Tone Reproduction of Photographic Scanners

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Abstract

The aims of this study were to analyze the tone reproduction of photographic scanners and to develop simple test procedures. The most important arguments proposed are the image noise, image resolution, sensitivity of the scanner, and the visual aspect of the images. A good scanner should show an image noise lower than ± 0.03 to 0.05 D for a pixel size of 10 μm and a resolution up to 10 μm. Furthermore, the dynamic density range and the fidelity of tone reproduction should be controlled. The study includes tests of the scanners most commonly used in photogrammetry and in the printing industry, but shows that their efficiency does not allow them to fully exploit the high image quality of modern aerial photographs.

Scope of the Study

The primary condition for the use of digital procedures in photogrammetry is the conversion of photographic images into a computer-compatible form. This conversion is commonly done with a scanner. Various tools coming from the photogrammetric or printing industry have been developed for this task. In the printing industry, desktop publishing in particular provoked a great demand for scanners of various qualities and performances.

In practical use, one realizes very quickly that there are considerable differences in image quality among the various scanners. A photographic image generally has a rather wide contrast range and a high resolution. Very often difficulties must be faced when converting those high-quality images into a digital form. When comparing an image displayed on a digital workstation and on an analytical plotter with a good optical system, one can see that the analytical plotter allows a much better detail recognition, even when the scanning on the work-station is done with a small pixel size. The difference is even more decisive when producing orthophotos. Practical work has shown that orthophotos made from aerial photographs by applying analog techniques as, for example, by using the Leica orthoprojector OR1, can be enlarged up to 10 times. Similar tests with digital orthophotos give the impression that the limits have already been reached with an enlargement of about 5 times. High requirements with regard to image quality also stem from automatic image correlation, especially when treating low-contrast areas.

Without a doubt, the best known scanner in the past was the Optronics, which was developed some 20 years ago. It was a drum scanner, in which the light density was measured by a photomultiplier. Since then, flat-bed scanners have been developed in addition to the drum scanners and the photo-multipliers have been replaced by CCD photodetectors as either line or matrix sensors. The illumination can be met in a variety of ways, thereby allowing the scanning of color images.

The scope of this study was to analyze the tone reproduction of different photographic scanners. This evaluation was done with a view to the acquisition of such an instrument by the Institute of Photogrammetry, which had been engaged for quite a long time in image correlation using CCD cameras integrated into an analytical plotter for image digitizing. However, the noise and the dynamic range considerably limited the possibilities of image correlation. Consequently, the idea was to purchase a scanner with a higher performance. Investigations showed, however, that the radiometric quality of scanners is rather limited and does not cope well with the high quality of aerial photographs. Due to the topicality of the subject, it seemed appropriate to make the results of this study available to a larger audience.

Requirements in Photographic Scanners

The most important criteria for the quality analysis of scanners can be summarized as follows:

- Geometry. With current aerial photographs, a level of precision on the order of ± 2 μm can be reached in aerotriangulation. This precision is also usually obtained with analytical plotters. Consequently, it is useful to require such precision for photographic scanners.
- Image Resolution. This parameter is decisively determined by the quality of the film and by the aerial camera. As will be shown later on, it seems appropriate to require a pixel size of 10 by 10 μm for black-and-white images whereas a pixel size of 15 to 20 μm might be sufficient for color photographs.
- Image Noise. The noise of photographic film is mainly defined by its granularity. When considering the values given by the producers, the sensor noise should not exceed ± 0.03 to 0.05 D for a pixel size of 10 by 10 μm, and an image noise as low as 0.02 to 0.03 D could be reached with Kodak Panatomic-X film. This presumes that the modulation transfer function of the scanners also allows a resolution corresponding to the pixel size.
- Dynamic Range. This should correspond to the contrast of aerial photographs which might range from 0.1 to 2.0 D for black-and-white pictures and from 0.1 to 3.5 D for color photographs.
- Color Reproduction. With the increasing use of color photographs, it is important to be able to scan color photographs.
- Data Compression. The great mass of data produced when digitizing images can be effectively reduced by data compression techniques.
- Instrument Handling. The handling of the instruments as well as the management of the considerable amount of data are important criteria; however, this aspect is not going to be discussed in more detail here.

Image Resolution of Aerial Photographs

The image resolution of aerial photographs is generally characterized by resolution in lines per millimeter. This is, however, a rather subjective criterion, depending heavily on the object contrast, and the use of the modulation transfer function (MTF) is much more suitable. The MTF indicates the con-

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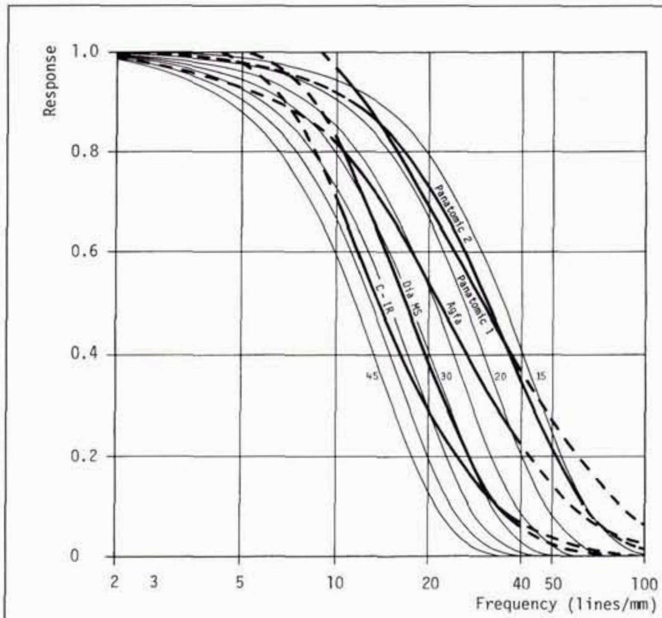

