Accuracy assessment of the DLR 3K camera system

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Summary:.The DLR 3K camera system is a near real time airborne digital monitoring system for rapid emergency mapping. The system consists of three non-metric Canon EOS 1Ds Mark II cameras arranged in an array. A self-calibration bundle adjustment was performed to assess the accuracy properties of the camera system and to (re)determine the interior parameters of the camera. Within the framework of the DGPF project for the evaluation of camera accuracies, a flight campaign with the 3K camera system was performed on 15th on July 2008 at the test site in Vaihingen/Enz. In this paper, the results of the self-calibration bundle adjustment are presented with focus on the absolute accuracies at the check points, the stability of the interior parameters, and the stability of the boresight misalignment. Last two issues influence the accuracy of the direct georeferencing, as the image data will be orthoprojected in near real time without using any ground pass information.

Zusammenfassung: *Genauigkeitsbestimmung des DLR 3K Kamera Systems.* Das DLR 3K Kamera System ist ein flugzeuggetragenes, digitales Nahe-Echtzeit Fernerkundungssystem für die schnelle Kartierung in Katastropheneinsätzen. Das System besteht aus drei nicht-metrischen Canon EOS 1Ds Mark II Kameras, die in einer Linie auf einer Plattform montiert sind. Um die Genauigkeitseigenschaften des Kamerasystems und die innere Orientierung der einzelnen Kameras erneut zu bestimmen wurde eine Selbstkalibrierung mit einer Bündelblockausgleichung durchgeführt. Dazu wurde am 15. Juli 2008 eine Flugkampagne im Rahmen des DGPF Projekts zur Evaluierung von photogrammetrischen Kamerasystemen in Vaihingen an der Enz durchgeführt. In diesem Artikel werden die Ergebnisse der Selbstkalibrierung vorgestellt, u.a. die absolute Genauigkeit an den Kontrollpunkten, die Stabilität der inneren Orientierungsparameter und die Stabilität der Kameraeinbauwinkel. Die beiden letzten Punkte haben v.a. auf die Genauigkeit der direkten Georeferenzierung Einfluss, da die Orthoprojektion in der Nahen-Echtzeit Prozesskette ohne Boden-Passinformation durchgeführt wird.

1 Introduction

For disaster monitoring from airplanes, a near real time sensor and processing system was developed at DLR. This system consists of three digital cameras, an onboard processing unit, a microwave data link, and a mobile ground station with processing units. Image data will be distributed directly to the security related and rescue ground forces in cases of disasters.

The most important product for the ground forces is the orthoprojected georeferenced image, which will be processed onboard by means of direct georeferencing using the near real time GPS/IMU data. Hence, main influencing factors on the accuracies of the orthoprojected images are the interior camera parameters, the determination of the boresight misaligment and the accuracies of the IMU angles.

In this paper, the results of a self-calibration bundle adjustment are presented based on the images from the flight campaign on 15th July 2008 in Vaihingen/Enz. This flight campaign was conducted within the framework of the DGPF project for the evaluation of camera accuracies (Cramer 2009). Special focus lies on the investigation of the stability of the interior parameters, the absolute accuracies at the check points, and the stability of the boresight misalignment for direct georeferencing applications.

2 System overview

The 3K camera system consists of three non-metric off-the-shelf cameras (Canon EOS 1Ds Mark II, 16 MPix). The cameras are arranged in a mount with one camera looking in nadir direction and two in oblique sideward direction (Fig 1), which leads to an increased FOV of max 110°/ 31° in across track/flight direction. The chip size is 24x36mm with a pixel size of 7.212µm. The image size is variable up to 3328x4992 pixel.

The camera system is coupled to a GPS/IMU navigation system, which enables the direct georeferencing of the 3K optical images. Interior camera parameters were determined by a laboratory calibration (Kurz, F., 2007). Fig 2 illustrated the image acquisition geometry of the DLR 3K-camera system. Based on the use of 50 mm Canon lenses, the relation between airplane flight height, ground coverage, and ground pixel size is shown, e.g. the pixel size at a flight height of 1000 m above ground is 15 cm and the image array covers up 2.8 km in width.

