their unopposed acceptance over drum scanners a reality.

2.2. Area array and linear array CCDs

CCD detectors are designed either in the form of area arrays for use in digital cameras aimed at moving scenes, or in the form of linear arrays used in still cameras, in document scanning, faxes, copiers or kinematic push-broom imaging devices. Linear sensors produce better radiometric quality and therefore are the preferred device in scanners. It is relevant to point out that in both cases, be it linear or area array sensors, their dimensions have been insufficient to scan a full aerial photograph in a single shot or strip (except ISM's XL-10 which uses three optically butted CCDs to scan in a single strip). Therefore, large format scanners usually need a mechanical unit to move the sensor or the scanner stage to collect all parts of the image.

Area array CCD sensors operate in a "stare-step" approach. The scan head moves to a predefined position and "stares" to grab an image tile, then it moves to the next predefined position to grab the next tile and so forth. A linear array CCD sensor will be continuously moved over the image, collecting a swath of imagery, then move in one direction to scan the next swath, etc. The scanned digital image must in both cases be assembled from the collected parts (the "xy-stitching approach").

2.3. Achieving high geometric and radiometric accuracy

Commercial flatbed scanners for the graphic arts industry are designed for highest radiometric capabilities, but ignore the need for geometric accuracy. Photogrammetric scanners are designed for an accurate geometry, either by high mechanical accuracy, or by special calibrations, but have so far largely ignored the radiometric requirements for accurate colour reproduction. Recently, this fact has been documented in a paper by Neumann and Baltsavias (2000). Kölbl has repeatedly encouraged the concern for colour and tone quality in the photogrammetric application (Kölbl and Bach, 1996; Kölbl, 1999).

At issue is, however, the achievement of both, high geometric as well as high radiometric accuracy.

One needs to understand that image co-ordinate measurements are primarily based on the examination of grey values in an image; it should thus be instantly obvious that high radiometric quality will improve the ability to make accurate measurements.

3. Description of the UltraScan 5000³

The UltraScan 5000 is the latest entry in the current range of competing photogrammetric scanners. It is designed as a flatbed device, using multiple-pass scanning with a linear CCD detector array (Gruber et al., 1998; Leberl et al., 2000). In contrast to other scanners, it was designed to address the needs of the photogrammetric market as well as of the high-end graphic arts applications. The basic scanner was introduced to the graphic arts industry in the fall of 1996 and then to the photogrammetric 1–2 years later. Fig. 1 provides a picture of the scanner and Table 1 summarises its specifications. The UltraScan 5000 covers a range of geometric resolutions from 10 dpi (2500 μm) to 5080 dpi (5 μm), and up to 10,160 dpi (2.5 μm) with software interpolation, and thereby covers a scan area of 280 or 330 mm \times 440 mm, and 265 mm \times 252 mm when using a roll film attachment. The geometric accuracy has been shown to be better than 2 μm (RMSE) for x and y (Gruber et al., 1998).

The scanner is equipped with a high-end tri-linear CCD-sensor, the Kodak KLI-6003 (Kodak, 2000) with 3×6000 elements for single pass colour scanning. The density range of the scanner is better than 3.4 D with a dynamic range (ratio of signal just before saturation/dark noise) of 72 dB. 16 native scan pixel sizes can be used offering a set of useful trade-offs between throughput and radiometric quality.

The operation of the UltraScan 5000 is supported by an intuitive graphical user interface. Its design was concerned with easy scan settings and a continuous feedback through a pre-scan display. For scan-

³ UltraScan 5000 is a product of Vexcel Imaging Austria. This company started operations in 1993 and shares a legacy with Vexcel Corporation (Boulder, CO, USA).



Fig. 1. UltraScan 5000 in various configurations. Top: basic scanner unit (left) and scanner with manual roll film attachment (right). Bottom: scanner with autonomously operating roll film attachment.

ning uncut rolls of film two options exist, namely either a manually operated attachment or an auto-

matic, thus robotic, roll film assembly, both as upgrades to the basic scanner.

Table 1
Technical specifications of the UltraScan 5000

Scanner unit	
Format	A3 + (280 mm × 440 mm at 5080 dpi (5 μm), 330 mm × 440 mm at 882 dpi (29 μm))
Native resolutions	16 different settings, selection corresponds to GUI settings
Optical resolutions	5080 dpi or 882 dpi, selection corresponds to GUI settings
Geometric output resolutions	Continuously selectable between 10,160 dpi (2.5 μm) and 10 dpi (2500 μm)
Geometric accuracy	Better than ± 2 μm
Density range	3.4 D
Radiometric accuracy	Up to ± 0.3 grey values at 1.0 D
Illumination	Transmissive and reflective light, user-selectable
Colour passes	One pass
Bits per pixel	At native 3 × 12 bit from A/D conversion, internal use of 3 × 16-bit per pixel (super-pixels)
Sources	Colour, greyscale or line art, negative black and white and colour scanning
Roll film	Optional attachment for either manual or automated operation
Software	
Graphical User Interface (GUI)	For Windows NT
Various output formats	TIFF, Tiled TIFF, TIFF-16, RAW, EPS, DCS, SCITEX
Output pixels	At 8 or 16 bits per colour channel
Photogrammetric support software	Includes special on-line geometric calibration

4. Some features of the UltraScan 5000

A special capability of the UltraScan 5000 is its radiometric quality. The technology for this capability can be characterised by several major elements.

4.1. Linear CCD detector array

The radiometric and colour performance of the electronic sensor are the basic quality parameters, since sensor chip geometry is generally good enough. Use of the Kodak KLI-6003 trilinear array with 6000 pixels for each of the three principal colours results in a radiometric range of 3.6 D or about 4000 linear grey values. The analogue signal is then converted to a digital one with 12-bit and stored in 16-bit. Lens, illumination, colour filters and CCD are components of a single system that need to fit.

