Enhancement & Simplification
of Leica ADS Calibration Process

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ABSTRACT:

This paper describes the new workflow for an on-site calibration of the multi-line Airborne Digital Sensor ADS from Leica Geosystems. All System elements such as the lens system (D064-810000), the filter and beam splitter module (Tetrachroid), the geometry of the CCD lines in the focal plate module (FPM) and the orientation of the inertial measurement unit (IMU) are calibrated in a single adjustment process.

Up to now a fixed set of nominal values has been used as initial input to the calibration. The newly developed method starts from individual lens system and focal plate data gathered during ADS production. This gives improved initial values and results in a significant reduction of iteration steps. Initial values for focal length, principal point, and IMU misalignment are derived from a bundle adjustment using a minimal number of automatically extracted tie points.

The main part of the calibration process starts with an extraction of a highly dense tie point pattern by automatic point matching on the 88 images of a bi-directional cross in 2 flight levels. The orientation parameters are derived from a combined adjustment tailored to the special ADS pushbroom geometry. The effect of parameters within the adjustment process is applied on the per sensor pixel coordinates.

After the self-calibration process, residuals are analyzed for each CCD line. Remaining systematics in the distribution of focal plane space residuals are modeled by a customizable spline function. Especially at the line ends, the spline fits remaining distortion effects better than the previously used polynomial fit. This yields less iterations in the calibration process. In order to minimize user interaction, automatic weighting is applied to eliminate the influence of tie point blunders. The weighting is based on the correction results and therefore requires some iterations to converge towards a optimal fit.

Besides reducing the number of iterations and user interaction time, the advantage of the new workflow is that it can be used by the customer to regularly check and maintain the high accuracy of the ADS. A step by step description of all calibration tasks is provided.

1. CALIBRATION AND VERIFICATION CONCEPT

1.1 Self-calibration by Bundle Adjustment

Well known classical photogrammetric methods can be applied to a pushbroom sensor with multi angle capabilities, although some adaptations to the substantially different imaging geometry of the multi-line pushbroom sensor have to be made. This document presents enhancement to the workflow for an on-site calibration of the Leica Airborne Digital Sensor (ADS) presented by Tempelmann and Hinsken 2003. All system elements such as the lens system (D064-810000), the filter and beam splitter module (Tetrachroid), the geometry of the CCD lines in the focal plate module (FPM) and the orientation of the inertial measurement unit (IMU) are calibrated in a single adjustment process.

1.2 Representation of the Interior Orientation for the Sensor Model

In order to keep the sensor model open for any kind of line sensors and focal plate layout, the sensor model uses no classical parametrization. After calibration the inner orientation parameters are represented in the so called ADS camera files (or calibration file), the IMU misalignment file and the ADS camera definition. There is one calibration file for each sensor line, which contains the viewing angle for each CCD element, represented by a nominal focal length and an x/y-coordinate for the center of each CCD element with respect to the focal plate coordinate system. Parameters used within the calibration process are transformed into these per element values.

2. ELEMENTS OF THE CALIBRATION FLOW

2.1 Camera Model for Triangulation

The camera model of classical photogrammetry can be used for a close approximation of a multi-line pushbroom sensor. Although only some lines inside the image field are used, the central perspective model, represented by a pinhole camera with a flat image and distortions in image space can be used. The ADS camera model uses a “focal plate space” (FPS) as substitute for the classical image space. The apparent image, the called “scene”, is a series of single line images with the same line position $(x,\ y)$ in FPS but different exterior orientation.

2.2 Exterior Orientation Parameters

The orientation fix method described by Hofmann and Müller (1988) is used for the ADS. A large number of tie points between three image strips of a flight line and between the flight lines of a block, makes it possible to model the trajectories and the angular orientation of the camera along the flight lines. This task is similar to the reconstruction of the relative orientation for the projection centers of a classical photogrammetric block. Long term experience shows the orientation fix method is suitable to substitute projection centers of a frame sensor for handling the exterior orientation in the bundle adjustment and self-calibration.

However, as the pushbroom sensor captures many line-images between two orientation fixes, the correct orientation at any point between the fixes is delivered by an IMU (Inertial Measurement Unit) attached to the focal plate system. It is used to determine all six degrees of freedom of the exterior orientation so precisely that only a linear correction of these values is required between two orientation fixes. For this purpose,. a number of about 15 tie points between neighboring orientation fixes delivers the needed redundancy for a stable bundle solution.

2.3 IMU Misalignment

The position of the IMU, relative to the FPS should be determined to a fraction of a ground pixel. As the position within the ADS is known in mm-precision and the minimum ground pixel size is about 50 mm, there is no need for a better determination. For the angular orientation, the situation is different. Initially it is known in the range of some arc minutes, a pixel, however, covers only 22 arc seconds. That's why the estimation of the angular IMU misalignment has to be part of the calibration process. The angular orientation of the IMU with respect to the focal plate space is stored in a separate IMU misalignment file. The independent and highly precise estimation is especially needed for "direct georeferencing", when no control points are used for a block adjustment.

