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Experiences with the airborne three-line camera system DPA[1]

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ABSTRACT

The digital stereo and multispectral imaging system *Digital Photogrammetry Assembly (DPA)* was developed for airborne photogrammetric and thematic mapping. Its special feature is the simultaneous image acquisition of high resolution (~0.2m ground pixel size) panchromatic imagery with multispectral data (~0.4m ground pixel extension). This combination delivers for the first time geometric and thematic data for airborne applications, which were only made available so far by using different sensor systems. With this concept the DPA system is for the time being outstanding and can be used for new and therefore most challenging mapping applications.

This paper gives an overview on the first rigorous tests of the stereo and multispectral DPA modules. For this reason three epochs were flown over testsites carefully selected and controlled by the Institute of Photogrammetry (ifp), University of Stuttgart. After a brief review of the DPA components the main objective of the paper is directed to photogrammetric restitutions and thematic mapping applications. First test results are presented although the final accuracy analysis could not yet be accomplished while writing this paper. The paper concludes with an outlook on possible digital camera design architectures which is an important issue for the development of new operational photogrammetric camera systems being able to substitute the analogue aerial cameras in use.

1. INTRODUCTION

The growing demand for fast and accurate data acquisition for mapping and GIS applications requires the provision of new sensors with a high automatic mapping potential. Up to now aerial photogrammetry was able to manage the many interests of topographic data acquisition for map scales 1:5 000, 1:25 000 as well as 1:50 000. Satellite born imaging sensors completed the scale series with satellite image maps in even smaller scales. Both imaging segments, analogue airborne imagery and digital spaceborn images represent a high standard in geometry and radiometry.

During the last ten years we could observe an amazing development in computer technology which had a huge impact also on photogrammetry. It is out of question, that photogrammetric object restitution can be automated to a high degree using digital data processing techniques. For this reason, all photogrammetric images should be available in softcopy format, which means, non-digital data is to be converted in an A/D process. High resolution photogrammetric scanners are offered by vendors of photogrammetric equipment to realize the *hybrid* approach of aerial photogrammetry. This might continue for the next years to come without any noticeable loss of precision of the analogue image data sources (H. Ziemann, 1997).

Besides the hybrid approach of photogrammetric data handling it is quite natural to ask for inflight digital data acquisition techniques. This requires the development of digital aerial camera systems (A. Hinz, 1997), which should be available in the very near future. The advantages of digital camera systems have been cited many times, such as also by M. Claus (1995) during the last Photogrammetric Week.

The idea of building a digital camera system for airborne and spaceborne applications is not new - it was strongly influenced by one person who made not only substantial contributions to the development of analogue and analytical plotters. The first developments in building such a digital optical camera system were started in the laboratories of Messerschmidt-Bölkow-Blohm (MBB, today Daimler-Benz-Aerospace DASA) in the mid 1970s. It was the pioneer Dr. Otto Hofmann, who experimented with linear Charge-Coupled Devices (CCD) to substitute a film-based data acquisition. As a result of these

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[1] This paper is dedicated to the 75th birthday of Dr. Otto Hofmann, the pioneer and inventor of digital imaging three-line scanning systems.

developments a first sensor called EOS (Electro Optical System) was developed to be used for experimental purposes only. An airborne application of EOS near Munich proved the concept and gave optimism to proceed with digital technology.

Since the end of the 1970s Dr. Otto Hofmann continued his visions by the development of a new high resolution spaceborn remote sensing system (MOMS). This has been made possible by funding through the Federal Ministry of Education, Science, Research and Technology (BMBF). Its primary task was to perform topographic data acquisition for medium scales. During the German Spacelab (D2) mission this sensor proved its capability for along-track stereo image recording with simultaneous recording of multispectral image information. Since May 1996 the MOMS is operating on-board the Russian Space Station Mir for a probably 2 years term (see contribution of H. Ebner, 1997).

Parallel to the MOMS developments the Ministry of Defense (BMVg) ordered an airborne digital camera system capable of simultaneous stereo and multispectral data recording as well. This system was called DPA (Digital Photogrammetry Assembly) and its design started in the mid of the 1980s. The purpose of DPA was directed to topographic mapping in scales of 1:25 000 and 1:50 000, primarily through automated DTM generation to accuracies of better than 3m, and through the generation of digital orthoimagery with sufficient information content to meet map specifications at scale 1:50 000 and even larger. Complementary to this mapping function would be multispectral imaging to support thematic mapping. The Bureau of Military Mapping Services (AmilGeo) was appointed to be the user of this camera system. DPA could be finished in 1995 and the Institute of Photogrammetry (ifp), University of Stuttgart, started with final acceptance tests.

2. THE DPA ARCHITECTURE

The mechanism by which DPA acquires stereo imagery for 3D object data extraction is the three-line scanning concept, which is depicted in Figure 1. One highlight at least from a photogrammetric point of view is the simultaneous recording of three image scenes along-track. The three stereo channels of the panchromatic band deliver a ground resolution of up to 0,25m (nominal distance 2,5km). In addition to this the stereo images can be combined with multispectral data with a ground pixel resolution of 0,5m.

