

# GEOMETRIC ACCURACY ASSESSMENT OF ADS40 IMAGERY UNDER VARIOUS NETWORK CONFIGURATIONS

V. Casella<sup>a</sup>, M. Franzini<sup>a</sup>, S. Kocaman<sup>b</sup>, A. Gruen<sup>b</sup>

<sup>a</sup>University of Pavia, Department of Building and Territorial Engineering, Via Ferrata, 1, I - 27100 Pavia, Italy  
(vittorio.casella, marica.franzini)@unipv.it

<sup>b</sup>ETH Zurich, Institute of Geodesy and Photogrammetry, CH-8092 Zurich, Switzerland  
(skocaman, agruen)@geod.baug.ethz.ch

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## ABSTRACT

The ADS40 camera is a commercial example of the airborne Three-Line-Scanner (TLS). Its particular sensor geometry requires new approaches and a specialization of methods and algorithms to solve the triangulation problem. The goal of the paper is to investigate the geometric accuracy performance of an ADS40 camera under various network configurations and using different trajectory models and different sets of additional parameters for self-calibration. Investigations are performed by two independent research Groups, the Institute of Geodesy and Photogrammetry (IGP), ETH Zurich, and the Geomatics Laboratory of the University of Pavia. Identical image and point datasets are used by both parties to test different trajectory models and additional parameters for self-calibration.

The test datasets contain three image blocks with 2000 m, 4000 m and 6000 m flying heights, which have been acquired over the Pavia Test Site (PTS), Italy using an ADS40 camera. The average ground resolutions are approximately 20 cm, 40 cm, and 60 cm for the three blocks. 50 signalized GCPs installed with white square markers of 60 cm side length are used in the tests.

The tests were performed with different numbers and distributions of GCPs and with and without self-calibration procedures. In addition, two different trajectory models are tested at the IGP, ETH Zurich. Also, direct georeferencing without the use of GCPs has been performed. The RMSE values, given in pixels, for planimetry and height, obtained with triangulation and self-calibration for the best cases of each block are:

- 2000 m block: 0.20 and 0.25
- 4000 m block: 0.20 and 0.30
- 6000 m block: 0.13 and 0.24

The accuracy results of both Groups are consistent and show significant improvements when self-calibration is applied.

## 1 INTRODUCTION

### 1.1 Background

The Linear Array CCD sensors have been introduced into the field of aerial photogrammetry almost a decade ago. The first commercial line scanner ADS40 was developed by LH Systems jointly with the DLR (Sandau et al., 2000). At the same time, Starlabo Corporation, Tokyo designed the airborne Three-Line-Scanner (TLS) system, later called as STARIMAGER, jointly with the University of Tokyo (Murai and Matsumoto, 2000).

For the triangulation of the TLS imagery, a modified bundle adjustment algorithm based on the collinearity equations has been developed at the IGP, ETH Zurich. It includes as options three different types of trajectory models (Gruen and Zhang, 2003): (a) Direct georeferencing model with stochastic exterior orientations (DGR), (b) Piecewise Polynomials with kinematic model up to second order and stochastic first and second order constraints (PPM), and (c) Lagrange Interpolation Polynomials with variable orientation fixes (LIM). These models are used in the triangulation process for the improvement of the exterior orientation parameters (EOP), which are measured by the GPS/IMU. A number of ground control points (GCPs) are needed for this approach in order to achieve high accuracies. In addition, the self-calibration capability has been added to the sensor model using basically a set of 18 additional parameters (APs) to model the systematic errors of the camera and of other

system components and tested in two different testfields (Kocaman et al., 2006).

The Orima approach to the triangulation problem uses the orientation fixes concept. The algorithmic details are given in Hinsken et al. (2002). When compared to the LIM of the IGP, ETH Zurich, the models are similar in terms of estimating the EOP at the orientation fixes. The Brown self-calibration model, originally developed for frame cameras, was adapted for the ADS40 sensor and is currently available in Orima (Tempelmann et al., 2003).

The triangulation approaches of ETH Zurich and the Orima software have been tested in the past using the ADS40 dataset acquired over the Vaihingen/Enz testfield, within the EuroSDR project framework "Digital Camera Calibration". The accuracy results of both approaches are almost identical when self-calibration is applied. They correspond to 0.22 and 0.38 pixels in planimetry and height, respectively. For more details see Cramer (2007).