Figure 1. Modulation transfer functions of different films (thick lines) and corresponding Fourier transforms of Gauss functions with their spread (thin lines). The curves were taken from Jaakkola (1985, Figure 17) and Kölbl (1986, Figure 6) with some modifications.

trast reduction of a sign wave with a given frequency. The Fourier transform of the MTF indicates the spread function which is the image function of an ideal point image in the object space. This spread function can be easily related to the pixel size. Different MTF functions characteristic of aerial photographs have been determined in a recent study of the OEEPE (Jaakkola, 1985; see Figures 1 and 2). According to this study, the spread function has a size of 20 to 25 μm, which is the distance between the two inflection points of the Gauss function for black-and-white films, and of 30 to 35 μm for color films. Similar investigations with Panatomic-X film and high-quality lenses gave values between 8 and 15 μm (Kölbl, 1986).

If one is to ensure that the original image quality of aerial photographs is not degraded by the scanning process, one should work with pixel sizes of approximately a half of the spread of the Gauss function; furthermore, the quality of the optical system of the scanner should not reduce this performance. This means that the spread function of the scanner itself should not exceed the pixel size. Consequently, for conventional black-and-white films, a pixel size of 10 by 10 μm might be appropriate, whereas, for color films, values between 15 and 20 μm might be sufficient. An even smaller pixel size would be useful for Kodak Panatomic-X or other high-definition films.

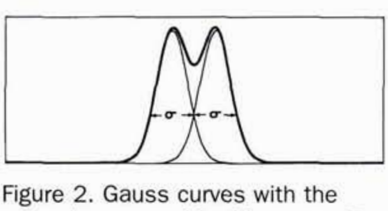

Figure 2. Gauss curves with the spread σ as used in this paper. The figure illustrates that it should be possible to distinguish two lines with a distance between them of σ when the spread of the point spread function is σ (Kölbl, 1986, Figure 3a).

Table 1. Overview of the Granularity (Diffuse Root-Mean-Square Granularity) of a Selection of Kodak and Agfa Films. The Granularity Refers to a Circular Window of 48 μm, Given as the Standard Deviation of Density Multiplied by 1000 (Taken from Kodak (1982) and Agfa (1986)).

Type of film	RMS Granularity
KODAK Plus-X Aerocon, Film 3411	26-28
KODAK Panatomic-X Aerographic, Film 2412	9
KODAK Tri-X Aerographic, Film 2403	30-40
KODAK Double-X Aerographic, Film 2405	26
KODAK Aerochrome Infrared, Film 2443	17
KODAK Aerochrome MS, Film 2448	12
AGFA Aviphot Pan 150 PE	25
AGFA Aviphot Pan 200PE	27

Granularity of the Photographic Emulsion

The granularity of aerial films is rather closely related to image resolution. Granularity is an important criterion for the selection of a film; a fine grained emulsion generally gives a high resolution. The granularity of the emulsion is carefully analyzed by manufacturers. The *Kodak Data for Aerial Photography* (Kodak, 1982) indicates the "Diffuse Root Mean Square Granularity." This granularity is measured on a microdensitometer with diffused illumination. A homogeneously exposed film probe is scanned at a 12× optical enlargement with a circular window of 48 μm. The standard deviation of the density value multiplied by 1000 is given (Kodak, 1982; Agfa, [1986]: see also Table 1). For example, the RMS granularity for Kodak Plus-X film ranges from 26 res. to 28 while, for Panatomic-X, the RMS granularity is 9 for a photographic density of 1. For Agfa Pan 150PE, the corresponding values for the granularity lie between 17 and 25 for a circular aperture of 50 μm. Consequently, an image noise of ± 0.017 to 0.025 D is to be expected when working with a quadratic pixel size of 45 by 45 μm (conversion from a circular aperture to a quadratic one). For a pixel size of 10 by 10 μm, one should expect primarily an image noise of ± 0.075 to 0.1 D, meaning values 4.5 times larger than the initial ones. In this case, one supposes that the gray values of neighboring pixels are not correlated. However, it will be shown later that neighboring pixels are generally heavily correlated, which provokes a smoothing of the image noise. If one assumes that the width of the spread function of the scanners corresponds to the assumed 10- by 10-μm pixel size, a smoothing of 50 percent has to be taken into consideration. Consequently, the image noise should amount only to ± 0.035 to 0.05 D; the corresponding tolerance values for Panatomic-X film would amount to only ± 0.02 D.

Dynamic Range of Aerial Photographs

According to the above-mentioned OEEPE publication (Jaakkola, 1985), one can also get an overview of the current density range of aerial photographs. In general, black-and-white films have less contrast than color films. In this study, signalized points have been observed with a density of the background varying between 0.2 and 2.0 D when using Kodak Panatomic-X film, whereas a range of 0.3 to 3.5 D was obtained for IR color film. Consequently, one has to require from scanners a density range of about 0.1 to 2.5 D for black-and-white films, whereas a density range of 0.1 to 3.5 D is needed for color films.

