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Transfer Functions in Image Data Collection

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ABSTRACT

The paper gives an introduction to the transfer function and the point spread function, then the considerations are extended to the analysis of the image noise and the dynamic range of digital images. In the last part of the paper a trial was made to determine these parameters for digital aerial cameras like the ADS40 and the DMC, but also for medium format cameras (Hasselblad and Rollei) currently also used for aerial imaging. Additionally a comparison was made with digital orthophotos produced from high quality aerial film cameras. It seems that the medium format cameras have almost a higher image quality than the digital aerial cameras, as no resampling process is necessary to create the images used for further photogrammetric operations; however, the digital aerial cameras have a greater dynamic range. Furthermore, the digital aerial cameras have about double the swath width of the medium format cameras. Due to the low noise of the digital images, it might be useful to work with subsampled images in order to make full use of the high image quality. The practical investigations are based on a very limited number of images and should be refined. Nevertheless, the high standard of digital imaging systems is self-evident compared to the results achieved with aerial film cameras.

1. INTRODUCTION

Optical transfer functions allow one to compute the light distribution in the image space as a function of the light distribution in the object space. This may sound quite theoretical but quickly takes on very concrete meaning if one thinks of the image quality of digital orthophotos and of the desired edge sharpness. When orthophotos are required, one observes in many cases that the pixel size and most probably also the geometric precision are precisely defined, but very seldom the required optical resolution or the edge sharpness. Other important criteria are the image noise, colour reproduction and tolerances for various artefacts.

All these factors are predefined by the quality of the imaging camera, the image scale and the subsequent image processing. In particular for colour images with classical aerial film cameras, the photographic film was the limiting factor. The recent development of digital aerial cameras and their increasing use in practice resulted in a substantial improvement of image quality, provided that the lens can cope with the increased resolution of digital image sensors and that the information is properly read out.

In order to remain as close to actual practice as possible, I would like first to give specifications concerning the image quality of orthophotos as they were used for a bid for tender in a Swiss canton (St. Gallen). This will be followed by considerations on the determination of the optical transfer function for digital cameras, an analysis of the image noise and the dynamic range. Finally a trial was made to analyze various digital cameras. These practical investigations refer to images of digital cameras which have been made available by the manufacturers and various enterprises using digital aerial cameras. The number of images was very limited and might not always be representative of the cameras. Therefore the results should be considered with great caution, but the technique presented is very easy and it should be up to every potential user of digital aerial cameras to perform these tests. Furthermore it is hoped that camera producers will publish more date on the quality of their cameras.

In principle it would also be necessary to include the colour reproduction within these considerations. However, it is not very easy to define objective norms for colour reproduction. Aerial images used for measurements or for the production of orthophotos use colour to improve the interpretability and to give a more “natural” appearance. For these applications it would be difficult to elaborate norms for colour reproduction and it is much more important to focus on brightness. This becomes obvious when considering digital cameras. Most of them achieve a higher image quality in black and white or for the green band when using a "Bayer filter". This is of course different for computer-assisted image interpretation, a field only marginally taken into consideration by modern digital cameras. Therefore we will not enter into more detail on colour reproduction.

2. SPECIFICATIONS CONCERNING THE IMAGE QUALITY OF ORTHOPHOTOS

In autumn 2003 I was invited to elaborate specifications for orthophotos in a bid for tender. In principle, the project management team had hoped to run the survey flight with a digital camera, but no firm was ready to make an offer at the time. Therefore, a classical film camera (Leica RC30) was finally used. In order to ensure the desired image quality it was important to specify radiometric requirements and tolerances for image quality. The pixel size was defined as 25 cm, the edge blurring less than 1 pixel and the planimetric precision as ± 15 cm. In detail, the following specifications were made :

"The pixel size of the orthophotos is defined as 25 cm. Furthermore, the tolerance for edge blurring is prescribed. The transmission from a bright area to a dark one should not exceed one pixel in "Zone A", this applying to objects of a size of at least 5 pixels in dark and bright areas and a contrast change of more than 50% (for example the bright region : grey value 180, dark region 90).

In mountainous areas (zone B) a transition of 2 pixels was allowed. It is understood that when checking these values one will take into consideration the effect of a spread due to the object structure (for example if the object edge is not parallel to the lines defined by the pixel matrix).

