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Comparing the photogrammetric performance of film-based aerial cameras and digital cameras

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ABSTRACT

The performance of imaging systems containing analogue, digitizing and/or digital steps has been compared in regard to micro-image quality and radiometric characteristics. It has been found that a conventional analogue approach based on the measurement of secondary film product (diapositive), a digital photogrammetric approach based on a digitized primary film product and a hypothetical digital photogrammetric camera give comparable image quality results under a number of made assumptions, the most important being the use of 7 µm pixels, a medium contrast scene and residual uncorrected image motion of also 7 µm. An analysis of the radiometric characteristics has led to the conclusion, that aerial photographs containing a density range not exceeding 2.0 can be scanned to achieve a fully resolved 8-bit density range from 0 to 2.0 with an scanner providing a 12-bit transmittance scan resolution (such as the Zeiss SCAI).

1. INTRODUCTION

A review of the present state-of-the-art of different componemts of image systems is given in preparation for a comparison of performance. The components reviewed include aerial cameras, aerial films, non-photographic recording of images emphasizing charge coupled devices, the Zeiss SCAI scanner and various digital cameras. In each case, those characteristics thought relevant in view of the following analysis are included. The comparison of performance is primarily based on an analysis of the micro image quality and the radiometric characteristics of various imaging systems but some remarks are also made in regard to data storage, data handling and plotting accuracy.

2. OVERVIEW OVER IMAGING SYSTEM COMPONENTS AND THEIR PERFORMANCE

The quality of the aerial photographic product needed for photogrammetric evaluation processes is dependent on the type of product used. Disregarding a possible influence of the atmosphere, the quality of the primary product, if a film product, depends mainly on the optical quality of the lens, the effectiveness of correcting for image motion and the resolution of the film. Secondary or tertiary products are often used for the actual evaluation. If the secondary product also is a film based product, its quality depends on the copying process and the resolution of the copying material; if it is a digital product, its quality depends on the parameters of the scanning process, primarily the pixel size and the radiometric scanning parameters. For reasons of completeness, digital cameras are included into this review even so they are not yet available for mapping photography with parameters similar to those of aerial cameras.

2.1 Aerial cameras

Aerial cameras are offered by mainly two manufacturers, Leica AG of Switzerland and Zeiss. The following discussion will limit itself to the RMK TOP camera of Zeiss which is in its present form (with fully integrated image motion compensation) offered with two lenses, the Pleogon A3 4/153 and the Topar A3 5.6/305. These lenses have an improved image quality towards the corners, four internal filters, improved colour correction and controllable internal diaphragms which stop down from f/4 respective f/5.6 to f/22. Stopped down one step to their so-called optimum aperture they have an area-weighted MTF which decreases roughly linearly from 1 to 0.5 for spatial frequencies from 0 to 80 lp/mm. The automatic exposure control of the camera determines the optimum combination of aperture (depth-of-focus consideration require additional stepping down at low flying altitudes) and exposure time, taking into consideration the overall lighting conditions and the image motion (forward motion can be corrected to 64 mm/sec., angular motion is controlled by means of a stabilized mount) to be compensated.

2.2 Aerial films

Aerial film still appears to have a bright future as the demand of, in particular, large scale aerial photographic images for cartographic applications is increasing in line with an increased demand for Geographic Information Systems. There are two major suppliers for aerial films; these are, in alphabetical order, Agfa and Kodak. The different types of film available for aerial photography can be grouped in two groups, films producing black and white (monochrome) images and films producing colour (chromogene) images. The requests on aerial films are slightly different for the two groups and can be listed as follows:

Black & white	Colour
• good detail rendering - high resolution - near IR sensitivity (less scattering, higher reflection)	• good detail rendering - high resolution - colour saturation - soft material (shadows)
• maximum speed vs. minimum granularity	• good colour match (orthophotos)
• appropriate processing / sensitometry	• standard processing systems
• dimensional stability	• dimensional stability
• good physical properties	• good physical properties

Aerial films are available to cover all flying heights usable with airplanes today (an increase in flying height normally reduces the available scene contrast) with nominal speeds varying between 40 and 600, usually having large exposure latitude ranges, low-contrast resolution ratings between 40 and 125 lp/mm and diffuse r.m.s. granularities between 9 and 40. The availability of forward/image-motion compensation in aerial cameras enables the use of films with lower sensitivity and increased resolution. The specifications for minimum and maximum densities and density range vary for different countries and different products. The values to be given in the following are those used for black&white photography procured for the Federal government of Canada and the result of extensive experiences:

the density range should be as close to 1.0 as possible; maximum density may at no time exceed 2.0; minimum density shall not fall under 0.2 within 10 cm of the image centre.

