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High Quality Photogrammetric Scanning for Mapping

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Abstract

Scanning of analog images has become the new key hardware technology specific to modern digital photogrammetry. Since specialized photogrammetric scanners have been introduced we observe a gradual development and enhancement of quality of the resulting scans. Originally, geometric accuracy of scanners was the overriding specification for these products. This is increasingly being augmented by a concern for good color and radiometric performance. This article discusses measures of radiometric range and resolution, and illustrates the ability of the UltraScan5000, a modern photogrammetric scanner manufactured by Vexcel Imaging Austria. The UltraScan5000 was introduced in November 1998 at the GIS/LIS'98 Conference in Ft. Worth, Texas. Since then a large number of installed systems on the entire globe proves on a daily basis the high quality of this scanning approach and the need for a superior performance in radiometry and color.

1. Introduction

Photogrammetric scanning has become of growing interest with the advent of softcopy photogrammetry. In the late 1980's, the then-existing scanning technology was of insufficient stability to transfer the geometric accuracy of photogrammetric film into a digital format. Specialized photogrammetric scanners began to appear about 10 years ago, with the introduction of Vexcel Corporation's flat bed VX3000 scanner[2] at the GIS-conference in Orlando, Florida, in October 1989 (Leberl et al., 1990 a,b; 1992). At that time the idea of electronic, thus low cost drum scanners was still not introduced -- this began in February 1990 with the announcement of a new 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 in the range of ± 500 µm were reported.

This justified the development of photogrammetric flatbed scanners, with a large enough format to keep a full size aerial image and accurate enough to meet the requirements of the photogrammetric work flow at about ± 2 µm. Since 1991, a number of such flat bed scanners has appeared in the market, as discussed in the literature (Baltsavias, 1998 and 1999). The

[1] [illegible]

need for scanners has been growing, inspite of predictions that digital cameras ultimately will eliminate the need for film scanners.

Scanners ideally should be capable of digitizing a full-frame aerial photograph in one single shot and at a geometric resolution of perhaps 2000 dpi or 12.5 µm per 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 swathes collected by a moving scan head.

It is the sensor type – either a linear or a square detector array – which defines the type of subimages. The linear array produces the swaths or image strips, the square array creates the 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 merge.

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 measurement 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 & 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 color diapositive film, maximum densities may exceed values of 3.0D. These ranges can even be larger in terrestrial still photography with good illumination for close range photogrammetry.

This paper will present some studies about the radiometric capabilities a scanner needs to meet, and illustrates this with the UltraScan5000.

2. Design Concepts of Photogrammetric Scanners

2.1 Drums versus Flat Beds

Photogrammetric scanners use so-called “flat beds”. 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 work flow of drum scanners cannot compete with the convenience of operating with the flat bed. This last fact is abundantly documented by the overwhelming acceptance of flat bed scanners in the graphic arts, ever since they came onto the market since about the end of 1996 and totally destroyed the market for all types of drum scanners.

For some time manufacturers of drum scanners made the argument that flat bed 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 new electronic linear array CCD sensors.

2.2 Square Array and Linear Array CCDs

CCD detectors are designed either in the form of square arrays for use in digital cameras aimed at moving scenes, or in 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 square array sensors, their dimensions have been insufficient to scan a full aerial photograph in a single shot or strip. Therefore large format scanners need a mechanical unit to move the sensor over the image area to collect all parts of the image.

Square array CCD sensors operate in a “stare-step” approach. The scan head steps into a predefined position and “stares” to grab an image tile, then the scan head steps into 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 step over to a new path to produce the next swath or sub-scan. The deliverable digital image must in both cases be assembled from the collected parts.

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 of the scan head’s motion, or by special calibrations, but ignore the radiometric requirements for accurate color reproduction.

At issue is, however, the achievement of both, a high geometric as well as a high radiometric accuracy. One needs to understand that image coordinate measurements are primarily based on the examination of density values in an image; it should thus be instantly obvious that high radiometric quality will improve the ability to make accurate measurements.

3. About the UltraScan 5000[3]

The UltraScan5000 is the latest entry in the current range of competing photogrammetric scanners. It is designed as a flat-bed device, using multiple-pass scanning with a linear CCD detector array (Gruber et al., 1998). In contrast with other scanners it was designed to address the needs of the mapping market as well as of the high end graphic arts applications. The basic scan engine was introduced into the graphic arts in the fall of 1996 and then into mapping two years later. Fig. 1 provides a picture of the scanner and Table 1 summarizes its specifications. The UltraScan 5000 covers a range of geometric resolutions from 50 dpi to 5080 dpi, and up to 10160 dpi with software interpolation, and thereby covers a scan area of about 300 mm by 450 mm, or 250 mm * 260 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 CCD linear sensor, the Kodak KLI 6003 sensor with 3*6000 elements for single pass color scanning. The density range of the scanner is better than 3.4 D at a signal/dark noise ratio of 72 dB. The optical unit allows to scan in a set of 16 native resolutions, achieved through eigth electronic binning factors and two lens positions. This offers a set of useful trade-offs between output pixel size, throughput and radiometric quality.

(a) Basic scanner unit

(b) Scanner with manual roll film attachment

(c) Scanner with autonomously operating roll film attachment

Figure 1. UltraScan 5000 high-end scanning device

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 prescan display.

For scanning uncut rolls of film two options exist, namely either a manually operated attachment or an automatic roll film assembly, both as upgrades to the basic scanner.