### 1.2 The datasets

The Pavia test site has been established by the Geomatics Laboratory, University of Pavia, Italy. A number of signalized and natural GCPs have been added to the site. Three different ADS40 test flights over the Pavia testfield have been performed in 2004 by the CGR Company, Italy, which is acknowledged for providing the dataset analyzed in the paper. Seven ADS40

strips were taken at three different flight altitudes (2000 m, 4000 m, and 6000 m). The staggered-array functionality was switched off and only one CCD line was used for image acquisition for the backward and forward views.

We have started our investigations with the 2000 m block (Casella et al., 2007, Kocaman et al., 2007a) and continued with the 4000 m dataset (Kocaman et al., 2007b). In this paper, we compare the results of all three blocks. Figure 1 shows the strip outlines of all image strips. The inner rectangle (black) denotes the actual processing area for triangulation. The average ground resolutions are ~20 cm, ~39 cm, and ~62 cm in the low-to-high flight altitude order.

Signalized GCPs with a size of 60 cm are used in this study. They are measured with a high-accuracy GPS. The red points in Figure 1 are used as control points in the tests of the 5 GCPs configuration. For the 12 GCPs configuration, the green points and the four red points in the corners are used. The black points are used as independent check points in all tests.

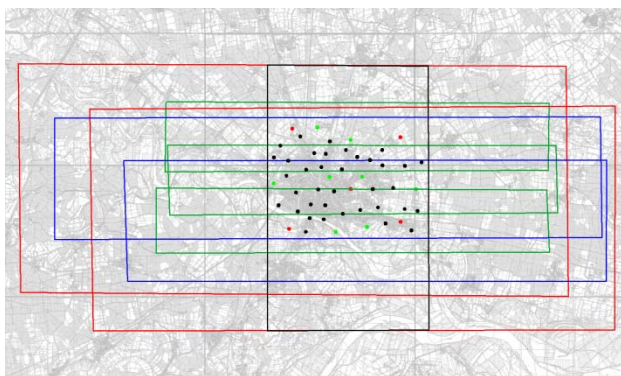


Figure 1. Structure of the blocks (2000 m in green; 4000 m in blue; 6000 m in red) and distribution of control points

## 2 METHODOLOGY

### 2.1 Camera and trajectory models: the ETH Zurich approach

Three different trajectory models have been developed and implemented by Gruen and Zhang (2003) for the triangulation of the TLS sensors. Two of them, the DGR and the LIM, are tested in this study. The DGR models the systematic errors of the image trajectory as a whole. 3 positional shifts, 3 attitude shifts and 3 attitude drift parameters are employed in the model. With the LIM, correction parameters for the given EOPs are determined in the so-called orientation fixes, which are introduced at certain time intervals. 6 correction parameters (one shift parameter for each EO element) per orientation fix are estimated in the adjustment. Between the orientation fixes, the estimated parameters are interpolated using Lagrange polynomials, in order to correct the given EOPs of an arbitrary scan line.

The physical structure of the TLS camera is considered in the self-calibration model. A total of 18 APs have been identified, implemented, and tested at the IGP, ETH Zurich (Kocaman et al. 2006). For the selection of the AP set one has to take into account that the triangulation is supported by the on-board GPS/IMU measurements, which are introduced as observations into the adjustment. The AP set then consists of lens-based and CCD line based parameters, as:

- $\Delta c$ : Systematic error in the focal length of the camera lens.

- $\Delta x_{pb}, \Delta x_{pm}, \Delta x_{pf}$ : Displacements of the line centers of the three Linear Array CCDs from the principle point (PP) of the camera lens, defined in flight direction.
- $\Delta y_{pb}, \Delta y_{pm}, \Delta y_{pf}$ : Displacements of the line centers of the three Linear Array CCDs from the principle point (PP) of the camera lens, defined across flight direction.
- *Lens Distortion Parameters*: Radial symmetric lens distortion ( $k_1, k_2, k_3$ ) and decentering distortion ( $p_1, p_2$ ) models of Brown (1971).
- $s_{yb}, s_{ym}, s_{yf}$ : Affinity is defined in  $x$ -direction by Beyer (1992) for close-range frame CCD cameras. In this study, affinity parameters for each CCD line are used in the  $y$ -direction.
- $\Delta \theta_b, \Delta \theta_m, \Delta \theta_f$ : represents the inclination angle between each CCD line and the  $y$ -axis of the camera coordinate system.

