DMC PRACTICAL EXPERIENCE AND ACCURACY ASSESSMENT

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ABSTRACT:

Accuracy of digital image data is expected to be better or at least the same as for analogue images. Since Z/I introduced its Digital Mapping Camera (DMC) into the market in early 2003, multiple projects have successfully been flown by different customers. The processing steps from data post processing to the final product generation are described. Investigations revealed a geometric accuracy which was at least similar and sometimes better than that usually achieved with analogue cameras under similar conditions. This result has been achieved despite the smaller base-to-height ratio of the DMC and is explained by the higher image coordinate accuracy resulting from a better radiometric quality of the digital image, and in particular by a better system geometry (flatness of the image plane, no film shrinkage, etc.) Taken user comments into account, the photogrammetric workflow using DMC imagery is discussed, and some experience with generating DTM and creating orthophotos is reported.

1. INTRODUCTION

Aerial cameras have been successfully used around the world for many decades. During the past two decades, the mapping sciences have progressively moved toward digital mapping, making use of multidisciplinary developments in the field of geomatics. The new Digital Mapping Camera (DMC), manufactured by Z/I Imaging Corporation, represents one of the latest developmental steps in this long history. The DMC adds digital capabilities to existing image capture technology. Because today's airborne camera systems are complex, the new DMC is more than simply the exchange of film for silicon. For this reason, several issues, such as data transfer rates, image postprocessing, colour fusion, calibration, image archiving, and image data management, have to be addressed.

The DMC is based on Charge Coupled Device (CCD) frame (matrix) sensor technology, which provides a very high interior geometric stability. The camera is designed to perform under various light conditions within a wide range of exposure times. Features such as electronic Forward Motion Compensation (FMC) and 12-bit-per-pixel radiometric resolution for each of the panchromatic and colour channel camera sensors provide the capabilities for operating even under less than favourable flight conditions. The DMC can produce small-scale or large-scale images with ground resolutions of fewer than five centimetres. The results are images with greatly improved radiometric resolution and increased accuracy of photogrammetric measurements (Dörstel 2003).

A further benefit of using the integrated DMC technology (hardware, firmware, and processing software) as an aerial photogrammetric solution is the completely digital workflow, which eliminates the process of scanning and film processing. This saves a considerable amount of time. In addition, postprocessing of the digital imagery is very fast; a typical flight project can be processed in a few hours.

The high radiometric sensitivity of the CCD array, together with the pixel size of 12µm and the forward motion compensation by electronic time-delayed integration (TDI), increases the amount of time allowed for running flight missions.

The DMC system is composed of multiple components and is divided into two parts: airborne and ground-based. The DMC system components are illustrated in Figure 1. ImageStation Mission Planning (ISMP) is the part of the DMC system that provides tools to quickly create and optimize a flight plan to be navigated with T-Nav, ASMS, or supported third-party photo flight control systems. ISMP can also use the mission planning data and the flight data to create or update a Z/I photogrammetric data management environment, generate reports, and create photo indexes in a so-called ISPM project.

The Airborne Sensor Management System (ASMS) consists of hardware (the ASMS Real-Time Controller (RTC)) and the software used to interact with the ASMS RTC. ASMS is the part of the DMC system that provides the navigation, camera triggering, and exposure position recording of the photo flights planned in ISMP.

As mentioned before, the DMC uses frame-based CCDs. This approach offers the best geometric accuracy for photogrammetric applications as determined by the two dimensional matrix of the CCD pixels structured on the silicon wafer. Besides this very stable image geometry, the DMC offers an outstanding ground resolution, even for large-scale imagery, because of the embedded Forward Motion Compensation (FMC). The electronics of the CCD matrix sensors, which are used in the DMC camera heads, can be operated in TDI mode. This allows a fully electronic FMC of the digital image that compensates for image blur (Hinz, 1999).