Whenever possible, the minimum density is to be read in a shadowed area. The maximum density is measured on some feature at least 5 mm in diameter, and measurements in areas of specular reflectance are avoided. The range specification associated with the minimum density takes uncorrected light fall-off towards the format corners into consideration. The emphasis on density range has resulted in the development of a special international standard for the speed rating of aerial films. In difference to other such standards defining the speed by means of one point and the standard development conditions and, hence, the slope of the D-logH-curve by a second point, is the speed of aerial films only defined by means of a speed point, which is located at 0.3 density units above base+fog of the film. As the exposure and development of the film are adopted to the average scene illuminance, the desired slope of the D-logH-curve of the developed film needs to be determined beforehand; it should fall within a larger range within which a film can be used. As the effective film speed changes with the

slope, the proper film speed needs to be determined prior to beginning with the exposure of the film as well. The slope needs to increase with a decrease in the scene brightness range, e.g. with an increase in taking height and a decrease in scale. In Canada it is mandatory to exposure gray wedges by means of a calibrated sensitometer onto the film prior to development in order to check for proper photographic processing.
Film transparencies used in various photogrammetric operations must meet their own specific requirements in regard to density and contrast. The use of light sources for the illumination of the photographs in plotters usually results in density range requirements slightly larger than those given above for black&white negatives. However, an increase in local contrast is usually desired and achieved by means of printing with a contrast-adjusting (dodging) printer. Density ranges for colour products should be similar to those for black&white products, those for colour infrared images somewhat higher (between 1.5 and 2).

2.3 Non-photographic recording

The photographic film has in some applications the primary disadvantage of requiring photographic processing, hence, the image data are only available after a significant time delay. The desire to access acquired image data more or less immediately has resulted in the development of several multi-detector image recording technologies, the most common types being an array of photodiodes on silicon wafers, the so-called charge coupled devices (CCD); other technologies include e.g multiplexed devices and charge-injection devices (CID). Also of interest could be a development called photothermoplast.
A CCD image sensor operates in several stages:

a) it converts incident illumination into a proportional quantity of electrical charges,
b) it stores the photo charges from each photo element in an associated potential well,
c) it transfers the accumulated charge packets sequentially along the capacitors to a readout stage,
d) each arriving photo-charge packet is at the readout stage converted into a proportional voltage signal,
e) the voltages are converted into digital values representing transmittances.

By means of electrodes overlying the potential-well structure, packets of charge can be transferred from well to well without loss or mixing. The keys to successful transfer are proper potential profiles, careful electrode clocking, and "clean" wells with no charge traps. In modern CCD devices, charges can be clocked at 20 MHz with charge-transfer inefficiencies smaller than one part in 10^5 per step. The last stage of the CCD transfers its charge onto an electrode which is small and has a low capacitance, providing a high charge-to-voltage conversion ratio and low noise. For this reason, a CCD imager operates well at low light levels. The major problem with a CCD imager is its performance at high light levels. Only a limited amount of charge can be stored in a CCD well and transferred successfully down the register. If too much charge is injected into a CCD well, the charge spreads into neighbouring wells, an effect called blooming. This effect can be combated by means of the including into the structure anti-blooming drains to carry away excess charge before it can spread to neighbouring wells.
The physical size of silicon solid-state imagers is limited by the size and quality of the silicon wafer on which it is fabricated. The yield of the fabrication process falls quickly with increasing imager area. The size of the photosites on an imager is determined by the lithographic methods used to fabricate it and by several design parameters, such as the capacitance required. The typical smallest photosite size achievable today in view of photogrammetric requirements is obtained for a photosite spacing of 7 µm giving a nominal one-inch linear array of 4096 pixels. If longer linear arrays are desired, several must be butted together. There are three possible solutions to this butting:

a) staggered array segments with time delay in the reconstruction which requires very accurate knowledge of the image velocity,
b) optical butting of the chips using a different lens for each chip (such in MOMS-01)
c) true physical butting if the linear arrays have no circuitry at the end with a loss of imagery for one pixel at each end which is replaced by interpolation.

The problems of butting can be avoided if one succeeds to use larger wafers. Of particular interest for photogrammetric applications are two-dimensional or area CCDs. Chips as large as $8K \times 9K$ appear to have been produced (on a six-inch wafer).
The dynamic range of CCD imager is the ratio of saturation voltage (the maximum output signal voltage, a function also of the photo-element size) and r.m.s. temporal noise (fluctuations in time of a given pixel signal in darkness); this range is today in the order of 3500:1, i.e. between 2^{11}:1 and 2^{12}:1. Each pixel can be expected to have a slightly different gain and offset which are affected for example by temperature and light level. In addition, pixel often do not show the same sensitivity over their entire area.
The micro-image quality of CCDs can be expressed by means of the contrast transfer function (CTF, derived using a pattern of black and white bars) or the modulation transfer function (MTF, using sinusoidal targets). CTF and MTF depended primarily on the size of the photo elements, the crosstalk between neighbouring pixels and the wavelength (longer wavelengths penetrate deeper into the wafer). Nominally, the MTF is a sinc function with a cut-off frequency equal to the reciprocal of the pixel dimension. At short wavelengths the MTF matches this function closely; the drop-off for longer wavelength can be significant unless the deeper penetration is counteracted.
Photothermoplast is a new technology originally developed in the former USSR and further developed by Jena Optronik GmbH, a Daimler-Benz Aerospace company. It is an optically reversible real-time intermittent storage medium which can be placed in the imaging chain between a lens and a CCD. It provides better resolution than both, photographic film and CCDs, it stores the image as does film, has a dynamic range comparable to film comparable to but somewhat smaller than (i.e. approx. 20:1), allows cycle time smaller than 3s, can be delivered in rolls as large as $28\text{cm} \times 500\text{m}$ and pre-view image data can be available in roughly 1 s. It could be used instead of photographic film in a specially fitted camera.