Scanner Unit	
Format	A3+ (280 mm x 440 mm @ 5080 dpi, 330 mm x 440 mm @868 dpi).
Native Resolution	16 different settings, user selectable
Optical resolutions	5080 dpi or 868 dpi, user-selectable
Geometric output resolutions	continuously selectable between 10,160 dpi and 50 dpi
Geometric accuracy	better than ± 2 µm
Density range	> 3.4D
Radiometric accuracy	up to $\pm$ 0.3 DN at 1.0D
Illumination	transmissive and reflective light, user-selectable
Color	One-pass color
Bits per pixel	at native 3 x 12 bits, internal use of 3 x 16 bit per pixel
Sources	Color, grayscale or line art, negative black&white and color 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, RAW, EPS, DCS, SCITEX
Output pixels	at 8 or 16 bits per color separate
Photogrammetric support software	includes special on-line geometric calibration

Table 1: Technical specifications of the UltraScan 5000.

4. Special Features of the UltraScan 5000

A special capability of the UltraScan5000 is its radiometric quality. The technology for this capability can be characterized by several major elements.

4.1 High Resolution Linear CCD Detector Array

The radiometric resolution of the electronic sensor is the basic quality parameter for any further output of a scanner. Use of the Kodak KLI6003 linear detector array with 6000 single CCD elements for each of the three principal colors results in a radiometric range of 3.6D or about 4000 linear density values, based on a 12 bit signal.

4.2 Infrared Cut-off Filters

Electronic detectors are sensitive to infrared light. Even if color filters are used to separate different wavelengths of the visible spectrum, an infrared component may pass through unless a special filter is used. 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 includes a set of infrared cut-off filters.

4.3 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. One proper method to avoid heat is by cooling the sensor. The UltraScan 5000 employs a Peltier cooling device.

4.4 Dynamic Implementation of Cooling

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 maximum.

4.5 Radiometric Calibration

The optical system of a scanner consists of numerous elements, such as the light source, glass plates of the stage, optical lenses 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.

4.6 Illumination

The amount of light reaching the CCD is a function of the illumination system. This must produce a correct amount of red, green and blue light. The illumination must be independent of the time of operation of the scanner or its age. A control circuit for the illumination to produce the correct amount of light is essential. In addition a versatile scanner needs to be able to scan both transparent as well opaque material, thus film as well as paper. This requires that two separate illumination systems be implemented.

4.7 Intuitive Graphical User Interface

Achieving optimal scanning results involves an operator to proof settings for colors and densities of an image. An intuitive graphical user interface must support this task. The GUI-software must offer functions for prescan display, automatic or manual dark point and bright point measurement, histogram manipulation, color look up tables and an unsharp masking filter. And of course the GUI will have to help the user in setting the scan-area, the geometric resolution, file format and file name.

5. The Assessment of a Scanner's Radiometric Performance

The development of scanner test procedures has been a topic of some previous research, for example by Baltsavias (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 density steps (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 step distance of 0.1 D (Kodak StepTablet ST 34), and with a color test target (Kodak Q-60). Test images result from scanning these targets.

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 variations have been produced by scanning under different scan settings (e.g. geometric resolution) and by testing each of the primary colors separately. The output of such tests represents the radiometric resolution by visually inspecting the resulting images and by comparing mean grey values in each grey step and looking at the noise σ within each grey step. The grey wedge may itself become noisy, given the regular and heavy use of a grey a look at the difference of two scans by subtracting one scan from the other, and to finally study the noise within each step of the grey wedge.

Beside absolute grey levels, we are interested in the linearity of the entire scanning process. This can be presented by a logarithmic plot of a cross section of the entire image.

All scans used in the following have been made by a linear look up table and grey values were stored in a 16 bit data format, nominally presenting 65,536 different grey levels.

5.2 A Selection of Test Results

The following selections of test results show the radiometric performance of the scanner at two optical resolutions at 15 µm and 25 µm pixel size and for each color channel. The grey wedge used for those tests covers a density range of 0.0 – 3.4 D at 0.1 D steps. The result of the test shows the radiometric resolution along the 35 steps of the grey wedge in Figure 2. The output images had to be enhanced in a number of separate sections to make the small differences visible on paper. Figure 3 shows the linear relationship between grey levels by a logarithmic graph. Table 2 presents the mean values and noise derived by a numerical evaluation of the image data from the Kodak ST34 grey wedge.

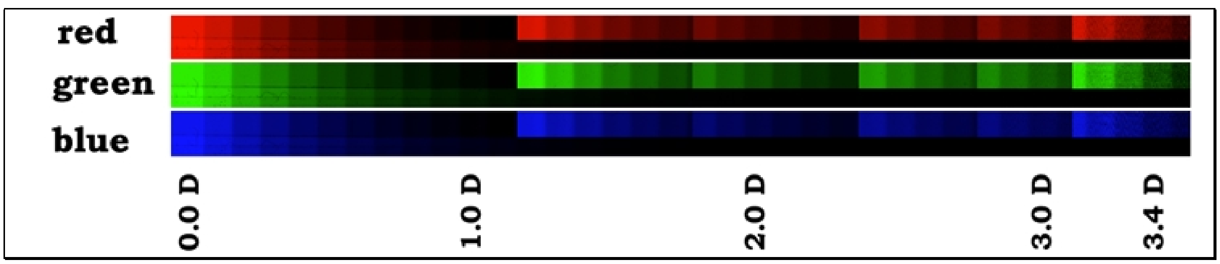


Figure 2: Result of scanning the Kodak Step Tablet ST 34 with the UltraScan5000, using independently the three color channels of the scanner. The images are partially enhanced to make small differences of densities visible in a printed paper.

