

IN-SITU CAMERA AND BORESIGHT CALIBRATION WITH LIDAR DATA

N. Yastikli^a *, C. Toth^b, D. Brzezinska^c

^a YTU, Department of Geodetic and Photogrammetric Engineering, 34349, Istanbul, Turkey - ynaci@yildiz.edu.tr

^b Center for Mapping, Ohio State University, Columbus Ohio, 43212 USA - toth@cfm.ohio-state.edu

^c Department of Civil and Environmental Engineering and Geodetic Science, Ohio State University, Columbus Ohio, 43210, USA - grejner-brzezinska.1@osu.edu

KEY WORDS: LiDAR, Digital Camera, Boresight, Calibration

ABSTRACT:

State-of-the-art airborne systems are based on the combination of imaging and navigation sensors, such as digital camera, LiDAR, GPS and IMU. Since these systems use direct georeferencing for imaging sensor orientation, the calibration of individual sensors and the relation between sensors (system calibration) is critical. Any difference between assumed calibration parameters and physical parameters can cause significant errors in object space. The calibration of digital cameras is usually performed in laboratory and the determined parameters may not reflect the flight conditions due to the effect of temperature and air pressure. For example, the change in the focal length as a result of actual flight condition is of vital importance for direct sensor orientation, since it corresponds to a scale factor for the height. Therefore, these parameters are frequently determined or refined with in-situ calibration. In general, a test field with distributed control points of high accuracy is used for in-situ sensor and boresight calibration. Finding such a test field nearby or within project area is not always possible.

This paper investigates the feasibility of using LiDAR data for in-situ calibration of digital camera. In addition, the determination of attitude and positional relationship between digital camera and IMU is also discussed. The experimental studies were carried out using data collected by a small format airborne digital camera, LiDAR, GPS and IMU. A test site was selected in the project area and control points were obtained from LiDAR point cloud and intensity data. The in-situ calibration of digital camera was based on a large number of tie points and the LiDAR derived control points using a conventional bundle block adjustment with self calibration. The displacement vector and attitude relationship between digital camera and IMU body frame was determined by comparing the GPS/IMU derived image orientations and the results of bundle block adjustment. The performance of the camera calibration parameters and boresight misalignment was analyzed by comparing the results of measuring points in stereo models formed using the bundle block adjustment and direct sensor orientation, respectively. The performance of the in-situ determined camera and boresight calibration parameters were tested using independent LiDAR-specific target points which were originally used for testing of the LiDAR data accuracy. In addition, the effect of orientation discrepancies as a model deformation was also checked by computing y-parallaxes for each model and generated orthoimage.

1. INTRODUCTION

In photogrammetry, the determination of image orientation, an important task for any kind of imagery used to be solved indirectly by block adjustment in the past. Recently, the direct determination of the exterior orientation parameters of imaging sensors became possible by the combined use of IMU and GPS. For accurate determination of object points based on GPS/IMU oriented imagery, the system calibration is of vital importance, and includes the determination of the boresight misalignment, the interior camera orientation, and the GPS antenna offset. The system calibration parameters can be classified into two groups: the calibration parameters of individual sensors and the relationships between sensors. The calibration between sensors is comprised of the GPS antenna offset (lever arm), and the determination of an offset vector and attitude difference between the IMU body frame and the imaging sensor.

The camera calibration process involves the geometric calibration, resolution determination and radiometric calibration of camera. The traditional aerial analog camera calibration

mainly focuses on the geometric calibration of camera. The laboratory calibration is a standard method for analog airborne frame cameras. The interior camera geometry, i.e. focal length, principle point location and lens distortion parameters are estimated based on goniometer measurements and included in the calibration certificate.

In-situ calibration, also called self-calibration originates from close range applications and the focal length, principle point location and lens distortion parameters are estimated from measurements reflecting actual conditions, which is usually different from lab calibration. The traditional close range in-situ calibration method requires a large number of signalized control points in 3D terrestrial calibration fields. If the object coordinates of signalized control points are known with high accuracy and sufficient number of images of the 3D calibration field from different position and different orientation is taken then the calibration parameters can be determined by using bundle block adjustment. Similarly, the camera calibration parameters can be estimated in standard airborne flight configuration with the camera positions could be provided by

* N. Yastikli

GPS. Obviously, the airborne in-situ calibration also requires a calibration field with signalized control points of high accuracy.

