'Photogrammetric Week 01' D. Fritsch & R. Spiller, Eds. Wichmann Verlag, Heidelberg 2001.

DMC – The Digital Sensor Technology of Z/I-Imaging

ALEXANDER HINZ, CHRISTOPH DÖRSTEL, HELMUT HEIER, Oberkochen

ABSTRACT

Aerial cameras manufactured by Carl Zeiss have been successfully used around the world for many decades. Z/I-Imaging is continuing this tradition with the digital camera system DMC. The DMC uses a modular design to achieve high geometrical resolution together with multispectral capabilities. It comprises a variable number of synchronously operating CCD-matrix based array cameras that can be built together in different configurations. Four parallel cameras can generate multi-spectral R,G,B and Near Infrared imagery for the acquisition of color composites. Four panchromatic images from converging cameras, are mosaiced digitally to form a single high resolution image. The color composite image and the composed panchromatic image have the same ground coverage. The resulting image is based on central perspective view and can be handled by existing photogrammetric workstations. Based on its outstanding electronic Forward Motion Compensation the DMC reaches ground resolutions better than 2 inches. Thus it can be used for the same wide range of applications as film-based aerial camera systems like the RMK-TOP which are mostly used for mapping applications with photo scale between 1:5.000 and 1:15.000. The paper describes the properties of the camera system and modules. Test results with system components will be discussed.

1. INTRODUCTION

For many decades Aerial Cameras developed and manufactured by Carl Zeiss Photogrammetry Division have been successfully used all over the world as high performance systems for aerial photography. Since October 1999, this Carl Zeiss tradition is being continued by the new joint venture Z/I IMAGING, which is operating world-wide covering the entire photogrammetric workflow end-to-end.

Aerial mapping cameras like the RMK, RMK-TOP and LMK have been used for decades. In recent years the airborne cameras have evolved into complex system solutions: compensation of aircraft motions, photoflight management with GPS navigation, and the use of measurement methods for the precise determination of the exterior orientation have been incorporated. Photographic cameras using long rolls of 240mm wide film with different specifications are still being used in a wide field of applications for image acquisition and image storage. This camera systems are mostly used for mapping applications with photo scale between 1:5,000 and 1:15,000. Some applications demand even image scales as small as 1:40,000 or as large as 1:1,500 for very high resolution images.

The digital camera system DMC uses a modular design to achieve high geometrical resolution and to enable customization for optimum system performance. The DMC comprises a variable number of synchronously operating CCD-matrix based cameras that can be mounted together in different configurations, depending on the application. This multi-camera approach allows the combination of high panchromatic resolution with multi-spectral capability.

2. AIRBORNE CAMERA SYSTEM

2.1. System Description

The following figure shows a typical installation of the DMC system in an aircraft.