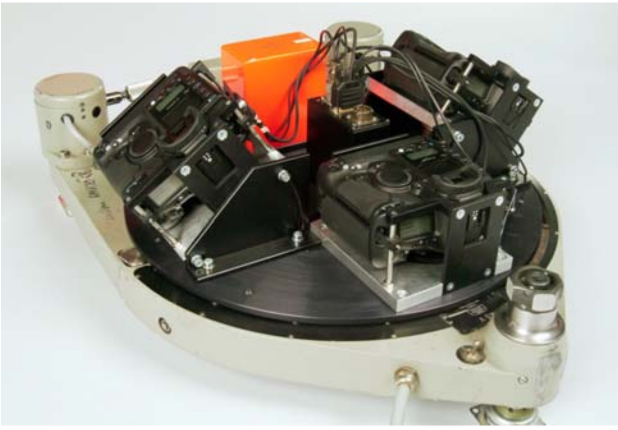


Fig 1 DLR 3K-camera system consisting of three Canon EOS 1Ds Mark II, integrated in a ZEISS aerial camera mount

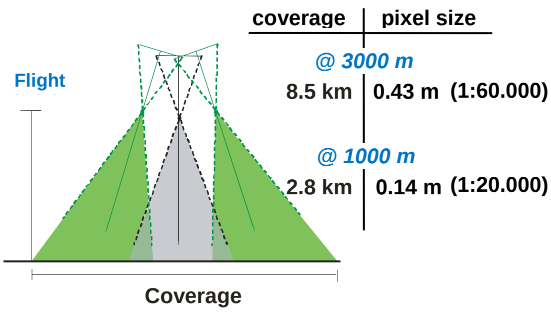
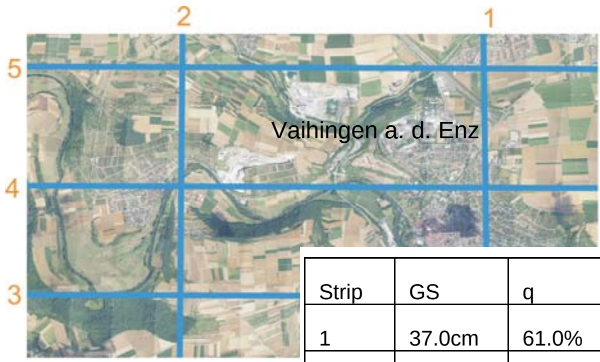


Fig 2 Illustration of the image acquisition geometry. The tilt angle of the sideward looking cameras is approx. 35°.

2 Flight campaign

For the flight campaigns, the test site in Vaihingen/Enz was chosen, which was established by the University of Stuttgart. This test site exists since 1995 and was used for several camera evaluation campaigns (Cramer 2005). There are 200 signalized points distributed over on area of 7.5km x 5.0km. This test site was imaged by the 3K camera system on 15th of July 2008 from five flight strips in different flight heights. Details of the flight configuration are listet in Figure 3.



Strip	GS	q	p	Hg	Nr	Dir
1	37.0cm	61.0%	60%	2600m	12x3	S-N
2	37.0cm	61.0%	60%	2600m	12x3	N-S
3	22.9cm	64.5%	60%	1350m	24x3	E-W
4	22.9cm	64.5%	60%	1350m	24x3	E-W
5	22.9cm	64.5%	60%	1350m	24x3	E-W

Fig. 3: Overview and details of the flight campaign in Vaihingen on 15th July 2008, including ground sampling distance (GS), across and along overlap (q and p), height above ground (Hg), number of images (Nr), and flight direction (Dir) for each flight strip

3 Calibration of the 3K camera system

Two calibrations of the 3K camera system were performed: one on a ground test field in 2006 (Kurz et. al, 2007) and one inflight in 2008. Table 1 shows the configuration and parameters of the bundle adjustment for the self calibration of the 3K camera system. Tie points were matched and all available control points were measured in 281 images from all three cameras. Tie points were matched only in selected overlapping areas to reduce the number of observations. Additionally, the GPS positions of the projection centers were introduced in to the bundle adjustment to increase the accuracy of the self calibration. Alltogether, a redundancy of 302940 was reached and five interior parameters were estimated for each camera.