2.4 Scanner for digitizing aerial films

A larger number of scanners were presented and discussed during the 1996 congress of ISPRS. For reasons of brevity, the Zeiss SCAI photogrammetric scanner is considered here as representing the standard achievable today. As it is subject to a separate presentation (Vogelsang, 1997), a short summary of its main features shall suffice:

- pixel size selections: 7, 14, 21, 28, 56, 112 and 224 µm based on 7 µm pixels,
- concurrent scanning of the red, green and blue partial images using three parallel linear arrays with 5632 7-µm pixels each (39.424 mm long),
- radiometric resolution: 12 bits for transmittance τ,
- radiometric modification of τ by means of functions and LUTs,
- maximum photo area for scanning: 250×275 mm,
- maximum scanning rate: 4 Mpixels/s resulting in a scanning time of 10 minutes for 14-µm pixels.

The SCAI provides a number of image processing functions such as:

- positive/negative presentation,
- rotation and mirror inversion of the image,
- histogram manipulation.

The SCAI can be used to scan single transparent photos and it can be equipped with an autowinder roll-film attachment for the processing of uncut aerial film rolls up to approx. 150 m in length which also provides for:

- automatic film advance and positioning to ± 3 mm into a specified position derived from an operator-set accurate position of the first photo to be scanned,
- scanning in unattended batch mode,
- scanning according to a pre-set photo sequence,
- scanning of 9.5" rolls using a reel width of 245 mm and reel diameters up to 168 mm,
- automatic rewindung of the film at a rate of 4 photos/s using frame edges as control.

2.5 Digital cameras

A larger number of digital cameras have entered into the data acquisition area in non-topographic applications of photogrammetry and in Earth observation from space platforms and airplanes. These can be grouped according to the type of CCD imager used: either a linear array or a area array. Linear arrays were/are used e.g. in the following sensors: MEIS (airborne, I from 1978, II from 1983), MOMS (01 in 1983 on Space Shuttle, 02 in 1993 on Space Shuttle, since 1997 on Priroda), HRV (from 1986 on SPOT satellites), OPS on JERS-1 (started 1992 for a two-year operation), MEOSS (1993 on failed Indian IRS-1E mission), HRSC (1989, 1997 on failed Mars mission), WAOSS (1997 on failed Mars mission), WAAC (airborne, derived from WAOSS, tests since 1995), DPA (airborne derivative from MOMS-02, tests started at the end of 1992 and continue through this year) and the Rollei ScanPack, an attachment to the Rolleiflex 6008 camera. Of those sensors mentioned, all but the ScanPack have multiple arrays to scan simultaneously for several spectral ranges, and MEIS II, MOMS-02, HRSC, WAOSS, WAAC and DPA have in flight-line stereo capability with two (MEIS II, OPS) and three (MEOSS, MOMS-02, HRSC?, WAOSS, WAAC and DPA) separate views.
Area arrays are found in cameras used for non-topographical applications. The following cameras are a selection of non-scanning devices: Kodak DCS 420 (14 × 9 mm², 1536 × 1024 pixel), Kodak DCS 460 (30 × 20 mm², 3060 × 2036 pixel), the Rollei ChipPack attachment (31 × 31 mm², 2048 × 2048 pixel) and the Rollei Q16 MetricCamera (60 × 60 mm², 4096 × 4096 pixel).
If the relationship between camera and object remains unchanged for a certain time (as is **not** the case in aerial photography), cameras employing scanning in the image plane can be used. Two types of scanning are used, macro-scanning (an area array is moved in larger steps) and micro-scanning (an area array is moved fractions of the pixel spacing). Macro-scanning has been employed in the UMK-Highscan camera (formerly produced by Zeiss Jena and now available from Industrievertreib und Industrieberatung GmbH (IVB) in Jena) using four CCDs with each 739 × 512 pixels and a pixel spacing of 11 µm to convert the 169.5 × 121.4 mm² large format divided into 21 × 23 windows into 15414 × 11040 pixels; the scan requires a few minutes. A much faster scan can be achieved using micro-scanning as in the JenScan camera (available from Rheinmetall Jena Image Technology GmbH, RJM), where a video CCD chip (748 × 512 pixel) is moved to a maximum of 36 positions within the area defined by the spacing between neighbouring pixels and using the fact that the sensitivity within this area is non-uniform and peaks near the centre, generating an image of up to 4488 × 3072 pixels in less than 5 seconds.

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3. COMPARISON OF PERFORMANCE