The self-calibration algorithm aims to determine the optimal set of APs for the optimal estimation of the object space coordinates of the image points. The APs are introduced as free unknowns into the adjustment, because a certain a priori stability is guaranteed by the use of GPS/IMU observations. The adjustment procedure starts with the full AP set and eliminates undeterminable parameters automatically in an iterative approach. The major problem for parameter elimination is the finding of robust criteria for rejection of undeterminable parameters. A stepwise parameter elimination algorithm proposed by Gruen (1985) is used here.

### 2.2 Camera and trajectory models: the University of Pavia approach

The Pavia group used the commercial software supplied by the ADS40 camera vendor: Socet Set 4.4.1, Gpro 2.1 and Orima 6.1. This is the same configuration used by the CGR company which supplied the data.

An image coordinate system is defined on the focal plane of the camera: the origin coincides with the principal point, the  $x$ -axis is parallel to the flight direction, and the  $y$ -axis is parallel to the sensor lines. The theoretical camera model assumes that the sensor lines are parallel to the  $y$ -axis and occupy the nominal positions. They are assumed to be straight and lie in a plane. The CCD elements are equally spaced and the lens is undistorted.

In-flight camera calibration is performed by the manufacturer and deviations from the theoretical model, caused by lens distortion, offset and inclination of sensor lines, are quantified. A mathematical model of deviations is estimated and then calibration files are written. They contain, for every sensor line, a look-up table with the image coordinates of the centre of each CCD element: these coordinates are determined in order to compensate for any deviation. The conversion between the pixel coordinates and the image coordinates of a certain feature is performed through the look-up tables, therefore the obtained pixel coordinates are nominally free of any distortions. In this paper, the **basic** camera model refers to the theoretical one, integrated into the calibrated look-up tables.

With the Orima software, it is possible to estimate a 7-parameter datum transformation in the case that GPS/IMU and GCP data relate to different reference systems. The misalignments between camera and IMU reference systems can also be treated as unknowns. In addition, a self-calibration method, which aims to improve the given calibration, can be performed. The Brown model (Brown, 1976) has been implemented in Orima. It has 21 parameters, was originally defined for large-format, analogue frame cameras and is here

adopted for line cameras. The second camera model considered in this paper, named **self**, includes these self-calibration parameters and also additional parameters concerning a datum transformation and the IMU misalignments.

The trajectory model implemented in Socet Set and Orima is based on the orientation fixes concept. For the mathematical description of this model, please see Hinsken et al. (2002). In the bundle adjustment, the exterior orientation parameters (EOPs) of predefined orientation fixes are estimated. The EOPs at any time are obtained through the so-called linear interpolation of corrections.

### 3 TEST RESULTS

The triangulation and the accuracy assessment have been carried out independently by the two Groups. The stochastic model parameters and the test network configurations are arranged identically. The trajectory models are tested both with and without self-calibration.

#### 3.1 Preparation of the test data

The image coordinate measurements of the signalized control points were manually performed in mono mode at the Geomatics Laboratory of the University of Pavia, with the programs Socet Set and Orima, and successively provided to the ETH Zurich Group. Tie points were extracted and measured automatically with the APM procedure of Socet Set. Images of the forward and backward panchromatic lines (non-staggered) and nadir RGB lines (composite) were used in the measurements.

Table 1. ETH Zurich results of direct georeferencing obtained using the forward intersection method

Block	2000 m block			4000 m block			6000 m block		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
<i>RMSE</i>	0.12	0.10	0.65	0.32	0.57	1.79	0.45	0.64	2.21
<i>Mean</i>	0.01	-0.01	-0.57	-0.14	0.34	-1.78	-0.31	0.40	-2.20
<i>Sigma</i>	0.10	0.10	0.22	0.15	0.18	0.39	0.28	0.35	0.78

#### 3.3 University of Pavia results

The **basic** and **self** camera models were assessed, each with 5 and 12 GCPs. For the sake of clarity, the assessment procedure is summarized: aerial triangulation is performed, in order to improve the external orientation parameters (EOPs) at the fixes; check points (CKPs) are inserted into the adjustment as tie points, so that the calculation determines their object-space coordinates, which are compared with those measured by GPS. When the **basic** camera model is adopted, the mere aerial triangulation is calculated and only the refined EOPs are determined. When the **self** camera model is adopted, new calibration look-up tables are also determined, during the adjustment, together with further parameters, such as a datum transformation and new IMU misalignments. Figures 2 to 4 summarize results for the three blocks considered. Continuous lines show the empirical RMSE figures and the dotted ones refer to the theoretical values, extracted from the variance-covariance matrix of the adjusted unknowns. The  $RMSE_{XY}$  values are calculated as the average of the single planimetric figures  $RMSE_X$  and  $RMSE_Y$ .