Constructive Elements of Scanners

General Set-Up

The set-up of a scanner is heavily influenced by the photodetector used. Photomultipliers can only be used as individual elements but show a very high response time. Most of the scanners working with photomultipliers are drum scanners. In this case, the film is mounted on a rotating drum. The photodetectors are generally mounted outside of the drum and scan the image line by line. The transparencies are illuminated by a light source mounted within the drum. In order to keep the heating as low as possible, one generally uses directed light, very often even laser illumination. This type of scanner makes it possible to obtain a high performance with regard to resolution and dynamic range. The disadvantage is, however, that the film must be mounted on a drum.

A mounting between glass plates is much more protective for the film, but this is only possible with flat-bed scanners. In this case, the film is mounted on a motor-driven cross carriage. An alternative is, of course, to move the illumination and the photo detector. The illumination can be diffused or directed; as a detector, one generally uses line sensors or matrix sensors.

Photodetectors

The most important photodetectors are currently the photomultiplier and the line or matrix sensor. The photomultiplier is based on the exterior light electric effect. If light touches a cathode, then electrons are detached which are attracted by the anode. The current produced in such a way is then measured.

In order to obtain greater sensitivity, the flow of photoelectrons produced on the photo cathode is amplified by the introduction of auxiliary cathodes, the so-called dynodes. These photosensors are then designated as photomultipliers. They have a very high sensitivity and also a high dynamic range. The sensitivity of a photomultiplier can be raised to the detection of individual photons. Moreover, they have a very low response time. From the beginning, there was therefore a great interest in using these sensors in scanners. However, photomultipliers cannot be combined with a sensor line or sensor matrices. Nevertheless, the high response time makes it possible to pass the film of a scanner very rapidly over the measuring device. It was therefore logical to use photomultipliers mainly in drum scanners.

For quite some time, photo diodes and photo transistors have been used for light measurements in addition to the photocells. The photo elements are based on the so-called interior light electrical effect or semiconductor photo effect. In this case, the photo electrons produced by the incident light remain within the semiconductor and serve as conducting electrons for the photo current. These solid-state image sensors can be mounted on a silicon chip as line or matrix elements. However, these elements of the photo detector matrix have to be coupled by electronic means for the read-out of the current produced. Such a connection is not easily applicable for each individual element of a matrix. A practical solution is the transfer of the charges from one element to the next. The electronic charge produced by the radiation can be transferred with nearly no loss over a whole line of matrix elements and will then be read out; hence, the designation charged coupled devices (CCD).

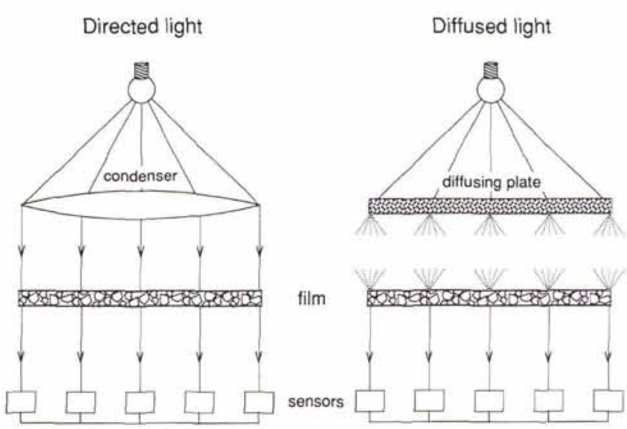

Figure 3. Illustration of an illumination system with directed light by a condensor (left) and diffused light by a diffusing plate (right).

According to this principle, it is understandable that matrix sensors offer less sensitivity than line arrays. According to the literature (Murphy, 1989), the dynamic range of a line detector is about 5 times higher than that of a matrix detector.

The Illumination System

An important role for image reproduction is also played by the illumination system. It is useful to distinguish between directed and diffused illumination (see Figure 3).

Directed illumination uses a condenser for enlarging a more or less point illumination source and images this light source into the aperture of the projection lens. An advantage of this type of illumination is the economic use of light energy, as only lamps with a rather modest heat radiation are necessary. In order to reduce even further this heat radiation, one can use fiber optics for the transmission of the light to the remote light source. A strongly directed light produces a very small optical opening angle and increases considerably the depth of field. An optical system with directed illumination might also be less sensitive to small effects of defocusing. On the other hand, light is rather coherent and can produce diffraction effects.

A diffused light is obtained when using milk glass for diffusion. This can be done by placing a milk glass or, even better, an opalescent glass plate directly onto the photographic film or by using fluorescent light which has a strong diffusing effect. More refined possibilities are the use of the "Ulbrichtkugel" or a light channel. The "Ulbrichtkugel" is an empty sphere, the inside of which is coated with magnesium dioxide. Light is introduced laterally and comes out through a very small opening. This opening should not exceed 1/50 of the sphere diameter (Vieth, 1974, p. 126).

It is remarkable that optical enlargers of today generally use only diffused illumination, whereas older instruments such as the famous rectifiers were generally equipped with Fresnel lenses as condensers. Many of the photo enlargers constructed today are equipped with a light channel. Photogrammetric instruments also very often use diffused light in order to get a more pleasant image quality.

In sensitometry, directed or diffused light also plays an important role. The quotient of transparency measured between parallel light and diffused light is known as the Callier quotient and is proportional to the graininess of a film. For the measurement of graininess, Kodak recommends using

Table 2. Overview of the Different Scanners Used for the Practical Tests.