2.4 Interior Orientation Parameters

The ADS camera model is not much different from a classical frame camera. Variations in the principal point x_0, y_0 have to be estimated. Additionally the lens distortion is modeled as presented in Tempelmann and Hinsken 2007.

For a lens system like that of the ADS, which has been optimized for resolution, telecentricity and thermal stability, introduction of a radial symmetric distortion had to be accepted. However as the images need anyway to be re-sampled to eliminate residual flight movements this is no obstacle in a digital workflow. Distortion is modeled by introducing the polynomial coefficients $e_1,\dots,e_6$ and its point of symmetry x_s, y_s .

$$dx_g(r\,,\,x) = x_0 + (x - x_s)\cdot(e_1 r + e_2 r^2 + e_3 r^3 + e_4 r^4 + e_5 r^5 + e_6 r^6)$$
$$dy_g(r\,,\,y) = y_0 + (y - y_s)\cdot(e_1 r + e_2 r^2 + e_3 r^3 + e_4 r^4 + e_5 r^5 + e_6 r^6) \tag{1}$$

$$\textit{where}\quad r = \sqrt{(x - x_s)^2 + (y - y_s)^2}$$

2.5 Additional Modeling of the Sensor Lines

The above formula represents the global orientation parameters. Additional offsets and distortions result from the composition of the focal plate from several independent CCD line sensors. In the ADS system, the height adjustment and flatness of the CCD lines will not introduce any distortions larger than 2 µm , due to the telecentric design of the lens system. Also the straightness of the lines is perfect (1 µm), but X-Y-position $x_{0\,line}$, $y_{0\,line}$ and orientation $b_{0\,line}$ of the CCD lines can vary in the range of 100 µm, due to assembly restrictions. Another type of small, but non-negligible, distortions results from the filter and beam splitter module (Tetrachroid). In order to limit the degree of freedom to relative movements inside the focal plate, constraints $\sum x_{0_{line}} = \sum y_{0_{line}} = 0$ and $\sum b_{0_{line}} = 0$ are added.

Sensor line correction is given by

$$dx_l = x_{0\,line} + b_{line}\,y\ ,\quad dy_l = y_{0\,line} \tag{2}$$

and adds up with (1) to the total correction

$$dx = c_{corr}(dx_g + dx_l) \text{ and } dy = c_{corr}(dy_g + dy_l)\ . \tag{3}$$

The principal distance (c) correction term $c_{corr} = c_{nom}/c$ normalizes all corrections to the nominal value c_{nom}.

2.6 Calibration Block Layout

In order to resolve any correlations between the orientation parameters (2.4,2.5,2.2) the ADS calibration cross is used for calibration flights. It consists of four bi-directionally flown strips, forming crosses at two flight levels. For an unbiased estimation, every flight line should be flown bi-directionally, connecting all scenes with a high tie point density. A second flight level at 1.5 times the height of the first level, removes the need for any ground control. It does not only allow a precise estimation of the principal distance without control points, as the block scale is fixed by the GPS/IMU heights of the two flight levels, it also reduces the correlations between the principal point and misalignment parameters.

A suitable surface features no water areas, minimal repetitive patterns, and no higher buildings due to rectification errors. The ground should be as flat as possible in order to get a homogeneous accuracy, long shadows as created by low sun elevation should be avoided.

3. ENHANCEMENTS OF THE CALIBRATION FLOW

3.1 Starting Values

Up to now a fixed set of nominal values has been used as initial input to the calibration. The newly developed method uses start values gathered during production of for the individual system components. The lens systems elements have to be precisely aligned with respect to their measured refractive power. These measurements are used to compute the distortion of a incoming ray.

Tests have shown the polynomial model of radial symmetric distortion used in the ADS sensor parameters (2.4) is well suited to model the lens systems characteristics as computed by the manufacturer (Fig. 1, Fig.2).

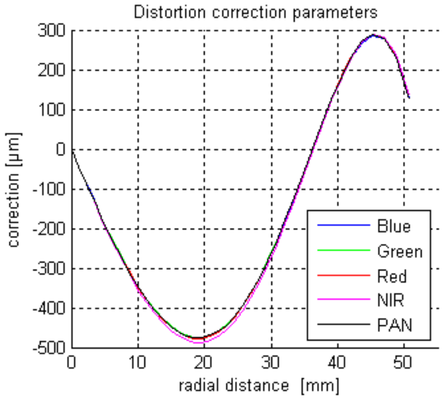

Figure 1: Example of radial distortion polynomial

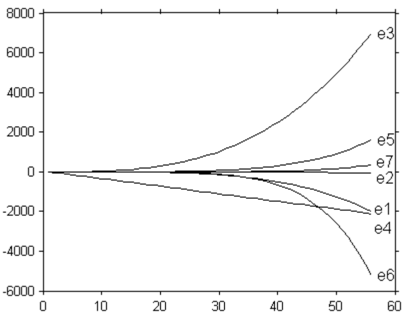

Figure 2: Sectral decomposition of distortion polynomial

During the assembly process, alignment marks on the CCD element are used to position them within the focal plate module. These measurements can be transformed into offsets from the nominal sensor line positions. However, the global shift and rotation of the of FPM and lens system can be 10 times larger.