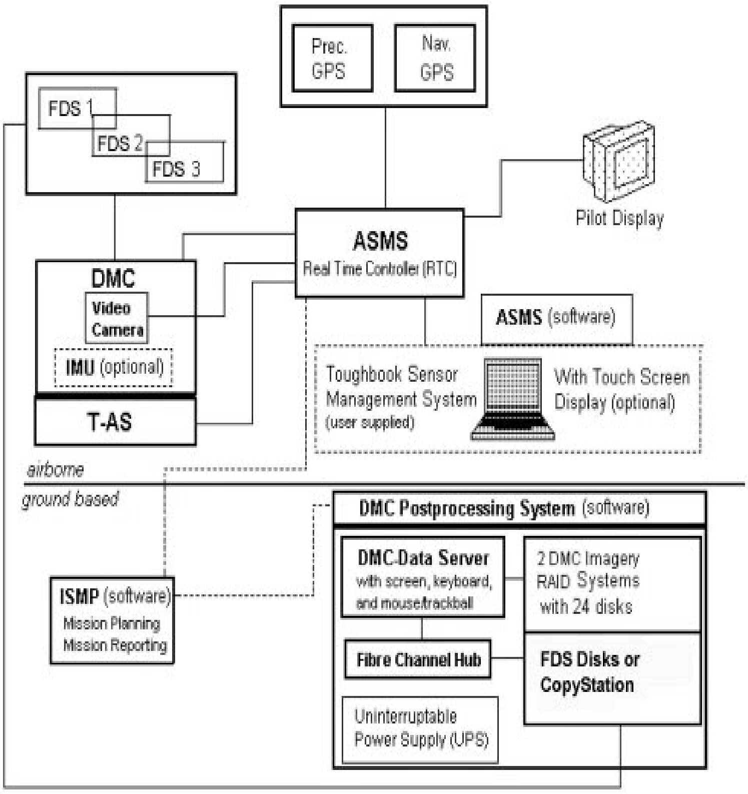

Figure 1. DMC system components

Ideally, one individual large-area CCD chip similar to the information contents of existing film formats would be the perfect geometric solution for an aerial image acquisition system. However, since the size of commercially available imaging sensors is limited, it is not possible to choose the ideal solution for the focal plane of an airborne digital camera to fulfil the normal photogrammetric requirements. The DMC, therefore, overcomes this limitation by parallel operation of several compact camera heads directed at the scene under slightly oblique field angles (Heier, et al, 2002).

The DMC consists of eight sensors: four panchromatic sensors and four multispectral sensors. The multispectral sensors are 3k x 2k in size, with one sensor capturing red data, one capturing blue data, one capturing green data, and one capturing near-infrared data. The four panchromatic sensors (Figure 2) each capture one image of a particular area (7k x 4k), which partly overlap one another. The four images are captured from slightly different positions and synchronous in time to about 0.01 msec. They are subsequently used to produce one large image composite, 7680 x 13824 in size as shown in Figure 2. Figure 3 shows the DMC installed on a Z/I gyro stabilized mount. From the image data captured by the DMC, one can produce a variety of output types using the postprocessing software.

The image data that the camera captures is stored on the three Flight Data Storage (FDS) units, which are connected to the camera during the flight. The total FDS disk space is large enough to hold data that will produce 2200 final output images. The FDS system has three individual, removable storage modules that are transferred to the ground-based postprocessing station. Table 1 shows the complete workflow including flight project planning and image data capturing.

The DMC postprocessing software is used for producing output images from the raw image data that is stored on the FDS connected to the DMC during the photo flight mission. The postprocessing software can produce several different types of output files from the set of raw images stored on the FDS. Full-resolution panchromatic image files are produced from images taken by the camera's four panchromatic sensors. Also, colour and colour-infrared output images can be produced using the full-resolution panchromatic imagery combined with the data from the multispectral sensors. This allows the possibility of producing four types of full resolution images (7680 x 13824): panchromatic, colour, near-infrared, and 4-band. Files matching the resolution of the colour and near-infrared (multispectral) sensors can also be produced (2048 x 3072). These images can be produced as colour, colour-infrared, 4-band, and near-infrared. A colour file is defined as a file consisting of only the red, green, and blue colour bands. Colour-infrared is defined as a file consisting of near-infrared, red, and green bands. 4-band files contain all bands, in the order red, green, blue, and near-infrared.

Postprocessing is completed in two steps: radiometric processing and then geometric processing.