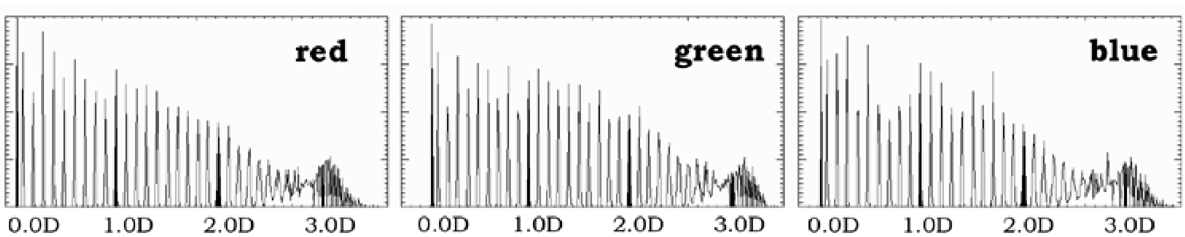


Figure 3: Histogram of the Kodak ST34 grey wedge image Figure 2.

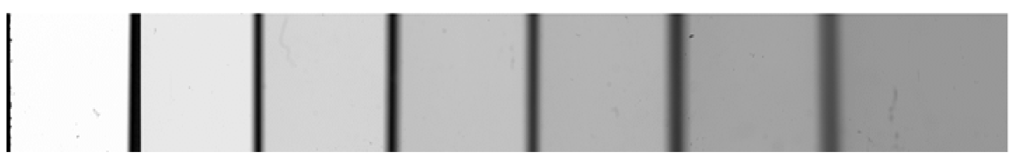
5.3 Special Experiments for Bright Image Areas

In bright areas the steps of the grey wedge at 0.15 D in the Kodak ST30 or at 0.1D in the ST34 are not small enough to do justice to the scanner's radiometric resolution. Therefore a special grey wedge target was created by means of several glass plates stacked on top of one another. Each glass plate shows a density of approximately 0.04 D and, 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. Figure 4 illustrates the image and its histogram: this shows clearly that the steps which are only 0.04D apart have all been resolved.

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

Table 2: Standard deviations of digital numbers DN at each grey step in a Kodak ST34 step wedge. Note how the standard deviation changes as a function of the density. In assessing scanners, it makes sense to specify the radiometric accuracy for specific densities, and not with one global number. Note that the UltraScan5000replicates the grey wedge with a radiometric accuracy of ± 0.3DN at a density off 1.0D.

(a)



D	0.0	0.04	0.08	0.12	0.16	0.20	0.24
DN	253.9	230.8	209.6	191.7	175.9	159.3	144.3
Sigma DN	0.15	0.35	0.30	0.29	0.27	0.21	0.53

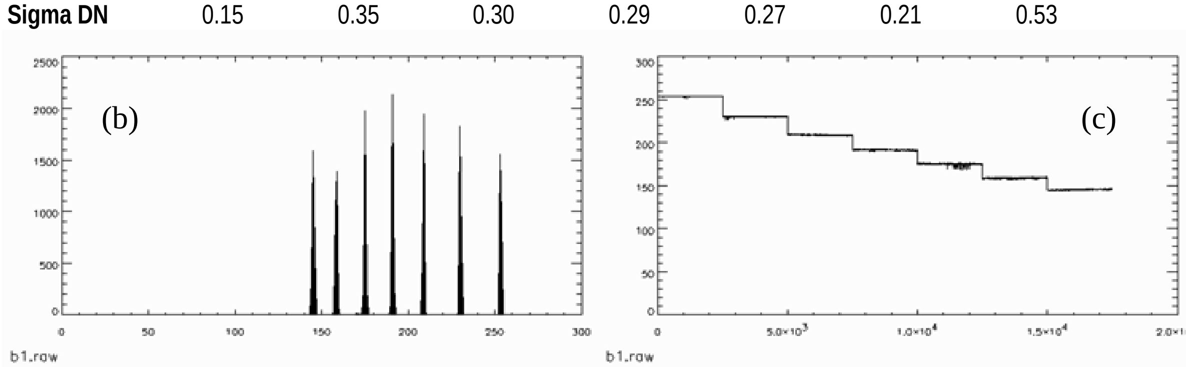


Figure 4: Image and histogram of 6 thin glass plates which are stacked on top of one another to serve as a grey wedge of very small density steps. These are being resolved by the UltraScan5000, illustrated by numbers, a historgam and a pixel plot.

A density range is between 0.0 and 0.24D and it is shown that the 7 steps can be unambiguously resolved. The histogram in Figure 4(b) of the digital image illustrates the mean grey values and noise in each grey step Figure 4. The individual steps are resolved

5.4 Special Experiments for Dark Areas

The frame of a diapositive film is the darkest area of the entire image. Therefore it is interesting to check if a structure laid on top of the film frame can be resolved. The experiment uses the dense area of the frame of a color positive aerial image. A small area of that frame was covered with a geometric resolution target showing a set of dark lines. As can be seen from Figure 5, the resulting image allows a clear separation between lines and background.