Analyzing the results, some trends are common to all the three blocks:

- in the **basic** scenarios, when no self-calibration is performed, the planimetric RMSEs are around 1 GSD, while the height RMSEs are in the range between 2 and 3 GSD;

Ground coordinates of control points were measured by the Pavia Group by GPS. The accuracies of the coordinates are better than 1 cm for all directions (X,Y,Z). 46, 50, and 49 GCPs were measured in the images of the 2000 m, 4000 m and 6000 m blocks, respectively. Two different GCP configurations (5 and 12 GCPs) were tested in order to quantify the effect of the number of GCPs on the results. The same GCP subsets were used as control points in all blocks.

The stochastic model plays a key role in the adjustment. Therefore a predefined set of a priori standard deviations were used for all tests with the following values:

- image coordinates: 1/3 pixel (= 2.2 micron)
- object coordinates of GCPs: 1.5 cm for X,Y, and 2 cm for Z
- GPS/IMU measurements: 10 cm for X,Y, and 20 cm for Z; 0.006<sup>g</sup> for  $\omega, \phi$ , and 0.009<sup>g</sup> for  $\kappa$ .

These values were kept identical in all tests.

#### 3.2 Direct georeferencing assessment

Direct georeferencing is performed by both groups using two different methods. The Pavia Group applied an aerial triangulation with very high constraints on the given trajectory values. The ETH Zurich Group used multiple weighted forward intersections. The results are quite similar in terms of object space residuals. Table 1 shows the results of the ETH Zurich Group. All three datasets show systematic errors, especially in the Z component, as can be seen from the mean of the residuals. The sigma variable is computed via error propagation from the covariance matrix of the spatial intersection.

- in the **self** scenarios, when self-calibration is performed, we achieve accuracies well below the GSD;
- considering 12 GCPs instead of 5 doesn't give, in general, a strong gain; the improvement is more significant for the Z component and in the **basic** scenarios;
- in the **basic** scenarios it is not possible to reach the usual photogrammetric accuracy levels, regardless of the GCP number. In the **self** scenarios top-quality, sub-pixel accuracies are attainable, even with only 5 GCPs.

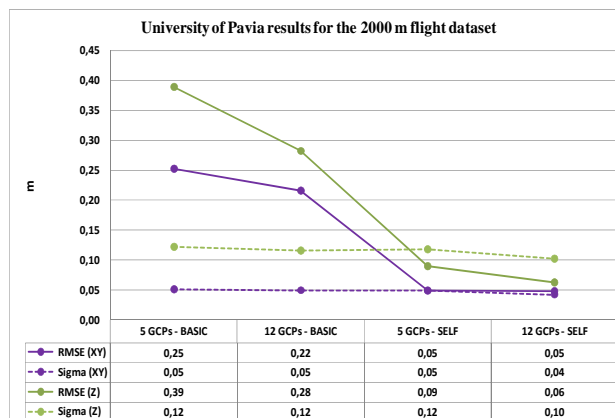


Figure 2. Accuracy figures for the 2000 m block, University of Pavia, in metres.

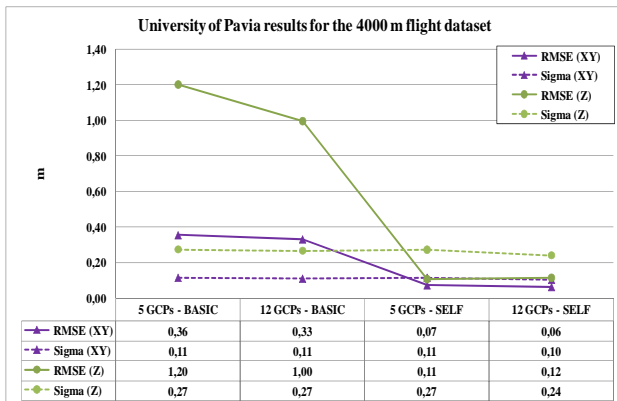


Figure 3. Accuracy figures for the 4000 m block, University of Pavia, in metres.