As all Kodak linear CCDs, KLI-6003 provides for exposure control for each colour line CCD to achieve colour balancing and organic colour filters applied on the sensor chip itself. Contrary to some other Kodak linear CCDs, especially the KLI-10203 which is often used in DTP and photogrammetric scanners and will be used here for comparison, the KLI-6003 shows some favourable characteristics: (a) the sensor pixel size is 12 μm compared to 7 μm , thus with a ca. three times larger area, a stronger signal (more photons) per sensor element can be collected and the saturation charge capacity is higher (maximum number of collected electrons per sensor element is 275 K) leading to a higher dynamic range for the same noise level; (b) only one CCD shift register per colour channel is used to read out the signal, avoiding multiplexing of two registers per channel and the related radiometric artifacts and cross-talk; (c) the organic colour filters are optimised for colour negative film and not reflective scans as for KLI-10203, and their responsivity in RGB is ca. three times larger.

A higher number of pixels may be easily provided by a CCD, but the illumination, lens and colour filters should be selected such that they produce a sufficient stream of photons. CCD-arrays, offering more pixels are often used to present “better” numbers and specifications but not necessarily higher performance.

4.2. Scan pixel size

The UltraScan 5000 operates with two different optical resolutions (lens positions), with scan pixel sizes of 5 and 28.8 μm , respectively. Using electronics, eight binning factors (between $1 \times$ and $8 \times$) per optical resolution can be selected. This leads to 16 native resolutions. The option of using different native resolutions to arrive at a specific selected output pixel size is unique and has quite an important role when striving for high throughput or quality. For example, radiometric resolution can be improved by the use of a higher native resolution and deriving from it so-called “superpixels” at a lower resolution. This may be at the expense of throughput. Throughput, on the other hand, can be optimised by using the nearest native resolution available for a chosen output resolution.

4.3. Infrared cut-off filters

Electronic detectors are sensitive to infrared light and in fact CCDs have the highest responsivity in NIR. Even if colour filters are used to separate different wavelengths of the visible spectrum, these filters often become transparent in the NIR (usually beyond 700 nm wavelength). Photons in NIR create free electrons deep in the CCD silicon layer, causing smear and MTF reduction. Because of the ability of infrared light to proceed even through dark film, this will affect the radiometric resolution significantly. To avoid this, the UltraScan 5000, as most scanners, includes a set of NIR cut-off filters.

4.4. Dynamic cooling of the sensor

Heat will increase the magnitude of the dark noise in an electronic sensor, and therefore will limit the radiometric resolution of the system. Dark current noise, for KLI-6003, doubles for every 9° higher temperature. One proper method to avoid heat is by cooling the sensor. The UltraScan 5000 employs a Peltier cooling device. Cooling a component may result in the appearance of condensation moisture. To avoid this effect, the cooling device must measure the temperature difference with the environment, and then control the cooling to not exceed a certain user-selected minimum cooling level.

4.5. Radiometric calibration

The radiometric result of a scanner is affected by numerous elements, such as the light source, glass plates of the stage, optical lenses, mirrors and the sensor. Each of those elements has a specific influence on the quality and intensity of the light. In order to measure this influence and to compensate for adverse effects on the resulting digital image data, the scanner's operating software must include a radiometric calibration procedure. This must be easy to handle and cannot take an excessively long time. The radiometric calibration of the UltraScan 5000 is based on the offset and gain measurements (i.e. dark current and maximum signal) for each sensor element of the CCD array. In order to include the light source of the scanner in the radiometric calibration procedure, these measurements are repeated at each subscan position. Therefore, variations of the light intensity at different positions over the scan area are being considered.

4.6. Illumination

The illumination system must produce a balanced and spatially uniform amount of red, green and blue light. It must be independent of the duration of the scanning job or of the scanner age. To achieve this uniformity over time, a control circuit is implemented to correct the amount of light to be generated by the lamp. Since UltraScan 5000 can scan both transparent as well as opaque material, two separate illumination systems are used.

4.7. Intuitive graphical user interface

The achievement of optimal scanning results is being supported by several tools for the operator so that the colours and grey values of an image can be set and checked by means of a pre-scan. The GUI software must not only offer the selection of the primary scan parameters such as resolution etc., but also enable pre-scan display, automatic or manual dark and bright point measurement, histogram manipulation, colour look-up tables and an unsharp masking filter.

5. Assessment of scanner radiometric performance

The development of scanner test procedures has been a topic of some previous research, for example by Baltasvias (1994) and Seywald (1996). The most convenient way to proof a scanner's radiometric performance is to scan a known target with a number of known density values (a so-called grey wedge). The digital image of that target has to be analysed through a predefined procedure to obtain a set of key numbers. It will be these key numbers that can describe what the scanner does in terms of radiometry.

5.1. Defining a test procedure

A test procedure to assess the radiometric performance of the UltraScan 5000 starts with a grey wedge with a density range of 3.4 D and a density step of 0.1 D (Kodak StepTablet ST 34), and with a colour test target (C-ROES T2X, see also <http://www.c-roes.de>). Test images result from scanning these targets. When purchased from the manufacturer, these targets are factory-calibrated. The grey wedge has been measured by a densitometer (Gretag Macbeth D 200-II) with a resolution of 0.01 D and by averaging a set of three to four independent measurements. The nominal density values can be compared with such measurements. Differences of up to 0.02 D between nominal values and densitometer measurements have been observed.

The test procedure is based on single and multiple scans of the targets, the analysis of the digital images derived from those and the visual inspection of the test images. Further test versions have been produced by scanning under different scan settings (e.g. geometric resolution) and by testing each of the primary colours separately. The output of such tests represents the radiometric resolution by visually inspecting the resulting images and by comparing mean and standard deviation (noise) of grey values for each density. The grey wedge may itself become noisy, given the regular and heavy use of a grey wedge in testing. Comparing different types of grey wedges one may observe more or less graininess within the different patches of the wedge, depending on the manufacturing process.

It may therefore appear useful to scan a grey wedge more than once, to take a look at the difference of two scans by subtracting one scan from the other, and to finally study the noise within each density of the grey wedge. Multiple scanning of the wedge helps to separate the noise of the scanner from the noise in the test target. Scanning the grey wedge by defocusing is an alternative method to avoid the impact of grain, although this can also reduce real noise.