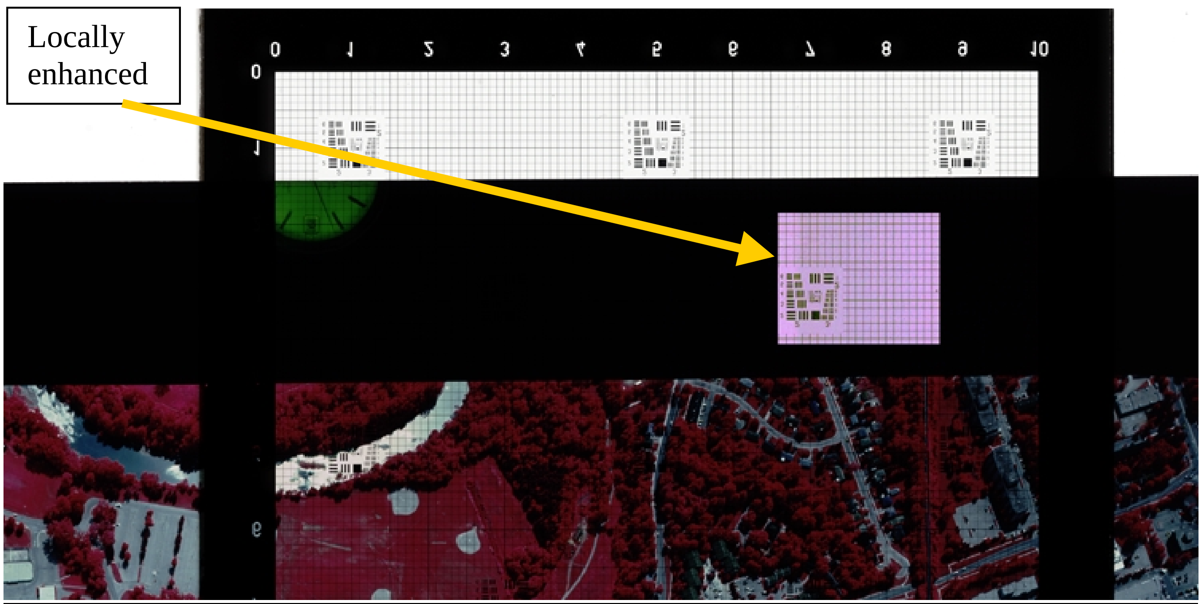


Figure 5: The frame of the particular color diapositive film is at a density of approximately 2.7. Scanning it together with a geometric resolution target shows that the structure of the target is being resolved and its details can be measured; a segment is locally enhancede to illustrate the result.

5.5 Scanning a Color Target

The color target Q 60-A of Kodak was used to test the color reproduction of the scanner. The color target shows a series of color steps for the primary colors red, green, and blue and the four secondary colors cyan, yellow, magenta and blue. Figure 6 shows the entire color target and the histogram of the different primary and secondary colors. It is obvious that all steps of the target are resolved by the scanner.

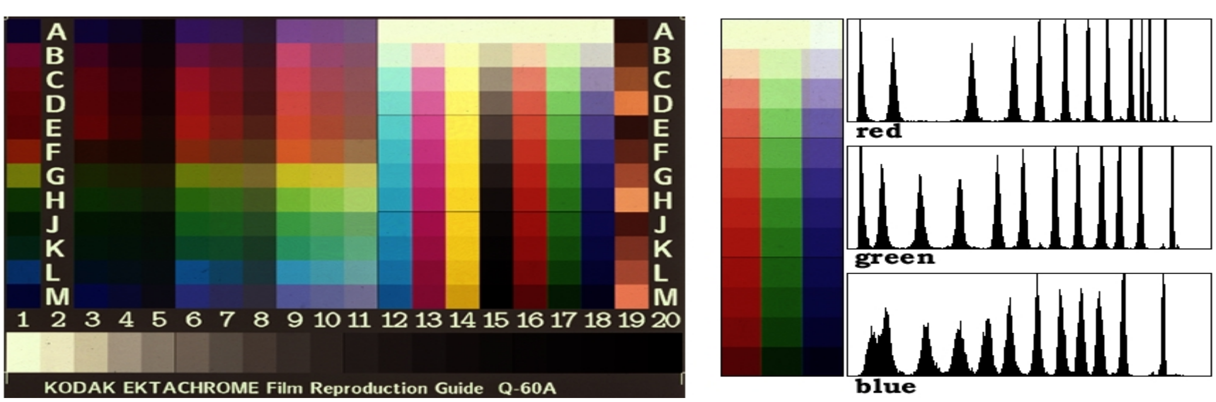


Figure 6: The Kodak color target Q 60-A is at left. In the center is a part of the target showing

5.6 Comparing Different Scanners

Baltsavias (1999) published radiometric perfomance values for photogrammetric scanner models DSW200 and DSW300 by LH Systems, Inc, the SCAI of ZI Imaging Inc. and the M-1 by Wehrli. In this assessment, the author employs a Kodak grey wedge STK 30 with 30 steps at intervals of 0.15D. Two adjacent steps are considered "resolved" if the difference *delta* of the mean grey values is larger than the sum of the standard deviations within each step, thus

Resolved if: $\sigma_{\text{step left}} + \sigma_{\text{step right}} < delta$ Equ. (1)

While we disgaree with this exact definition of "resolved", Baltsavias' (1999) paper created one of the rare comparisons of radiometric performance of photogrammetric scanners. If we use this same definition also for the UltraScan5000, we can extract from Table 2 the comparable radiometric values that Baltsavias (1999) provides for the SCAI, DSW and RM-1 scanners. This is summarized in Table 3 with the only purpose of comparing scanners, not to actually accept the given radiometric ranges. The UltraScan5000 offers a performance that is superior to the other scanner products.