Sensor	Type of construction	Trademark	Illumination System	Minimum Pixel size	Maximum Bit/pixel	Variability of Pixel size
Photo-multiplier	Drum-Scanner	Screen DT-S1030AI	directed	13 µm	10 b/w	Software
	Drum-Scanner	Crosfield	directed	14 µm	10 b/w	Software
	Flatbed-Scanner	Perkin Elmer	directed	22 µm		Exchangeable optic
Line-CCD	Flatbed-Scanner	Du Pont High_Light 1850/1875	diffused	10 µm	12	Software
		PhotoScan PS1 (Zeiss)	directed	7.5 µm	8/color	Software
		Wehrli	*directed*	*12 µm*		*Zoom-lens*
		Agfa ACS100	diffused	10 µm	12	Zoom-lens
		Agfa Horizon	directed	21 µm		Software
Matrix-CCD	Flatbed-Scanner	Vexcel VX 3000	diffused	10 µm		Zoom-lens
		DSWI00 (Helava)	diffused	13 µm	12	2 cameras
		Philips CCD in the DSR15	directed or diffused	8*12 µm	8	Software

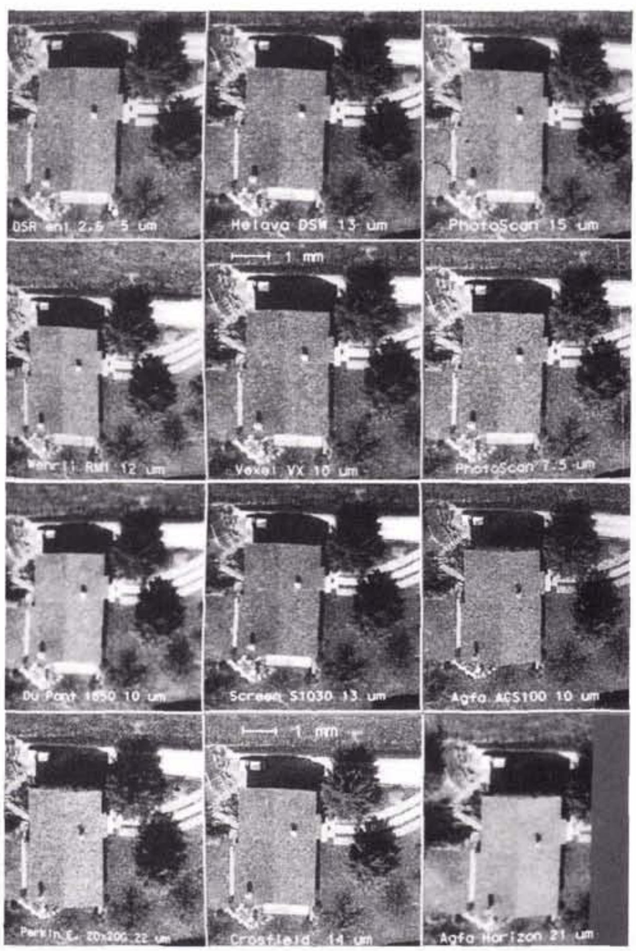

Figure 4. Comparison of an image section scanned on different instruments, displayed on a CRT screen.

only diffused light, as the corresponding measurements with directed light are not properly defined.

Experimental Investigations

As already mentioned, the practical investigations concentrated on the analysis of scanners with a view to purchasing a system. Consequently, the tests were limited and consisted in the digitizing of a few typical aerial photographs (a medium-contrast black-and-white photograph, a high-contrast Panatomic-X photograph of a snow-covered area, and a false color photograph). A more detailed analysis then concentrated on the medium-contrast image only. After testing one or the other scanner considered as interesting for the tasks of the Institute, an attempt was later made to extend this series of tests in order to get an overview of the tone reproduction of the different scanners. Table 2 gives an overview of the different scanners incorporated in this study. The investigations included two drum scanners, mainly used in the printing industry, and nine flatbed scanners, only one of which (DSR 15 analytical plotter) must be considered as experimental. In total, three of the tested scanners come from the printing industry. Figure 4 shows a comparison of image sections resulting from the different scanners. This comparison shows that images can differ considerably with regard to noise and sharpness. However, the visualization also makes it possible to detect other image errors such as strips or blurring effects.

The numerical analysis focused on the determination of the image noise, the resolution of the digital images, and the sensitivity of the scanner. In parallel, the general aspects of the scanned photographs have been evaluated. The medium-contrast photograph can be considered as a typical aerial photograph with a built-up area and a zone of very poor contrast. This photograph was taken on Agfa PAN 150 film with a Leica RC20 camera equipped with an Aviogon lens. As it appeared too risky to scan the original negative, a positive copy was made on Agfa duplicating film. Care was taken that a new copy free of scratches or other damage be available for every test.

The main objective of the test was to find a scanner with rather low noise and good tone reproduction. When analyz-

TABLE 3. OVERVIEW OF THE IMAGE NOISE AND OF THE SIZE OF THE SPREAD FUNCTION DETERMINED FOR THE DIFFERENT SCANNERS. COLUMNS 2 THROUGH 5 GIVE THE ROOT-MEAN-SQUARE DEVIATION OF GRAY VALUES COMPUTED FOR AN IMAGE MATRIX OF 20 BY 20 PIXELS OF HOMOGENEOUS AREAS EXPRESSED IN DENSITY, COLUMNS 8 AND 9 GIVE THE CORRELATION COEFFICIENTS BETWEEN NEAREST NEIGHBOR PIXELS, AND COLUMNS 10 THROUGH 13 REPRESENT THE STANDARDIZED IMAGE NOISE FOR A POINT SPREAD FUNCTION OF 10 µM (F.E. C10 = C2*C7(x)/10)