Beside absolute grey levels, we are interested in the linearity of the entire scanning process. This can be represented by plotting each density versus the logarithm of the corresponding mean grey value, e.g. from a 40×40 pixel patch of each density step.

All scans presented below have been made by a linear look-up table and grey values were stored in 16-bit, nominally presenting 65,536 different grey levels. For these tests, D_{\min} and D_{\max} need not to be set. The saturation charge capacity of the sensor is almost reached at a density of 0.0 D (D_{\min}) for the used illumination power and exposure time, whereby the latter is determined during the radiometric calibration. Maximum density (D_{\max}) does not need to be set provided the output signal of the scanner is being stored in a linear scale.

5.2. Test results

The following selection of test results shows the radiometric performance of the scanner at two optical resolutions of 15 and 25 μm pixel size for each colour channel. The grey wedge used for these tests

covers a density range of 0.0–3.4 D at 0.1 D steps. The scanned grey wedge is shown in Fig. 2 for a control of the visual separation of the 35 densities. The scanned images had to be enhanced in separate regions by stretching the density range region of 0.0 to 1.1 D, 1.2 to 1.7 D and so forth, each to 256 grey values, to allow visualisation of the small differences between neighbouring grey values on print. Fig. 3 shows the linear relationship between logarithm of grey levels and density. Table 2 shows the mean and standard deviation (representing noise) of grey values for each density of the Kodak ST34 grey wedge (green channel). The noise values for the red and blue channels were slightly worse. The scanned 16-bit grey values were linearly stretched to the range 0–256. Each entry in Table 2 was computed in a region of interest for each density of the grey wedge, typically consisting of 40×40 pixels, approximately at the centre of each step. The sensor was cooled to typical room temperature. From Table 2, it is clear that the standard deviation changes as a function of the density. Thus, in assessing scanners, it makes sense to specify the radiometric accuracy for specific densities, and not with one global number. Note that the UltraScan 5000 shows a radiometric accuracy of ± 0.3 grey values at a density of 1.0 D, which is close to the average density of aerial films.

5.3. Special experiments for bright image areas

In bright areas, e.g. at 0.1 D, the steps of the grey wedge are not small enough to do justice to the scanner's radiometric resolution. Therefore, a special

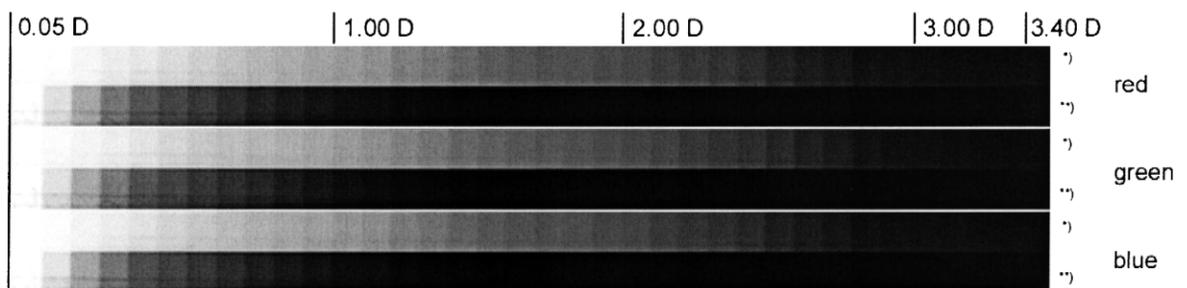


Fig. 2. Scanned Kodak Step Tablet ST 34 (25 μm scan pixel size) presenting the RGB channels. The upper lines show the logarithmically transformed signal (marked with *), the lower lines show the linear signal of the scanner (marked with **).

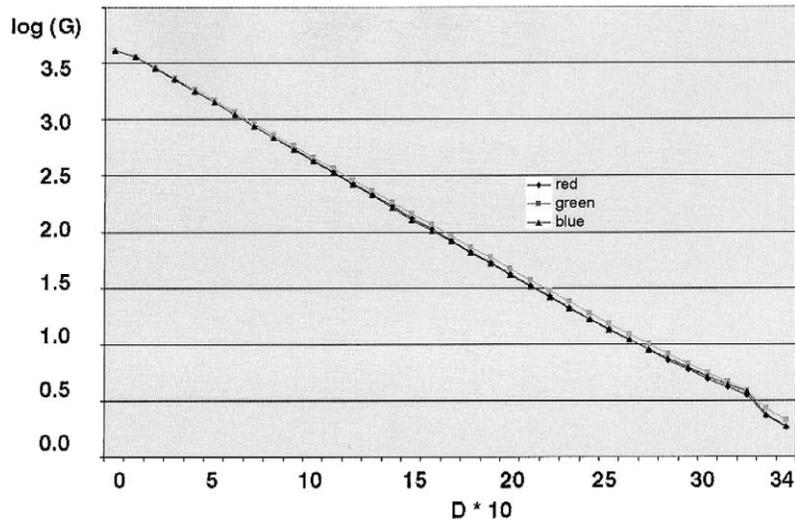


Fig. 3. Grey value linearity for the RGB channels shown in Fig. 2 using the logarithm of 16-bit grey values and nominal density values multiplied by 10. Each grey value is the average of 40×40 pixels.

grey wedge target was created by means of six glass plates stacked on top of each other. Each glass plate shows a density of approximately $0.04 D$ and by putting glass plates on a staple, densities of 0.00, 0.04, 0.08, 0.12, 0.16, 0.20 and 0.24 D have been

produced and scanned. D_{\min} and D_{\max} remain at settings typical for operational photogrammetric scanning (e.g., 0.0 D for D_{\min} and 2.8 D for D_{\max}). Fig. 4 illustrates the image and its histogram: this shows clearly that the density steps which are only

Table 2

Mean and standard deviation of grey values for each density of the Kodak ST34 grey wedge (green channel) scanned by the UltraScan 5000

