IN-FLIGHT PERFORMANCE EVALUATION OF DIGITAL PHOTOGRAMMETRIC SENSORS

E. Honkavaara [a,*], L. Markelin [a], R. Ilves [c], P. Savolainen [b], J. Vilhomaa [c], E. Ahokas [a], J. Jaakkola [a], H. Kaartinen [a]

[a] Finnish Geodetic Institute, Geodeetinrinne 2, FIN-02430 Masala, Finland – (eija.honkavaara@fgi.fi, lauri.markelin@fgi.fi, eero.ahokas@fgi.fi, juha.jaakkola@fgi.fi, harri.kaartinen@fgi,.fi)
[b] FM-Kartta Ltd, P.O. Box 14, FIN-00511 Helsinki, Finland – (pekka.savolainen@fm-kartta.fi)
[c] National Land Survey, P.O. Box 84, FIN-00521 Helsinki, Finland – (risto.ilves@nls.fi, juha.vilhomaa@nls.fi)

Commission I

KEY WORDS: Accuracy, Analog, Camera, Comparison, Digital, Geometric, Photogrammetry, Quality, Spatial

ABSTRACT:

Digital photogrammetric large format cameras revolutionize the photogrammetric processes. To assess the performance of state-of-art digital photogrammetric cameras, the Vexcel UltraCamD was evaluated in a comprehensive test in October 2004. Central features of the test were large number of images, rigorous permanent test-field, image acquisition from several flying heights, repetitive flights from single flying height, and simultaneous acquisition of analog images. Testing was performed in late autumn in ultimately difficult illumination conditions. In this article the test is described and the most central results of the image quality analysis are given. The results indicated that the spatial resolution and geometric accuracy of the acquired UltraCamD images were not as high as of analog images; on the other hand, the radiometric quality of UltraCamD outperformed that of RC20. It is important to notice that the obtained results reflect the quality of the whole imaging system. During the flights there were problems in the camera mount and the navigation system; effects of these have not been further evaluated. Thus results of other systems are needed in order to find out whether these results are related to the UltraCamD in general, to this specific UltraCamD or to the whole process.

1. INTRODUCTION

Digital large format cameras are challenging the conventional analog photogrammetric cameras. It is obvious that the digital sensors will change the photogrammetric processes in many ways. At the moment there are many international works beginning, which aim to comprehensive testing of digital sensors. In-flight calibration of geometry and radiometry are important topics for the future research.

In-flight performance analysis of the sensors is an essential procedure for the users and developers of the sensors as well as for the users of the images. The performance analysis has many components, including the technical performance, easiness of use, reliability and image quality. This article concerns the image quality. The most fundamental image quality components are geometric accuracy, spatial resolution and radiometric quality. Significant question is what is the importance of these image quality components in various applications, like interactive or automatic DEM/DSM generation, cartographic object extraction, change detection etc.

Several photogrammetric digital large format cameras are already in operation, but until now only very limited number of in-flight performance analyses has been reported. The analyses have mostly concerned the geometric quality, which is the fundamental quality component of photogrammetric cameras. Kremer *et al.* (2004) reported the first results of direct georeferencing using UltraCamD and IGI Aerocontrol. Dörstel (2003) has recently reported about the geometric accuracy of DMC. Geometric performance of ADS40 has been reported by Alhamlan *et al.* (2004). Typically the test set-ups have been such that it is impossible to evaluate what would be the performance of analog camera in similar conditions or to compare various digital cameras.

In order to evaluate the performance of UltraCamD, excessive series of test flights were executed in October 2004 in Finland over the comprehensive photogrammetric Sjökulla test-field of Finnish Geodetic Institute (FGI) and some other additional test-fields. The test participants were FGI, FM-Kartta Ltd, Geotec Vermessungsgesellschaft mbH and National Land Survey of Finland (NLS). The aim was to include many aspects of digital camera performance evaluation to the same test. Important part of the test was the use of analog camera as the reference. The test set up was such that the analog camera and UltraCamD provided the same image width in ground.

In this article we will describe the comprehensive digital camera test and give the most central results. Materials and methods used are described in Chapter 2. Results are given in Chapter 3 and discussed in Chapter 4. Markelin *et al.* (2005) give the first results of the radiometric quality evaluation.

