On the accuracy potential of large format solid state matrix sensor cameras onboard an aircraft

Hans-Gerd Maas
Delft University of Technology
Faculty of Civil Engineering and Geo Sciences
Thijsseweg 11, 2629JA Delft, The Netherlands

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Abstract:

The continuing progress in the resolution and quality of solid state matrix sensors has made the use of digital cameras onboard an aircraft an interesting option. Although by far not yet comparable to the resolution of scanned 9" x 9" film, direct digital data capture is meanwhile a viable alternative for a number of applications. Direct digital data capture avoids time consuming development and scanning processes and does yield a potential for online or even realtime data processing. While first realizations of digital cameras onboard an aircraft were based on linear array sensors used in a pushbroom principle, area sensors with resolutions of up to 4090x4096 pixels being commercially available today are gaining importance.

This paper presents four practical studies on the helicopter-based use of high resolution digital stillvideo cameras for aerotriangulation and the automatic generation of digital elevation models and orthophotos. Test regions include mountain areas, an alpine village, the bottom of a shallow lake and a landslide area in Switzerland. The current performance and future developments of solid state matrix sensors are shown, and the advantages and disadvantages of the use of digital cameras in aerial applications are discussed.

Using self-calibration bundle adjustment techniques, externally verified accuracies of 2cm for planimetry coordinates and 5cm for height coordinates were obtained in digital aerotriangulation using imagery of 1 : 18'000 scale; using 1 : 64'000 small scale digital imagery over an area of 3.6 x 2.4 km^2, a checkpoint rms of 14cm for planimetry coordinates and 25cm for height coordinates was obtained. In the generation of digital elevation models by multi image feature based matching, a precision of 0.03% of the flying height above ground could be achieved.

1. Introduction

High resolution solid state matrix sensor cameras have found large interest among photogrammetrists in the last few years. However, the limited resolution of such sensors has so far restricted their practical use to applications in digital close range photogrammetry. While the employment of solid state sensor cameras has meanwhile become a standard in scientific and commercial systems for close range applications, aerial images are still predominantly recorded on film and subsequently scanned for the use in digital photogrammetric stations.

Solid state sensor based cameras, which have been developed for aerial applications in the last years, have mainly been based on linear array sensors. Moved over the terrain in a pushbroom principle, these sensors offer a significantly higher resolution as compared to matrix sensors today. The concept of the three-line camera in combination with navigation sensors does furthermore provide a basis for stereo processing and 3-D terrain data acquisition.

Nevertheless, the advantages of stable geometry and compatibility with wide-spread processing tools depict a strong argument for the use of two-dimensional sensors. With the benefits of direct acquisition and processing of digital image data as well as the accuracy potential of solid state sensors, the increasing resolution of solid state matrix sensors has started to make digital cameras with area sensors interesting for a number of applications in aerial photogrammetry. Cameras with 4096x4096 pixels are now commercially available, and prototype sensors with up to 9216x7168 pixels have been developed and produced.

A number of authors have reported test applications of solid state cameras from aerial platforms for different purposes in the past (e.g. Maggio/Baker 1988, King 1992, Mausel et al. 1992, Novak 1992, Thom/Jurvillier 1993, King et al. 1994, Fraser/Shortis 1995, Abdullah 1996, Mills et al. 1996, Maas/Kersten 1997). To evaluate the potential and problems of the use of high resolution solid state cameras onboard an aircraft in practical applications, several pilot studies with different aims were conducted.

These pilot studies include:

- Two projects on aerial triangulation with signalized targets and natural points, based on blocks of 5x10 and 5x7 images acquired with a 1524x1012 pixel digital stillvideo camera Kodak DCS200 over an alpine village and a landslide area in Switzerland.
- Two projects on the generation of digital terrain models and digital orthophotos based on imagery of a digital stillvideo camera Kodak DCS200.
- The generation of a digital elevation model and a multimedia digital orthophoto of the ground of a lake, based on 24 images of a 3060x2036 pixel digital stillvideo camera Kodak DCS460.
- A high-altitude flight over an alpine region using a Kodak DCS460.

