IMPACT OF CAMERA AND SYSTEM CALIBRATION ON PHOTOGRAMMETRIC RECONSTRUCTION USING MEDIUM FORMAT DIGITAL CAMERA

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ABSTRACT:

Current advances in digital and electronic products have led to the availability of inexpensive and reliable Medium Format Digital Cameras (MFDCs) that can be used in many photogrammetric applications. In this research, the impact of camera and system calibration on object space reconstruction is investigated under different georeferencing scenarios (i.e., indirect georeferencing and integrated sensor orientation). First, camera calibration is conducted using a MFDC (i.e., the Rollei-P65). Based on different camera calibration datasets – such as indoor, in-situ, and camera calibration certificates, the equivalency of the calibration techniques as well as the adequacy of the distortion models are evaluated while considering relative and absolute quantitative measures. Previously developed camera stability analysis technique will be used for testing the adequacy of the utilized distortion model as well as the equivalency of different calibration techniques. Afterwards, system calibration is conducted to estimate the lever-arm and boresight parameters (i.e., mounting parameters) using different calibration datasets. The mounting parameters are estimated through an integrated sensor orientation (i.e., GPS/INS-assisted Aerial Triangulation) using minimum amount of control information. The estimated system calibration parameters are evaluated by investigating both relative and absolute quantitative measures using different camera calibration parameters. The experimental results have shown that the indoor calibration provides reliable estimate of the internal camera characteristics and leads to accurate system calibration and object space reconstruction.

1. INTRODUCTION

Photogrammetry focuses on accurate derivation of spatial and descriptive information from imagery to satisfy the needs of several applications such as mapping, DEM generation, orthophoto generation, construction planning, 3D visualization, and change detection. Accurate 3D reconstruction requires careful calibration of the photogrammetric system. When the object-space reconstruction from overlapping images is carried out trough an indirect georeferencing procedure, the photogrammetric system involves only the camera calibration procedure. However, when dealing with multi-sensor photogrammetric system, which is the case of direct sensor orientation, besides individual sensor calibration (camera, GPS and INS), system mounting parameters calibration is also needed. In the camera calibration procedure, the internal characteristics of a camera, which are defined by its Interior Orientation Parameters (IOP), are determined. In the system calibration, on the other hand, the mounting parameters (i.e., lever-arm offsets and boresight angles) relating the photogrammetric system components, such as the camera, the GPS and INS systems are determined. Direct sensor orientation can be subdivided into (i) Integrated Sensor Orientation and (ii) Direct georeferencing (Jacobsen, 2004). In the Integrated Sensor Orientation (i.e., GPS/INS-assisted aerial triangulation) GPS/INS position and attitude information are available and used as prior information in the bundle adjustment procedure. In the Direct georeferencing, GPS and INS position and attitude information are available and used together with the image coordinates of tie points in a simple intersection procedure.
The camera interior orientation parameters include the principal distance, the coordinates of the principal point, and the distortion model parameters. A distortion model is the mathematical representation of the corrections that compensate for various deviations from the assumed collinearity condition. There exist several variations of distortion models that can be used to model inherent distortions such as the Brown-Conrady model (Brown, 1966; Brown 1971), the USGS Simultaneous Multi-frame Analytical Calibration (SMAC) model (USGS, 2008), and the Orthogonal polynomials model. In Habib et al. (2008), the equivalency between some of these distortion models has already been verified. In this research work, the Brown-Conrady distortion model will be utilized.
Methods for camera calibration can be categorized into two groups: laboratory and analytical calibration methods. The laboratory calibration is carried out under controlled environment conditions using specially designed devices (e.g., multi-collimator) to determine the internal characteristics of the camera. The analytical camera calibration utilizes bundle adjustment with self-calibration, where control information is usually required. There are two types of analytical calibration: indoor and in-situ. The indoor calibration utilizes a test field, which can be either 2-D (e.g., calibration wall) or 3-D (e.g., calibration cube), with precisely surveyed ground control points (GCPs), and convergent images are taken for the calibration procedure. The in-situ calibration, on the other hand, utilizes a test field with precisely surveyed GCPs, and airborne images are taken for the calibration procedure. In order to decouple the flying height and the principal distance in the in-situ calibration, oblique images should be taken and/or the test field should have significant terrain height variations (Jacobsen, 2003).
Traditionally, large format analogue cameras have been used in photogrammetric activities. In the last few years, however,