During image registration, one has to take care that the dynamic range of the natural scene will be entirely captured. For image registration with photographic positive films, one should respect the following density values : meadow areas should show up in the green spectral band in a density of 1.2 with a tolerated variation of ± 0.3 D. Dark casted shadows should not be darker than 1.7 D. Bright areas should come close to the film fog in case of mirror reflection (maximum 0.1% of the image surface). Corresponding density tolerances should be used for negative films and digital images after scanning or when using a digital camera. For negative films, dark shadows should be 0.4 D above the film fog. In digital images, shadow areas should not have grey values below 30 and the grey value of 255 for 8-bit images may be reached only for 0.1% of the surface of an image. Noise and separation of the colour channels are also other important parameters for the evaluation of digital orthophotos. The noise on homogeneous image elements must remain below 10% of the grey values, this applying to grey values between 255 and 30 (30 corresponds to dark shadows). The noise is computed from the standard deviation of the grey values in homogeneous areas of at least 15 pixels in which the noise of the object variations can be assumed to be below one half of the tolerance. Furthermore, one has to take care that when scanning the images the colour channels are properly separated; the overlap between adjacent bands may not exceed 3%".

The prescribed edge sharpness had been an important criterion for the choice of the supplier. Based on earlier projects of the supplier, an appraisal was made of whether the specifications would be met. Meanwhile, the project was already partly finalized and the quality control showed that the specifications are indeed largely met. The image sharpness is very satisfying and various tests showed that the image can even be reproduced with a smaller pixel size (cf. fig. 1).

It is understood that it is not only the process of the image taking but the whole chain of image processing which defines the image quality of an orthophoto. These considerations are important if one wants to judge digital imaging systems, as the user will hardly be able to work with the initial data. Both in line cameras and frame cameras, the original images are processed in order to create homogeneous images which are again processed to achieve the end product.

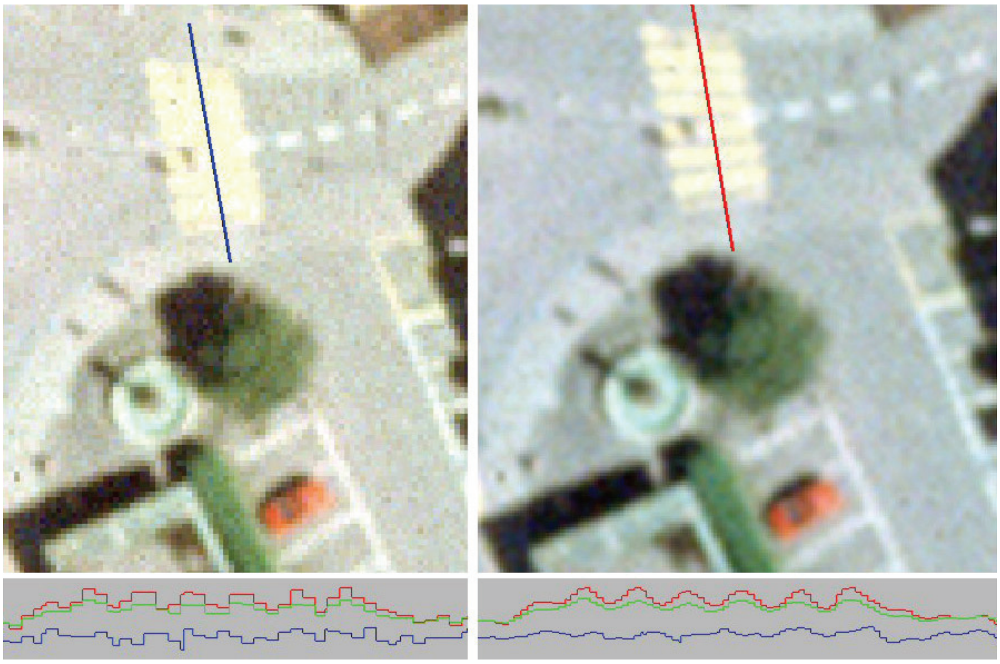

Fig. 1 : Orthophoto GSD 25 cm. Left : original pixel size, right : subsampled to 12 cm. The lower part shows the density profiles over the pedestrian crossing (upper line : red band, lowest line : blue band). Image reproduced by courtesy of the Vermessungsamt St. Gallen.

3. THE MODULATION TRANSFER FUNCTION OR SPREAD FUNCTION OF DIGITAL IMAGING SYSTEMS

As already mentioned, the image resolution or the image sharpness are of basic importance for the judgment of the quality of an imaging system. In addition to this criterion, one should also take into consideration the image noise of the sensor, the dynamic range and possibly the colour reproduction.

3.1. Basic explanations concerning the modulation transfer function and the spread function

For a long time image resolution was used as a parameter in judging the image quality of aerial cameras. This implied analyzing the distance of double lines which could just be separated (cf. calibration protocol of aerial cameras).