The position of the principal point, the focal length and IMU misalignment are set to their nominal values and they are used during a first hierarchical APM with a large search range for a small number of tie points. Initial values are obtained from a first coarse bundle adjustment. This improved initial values now allow a highly dense APM run with limited search range.

3.2 Tie Point Matching

The main part of the calibration process starts with an extraction of a highly dense tie point pattern by automatic point matching on the 88 images of a bi-directional cross in 2 flight levels. Figure 3 illustrates the final triangulation result of such a block.

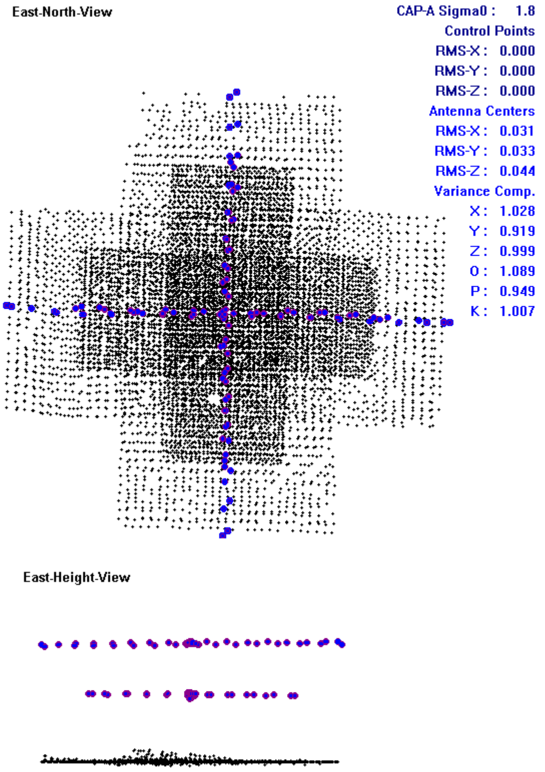

Figure 3: Triangulation result of a calibration block. Shown are the matched tie point (small dots) and the orientation fixes (large dots).

The used 14 point lines pattern leads to about 2500-8000 tie points. Continuous improvements to the Leica APM algorithm lead to a time reduction from 24h to 6-8h per APM run. Error: Reference source not found shows the block layout with matched tie points.

3.3 Residuals Analysis

The parameter set used in self-calibration process is designed for modeling all major aspects of the interior orientation. However some small irregularities of any nature are still remaining. Therefore the residuals are analyzed with a redesigned post-processing package to correct the FPM coordinates of CCD pixels for any remaining systematics.

First residuals of tie point coordinates in the self-calibration process are sorted by position within the recording CCD line, separated by x and y in FPS. This results in a point cloud with density maximum at the most likely position of the CCD line. When fitting any correction curve, the challenge is to remove the influence of unevenly distributed APM mismatches. This can be overcome by starting a approximate positions derived by maxima in a accumulation raster. To eliminate the impact of blunders all points are weighted based on a probability distribution obtained form the previous iteration and therefore requires some iterations to converge towards a optimal fit. Especially at the line ends, the spline fits remaining distortion effects better than the previously used polynomial fit. This yields less iterations in the calibration process.