2. MATERIALS AND METHODS

2.1 Test-field

The tests were performed mostly in the permanent Sjökulla test-field of FGI, which has been in operation since 1994

---

* Corresponding author

Figure 1. Overview of Sjökulla test site during testflights. The test figures used in this studyare: 1) permanent dense spatial resolution test bar targets, 2) transportable grey scale with 8 steps and 3) transportable Siemens star. Photo by Meixner.

Table 1. Details of test flights in Sjökulla. Number of images is given for the full block and for the images at test site. The possible use of the images: SR: spatial resolution analysis, R: radiometric quality analysis, G: geometric quality analysis. FH=Flying height

Location	Date	Camera	Number of images		GSD (cm)	FH (m)	Scale number	Exposure (s)	Use
			Tot	Test-site					
Sjökulla	11.10	UC, Meixner	32	10	4	450	4444	1/125-1/175	SR, R, G
	14.10	UC, Geotec	64	11	4	450	4444	1/125	SR, R, G
		RC, pan	8	4	4, 2	450	2074	1/500	SR, R
	14.10	UC, Geotec	26	13	8	900	8889	1/125	SR, R, G
		RC, pan	22	9	8, 4	900	4152	1/500	SR, R
	15.10	UC, Geotec	28	16	8	900	8889	1/90	SR, R, G
	15.10	UC, Geotec, man	26	15	8	900	8889	1/90	SR, R, G
		RC, col	34	10	8, 4	900	4152	1/300	SR, R
	15.10	UC, Geotec	5	5	25	2810	27778	1/90	SR, R
		RC, col	4	4	25, 12.5	2810	12975	1/300	SR, R
	15.10	UC, man	5	5	25	2810	27778	1/90	SR, R
		RC, col	4	4	25, 12.5	2810	12975	1/300	SR, R
	15.10	UC, Geotec, man	5	5	50	5630	55556	1/90	SR, R

(Kuittinen *et al.* 1994, Ahokas *et al.* 2000). The test field was established for the use of image producers in yearly in-flight system validation. The Finnish image producers have regularly used it, thus the new results can be compared with the long-term results obtained during the 10 years lifetime of the test-field.

During the test flights the Sjökulla test-field contained the usual permanent targets for geometry, radiometry and spatial resolution analysis as well as several transportable test figures. Overview of the test-field during the flights is shown in Figure 1. For the system performance evaluation the most important test figures were dense permanent test bar figures for spatial resolution analysis (line widths 3 cm to 12 cm; aligned in flight and cross-flight directions; contrasts 1:3 and 1:5; bar width ratio $\sqrt[6]{2}$), transportable Siemens-star for spatial resolution analysis (radius 6.8 m, 5° sectors; maximum sector width 1 m; contrast 1:8-1:10), transportable 8-step grey scale for radiometric quality analysis (reflectances 5%-70%) and

ground control points (GCPs) for geometric quality analysis. The GCP configuration at the large-scale test-field is shown in Figure 2.

2.2 Equipment and flights

The test included two, technically similar, UltraCamD cameras. During another mission, reference images were acquired simultaneously from the same platform by analog RC20 camera. The test flights were performed late autumn (October 11th-15th) mostly at noon; the sun angle was approximately 20°.

The first mission was purchased from Meixner Consulting Engineers. Aperture was 5.6 and exposure times were 1/125-1/175 s. The flying speed was approximately 80 m/s. GPS data was acquired during the mission, but unfortunately its quality was not sufficient for the accurate analysis. During this mission two large-scale blocks were acquired.
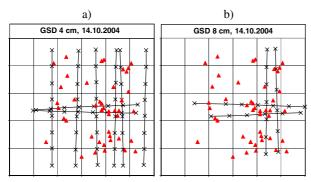
Figure 2. Block structures and GCP configurations at Sjökulla large-scale test-field; 44 GCPs. a) Geotec, GSD 4 cm; comprehensive block and b) Geotec, GSD 8 cm; cross-block (other two blocks with 8 cm GSD had similar structure).

Table 2. Blocks used in the analysis of point determination accuracy.