The characteristic features of DPA, for both the stereo and multispectral module, are given in Table 1. Using a Fairchild CCD 191 linear array with pixel size of 10µm the swath width finally results in 3km for stereo and multispectral data recording (both seen from 2,5km flying height).

In total seven channels for stereo and multispectral image data recording are available. The stereo module is recording in the panchromatic range (515-780nm), whereas the multispectral channels represent bandpass filters of the visible light spectrum (VIS) and the near infrared (NIR). With the restriction of the data flow within the image data recording onto a high density digital tape recorder (AMPEX) two operation modes were introduced. Mode A allows for stereo data recording, and mode B for multispectral data.

The geometric conditions for the evaluation of DPA stereo data are quite similar to those of other pushbroom scanners such as SPOT and MOMS. The perspective geometry is only valid on the sensor line, whereas it is close to a parallel projection in the flight path direction. Thus, we have a ‘line central projection’. In the DPA stereo module the interior orientation between the three linear-array sensors, which incorporate quadratic pixels of 10µm size, is established through laboratory system calibration, with the possibilities of self calibration being denied in the standard along-track imaging configuration. The parameters of the interior orientation (shifting of the two convergent F/A stereo channels, offset of the multispectral line arrays, focal lengths of the lenses, distortion, etc.) were investigated in the DASA laboratories, Ottobrunn, Munich/Germany.

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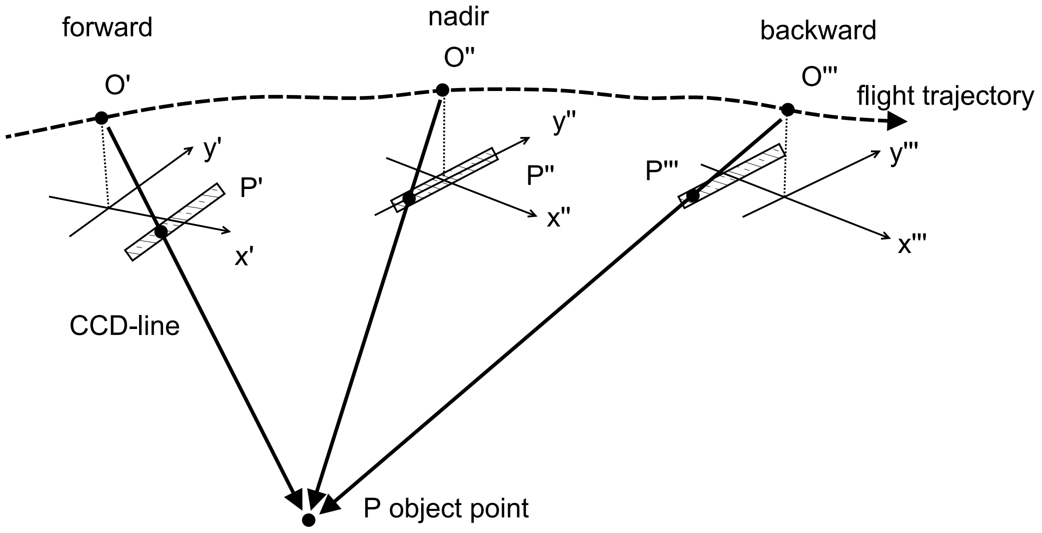

Figure 1: DPA imaging geometry.

6 CCD line detectors (2 per line)	FAIRCHILD CCD 191
pixel size (10µm*10µm)	line image format: 12cm
NADIR channel FORE channel AFTER channel	12,000 pixels/line (Mode A) 12,000 pixels/line (Mode A) 12,000 pixels/line (Mode A)
convergence (stereo) angle	25deg
focal length	80mm
radiometric resolution	12bit→8bit
geometric resolution	0,25m (from 2,5km flying height)

Table 1a: Design parameters of the DPA stereo module.

4 CCD line detectors	FAIRCHILD CCD 191
pixel size (10µm*10µm)	line image format: 6cm
spectral bandpass	440-525nm 520-600nm 610-685nm 770-890nm
focal length	40mm
radiometric resolution	12bit→8bit
geometric resolution	0,5m (from 2,5km flying height)

Table 1b: Design parameters of the DPA multispectral module.

For both modules the field of view (FOV) amounts to ±37deg. In Figure 2 the optic module is represented in more detail - it is interesting to note that the combination of two linear CCD arrays was realized using a double lens principle.