2. High resolution CCD cameras

Since the appearance of the first solid state cameras with very limited resolution in the late 1970s, there has been a slow but steady growth in the resolution of sensors, with 4096x4096 pixel cameras being commercially available today. Major limitations to much higher resolutions are placed by both technical and economic constraints: It is estimated that the production cost of CCD sensors grows with the 5th power of the area of the sensor (Theuwissen, 1996); on the other hand, the pixelsize cannot be arbitrarily reduced due to the light sensitivity characteristics of silicon. Moreover, the mass market is currently only interested in CCIR or NTSC videonorm image sensors with resolutions of approximately 760x570/480 pixels. Nevertheless, there is a growing interest in high resolution solid state sensors for applications in industrial measurement, science, medicine, graphics and several other fields. The following list shall give a brief overview on the current status of high resolution CCD cameras in 1997:

- The probably widest spread high resolution camera in photogrammetry is the Kodak DCS460 stillvideo camera with a $28x18mm^2$ sensor with 3060x2036 pixels and its predecessors DCS200/420 with a $14x9mm^2$ sensor with 1524x1012 pixels.
- Cameras with 2048x2048 pixel resolution are available from a number of manufacturers (Dalsa, EG&G, Kodak, Leaf, Leica/GSI, Loral Fairchild, Photometrics, Rollei, Thomson, a.o.).
- A prototype of a 4096x4096 pixel sensor with 7.5µm pixel size, 6'000 e^- pixel capacity and a read-out time of 18 seconds has been presented by Loral Fairchild in 1993. (Thom/Jurvillier, 1993) report a number of problems in the application of the sensor onboard an airplane. Recently, two new 4096x4096 pixel cameras with more promising specifications have come onto the market (Kodak Megaplus 16.8, Rollei Q16 with Dicomed sensor), but have not been tested in practical aerial applications yet.
- A 5120x5120 sensor was presented by Dalsa in 1993 (Janesick, 1993), but has obviously never been commercially available.
- A 9216x7168 pixel sensor, produced by modular stitching technology, has been developed by Philips, but cannot be considered ready for practical use yet (Theuwissen, 1996). A 7168x4096 pixel sensor from Philips seems to be available soon.

For the pilot studies described in this report, a Kodak DCS200 and a Kodak DCS460 were used; both were operated hand-held from a helicopter (Figure 1).

Figure 1: Hand-held use of a stillvideo camera in a helicopter

A disadvantage of the cameras, besides the limited resolution, is the relatively slow data transfer (8 seconds per image with the DCS460), requiring relatively slow aircraft velocities. For this reason, and also due to the limited storage capacity and the rigidness of the camera body (Maas/Niederöst, 1997), a stillvideo camera onboard an aircraft can certainly only be considered a compromise. For professional use, machine vision type CCD cameras with rigid bodies and datarates of up to 30MB/sec, integrated with GPS/INS and connected to an onboard host computer with realtime image display and fast disk arrays, would be more appropriate.

A general advantage of solid state camera imagery over scanned film is the accuracy potential of the sensors. In close range applications with signalized targets, well-defined edges or good texture on flat surfaces, precisions in the order of $^1/_{50}$ of a pixel (~ 0.2µm) in image space can be regularly achieved, translating into relative accuracies beyond 1 : 100'000 in object space if the camera is properly calibrated. Moreover, the radiometric performance of CCD sensors is usually also significantly better as compared to scanned film.

3. Pilot studies

In the following, four pilot studies on the potential of stillvideo cameras onboard an aircraft are presented. These studies concentrate on the accuracy potential in aerotriangulation and the generation of digital terrain models. The datasets were triangulated using both signalized control points and natural tie points. Automatic point transfer techniques for aerotriangulation were not used due to the irregular flight pattern of the helicopter, the lack of helicopter navigation data and the deviations of the optical axis of the hand-held camera from the vertical. Instead, an interactive scheme based on manual point identification and automatic subpixel accuracy measurement by least-squares matching was chosen. As both cameras used in the studies were uncalibrated non-metric cameras, self-calibrating bundle adjustment techniques were applied.