Density (D)	Grey value mean (8-bit range)	Grey value standard deviation	Density (D)	Grey value mean (8-bit range)	Grey value standard deviation
0.0	255.91	0.51	1.8	4.58	0.07
0.1	225.73	2.39	1.9	3.70	0.05
0.2	180.33	1.26	2.0	2.92	0.04
0.3	144.52	0.90	2.1	2.33	0.03
0.4	114.07	0.87	2.2	1.87	0.03
0.5	91.56	0.73	2.3	1.50	0.03
0.6	72.13	0.63	2.4	1.18	0.03
0.7	57.13	0.72	2.5	0.95	0.03
0.8	45.44	0.46	2.6	0.76	0.03
0.9	36.17	0.37	2.7	0.62	0.03
1.0	28.91	0.30	2.8	0.51	0.03
1.1	23.02	0.23	2.9	0.42	0.03
1.2	18.22	0.23	3.0	0.35	0.03
1.3	14.60	0.17	3.1	0.29	0.02
1.4	11.53	0.17	3.2	0.24	0.02
1.5	9.04	0.12	3.3	0.21	0.02
1.6	7.29	0.09	3.4	0.17	0.02
1.7	5.79	0.07			

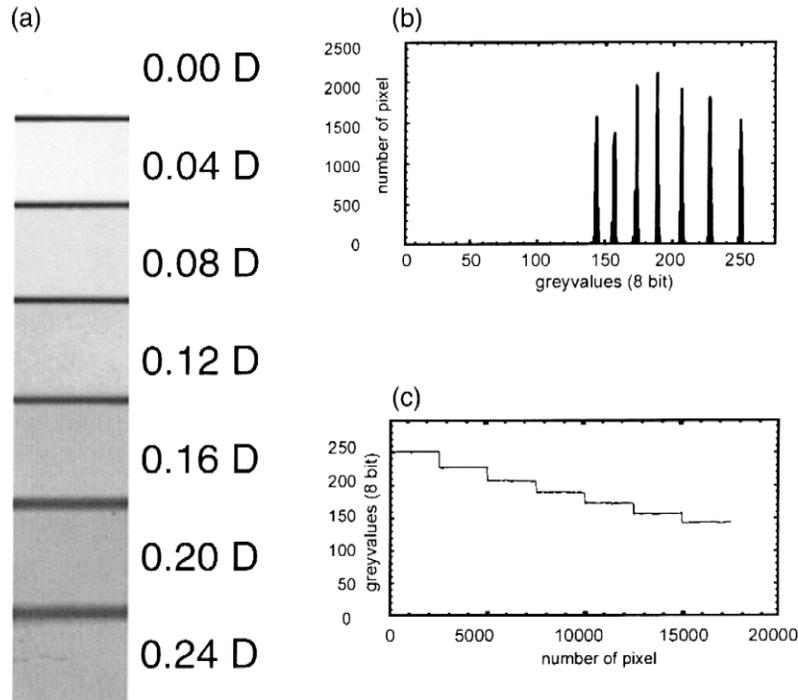


Fig. 4. Six thin glass plates which are placed on top of each other to serve as a grey wedge of very small density steps: (a) scanned plates and their corresponding density values; (b) histogram of the grey values of each plate; (c) a so-called “pixel plot”, i.e. grey values in averaged profiles along the plates.

0.04 D apart have all been unambiguously resolved. The dark stripes in Fig. 4a) are an effect of the plate edge where light is reflected, and are excluded from the histogram. It is obvious, that no saturation takes place and the automatically evaluated exposure time from the radiometric calibration procedure is correct.

5.4. Special experiments for dark areas

The frame of a diapositive film is usually the darkest area of the entire image. Therefore, it is interesting to check if a structure laid on top of the film border can be resolved. The experiment uses the dense border of a colour infrared aerial image. An area of that frame that was covered with a geometric resolution target was scanned and 16-bit data per colour channel were stored. The narrow density range of about 2.5 to 3.0 D was locally stretched within a small window to make the underlying resolution target visible. As it can be seen in Fig. 5, the resulting image allows a clear separation between the structure of the target and the background.

5.5. Scanning a colour target

The colour target C-Roes T2X (manufactured in accordance with ANSI IT8.7/1) was used to test the colour reproduction of the scanner. The colour target shows a series of colour steps for the primary colours cyan, yellow, magenta, red, green and blue as well as for black and a set of other colours as defined by the ANSI IT8 subcommittee. Fig. 6 shows the entire colour target, scanned at 50 μm pixel size, the subarea of the target containing columns 13 to 19 (primary colours and black) and a diagram comparing the given Lab co-ordinates of the target and the measured Lab co-ordinates from the scanned image.

5.6. Comparing different scanners

Baltsavias (1999) published radiometric performance values for the photogrammetric scanner models DSW200 and DSW300 by LH Systems, Inc., the Zeiss SCAI, the ISM XL-10 and the RM-1 by Wehrli.