SCANNER	Low End D	High End D	Mean Noise DN	Pixel Size Micrometers
DSW200	0.05	1.90	1.1	12.5
DSW300	0.05	1.95	1.2	12.5
SCAI	0.05	1.95	1.1	14.0
Raster Master 1	0.05	1.50	1.5	12.0
UltraScan5000	0.00	3.00	0.3	25.0

Table 3: Summary of radiometric comparison between photogrammetric scanners DSW200, DSW300, SCAI, RM-1 and UltraScan5000. This is taken from Baltsavias (1999), using the definitions and terminology employed in this paper. The UltraScan-data are taken from Table 2, but one needs to consider that Table 2 was developed using the Kodak ST 34 and not the Kodak ST 30 step wedge which was employed by Baltsavias.

5.7 When is a Step Wedge "Resolved"

The paper by Baltsavias (1999) assumes that a certain definition of "resolution" in radiometry be valid. We have shown visually in Figure 2 that one measure of "resolving" adjacent steps is one's ability to visually discern them. Baltsavias' definition, however, contradicts the usual conclusions about "resolution". In his definition, steps that are visually clearly resolved would not be classified as "resolved". Numerically, one might argue that in contrast to Baltsavias' definition one should call two steps resolved if

Resolved if: $\text{sqrt}(\sigma^2_{\text{step left}} + \sigma^2_{\text{step right}}) < \text{delta}$ Equ. (2)

The "observation" one wants to make is of the density difference *delta* between two steps on a step wedge. Its uncertainty would be the pythagorean sum of the uncertainties in each grey step, rather than their arithmetic sum.

With this definition, a larger set of steps will be "resolved" than under Baltsavias' definition, and this will also better reflect the visual experience.

6. Geometric Performance

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

6.1 Geometric Resolution

Geometric resolution depends mostly on the resolving power of the optical components of a scanner and the chosen settings for the pixel size. A test of the geometric resolution results from scanning a special target with very small geometric details. The so-called USAF-target uses a pattern of black and white bars of different size. Figure 7 shows a USAF-target scanned with the UltraScan 5000 at a pixel size of 5 µm (5080 dpi) and at a pixel size of 25 µm (1016 dpi).

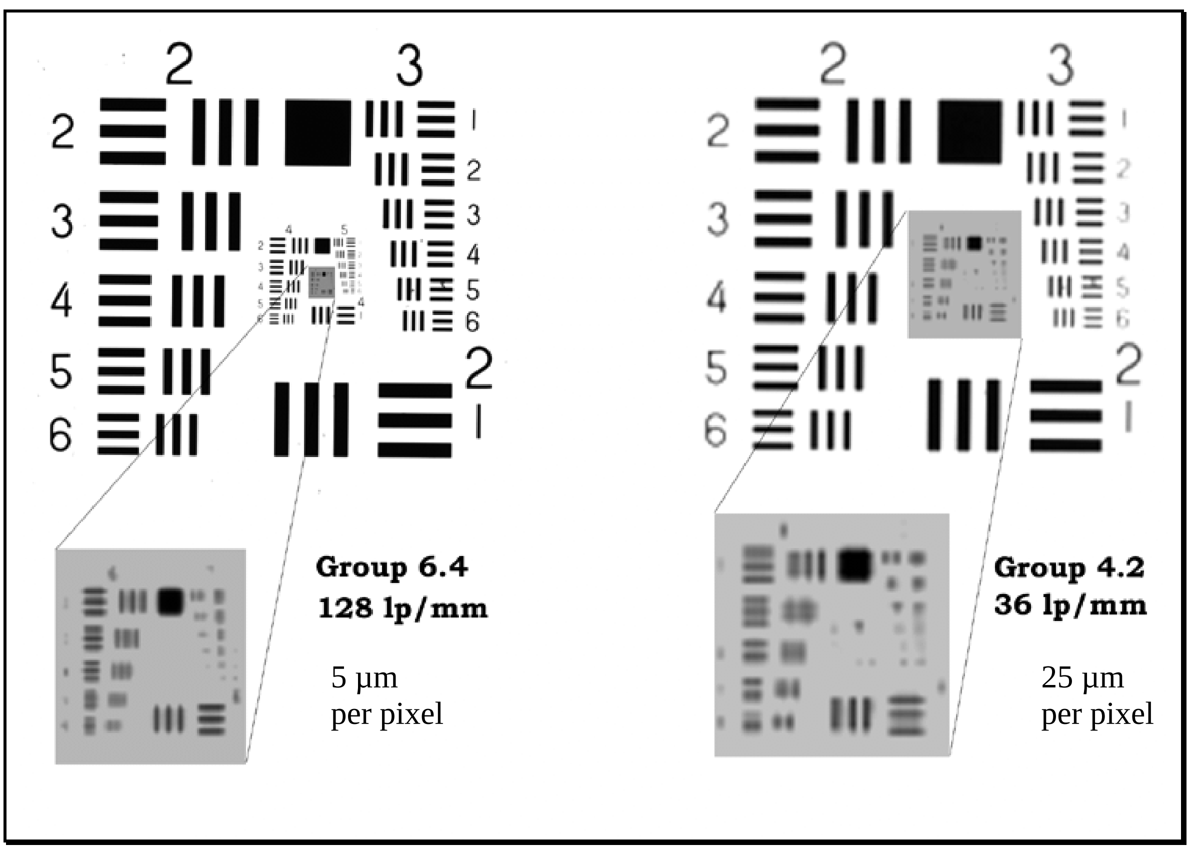


Figure 7: USAF resolution target, scanned at 5 µm pixel size at left and at 25 µm pixel sizeat right. Using the Kell factor, the theoretical resolution for a 5 µm pixel size is at 80 lp/mm and for a 25 µm pixel size is at 16 lp/mm. These values are being easily achieved by the scanner.