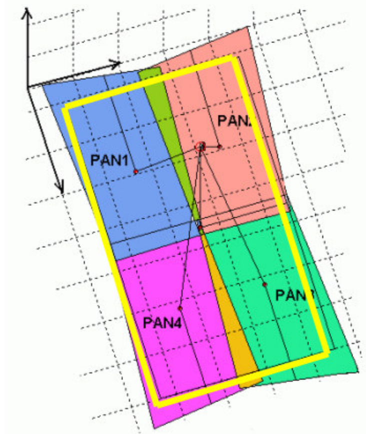

Figure 2. Footprint of 4 pan images projected into the virtual image (yellow area)

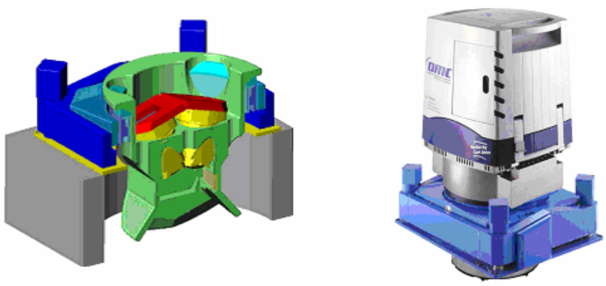

Figure 3. Left: Lens cone with panchromatic camera head
Right: DMC with gyro stabilized mount

Radiometric processing compensates for the effects of temperature, aperture, and other radiometric factors (Diener et al. 2000; Heier 2001). The intermediate images, generated from radiometric processing, are written to the intermediate RAID storage on the postprocessing server. The intermediate images are then geometrically corrected for lens distortion based on a calibration of the individual camera heads and are subsequently combined to form the image composite (see Dörstel et al. 2003 and below for details). The final output images are written to the output RAID storage designated for the final images on the postprocessing server. The final output image data can then be transferred to a data management and distribution system, such as Z/I's TerraShare, where it can be archived or distributed to the destination defined by the operator.

Processing Site	Processing Step	Details In Step
Office	Preprocess-ing	Mission planning
Airplane	Photo Flight	Navigation and flight manage-ment system Camera software control module Quickview (inflight quality check) Data storage
Office	Postprocess-ing	Connection of flight data Storage (FDS) or Copy Station disks Postprocessing • Radiometric correction • Geometric correction • Mosaicking (generation of virtual images) Color image generation Data distribution
Office	Data Exploitation	Data processing via photogrammetric and/or GIS tools

Table 1. Typical DMC Workflow

2. IMAGE COMPOSITE GENERATION

The aim of generating image composites from the different raw panchromatic and multispectral images is to generate a central perspective image in such a way that, in subsequent processing steps, standard photogrammetric procedures and software can be used.

First of all, each of the four camera heads needs a precise geometric calibration. This step is also known as 'single-head-camera geometric calibration' and applied at manufacturing site. The information generated during this procedure is delivered on a calibration CD to the customer together with the complete DMC System. During system installation the calibration data is stored at the postprocessing workstation. When the aircraft lands, the mission data is transferred to the postprocessing workstation.

Within one exposure, the raw images are captured from slightly different positions (Figure 4, upper part). Relative to the tilted panchromatic images, the image composite is placed in an average position and can be thought of as a perfectly nadir-looking image. In Figure 4 the relation between two individual camera heads is depicted. In order to generate the image composite, the geometric relations between the four individual images and the image composite must be given. Assuming known values for this relative orientation, e.g. from a prior calibration, the individual images are merged together and projected to a horizontal reference plane (see Figure 4) to form one perspective image (see Tang et al. 2000 for the related equations). In this step, the focal length of the image composite can be chosen freely. In order to avoid under- or over-sampling, a value close to the actual focal length of the individual camera heads should be used. Also, lens distortions of the individual camera heads can be respected in this step. It should be noted, however, that the image positions need to be corrected prior to the merge.