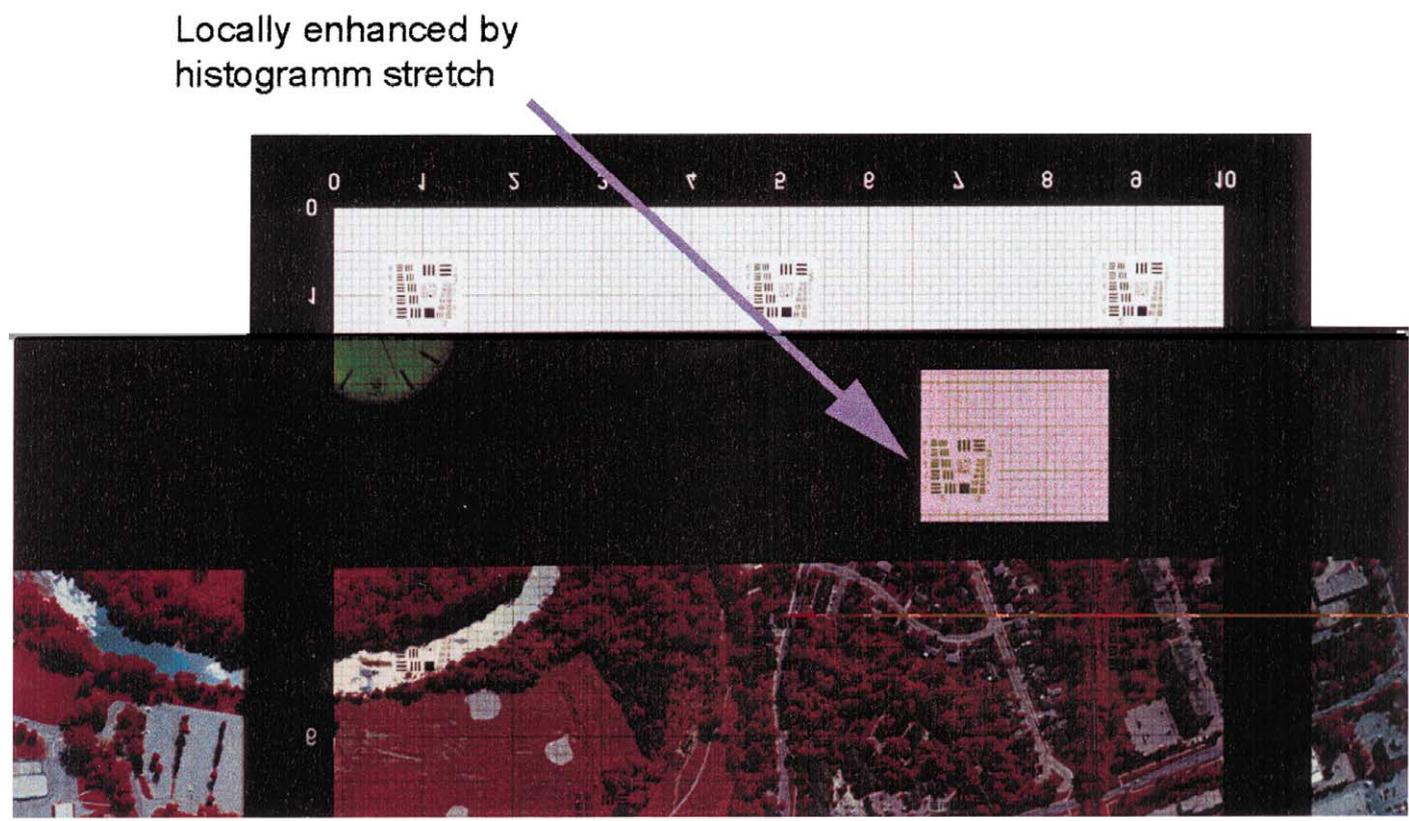


Fig. 5. Black border of a colour infrared diapositive film with density of approximately 2.7 D scanned together with a geometric resolution target showing that the structure of the target is being resolved and its details can be measured in an area that is locally enhanced by histogram stretch.

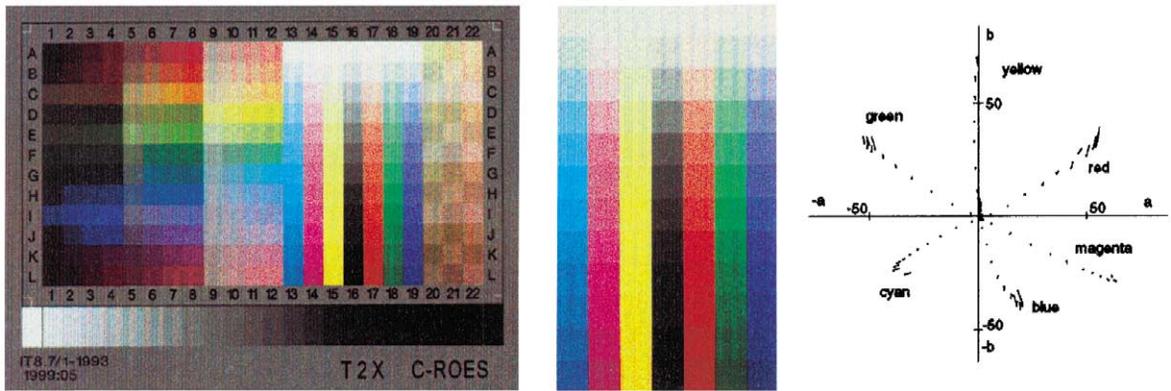


Fig. 6. The C-ROES colour target T2X on the left. The central part shows the steps of the six primary colours and black. On the right, the residuals of a and b components (Lab colour space) of the 72 fields of the primary colours (mean values) are shown after an affine transformation of the values in the scanned image to the nominal calibrated values of the target.

In these tests, a calibrated Kodak grey wedge ST 2 with 20 density steps from ca. 0.05 to 3.05 D at intervals of 0.15D was employed. A density is considered “resolved”, if certain conditions apply (explained in detail in Baltasvias and Kaeser, 1999), among them the most important being that the absolute difference ‘delta’ of the mean grey values between the current density and each of its neighbouring ones is larger than the sum of their standard deviation, i.e.

$$\sigma_{\text{left}} + \sigma_{\text{current}} < \text{delta}_{l/c} \quad (1a)$$

$$\sigma_{\text{right}} + \sigma_{\text{current}} < \text{delta}_{r/c} \quad (1b)$$

Baltasvias’ (1999) paper is a rare comparison of radiometric performance of photogrammetric scanners. If we use Eqs. (1a) and (1b) also for the UltraScan 5000, we can extract from Table 2 the comparable radiometric performance values that the author provides for the SCAI, DSW 200 and 300, and RM-1 scanners. Baltasvias is also using the criterion that mean grey values for each density, rounded to their nearest integer, should be different in order to be resolved. This is not the case for the densities 2.1 to 3.1 D, which are otherwise resolved based on the criterion of Eqs. (1a) and (1b). This makes clear, that when a scanner can resolve many densities (grey values), the digitisation should be

with sufficient bits (more than 8) to allow their separation. Although Table 2 is based on the Kodak ST 34 and not the Kodak ST 2 grey wedge which was employed by Baltasvias, the mean and standard deviations should not be affected by the use of two different calibrated grey wedges, as long as their fabrication process is similar, selected test regions per density avoid borders, number of pixels per test region is large enough and statistically significant, scan pixel size is similar (here the case), used LUT are identical (in both tests always linear), and the used density range and exposure time are similar (unknown whether this is the case). The results are summarised in Table 3 only for the sake of relative comparison, and not to actually adopt the presented density and noise values in an absolute sense. The UltraScan 5000 offers a performance that is superior to the other scanners.

