ADS40 Calibration & Verification Process

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Abstract

As the ADS40 with its pushbroom geometry is totally different from classical photogrammetric camera concepts, there are no international guidelines and standards, which could be applied to the system.

The new calibration concept, developed for ADS, is a system calibration process, which calibrates the image-relevant system components simultaneously. Besides the optical system, composed of the lens system (DO64) and the filter and beam splitter module (FCO40), also the geometry of the CCD lines in the focal plate module setup (FPM40) and the orientation of the inertial measurement unit (IMU) are relevant to the geometry of an ADS image.

As an independent laboratory calibration of the single components would be either impossible in the required accuracy (so for the IMU orientation) or result in a badly propagated error (so for the FCO40), the ADS calibration process is based on a calibration and verification procedure for the complete system under practical working conditions.

1. Calibration And Verification Concept

1.1 Self-calibration by Bundle Adjustment

Although the imaging geometry of a multi-line pushbroom sensor is substantially different from that of a frame camera, most of the classical photogrammetric methods can be applied to a pushbroom sensor with three-line stereo capabilities like the ADS40. This applies also to the bundle adjustment and self-calibration techniques, if a proper replacement for the projection centres of frame images is established (Hinsken, L. et al. 2002).

The calibration by photogrammetric means has the great advantage over a laboratory calibration that it is done in the real working environment of the sensor and, as experience shows so far, that it leads to a precision, which is a real challenge for any two-dimensional geometry measuring device.

1.2 Verification on a Test Field

The probably best approach to verify the quality of the sensor calibration and other system components is to test the sensor under realistic working conditions. This means, to fly a photogrammetric block on a test field with precisely measured control and check points. After fitting the block to the control points, the RMS and maximum ground space residuals give a realistic view of the overall geometrical quality of the system (Fig. 1).

This approach is not only used internally, it has also been used on customer side for the certification of the sensor in Japan on the Tsukuba test field.