Scanner	Measured image noise in [D]				Pixel size	Spread (x · y)	Corr. 1.Pix	Corr. 2.Pix	Image noise reduced to a spread of 10µm in [D]				Light type
	0.4 D	0.5 D	0.6 D	0.7 D	in [µm]	in [µm]	in [%]	in [%]	0.4 D	0.5 D	0.6 D	0.7 D	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Du Pont High_Light 1850 2540dpi	0.011	0.014	0.017	0.021	10	40*46	72.3	53.3	0.044	0.060	0.073	0.090	
1875 2540dpi off.	0.008	0.009	0.009	0.008	10	62*56	88.1	68.4	0.047	0.053	0.053	0.047	
1875 1132dpi soft	0.013	0.018	0.023	0.028	22	40*44	48.6	16.8	0.055	0.076	0.097	0.118	
1875 1132dpi off	0.009	0.011	0.013	0.014	22	60*64	64.0	35.8	0.056	0.068	0.081	0.087	
Helava DSW100	0.024	0.023	0.024	0.028	13	25*34	58.3	25.0	0.072	0.069	0.072	0.084	
Vexcel VX3000 10µm	0.036	0.038	0.044	0.051	10	18*18	40.9	16.0	0.065	0.068	0.079	0.092	diffused
24µm	0.021	0.019	0.019	0.020	24	58*52	54.0	27.7	0.116	0.105	0.105	0.110	
Philips - CCD in the DSR15- **diffused**													
- dark (GV 90 ~ 0.4D)	0.017	0.018	0.017	0.019		36*40	62.6	49.4	0.065	0.068	0.065	0.072	
- medium (GV 130 ~ 0.4D)	0.013	0.012	0.013	0.013	8•12	38*48	69.6	54.6	0.056	0.052	0.056	0.056	
- bright (GV 230 ~ 0.4D)	0.017	0.015	0.013	0.017		43*66	79.7	64.4	0.095	0.083	0.072	0.095	
Philips - CCD in the DSR15- **directed**													
- dark (GV 80 ~ 0.4D)	0.024	0.022	0.018	0.018		36*36	68.5	48.6	0.086	0.079	0.065	0.065	
- medium (GV125 ~ 0.4D)	0.025	0.022	0.025	0.020	8•12	40*50	78.7	57.6	0.113	0.099	0.113	0.090	
- bright (GV 240 ~ 0.4D)	0.026	0.022	0.017	0.016		42*52	82.7	59.0	0.122	0.103	0.080	0.075	
Agfa ACS100 - 2400dpi (EPFL)	0.025	0.026	0.027	0.029	10	35*38	74.2	37.9	0.093	0.096	0.100	0.107	
- 1800dpi (firm)	0.044	0.045	0.044	0.049	14	34*34	59.8	13.6	0.150	0.153	0.150	0.167	
- 900dpi (firm)	0.088	0.089	0.134	0.121	28	30*30	12.4	6.4	0.264	0.267	0.402	0.363	
- 300dpi (firm)	0.190	0.142	0.103	0.061	85	250*145	62.3	14.4	3.8	2.8	2.1	1.2	
Agfa Horizon - 1200dpi	0.010	0.011	0.011	0.011	21	114*120	87.5	65.5	0.117	0.129	0.129	0.129	directed
Screen DT-S1030AI 2000dpi	0.038	0.037	0.026	0.026	13	26*36	58.4	15.9	0.123	0.115	0.079	0.079	
Crosfield - 900dpi	0.062	0.058	0.054	0.050	28	34*52	27.3	9.5	0.267	0.249	0.232	0.215	
1800dpi	0.060	0.059	0.059	0.058	14	19*33	37.4	14.7	0.156	0.153	0.253	0.151	
Perkin Elmer 20 x 20 G	0.042	0.047	0.053	0.064	22	22*22	8.6	1.9	0.092	0.103	0.117	0.141	
Wehrli RM1	0.027	0.024	0.026	0.026	12	29*32	61.8	20.3	0.084	0.074	0.081	0.081	
Zeiss PhotoScan PS1 7.5µm	0.058	0.060	0.071	0.080	8	12*14	46.6	9.1	0.075	0.078	0.092	0.104	
15µm	0.024	0.026	0.029	0.029	15	27*36	50.9	19.4	0.074	0.081	0.090	0.090	

ing the graininess or noise of an image, one quickly realizes that image noise is closely related to pixel size and also to resolution. Images scanned with a small pixel size generally have a larger image noise than images with larger pixels, as the larger pixels can be obtained by computing the mean of the smaller pixels; the computation of the mean naturally causes a smoothing approximately proportional to the square root of the number of pixels. Consequently, it can be expected that image noise increases in an inversely proportional way to the dimension of the pixels. In parallel, the imaging system can have an important smoothing effect, while the optics or other factors cause a strong smearing effect. It was consequently of great importance to determine the MTF of the imaging system prior to any other analysis.

Determining the MTF of a Digital Image

As for the evaluation of the performance of lenses, one can also determine the modulation transfer function (MTF) for a scanner. The point spread function corresponds to the autocorrelation function of an image, provided that the image content can be considered as random (white noise). This type of computation can be easily done with digital images, preferably for rather homogeneous areas.

The autocorrelation function was determined for pixel matrices of 20 by 20 elements. The correlation values for neighboring pixels were then approximated by a Gauss function; the parameters obtained for the spread are given in Table 3, Column 7. The inverse of this value, multiplied by 1000, is a rough measure of the resolution in lines per millimetre. The same table gives the correlation between neighboring pixels (Columns 8 and 9). Rather large correlations of nearly 50 percent or even more were obtained for nearest neighbors, but then the correlation coefficient decreased rapidly. Very similar results for the spread functions were obtained when computing the autocorrelation function across a very distinct line.