3.1 Micro-image quality

The characteristics of the micro behaviour of the photographic emulsion and other image-recording media (micro-image quality) can be described with a larger number of terms; many of these are subjective such as graininess and resolving power. Only objective (say measurable under controlled conditions) terms will be used in the following discussion with the exception of resolving power.
Granularity is a measure of photographic noise resulting from an unequal distribution of silver in an area exposed to have the same density. The so-called r.m.s. granulatity given in data sheets for photographic materials is the standard deviation of transmittance values measured with an aperture of a certain diameter (usually 50 µm) for an area of supposedly uniform density (usually 0.8), given in %. It is conceivable to define a respective measure to express the non-uniformity in the response of CCD pixels.
An aerial imaging system is designed, constructed and deployed to collect information about objects on the ground. The success of a mission is closely correlated with the quality of the imagery. For decades, the preferred measurement for system performance has been (tri-bar) resolution; however, since aerial images are comprised of single objects rather than repeated patterns, the ability to discern certain objects is not strictly a function of the resolving power. Other disadvantages of the resolving power are for example: (1) the results are affected by the photographic development, (2) it is only a threshold spatial frequency response measurement involving the human eye, (3) it is dependent on the shape of the target used, (4) it does not take granularity into account, and (5) it can not be used with reasonable accuracy to analyse an imaging system.
A more comprehensive approach to micro-image evaluation avoiding the disadvantages of resolving power is based on the use of Fourier analysis involving spread functions and transfer functions. A point spread function (PSF) describes the distribution of light intensity in the image of a point and sets an upper limit to the number of possible image points per unit area. Similarly, a line spread function (LSF) describes the image of a line consisting of many very densely spaced points, and an edge spread function (ESF) the image of an edge consisting of many very densely spaced lines. If the input to a system can be broken down into an additive combination of elementary inputs each giving a known output, and if the total output can be found by simply adding the weighted values of the known outputs, one speaks of a linear system. In such a linear system, the Fourier transform of a line spread function results in a modulation transfer function (MTF). If $I(x)$ is a cosinusoidal distribution of object illuminance, then the modulation M_0 of an object is defined by

$$M_0 = (I_{max} - I_{min}) / (I_{max} + I_{min}) = a_0 - a\cos(\omega x) \tag{1}$$

where ω is the angular spatial frequency in radians, a_0 the average amplitude and a the amplitude of $I(x)$. The ratio of image modulation and object modulation at a particular frequency gives the sine-wave response of an imaging system, and the ratios at all frequencies ω give the so-called modulation transfer function MTF = $F(\omega) = M_i(\omega) / M_0(\omega)$ which can be shown to be the normalized amplitude spectrum of a linear system. Asymmetries in the LSF result in phase shifts as a function of frequency, and the combination of MTF and phase data (PTF) is known as optical transfer function (OTF), hence MTF = |OTF|. If the input target is not sinusoidal but square and is expressed as a series of sinusoidal elements), one can apply a similar approach and obtain for the amplitude the so-called contrast transfer function (CTF) which can be converted, if desired, to an MTF.

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a	b	c	d	e	f	g	h	i	j	k	l
0,00	1,000	0,0	0	0,000	1,000	1,000	1,000	1,000	1,000	1,000	0,025
0,05	0,936	13,3	10	0,220	0,992	0,876	1,067	1,218	0,997	0,836	0,025
0,10	0,873	26,6	20	0,440	0,968	0,558	1,028	1,000	0,994	0,508	0,030
0,15	0,810	39,9	30	0,660	0,929	0,183	0,912	0,788	0,990	0,309	0,049
0,20	0,747	53,2	40	0,880	0,876	-0,105	0,815	0,600	0,987	0,212	0,081
0,25	0,685	66,5	50	1,100	0,810	-0,216	0,730	0,451	0,984	0,155	0,118
0,30	0,624	79,8	60	1,319	0,734	-0,160	0,657	0,339	0,981	0,109	0,161
0,35	0,564	93,1	70	1,539	0,649	-0,020	0,592	0,262	0,978	0,074	0,229
0,40	0,505	106,5	80	1,759	0,558	0,097	0,535	0,212	0,975	0,049	0,338
0,45	0,447	119,8	90	1,979	0,464	0,126	0,480	0,180	0,971	0,029	0,510
0,50	0,391	133,1	100	2,199	0,368	0,067	0,435	0,158	0,968	0,017	0,862
0,55	0,337	146,4	110	2,419	0,273	-0,026	0,400	0,140	0,965	0,011	1,471
0,60	0,285	159,7	120	2,639	0,183	-0,086	0,361	0,119	0,962	0,009	2,273
0,65	0,236	173,0	130	2,859	0,098	-0,079	0,333	0,110	0,959	0,007	2,778
0,70	0,188	186,3	140	3,079	0,020	-0,020	0,300	0,101	0,955	0,006	3,571
0,75	0,144	199,6	150	3,299	-0,047	0,045	0,281	0,092	0,952	0,005	4,167
0,80	0,104	212,9	160	3,519	-0,105	0,071	0,250	0,083	0,949	0,004	5,000
0,85	0,068	226,2	170	3,739	-0,150	0,046	0,225	0,074	0,946	0,003	6,250
0,90	0,037	239,5	180	3,958	-0,184	-0,008	0,205	0,065	0,943	0,002	8,333
0,95	0,013	252,8	190	4,178	-0,206	-0,051	0,185	0,056	0,940	0,001	12,500
1,00	0,000	266,1	200	4,398	-0,216	-0,054	0,162	0,047	0,936	0,000	25,000

Table 1: MTFs for different imaging steps (see text).