	Total number	Image coordinates	Control point coordinates	Navigation- and other parameter	
Observations	607101	605976	249	876	
		Tie point coordinates	Exterior image para-meters	Interior parameters	Drift and offset pa-rameters
Unknowns	304161	100806	285	15	18
Redundance	302940				
Sigma a pos-teriori	2.39µ				

Table 1 Parameters of the bundle adjustment based on images from 15th July 2008.

A five parameter interior camera model was chosen for the calibration: the focal length c, the principal point x_0 and y_0, and the radial distortion parameters A_1 and A_2. The radial distortion Δr is then calculated by

$$\Delta r = A_1\left(r^3 - r \cdot r_0^2\right) + A_2\left(r^5 - r \cdot r_0^4\right) \qquad (1)$$

where r is the radial distance to the frame center and r_0=0.014 the reference radius.

Table 2 lists the results of the first calibration in 2006 in comparison with the inflight self calibration based on the flight campaign in Vaihingen on 15th July 2008. The estimated focal lengths in 2006 were shorter than the focal lengths derived from inflight self calibrations in 2008. In 2006 problems arose due to the short distance of around 10 meters to the laboratory test field, which distorted the estimation of the focal length. Thus, the difference in the estimated focal lengths reaches 0.16 mm due to the different object distances during the calibration (see Table 2).

The principal points moved up to 46µm in different random directions between the years, which corresponds to around 6 pixel based on the pixel size of 7.212µm. Reasons for the instability of the principal points as well as for the changes of the focal length may be also thermal or gravity effects.

Significant differences in the radial distortion parameters are visible. The different object distances do not account these differences, instead the different aperture values during the calibration are considered as main contributor to these differences.

	Left		Nadir		Right	
	2006	2008	2006	2008	2006	2008
Focal Length c [mm]	51.316	51.476 ±0.001	50.963 ±0.022	51.112 ±0.001	51.156	51.316 ±0.001
Principal point y_0 [µm]	-21.3	-16.5 ±2.3	-52.0 ±0.6	-17.6 ±1.8	7.6	-39.2 ±3.3
Principal point x_0 [µm]	-8.1	-9.1 ±0.4	-99.2 ±0.8	-43.9 ±0.4	2.2	-23.3 ±0.6
Radial Distortion A_1 [m^{-2}]	-57.540	-51.475 ±0.350	-55.930 ±0.767	-53.671 ±0.406	-56.673	-51.902 ±0.061
Radial Distortion A_2 [m^{-4}]	29568.7	23007.0 ±706.7	28396.5 ±1654.0	25418.5 ±821.5	28210.5	22103.7 ±122.5
Aperture	11.3	7.0	11.3	7.0	11.3	7.0

Table 2 Comparison of the interior camera parameters derived from calibrations in the year 2006 and 2008.

The result of the self calibration are visualized in Figure 4, which shows the radial distortion of the three lenses (Canon EF1.4) and the movement of the prinicpal point. The distortions reach enormous 0.35mm at the image edges and the principal point moved up to 0.1mm between the calibrations.

	Theoretical RMSE	Empirical RMSE	Empirical RMSE (without systematics)	RMSE of the direct georeferencing
X	0.128 m	0.647 m	0.331 m	~ 3 m
Y	0.147 m	0.651 m	0.380 m	
Z	0.325 m	0.576 m	0.527 m	

Table 3 Absolut accuracies of the 3K camera system

The results of the final accuracy assesment of the 3K camera system are listed in Table 3. The RMS errors of the coordinates at the check points are calculated in three ways: first by the theoretical standard deviations from the bundle adjustment, second by the differences between real and estimated coordinates, and last by the differences between real and measured coordinates from the direct georeferencing. The theoretical and empirical RMSEs without systematics correspond quite well and average out a full ground pixel size in X- and Y-direction and more than double in Z-direction. In the absolute empirical RMSE systematic errors of -0.56, -0.53 resp. -0.23m in X-, Y- resp. Z-direction are enclosed, which may be caused by systematic GPS offsets. Thus, the absolute empirical accuracy reaches up to 0.65m in XYZ-direction.