However, various studies showed that the image resolution is not really meaningful, since it means that the loss of contrast for longer frequencies is not taken into consideration. Furthermore, it is difficult to deduce the edge sharpness from the image resolution. It is much more efficient to work with the modulation transfer function (cf. for example the specifications for the various films in Kodak, 1976) or the spread function, equivalent to the image point function. The modulation transfer function expresses the loss of contrast for various frequencies of a sine wave pattern, whereas the spread function describes how an ideal object point will be reproduced in the image. With the help of a Fourier transformation, it is possible to convert the spread function directly into the modulation transfer function and vice versa. So the 2 functions have practically the same meaning. Contrary to this, the resolution expressed in line pairs per millimeter can only be linked to the modulation transfer function in a very restricted manner. It is possible to consider the image resolution as the cutoff frequency of the modulation transfer function (e.g. frequency at a contrast loss of 90%, but this is a very rough estimation).

Former investigations by the author showed that the point spread function should not be considered as a simple Gauss function (O. Kölbl, J. Hawawini, 1986). In particular, one has to take into consideration that for longer frequencies one observes a stronger contrast reduction which means that the spread function has a larger foot than the simple Gauss function (cf. fig. 2-4). These considerations are important, as a contrast loss of only let's say 30% for 10 or 20 lines/mm influences the detail reproduction in an image much more drastically than the cutoff frequency as expressed by the image resolution.

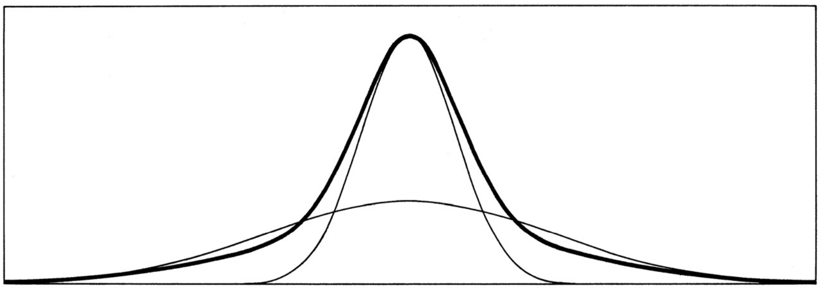

Fig. 2 : Spread function (heavy line) composed of two Gauss functions with different σ values (thin lines). The sum was reduced to make its maximum correspond to the higher Gauss function.

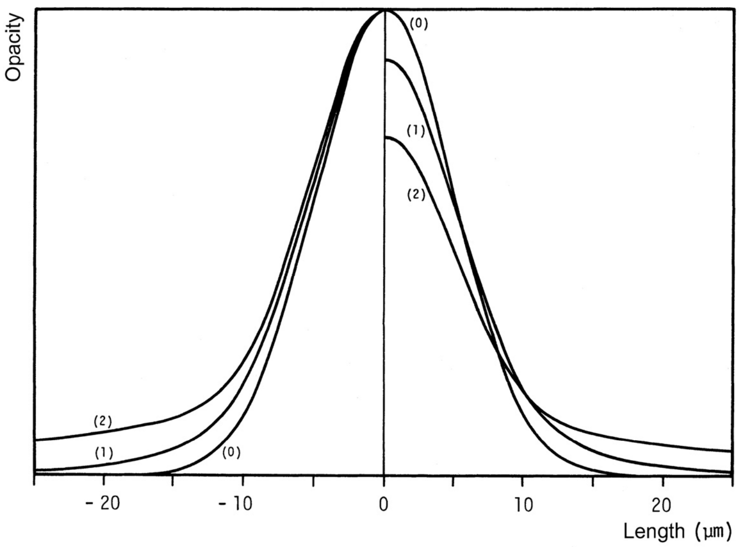

Fig. 3 : Spread function according to formulas (0), (1) and (2) for a σ = 14 µm. Left diagram : functions without normalization, right diagram : normalized curves. One notices the effect of the contrast reduction of small signals when the base of the spread function is enlarged.

$$I(x) = n_0 \cdot \exp\left[-4\left(\frac{x - x_0}{\sigma}\right)^2\right] \quad (0)$$

$$I(x) = n_1 \cdot 0{,}85 \exp\left[-4\left(\frac{x - x_0}{\sigma}\right)^2\right] + 0{,}15 \cdot \exp\left[-1\left(\frac{x - x_0}{\sigma}\right)^2\right] \quad (1)$$

$$I(x) = n_2 \cdot 0{,}85 \exp\left[-4\left(\frac{x - x_0}{\sigma}\right)^2\right] + 0{,}15 \cdot \exp\left[-0{,}25\left(\frac{x - x_0}{\sigma}\right)^2\right] \quad (2)$$

Fig. 4 : Formulas describing different point spread functions according to fig. 3.