6.2 Geometric Accuracy

The geometric accuracy can be verified by scanning a well defined grid plate and then comparing the pixel coordinates of the grid pattern in the digital image to the known coordinates of the grid plate. From a least squares adjustment one is able to derive the remaining residuals between individual grid positions. In addition the statistics of the entire data set, namely the root mean square errors of the transformed pixel coordinates, can be of the grid plate scanned at a pixel size of 5 micrometers (5080 dpi) and the remaining residuals of the individual grid positions.

6.3 A Two Step Calibration

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 for each individual subscan and the principal distance and distortion values of the optical system. This so-called “off-line” calibration is based on a special calibration grid plate and the digital image of that grid plate derived by scanning the plate at the highest resolution. This type of calibration will be performed occasionally only.

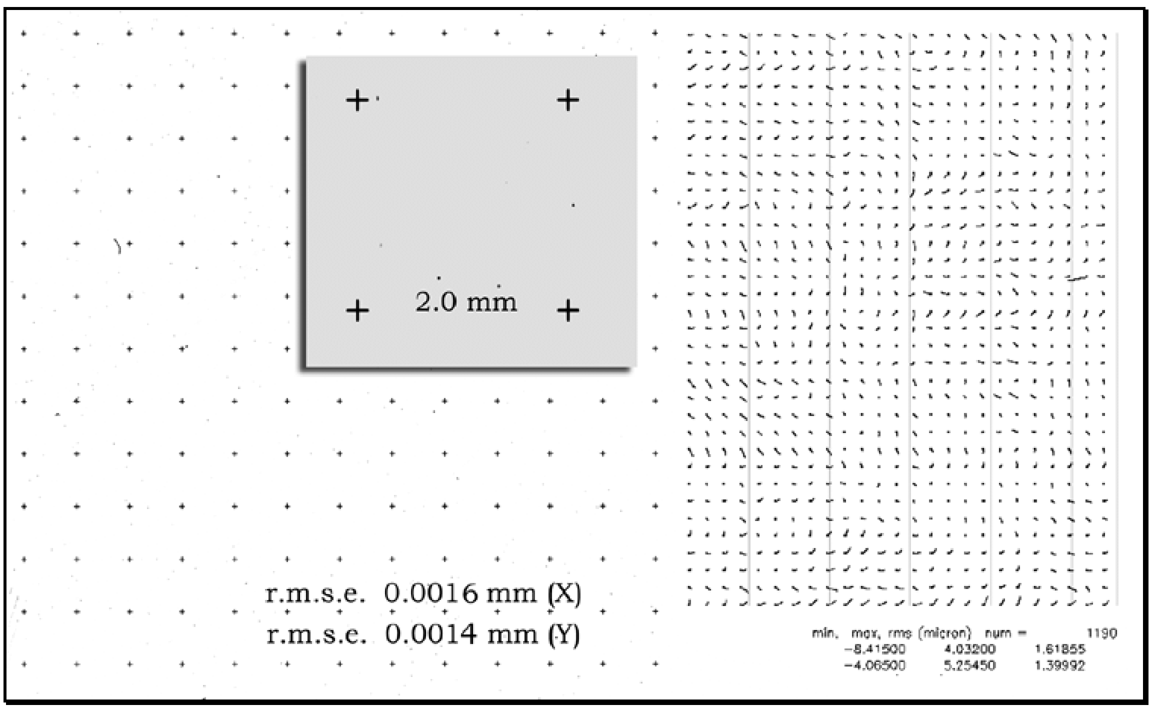


Figure 8: Scanning a dense grid plate: Small crosses are placed at a distance of 2 mm. The result of the geometric accuracy test shows in X ± 1.6 µm and in Y ± 1.8µm r.m.s.e. The diagram presents the residuals after an affine transformation.

The second part of the calibration is the “on-line” calibration during each production scan. It measures the actual geometric position of each individual subscan during scanning.This is based on a job sheet with reseau marks. In contrast to the older VX-series of scanners, these marks in the UltraScan5000 do not interfere with the image since they are outside the actual scan area.

7. Versatility of UltraScan 5000

Scanning performance includes the system’s ability to change and tune parameters. The UltraScan5000 offers a set of different parameters to tune the scanning procedure and to offer a best quality/performance ratio. These parameters can be set through the User Interface software and allows to influence the geometric output resolution, the density range of the scan, the native resolution.

The option of setting a variety of different native resolutions to arrive at a specific output enhanced quality. To make this possible the UltraScan 5000 operates with two different lens positions, where basic pixel sizes of 5 micrometers and 28.8 micrometers are achieved. Using electronic binning in the sensor of the scanhead one has the choice of a selection of eigth binning factors (between 1x and 8x) . The binning leads to 16 native optical resolutions (8 for each lens position) and therefore to a selection of scan settings which can be optimized for throughput or radiometric quality.