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digital cameras are becoming more common in photogrammetric activities and are rapidly replacing the need for the conventional large format analogue cameras. This trend can be explained by the ease of use, decreasing cost, and increasing resolution of digital cameras. The airborne digital cameras that are currently available can be grouped into two main categories: the first group includes large format digital cameras, such as line cameras (e.g., ADS50 from Leica Geosystems) and large format frame cameras (e.g., DMC™ from Zeiss/Intergraph); while the second group includes medium to small-format digital cameras (e.g., Rollei-P65). For large format analogue cameras, the well defined laboratory calibration process is executed. The laboratory calibration is usually performed by system manufacturers and dedicated organizations (such as the USGS, NRCan), where trained professionals ensure that high calibration quality is upheld. In contrast to the standard analogue cameras, the calibration process for digital cameras is a more complex task. The difficulty is attributed to the large variety of camera designs available in the market, which would demand different facilities and calibration approaches (Cramer, 2004). This is not critical for large format digital cameras that are specifically built for mapping applications. For these cameras, the calibration process is conducted by the system manufacturer (e.g., Leica or Z/I). This is not the case for MFDCs, which are not manufactured for photogrammetric purposes and have been increasingly used in photogrammetric activities. The increased use of MFDCs by the photogrammetric community is noticeable, especially in conjunction with LiDAR systems and in smaller coverage flight blocks. The preference given by some data providers to MFDCs is attributed to its lower cost when compared with large format digital cameras. The wide spectrum of existing designs for MFDCs coupled with the large number of this type of camera in use by the photogrammetric community makes it impracticable for the system manufacturer and/or some few specialized organizations to execute the laboratory calibration. In addition, the stability of MFDCs is also a concern, given the fact that these cameras are not manufactured for photogrammetric purposes. Therefore, it has become more practical for the data providers to perform their own calibrations and stability analysis of the utilized cameras. In this context, more attention should be placed towards the method and quality of the camera calibration. More specifically, the appropriate calibration procedure and stability analysis as well as the adequate model to represent the inherent distortions in the implemented camera should be carefully investigated.

As already mentioned, in direct sensor orientation, besides the camera calibration, the system mounting parameters calibration is also needed and is crucial for obtaining an accurate object space reconstruction. The method for the estimation of the system mounting parameters can be carried out through a two-step or a single-step procedure. In the two-step procedure, the system mounting parameters are estimated by comparing the GPS/INS positioning and orientation results with the exterior orientation parameters determined from an independent aerotriangulation solution. As an example, in Skaloud (1999) the mounting parameters are estimated for each image separately and then the results undergo an average weighting procedure. In the single-step procedure, on the other hand, the mounting parameters are estimated in the bundle adjustment procedure. There are two approaches for the single-step procedure. In the first approach existing bundle adjustment procedures are extended with added constraints (Grejner-Brzezinska, 1999), while in the second approach, GPS/INS measurements and the system mounting parameters are directly incorporated in the collinearity equations (Pinto and Forlani, 2002).

In this paper, the MFDC Rollei-P65 is investigated. Using this camera, the distortion model adequacy will be evaluated and the equivalency of camera calibration techniques/datasets, such as the indoor and the in-situ, will also be tested. In addition, system calibration will be conducted through an integrated sensor orientation to estimate the lever-arm and boresight parameters (i.e., mounting parameters) using different calibration datasets. The single-step procedure that extends the existing bundle adjustment procedure with additional constraints will be utilized. This paper starts by presenting the methodology that will be used to test the adequacy of the distortion models and the equivalency of the calibration datasets. Then, the aspects involved in the design and implementation of an in-flight mounting parameters calibration, as they relate to control and flight configuration requirements, are investigated. Finally, experimental results using real data are presented followed by conclusions and recommendations for future work.