Based on the orientation and camera parameters of the aerotriangulation, digital surface models were automatically determined from the datasets, using multi-image feature based matching techniques (Maas, 1996) or multi-image least-squares matching. Based on the digital elevation models and the digital images, orthophotos were produced.

3.1. Urmein

The pilot study 'Urmein' (Kersten, 1996) was conducted in 1995 over an alpine village covering an area of approximately 500x500m^2 with 130m height difference. The aim of the study was the determination of coordinates of signalized points (e.g. for cadastrial photogrammetry) and the derivation of an orthophoto. A total of 50 images was captured with a Kodak DCS200 equipped with an 18mm lens. The flying height above ground was 350m, corresponding to an average image scale of 1 : 18'000. The average image overlap was 70% both along and across stripes, with relatively large deviations dur to navigation and handling problems. Reference coordinates of 36 signalized points, which served as control and check points, were determined with GPS.

Figure 2: Overview image of Urmein

3.2. Talegnas

In the study 'Talegnas' a block of 5 x 7 images was acquired with a Kodak DCS200 over a land slide area, where distressing cravasses had occurred in recent time. The aim of the study was the examination of the suitability of digital photogrammetry for 3-D deformation measurements in land slide areas using signalized or natural points. In addition, a digital terrain model had to be determined.

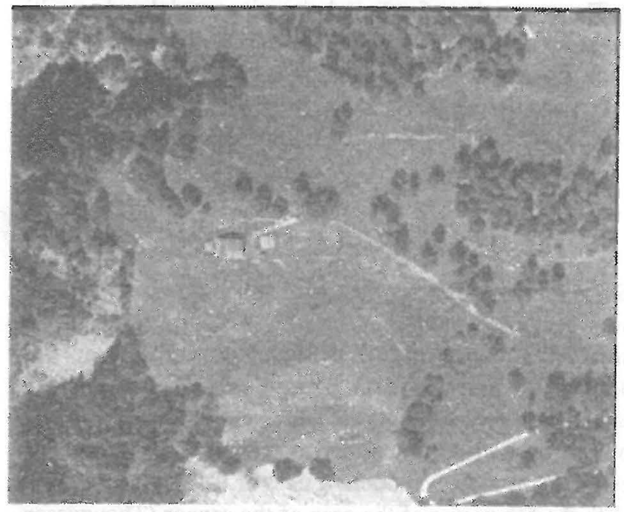

Figure 3: Talegnas land slide - overview image

A total of 60 points in an area of 400x300m^2 were signalized with 60cm white plastic disks. Reference coordinates of the signalized points were determined with GPS. The flying height above ground was 300m, corresponding to an average image scale of 1 : 16'000.

3.3. Lenzerheide

Aim of the study 'Lenzerheide' (Maas, 1997) was the determination of a digital terrain model and an orthophoto of the ground of a shallow lake as a basis for sedimentation monitoring. With the lake being only a few meters deep and clear water, visibility to the ground was guaranteed for large portions of the lake at certain daytimes, and helicopter based photogrammetry was found to be an interesting alternative to conventional geodetic techniques or sonic depth finders.

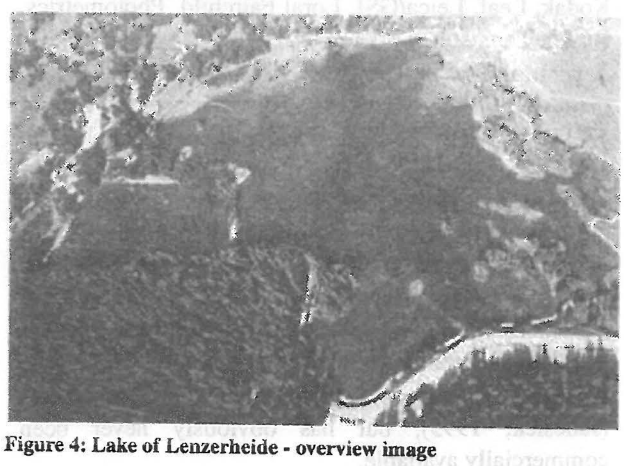

Figure 4: Lake of Lenzerheide - overview image

The lake has an extension of approximately $1000x700m^2$ and was imaged with a Kodak DCS460 in two slightly convergent stripes of 12 images each. The flying height above ground was 400m, the average image scale was 1 : 22'000 with a 18mm lens.