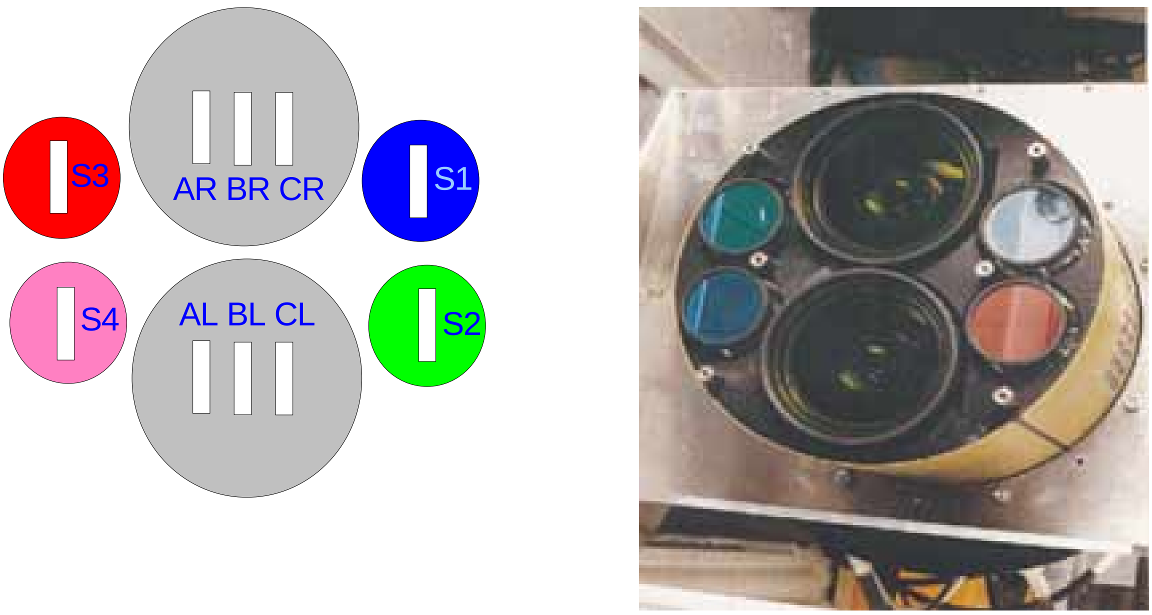
(a) scheme
(b) frontal view

Figure 2: DPA optics module.

The reconstruction of parameters of the exterior orientation for the DPA image recording unit is delivered by an Inertial Navigation System of type SAGEM, which is fixed onto the camera body and records (with the readout frequency of the CCD line arrays) the linear acceleration observations and angular rates. Using double and single integration of the observation equations position and attitude parameters can be computed for every three-line image (K. P. Schwarz, 1995; M. Cramer, 1997).
If the interior orientation between the linear CCD arrays is more or less fixed, thus enabling collinearity equations to be written for all three lines, the exterior orientation varies from one three-line image to another three-line image. For a better understanding the phrase three-line image will be defined as follows: this image consists only of three lines, the nadir image line and the fore and after looking stereo image lines. This excludes a priori the application of standard procedures used in photogrammetric aerotriangulation. However, a modified bundle block adjustment is then possible, if the parameters of the exterior orientation for highly correlated adjacent scan lines are reparamerized. But high frequency movements of the aircraft let us not proceed with techniques which were developed in the MOMS project, where generally a very smooth flight path (orbit) is presupposed.

3. TESTFLIGHTS

In order to check the DPA mapping capabilities a comprehensive work package was defined and utilized during the acceptance test. At first, the integration of GPS was recommended by ifp to determine the position parameters of the DPA projection centers and thus controlling and supporting the INS observations. Secondly, the simultaneous recording of analogue imagery using a RMK (classical wide angle lens, common forelap and sidelap) not only for the point determination of the testsite for the stereo acceptance test, but also to evaluate and assess digital DPA imagery was seen as a necessity. These components finally made the rigorous assessment of the DPA camera system feasible.

3.1 Testsite Vaihingen/Enz

The DPA assessment was originally planned to be independent for the stereo and the multispectral module, respectively. In order to assess the DPA stereo mapping capability the testsite Vaihingen/Enz was chosen (located about 20 km west of Stuttgart) representing high undulated terrain with all groups of vegetation (see Figure 3).The testsite has an extension of about 4,5km by 7km - 200 signalized points represented the reference frame for the final DPA acceptance test study. These points can be classified in more detail: 38 GCPs were signalized and determined by differential GPS with point inaccuracies of σ_P=2-3cm. Additional to the GCPs 38 tie points were signalized with the same white GCP PVC plates of size 1m*1m, and were determined by classical aerotriangulation using the RMK imagery. Moreover, 120 signalized points served as check points for the DPA point determination. Also the check points were determined using RMK images and aerotriangulation techniques. The RMS point errors for tie and check points amount to $\sigma_{X,Y}$<2.0cm and σ_Z<3.4cm (see Table 2).
The Vaihingen/Enz testsite was flown threefold, but only the epochs July 1995 and October 1996 could finally be used within the acceptance test. Table 2 classifies in more detail the final accuracy reached using classical bundle block adjustment for the point determination task.

	# points	mean σ(cm)		maximumσ(cm)		# points with σ>5cm
		$\sigma_{X,Y}$	σ_Z	$\sigma_{X,Y}$	σ_Z	
testflight 1995	201	1.7	2.9	4.4	6.2	5
testflight 1996	190	2.0	3.4	4.0	6.4	18

Table 2: Theoretical accuracy of the estimated point coordinates of testsite Vaihingen/Enz.