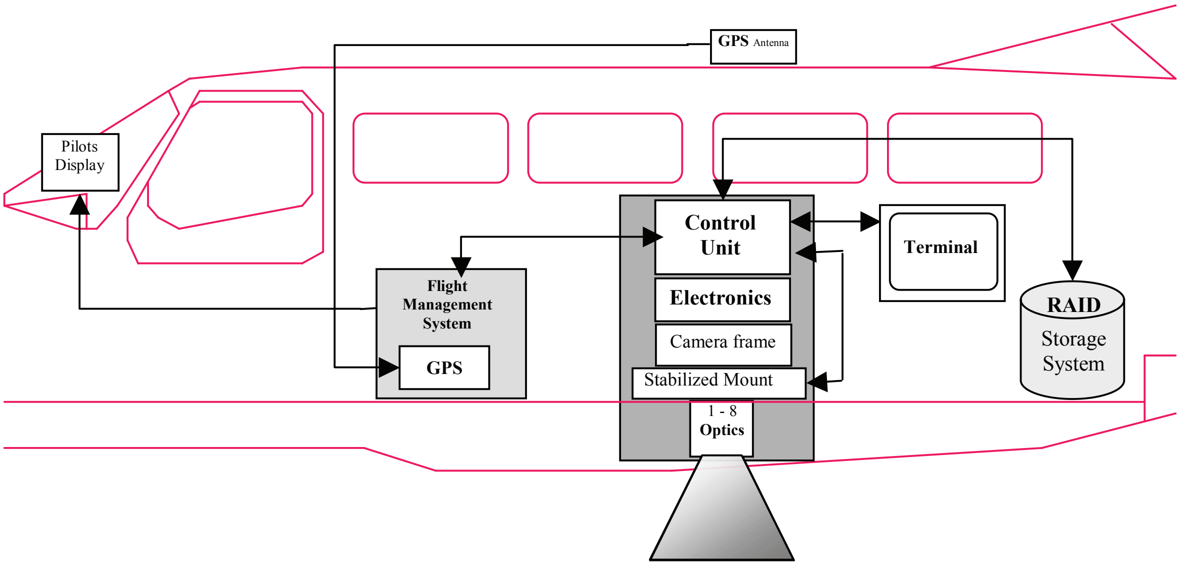


Figure 1. ***DMC*** Airborne Configuration

Figure 2. DMC Camera unit

The DMC camera head has similar dimensions as the RMK-TOP camera and fits in the existing gyro stabilized platform T-AS. The camera itself consists of an optics frame, which slips into the platform bore. The frame can take up to 8 camera modules: 4 high resolution panchromatic CCD lens modules and 4 multispectral channels with reduced resolution. The camera modules are mounted inside the optics frame. Special efforts have been invested on rigid mounting technology for the individual camera heads in order to ensure precise alignment of the optical axes to each other.

The DMC is operated via the terminal and the flight management system (FMS) with pilot's display. The same FMS can also be used to operate an already existing film camera system An optional inertial measurement system can be integrated directly inside the camera frame for maximum rigid coupling to the system..

On top of the optics frame above the stabilized gyro-mount is the camera electronics box (blue colored part in figure 2). This unit houses the complete camera head electronics, which controls the camera modules, includes the power electronics for the shutters, collects the image data and communicates with the control unit. The control unit configures the complete system, communicates with the external systems, monitors the data flow and stores data onto the RAID. For easier installation of the camera in the aircraft, the control electronic box (grey colored part in figure 2) can be removed as separate part from the camera. The following block diagram shows some details of the camera concept:

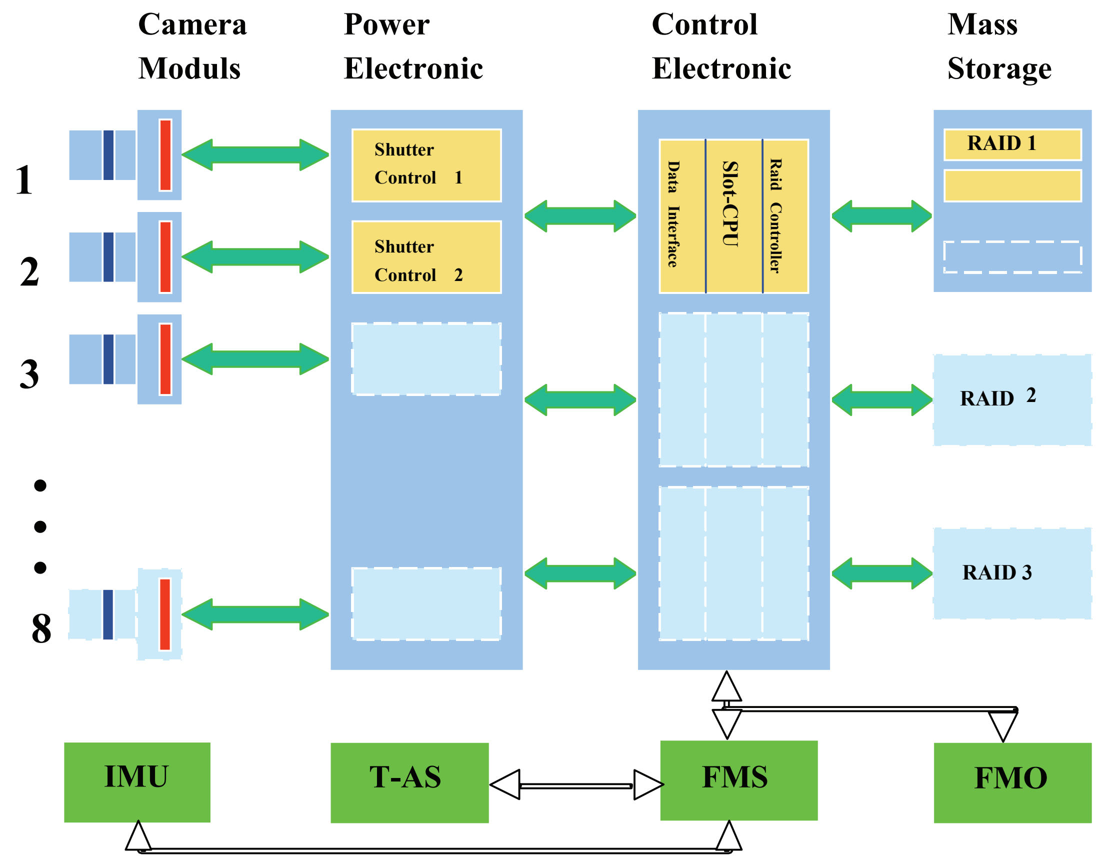


Figure 3. Block diagram DMC flight system

The single camera modules, 1 to an maximum of 8, are autonomous units and are mounted inside the optics frame. The front end electronics, with signal conditioning, analog digital conversion, CCD timing and processing is directly integrated inside the camera modules. In this way best S/N (Signal to Noise) of the CCD-signals is ensured and EMI (Electro Magnetic Interference) within the system is minimized.

The electromechanical shutter is placed in the center of the lens. The advantage of this solution is an distortion free image, since all image points are exposed through the same optical path at the same moment in time. A slit shutter, as used in a standard reflex camera, causes geometric distortion inside the image field, since the aircraft is moving during exposure time.

The shutter is driven by wear resistant piezoelectric actuators, thus enabling a minimum of moving parts to ensure very high reliability. This special design, combined with a sophisticated electronic control loop, incorporates shutter and iris function in one compact optoelectronic unit. A focus of the shutter development was to achieve precise synchronization of all lenses to ensure exposure of all images at exactly the same time interval in order to exclude geometric errors.

Depending on how many camera modules are used in the system, the control electronics consists of up to 3 complete PCI-bus based slot PC´s, which are operating all in parallel. The image data of the camera modules are transferred via a parallel bus to high speed frame grabber PCI-bus cards.
Finally, the data are transferred via a separate FC-AL link from each slot-CPU system onto a ruggedized RAID hard disk system with removable storage units. Full modularity allows easy adaptation of standard storage devices to the system. Currently one RAID unit is equipped with a storage capacity of 280 GByte. With a maximum of 3 units the total storage capacity is 840 Gbyte. At full resolution (12bit) and color mode more than 2,000 images can be taken. This is more than 3 rolls of 500 ft film taken with a classical film camera.
An optional Inertial Measurement Unit (IMU) can be integrated into the system, opening up the possibility to work without ground control, or with a reduced set of ground control points.

2.2. Optical Concept

The centerpiece of the system is the camera head and the CCD matrix sensor as the key element. For technological and economical reasons, it is not possible to choose the ideal solution which would be one individual, large-area very expensive CCD chip with the size of a "silicon pizza", similar to existing film formats.

However, for the image recording procedure it is important to have a ground coverage with one shot as wide as possible. This is provided by parallel operation of several compact camera heads, where each CCD has its own lens. The modules are directed to the scene at slightly displaced field angles. Figure 4 shows a ground print taken with four such camera heads. This modular approach permits simple scalability of the overall system.
The principle of parallel image recording has been established and successfully used by Carl Zeiss for more than 30 years in reconnaissance cameras such as KS-153, and drone camera systems such as KRb 8/24.

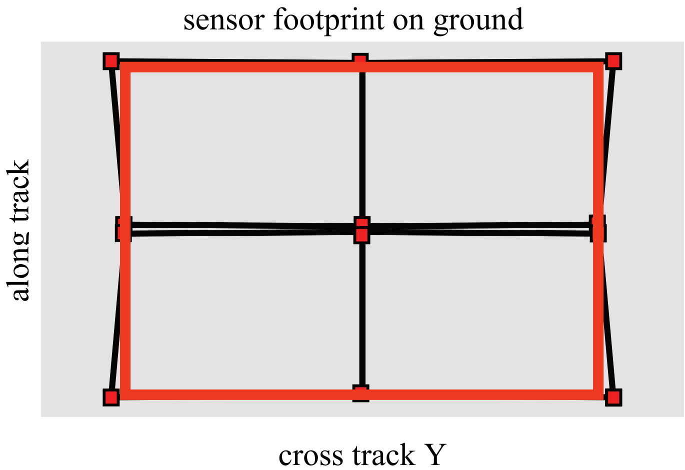


Figure 4. Ground coverage of 4 head camera

The high resolution version of the DMC is equipped with four 7k x 4k large area chips and f/4 high performance lenses with a focal length of 120 mm in the panchromatic channel. Special care has been taken to assure homogenous and flat response of the MTF (Modulation Transfer Function) over the entire image field of the lenses.