The following table contains a larger number of MTFs which will be used for system analysis. The columns represent:

a) relative frequencies,
b) values for a diffraction limited lens (ideal MTF assuming a circular aperture without obstruction),
c) frequencies corresponding to the values in column b for a 153/5.6 lens; with a limiting resolution of $1.22\lambda/d$ which results for $\lambda = 550$ nm in a cut-off frequency of 266 lp/mm,
d) frequencies for a cut-off frequency of 200 lp/mm (to approx. 75% of diffraction limit),
e) auxiliary values used to calculate columns f and g,
f) ideal MTF for a CCD with 7-µm pixel size; this curve also indicates the effect of 10% uncorrected image motion assuming an image scale of 1 in 5000, an exposure time of 1/100 s and an aircraft speed of 126 km/h,
g) ideal MTF for a CCD with 28-µm pixel size, or 28 µm uncorrected image motion,
h) MTF for a black&white film (Aviphot Pan 200 S PE1, data sheet dated 199106); data given as graphical log-log presentation up to 100 lp/mm, the rest estimated as straight-line extension of that curve,
i) MTF for a colour film (Aviphot Color N 200 PE1, data sheet undated); data given as graphical log-log presentation up to 70 lp/mm, the rest estimated as straight-line extension of that curve,
j) MTF for photothermoplast,
k) MTF for the human eye, assuming a magnification factor of 20 and an observation distance of 50 cm,
l) contrast modulation threshold function for the human eye assuming a contrast 0.025 at $\omega = 0$.

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The component MTFs given in table 1 will now be combined using column d as reference frequencies to enable a number of conclusions regarding the use of film and digital data in photogrammetry. One of the attractive features of the use of transfer functions is the fact, that the performance (MTF) of a system can be derived by multiplying the MTFs of the imaging steps. The results are given in table 2 with the following columns (column numbers a to l refer to columns in table 1):

- o) reference frequencies (copy of column d in table 1),
- p) MTF for a black&white film high-contrast negative (contrast ratio 1000:1) including columns b (lens), f (uncorrected image motion) and h (black&white film),
- q) MTF for a black&white-film medium-contrast negative (contrast ratio 6.3:1); the change in contrast is applied by means of a CTF = $(C_{max}-C_{min}) / (C_{max}+C_{min})$ = (6.3 - 1) / (6.3 + 1) = 0.73 for all ω,
- r) MTF for a black&white-film low-contrast negative (contrast ratio 1.6:1); the change in contrast is applied by means of a CTF = 0.23 for all ω,
- s) MTF for a black&white-film high-contrast diapositve (using the values from column h) from a medium-contrast negative (column q),
- t) MTF for a black&white-film high-contrast diapositve from a low-contrast negative (column r),
- u) MTF for a medium-contrast negative scanned with 7 µm pixels,
- v) MTF for a medium-contrast negative scanned with 28 µm pixels,
- w) MTF for an as yet to be scanned image taken of a medium-contrast object with a mapping camera and thermoplast material including columns b (lens), f (uncorrected image motion) and j (thermoplast),
- x) MTF for an image taken of a medium-contrast object with a digital camera including columns b (lens), f (uncorrected image motion) and f (pixel size = 7 µm),

o	p	q	r	s	t	u	v	w	x
0	1,000	0,730	0,230	0,730	0,230	0,730	0,730	0,730	0,730
10	0,991	0,723	0,228	0,771	0,243	0,717	0,633	0,676	0,673
20	0,869	0,634	0,200	0,652	0,205	0,614	0,354	0,613	0,597
30	0,686	0,501	0,158	0,457	0,144	0,465	0,091	0,544	0,510
40	0,533	0,389	0,123	0,317	0,100	0,341	-0,041	0,472	0,418
50	0,405	0,296	0,093	0,216	0,068	0,240	-0,064	0,399	0,328
60	0,301	0,220	0,069	0,144	0,045	0,161	-0,035	0,328	0,245
70	0,217	0,158	0,050	0,094	0,029	0,103	-0,003	0,261	0,173
80	0,151	0,110	0,035	0,059	0,019	0,061	0,011	0,200	0,115
90	0,099	0,073	0,023	0,035	0,011	0,034	0,009	0,147	0,070
100	0,063	0,046	0,014	0,020	0,006	0,017	0,003	0,102	0,039
110	0,037	0,027	0,008	0,011	0,003	0,007	-0,001	0,065	0,018
120	0,019	0,014	0,004	0,005	0,002	0,003	-0,001	0,037	0,007
130	0,008	0,006	0,002	0,002	0,001	0,001	0,000	0,016	0,002
	79,1	64,5	46,3	**59,1**	**42,5**	***59,9***	***32,4***	71,9	*64,2*

Table 2: MTFs for different imaging systems (see text).

The last line in table 2 contains the spatial frequency for the respective points of intersection of the curves represented by the values in the columns and the contrast modulation threshold curve given in column l of table 1. These numbers can be interpreted as resolving power values for the different systems. The first three columns (p, q, r) demonstrate the effect of decreasing object contrast, the next two columns with straight bold numbers values to be expected for analogue diapositives, the two bold italics numbers to be expected when digitizing black&white negatives, the italics value in column x a

fully digital system, and a possible future system (using thermoplast as recording medium) is given in column w. All values within the body of the table written in italics fall below the contrast modulation threshold curve and are therefore not of interest if a human observer is involved.
Under the assumptions made her, the resolving power values are for quality products (medium-contrast negatives as part of the imaging chain) similar, if either a second-generation photographic product (a film diapositve), a first-generation photographic product (a negative) scanned with a 7 µm pixel or a digital image obtained with a camera with 7 µm pixels is used by a human operator in the photogrammetric evaluation process. Using larger pixels degrades the resolving power as do a further reduced object contrast or an increased uncorrected amount of image motion.