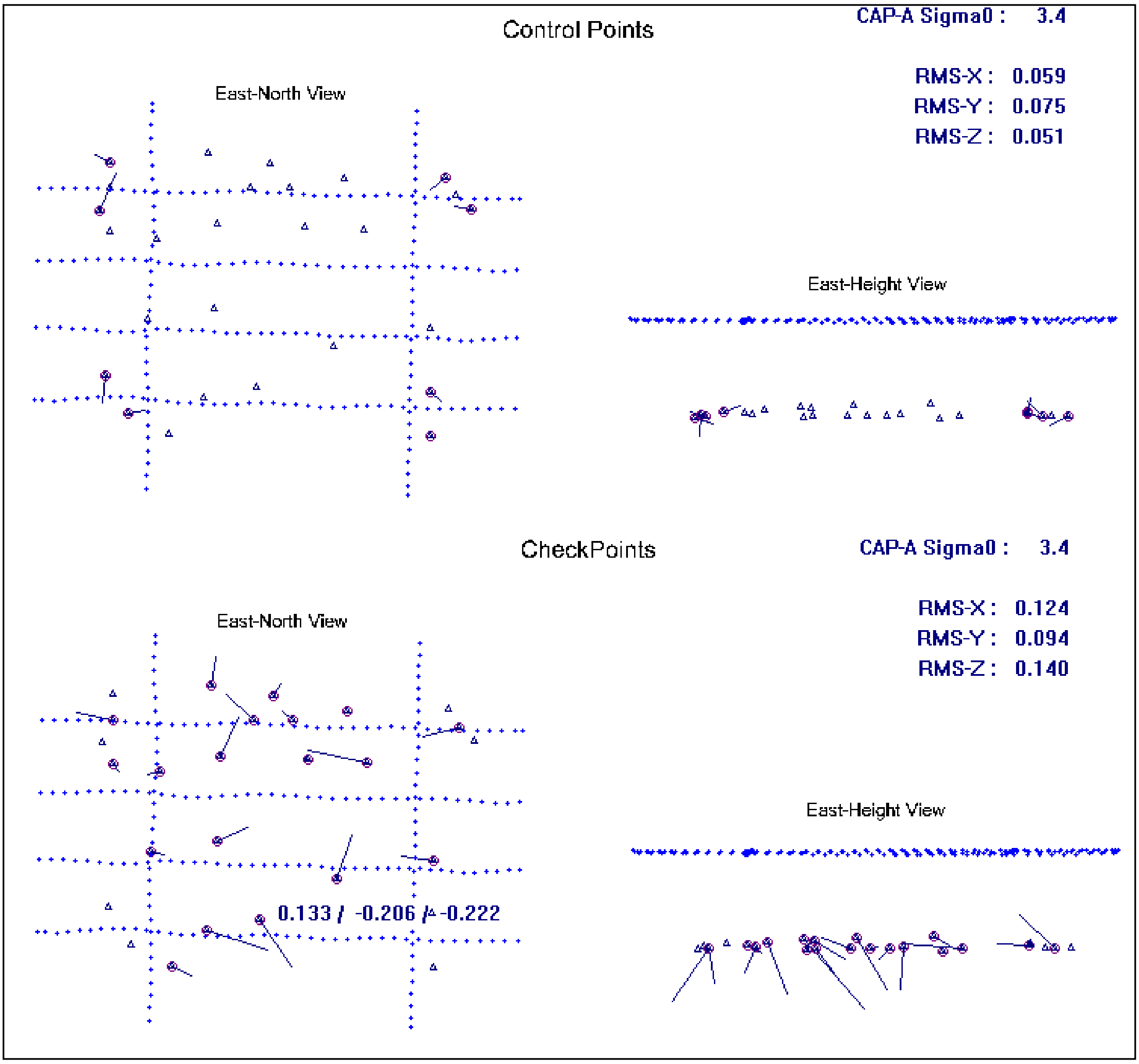


Fig. 1: Triangulation result of a verification block with 0.2m ground sample distance.
Shown are enlarged residuals vectors for check and control points and the numerical values for the check point with the largest residuals. Also shown are the RMS values of the residuals. The point lines (small crosses) in west-east and north-south direction are the orientation fixes, which show the block layout with four parallel strips with 20% sidelap and two cross-strips.

2. Elements Of The Calibration Flow

2.1 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 parametrisation. Instead of that, 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 centre 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. Besides that, the angular orientation of the IMU (c.f. 2.5) is stored in a separate file.

2.2 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. It must however be noted that the classical image space becomes here the "focal plate space" (FPS), while the apparent image, the "scene", is a series of single line images with the same line position in focal plate space.

2.3 Orientation Fix Approach

Hofmann O. and Müller F. (1988) describe already a method, which is also used now for the ADS40, to replace the projection centres of classical photogrammetry by a series of orientation fixes (or orientation points) along the flight path. Using a large number of tie points between the three image strips of a flight line and between the flight lines of a block, it should be 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 centres of a classical photogrammetric block.

However, as the pushbroom sensor captures many line-images between two orientation fixes, we have also to estimate an interpolation function, which delivers the correct orientation at any point between the fixes. For this purpose, an IMU (Inertial Measurement Unit) is 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. A number of about 15 tie points between neighbouring orientation fixes delivers the needed redundancy for a stable bundle solution.

2.4 Datum Transform

Although the combination of IMU and phase-differential GPS data results in a highly precise orientation of the complete block, a datum transform can be necessary to fit the internally stable block into the local datum.

2.5 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 ADS40 is known in mm-precision and the minimum ground pixel size is about 150 mm, there is no need for a better determination. For the angles, the situation is different. While they are known in the range of some arc minutes, 1/10 of a pixel is only 2.2 arc seconds.

That's why the estimation of the IMU misalignment has either to be done during the adjustment of a normal block flight or independently by either a special "boresighting" flight or as a part of a calibration. The independent and highly precise estimation is especially needed for "direct georeferencing", when no control points are used for a block adjustment.

2.6 Interior Orientation Parameters

A multi-line pushbroom sensor suffers from the same lens distortions as a classical frame camera. That's why, the basic set of interior orientation parameters is still valid: principal distance (c), principal point of auto-collimation ("PPA": X_0, Y_0), radial-symmetric distortion (a_1 in r^3, a_2 in r^5, a_3 in r^7). For a lens system like that of the ADS40, which has been optimised for resolution and telecentricity, but where a large distortion had to be accepted, also the estimation of the distortion symmetry centre ("PPS": X_1, Y_1) and polynomial coefficient for the even powers of the radius (r^2, r^4, r^6) will be helpful.