This effect has been demonstrated for aerial film cameras; it is understood that in this case also the film was included but the different cameras showed quite different behaviors. For this work we used special targets (cf. fig. 5).

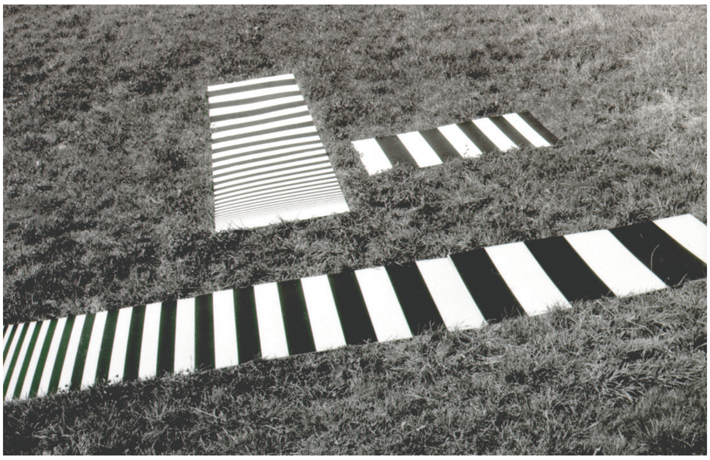

Fig. 5 : Targets for the determination of the modulation transfer function.

3.2. Practical derivation of the spread function from edge blurring

The spread function allows one to simulate the blurring of edges. If one considers the object function of a series of discrete object points, then one can compute the image function with the help of a convolution where the spread function is the filter. It is understood that one could theoretically also work with a Fourier transformation of the object function and of the image function. By simply dividing the amplitudes, one could immediately derive the modulation transfer function of the imaging systems and by retransformation into the object space one would obtain the spread function. In this case however, it is a serious disadvantage that the noise of the image function is an important disturbing factor which can easily lead to misinterpretations of the spread function. It is much easier to suppress the effect of the noise by direct comparison of the image function with a simulated one computed by convolution from the object function and a supposed spread function. One disadvantage of edges analysis is the difficulty of getting reliable information on the contrast reduction on the longer frequencies, as their effect may be drowned by other disturbances.
The analysis of the various digital cameras presented in section 5 is based on the edge analysis as described here. Due to the very short time of about 6 weeks available for the preparation of the article, I had to limit in a first approach the spread function to a simple Gauss function. However, when analyzing the differences between the simulated image function and the measured one, it becomes evident that the mathematical model of the spread function should be refined. It is intended to finalize this for the oral presentation in September.

3.3. Limitations by diffraction

When analyzing the camera quality, one should take into consideration that it is not only the quality of the lens which might cause an image spread but also the diffraction. The convergence of a bundle of rays in an imaging system is limited by the aperture; due to interference of the light waves within these bundles the convergence of the rays is disturbed. In general, the size of the diffraction disk is computed according to the formula :

$$R = 2 \times \lambda \times F_{number}$$

In this case R indicates the distance between the center of the diffraction image and the successive maximum wave circle, λ is the wavelength of the light and the F_{number} is the opening value. If one takes into consideration that the wavelength of visible light is about 0.4-0.7 μm one obtains a value for the diameter of the diffraction disk approximately equal to the F_{number} in microns. Consequently, for a pixel size of 8-10 μm the effect of diffraction is practically not noticeable, except for openings of the aperture smaller than 1:5.6. Let us mention in this context that the IKONOS satellite has a focal length of 10 m and a parabol mirror size of 70 cm, which gives a F_{number} of 14 whereas the pixel size is 10 μm. In this case, the diffraction disk is slightly larger than the pixel size.

3.4. Reduction of the edge blurring by image enhancement

By various filter techniques it is possible to sharpen the images, the best-known filter being the "Mexican hat". In principle this effect also occurs in photography, mainly due to the diffusion of the developer when processing the film. This effect should of course be taken into consideration when determining the point spread function by edge analysis. For technical reasons it was not yet possible to model this effect. Edge enhancement was mainly used in processing of the images of the Rollei camera and is clearly visible in the density profiles presented in figure 6. On the other hand, such effects might also represent an opportunity in digital photogrammetry, as they might enhance the interpretability of the images.

4. NOISE AND DYNAMIC RANGE OF DIGITAL IMAGES

When using photographic film, it was mainly the graininess of the film which produced image noise. For photographic films we used the 'diffuse RMS granularity' as an indicator which was measured for a circle of 48 μm. It amounts to 0.019 D for the Kodak plus X film and to 0.013 D for the Panatomic reconnaissance film. In this context it should be taken into consideration that the exposure of a silver crystal required 1-3 or even more photons. The size of these silver crystals corresponds to around a micron and they are randomly distributed.