The accuracies of table 2 were estimated using the covariance matrices of the bundle block adjustment. For the X,Y object point coordinates all standard deviations are less than 4.4cm, only in height a nominal value of 5cm could not be maintained in all points to be determined. Nevertheless, the accuracy of the bundle block adjustment shows that all photogrammetrically determined points resulting from an RMK image scale series of 1:13 000 were well suited as reference for the assessment of the DPA stereo module.
The flying height during DPA flights was chosen to be 2 000m with a resulting ground pixel size of 0.25m for all three time epochs and an DPA image scale series of about 1:25 000.

3.2 Testsite Elchingen/Grosskuchen

This testsite was chosen for the acceptance test of the DPA multispectral module. It is located 80km east of Stuttgart and contains typical terrain classes of vegetation which are to be derived by pixel-based classification techniques. One reason for choosing this testsite was the availability of digital reference data, such as cadastral data (ALK), topographic data (ATKIS), and in-situ registered landuse data. Also this testsite was flown three times, but final assessment data were derived from the August 1996 and October 1996 testflights only. The extension of this testsite amounts to 3 km by 7.8 km.
Under the restrictions of using this testsite for thematic mapping, particularly for multispectral classifications, no points were signalized. As shown in the evaluation section, main interests were directed to the band-to-band registration (see Figure 4), georeferenced multispectral images, and automated extraction of terrain features.

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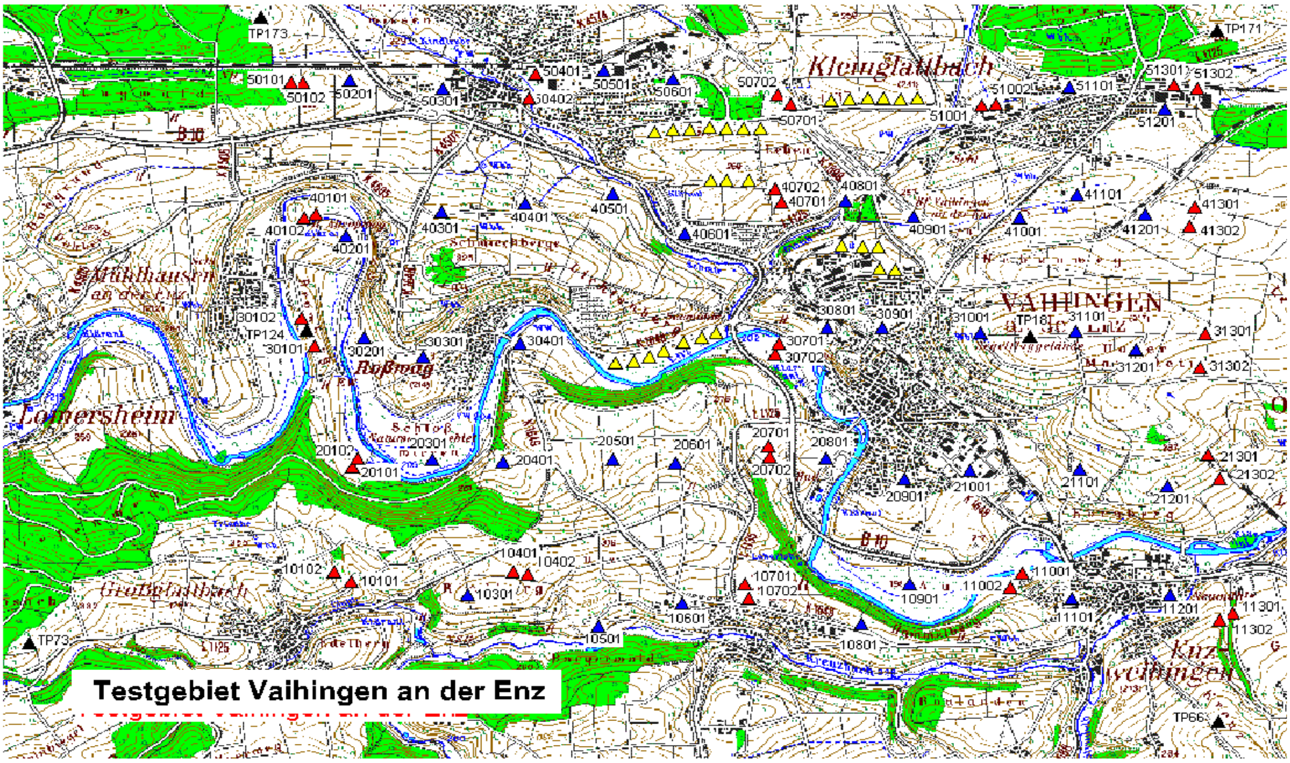