5.7. When is a grey wedge “resolved”

Using the definition of “resolved” in Eqs. (1a) and (1b) as proposed by Baltasvias and Kaeser (1999), we would find densities denoted as “unresolved” that an observer would still be able to separate visually. We argue that the “observation” one wants to make in a grey wedge is the density difference delta between two adjacent density steps

Table 3

Comparison of radiometric performance parameters between various photogrammetric scanners

Scanner model	D_{\min}	D_{\max}	Mean grey value standard deviation	Scan pixel size (μm)
DSW 200	0.05	1.90	1.1	12.5
DSW 300	0.05	1.95	1.2	12.5
SCAI	0.05	1.95	1.1	14.0
Rastermaster 1	0.05	1.50	1.5	12.0
UltraScan 5000	0.00	3.10	0.60 ^a	12.5

^aThis value represents the summed squares for the densities 0.0–3.1 D (dynamic range in this test). When using the mean value, as for the other scanners above, the respective value is 0.33 grey values.

(density may be replaced by grey values when investigating digital images). Its uncertainty, expressed by

the standard deviation, would have to be small enough, as to not “drown” the signal, represented by

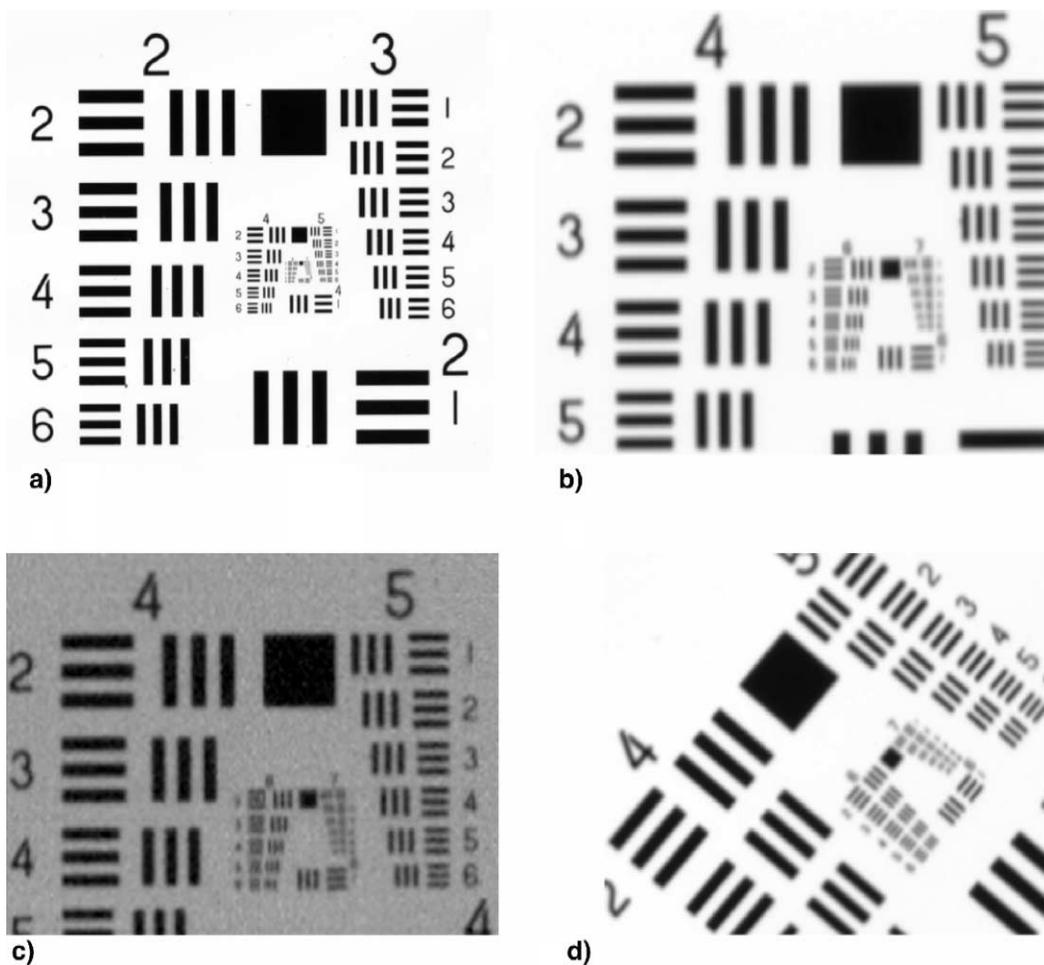


Fig. 7. USAF resolution target scanned at $5 \mu\text{m}$ pixel size: (a) Overview of the target; (b) Zoom-in of the central groups of lines (4–7) of (a); (c) as (b) scanned at reduced contrast by applying a neutral filter of optical density 2.3 D; (d) as (b) after rotating by approximately 45° .

the absolute density difference ‘delta’. We take this consideration as the basis for the proposal to call adjacent density steps “resolved” if:

$$\text{sqrt}(\sigma_{\text{neighbour}}^2 + \sigma_{\text{current}}^2) < \text{delta} \quad (2)$$

With this definition, a larger number of densities would be “resolved” than under Baltsavias’ definition, and this will also reflect better the visual experience. In the UltraScan’s case, the definition in Eqs. (1a) and (1b) produces a resolution of 3.0 D, and Eq. (2) of 3.4, using the ST 34 grey wedge.

6. Geometric performance

The geometric performance of a scanner is defined by its ability to resolve small geometric details of the original film, and to position the object features in the image at their correct geometric location.