With the transition from analog camera to digital camera technology, the method of camera calibration needs to be revised. The ASPRS and the EUROSDR continue their research on digital camera calibration and validation (Stensaas, 2005, Cramer, 2005). The lab calibration method is still used for geometric calibration of large format digital cameras such as ZI Imaging DMC and Leica ADS40 together with in-situ calibration (Dörstel et al., 2003, Tempelmann, et al., 2003). For medium format digital cameras such as the Applanix/Emerge DSS geometric calibration is done by terrestrial and airborne calibration (Mostafa, 2004). The terrestrial in-situ calibration method is used for geometric calibration of the Vexcel Ultracam_D large format digital camera (Kröpfl, et al, 2004). The U.S. Geological Survey (USGS) began its certification efforts with digital aerial cameras in January 2006 (Stensaas, 2006). Current investigations at USGS focus on geometric and spatial characterization and calibration, although research on radiometric characterization and calibration of airborne sensors also continues with the recently established digital camera calibration lab at the USGS Center for Earth Resources Observation and Science (EROS). To perform in-situ camera calibration, a calibration range was established also at USGS EROS with 150 surveyed panels and one CORS station (<http://calval.cr.usgs.gov>).

In contrast to conventional orientation techniques, the direct sensor orientation is very sensitive to changes in sensor geometry because of the extrapolation from the camera projection center to the ground. Therefore, the accurate calibration of mobile multi-sensor systems, including imaging sensor, GPS, IMU, etc, is of high importance. For example, the offset between the GPS antenna and the IMU or imaging sensor can be precisely measured by conventional survey methods. The determination of the boresight misalignment, however, is a more difficult task because the attitude relation between the IMU body frame and the imaging sensor cannot be measured directly. Thus, the boresight misalignment is determined by a comparison of the GPS/IMU derived image orientation with the results of a bundle block adjustment over a reference area containing control points.

This research was motivated by the circumstances of a LiDAR mapping project, where a small format digital camera was installed next to the LiDAR system in the last minute before the airborne surveys started. Except for an earlier lab camera calibration, there were no measurements and no dedicated data acquisition performed to support boresight calibration of the camera. Furthermore, there was no target range or any area with signalized controls in the project area. Therefore, this investigation aimed to determine the system calibration parameters for that camera based on using only the LiDAR data acquired in the project. The sensor suite included the small format Redlake MS 4100 RGB/CIR digital camera and the Optech 3100 ALSM, supported by the Applanix georeferencing system (Novatel GPS and LN200 IMU). Experiments with the data set and the results obtained are analyzed and discussed to assess the performance of system calibration for the Redlake MS 4100 camera.

2. PROJECT AREA AND DATA ACQUISITION

The project B4, codenamed to reference to the “before” status of a widely anticipated major earthquake, the Big One, is a National Science Foundation (NSF) sponsored project, led by scientists from The Ohio State University (OSU) and the U.S. Geological Surveys (USGS), to create an accurate surface model (DEM) along the San Andreas and San Jacinto Faults in southern California. Besides the USGS, the OSU-led team included NCALM (National Center for Airborne Laser Mapping) from the University of Florida, UNAVCO (a non-profit, membership-governed consortium, supporting Earth science) and Optech International.

The airborne surveys took place May 15-25, 2005. A Cessna 310 aircraft was hired and Optech International provided the ALTM 3100 system at no cost to the project. The state-of-the-art Optech 3100 system was configured for 70 kHz, resulting in an about 2 pts/m² LiDAR data. An experimental Redlake MS 4100 digital camera was installed next to the Optech 3100 system, providing imagery of 1K by 2K resolution in four bands. The images were captured at 1 Hz, synchronized to the 1PPS GPS signal. The project area, encompassing about 1,000 km of fault line, was segmented into smaller sections during flight planning, including the San Andreas and San Jacinto Fault lines.