Each lens is calibrated with a standard goniometer technique. Geometric distortion is described with the parameter model of Brown (1971):

The radial distortion is modeled by : $\Delta r = r^3 K_1 + r^5 K_2 + r^7 K_3$,

decentering is described by

$$\Delta x_d = (r^2 + 2\bar{x}^2)P_1 + 2\bar{x}\bar{y}P_2$$

$$\Delta y_d = 2\bar{x}\bar{y}P_1 + (r^2 + 2\bar{y}^2)P_2$$

other parameters are typically much less significant.

Typically the residuals of a calibration of a panchromatic camera head system (completely mounted with a CCD-unit) to this model is less than 1/20 of a pixel (<0,6 µm).

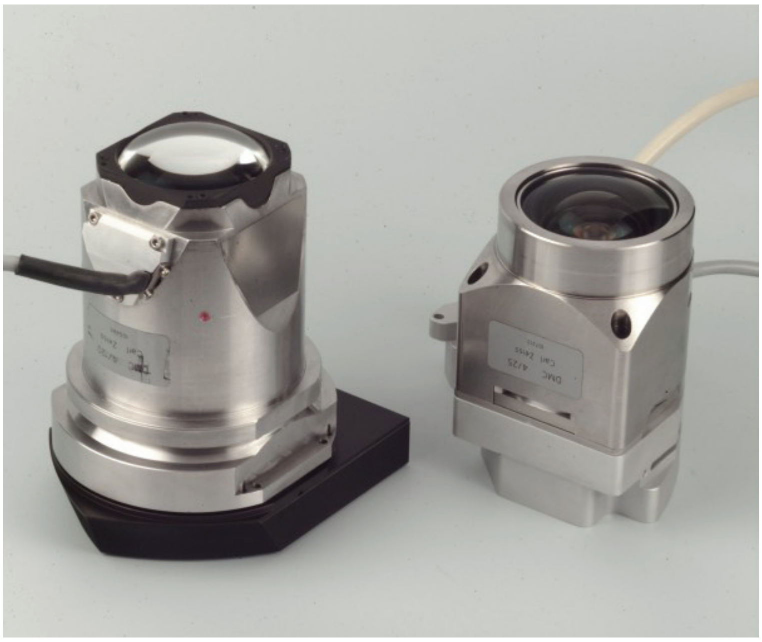


Figure 5. panchromatic (left) and multispectral (right) camera heads

Figure 5 shows a panchromatic and multispectral camera module with CCD and complete front end electronic mounted. As can be seen, the front of the housing of the panchromatic lens has been shaped to a rectangular wedged form in order to mount the lenses as close as possible together. This is necessary to meet the stringent space limitations and to achieve high optical throughput.

Figure 6 shows the arrangement of the 4 panchromatic channels in the optics frame. The resulting resolution of the system on ground is > 13,000 pixels across track and approx. 8,000 pixels along track. The resulting cross track coverage angle for the system is 74°. The mechanical size of the optics frame is compatible with the RMK lens cone dimensions to fit into the existing T-AS gyro stabilized mount.