As a consequence of the relatively poor texture on the ground, the application of feature based matching techniques using discrete points extracted by an interest operator failed due to the low probability of the interest operator detecting corresponding points in multiple images. Instead, least squares template matching with relative large patches (21 x 21 pixel) was applied and lead to satisfactory results in about 75% of the area. Gaps caused by insufficient contrast or shades were filled by land based tacheometer measurements to a 10m rod manoeuvered from a boat. The intersection of multiple twice broken beams for 3-D coordinate determination was handled by a multimedia module (Maas, 1995), assuming the lake surface to be flat. To warrant sufficient flatness of the surface and good ground visibility, a calm morning was chosen for the flight. The shoreline was rather undefined due to reed coverage and had to be extracted interactively.

3.4. Oberalp

To show the potential of the application of solid sensor based cameras for small scale imaging, a larger pilot study was conducted on Oberalp pass in Switzerland. In this study, a mountainous area of $3.6 x 2.4km^2$ was imaged using a Kodak DCS460 with an 18mm lens. The block consisted of 4 x 8 images with 80%/60% overlap. The average flying height above terrain was 1200m, corresponding to an image scale of 1 : 64'000 and a ground pixel of $0.6 x 0.6m^2$, with large deviations due to terrain height differences of more than 1000m in the block.

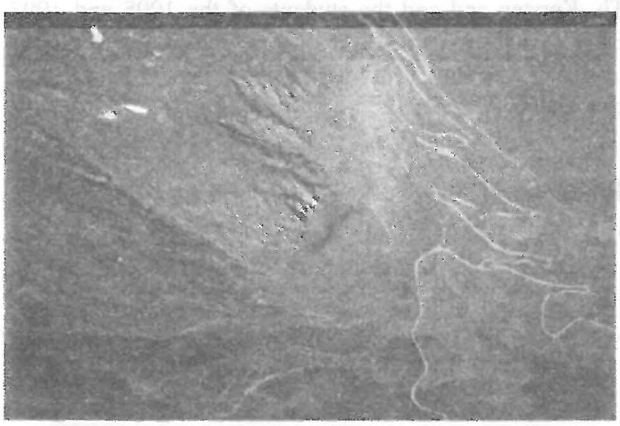

Figure 5: Image from the block 'Oberalp'

38 points were signalized, some of them to be used as control points and most as check points. $1 x 1m^2$ white plastic plates were used for signalizing; sampling, defocusing and diffraction limitation make these targets appear with a diameter of 3 pixels in image space, allowing for the use of subpixel accuracy image measurement operators. To limit the size of the targets, no extra black background material was used; most plates were placed on grass or gravel, thus reducing the accuracy potential of least squares template matching due to background inhomogeneities. The signalization problem has to be considered one of the major problems of the application of solid state sensor cameras onboard an aircraft: Subpixel accuracy can only be achieved by 'superpixel' targets, thus requiring rather large signals. This makes the integration of cameras and GPS with the aim of reducing control point requirements even more important. Reference coordinates of these signalized points and were determined by GPS.

4. Results

The results of the aerotriangulation of the four studies are summarized in Table 1. The results of the studies 'Urmein' and 'Talegnas' are analyzed in more detail in (Maas/Kersten, 1997). Considering the suboptimalities of signalizing, an externally verified accuracy of 2cm for the planimetry coordinates (the height is not relevant for cadastrial applications) can certainly be considered satisfactory. The project 'Lenzerheide' suffered from badly signalized control points, which had to be measured manually; however, the accuracy of the triangulation is sufficient for the determination of the digital depth model of the lake. The results of the aerotriangulation with DCS460 imagery in the project 'Oberalp', related to the smaller image scale, are slightly worse than the results obtained in the studies with the DCS200. This may be attributed to smaller targets, the mechanical instability of the stillvideo camera body (Maas/Niederöst, 1997) and possibly also to the unmodeled topography of the Kodak KAF6300 CCD sensor. The latter two issues become more evident with the wide opening angle resulting from an 18mm lens on a $28x18mm^2$ sensor. (Maas/Niederöst, 1997) suggested to parametrize the bundle with partly independent interior orientation parameter sets to cover the problem of a varying principle point caused by the mechanical instability of the camera body; the network geometry in this project, however, proved to be to weak for such a parametrization.