2.7 Additional Modelling of the Sensor Lines

Additional offsets and distortions result from the composition of the focal plate from several independent CCD line sensors. In the ADS40 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 and orientation 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 beam splitter and filter assemblies on the focal plate cover.

ORIMA uses the additional parameter set of Brown D.C. (1976). These parameters model certain system effects of the three-line sensor surprisingly well. The used set contains some parameters, which are not useful for the three-line sensor, like the platen flatness group, which must be turned off. Analyses have shown that this set alone is not sufficient for the ADS sensor geometry, but that the remaining effect can effectively be modelled by 6^{th} degree polynomials for X and Y of each sensor line.

3. Preliminary Implementation Of The Calibration Flow

3.1 Calibration Block Layout

Already a single flight line with a high tie point density between the three scenes allows for a coarse estimation of the IMU misalignment and some internal orientation parameters.

For an unbiased misalignment estimation, this strip should however be flown bi-directionally. This configuration with a repetitive pattern of at least five tie points across the strip, which tie all the involved six scenes, has turned out to be the minimum requirement for a “boresighting flight”.

For the estimation of interior orientation parameters, the bi-directional line is not enough. Many of the D.C. Brown parameters, the principal point and the misalignment are still highly correlated in such a configuration. Most of these correlations can be removed by adding a cross line to the flight pattern and it should again be a bi-directional line, to avoid bias effects from asymmetry of the block. All parameters, except for the focal length can be estimated with a flight over flat terrain without any need for control points. Control points are needed only to introduce a scale into the block, that means for the estimation of the principal distance.

The same bi-directional cross flown on a second flight level at 1.5 times the height of the first level, removes the need for any ground control. The results were so good that it became our standard calibration flight configuration. 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.

3.2 Tie Point Matching

In order to get a point density, which is high enough for the additional sensor line modelling, a very dense tie point pattern must be used. The used 14 point lines pattern leads to about 3000 ground points with about 35000 Rays to the three panchromatic channels and 40000 Rays to the four colour channels of the ADS40. In the block centre, which is covered by all the strips, there are points with up to 56 rays. Fig. 2 shows the block layout with matched tie points.

Although the matching is done in L1 (plane rectified) scenes, the results are delivered in L0 (raw) image coordinates, ready for processing by the bundle adjustment.