When using digital image sensors, the random arrival of the photons create the "shot noise". Many other sources of noise were identified causing temporal or spatial effects (cf. for example Kodak).

For the user, it is interesting to have a simple means of estimating the magnitude of the noise and finally of finding an indicator of the possible detail recognition.

The shot noise is proportional to the square root of the number of photons arriving. Typically a sensor might collect 100,000 photons at the most. In this case the noise is 100. Converting the charge of 100,000 photons to a grey value of 255 corresponds to a noise of 0.8 grey values, whereas when encoding in 12 bit (DMC or IKONOS) one has a maximum of 4096 and a noise of 13. This corresponds to the values observed for the different digital cameras. However in dark areas the picture information gets lost much quicker than according to the shot noise. The dark current noise and other effects might play the decisive role. For the DMC the lowest image forming values were 120 - 200 and for the medium format 8bit cameras this value was around 40. Provided that the registered grey tone values are proportional to the object reflection, one can compute the dynamic range which is then about 1:30 for the DMC and only 1:6 for the medium format cameras. The dynamic range for colour films are about 1:10 (1D) and for black and white films considerably higher.

In order to verify the response of the digital cameras, we controlled the contrast of similar objects in sunlight and shady areas. According to these measurements the grey tone values are effectively largely proportional to the image brightness.

Effects of the dark current or non uniform pixel response are difficult to identify apart from the limited dynamic range; furthermore, we observed that the image noise seldom decreases according to the binomial law.

5. PRACTICAL ANALYSIS OF VARIOUS DIGITAL AERIAL CAMERAS

In order to illustrate the above theoretical considerations we analysed images of various digital cameras taken from the air. In order to obtain these images I had contacted practically all producers of digital cameras and also companies using these cameras. Leica Geosystems delivered the "Waldkirch" image; ICC Barcelona made available images taken with the DMC and the Rollei camera; MFB-GeoConsulting GmbH, Messen/Switzerland, made available images of the IKONOS satellite and the Firm "UW+R SA", Switzerland made available images taken with the Hasselblad H1 and the Hasselblad Biogon. Furthermore, the Vermessungsamt St. Gallen supplied the Orthophotos of its Canton. Nevertheless this study is far from a systematic analysis, and the results are only significant for the available image material which must not be considered as representative of the camera. Furthermore as spread function I used a simple Gauss Function (cf. formula (0)) at the time of writing the article, although it appeared clearly that a better approximation of the edges will be achieved by more complex functions. Up to now no attempt has been made to take an edge enhancement into consideration, as observed especially on images of the Rollei camera. From all the cameras 2 image sections were selected and the density profile was measured. These images and the density profile are shown in figure 6 and enable one to get a rough impression of the performance of the cameras. The numerical values of the spread functions were derived from a number of surface areas in a numerical form and were not limited to a randomly selected profile. The analysis was deliberately limited to the panchromatic images, as most of the cameras have a higher performance for the registration of the panchromatic image or the green band for sensors with the Bayer filter (Rollei, Hasselblad).

5.1. The ADS40 from Leica Geosystems

The ADS40 is a line camera with three panchromatic line sensors (forward, nadir, backward) and four colour line sensors (red green blue and infrared), all sensors are read out in 12 bit. The panchromatic line sensors consist of two linear arrays, each with 12,000 pixels, but staggered by 0.5 pixels in order to reduce the aliasing effect and to increase image quality. The image sensors have a pixel size of 6.5 µm. The lens is a telecentric system with a nominal focal length of 62.5 mm/f4. Because of the linear sensor structure, the second dimension of the image is generated by the aircraft movement and is influenced by attitude disturbances. To correct this effect, the camera position and its inclinations are measured by an Inertial Measuring Unit (IMU) and a GPS; the camera mount is also stabilised on the basis of the IMU measurements.

The raw images are resampled and corrected for the remaining effects of the camera inclinations and variations of the airplane trajectory. No raw images were available and only the corrected images were analysed, which means that a resampling has already taken place.

The "Waldkirch" image is a 8bit image with 12,519 x 51,718 pixels and a GSD of about 20 cm. The lateral enlargement of the image is due to the post-processing and the correction of remaining effects of the camera inclination. According to the edge analysis, one can conclude that the point spread function is rather uniform with a size of about 2 pixels (cf. also fig. 6 line 1). One achieves approximately the same results when measuring in flight direction or perpendicular to the flight direction. A test on the very edge of the image also gave a spread of 2 pixels. As no raw images were available it cannot be said whether the image quality is limited by the lens or by the resampling process; quite obviously, the resampling for image rectification will also introduce a reduction in image quality depending on the processing.