3.2 Radiometric image characteristics

The term radiometry generally describes the transport of energy through a(n optical) system. The radiometric characteristics of an imaging system describe how a specific system responds to scene energy of varying intensity. Knowledge of these characteristics is often useful, and sometimes essential, to the process of image analysis. For example, a photograph can be thought of as the visual record of the response of many small detectors of energy incident upon them. The result of exposure at a point of the film is, after development, accumulated silver whose light absorbing quality is systematically related to the exposure at that point. The resulting opacity $O = \Phi_{absorped} / \Phi_{incident}$ is determined by measuring the transmittance $\tau = \Phi_{transmitted} / \Phi_{incident} = 1 / O$. Since the human responds to light levels nearly logarithmically, it is in connection with photography convenient to work with the density $D = \log O = \log (1/\tau)$. CCDs, on the other hand, respond nearly linearly to incident energy, i.e. digital values arrived from the initially recorded analogue voltages are transmittance values.
The required radiometric characteristics can be derived from the maximum possible intensity range to be covered and the transmission characteristics of the imaging system. A scene containing as extreme surfaces in regard to reflection chalk and black soil yields an intensity ratio in the order of 5.3:1; a wide angle lens having an uncorrected illuminance drop-off in the format corners according to the $\cos^4$ law to approx. 25% contributes an intensity ratio of 4:1; combining both necessitates a dynamic range, also called exposure range, of the recording material of at least 21.2:1. In addition, it is desirable to have a certain margin for wrong exposure called exposure latitude; a factor 2 doubles the range to ~ 43:1. Negative photographic films can be adopted to rather large exposure ranges through development yielding a sufficiently small gradient for the D-logH curve to obtain the desired density range for the image. CCDs have a dynamic range of approx. 3500:1, and thermoplast of approx. 20:1.
An additional component to be considered is the presentation form of the image during the evaluation; analogue images are used in some photogrammetric instruments, digitized images in others, and the evaluation of satellite images is generally based on digital images. When working with digital data, the radiometric characteristics of the video display unit (VDU) must be taken into consideration as long as a human operator is involved. If the final product is to be an image-based product such as a photomap, the desirable radiometric characteristics of that product must be achieved independent of the production steps leading to the final product.
Cathode ray tubes (CRT) used in VDUs do not respond linearly to the voltage applied when projecting an image; the resulting brightness of the glowing phosphor has a relationship to the applied voltage that is roughly a power-law function. This function can be written as $\tau^{1/\gamma}$ with $\gamma \approx 2$ (TV monitors usually have $\gamma \approx 2.2$ and SGI workstation monitors $\gamma \approx 1.7$). However, there is a complication with the use of this function as TV systems were designed to have black and white normalized to fixed voltage levels; hence, the power law function is only used to redistribute the levels between the two extremes. Changing the value for γ therefore produces the greatest alteration in the mid-tones which makes an image look more or less contrasty, however, strictly speaking, this change has nothing to do with contrast which is defined as the ratio of the white to the black level.

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When scanning an image, the operator is able to set γ to a value giving a pleasantly looking picture on the screen which may not at all be suitable for later applications. It is therefore suggested that users of digital or digitized images perform a tone reproduction analysis of all steps included in reaching a final result from first generation images, and that look-up tables (LUT) be developed for each step in an image-application chain, e.g including for the derivation of an orthophoto map the steps primary image - (secondary image -) scanner - monitor - ortho photo - mosaicking - (colour separation -) printing. Comparing here for reasons of brevity only an original positive image and a rectified photo to be derived digitally, one needs to convert the transmittances τ delivered by the scanner into densities *D*. As $D = \log(1/\tau)$, a conversion from linear to logarithmic values is required.
Radiometric resolution is the smallest detectable exposure range, in the case of the scanner in linear units. As the dynamic range of CCDs is approx. 3500:1, we need to represent at least 3500 distinct transmittance values which translates into $2^{12} = 4096$ with a reduction in the dark areas to insure that a reduction below the noise level cannot happen (approx. the first 85 values for the SCAI). Assuming that the aim is the derivation of an equally spaced density range, it is worthwhile to compare the respective radiometric resolutions (table 3) where the rows show the following:

1) (D) Densities *D* between 0 and 3
2) (85D) *D* multiplied with 85 to convert to the 8-bit range
3) (T) τ
4) (dT) $\Delta\tau$ calculated for the densities D_i in row 1 and for (D_i + 1/85)
5) (255dT) $\Delta\tau$ multiplied with 2^8-1
6) (511dT) $\Delta\tau$ multiplied with 2^9-1
7) (1023dT) $\Delta\tau$ multiplied with 2^{10}-1
8) (2047dT) $\Delta\tau$ multiplied with 2^{11}-1
9) (4095dT) $\Delta\tau$ multiplied with 2^{12}-1
10) (8191dT) $\Delta\tau$ multiplied with 2^{13}-1
11) (16383dT) $\Delta\tau$ multiplied with 2^{14}-1
12) (32767dT) $\Delta\tau$ multiplied with 2^{15}-1