8. The UltraScan5000 in Operation

No theoretical experiment can replace an operational test. Among a series of aerial images a set of different materials have been selected and scans have been performed to illustrate typical scan results. The following illustrations in Figures 9 and 10 were scanned by the UltraScan5000 and document its ability to produce a high geometric resolution and excellent reproduction of color or grey tones. A black/white negative and a so-called “masked” color negative film were used for the tests. The images shown in these illustrations indicate the versatility of a modern photogrammetric scanner, and the ability to combine great geometric resolution with a high radiometric fidelity and range.

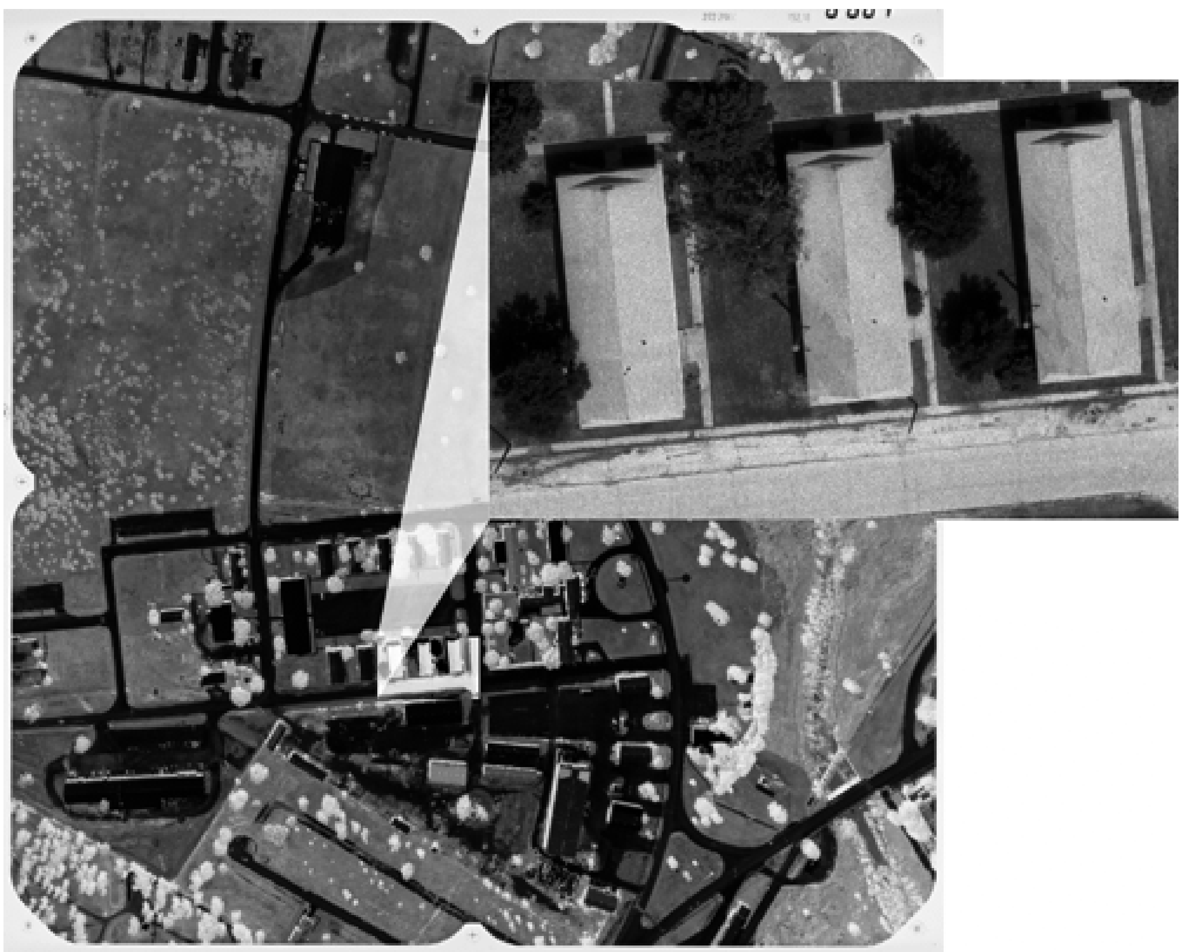


Figure 9 : Scanning of black/white negative film (shown in the background) and an enlarged section of high contrast, scanned at 25 µm pixel size (note the details in the bright area as well as in the shadow).

9. Conclusions

Using the UltraScan5000 as the reference photogrammetric scanner, we are presenting ideas about the assessment of the performance of photogrammetric scanners. The focus of the presentation is on radiometry, a feature of scanners that has not been properly recognized in the past. However, radiometry and color performance are rapidly gaining in importance, as scanning moves from the support of orthophoto production to the automated aerial triangulation, stereo matching for generation of digital elevation models and extraction of object details.