Block	UC 4 cm	UC 8 cm	RC, 2118	RC, 2122
GSD (cm)	4	8	6.6	8
Optic (mm)	101.4	101.4	214.108	153.030
Flying height (m)	450	900	710	610
Scale	1:4444	1:8889	1:3300	1:4000
Image width (m)	460	920	759	920
Overlaps (p=q)	60%	p: 80%	60%	80%
Images/ strip	8	6-7	5	6

The second mission was performed using hired UltraCamD of GeoTec Vermessungsgesellschaft mbH. The camera was installed in the OH-ACN aircraft of NLS (Rockwell Turbo Commander 690A turbo twin propeller aircraft with a pressurised cabin and two camera holes). The navigation system was IGI CCNS4. The UltraCamD was mounted on GSM3000 gyro stabilised camera mount. System included IGI AEROControl GPS/IMU-system for direct sensor orientation determination. The aperture was 5.6 and the exposure times were 1/32-1/125 s. The gyro stabilised mount did not function correctly, which resulted in some images with serious image motion; these images were excluded from the detailed analysis. To see what was the effect of the problems with the automatic mount, one 8 cm GSD flight was performed with manual mount (man). Accurate GPS/IMU-processing failed also in this second mission. This mission was executed during two days and it included more than 700 images.

Reference analog images were acquired by RC20 camera of NLS during the second mission. Intermediate angle optic (214 mm) was used, which provides approximately the same image width in ground as UltraCamD. In the analog camera panchromatic (Kodak Double-X Aerographic Film 2405, 400 ASA) and colour (Kodak Aerocolor III Negative Film 2444, 300 ASA) films were used. The camera mount was PAV 11A-E (not gyro stabilised); FMC was applied. The films were scanned by Leica Geosystems DSW 600 scanner.

2.3 Imagery

Test blocks were acquired in photogrammetric test-fields in Sjökulla, Espoo and Jämsä, and also in several other areas. Calibration blocks with bi-directional perpendicular flight lines were acquired from several flying heights; examples of blocks flown in the large-scale test-field are shown in Figure 2.

Furthermore, large-scale (GSD 4 cm + 8 cm) and medium-scale (GSD 25 cm + 50 cm) blocks were acquired consecutively so that they can be adjusted simultaneously. Also normal mapping blocks were acquired in urban and agricultural areas. Details of the images in the Sjökulla test-field are shown in Table 1; this data is analysed in this article.

UltraCamD GSDs were 4 cm, 8 cm, 25 cm and 50 cm. The UltraCamD images were processed to high-resolution (pan-sharpened) and low-resolution (no pan sharpening) PAN, CIR and RGB images with 8 bit and 16 bit pixel depths using the OPC software (UltraCamD Office Processing Center V1.3.2). Also raw images were analysed. Total number of UltraCamD images was over 800, and 10 different versions were calculated from most of the images.

A total of 31 RC20 images were obtained over the image quality test-field and each was scanned to 4 different formats (8 bit and 12 bit pixel depths, 10 μm and 20 μm pixel size). Scanning the analog images with 20 μm pixel size provided the same GSD as UltraCamD. The 10 μm pixel size and 12-bit pixel depth shows the highest image content that can be obtained from film images. Two older analog image blocks of NLS from the same test-field and with similar structure as the Geotec 4 cm block (Figure 2a), but with higher flying height, were used as reference in the analysis of the geometric quality (see Table 2).

2.4 Methods

2.4.1 Geometric quality evaluation: Geometric quality of the following blocks was evaluated:
1. UltraCamD, GSD 4 cm, comprehensive block structure (Figure 2a), 14.10
2. Sub-block of block 1: 4 parallel strips
3. RC20 of NLS, 2118. Similar structure as of block 1.
4. Sub-block of block 3: 4 parallel strips
5. RC20 of NLS, 2122. Similar structure as of block 1.
6. Sub-block of block 5: 4 parallel strips
7. UltraCamD, GSD 8 cm, cross shaped block (Figure 2b), 14.10
8. UltraCamD, GSD 8 cm, cross shaped block (Figure 2b), 15.10
9. UltraCamD, GSD 8 cm, cross shaped block (Figure 2b), manual mount, 15.10

All the evaluated UltraCamD blocks were acquired by Geotec camera. Altogether 44 GCPs were available (see Figure 2). Accuracy of the GCPs is approximately 1 cm in X and Y and 2 cm in Z. Details of the blocks are given in Table 1 and Table 2.

The image measurements of UltraCamD blocks were performed by FM-Kartta Ltd. using MATCH-AT-software. The RC20-blocks have been measured by NLS using the SocetSet and Orima. The blocks were analysed at FGI using FGIAT block adjustment software.