D	0,00	0,30	0,60	0,90	1,20	1,50	1,80	2,10	2,40	2,70	3,00
85D	0,0	25,5	51,0	76,5	102,0	127,5	153,0	178,5	204,0	229,5	255,0
T	1,00000	0,50000	0,25000	0,12500	0,06250	0,03125	0,01563	0,00781	0,00391	0,00195	0,00098
dT	0,02673	0,01339	0,00671	0,00336	0,00169	0,00085	0,00042	0,00021	0,00011	0,00005	0,00003
255dT	7	3	2	1	0	0	0	0	0	0	0
511dT	14	7	3	2	1	0	0	0	0	0	0
1023dT	27	14	7	3	2	1	0	0	0	0	0
2047dT	55	27	14	7	3	2	1	0	0	0	0
4095dT	109	55	27	14	7	3	2	1	0	0	0
8191dT	219	110	55	28	14	7	3	2	1	0	0
16383dT	438	219	110	55	28	14	7	3	2	1	0
32767dT	876	439	220	110	55	28	14	7	3	2	1

Table 3: (see text).

The table shows which density ranges (with a radiometric resolution of ΔD = 1/85 corresponding to 1 in 2^8) can be produced with radiometric resolutions of $\Delta D = 1/2^n$ corresponding to 1 in 2^n; e.g. n = 10 would allow to use a density range from 0 to 1.5. As aerial photographs should not have density ranges exceeding 2,0 one should be able to set maximum (and minimum) desirable densities at the scanner and than spread this range into the 2^8 bits as was done for the following table 4 where the same annotation applies to the lines as in table 3:

D	0,00	0,20	0,40	0,60	0,80	1,00	1,20	1,40	1,60	1,80	2,00
85D	0,0	25,5	51,0	76,5	102,0	127,5	153,0	178,5	204,0	229,5	255,0
T	1,00000	0,63096	0,39811	0,25119	0,15849	0,10000	0,06310	0,03981	0,02512	0,01585	0,01000
dT	0,01790	0,01129	0,00713	0,00450	0,00284	0,00179	0,00113	0,00071	0,00045	0,00028	0,00018
255dT	5	3	2	1	1	0	0	0	0	0	0
511dT	9	6	4	2	1	1	1	0	0	0	0
1023dT	18	12	7	5	3	2	1	1	0	0	0
2047dT	37	23	15	9	6	4	2	1	1	1	0
4095dT	73	46	29	18	12	7	5	3	2	1	1

Table 4: (see text).

The table shows which density ranges (with a radiometric resolution of ΔD = 1/127,5 corresponding to 1 in 2^8) can be produced with radiometric resolutions of $\Delta D = 1/2^n$ corresponding to 1 in 2^n; e.g n = 12 (available at the SCAI) would allow to use a density range from 0 to 2.0 (the entire range). Hence, suitable LUTs should be defined and used. The alternative would be the use of $\tau^{1/\gamma}$ with a suitably chosen γ, however, this originally implied the use of a density range of 3.0 which can now possibly also be modified.
LUTs should also be used to convert from scanned negatives to positive image data because of the non-linearities in the photographic process. In addition, an inversion of gray values fails to correct the relationship between exposure ($H = E \times t$, H .. exposure, E .. illuminance meeting the image plane, t .. exposure time) and density – log$H$:D – which is quite different for negative and positive images but can be derived using a tone reproduction diagram.

3.3 Image storage and handling

The problems related to image storage will be discussed based on the volume of aerial photographs accumulated in the Federal German state Sachsen-Anhalt (LSA) which has an area of approx. 20563 km² (~ 6% of the area of Germany). The state has undertaken an active aerial photography program since 1992 for the purpose of updating the topographical base map scaled 1 in 10 000 (TK10) and the renew the land registration maps (LK) to be converted into 1 in 1000 maps bordered by grid lines of the LSA plane co-ordinate system. The photography for the TK10 was flown first in 1992 at a scale of 1 in 14500, and periodic reflights have commenced. The photography for the LK was flown over the years 1993 to 1996 at a scale of 1 in 3700. These black&white photographs are held at the state survey office (LVermD) air photo library which also holds the photos of a state-wide CIR coverage (1 in 10000) and older (1 in 14500?) photographs, totalling 0.5 million images. Assuming that each acquired roll of film held 500 exposures, the library would now contain approx. 1000 rolls of film if the decision had not been made to cut the film and store single images instead. If these images had been digitally acquired or were to be stored digitally after digitization, the following amount of data would result for the given pixel sizes and an assumed format of 9"×9" (~23×23cm²):

Scale	Type	Number	Size [Gbyte] 7µm pixel	Data [Gbyte] 7 µm pixel	Size [Gbyte] 28 µm pixel	Data [Gbyte] 28 µm pixel
1: 3 700	b&w	350 000	1.0665	373 275	0.0667	23 345
1:10 000	CIR	13 000	3.1995	41 594	0.2000	2 600
1:14 500	b&w	137 000	1.0665	146 110	0.0667	9 138