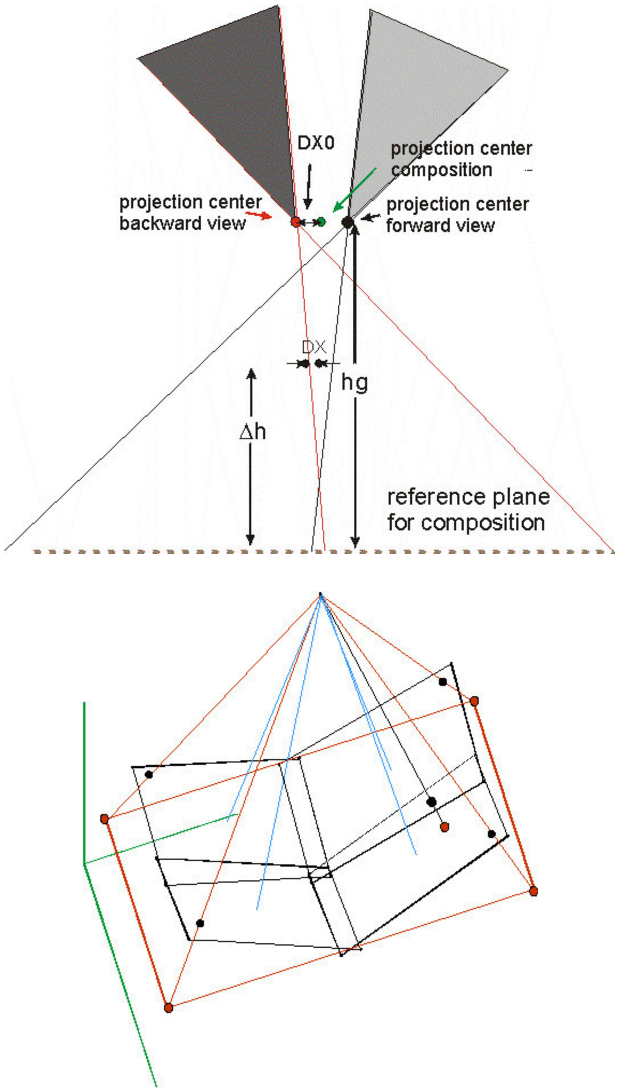

Figure 4. Principle of the combination of convergent sub-images to an image composite

Above: cross-section Below: 3-D situation

3. ERROR ANALYSIS OF IMAGE COMPOSITE GENERATION

In terms of geometric accuracy of the image composite, there are three issues which need to be discussed: (a) all raw images must be acquired synchronously in time, (b) the systematic effect resulting from the different perspective centres must be negligible, and (c) the relative orientation of the camera heads must be stable.

The first requirement can be met by releasing the shutters of the individual DMC camera heads with a precision of less than 0.01 msec. This ensures that we can assume all eight images of one exposure instant to be taken synchronously and from the same location. Thus, we do not need to model the influences of different TDI shifts or to model the projection centre coordinates as a function of time.

Due to the slightly different location of the projection centres of the individual camera heads, the generation of the central perspective image composites involves a systematic displacement of all pixels. In theory, this step requires the exact knowledge of the height of each point on the ground. Since such information is not generally available, the horizontal reference plane is used as an approximation instead. Thus, there is a residual relief displacement effect for all areas which do not exactly lie in this plane. The size of the relief displacement depends on the height variation in object space relative to the flying height above the ground. To this end, an investigation (Tang et al. 2000) was carried out which showed that the resulting error in the central perspective image composite could be neglected, even for very high accuracy requirements if the height variation is not extreme. The results of this investigation are shown in Figure 5.

As a mechanical part inside an aircraft can never be constructed to be absolutely stable over short and long time periods, the camera mount for the DMC was designed to allow for angular deformations. This leads to a further assumption for our platform calibration model. Based on tie points determined automatically in the overlapping areas, we use a separate bundle adjustment for each imaging instant to compute the parameters of relative orientation between the individual camera heads. Since we only assume angular movements based on the mechanical design, we overcome the problem of high correlation between the unknowns to be estimated by solving only for the angular parameters.

A typical accuracy for the tie point coordinates after the bundle adjustment is in the order of 1 or 2 µm, corresponding to 1/6 to 1/12 of a pixel having a size of 12µm. Our experience has shown that automatically determining tie points in this case does not pose a problem. Because of synchronous imaging, moving objects like cars and waves can also be used as tie points. As an example, the residuals of an arbitrary computation are shown in Figure 6. It should be noted that, in order to reliably compute the orientation parameters, a much coarser distribution of about 30 to 50 points is also enough.

It is an interesting question how stable the camera configuration actually is, and thus an internal bundle adjustment often needs to be carried out to ensure an accurate generation of the image composites. We have investigated several DMC flights and have found only very small and random variations in the parameter values. Nevertheless, to be on the safe side, we currently recommend checking the stability of the camera head configuration at every exposure, since matching and parameter computation is very fast and thus negligible in terms of the overall computing time.