2. ADEQUACY OF DISTORTION MODELS AND EQUIVALENCY OF CALIBRATION DATASETS

In this section, the methodology for evaluating the distortion model adequacy and for verifying the equivalency of the calibration techniques/datasets is introduced.

2.1 Adequacy of Distortion Model

A model can be classified as being one of three categories: inadequate, adequate, or over-parameterized. An adequate model has the minimum number of distortion parameters needed to sufficiently describe the inherent distortions in the implemented camera. Insufficient and over-parameterized distortion models should be avoided since they will have an adverse effect on the system calibration (mounting parameters) as well as the reconstructed object space. The adequacy of a model with a set of parameters can be carried out by adding one parameter at a time until the minimum number of parameters that is capable of properly representing the phenomenon under investigation is determined. In this work, the adequacy of the distortion model is evaluated by incrementally increasing the model parameters while checking:

(1) <u>The outcome of the bundle adjustment with self calibration procedure:</u>

   a. A-posteriori variance factor $(\hat{\sigma}_o)^2$: Reduction in the a-posteriori variance factor indicates a transition from an insufficient distortion model to a better one. On the other hand, insignificant change in the a-posteriori variance factor indicates a transition from an adequate distortion model to an over-parameterized one.
   b. The accuracy of the estimated distortion parameters: Poor accuracy should be expected for insufficient and over-parameterized models.
   c. Correlations among the elements of the IOP and EOP: Higher correlations are expected for over-parameterized models.

(2) <u>Analysis of the bundle similarity</u>: The bundles defined by each of the distortion models will be checked for similarity. For that purpose, the ROT (Rotation) bundle similarity method previously used for camera stability analysis will be employed (Habib et al., 2006). This method evaluates the similarity of the bundles while sharing the same position in space. In other words, the ROT procedure allows for relative rotations between the

two bundles to assure the best similarity possible. To evaluate the degree of similarity between two defined bundles, a similarity measure ($RMSE_{offset}$) value is computed. The two bundles are deemed similar if the computed $RMSE_{offset}$ is within the range defined by the expected standard deviation of the image coordinate measurements (i.e., 1/2 pixel). For details on how the $RMSE_{offset}$ is computed, interested readers can refer to Habib et al. (2006) and Habib et al. (2008). The adequacy of the distortion model using the bundle similarity method will be checked as follows:

a. The transition from insufficient to adequate models should be manifested in a change in the shape of the reconstructed bundles.
b. The transition from adequate to over-parameterized models should be manifested in having bundles with similar shapes.

(3) Analysis of the impact of the calibration datasets on different georeferencing procedures: the adequate model according to 1) and 2) will be verified/confirmed by analyzing the outcome (i.e., a-posteriori variance factor $(\hat{\sigma}_o)^2$ and RMSE analysis) of the indirect georeferencing and GPS/INS-assisted aerial triangulation procedures. In addition, the validity of the estimated lever-arm components, i.e., the proximity of the physically measured lever-arm parameters to the estimated ones through the GPS/INS-assisted aerial triangulation will be verified as well.

2.2 Equivalency of Calibration Techniques/Datasets

Various calibration techniques, such as laboratory, indoor, and in-situ calibrations can be used to estimate the internal characteristics of a camera. However, one might wonder if the calibration parameters estimated using the different calibration techniques are equivalent or not. In this paper, we would like to verify the equivalency of the calibration datasets from the camera calibration certificate, indoor and in-situ calibrations. Similar to the methodology for checking the distortion model adequacy, first the quality of the outcome from the bundle adjustment with self calibration procedure (i.e., the a-posteriori variance factor, the accuracy of the estimated parameters, and correlations among the estimated parameters) for the indoor and the in-situ calibrations will be analyzed. Then, the bundle similarity methods will be utilized to check the equivalency of the calibration datasets. More specifically, if two bundles defined using the calibration parameters estimated using two different calibration techniques are deemed similar (i.e., $RMSE_{offset}$ < ½ pixel), then these two calibration techniques/datasets are deemed equivalent. Finally, the performance of the calibration procedures is also evaluated for different georeferencing scenarios.