The accuracies reached by the direct georeferencing are clearly worse in the magnitude of meters, as here the IMU and the DEM accuracy, as well as the interior and boresight determination influence the accuracy.

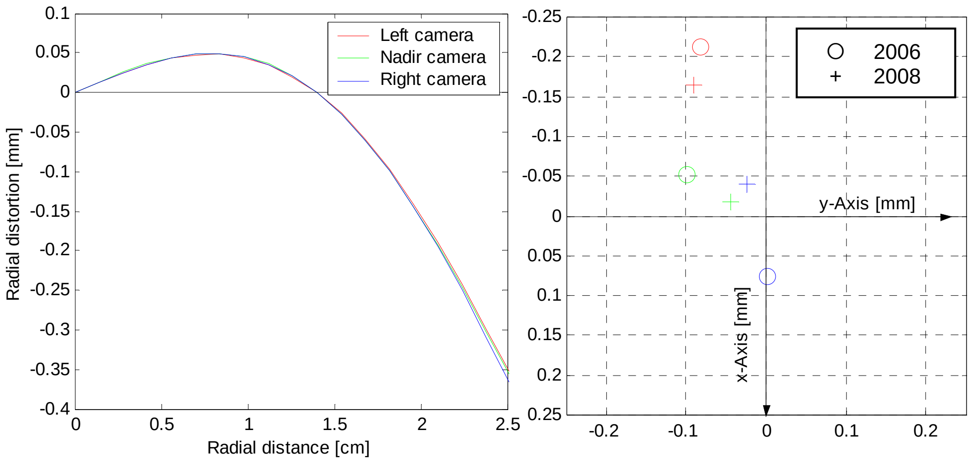


Fig 4 Left: Visualization of the radial distortion; Right: Movement of the principal point.

4 Boresight determination

Images from the 3K camera system are mainly orthoprojected by means of direct georeferencing using the GPS/IMU data. For this, the boresight misalignment angles must be determined correctly. For our purpose, the boresight angles are considered as constant during one flight campaign. Between the flight campaigns, the boresight angles are changing as the mounting of the IMU system must be adjusted to the different DLR airplanes. Hence, an easy way of boresight misalignment determination is implemented without using ground control points (Kurz et. al, 2007), as the borsight angles must be estimated repeatedly for each flight campaign.

Another import issue is the investigation of the stability of the boresight angles within and between the flight strips. Drifts of the GPS/IMU system, vibrations of the camera bodies, thermal effects, and other disturbances could change the boresight angles, and thus break the assumption of stable boresight angles.

The bundle adjustment of the data from 15th July is a valuable database to determine the stability of the boresight angles within the flight strips. The exterior image attitude of all images from the bundle adjustment, which is independent of the IMU measurement, are compared with the measured IMU angles roll, pitch, and yaw. The difference between the estimated image attitudes and the measured IMU angles are simplifiying the boresight misalignment angles regarding the roll, pitch, and yaw, which are called here the *effective boresight angles.*

In Figure 5, the effective boresight angles for each image and for each camera are statistically evaluated and compared to the mean value (black continuous line) and to the boresight angle from the method in (Kurz et. al, 2007) (black dashed line). For the plotted errorbars, only the standard deviations of the image attitudes from the bundle adjustment were used, i.e. the standard deviations of the angles from the IMU Systems (IGI IIb) with 0.01° resp. 0.1° in roll, pitch resp. yaw must be added to the plotted errorbars. With this, the stability of the boresight angles can be statistically evaluated.