Geometric quality evaluation contained the analysis of camera geometric calibration and image deformations, and analysis of accuracy of point determination.
– Geometric calibration. Principal point coordinates and common image deformations parameters (physical image deformations: radial and tangential distortion, affinity and shear, and Ebner's parameters) were determined in the

block adjustment. Calibration was evaluated using the full UltraCamD blocks (1, 7, 8, 9) and full GCPs.

– Point determination accuracy was evaluated using the blocks 1-9. 12 well-distributed targeted points were used as GCPs. Theoretical accuracy (RMS value of standard deviations of point unknowns obtained from the block adjustment) and empirical accuracy (RMSE of differences in 26-29 checkpoints) were evaluated.

2.4.2 Spatial resolution evaluation: Spatial resolution was analysed using an in-house developed RESOL-software (Kuittinen *et al.* 1996, Ahokas *et al.* 2000). The software determines from a bar figure the smallest line that can be detected. The RP-value in lines/mm was obtained by calculating the width of the smallest detected line in the image; the scale number was determined from the test figure. For each flight averages of the RP-values and the smallest detected line widths in ground were used as quality indicators.

3. RESULTS AND DISCUSSION

3.1 Geometric accuracy

Standard deviations of unit weight are shown in Figure 3 (adjustments without additional parameters and with principal point and physical distortion corrections). With the additional parameters the values were 1.3-2 μm.

Typically most of the additional parameters were significant in the UltraCamD blocks, which indicate that images have some deformations. It is unclear if the traditional deformation parameters are optimal for the UltraCam-images. The principal point corrections appeared to be the most significant correction. Principal point correction in x-direction (flying direction) was quite large; it was approximately 70 μm in the 4 cm GSD flight and approximately 50 μm in the 8 cm GSD flights. Corrections of 3 repetitive blocks with 8 cm GSD were similar.

Kraus (1993, p. 284) gives the expected values for the point determination accuracy of targeted points in normal mapping blocks (p=60%, q=30%) with additional parameters. The expected height accuracy is 0.03‰ of the object distance and the expected planimetric accuracy is 3 μm in image.

Accuracy of point determination is shown in Figure 4. Three different accuracy estimates are shown: theoretical accuracy of the point unknowns, empirical accuracy without additional parameters and empirical accuracy with principal point and physical distortion corrections. The block numbering was described in Chapter 2.4.1.

It appeared that performance of UltraCamD was slightly different in different days; within one day the performance appeared to be similar. The additional parameters had larger effect to the height accuracy in the blocks flown in 14.10 (1, 2, 7), and especially in the block with 4 cm GSD. The effect of additional parameters was smaller on the blocks flown in the second day (8, 9). When additional parameters were used, the Z-accuracy was approximately 0.06-0.07‰ of the object distance, which is slightly worse than expected; without additional parameters the corresponding ratio was 0.08-0.15‰. With GSD 4 cm block (1-2) the planimetric accuracy was approximately 1 cm (2 μm in image). Accuracy of X-coordinate
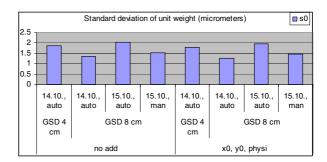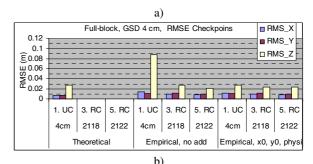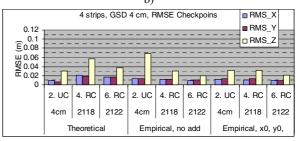

Figure 3. Standard error of unit weight, full blocks.
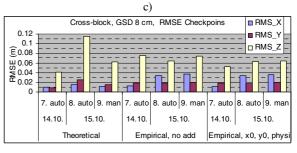

Figure 4. Point determination accuracy. Theoretical accuracy of point unknowns and empirical accuracy are shown. a) Comprehensive blocks (1, 3, 5), b) block with 4 strips (2, 4, 6). c) Cross-shaped blocks with 8 cm GSD (7, 8, 9).

of the second day blocks (8, 9) was worse than of other blocks (ground: approx 3.5 cm, image: approx 4 μm).

The empirical accuracy of two consecutive blocks, one with automatic and other with manual mount, was practically the same. However, the standard error of unit weight with manual mount was clearly smaller (1.5 μm vs. 2 μm).