When analyzing image resolution, one is surprised that the Agfa-Horizon scanner seems to have an image resolution of only 0.1 mm or about 10 lines per millimetre. Other scanners have a resolution much closer to the pixel size, but the size of the spread is in general 2 to 3 pixels. Only the Perkin Elmer scanner had practically no correlation between neighboring pixels. This is not surprising if one considers that the system operates with a photomultiplier, a low measuring rate, and microscope optics scanning sequentially pixel by pixel.

It is most probable that not all factors influencing the resolution were properly located. For example, the DSR15 shows a strong increase of the spread with increasing light intensity (decreasing resolution with increasing light intensity; see Table 3, Column 7). Nevertheless, an interesting value is determined by the autocorrelation function characterizing the resolution of digital images much better than the pixel size only.

Analysis of Image Noise

Image noise was computed again from pixel matrices of 20 by 20 elements of homogeneous areas. For each image, some 20 different matrices were used with different densities. In the first line, a scanner gave gray values mostly without clear relation to the density of the photograph. For a proper comparison of the measurements, it was therefore necessary to establish a clear relation; density was chosen as reference. Figure 5 shows the relation between the gray values measured on the PS1 and the corresponding density of the test patches as measured on a Macbeth densitometer (diaphragm 0.1 mm).

Table 3 gives an overview of the computed image noise reduced to density values. Image noise is given for densities between 0.4 and 0.7 D (Columns 2 through 5), which occurred frequently in the photograph used. The same table also gives the pixel size used for scanning (Column 6) and the size of the point spread function (Column 7). The point spread function was then used to standardize image noise for a uniform point spread function of 10 μm (Columns 10 through 13). This corresponds to a scan with a pixel size of 10 μm, provided that the correlation to the neighboring pixel is not higher than ~10 percent (exact value 6.7 percent!).

After the conversion of the image noise to a standardized pixel spread function of 10 μm, one gets a rather uniform result with an image noise of ± 0.1 D. Somewhat higher values are obtained with scanners from the printing industry, e.g., Screen, Crosfield, or Agfa Horizon. The lowest image noise was also obtained from a scanner of the printing industry, the Du Pont High Light 1850. The experimental results confirm that scanners with diffused light give about 20 percent less image noise than scanners with directed light. This is also shown very clearly by the comparative test on the DSR15. The same equipment was used in this case; only the illumination system was changed. For the test with directed light, the original light source was used, whereas a diffuser plate and a stronger light source were used in the other case.

However, these tests did not reveal the source of the image noise. According to the prior computations, one should expect an image noise of ± 0.03 to 0.05 D for the film used. Only the Du Pont High Light is close to the expected values, whereas all other scanners seem to generate additional noise within the electronic system. Specific tests on the DSR15 using films with different graininess (Kodak Double-X and Kodak Plus-X) did not give the expected results. Image noise did not increase with the graininess of the film; it seems that the effect of graininess is much smaller and does not influence significantly the image noise, apart from the above mentioned effect of the illumination.

Sensitivity of the Scanners

The resulting measurements from the photographic material used give little information on the dynamic range of the scanners tested. The photographs used have a low contrast, and most of the picture information is limited to a density between 0.4 and 1.0 D. This rather poor image contrast appeared ideal in the beginning, as the dynamic range of a CCD camera used earlier by the Institute of Photogrammetry had a very limited density range, and a brightness saturation of one pixel resulted in a blurring of the whole scan line. Meanwhile, the scanners have been mainly equipped with array sensors with an internal measuring range of 10 to 12 bits or even more. The usual 8-bit values are obtained after conversion, allowing for much greater internal sensitivity. Consequently, the results presented can only give an indication of the tendency, but no concrete values on the dynamic range.

Table 4 gives an overview of the reduction of sensitivity with an increase of density. One may note that many scanners have a constant relation between gray values and the density of the photographs and clearly have a rather high dynamic range far beyond a density of 1 D such as in the Crosfield or Screen scanners. These scanners use photomultipliers which generally show very high levels of sensitivity. On the other hand, a much smaller dynamic range must be expected from scanners with CCD-matrix sensors. This is extremely well demonstrated on the DSR15; however, the dynamic range of this instrument is also considerably reduced by parasite light, which is difficult to control, due to the open construction of the plotter. The values in Table 4 show that parasite light is much more important when working with diffused light than with the original illumination source of the instrument (directed light). The measurements on this instrument also show that an increase of the light intensity does not allow a better observation of the dark areas of the photographs. This might appear to be a paradox and could be explained by the diffusion of light from the surrounding brighter parts of the image.

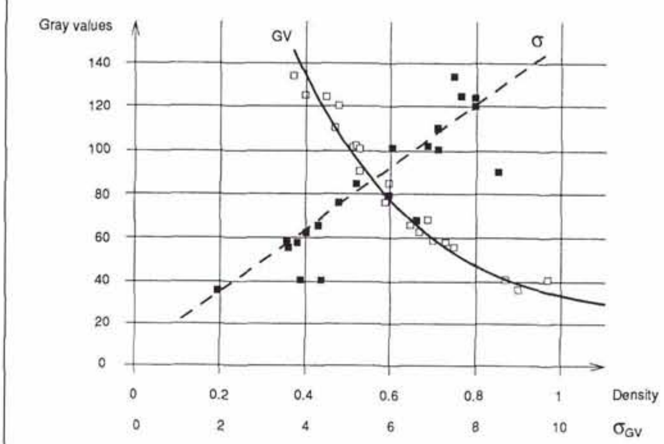

Figure 5. Relation between gray values obtained by scanning and the density of the corresponding batches for the PS1. The same diagram gives the image noise in gray values and the density values.