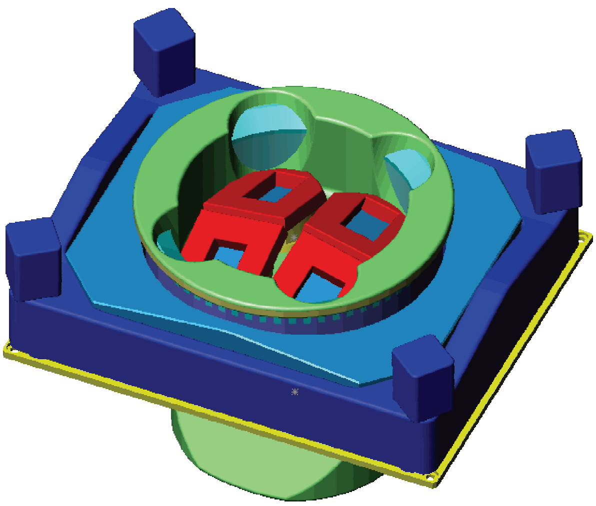


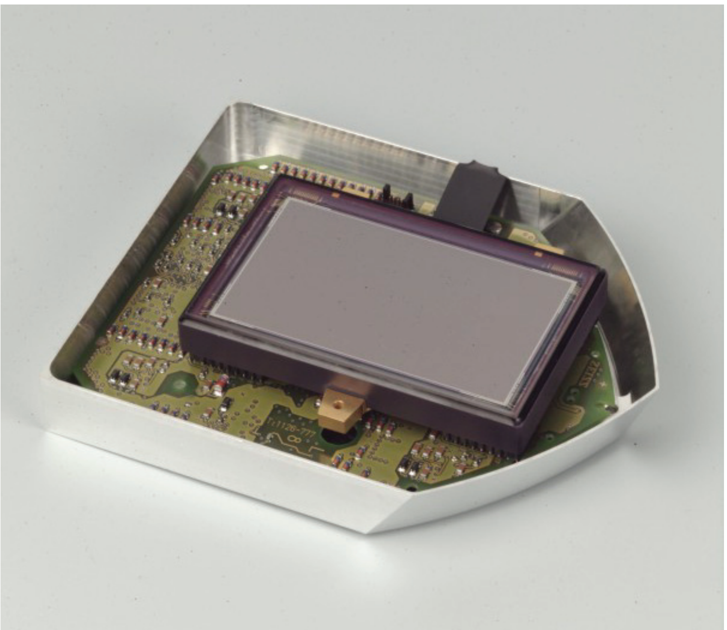
Figure 6. Panchromatic channels in gyro stabilized mount

Figure 7. Mainframe with Pan lenses (upper) and multispectral lenses (lower part) mounted

The color channels are mounted on the outer rim of the optics frame, up to 4 channels can be added to the system. This allows the collection of images for instance in the Red, Green, Blue and a separate Infrared channel for taking simultaneous true and false color images at the same time.
In order to achieve high quality color separation, each color channel features a separate lens, a CCD-chip and a high performance color filter, based on non-organic material. The color channels have reduced ground resolution compared to the panchromatic channel and the lenses are looking down in central perspective view. A high performance wide angle lens with high opening f/4 and f=25 mm is combined with a 3k x 2k CCD chip. The resulting overlap of the spectral channels (given in grey bold rectangle) and the panchromatic channel (black thinner lines) is illustrated in figure 4.

2.3. CCD - Sensors

The CCDs are full frame sensors with high optical fill factor and sensitivity and are manufactured by the Philips company in Eindhoven. Pixel size is 12 µm x 12 µm, offering a high linear dynamic range > 12 bit. The architecture of the CCDs offers 4 readout registers on every corner of the chip. This provides high readout rates, which is important for a good S/N ratio of the signals and a repetition rate of the system achieving one image every 2 seconds. The front end electronics, generating the CCD control, timing signals and the digital signal read out circuits are placed directly behind the CCD housing in order to ensure low noise performance of the system. Digitizing of the CCD signals is done with 12 bit resolution.



The figure shows the 7k*4k CCD-Chip and the front end electronics.
The high resolution CCD-chip is packaged into a customized Al_2O_3 housing. Special care has been taken in the development of this housing to ensure very high stability of the geometry during pressure (flying height) and temperature variations.

Figure 8. 7k*4k CCD-Chip package and front end electronics

2.4. Radiometric Resolution

The high sensitivity of a CCD sensor, along with its wide dynamic range, offers distinct radiometric advantages over film material, as it permits markedly higher contrast to be recorded in the image. In urban areas, in particular, this even enables the recording of heavily obscured structures. Whereas a film generally does not provide a dynamic range of much more than 6 to 7 bits, a CCD chip offers 10 to 12 bits.

The radiometric quality of a digital image sensor is given by the signal to noise ratio of the CCD-pixel, which is defined by the number of signal electrons divided by the number of noise electrons (Theuwissen, 1995).