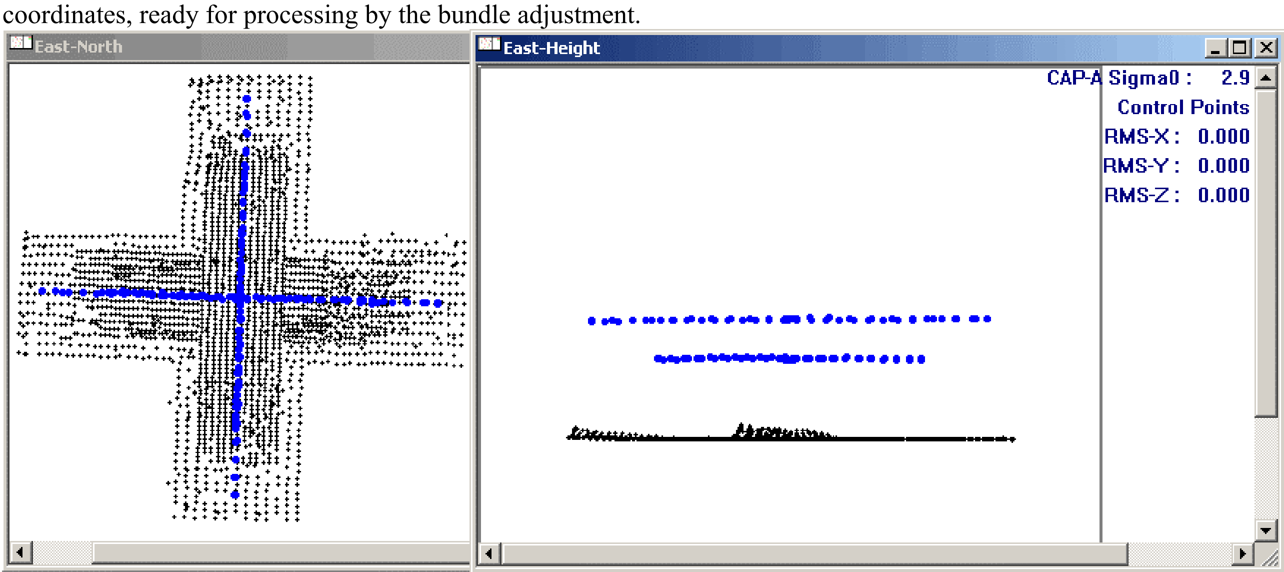


Fig. 2: Triangulation result of a calibration block.
Shown are the matched tie points (small dots) and the orientation fixes (large dots).

3.3 Robust Adjustment using ORIMA

The three stereo lines are used for the block adjustment and additional parameters estimation. Using the robust estimation feature of ORIMA, the interactive work is reduced to selecting the significant additional parameters and tuning the variance components for the GPS/IMU observations. The graphical user interface provides also convenient ways for interactive quality checks and elimination of ill-defined points.

Corrections derived from the adjusted additional parameters are applied to all sensor lines, including the spectral lines. The image point residuals after bundle adjustment are subject to further analysis and modelling of remaining systematic effects.

3.4 Residuals Analysis

As described in 2.7, the classical additional parameters, as implemented in the current version of ORIMA, are not fully sufficient to model the ADS40. Besides the required per-line modelling of offsets and distortions from the focal plate and filters assembly, also the uncommon radial distortion of the lens system cannot be fully modelled without an estimation of the symmetry centre of the distortion and the polynomial coefficients for even powers of the radius.

For the three stereo lines, the additional parameters set of the current ORIMA version delivers a σ_0 close to 4.5 μm. This is about 2/3 of a 6.5 μm pixel and higher than we can expect from the ADS40 and tie point matching performance.

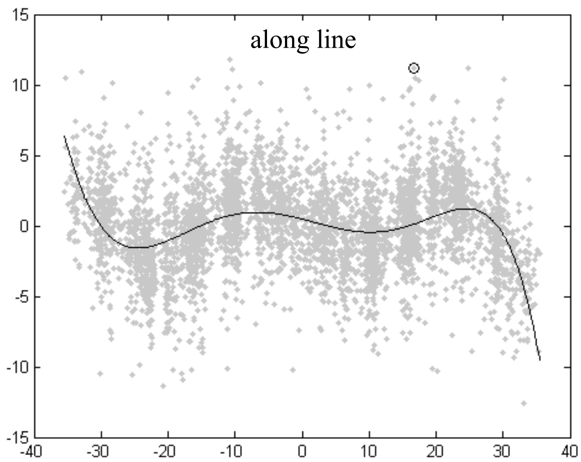
A look into the residuals of each stereo line, sorted by position on the line, shows the reason for the accuracy degradation. There are clearly systematic effects, as shown in Fig. 3a.

Instead of working directly on the implementation of a pushbroom-specific additional parameters set into ORIMA, we decided to test it independently from ORIMA with a post-processing package for the residuals, before doing the actual implementation. It turned out immediately, that a sixth degree polynomial model, as well along as across each sensor line, can perfectly compensate the systematic residual effects.

The method works so well, that we decided to use it for the ADS40 calibration until we have an ORIMA version with a new additional parameters set. It provides also a good basis to analyse the required parameters.

3.5 Iterating to the Final Result

Starting from the most simple camera model, that means straight sensor lines in nominal positions and a distortion-free lens with the nominal principal distance, it takes 4 to 6 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 and takes currently more than a day, with most time spent on the fully automatic tie point matching. Starting with the results of a laboratory calibration can save one iteration only.