3.4 Iterating to the Final Result

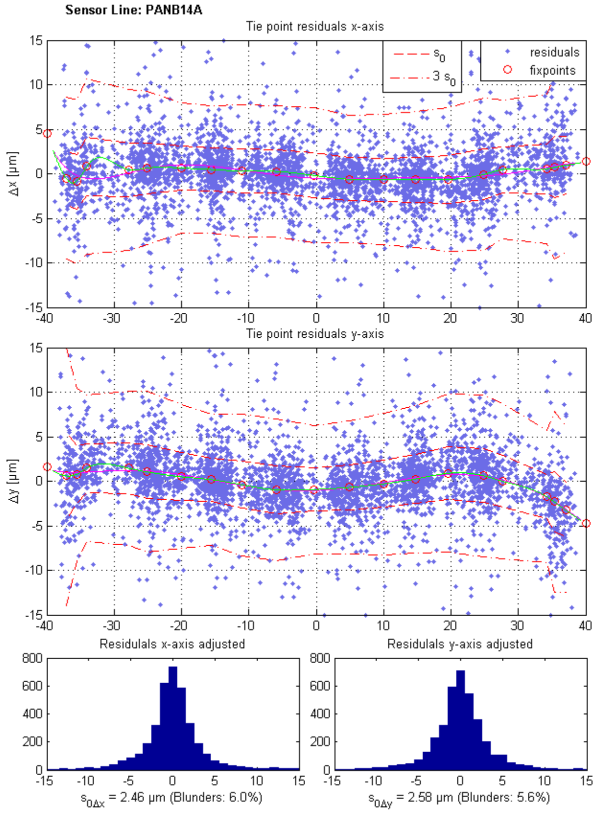

Figure 4: Typical residuals distribution before correction

The residual analysis is started after the first full APM run. It takes 4 to 5 iterations, until neither the additional parameters estimation nor the residuals analysis show any significant effects. Each iteration consists of rectification of the scenes with the new calibration files, tie point matching, bundle adjustment and residuals analysis. Start values from production data usually reduce the number of iterations by one.

Figure 4 shows the situation at the end of the second iteration, where the systematic effect is in the range of one pixel (6.5 µm) and Fig. 5 at the end of the iterations, where the systematic effect is less than 1µm. The horizontal axis is the position on the line in [mm], the vertical axis the residual in [µm].

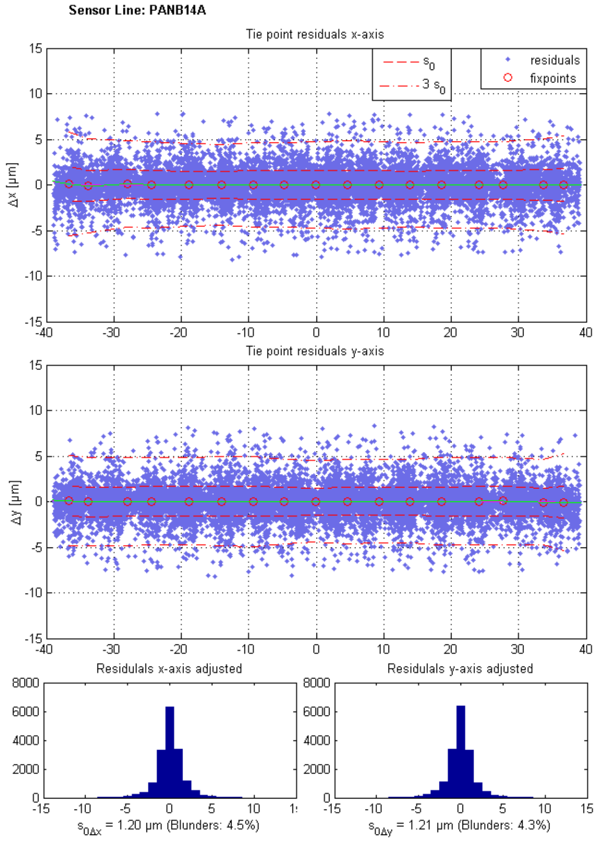

Figure 5: Typical residuals plot for the final calibration

The iterations improve the triangulation quality step-by-step and by reduction of correlations between the sensor parameters. The two flight levels layout of the calibration block help to reduce all correlations to reasonable values of less than 0.5, which does not affect the stability of the result. At the end of the iterations, we typically get a σ_0 of 1.0 µm to 3.0 µm (Fig. 2) for all ADS systems, depending on the tie point matching quality. The Spline fit accuracy for all residuals along the sensor line is at least 10 times better due to averaging over a large sample of residuals. This is sufficient since the single point measurement accuracy is expected to be in up to a 1/10 of one pixel.

3.5 Time improvements

Using more accurate starting values usually saves one iteration. Computation of starting values takes about 4 hours and allows to start a full 14 line APM run on the same working day. Another benefit for calibration is the improved computation speed in APM. It has been decreased from 24 hours to 6-8 hours over time. Calibration requires highly dense tie point patterns. Improved APM speed significantly reduces the overall computation time.

The ORIMA processing of the calibration block is still time consuming and takes about 4 hours per iteration. Residual analysis has developed into a fully automated process. This reduces the per iteration user interaction time from 45 to 30 minutes. Reducing the number of iterations led to a 25% decrease in overall processing time from 80 down to 60 hours.

3.6 Conclusions and Future Enhancements

Although the current processing method with the combination of bundle adjustment with additional parameters and residuals analysis has proven to be reliable to deal with any unforeseen obstacles. The flight-based calibration yields results, which are better than any reasonable laboratory equipment can be.

Besides of reducing the number of iterations and user interaction time, the advantage of the new workflow is that it will provide the base for tighter integration into the standard processing software. This enables the customer to regularly check and maintain the high accuracy of the ADS.

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