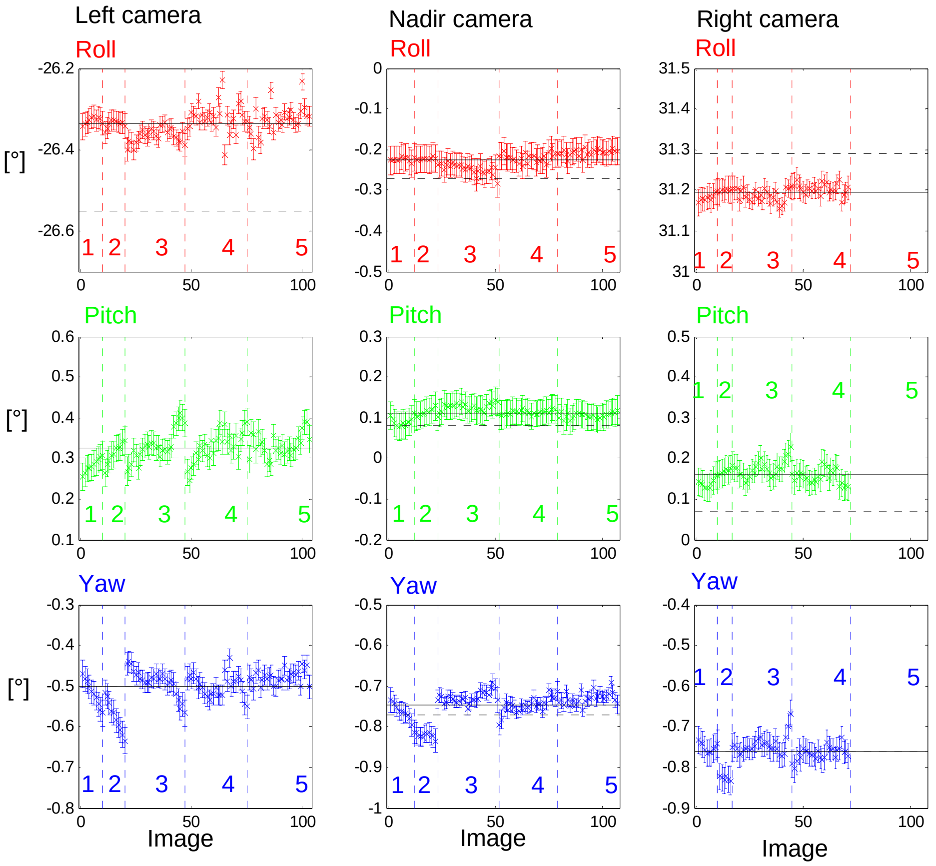


Fig 5 Plots of the *effective boresight angles* regarding roll, pitch, and yaw for each image and for each camera. The associated flight strips are marked with coloured numbers.

The plots of the effective boresight angles show higher variations and systematic drift effects in the boresight yaw angle (blue), which can be explained by the higher standard deviation of yaw angles 0.1°.

At the effective roll and pitch angles, variations within the strips occur, but they lie except for some outliers in the limits of the expected accuracies, i.e. there is no statistically significant instability in the boresight misalignment. Higher deviations at the end of the strips may be caused by reduced stability of the block adjustment at these images.

The comparison of the mean boresight angle (continouos line) with the independent estimated boresight angles (dashed line) shows good correspondence for the boresight pitch and yaw. Systematic deviations are detected for the boresight roll, which seems slightly overestimated for the left and the right camera in case of the independent estimation without pass information. A reason for this may be gravity effects caused by the oblique view of the cameras.

5 Conclusions

The accuracy of the 3K camera system was evaluated based on the images from the flight campaign on 15th July 2008 in Vaihingen/Enz. A self calibration bundle adjustment was performed and the reached accuracies average out as expected a full ground pixel size. Based on a former calibration in 2006, the stability of the interior orientation was evaluated and also the boresight stability was evaluated using the GPS/IMU data. Summing up, variations of the interior camera orientation occur whereas the boresight misalignment remained quite stable in our investigations. The accuracy of the direct georeferencing is in the maginitude of meters, as the IMU accuracy limits the overall accuracy.

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