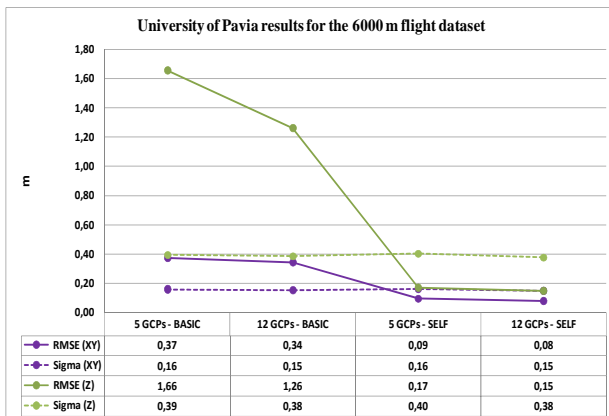


Figure 4. Accuracy figures for the 6000 m block, University of Pavia, in metres.

Not surprisingly, the best configuration is **self** with 12 GCPs, for all the blocks. The obtained accuracies are summarized for this scenario, for the planimetric component and for Z (all in GSD units):

- for the 2000 m block: 0.25 in X,Y and 0.30 in Z;
- for the 4000 m block: 0.15 in X,Y and 0.31 in Z;
- for the 6000 m block: 0.13 in X,Y and 0.24 in Z.

In the **self** scenarios, the camera's internal geometry is re-determined and other parameters are re-estimated, as previously explained. The many experiments which we have performed, whose results cannot be shown here because of the space constraints, clearly show that the most important contribution to the level of accuracy is given by camera self-calibration, while the other additional parameters only give minor benefits. Therefore, self-calibration is necessary to reach sub-pixel accuracies.

### 3.4 ETH Zurich results

The DGR and the LIM models were tested in two different GCP configurations (5 and 12). The self-calibration method was applied to both models and the results are compared with the no-self-calibration case. The LIM was tested with two different numbers of orientation fixes in each block. The larger fix number in each block is chosen to match approximately the interval of the Orima orientation fixes. The fix number 4 is applied in all blocks to check the effect of a smaller number of orientation fixes.

The **a posteriori sigma naught** ( $\sigma_0$ ) values of the ETH Zurich tests range between 0.38-0.48 pixels for the 2000 m block, between 0.44-0.52 pixels for the 4000 m block, and between 0.49-0.53 pixels for the 6000 m block.

The test results of the 2000 m, 4000 m, and 6000 m blocks are demonstrated in Figures 5, 6, and 7, respectively. The self-calibrating versions are denoted in the Figures by "SC".

In the 2000 m block, the DGR produces the most accurate and stable results in both GCP configurations and with self-calibration. The LIM with 18 orientation fixes seems unstable, which implies that there are too many unknowns parameters in the system. Going from 5 to 12 GCPs comes with an improvement of the accuracy values in all models.

In the 4000 m block, The DGR and the LIM results with self-calibration are very similar in planimetry, while in height the DGR performs slightly better. The results of the 5 and 12 GCP cases are very similar in all self-calibration tests.

When the DGR and LIM results of the 2000 m and 4000 m blocks are compared, the LIM performs slightly better in height when self-calibration is not applied. With self-calibration, the DGR results at the same level of accuracy, and sometimes even better. This implies that the given trajectory values of these two blocks contain uniformly distributed errors, i.e. free of jumps and discontinuities, and even a less complex model is sufficient for modeling.

In the 6000 m block, this pattern changes in favor of the LIM with the larger number of orientation fixes. In the 5 GCP case, the LIM-10 produces the best results with self-calibration, both in planimetry and in height. In the 12 GCP case, while the RMSE<sub>XY</sub> values of all models are equal, the RMSE<sub>Z</sub> values improves with the LIM-10. Going from 5 to 12 GCPs, there is an improvement in all models. However, considering the 62 cm footprint, the improvement is not really significant.

In all cases, the self-calibration results in great improvements. When the results of the 12 GCP cases **without self-calibration** are compared to the results of the 5 GCP cases **with self-calibration**, the results of the latter ones are comparable (RMSE<sub>Z</sub> of 2000 m block) or better (RMSE<sub>XY</sub> of all and RMSE<sub>Z</sub> of 4000 m and 6000 m blocks). Therefore, the use of self-calibration (with appropriate care) is highly recommended to obtain a good level of accuracy even with a small number of GCPs.