This diffusion probably also explains most why many of the other scanners lose their sensitivity in darker areas which finally indicates the determined values (see Columns 5 and 9, Table 4). This means that the measured density of small dark areas is reduced by the scanning process, and that detail recognition in dark areas might also be reduced in comparison to the original photographs. In this sense, it is understandable that the Zeiss PhotoScan also shows in this example a density limit of 1.1 D, although photographs with a much higher density can be scanned on that instrument. Nevertheless, the dynamic range of this instrument showed also clear limitations when we tried to scan a Panatomic-X image of a snowy scene with extended areas of a density up to 3.0 D.

Visual Analysis of Image Disturbances

A numerical analysis of the scanned images might appear very objective due to the clearly defined computation process. Such a process also clearly provides comparable results, as long as all images are obtained under the same conditions. However, the scanning process is very often combined with procedures for image correction and image improvement. For example, the images from the Crosfield scanner had undergone a rather strong edge enhancement (Figure 6); the image scanned on the Screen scanner shows a different image resolution in the scanning direction and perpendicular to it (Figure 7 and Table 3, Column 7); and the Vexcel scanner gave a repeating pattern in low-contrast areas (Figure 8). On a great number of scanners, it was also possible to observe the remaining errors due to the limited scan width and to the necessary tone adoption. This type of tone adoption is, of course, very important for matrix scanners, but is also often applied for array scanners.

This brief review of image disturbances shows that, in

Table 4. Analysis of the Sensitivity of the Scanners.

Scanner	Max. sensit.	Sensitivity in Density			Corresponding grey value				Look-up-table (LUT)/
	in [D/10GV] in 0.4 D	Sensit. reduced to 1/2	Sensit. reduced to 1/4	Estim. Minim.	Max. sensit. in GV in 0.4 D	Sensit. reduced to 1/2	Sensit. reduced to 1/4	Estim. Minim.	*Change of Light intensity* **(ChLI)**
1	2	3	4	5	6	7	8	9	10
Du Pont High_Light 1850 2540dpi	0.025	const	const	>>	210	-	-	<<	Lut/ChLI
1875 2540dpi off	0.025	const	const	>>	220	-	-	<<	
1875 1132dpi soft	0.025	const	const	>>	220	-	-	<<	
1875 1132dpi off	0.025	const	const	>>	230	-	-	<<	
Helava DSW100	0.035	0.7	0.9	1.0	120	60	40	~30	Lut
Vexcel VX3000 10µm	0.045	0.8	1.0	1.2	130	40	30	~20	
24µm	0.035	0.7	0.9	1.2	110	40	20	~10	
Philips - CCD in the DSR15- **diffused**									
- dark (GV 90 ~ 0.4D)	0.078	0.9	1.0	1.3	90	40	30	~20	Lut/ChLI
- medium (GV 130 ~ 0.4D)	0.050	0.8	0.9	1.1	130	60	50	~40	
- bright (GV 230 ~ 0.4D)	0.025	0.7	0.9	1.2	240	120	100	~80	
Philips - CCD in the DSR15- **directed**									
- dark (GV 80 ~ 0.4D)	0.050	0.7	0.8	1.2	80	30	20	~10	Lut/ChLI
- medium (GV125 ~ 0.4D	0.035	0.8	0.9	1.0	130	50	30	~20	
- bright (GV 240 ~ 0.4D)	0.025	0.8	0.9	1.2	240	70	50	~40	
Agfa ACS100 - 2400dpi (EPFL)	0.038	const	const	>>	190	-	-	<<	Lut
- 1800dpi (firm)	0.035	0.7	0.9	1.2	140	70	50	~40	
- 900dpi (firm)	0.045	0.8	1.0	1.2	130	60	50	~40	
- 300dpi (firm)	0.040	0.7	1.0	1.1	140	60	50	~40	
Agfa Horizon - 1200dpi	0.030	0.8	-	>>	120	20	-	<<	Lut
Screen DT-S1030AI 2000dpi	0.020	0.7	0.9	>>	180	40	10	<<	Lut
Crosfield - 900dpi	0.050	const	const	>>	190	-	-	<<	Lut
1800dpi	0.045	const	const	>>	200	-	-	<<	
Perkin Elmer	0.045	0.9	1.1	1.3	190	100	90	~70	
Wehrli	0.045	0.7	0.9	1.2	80	40	20	~10	Lut
Zeiss PhotoScan PS1 7.5µm	0.015	0.6	0.7	1.1	220	100	70	~20	Lut
15µm	0.028	0.6	0.8	1.1	130	80	50	~20	

addition to the various numerical analyses, a visual image inspection is very important and might reveal very fundamental problems in a scanner. It is not our intention here to provide a complete overview of the image disturbances detected, and the few aspects mentioned only serve as examples.