6.1. Geometric resolution

Geometric resolution depends mostly on the resolving power of the optical components of a scan-

1 Pixel = 5 micrometer

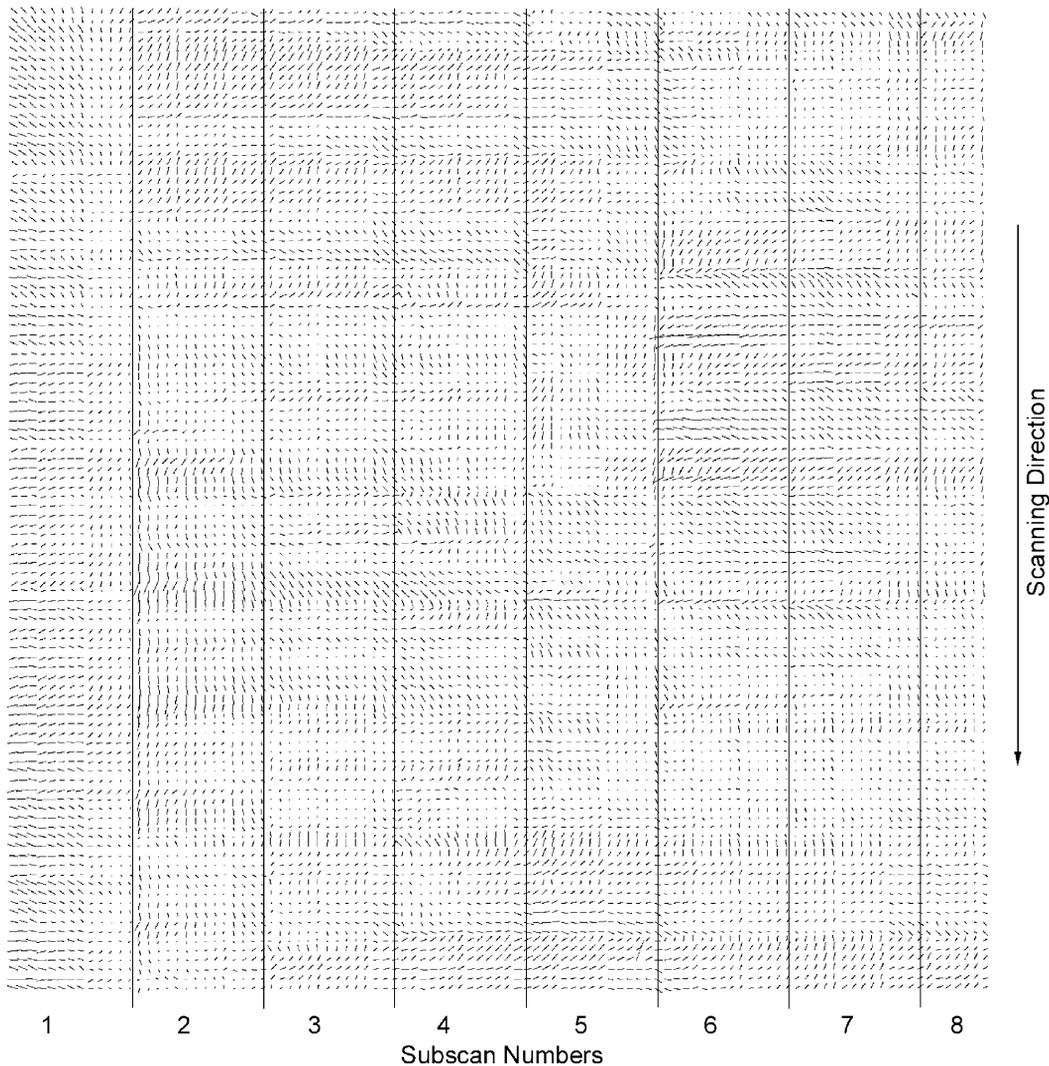


Fig. 8. Residuals of a dense grid plate with 2 mm grid spacing after an affine transformation between pixel and reference co-ordinates.

ner and the chosen settings for the pixel size. Geometric resolution can be tested by scanning special resolution targets of varying pattern size and orientation. The so-called USAF-target uses a pattern of black and white three-line pairs of different size. Fig. 7 shows a USAF-target scanned with the UltraScan 5000 at a pixel size of $5\ \mu\text{m}$ and at a pixel size of $25\ \mu\text{m}$. The target was produced by Heidenhein on glass. Using the Kell factor, 71 lp/mm (the group 6.2 of the USAF Target) should be resolved by a $5\ \mu\text{m}$ scan pixel size, which is visible in Fig. 7b–d. The scan direction is from top to bottom of the figure. Due to scanner head motion and image smearing, the vertical lines are better resolved than the horizontal ones (cf. Fig. 7b), while Fig. 7d, showing the target with 45° rotation, has a similar resolution in both directions.

6.2. Geometric accuracy

The geometric accuracy can be verified by scanning a well-defined grid plate on glass, which in this case was manufactured by IMT, Switzerland (see <http://www.access.ch/imtag>) and was accurate

to within $\pm 1\ \mu\text{m}$ with a format of $260\ \text{mm} \times 260\ \text{mm}$. The grid plate spacing is very important. It should be small enough to reveal local errors, especially systematic ones, and for this plate was 2 mm. The pixel co-ordinates of the grid pattern, which have been determined in the digital image with an accuracy of approximately 0.2 pixels by image correlation methods, were compared to the known co-ordinates of the grid plate. From an affine transformation between the two co-ordinate sets, estimated by least squares adjustment, residuals (errors) at individual grid positions can be computed. The RMSE in this test, with $5\ \mu\text{m}$ scan pixel size, was $1.6\ \mu\text{m}$ in x and $1.8\ \mu\text{m}$ in y . Fig. 8 shows the grid plate image and the residuals over an area of $210\ \text{mm} \times 210\ \text{mm}$.

6.3. A two-step calibration procedure

The geometric accuracy of the UltraScan 5000 is based on a two-step calibration procedure. The first part of this procedure creates a calibration table which describes the mechanical and optical status of the scanner by calibrating each path of the scan-head



Fig. 9. Scanned black/white negative film with $25\ \mu\text{m}$ pixel size on the left and an enlarged area of high contrast showing details in bright as well as shadow areas.

for each individual scan swath and the principal distance and distortion values of the optical system. This so-called “off-line” calibration is based on a calibration grid plate scanned at the highest resolution. The area to be calibrated is typically $260\text{ mm} \times 260\text{ mm}$. This type of calibration is typically performed once a month. Nevertheless, the actual status of the scanner can be determined automatically at any time by producing a so-called calibration protocol.