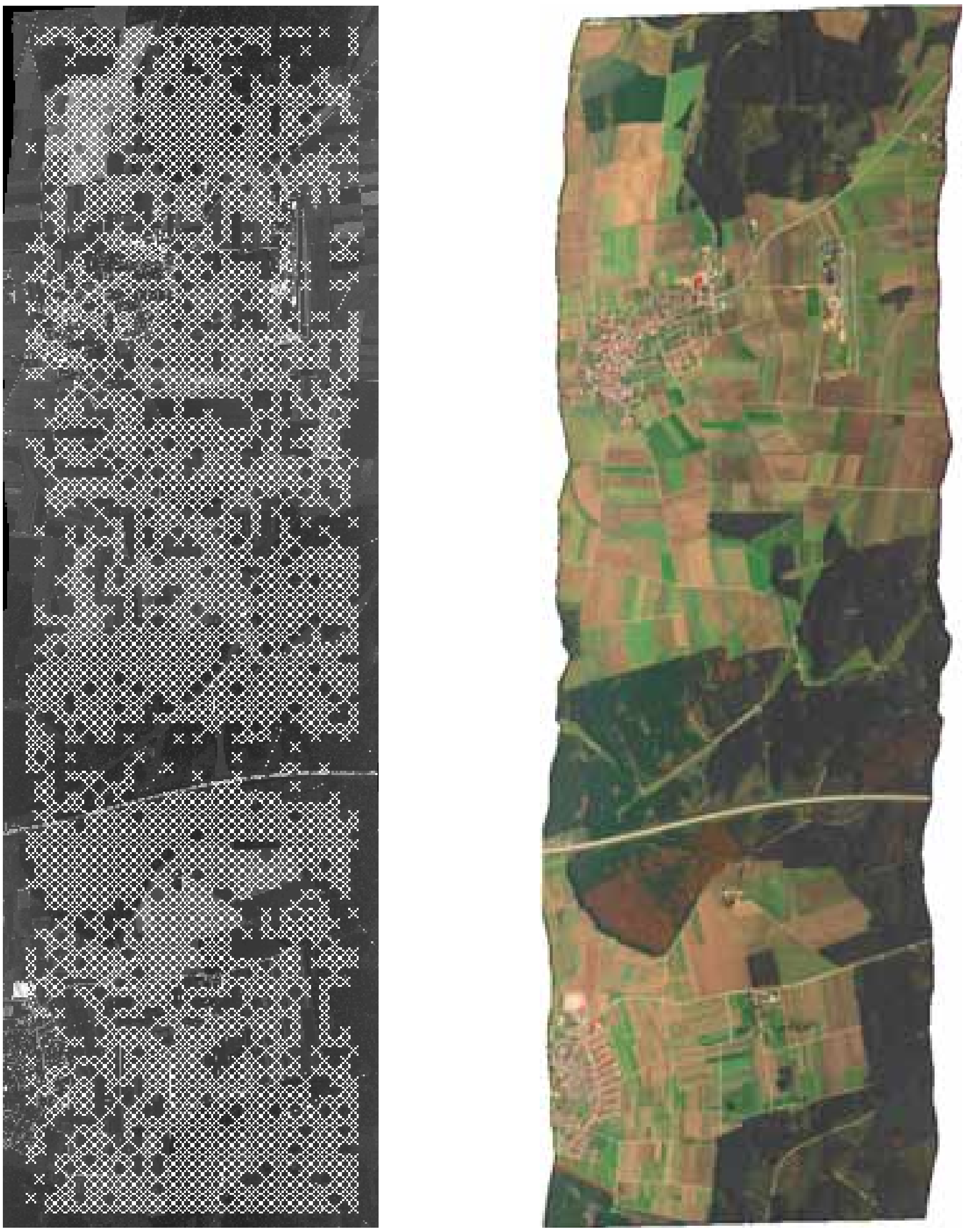
Figure 3: Testsite Vaihingen/Enz (VE).

4. EVALUATIONS

The DPA testflight data from the time epochs mentioned above were all evaluated with software available and developed at ifp. One first problem to overcome was the GPS/INS integration. In order to synchronize imagery data of all kind, no matter whether they are recorded by an RMK or DPA, the spatial and temporary offset between DPA imagery, INS observations, GPS phase measurements and in our case the analogue RMK images had to be resolved. The spatial offset can be determined by classical geodetic methods, however, the time shift has to be zero not to evaluate onto several time scales. Generally, the exposure times of all sensors are referenced to the GPS time scale.

In our testflights standard two-frequency GPS receivers were used. In the July 1995 campaign Astech P12 receivers recorded the stationary and kinematic GPS signals, whereas in the campaigns August and October 1996 Trimble SSE4000 receivers represented the GPS equipment. The receiver mounted in the aircraft was capable to record an additional input channel for registering time sync pulses. All GPS data were captured at a 1Hz data rate. In order to obtain a maximum accuracy level of the kinematic GPS positioning, only differential phase observations in addition to precise satellite orbits were the input of our post-processing. Moreover, the phase ambiguities due to signal loss to single satellites were once and again new determined with on-the-fly algorithms implemented in our software packages.