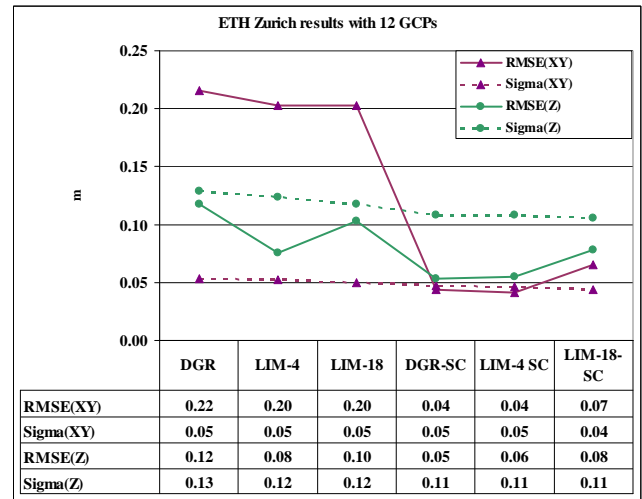
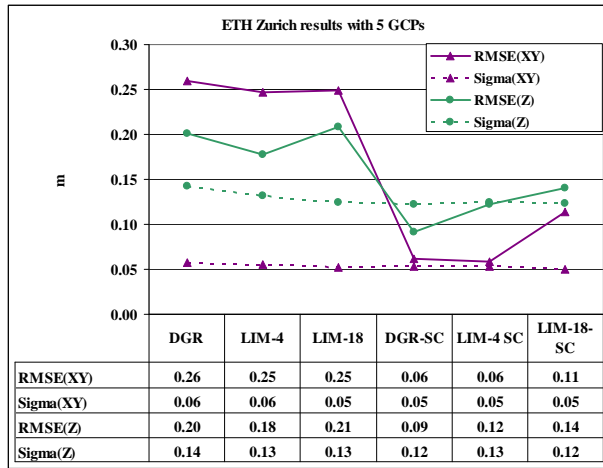


Figure 5. Accuracy figures for the 2000m block, ETH Zurich

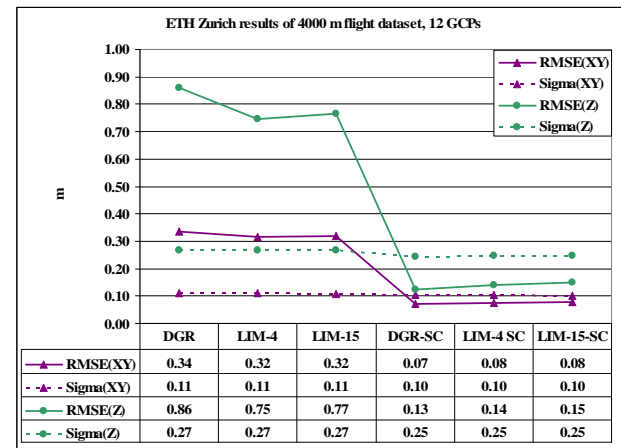
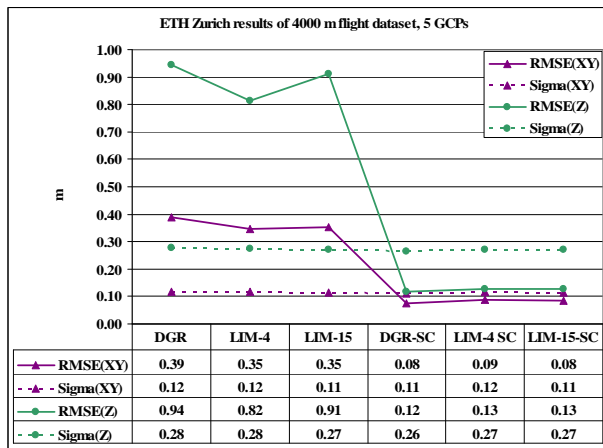