The number of signal electrons can be specified in terms of the number of photons impinging on the sensor $\Phi_0/(h.\nu)$ (= photon flux/energy of a single photon), the pixel area A_{pixel}, the quantum efficiency η and the integration time T_{int} :

$$Signal = \frac{\Phi_0}{h.\nu} * A_{pixel} * \eta * T_{\text{int}} \qquad [1]$$

The number of noise electrons can be split up into three main noise sources :

- photon shot noise, equal to the square root of the number of signal electrons, given by [1],
- noise electrons generated in the CCD channels (e.g. incomplete transfer, shot noise on dark current, fixed-pattern noise, ...), all summed in n_{sens},
- output amplifier noise : n_{out}.

thus the number of noise electrons can be written as :

$$Noise = \sqrt{\frac{\Phi_0}{h.\nu} * A_{pixel} * \eta * T_{\text{int}} + n_{sens}^2 + n_{out}^2} \qquad [2]$$

If all these contributions are put in the definition of S/N, this yields :

$$\frac{S}{N} = \frac{\frac{\Phi_0}{h.\nu} * A_{pixel} * \eta * T_{\text{int}}}{\sqrt{\frac{\Phi_0}{h.\nu} * A_{pixel} * \eta * T_{\text{int}} + n_{sens}^2 + n_{out}^2}} \qquad [3]$$

For normal light levels the noise is dictated by the amplifier noise, fixed pattern noise and read out noise of the CCD. Fixed pattern noise is minimised by the radiometric correction of the individual pixel sensitivity. The signal is thus linear depending on the incoming photon flux Φ_0 (light intensity), the integration time and the area of the CCD-pixel itself. This linear functional relation shows, that for best performance of the CCD the exposure time (defined by the integration) must not be chosen to short, it needs to be adapted to approximately half the saturation level for optimum radiometric resolution of the system. Since the forward motion compensation feature of the DMC allows free choice of the exposure time, optimum illumination conditions for the CCD can be chosen independent from the v/h ratio of the photo flight.
The CCD pixel size is 144 μm^2 (12µmx12µm) which is considerable larger (factor 3.5) than a typical line sensor of 42μm^2 (6.5µmx6.5µm), thus enabling full 12 bit radiometric resolution of the system.

2.5. Technical Specifications

The modular design of the DMC allows to adapt the system to specific needs of the customers applications. the following table gives an outline of the high end system.

Technical data and parameters of the DMC high end configuration (panchromatic channel only)

Parameter	Value
Module/Sub-image:	
Calibrated focal length ***c*** [mm]	120
Pixel size [µm]	12
Radiometric resolution [bit]	12
Image size [Pixel]	4096×7168
Image size [mm]	49.15×86.02
approx. Field of view (‖along/across track)	23°/39°
Virtual image:	
Defined focal length c_{virt} [mm]	120
Pixel size [µm]	12
approx. Image size [Pixel]	8,000×13,000
approx. Image size [mm]	95×168
approx. Field of view (‖along/across track)	44°/74°

3. TEST RESULTS

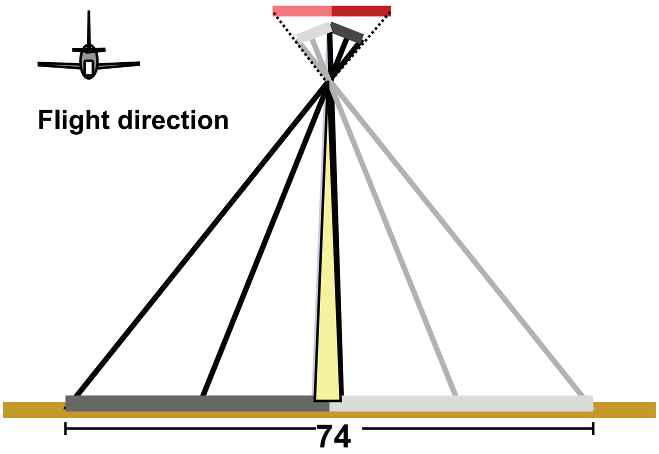


Figure 9. cross track coverage of dual camera head

A test flight with a 2-head camera system was made in Nov. 2000 together with Hansa Luftbild, Münster in cooperation with the Institute of Photogrammetry in Stuttgart, Germany. The cameras have been orientated in forward looking orientation and are combined to increase the cross track coverage as indicated in figure 9.