3. GEOMETRIC CALIBRATION OF SMALL FORMAL DIGITAL CAMERA

The Redlake MS 4100 RGB/CIR digital camera has four CCD sensors each with 1920 x 1075 pixels and pixel size of 7.4 μm x 7.4 μm. The camera was laboratory calibrated in RGB mode and a focal length was estimated for 25.966 mm in the calibration report. The calibration values were used as initial calibration parameters for the in situ calibration of the Redlake MS 4100 camera. The camera was configured for CIR image capture for the airborne surveys. The CIR imagery has 1892 x 1060 pixels, different from the RGB images. The approximate image size is 8 mm in the flight direction and 14.2 mm across the flight direction.

A reference block with 21 images was selected from a typical flight on May 25, 2005, where several man-made structures were available; the 3D view of the selected block, based on LiDAR intensity image, is shown in Figure 1. 25 control points extracted from the LiDAR point cloud and intensity data were used to perform an airborne in-situ calibration of the Redlake MS 4100 digital camera; the image block is shown in Figure 2. The availability of good control points is a crucial requirement for in-situ calibration. Since no conventional control points were available in this project, control points were derived from the LiDAR point cloud using LiDAR intensity as a tool for point identification. A measured control point in the CIR image and in LiDAR intensity image is shown in Figure 3. The expected root means square error of LiDAR points is ± 10 cm all component (Csanyi and Toth, 2007).

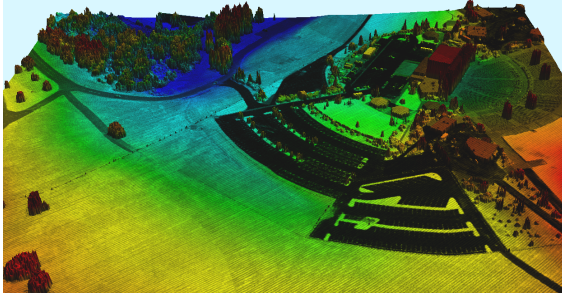


Figure 1. The 3D view of geo-registered LiDAR point clouds intensity image

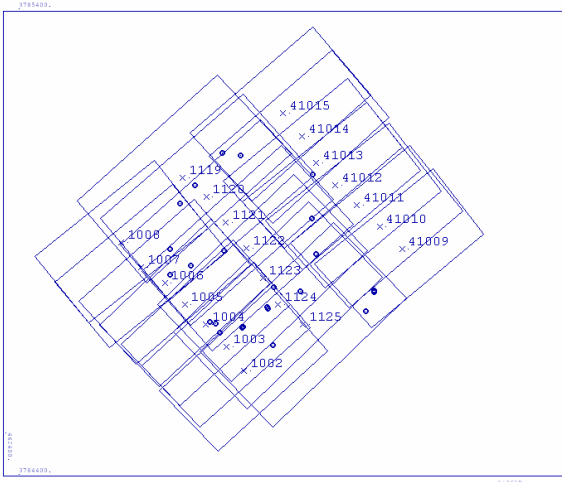
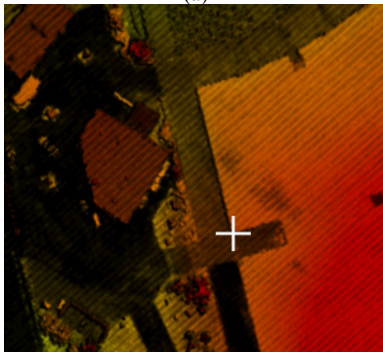


Figure 2. The reference block and control points distribution



(a)



(b)

Figure 3. Control point in CIR image (a) and LiDAR intensity image (b)

The block was flown in approximately 650 m above ground, corresponding to an image scale 25300. Each image is covering an approximately 200 m x 360 m area. The height to base relation is about 10 for an average endlap of 68%. In other words, the 17.5° view angle in the flight direction with is very small comparing to the normal analog camera, which is 73.9° at the 153 mm focal length. The small view angle in the flight direction requires more images in the flight lines, but more importantly, it significantly reduces the Z accuracy of the determined object points.