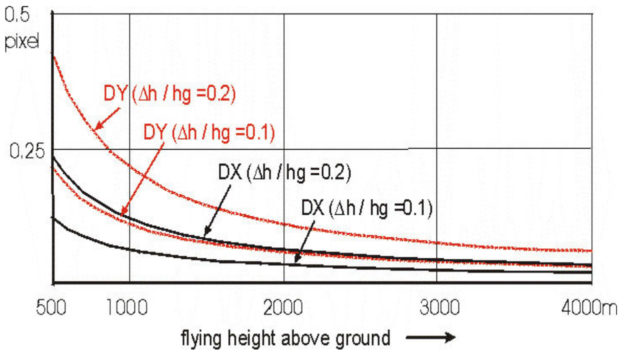

Figure 5. Influence of the projection centre offset on the image composite as a function of the height differences (Δh) in the imaged area to the flying height above ground (hg)

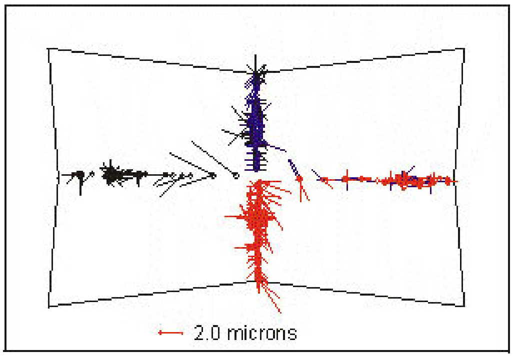

Figure 6. Example of the residuals of the internal bundle orientation, σ_0 = 0.82µm based on 999 observations

4. DMC IN PRACTCAL APPLICATIONS – RESULTS AND REACTIONS FROM USERS

Because the DMC has been on the market for a number of years, there have been various reports about the accuracy of a DMC test flight and about the practical use of the DMC and its advantages over film images. As far as accuracy is concerned, we only give one example here and refer the interested reader to other publications for in-depth studies (Dörstel 2003).

4.1 Short discussion of DMC accuracy potential

The one example we mention here deals with imagery taken over Z/I Imaging's test field in Elchingen, Germany at a scale of approximately 1:13.000 and a flying height of 1500 m above ground. Thus, the pixel size of 12µm corresponds to about 0.13 m on the ground. Three overlapping strips were flown in an east-west direction, and another three in a north-south direction, providing a very stable block of about 20 images with 60% end and 60% side overlap.

Tie-point coordinates were determined automatically using ISAT (Madani, et al, 2001) image coordinates of some GCPs, and a number of check points were measured manually. In the subsequent bundle adjustment, object coordinates for the check points were computed. The resulting standard deviation σ_0 of the image coordinates amounted to 1.7 µm or 0.14 pixels. A comparison with known values yielded an empirical standard deviation of 0.036 m in planimetry and 0.06 m in height.

In comparison, film cameras regularly deliver a σ_0 of approximately 5 µm. At the given scale of 1:13.000, this amounts to a check-point accuracy of approximately 0.065 m in planimetry and (for a wide-angle camera) to 0.10 m in height. Thus, although the DMC has a smaller base-to-height ratio than a standard photogrammetric wide-angle camera and thus the ray intersection in object space is less favourable, the resulting accuracy potential in object space is still superior due to better measurement accuracy in image space and a better system geometry (flatness of the image plane, no film shrinkage etc.). It should be noted, however, that the reported results have been achieved based on imagery flown for a dedicated accuracy test, thus the actual values may be somewhat larger in production work.

4.2 User comments

In user tests and in actual production work, a large number of DMC blocks were captured (see Table 2 for details). Flights occurred at various flying scales and over different terrain types and the project sizes varied considerably. Some of the blocks were flown with GPS and IMU. Different products were generated from these DMC blocks. In a highway corridor-planning project, images with a ground resolution of a few centimetres were acquired, and an orthophoto with a resolution of less than 0.1 m was computed (Table 2, A).

In the following we report some results, obtained by various Z/I Imaging software products, from these blocks and also comments from users which they made while capturing and processing these data:

"We consistently observed a standard deviation of the automatically generated image coordinates of 2 to 3 µm. Together with the very stable system geometry, these results are responsible for the fact that the DMC meets *very high accuracy demands* and seems to be able to support contour mapping down to a 0.3 m (1 ft.) contour interval at NMAS 1947 standards and maybe even to ASPRS Class I."