Figure 6. Accuracy figures for the 4000 m block, ETH Zurich

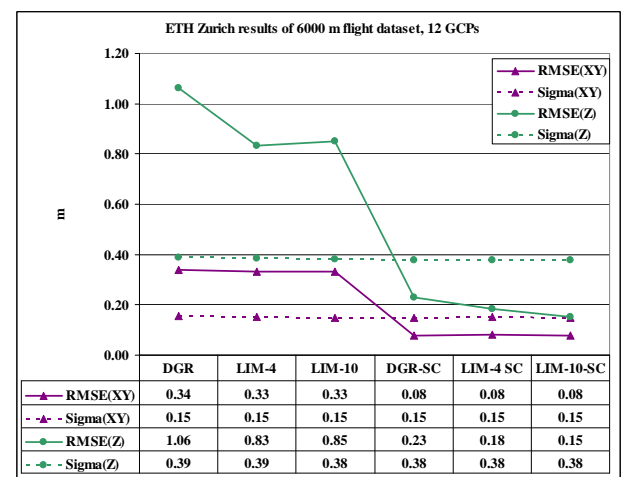
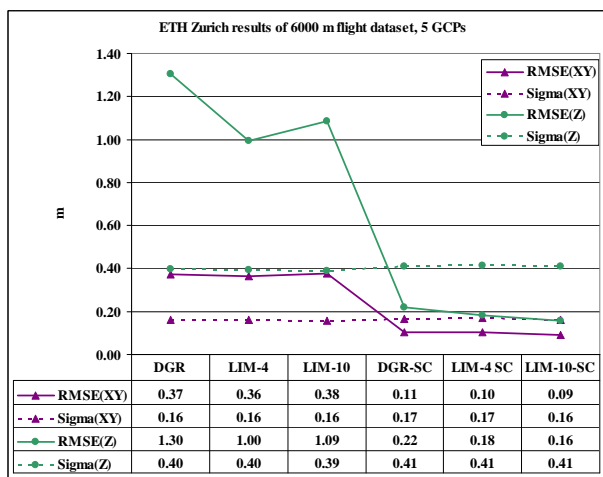


Figure 7. Accuracy figures for the 6000m block, ETH Zurich

#### 4 CONCLUSIONS

Three ADS40 image blocks acquired over the Pavia, Italy test site were processed in this study, in terms of direct georeferencing and triangulation, including self-calibration. The results obtained by the Geomatics Laboratory, University of Pavia and the IGP, ETH Zurich are compared to each other.

Different trajectory models and self-calibration methods were used by the two Groups.

The direct georeferencing results of both groups are identical in terms of RMSEs. Although slight differences in the standard deviations are observed, they can be explained by the differences of the methods used (Casella et al., 2007). All

indicate, even without any further processing, a good level of accuracy in planimetry (0.5-1.2 pixels), but not as good in height (3.3-4.6 pixels).

For triangulation and self-calibration the University of Pavia approach uses Orima of Leica Geosystems. At the IGP, ETH Zurich, a modified bundle adjustment is used together with two optional trajectory models (DGR and LIM). The results of both Groups are almost the same when the self-calibration is applied.

According to the experiments carried out at the University of Pavia, the camera's self calibration is necessary to attain sub-pixel accuracy and the adoption of 12 GCPs, instead of 5, doesn't particularly improve the results. For the best configuration, **self** with 12 GCPs, the accuracy values are, in GSD units: 0.25 for the average planimetric component and 0.30 for height for the 2000 m flight; 0.15 and 0.31 for the 4000 m flight; 0.13 and 0.24 for the 6000 m flight.

When the results of the LIM of ETH Zurich and the Orima model, both **without self-calibration** are compared, the planimetric RMSE values are almost identical. However, the LIM of ETH Zurich performs better in height, with a difference between 1.3-2.8 times. The sigma values (standard deviations of object point coordinates) obtained in all tests of both Groups are almost equal.

In the ETH Zurich investigations, when the DGR results are compared with the LIM, they show different characteristics in all three datasets. The best RMSE values in the 2000 m and 4000 m blocks are obtained from the DGR model. In the 2000 m block, the LIM appears relatively instable. In this block the use of more GCPs shows a positive effect on the results. In 4000 m block, the DGR and the LIM results are quite similar and there is almost no improvement when more GCPs are used. Opposite to these two flights, in the 6000 m block the LIM with 10 orientation fixes delivers the best results. Considering all results of all three datasets, it can be recommended to use the LIM with dense orientation fixes only when a fairly large number of GCPs is available. When accurate image trajectories are available, the DGR model shall be enough for modeling the errors. In all cases, the self-calibration improves the triangulation accuracy significantly.

All in all, there are still not enough appropriate datasets available worldwide in order to make conclusions of general value. The issue of aerial Linear Array camera accuracy performance still needs further empirical investigations, also in order to validate the different camera, trajectory and additional parameter models.

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