To analyze the estimated system calibration parameters of Redlake MS 4100 digital camera, different sets of the system calibration parameters were computed. Extensive manual measurements were carry out to obtain about 370 tie points that were used in the subsequent processing, using the BLUH bundle block adjustment software from the University of Hannover. All the computations were done in the UTM coordinate system (Zone 11) with ellipsoidal height.

The various combinations of the adjustment runs with different parameters and results are given in Table 1. The focal length $f = 25.966$ from the USGS/EROS calibration report was used as initial value for first two approaches. The twelve additional parameters were introduced to the bundle block adjustment in the second approach (Jacobsen, 2006). The radial symmetric lens distortions and systematic image errors are determined with additional parameters introduced into the bundle block adjustment. The radial systematic lens distortions from both the USGS/EROS calibration report and the bundle block adjustment with additional parameters are shown in Figure 4.

| Approach | | σ_0 [μm] | RMS at Control Points [m] | | |
|----------|---|---------------------------------|---------------------------|------|------|
| | | | X | Y | Z |
| 1 | Bundle block adjustment | 5.5 | 0.33 | 0.33 | 1.28 |
| 2 | Bundle block adjustment with 12 add parameters | 4.3 | 0.31 | 0.23 | 0.25 |
| 3 | GPS supported bundle block adjustment with 13 additional parameters | 5.2 | 0.33 | 0.23 | 0.51 |
| 4 | Bundle block adjustment with improved image coordinate and focal length | 4.3 | 0.31 | 0.23 | 0.24 |
| 5 | GPS supported bundle block adjustment with improved image coordinate and focal length | 5.4 | 0.34 | 0.23 | 0.55 |

Table 1. Reference bundle block adjustment results in UTM

The systematic image errors defined as differences between assumed mathematical model and real image geometry can be estimated in the bundle block adjustment by additional parameters. The systematic image errors of the Redlake MS 4100 digital camera were also determined with introduced additional parameters as shown in Figure 5.

The additional parameter, 13 was introduced to the bundle block adjustment in third approach and it led to a change of the focal length by 123 μm . The affine model deformation of UTM system in this test area was causing a 10 μm correction for the focal length (Yastikli et al., 2005). The remaining part of the

correction for the focal length could be explained by the effect of actual flight condition such as air pressure and temperature. The additional parameters for the location of principle point were not introduced to the adjustment because the strips, which were flown in twice in opposite directions, were not available in the reference block. Therefore, the separation of GPS shift and the correction of principle point position were not possible. The corrected focal length, however, resulted in improved image coordinates, including new radial symmetric lens distortions and symmetric image errors. The traditional bundle block adjustment and GPS supported bundle block adjustments were repeated with the improved image coordinates and corrected focal length in approaches 4 and 5.

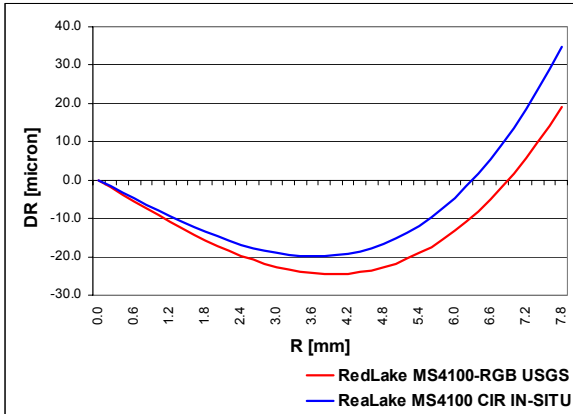


Figure 4. The radial systematic lens distortion from calibration report and reference block adjustment