The RC20 blocks (3-6) gave very accurate results; the planimetric error was approximately 1 cm (2-3 μm in image) and the height error was 2-3 cm (0.03‰-0.04‰ of the object distance). The use of additional parameters did not significantly affect the accuracy of the RC20 blocks. The obtained accuracy is about the same as the accuracy of the checkpoints.

Figure 6. Detail from GSD 8 cm flight (15.10). Left to right: UltraCamD; RC20 with 20 μm pixel size; RC20 with 10 μm pixel size.
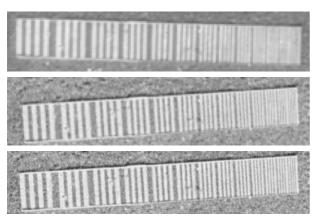

Figure 7. Example of resolution bar targets from simultaneous UltraCamD and RC20 images; GSD 4 cm flight (14.10). From top to bottom: UltraCamD, RC20 with 20 μm pixel size and RC20 with 10 μm pixel size.
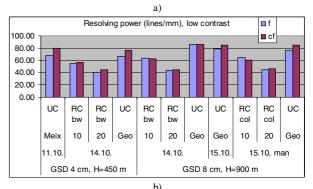
The analog images (blocks 1-6) had equal or better empirical accuracy than UltraCamD images, eventhough their image width was 65-100% larger in ground (Figure 4 a,b). There are several possible reasons for the worse accuracy of UltraCamD. One possible explanation is the problems with camera mount and navigation system. It is also possible that the camera has shaken during transportation. The measurement of the images in different environments can also cause some differrences, but this is not very likely. Finally, it is also possible that the pro-perties of UltraCamD have caused the observed behaviour.

3.2 Spatial resolution

Appearance of UltraCamD and RC20 images was different. UltraCamD images were noiseless, but appeared to be slightly blurred. RC20 images were sharp, but noise was clearly visible, especially in the images scanned with 10 μm pixel size. Examples of images are shown in Figure 6 and Figure 7.

Based on pixel sizes, the maximal RP-values are 111 lines/mm for UltraCamD; for film images the values are 100 lines/mm with 10 μm and 50 lines/mm with 20 μm pixel size.

Resolution was analysed in the flying direction and in the cross-flight direction using the permanent dense bar figures; contrasts were 1:3 and 1:5. Difference between two contrasts was small and also results were very similar, thus only the results with contrast 1:3 are further discussed.
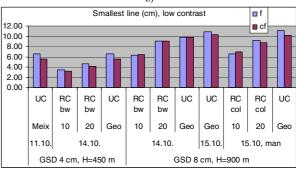

Figure 5. Spatial resolution of 4 cm and 8 cm GSD flights in flying direction (f) and cross-flight direction (cf). a) Average resolving power in lines/mm. b) Average smallest resolvable line in cm. (bw: black/white film, col: color film, man: manual mount, 10: 10 μm pixel size, 20: 20 μm pixel size).

In the analysis of UltraCamD images it appeared that the RP-values were better in the cross-flight direction than in the flight direction (Figure 5a). Furthermore, the 8 cm GSD resul-ted in better RP-values than 4 cm GSD. Results of 3 flights with 8 cm GSD as well as results of 2 different UltraCamDs with 4 cm GSD were very similar. With 4 cm GSD the average RP-values were 67 lines/mm in the flying direction and 78 lines/mm in the cross-flight direction; with 8 cm GSD the cor-responding average RP-values were 80 and 85 lines/mm. Image motion is one possible explanation for the behaviour.

With RC20 the RP-values were better in the higher flying height as well (Figure 5a). Effect of flying direction appeared to be smaller than with UltraCamD, and the resolution was normally better in the flying direction, which is opposite to the

UltraCamD result. RP-value of the 4 cm GSD flight was 54 lines/mm in flying direction and 56 lines/mm in the cross-flight direction (10 μm scanning). In the 8 cm GSD flight the corresponding averages were 64 lines/mm and 61 lines/mm. Scanning with 10 μm pixel size gave significantly better resolution than scanning with 20 μm pixel size. The increasing distance from the image centre decreased the resolution more clearly in the case of 10 μm scan than in the case of 20 μm scan.