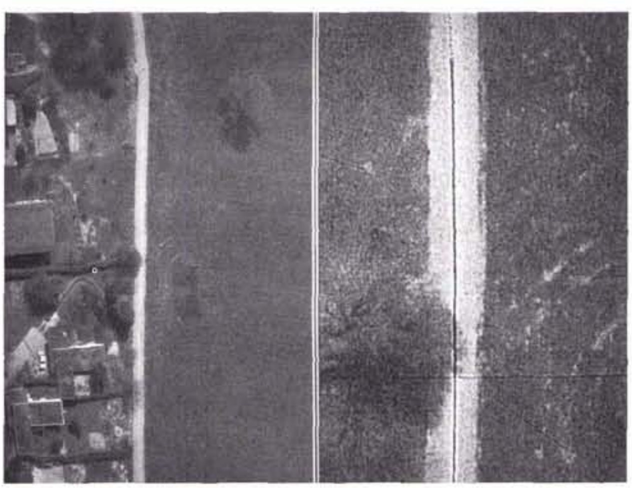

Figure 6. Section of the image scanned on the Crosfield scanner, showing the effect of edge enhancement.

Conclusions

The main objective of this paper was to present a number of testing procedures concerning tone reproduction, which can be easily applied by a photogrammetrist interested in the use

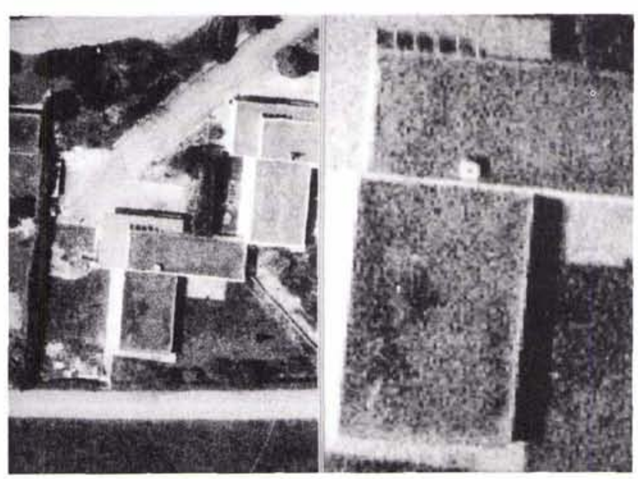

Figure 7. Section of the image scanned on the Screen scanner, showing the different levels of image resolution, in the scanning direction (vertically) and perpendicular to it.

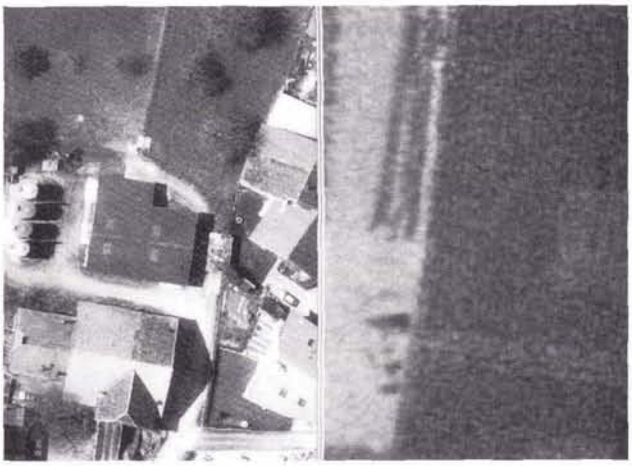

Figure 8. Section of the image scanned on the Vexcel scanner, showing a repeating pattern due to image processing, most probably due to the adaptation of the individual batches of the matrix camera.

of digital images. The most important arguments concerned image noise, image resolution, the sensitivity of the scanner, and the visual appearance of the images. A good scanner should show an image noise lower than ± 0.03 to 0.05 D for a pixel size of 10 µm, although only one scanner came rather close to these values. Depending on the purpose of the image, one can also fairly state that a good scanner should allow a resolution up to 10 µm (pixel size and size of the point spread function). The greatest difficulty might be presented by a thorough control of the dynamic range and the fidelity of tone reproduction. It is possible that the sensitivity of a scanner is considerably reduced in dark areas, affecting detail recognition in these zones. Nevertheless, it seems that all scanners reach their limits in dark areas, and reasonable tolerances should be applied corresponding to the effective requirements of production.

We had the feeling that such a study did not make sense without showing the practical application to various products with the arguments put forward. It is, however, clear that the results of these tests allow only a very limited comparison of the products. As already mentioned, the results are heavily influenced by the current calibration of the instrument, the skill of the operator, and other exterior factors, which have practically nothing to do with the effective quality of an instrument. Many of the tests are already older than a year and many elements might have changed meanwhile. For example, earlier tests on the Vexcel scanner gave a rather low image resolution; when discussing the results with the manufacturer, it became evident that these results are no longer representative of the instruments, and a new scan gave the results shown in the tables and corresponding to the performance of a good scanner of that type.

Although many restrictions have to be made concerning this study, one nevertheless gets the impression that the development of scanners is still in progress and that no final stage has yet been reached. At a congress on Infography in Zurich in 1993, one could observe the rapid developments in the printing industry. Most of the scanners shown at the 1992 congress had already been replaced a year later by new or improved models. The development in the photogrammetric industry might be different, but will also be influenced by the progress in electronics and by the requirements of the practice. Digital photogrammetry and digital image processing have considerable advantages compared to analog techniques. However, it seems that it is not yet possible to take full advantage of these new promising techniques due to limitations in the scanning process. The photogrammetric industry has always played a key role with regard to image quality, and it is difficult, in photography, to find lenses with similar standards to those produced for aerial cameras. Consequently, a substantial increase in scanning quality might also require special developments.

The authors are grateful to all firms having contributed to this study by scanning photographs on their products. All the scanners included in this test certainly have a number of special advantages which were not brought out within this study, which concentrated only on rather limited aspects. Consequently, we would like to encourage all firms to continue in their line of research.

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