The second part of the calibration is the “on-line” calibration during each production scan. It measures the actual geometric position of each individual swath

during scanning. This is based on an auxiliary target with reseau marks placed outside the scan area. In contrast to the older VX-series of scanners, these marks in the UltraScan 5000 do not interfere with the image since they are outside the actual scan area.

7. Versatility of UltraScan 5000 and use in production

Scanning performance includes the system’s ability to change and tune parameters, either automatically or manually. The UltraScan 5000 provides a set



Fig. 10. Scanned colour negative film with an orange mask of density 0.3 D on the left and enlarged positive area showing excellent reproduction of colours and tones ($25\ \mu\text{m}$ scan pixel size).

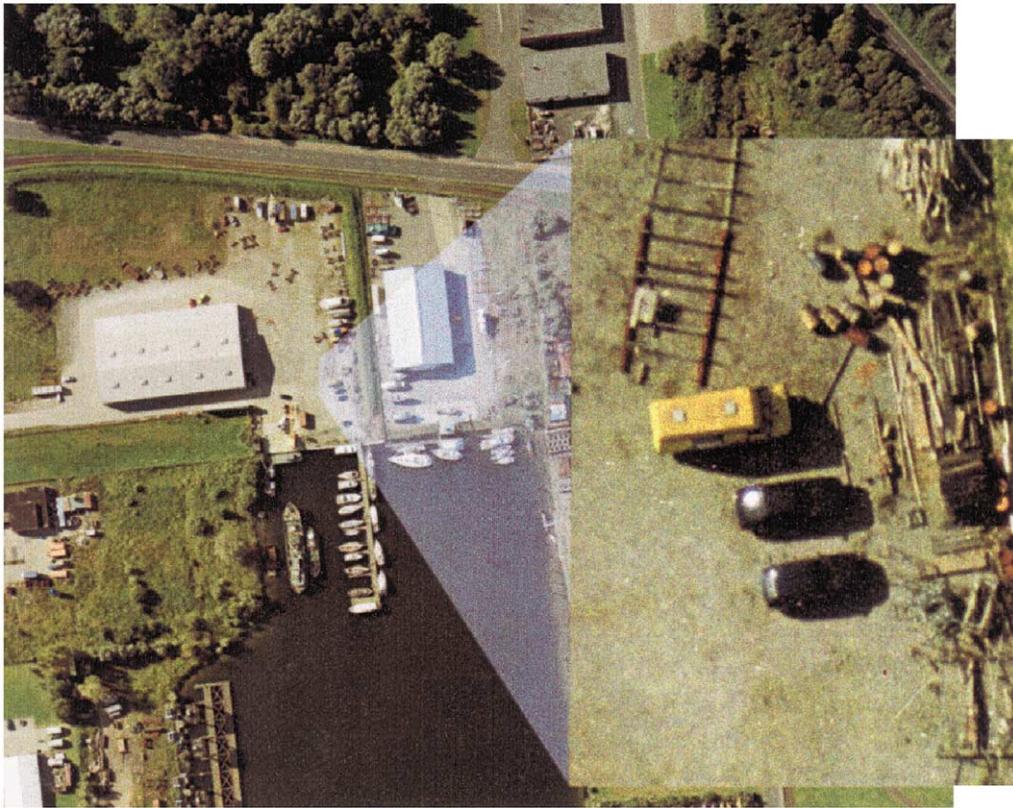


Fig. 11. Colour negative film Agfa Aviophot Color X 100 of image scale 1:5000, scanned in positive at $5\ \mu\text{m}$ pixel size. Note the enlarged area on the left, which represents a $5\ \text{mm} \times 3.5\ \text{mm}$ rectangle in the original film (1000 by 700 pixels). Image by Weser Bildmessflug, Bremerhaven, Germany.

of different parameters to tune the scanning procedure and offers, depending on needs, an optimal quality/throughput ratio. These parameters can be set through the GUI-software and allow to influence among other the geometric output resolution, the density range of the scan and the native resolution. Theoretical experiments need to be augmented by tests using real data. Thus, various aerial images of different type have been selected and scans have been performed to illustrate typical scan results. Fig. 9 and 10 show the ability of UltraScan 5000 to produce a high geometric resolution and excellent reproduction of grey tones and colour, respectively. A black/white negative and an orange-mask colour negative film were used for the tests. In Fig. 11 we show the result of a $5\ \mu\text{m}$ scan, exploiting the new Agfa Aviophot Color X100 colour negative film and its remarkable small grain.

For production, the throughput of a scanner is important. At a pixel size of $20\ \mu\text{m}$, a colour image can be scanned with UltraScan 5000 within 15 min including set-up. This results in an annual productivity of 23,000 aerial images, if one employs the robotic roll film attachment.

8. Conclusions

Using the UltraScan 5000 as an example, we presented ideas about the assessment of the performance of photogrammetric scanners. The focus of the presentation is on radiometry, a scanner performance parameter that has not been paid appropriate attention in the past. However, radiometry and colour performance are rapidly gaining in importance, as scanning moves from the support of orthophoto pro-

duction to automated aerial triangulation, stereo matching for DEM generation and extraction of object details.

Radiometric range in excess of 3.4 D and radiometric resolution better than ± 0.04 D (this corresponds to approximately ± 1 grey value at a density of 1.0 D) are feasible and useful (see also Kölbl and Bach, 1996). It is also necessary to understand that radiometric accuracy is a function of the film density and, thus, accuracy specifications using a single number are not fully describing a scanner performance. Instead, it would be preferable to have this accuracy assessed for various densities. Using scanner settings for best radiometric performance, the UltraScan delivers grey values with a noise level of ± 0.7 grey values at 0.5 D, ± 0.3 grey values at 1.0 D and ± 0.04 grey values at 2.0 D. The density range and noise level of the UltraScan 5000 as shown in these tests were better than the respective values of other photogrammetric scanners.

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