The estimated amount of digital data is incredibly large and contains significant redundancy in view of the fact that the 1 in 3700 and the 1 in 14500 photographs were flown using 80% forward overlap. It is not known how the day-to-day handling of so many photographs and associated digital data takes place. Most of the work for the LK has apparently been contracted out and was/is performed using the original negatives. The work for the TK10 is done (to a larger extent?) in-house requiring the handling of larger amounts of digital data; scanning is done with a 30 × 30 µm² pixel.
Storage media (CCD juke box) costs today in the order of 150 DM/Gbyte. Assuming the data amount listed in the preceding table for 7 µm pixels, namely 560979 Gbytes, an investment of 84 million DM would be required just to store the data; and for a 28 µm pixel 5.3 million DM would still be required.
An alternate strategy is the digitizing of the photographs on demand. Assuming that the scan time is limited by the data transfer rate, the scan time given for a 14 µm pixel of less than 10 minutes can be translated to other scan times as follows: scanning with a 7 µm pixel increases the scan time fourfold, scanning with an 28 µm pixel reduces the scan time to a quarter. If a SCAI with autowinder attachment is available and the film rolls are not cut, the scanning can be done largely unattended in batch mode; however, if the rolls are cut to single photographs, each photograph must be handled by an operator, increasing the cost for scanning substantially.
If one assumes that all of LSA were to be imaged using the DPA with the assumption of 20% over neighbouring strips, a ground resolution of 28 µm × 14500 = 0,4 m (and 12000 pixels / line resulting in a swath width of 4800 m), LSA could be covered by 160 billion pixels / panchromatic CCD line, i.e. 480 Gbyte of data would be collected for each total coverage of LSA. These data would be more difficult to process because of the line rather than frame nature of the image.
The need for image compression appears obvious when looking at the amount of image data indicated above. But not only the storage of these data is a problem, the transmission over data nets between computers is likely a problem as well. Image can be compresses because of a certain amount of redundant and/or relevant information. Redundancy relates to statistical properties of the image; it can be spatial (correlations between neighbouring pixels), spectral (correlations between spectral bands) and temporal (correlation between neighbouring frames of an image sequence). Irrelevancy which is based on limitations and variations of the human visual system, can be divided similarly. Of are interest here are primarily the spatial redundancy, if colour photography were flown, the spectral redundancy. Depending upon the use of the digital data, one could apply loss-less (reversible) or lossy (irreversible) compression. Unfortunately, only modest compression ratios (an average of 2:1 for a one-band image) are possible with loss-less compression. Much higher compression ratios can be achieved with lossy techniques in exchange for degradations, and investigations are needed to determine the extent of acceptable degradations for images used in photogrammetric tasks.

3.4 Image measurement

There are also significant differences in the appearance of the data during the measurement, as shall be indicated here for the task of orienting a model; the comparison is made between the Zeiss PHODIS and the Zeiss Dicomat. At the Dicomat, the images are seen through oculars which are stationary, change in magnification manifests itself as a change of the size of the image area seen and the measuring marks moves continuous in the model space. At PHODIS ST30, stationary oculars no longer exist, a change in the magnification is introduced by changing the zoom factor, and the measuring mark moves continues until it reaches the monitor screen limit. In the latter case, a jump of measuring mark and model occur returning to the screen centre, and at the same time a change occurs in the setting of the reference depth such that the measuring mark is reset to the screen level. Especially when measuring large-scale photographs, elevated objects such as building protruding significantly into the space between screen and operator, cause problems during the measurement which can be overcome by reducing the magnification, in other words, frequent rezooming may be desirable. The

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orientation processes are easier and faster to carry out on PHODIS because of the semi-automatic measurement procedures; the exception are pugged points if they appear only in one photograph. Experiences permitting a comparison of accuracies achievable from analogue and digital image data could not yet be made in a sufficient extent to include them into the paper. The same applies to the default setting for standard deviations; however, is was noted when using test field photographs with a larger number of known points that the best result appears to be obtained when the default standard deviation for the image co-ordinates is not set too small, e.g. such that the value corresponds to $\sigma_0 \times m_{image}$.

4. CONCLUSIONS

The intent of this investigation has been to show whether the changes in restitution technology on one side and in data acquisition technology on the other side can be expected to lead to major changes in the photogrammetric end result. The investigation was carried out primarily by cascading system component MTFs which were in part extracted from the literature and in part derived based on qualified guesses about scene contrast (assumed to be "medium", i.e. 6.3:1) and uncorrected image motion (assumed to be 7 µm). The result of the investigation was somewhat unexpected and surprising at the same time: it shows that the common contributors scene contrast, lens, uncorrected image motion and human observation (using a 20× magnification and an observation distance of 50 cm) introduce a measure of similarity which led to threshold modulation resolving power values of nearly the same size for four investigated alternatives: (1) measurement of an analogue secondary image, (2) evaluation of a primary image scanned with a 7 µm pixel, (3) evaluation of a primary digital image of 7 µm pixel size (and (4) evaluation of a thermoplast image (to be scanned using a 7 µm pixel size). With the image quality not being able to provide a conclusive answer, a comparison of the radiometric characteristics has been performed next, and it is shown that digital approaches have problems to match the performance of film in regard to density reproduction primarily as a result of producing original digital image data first as transmittance rather than as density. Some additional considerations concerning image storage and handling show that significant advances need to be made to be able to match the convenience and efficiency of storing large amounts of data on film using digital technology. The latter statement in favour of film obtained reinforcement through the fact that a increase in pixel size for acquiring digital data results directly in a significant loss of image quality.

5. REFERENCES

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