The results of the DTM generation by multi image feature based matching are summarized in Table 2. The application of multi image feature based matching for DTM generation in the studies 'Urmein' and 'Talegnas' is described in more detail in (Maas, 1996). On average, a DTM point precision in the order of 9cm or 0.3‰ of the flying height above ground was achieved. At this precision level and scale, the definition of the earth's surface and ground coverage depict a limiting factor. If put in relation to the small sensor format of the cameras, the precision is better than the results which are usually achieved from scanned film. Considering the large patch size, the 14cm height precision in the project 'Lenzerheide' can also be considered satisfactory. In the project 'Oberalp', an internal DTM point precision in the order of 40cm or 0.3‰ of the flying height above ground was achieved. 76 check points in the DTM yielded an rms deviation of 42cm. Here, the deteriorating effects as mentioned above are compensated by the reduced effect of terrain coverage in small scale imagery.

Project	area [km^2]	camera	images	av. scale	co	ch	ray	$\hat{\sigma}_0$ [μm]	theoretical precision [mm]			checkpoint RMS [mm]		
									$\hat{\sigma}_X$	$\hat{\sigma}_Y$	$\hat{\sigma}_Z$	μ_X	μ_Y	μ_Z
Urmein	0.5x0.5	DCS200	50	18'000	5	31	4.9	0.7	16	17	64	23	18	47
Talegnas	0.4x0.3	DCS200	5x7	16'000	5	61	6.9	0.8	14	13	50	18	28	64
Lenzerheide	1.0x0.7	DCS460	2x12	22'000	10	-	3.1	1.5	150	65	142	-	-	-
Oberalp	3.6x2.4	DCS460	4x8	64'000	9	29	6.5	1.3	74	65	182	159	142	261

Table 1: Aerotriangulation results in pilot studies

Project	$\hat{\sigma}_H$ [cm]	‰ of flying height	μ_H [cm]
Urmein	9.1	0.26	n.a
Talegnas	9.5	0.32	n.a.
Lenzerheide	14.0	0.35	n.a.
Oberalp	39.4	0.33	42.0

Table 2: DTM results in pilot studies

co: number of control points
ch: number of check points
ray: average number of rays per point
theoretical precision: results from covariance matrix
checkpoint RMS: RMS of checkpoint coordinate differences

5. Conclusion

The results of these pilot studies prove the high accuracy potential of digital images acquired directly by a solid state matrix sensor without intermediate storage on film. An accuracy potential in the order of 1/10 pixel (1 micron) in image space could be achieved. This is significantly worse than the accuracy figures as usually achieved with well signalized points in digital close range photogrammetry, but better than the results as achieved using scanned film - disregarding the much smaller image format of solid state imagers. Using 1500x1000 pixel imagery of 1 : 18'000 scale, large image overlaps and self-calibration techniques, externally verified accuracies of 2cm for planimetry coordinates and 5-6cm for height coordinates were obtained in digital aerotriangulation, and a precision of 0.3‰ of the flying height above ground was achieved for digital elevation models. In a 4 x 8 image block using 3000x2000 pixel 1 : 64'000 small scale imagery with 80%/60% overlap, externally verified accuracies of 14cm for planimetry coordinates and 25cm for height coordinates were obtained.

Image acquisition with large format aerial cameras and subsequent scanning will remain the standard procedure in aerial photogrammetry for a long time. However, although economic high resolution stillvideo cameras do still show some stability and calibration problems, they may be used for certain tasks already today. With the progressing development of solid state sensor technology, the integration of a high resolution CCD sensor into a metric aerial camera with realtime disk arrays, extended flight management systems and onboard GPS is becoming interesting for an increasing range of applications in aerial photogrammetry.

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