We should mention in this context that values of the MTF of the ADS40 lens have been published (cf. R. Schuster, B. Braunecker, 2000). According to laboratory measurements, the point spread function has a value of 10 µm in flight direction and swath direction, corresponding exactly to 1.53 pixels, quite close to the value of 2 pixels indicated above and derived from the rectified images.

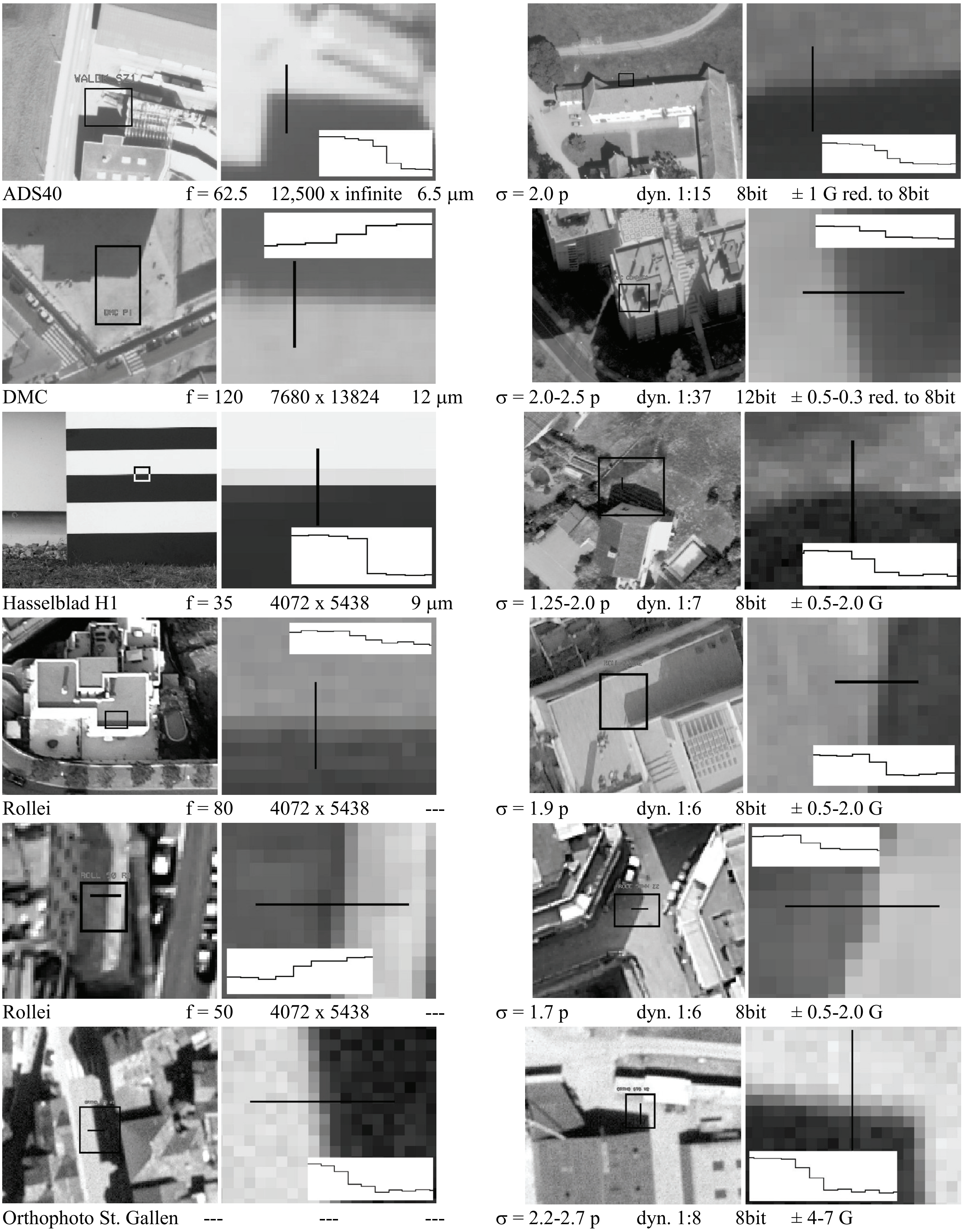

Fig. 6 : Extraction of digital images and micro enlargement with the presentation of the grey value profiles. The images show some differences in the image quality. The numerical values characterize the camera, after the focal length is given the size of the image sensor in pixels, follows the pixel size in microns and the spread of the point spread function. Dyn stands for the dynamic range and the last value gives the image noise.