Comparison of RP-values of UltraCamD and RC20 does not give a correct picture of the image quality, because the systems have different scales. Due to this the smallest resolvable line in ground was evaluated (Figure 5b). From RC20 images, both with 10 and 20 μm pixels, considerably smaller lines could be detected than from simultaneously acquired UltraCamD images. E.g. in the 4 cm GSD flight, from analog images, scanned with 10 μm pixel size, typically even the smallest lines (3 cm) could be detected. In the simultaneous UltraCamD images the smallest lines were in average 5-6.5 cm.

4. DISCUSSION AND CONCLUSIONS

Digital photogrammetric sensors will revolutionize the photogrammetric processing. In this article results of a comprehensive quality evaluation of UltraCamD images were reported; this is an important part of the process of adoption of the new sensors to the practice. Markelin *et al.* (2005) report the results of the radiometric quality evaluation.

The important features of the testing were the following. Test included a total of 10 flying hours in order to evaluate system reliability and technical performance. Flying over an accurate test-field enabled the accurate and reliable image quality measurement. The use of several flying heights and several consecutive flights enabled the evaluation of the system stability. The results can be linked to the analog cameras, because during the test RC20 analog camera was operated simultaneously. Additionally, the same test-field has been used in the evaluation of analog cameras since 1994. The study proofed the power of the use of a permanent test field in the image quality analysis.

The major problems of the tests were that the accurate GPS and GPS/IMU-processing did not succeed and that during the second mission the gyro stabilised camera mount did not function correctly. Because of these problems the proper evaluation of camera interior orientation and of the use of the cameras in direct georeferencing was not possible. Furthermore, these problems can have caused deterioration of image quality. It is also important to notice that the conditions were ultimately difficult during the flights because the mission was performed late autumn with very low sun angles (22° or less).

In UltraCamD the height accuracy at targeted checkpoints was 0.06-0.07‰ of object distance, which is worse than expected for normal photogrammetric blocks. Planimetric accuracy was mostly in accordance with the expectations (2-4 μm). Additional parameters had significant effect on the results, and it is possible that the used deformation models were not optimal for UltraCamD. The detected large principal point offset in the flying direction (50-70 μm) requires further evaluations.

Results of the comparison of RC20 and UltraCamD were the following. RC20 had clearly better spatial resolution than UltraCamD when the cameras were operated from the same flying height. Film camera appeared to have better geometric accuracy than UltraCamD. Radiometric quality of UltraCam outperforms that of RC20.

This evaluation indicated that in order to obtain the same geometric image quality as RC20, UltraCamD should have significantly smaller image width in ground than conventional photogrammetric cameras. However, one has to bear in mind two facts. First of all, these results indicate the quality of the whole imaging system, thus more results from different systems are needed in order to find out if the results are specific for the evaluated system and process or to the UltraCamD. Secondly, when evaluating the economical and interpretation questions in general, important notices are the fundamental properties of the digital large format cameras, namely the superior radiometric quality and that they provide PAN, R, G, B and VNIR channels simultaneously.

More detailed results of each quality component will be published soon.

REFERENCES

Ahokas E., Kuittinen R., Jaakkola J, 2000. A system to control the spatial quality of analogue and digital aerial images. In: International Archives of Photogrammetry and Remote Sensing, Vol. 33. Pp. 45-52.

Alhamlan, S., Mills, J. P., Walker, A. S., Saks, T., 2004. The Influence of Ground Control Points in the Triangulation of Leica ADS40 Data. International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences. Vol 34, Part B1.

Dörstel, C., 2003. DMC – Practical Experiences and Photogrammetric System Performance. In: Photogrammetric Week ´03.

Kraus, K, 1993. Photogrammetry, Volume 1: Fundamentals and Standard Processes. ISBN 3-427-78684-6.

Kremer, J., Gruber, M., 2004. Operation of UltraCamD Together with CCNS/Aerocontrol – First Experiences and Results. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol 34, part B1.

Kuittinen R., Ahokas E., Högholen A., Laaksonen J, 1994. Test-field for Aerial Photography. The Photogrammetric Journal of Finland. Vol. 14, No 1, pp. 53-62.

Kuittinen R., Ahokas E, 1996. Transportable Test-Bar Targets and Microdensitometer Measurements: A Method to Control the Quality of Aerial Imagery. International Archives of Photogrammetry and Remote Sensing. Vol. 31 Part B1. Pp. 99-104.

Markelin, L., Ahokas, E., Honkavaara, E., Kukko, A., Peltoniemi, J., 2005. Radiometric quality comparison of UltraCamD and analog camera. This proceedings.