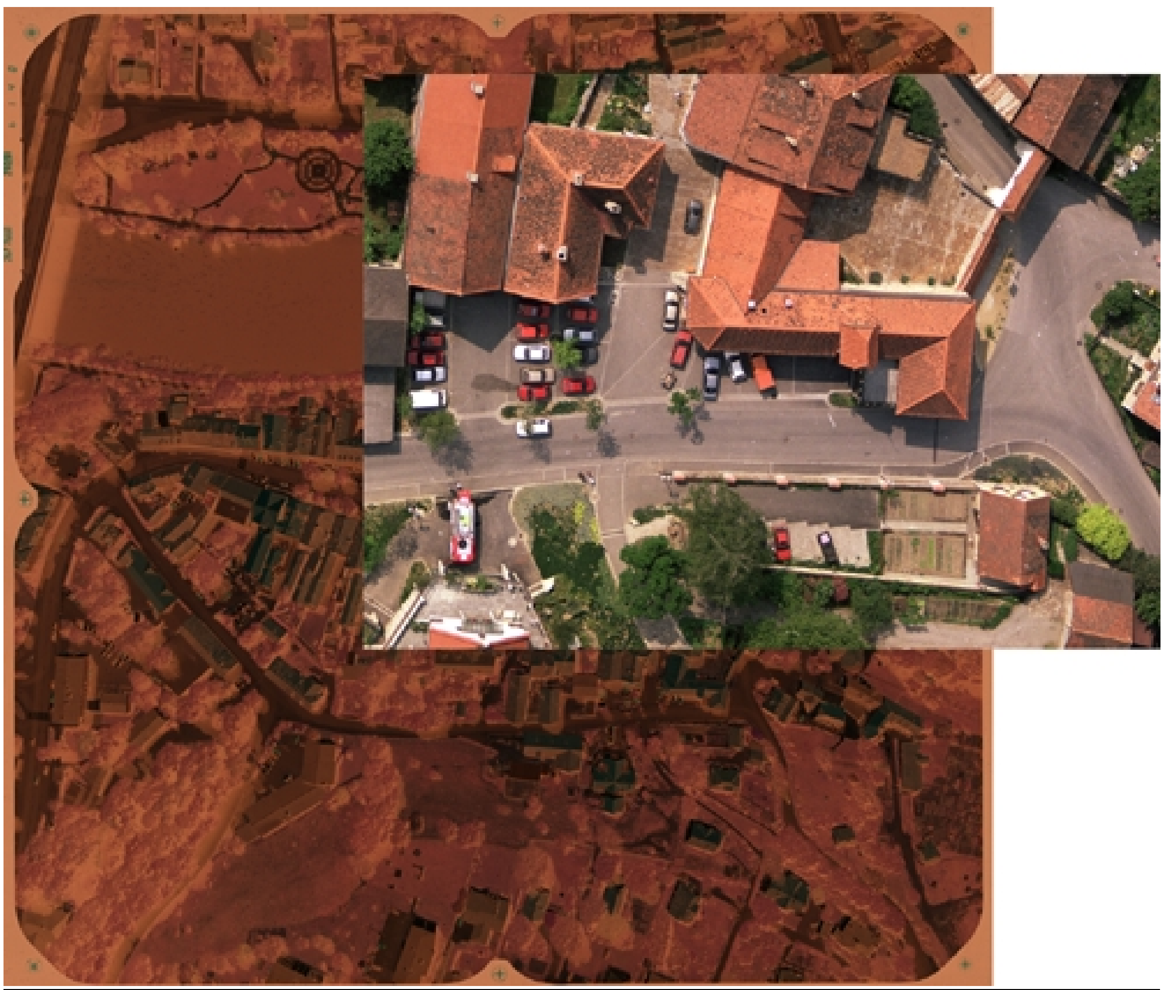


Figure 10: Scanning masked color negative film: the original negative film shows an orange mask of density 0.3 D (see the large image in the background). The scan is with 25 µm pixels and the enlarged positive section shows excellent reproduction of colors and tones.

Radiometric range in excess of 3.4D, and radiometric resolution better than ± 0.04D are feasible and useful. It is also necessary to understand that radiometric accuracy is a function of the document's density, so that customary specifications of a single number for that accuracy are not fully describing the perfomance of a system. Instead it would be preferable to have this accuracy described at various densities. Using scanner settings for best radiometric performance, the UltraScan delivers grey values with ± 0.6 DN at 0.5D, ± 0.3DN in the red and blue channels. These represent numbers that are unsurpassed by any other photogrammetric scanner.

References

Baltsavias E. (1994) *Test Calibration and Procedures for Image Scanners*, International Archives of Photogrammetry and Remote Sensing, Vol. XXX, Part B1, Como 1994.

Baltsavias E. (1998) *Photogrammetric Film Scanners*. GIM Geomatics Info Magazine, Vol. 12, July, pp. 55-61.

Baltsavias E. (1999) *On the perfomance of photogrammetric scanners*. Proceedings of the Photogrammetirc Week 1999, Univ. Stuttgart, Germany, pp 155-173.

Gruber M., F. Leberl, G. Thallinger (1998) Novel High Precision Photogrammetric Scanning. Proceedings of the GIS/LIS'98 Conference, Ft. Worth, Texas. Publ. By the Am. Soc. for Photogrammetry and Remote Sensing.

Leberl, F., M. Best, D. Meyer (1992) *Photogrammetric Scanning with a Square Array CCD Camera*. International Archives of Photogrammetry and Remote Sensing, Vol. XXIX, Part B2, Washington 1992.

Leberl F. et al. (1990a) *Mensuration Frame Grabbing Apparatus*, US-Patent # 4,928,169.

Leberl F. et al. (1990b) *Reseau Apparatus for Photogrammetry Devices*. US Patent # 4,841,455.

Seywald R. (1996) *On the Automated Assessment of Geometric Scanner Accuracy*. International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, Part B1, Vienna 1996.