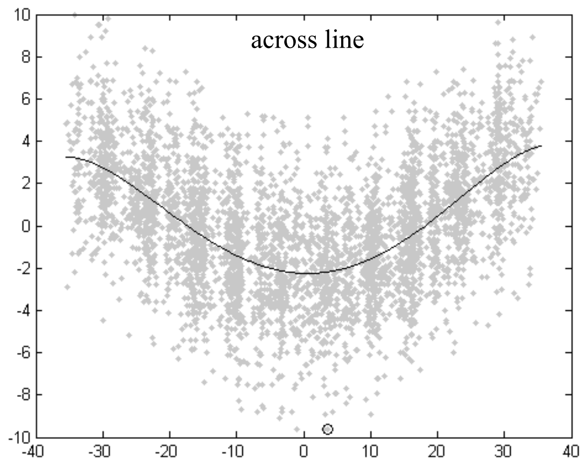


Fig. 3a: Typical residuals plot before correction.

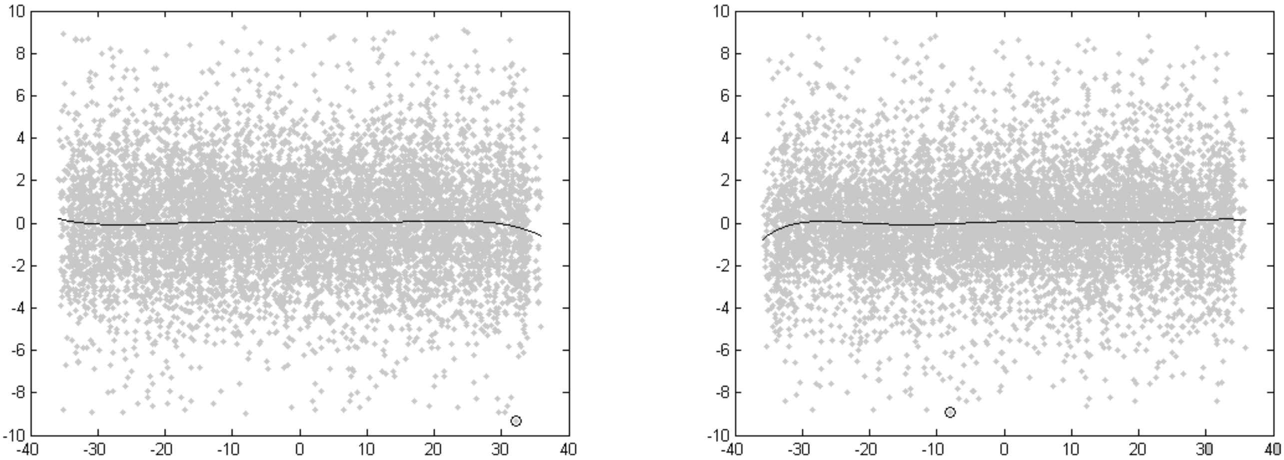


Fig. 3b: Typical residuals plot for the final calibration.

Fig. 3 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 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]. The lower number of points and the clustering along the x-axis in fig. 3a is due to a coarser tie point pattern than used for the later iterations.

The iterations are needed to improve the triangulation quality step-by-step and to resolve correlations between the sensor parameters at the same time. At the end, all correlations are very low, except between the principal point (PPA) position and the IMU misalignment angles. The two flight levels layout of the calibration block help to reduce them to reasonable values of about 0.5, which do not affect the stability of the result.

At the end of the iterations, we typically get a σ_0 of 2.5 μm to 2.9 μm (Fig. 2) for all ADS40 systems, which is as good as we can expect, based on the tie point matching quality. The 6^{th} polynomial degree residuals fit show deviations of less than 1 μm for 90% of the line length and less than 2 μm at the line ends. These deviations vary randomly inside that range, if additional iterations are appended.

4. Conclusion And Future Enhancements

Although the current processing method with the combination of bundle adjustment with additional parameters and residuals analysis is somewhat uncommon, the flight-based calibration yields results, which are better than originally expected and also better than any reasonable laboratory equipment can be.

At the time of writing this paper, the analyses of the required parameters set are nearly done and we are preparing for the implementation of the parameters into ORIMA. We do not expect an increased accuracy from this step, but it will make the process more user-friendly than the current combination of triangulation and residuals analysis. Besides that, we will get a clearer statistical analysis of the results.

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