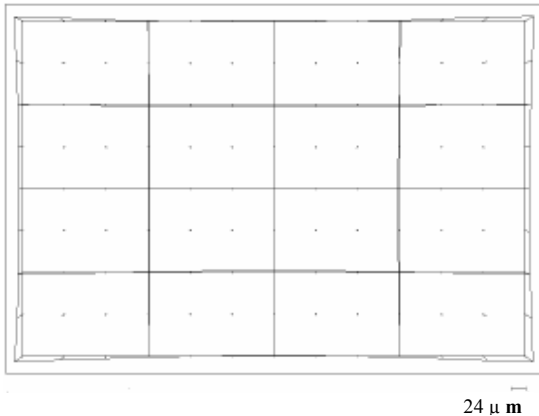


Figure 5. Systematic image errors determined by introduced additional parameters to the reference adjustment

4. BORESIGHT MISALIGNMENT

As discussed earlier, determination of boresight misalignment including the determination of a displacement vector and attitude difference between the IMU body frame and the digital camera is a critical issue for direct sensor orientation. The image orientation determined by GPS-supported bundle block adjustment, with improved image coordinate and focal length in approach 5 was used for the determination of the boresight misalignment in our research. The orientations from the GPS-supported bundle block adjustment were compared to the orientations obtained from GPS/IMU processing. The shift parameters were determined by comparing the projection

centers from the reference adjustment to the GPS/IMU-derived projection centers as well as to lever arm measurements.

In general, the IMU is fixed to the camera body as close as possible and is aligned parallel to the camera. In our installation, the camera was installed perpendicular to the flight direction, resulting in a 90° rotation between the x axis of camera and that of the IMU. The orientations from the reference bundle block adjustment were transferred into roll, pitch and yaw and the boresight angles were determined as 0.18476° for roll, 1.29884° for pitch and 0.34447° for yaw. The determined shift values were -0.384 m for X, 0.076 m for Y and 0.050 m for Z.

The boresight angles were also estimated using the POSCal utility of the Applanix POSEO software version 4.1. The POSCal computation is based on least squares adjustment and the required inputs are the image coordinates, control points and GPS/IMU-derived projection centers and orientations. The 90° rotation between the x axes of the camera and IMU had to be also defined for the computation. The determined boresight angles were 0.16867° for roll, 1.27303° for pitch and 0.40910° for yaw.

The GPS/IMU-derived attitudes and positions were improved by the BLUH and Applanix POSCal boresight misalignment. Based on the improved GPS/IMU derived attitudes and positions, the object coordinates of measured tie points and check points were computed by combined intersection (direct sensor orientation). The 25 control points derived from the LiDAR point cloud were used as check points. The σ_0 of the direct georeferencing and root means square errors at check points can be seen in Table 2.

| | Approach | σ_0 [μm] | RMS at Control Points [m] | | |
|---|---|------------------------------|---------------------------|------|------|
| | | | X | Y | Z |
| 1 | Direct georeferencing using BLUH boresight misalignment | 52.2 | 1.14 | 0.79 | 5.35 |
| 2 | Direct georeferencing using Applanix boresight misalignment | 46.0 | 1.18 | 0.70 | 5.57 |

Table 2. Reference bundle block adjustment results in UTM

The effect of the orientation discrepancies can be seen as y parallaxes. The y parallax in the model is important for stereo model setup. The comparison of the model y parallaxes from direct sensor orientation based on BLUH and Applanix boresight angles, and GPS supported bundle block adjustment can be seen in Figure 6. The similar results obtained for both direct sensor orientations clearly indicate an unacceptable quality for stereo models.

To further check the quality of the sensor calibration and boresight misalignment, orthoimages were generated using GPS supported bundle block adjustment results and GPS/IMU derived attitudes and positions improved by BLUH boresight misalignment. The effect of orientation discrepancies to the orthoimages can be seen comparing the LiDAR intensity images and the generated orthoimages in Figure 7.