The DPA camera system represents with its INS and the AMPEX tape recorder one logical unit. The HDDT stores all DPA imagery and the INS data. At regular, by the hardware fixed time intervals - every time after storage of 512 data blocks, in which 1 DPA block corresponds to 2 stereo line scans or 1 multispectral line scan, respectively - this unit sends a sync impulse. In case of not having another imaging sensor on-board, this impulse is another input of the GPS receiver and therefore registered at the GPS time scale. Thus, the DPA imagery and INS data are directly synchronized with the GPS phase measurements.



(a) feature pattern for band-to-band registration (b) registered RGB DPA image Oct. 1996

Figure 4: Testsite Elchingen/Grosskuchen (EG).

If further imaging sensors are simultaneously used, for example the RMK and DPA, then time synchronization of all data sources becomes an important issue. For this reason, a sync scheme was developed which is depicted in Figure 5. The main feature is the exchange of sync signals.

The DPA and RMK generate one impulse each during their actual exposures, which is passed via a digital I/O port to a Laptop computer and registered with an internal time scale. In order to maintain the reference for the GPS time scale the PC sends a regular signal to the GPS receiver with a time interval of 10s. The receiver registers this signal at GPS time scale. Using a least-squares adjustment the matching of the local time to the GPS time is carried out. Afterwards, the sync impulses of DPA and RMK, registered at the local time scale, are transformed onto the GPS time scale using a time offset and drift parameter. This approach allows the time matching with an accuracy of better than 1ms.

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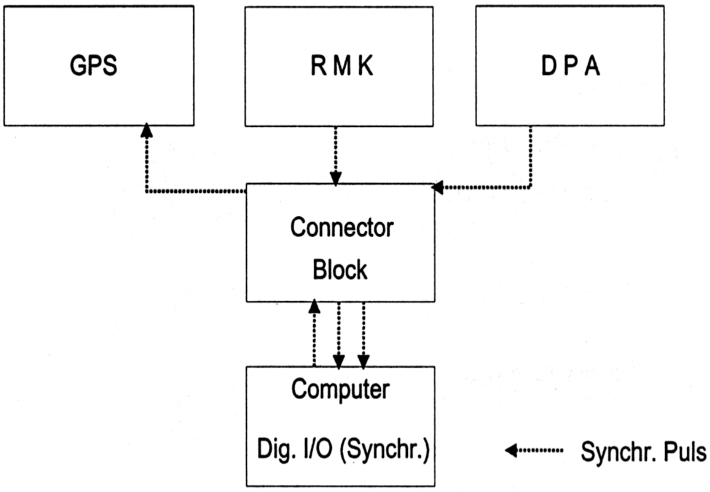

Figure 5: Scheme of time synchronization between GPS, DPA, and RMK.

4.1 Photogrammetric restitutions

After the GPS/INS integration the flight path is reconstructed by the exterior orientation parameters for every scan line j. Thus we have

- position X_{0j}, Y_{0j}, Z_{0j}, and
- attitude information ω_j, ϕ_j, κ_j

The attitude information is fixed by the three Eulerian angles arranged in the order: roll, pitch and azimuth. A comparison of the flight path positions and attitudes when using classical aerotriangulation with RMK imagery against the direct GPS/INS solution comes out with accuracies of σ_{Pos} =0.2-0.3m and σ_{At} =0.0067deg. This gives first hints on the accuracy level which could be reached with the DPA camera system.
The campaign July 1995 indicated problems with the stabilized platform which could be proven of being dependent on a special hardware device. After having repaired the platform these problems did not anymore occur in the other two campaigns. It should be noted, that using the exterior orientation parameters also these warped images could be rectified to an errorfree image geometry. The math model for this unwarping process is based on the collinearity equations. Using the pixel-by-pixel method for image rectification the pixels of the warped image could be resampled onto a horizontal plane with a mean terrain height Z_m. The following relations are valid

$$X = X_{0j} + (Z_m - Z_{0j}) \frac{r_{11j}x + r_{12j}y - r_{13j}c}{r_{31j}x + r_{32j}y - r_{33j}c}$$

$$Y = Y_{0j} + (Z_m - Z_{0j}) \frac{r_{21j}x + r_{22j}y - r_{23j}c}{r_{31j}x + r_{32j}y - r_{33j}c}$$

with $r_{11}...r_{33}$ as elements of the rotation matrix and x,y the coordinates of the warped image. Within the horizontal plane $Z=Z_m$ the unwarped pixels represent an irregular grid, as they have different exterior orientations. In order to arrive at a regular image structure a resampling has to be carried out. This unwarping process is demonstrated by Figure 6, in which an excerpt of two warped and their corresponding unwarped images are illustrated.