The dynamic range of the analyzed image is about 1:15 corresponding to a logarithmic value of ΔD=1.17. Effectively no grey tone values below 17 were observed and the maximum value is equal or just below 255 for a very small object. According to a control of the contrast one may conclude that the grey values are proportional to the object brightness. The image noise is estimated at one grey value over the whole grey tone range. This would mean that the noise for bright areas corresponds approximately to the shot noise, assuming that 100,000 photons can be integrated.

5.2. The DMC from Z/I Imaging

The aerial camera DMC of Z/I Imaging is a frame camera combining several cameras. In its standard form it uses 4 diverging panchromatic cameras with a focal length of 120mm/f4 and 4 vertical cameras with colour filters with a focal length of 25 mm and a chip size of 3584 x 2048. The panchromatic cameras were originally equipped with 4 CCD of 3584 x 2048 pixels giving 4096 x 7168 pixels (pixel size 12 μm), whereas other image sensors are now available. The individual images of the DMC are then combined to a virtual image of 7680 x 13824 pixels. The raw images as well as the combined or "virtual" images are encoded in 12bit. The camera allows for a forward motion compensation, which means that the image information is shifted during the exposure to the successive sensor lines.

The analysed images were made available by ICC Barcelona. We had access to the raw images and to the panchromatic images of a stereo couple taken over the city of Barcelona, with a GSD of about 20 cm. All the images are encoded in 12bit. The spread obtained is 2-2.3 pixels in the central region and 2.5 pixels at the very edge. No difference was noticed when analysing the spread in flight direction or perpendicular to the flight direction.

It seems that various images used in demonstration material have a poorer image quality, but it makes no sense to include them here in this study as the reasons for the differences in the image quality are not known.

Image forming grey tone values go down to 110 and only view image spots reach a value of 4095, concerning only areas with mirror reflection. The image could be cut to a grey value of 3000 without losing significant elements. In principle the dynamic range of the analysed image is 1:37, equivalent to a logarithmic value of ΔD =1.57 which corresponds to the Kodak Panatomic film; however, the image noise of the high definition film Panatomic is about 10 times higher than that of the DMC. The image noise was measured with 10 grey values for a value of 2000 G and went down to 5 for a grey value of 158. This would mean that the noise corresponds to the shot noise, assuming that up to 100,000 photons are integrated.

5.3. The Hasselblad H1

The Hasselblad H1 is a completely newly designed medium format digital camera with the Imaconxpress sensor 132C of 4072 x 5438 pixels (pixel size 9 μm). The sensor captures colour images in using the Bayer filter. The camera uses high performance Fuji lenses (HC 35 mm/f3.5, HC 80mm/f2.8, HC 150mm/f3.5, zoom lenses and some other focal lengths are in preparation).

At UW+R the camera is integrated in the hand-held "Helimap" system including a laser scanner (Riegel) and a GPS and INS system. This system was developed in collaboration with the Institute of Photogrammetry and the Institute of Topometry of EPFL.

The point spread function for the 35 mm lens was determined on the mentioned test targets (cf. fig 5) and on shadow edges of aerial photographs. The raw images are encoded in 16bit for the 3 bands and are then converted to 8bit per band. For the 35 mm lens one obtains in the central part for the green band a spread of only 1.25 pixels with the test patterns and 1.5 pixels for aerial photographs. At the very edge the spread increases to about 2.0 pixels. Additionally, one observes a chromatic aberration which amounts at the edges to about 2 pixels in the red and blue band. This chromatic

aberration can be corrected numerically. Compared to the above aerial camera, one should take into consideration that in particular the DMC operates with colour cameras with a considerable lower resolution than the main camera and consequently this effect should not be overestimated in this context.
The spread was also determined for the Fuji 80mm lens and is 1.3 pixels in the central part and 1.6 pixels in the edge.
The dynamic range of the analysed images is about 1:7, corresponding to a logarithmic value of $\Delta D=0.9$. No grey tones below 35-40 are observed. The image noise determined on a very homogeneous area is ± 0.5 for bright areas with a mean grey value of 200 and increases to ± 1.2 to ± 2 in darker areas with a grey value of 60. The noise in the bright area might be due to the shot noise for the integration of 100,000 photons but in the dark areas a regular background noise appears, especially visible in shadow areas. Hasselblad even recommends to make images with closed shutter in order reduce this dark current noise.