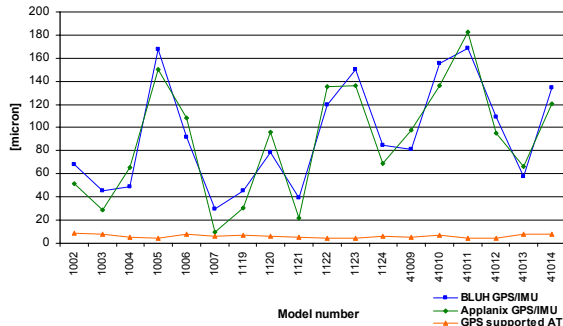


Figure 6. Comparison of the y parallaxes

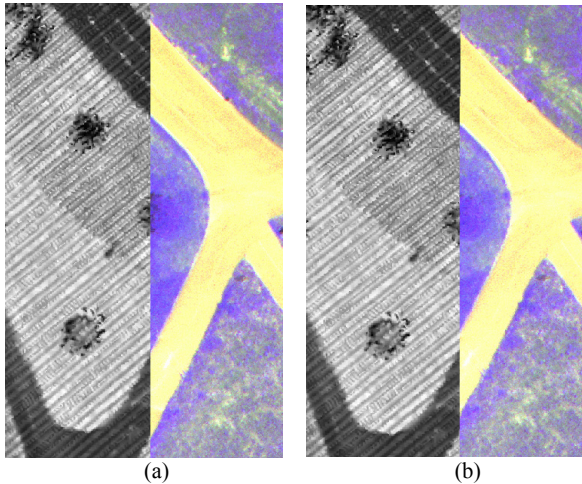


Figure 7. The geo-registered LiDAR intensity image and orthoimages based on reference adjustment (a) and direct georeferencing (b).

The in-situ camera and boresight calibration were determined based on the data collected on May 25, 2005. The performance of the calibration process was tested by using a limited number of target points which were originally used for the validation of the LiDAR accuracy. Figure 8 shows the LiDAR-specific targets, made of trampolines with 2m diameter, and GPS-positioned at cm-level accuracy. The image coordinates of check points were measured and the GPS/IMU-based exterior orientation was used in the intersection. The overall results of the in-situ camera and boresight calibration performance check as a root means square errors at target points are shown in Table 3. The obtained root mean square errors at target points and mean square error of intersection confirmed that the determined in-situ camera and boresight calibration is optimal and stable, as there is not change day to day and from one location to another.

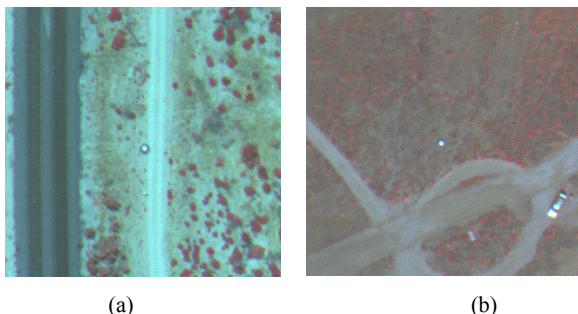


Figure 8. Target points 43142 (a) and 46466 (b)

| Target Number | Day | Model Number | MSE of Intersection | RMS at Target Points [m] | | |
|---------------|--------|--------------|---------------------|--------------------------|-------|------|
| | | | | X | Y | Z |
| 43142 | May 23 | 501 | 59.8 | -1.20 | -0.09 | 0.80 |
| 43143 | May 23 | 506 | 30.8 | 0.39 | 0.68 | 2.0 |
| 43144 | May 23 | 505 | 29.6 | 0.85 | 1.257 | -2.5 |
| 47803 | May 24 | 457 | 48.4 | 2.44 | 2.89 | 4.89 |
| 47804 | May 24 | 457 | 48.4 | 2.13 | 2.59 | 4.28 |
| 46465 | May 26 | 199 | 30.9 | 0.24 | 1.54 | 0.71 |
| 46466 | May 26 | 324 | 53.8 | 0.56 | -0.59 | 5.82 |

Table 3. The results of performance check in-situ and camera calibration with LiDAR specific target points

5. CONCLUSIONS

The system calibration of airborne mobile mapping systems, including the boresight misalignment and geometric calibration of the imaging sensor has vital importance for achieving accurate geospatial data extraction performance, as the GPS/IMU-based direct sensor orientation is extremely sensitive to system calibration errors. Any discrepancies between the assumed mathematical model and physical condition during the data acquisition can cause an error in object space. Because of this, the determination of the displacement vector and attitude difference between the camera and IMU body frame (boresight misalignment) and geometric calibration of camera are a critical issue for direct georeferencing.