The system was installed on board of a Cessna twin engine aircraft. Test flights at different altitudes have been carried out at a flying speed of 70 m/sec. Figure 10 shows the result of a test flight at 740m flying height above ground over the Carl Zeiss plant in Oberkochen. The image was rectified and mosaicked and has a resulting resolution of 13.500x4000 pixels, showing the typical butterfly shape of the oblique view of the camera axis. Since the quality of the image is strongly reduced by the resolution of the printout, zoomed in details can be seen better in the enlargements shown in figure 11, which show a ground resolution of 3". The total symmetrically resolved Siemens Star (diameter 6m) shows the perfect compensation of the forward motion blur which was 4 pixels under the test conditions.

Figure. 10. Test Flight over Carl Zeiss Plant Oberkochen

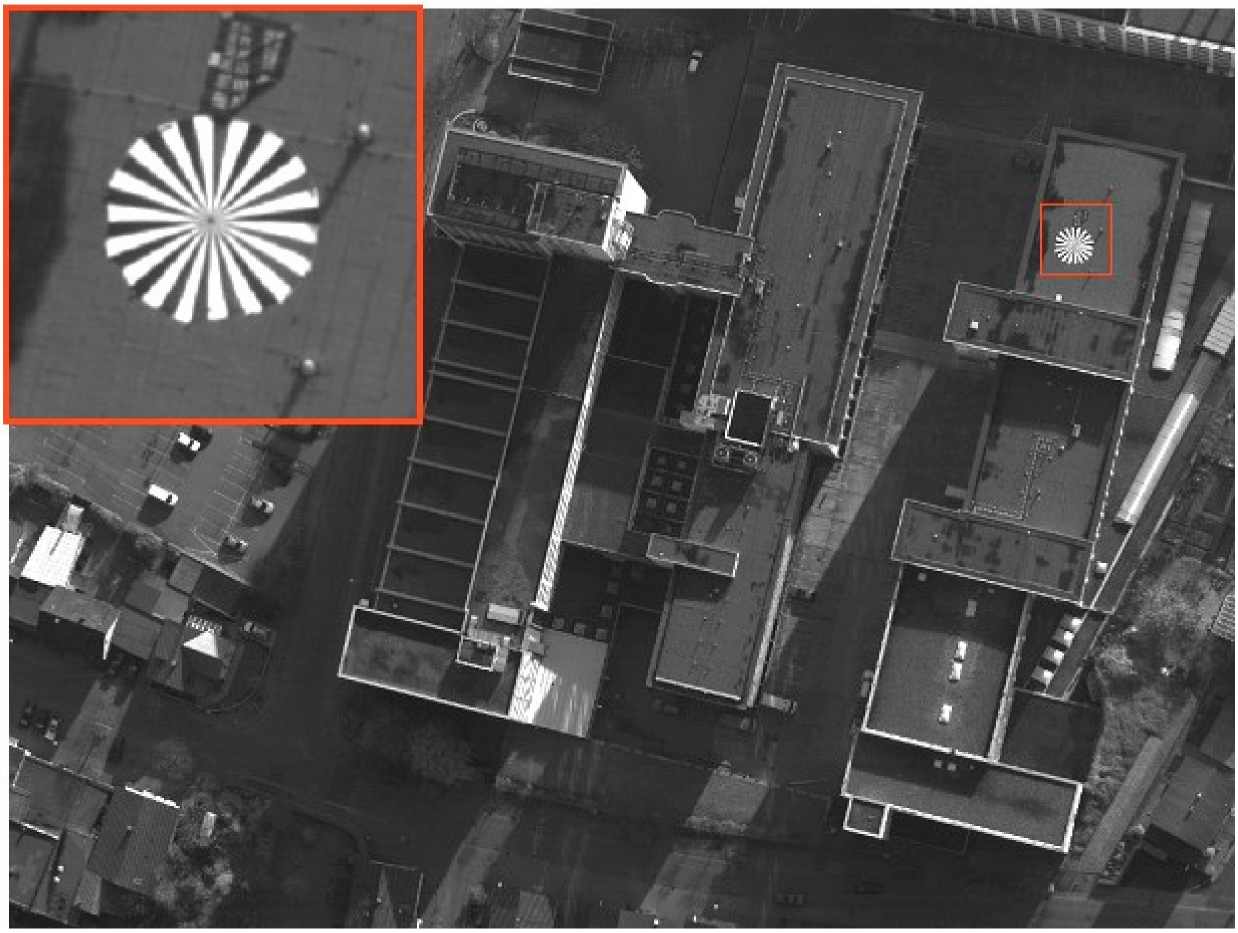


Fig. 11 Detail of figure 10, flying height: 740m above ground, GSD = 3"