"The DMC *image quality is excellent*, there is no graininess or fuzziness as is so problematic with scanned film, there are no scratches or other artefacts that occur on film, and the spatial resolution is nearly as good as modern film cameras show in[1] their system resolution calibrations at the USGS lab. In comparison with scanned film in softcopy, the DMC imagery is clearly superior, because it eliminates that extra scanning process."

"In comparison with a film camera operation without in-house film development and film scanning capability, the DMC gives *much faster turnaround*, even though it does require a fair amount of time for imagery postprocessing."

"The DMC's FMC capability gives it *more latitude in terms of lighting conditions* (cirrus overcast, poor contrast surfaces, poor reflecting surfaces, and time of year and day [but only if shadow length specs are relaxed]). It provides a better S/N ratio by allowing more dwell time (longer exposure) on each pixel, or alternatively, faster speeds along the flight line."

For orthophoto production the smaller base-to-height-ratio of about 0.3 (vs. 0.6 for a wide angle film camera) means that its imagery frames have an overall average closer-to-vertical viewing angle. This means more consistent radiometric response along strips and between strips. This helps to make up for its smaller footprint requiring more images per km^2 for a given pixel size in comparison with a conventional film camera. This also means less relief displacement: less lean is visible on features such as buildings and trees, and a less accurate DTM can be used to still satisfy ortho XY-accuracy specs.

Unfortunately, the lower base-to-height-ratio may be a liability issue in the arena of 3-D contour mapping because it reduces the exaggerated relief effect that helps a stereo compiler to capture more subtle changes in ground elevation when compiling a DTM for contour generation. Whether this will have a significant effect on DTM accuracy is not yet known, but it is something that should be investigated. For now, we should

Project Name	**A**	**B**	**C**	**D**	**E**	**F**
Project size (km^2)	7.5	180	1150	2300	4100	1020
Terrain Type	Flat Urban	Flat Urban Forest	Flat Urban Mountain Rural	Hilly Urban	Flat Forest	Hilly Urban
Scale	1:3,800	1:10,200	1:11,450	1:21,600	1:43,250	1:21,600
Pixel size, aerial image (m)	0.05	0.12	0.14	0.25	0.5	0.25
AT σ_0 (µm)	2.3	2.3	2.5	2.1	NA	2.5
Geo-Ref. Strategy	AT+ Control	AT+ GPS	AT+ GPS	AT+ GPS	GPS + IMU	AT+ GPS
RMS XY	NMAS 1947[1]	NMAS 1947	NMAS 1947	3 m.	4m CE90[2]	NMAS 1947
RMS Z	NMAS 1947	NA	NA	NA	NA	NA
3-D Feature	Planimetry 0.3m contour line	No	No	No	No	Building
DTM	Manual	USGS DEM	Automatic	Automatic	USGS DEM	NA
Delivery Product	Pan Ortho + Mapping	Colour Ortho	Colour Ortho	Colour Ortho	Colour, IR Ortho	Building Polygon
Pixel size, ortho-photo (m)	0.075	0.12	0.15	0.3	2.0	0.25

Table 2. Customers' DMC Projects

[1] Information about ASPRS standards can be found at www.fgdc.gov/standards/documents/standards/accuracy/chapter3.pdf

[2] CE 90 means 90% probability of a given point's coordinates falling within that circle's radius.

be a bit conservative in our mission flight altitude planning by flying lower in hopes that a finer pixel will offset a reduction in relief exaggeration.

The DMC's greater radiometric depth of 12 bits vs. the usual scanned imagery's 8 bits does not appear to improve the matching process. In preliminary tests we have confirmed this by resampling DMC imagery from 12 bits down to 8 bits and running auto-matching. More investigation is necessary in this area.