5.4. The Rollei Camera AIC modular LS

The Rollei Camera AIC is a newly designed digital camera for aerial and industrial purposes. It can be equipped with the Rollei System 6000 lenses and Rodenstock/Schneider professional lenses. The images were made available by ICC Barcelona; we had 2 images taken over the city of Barcelona with a focal length of 50 mm and two with f=80 mm, frame size 4080 x 5440 pixels.
For the 80 mm lens we found a spread of about 1.9 pixels and for the 50 mm lens a spread of 1.7 pixels. However it seems that the edges are sharpened by some image post-processing or other procedure and the real spread might be larger.
The dynamic range of the analysed images is about 1:6 which is similar to the Hasselblad and the image noise is also quite similar: ± 0.5 for bright areas with a mean grey value of 240 and increasing to between ± 1.2 and ± 2 for areas with a grey value of 90. The grey tone histograms of the images do not show values below 40.

5.5. The Orthophotos from St. Gallen

The orthophotos from St. Gallen are included here in order to establish the relation to digital images taken by an aerial film camera. The aerial photographs on a scale of 1:10,000 were taken by a Leica RC30 f = 300 mm on Kodak reversal colour film 2427. The pixel size (GSD) of the final orthophotos is 25 cm, the images were scanned on a Wehrli scanner with a pixel size of 17 μm.
The size of the spread function is 2.2 -2.7 pixels, and the dynamic range again 1:8. No grey tone values below 30 are shown in the histogram. The image noise is considerably higher in these images than in images taken by a digital camera. We measured ± 4 in bright areas and ± 7 in shady areas with a grey value of 50; the images are encoded in 8bit. When interpreting the noise, one should take into consideration that the contrast in dark areas was enhanced for about 30% compared to bright areas.
Anyhow, one can state that the images are close to the given tolerances discussed in section 2, especially if one takes into consideration that a spread of two pixels still allows one to identify edges with a transition of more or less only one pixel. However, this example shows clearly that images on film have a noise of about 5-10 times as large as digital images; as was stated earlier, this corresponds to the graininess of the film. Nevertheless, details as for example white cars in shady areas can still be recognized in these orthophotos.

6. CONCLUSION AND PERSPECTIVES

The study shows that current digital aerial cameras as produced by Leica Geosystems and Z/I Imaging have a high performance and seem to be largely equivalent to film cameras in terms of the information content. The film of 23 x 23 cm does not give more information than a camera with a 12,000 pixels swath width. However, the great progress of the digital cameras is the noise level that is lowered by a factor of 5 to 10 depending on the pixel size of the scanner for the film. This low noise level and the stability of the image sensor compared to film cameras enables much higher measuring accuracy.

The sharpness of the images is more or less the same for all digital cameras, although the medium format cameras seem even slightly better at the first glance. Most properly this is due to the particularity of band extraction. The medium format cameras use the Bayer filter and only the green band was used for the image analyzes whereas the digital aerial cameras register the whole spectre from red to blue and effects of chromatic aberration cannot be corrected in this case.

The dynamic range is lower for the medium format cameras like the Hasselblad or the Rollei and of course the sensor size is also much smaller. Regarding the extent to which the combination of 4 diverging Hasselblad or Rollei cameras mounted on a single frame might cope with the digital aerial cameras like ADS40 or DMC, there is no easy answer, but it might be an option. Of course the DMC has the advantage of the forward motion compensation which is not readily available for the medium format cameras. Moreover the smaller image format might complicate the aerial triangulation if no special precautions are taken to tie together the individual images.

The topic of the article was the "Transfer functions for digital image collection". Along with the transfer functions itself, the considerations were deliberately extended to the image density. An image function should be considered as tree dimensional, namely the planimetrical location and the intensity. Compared to film cameras, the image noise is considerably reduced, a fact which should be taken into consideration when working with these images. Every ordinary computation is executed with more digits than required or defined by the measuring precision. In image processing it might also be useful to proceed in a similar way, which means that the original images should be blown up to 4 or more pixels using appropriate interpolation algorithms as shown with the orthophoto of St. Gallen in section 2. Then the image is corrected for the deformations and converted into an orthophoto and only in the final stage does one reduce the image to its desired size. In this way it might be possible to overcome the paradox by which some almost amateur-type cameras have at first glance a higher image quality than the high quality aerial cameras.

The results presented here should be considered with great caution. The author has personal experience only with the Hasselblad camera for aerial photographs and realized at the time that the lens was a limiting factor. Before the development of the H1 series using Fuji lenses only the Biogon lens coped with the digital sensor Pro Back of Kodak. All other images included within this study were obtained graciously by various colleagues, the manufacturer of the cameras or the users. Nonetheless, the number of images is insufficient for a representative study. It is hoped that the methods presented for image analysis could serve as a basis for further studies and also that manufacturers will more readily publish the MTF, the image noise and the dynamic range of their imaging systems.

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