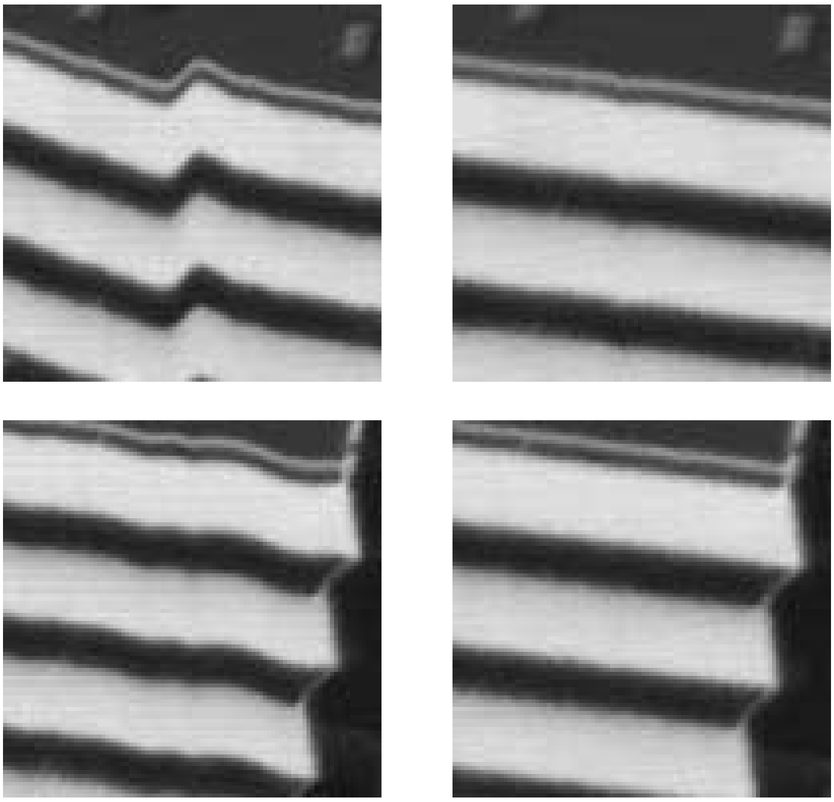

Figure 6: Warped (right) and unwarped (left) DPA images.

A first preliminary point determination using DPA imagery could be carried out but was not yet satisfactory because model errors within our bundle block adjustment did not allow to propagate the GPS/INS flight path restitution accuracy down to the earth surface. We reached an accuracy of nearly the same level as reported by O. Hofmann et. al (1993). Dependent on several test runs some results are given in Table 4.

# test run	# GCPs	# unknowns	σ_0(μm)	μ_X (m)	μ_Y (m)	μ_Z (m)
6	9	12	63,6	0,58	1,03	1,94
8	6	12	36,8	0,59	1	0,62

Table 4: DPA point determination accuracy.

4.2 Thematic mapping

One important issue of multispectral classification is the well-balanced dynamic range. All dynamic ranges have to be chosen such that features with less reflections are being represented with grey values 0 and the most reflected with grey value 255. Thus, an optimum grey value distribution is reached for a multispectral classification.

In order to quantify the grey value distribution over the whole dynamic range entropy figures are computed. These figures indicate the information content of grey values in one channel. The higher the entropy figure, the better the information content of digital image data. Therefore, it can be proven, whether the available information content of image data is to be represented with less than 8bit, without loosing information. In general terms, entropy is dependent on the landuse distribution of the imaged area, for example the entropy figure is bigger in areas with dominating vegetation in comparison with homogeneous arid zones. The multispectral DPA imagery is transformed from 12 bit to 8bit during data storage on the HDDT, therefore the theoretical maximum value is 8. The minimum value is 0 and this is only given in case of 1 grey value. An evaluation using the EG image data of the July 1995 campaign is indicated by Table 3.

channel	Blue	Green	Red	near Infrared
Strip 1	6.9	7.4	7.3	7.3
Strip 2	7.0	7.5	7.3	7.3
CIR image	--	7.5	7.3	7.4

Table 3: Entropy figures of EG.

This comparison with the color infrared image of the scanned aerial photograph does not lead to any important conclusions, because during scanning the parameter were chosen such that the dynamic range was well-balanced and therefore a high entropy figure is being automatically obtained.

Another important issue of multispectral imaging is band-to-band registration. This can be solved twofold: (1) by laboratory calibrations and (2) by photogrammetric image matching techniques. The latter one was preferred because the camera provider could not offer calibration values (offsets) directly after the campaigns. Ideally, the registration of a multispectral bandpass is guaranteed when using one lens. In the contrary, the DPA multispectral module consists of 4 lenses. In principle, the lenses are calibrated such that there is no offset between different CCD linear arrays and all 4 linear arrays are strictly nadir looking.

The band-to-band registration developed during our acceptance test study is directed to the matching of two channels onto each other. As reference channel served the green spectral window. Altogether, three steps are carried out to overcome non-calibrated multispectral CCD linear arrays:

- location and measurement of tie points
- transformations
- resampling

For step 1 an intensity-based least-squares matching (IBM) was applied. The matching is to be performed in a regular grid, therefore the left image serves as reference (master) and its grid is transformed into the right image. The approximate values of the transformation parameters are derived using image pyramids, for which a coarse grid is sufficient. Identical points are then found by IBM. Due to radiometric differences of the multispectral channels the grid has to be dense, otherwise not enough identical points between two channels can be found. Figure 7 indicates an excerpt of the 4 DPA multispectral channels.