In this research, a system calibration was performed to integrate a small format camera into a high-performance LiDAR system. The investigation clearly showed that the Redlake MS 4100 digital camera could be successfully calibrated and boresighted to the LiDAR system, using only control information derived from the LiDAR data. Using a block of 21 images and 25 LiDAR-derived control points, bundle block adjustments with various parameters were used to perform an in situ camera calibration. The focal length, the radial symmetric lens distortions and systematic image errors were accurately estimated (with respect to the camera quality). In addition, the boresight misalignment was simultaneously estimated using the BLUH and Applanix software products. The effect of orientation discrepancies were checked by computing y-parallaxes for each model at the reference block. In addition, an independent performance check was performed using LiDAR-specific ground targets. The combined results clearly proved that the determined in-situ camera and boresight calibration parameters were optimal and stable; in fact, the achieved accuracy appears to be quite good compared to the camera quality.

ACKNOWLEDGEMENTS

The B4 project was funded by the National Science Foundation and the ALTM 3100 system was generously provided by Optech International. The authors wish to acknowledge the support from the National Science Foundation and the contribution of many researchers from OSU, USGS, NCALM, UNAVCO and Optech International who participated in the B4 mapping project, as well as, the many OSU students who did much of the GPS observations. The authors acknowledge the financial support given by The Scientific and Technological Council of Turkey (TUBITAK) provided for the post doctoral research studies of Naci Yastikli at The Ohio State University.

REFERENCES

Cramer M., 2005. EuroSDR: Digital Camera Calibration and Validation, *GeoInformatic* 2(8), March 2005, pp. 16-19 .

Csanyi, N. and Toth, C. (2007): Improvement of LiDAR Data Accuracy Using LiDAR-Specific Ground Targets, *Photogrammetric Engineering & Remote Sensing*, Vol. 73, No. 4, April 2007 pp 385-396.

Dörstel C., Jacobsen K., Stallmann D., 2003. DMC – Photogrammetric Accuracy – Calibration Aspects and Generation of Synthetic DMC Images, in: Grün A., Kahmen H. (Eds.), *Optical 3-D Measurement Techniques VI*, Vol. I, Institute for Geodesy and Photogrammetry, ETH Zürich, 74-82.

Jacobsen K., 2006. Blim (Program System BLUH) User Manual, Institute of Photogrammetry and GeoInformation, University of Hannover. April 2006.

Kröpfl M., Kruck E. B., M. Gruber A., 2004. Geometric Calibration Of The Digital Large Format Aerial Camera Ultracam_D, *Proceedings of ISPRS Congress 2004, Istanbul*, July 2004, digitally available on CD, 3 pages.

Mostafa, M. 2004. Camera/IMU boresight calibration – new advances and performance analysis
http://www.applanix.com/media/downloads/products/articles_applanix/DSS_2004_07_TestResults.pdf (accessed August 28, 2006)

Stensaas G., 2005. Mapping Path to Digital Sensor Calibration, *ASPRS Photogrammetry- Part2: Digital Sensor Calibration: Research, Policies and Standards*, ASPRS Spring Meeting, March9, 2005, Baltimore, USA.

Stensaas G., 2006. The USGS Plan for Quality Assurance of Digital Aerial Imagery.
http://calval.cr.usgs.gov/documents/The_USGS_and_IADIWG_Plan8.doc (accessed March 28, 2007)

Tempelmann U., Hinsken L., Recke U., 2003. ADS40 calibration and verification process. in: Grün A., Kahmen H. (Eds.), *Optical 3-D Measurement Techniques VI*, pp. 48-54

Yastikli N., Jacobsen K., 2005 Influence of System Calibration on Direct Sensor Orientation. *Photogrammetric Engineering and Remote Sensing*, Vol. 71 No 5. May 2005 pp. 629-633.