4. PERFORMANCE COMPARISON :

Airborne digital cameras based on different technical concepts are getting available. For a real and objective performance comparison between these developments one has to look into the application related cost situation (Heier, 1999). Thus, a performance comparison only on the basis of counting picture elements would be a mistake. As regards ground resolution, accuracy, Pixel footprint, light conditions and system compatibility, the DMC offers the best system performance with the technology available today.

1. Resolution
The DMC offers an outstanding ground resolution even for large image scales due to the fact that FMC is implemented (Hinz, 1999). A ground resolution of less then 2 inches has already been proven in a test flight performed in January 2000 (Hinz, 2000).
2. Accuracy
The DMC accuracy is defined by the solid state surface of the silicon matrix sensor itself, together with rigid interior orientation of the high precision lenses. Differential GPS measurements and INS results can optionally be used.
3. Pixel footprint:
Due to the framing concept, the DMC delivers quadratic pixel footprints. Influences from airspeed or sudden aircraft movements are eliminated because the image geometry is frozen with one exposure shot.
4. Light conditions - number of days with acceptable conditions
In view of the fact that FMC is an inherent feature of Z/I Imaging's digital camera, high resolution imagery can be taken also under weak light conditions. When using a camera without FMC capabilities, it is not possible to reduce the air speed below certain limits.
5. System Compatibility
The DMC is based on the central perspective image which has been established in photogrammetry for nearly 100 years. All existing exploitation systems can handle these data.
6. Reliability
The image taken with a frame sensor can be used even if the GPS results are not of the expected accuracy. With a line sensor, however, if the GPS results are not satisfactory or missing for any reason, the flight needs to be performed again, because the direct sensor orientation is corrupted.

5. CONCLUSION

New applications and new image data sources will have significant impact on the aerial imaging market in the coming years. These changes, as well as advances in sensor and computer technology, will soon make the use of digital airborne cameras economical. Before digital sensors can replace film technology, some major problems will have to be solved, mainly in sensor resolution and data processing.
The digital camera introduced by Z/I Imaging is based on a matrix CCD sensor. This approach offers the best geometric accuracy for photogrammetric applications, without restrictions defined by the accuracy of INS and GPS data. The high intrinsic accuracy is determined by the two dimensional matrix of CCD pixels structured on a silicon wafer. It effectively offers several million well-defined fiducial marks (each CCD pixel) in the focal plane of the aerial image. The modular approach allows the combination of several compact camera heads offering cross track coverage in the same range as standard wide angle aerial cameras. High flexibility in the modular design allows the adaptation of spatial and radiometric resolution according to customer needs. This can be

achieved by combining different numbers of panchromatic and multispectral camera modules. The resulting digital image has the usual central perspective geometry, thus maintaining compatibility with existing softcopy solutions. The coexistence of large format film-based aerial cameras and the new digital generation of cameras will be carefully observed. The introduction of the new digital camera systems will be an evolutionary process with demanding objectives.

6. REFERENCES

Brown, D C., 1971: Close-range camera calibration.
Photogrammetric Engineering, 37(8), pp. 855-866.

Heier, H. ;1999. Applications and Market for Digital Airborne Cameras
Photogrammetric Week ´99, Eds D. Fritsch / R. Spiller, Wichmann, Heidelberg pp 43-49

Hinz, A. ;1999. The Z/I Imaging Digital Aerial Camera System, Photogrammetric Week ´99,
Eds D. Fritsch / R. Spiller, Wichmann, Heidelberg

Hinz, A. ; Dörstel, C, Heier, H., 2000. DIGITAL MODULAR CAMERA: System Concept and Data Processing Workflow, Proc. IAPRS Vol. XXXIII, Amsterdam, 2000

Theuwissen, A., 1995. Solid-State Imaging with charge coupled devices, Kluwer Academic, 1995