The accuracy of the band-to-band registration when applying intensity-based matching techniques comes close to 0.1-0.2 pixels.

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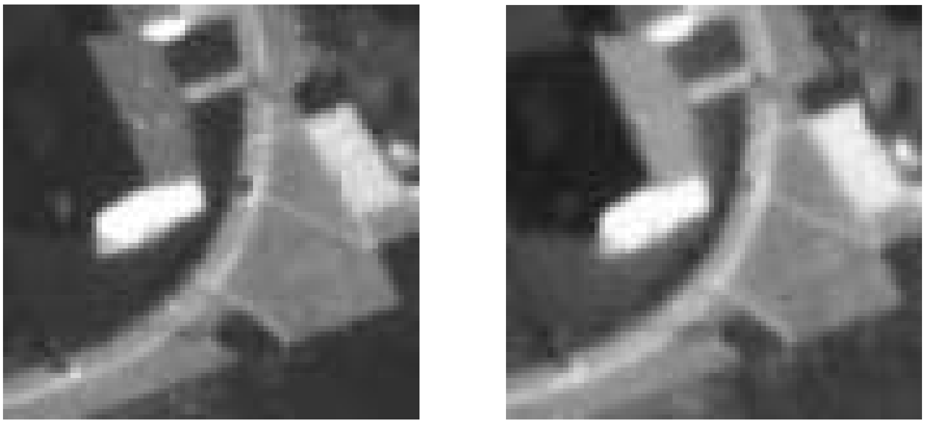
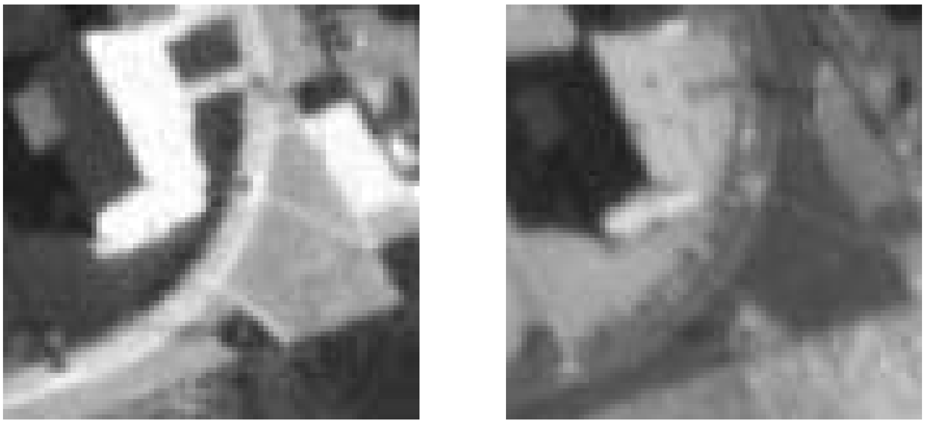


blue green



red near IR

Figure 7: Band-to-band registration of DPA multispectral channels.

5. CONCLUSIONS

The DPA camera system has proven the concept of stereo and multispectral mapping using three-linear pushbroom CCD arrays. This concept goes back to 1972 when Dr. Otto Hofmann invented the trilinear camera. The evaluation of the testflights over the testsites Vaihingen/Enz and Elchingen/Grosskuchen gives optimism for the near future that new digital camera systems will be developed for digital photogrammetric purposes. Although the three-linear camera concept is generally weak in geometry this can be overcome by GPS/INS integration. Resulting georeferenced digital imagery comes very close to full-frame or perspective geometry.

The ingredients of such a digital camera systems are already available. However, one main question arises: which architecture goes close with the technical developments, particularly in the domain of CCD and CMOS semiconductors.

Let us consider long linear CCD arrays: they are available at very attractive prices and also permit to put several sensors parallel to each other. This allows not only multispectral imaging but may also help to improve the size of the linear array. Moreover, color CCD linear arrays are offered at a resolution of 10,200 pixels per line and each color, for example the KODAK KLI-10203 linear array having a pixel size of 7µm with independent electronic exposure control.

However, there is a tendency to use concepts of digital still video cameras. Detector chips with 3,088x2,056 are already in use in digital close range photogrammetry (e.g. the KODAK DCS460). New products such as Rollei’s Q16 or of KODAK make use of 4,096x4,096 CCD elements. Military aerial reconnaissance cameras go even further. It is interesting to note, that Philips invented last year a full frame CCD array consisting of 7,000x9,000 pixels. But the ideal discretization of a 23cmx23cm image format would be the Silicon Pizza approach. This is not to be realized in the near future. Perhaps a combination of pushbroom linear arrays with full-frame CCD sensor elements is a feasible solution for the next ten years, in which the linear array consists of several 4Kx4K chips attached to each other. The pushbroom linear array camera with single line arrays and invented by Dr. Otto Hofmann could be realized at reasonable costs today. This architecture is simple, efficient, of low-cost and rigorous.

6. ACKNOWLEDGEMENTS

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