As for the generation of *pan-sharpened colour orthophotos*, the processing sometimes creates false-colour artefacts that must be carefully compensated for in each set of imagery. In some cases, the final product shows "bleed-over" effects because it is not possible to correctly assign, for example, the correct R, G, B, and NIR values for a 0.3m pan pixel from a 1.4m colour/CIR pixel. As long as one doesn't magnify the imagery too much, the effect is usually not noticeable, but it is there. Fortunately, if one were using the DMC imagery in the context of a multispectral classification process, one would probably be quite satisfied just to work with the raw colour/CIR coarse/not-pan-sharpened imagery. Also, if one is using the pan-sharpened imagery just to do visual interpretation and if one doesn't zoom-in too much, the quality of the colour/CIR imagery is quite adequate and still looks markedly superior to scanned film.

5. CONCLUSION

In this paper the design of the Digital Mapping Camera (DMC) has been introduced in some detail. The data flow of DMC image acquisition and georeferencing is presented. The technical data of some DMC projects flown at various flying heights over different terrain types to produce different output products are given. As shown in Table 2, all results met the mapping accuracy requirements.

Overall, the DMC offers much better quality in spatial resolution for panchromatic imagery, and its multiband resolution is adequate for real-world colour/CIR multispectral analysis application. The DMC's FMC capability gives it more latitude in terms of lighting conditions (cirrus overcast, poor contrast surfaces, poor reflecting surfaces, and time of year and day [if shadow length specs are relaxed]), superior potential capital utilization efficiency can be achieved if it is placed on a faster platform, and, most importantly, the DMC's accuracy is sufficient to support 3-D mapping to any map accuracy standard.

Automatic image matching software needs to be modified to take advantage of the higher dynamic band of DMC imagery. More investigation is needed to analyze 12-bit vs. 8-bit imagery as well as the impact of the DMC's reduced B/H ratio on overall height accuracy when collected DTMs are used in support of contour mapping.

6. ACKNOWLEDGEMENTS

This paper has been prepared with the use of several DMC blocks provided by 3001, Inc. We used some of these blocks for accuracy analysis as well as for georeferencing comparing direct and indirect sensor orientation. We acknowledge the help of Gregory Horwell of 3001 who has provided us with valuable analysis of several DMC practical projects.

7. REFERENCES

Diener S., Kiefner M., Dörstel C., 2000. Radiometric normalisation and colour composite generation of the DMC, International Archives of Photogrammetry and Remote Sensing, Vol. XXXIII, Part B1, pp. 88-92.

Dörstel C., 2003. DMC - Practical experiences and Photogrammetric System Performance, in: Fritsch D. (Ed.), Photogrammetric Week 2003, Wichmann, Heidelberg, pp. 59-65.

Dörstel C., Jacobsen K., Stallmann D., 2003. DMC – photogrammetric accuracy – calibration aspects and generation of synthetic DMC images, in: Grün A., Kahmen H. (Eds.), Optical 3-D Measurement Techniques VI, Vol. I, Institute for Geodesy and Photogrammetry, ETH Zürich, 74-82.

Heier H., 2001.: Deploying DMC in today's workflow, in: Eds Fritsch D., Spiller R. (Eds.), Photogrammetric Week 2001, Wichmann, Heidelberg, pp. 35-45.

Heier H., Hinz A., 2002. Results from the Digital Modular Camera DMC. Proceedings ASPRS, Washington D.C., USA.

Hinz A., 1999. The Z/I Imaging Digital Modular Camera, in: Fritsch D., Spiller R. (Eds.), Photogrammetric Week ´99, Wichmann Verlag, Heidelberg, pp. 109-115.

Hinz A., Dörstel C, Heier H., 2001. DMC – The Digital Sensor Technology of Z/I-Imaging, in: Fritsch D., Spiller R. (Eds.), Photogrammetric Week 2001, Wichmann, Heidelberg, pp. 93-103.

Madani, M., Dörstel, C., Zeitler, W., Tang, L., 2001. Z/I Imaging New Automatic Aerial Triangulation System 2001. ASPRS Annual Conference, ST. Louis, MO, April 22–26.

Madani, M. and M.M.R. Mostafa, 2001. ISAT Direct Exterior Orientation QA/QC Strategy Using POS Data. Proceedings of OEEPE Workshop: Integrated Sensor Orientation, Hanover, Germany, September 17-18, 2001.

Tang L., Dörstel C., Jacobsen K., Heipke C., Hinz A., 2000. Geometric accuracy potential of the Digital Modular Camera, International Archives of Photogrammetry and Remote Sensing, Vol. XXXIII, Part B4/3, pp. 1051-1057.