3. SYSTEM MOUNTING PARAMETERS CALIBRATION

In this section, the aspects involved in the design and implementation of an in-flight mounting parameters calibration, as they relate to control and flight configuration requirements, are investigated. First, the GPS/INS-assisted camera mathematical model (point-positioning equation) is discussed. Then, the concept of the mathematical analysis of the GPS/INS point-positioning equation, leading to the determination of the optimum flight configuration and the control requirements for mounting parameters estimation, is described.

3.1 GPS/INS Assisted Camera Mathematical Model

The position of the object point, $\vec{X}_G$, can be derived through the summation of three vectors ($\vec{X}_{GPS/INS}$, $\vec{P}_G$, and $\vec{r}$) after applying the appropriate rotations: $R_{yaw,\,pitch,\,roll}$ and $R_{\Delta\omega,\Delta\phi,\Delta\kappa}$, and scale factor λ as presented in Equation 1. In this equation, $\vec{X}_{GPS/INS}$ is the vector from the origin of the ground coordinate system to the origin of the IMU coordinate system. This vector is derived from the GPS/INS integration procedure while considering the lever-arm offsets between the phase center of the GPS antenna and the IMU body frame. The term $\vec{P}_G$ is the offset between the camera perspective center and IMU coordinate systems (lever-arm offsets), and $\vec{r}$ represents the vector from the perspective center to the image point $(x - x_p - \Delta x, y - y_p - \Delta y, -c)$ with respect to the camera frame coordinate system. The magnitude of the vector $\vec{r}$, after applying the scale factor λ, corresponds to the distance from the camera perspective center to the object point. It should be noted that $x - \Delta x$ and $y - \Delta y$ represent the distortion-free image coordinates, and c represents the calibrated principal distance. The term $R_{yaw,\,pitch,\,roll}$ stands for the rotation matrix relating the ground and IMU coordinate systems (derived through the GPS/INS integration process), $R_{\Delta\omega,\Delta\phi,\Delta\kappa}$ represents the rotation matrix relating the IMU and camera frame coordinate systems (defined by the boresight angles). The boresight angles and lever-arm offsets are determined in the system mounting parameter calibration procedure.

$$\vec{X}_G = \vec{X}_{GPS/INS} + R_{yaw,\,pitch,\,roll}\,\vec{P}_G + R_{yaw,\,pitch,\,roll}\,R_{\Delta\omega,\,\Delta\varphi,\,\Delta\kappa}\,\lambda\,\vec{r} \qquad (1)$$

3.2 Flight Configuration and Control Requirements

In this section, the optimum flight configuration and the minimum ground control requirement for the estimation of the system mounting parameters will be investigated. For that purpose, the impact of biases in the system mounting parameters on the derived object space will be analyzed through mathematical analysis of the GPS/INS-assisted camera point positioning equation.

Note that point reconstruction from overlapping imagery is only possible if conjugate light rays intersect. In the presence of biases in the system mounting parameters, intersection will occur only if these biases do not introduce artificial Y-parallax (assuming flight direction parallel to the X axis). Therefore, an appropriate analysis of the impact of the biases on the object space should also verify whether an artificial Y-parallax is introduced in the presence of such biases. If an artificial Y-parallax is introduced by a specific bias, then such a bias can be recovered using a control-free stereo-pair. In other words, the introduced artificial Y-parallax provides a constrain allowing for the recovery of such a bias. The concept of the proposed mathematical analysis is outlined in the next paragraphs.

In order to investigate whether biases in the system mounting parameters will introduce artificial Y-parallax, we can generate a pair of normalized images from the stereo-pair under consideration. More specifically, an image pair which is parallel to the xy-plane of the IMU body frame (considering that the baseline is parallel to the x-axis of the IMU body frame) can be generated. In the normalized image pair, no Y-parallax exists. To analyze the impact of the biases in the mounting parameters on the normalized image plane, we can differentiate the equations that express the normalized coordinates in terms of the mounting parameters. The outcome of such analysis, after ignoring higher order terms, corresponds to the displacements in the normalized image coordinates caused by each of the mounting parameters biases. Based on these derived displacements, it is possible to verify whether or not these displacements will introduce artificial Y-parallax. One can note that biases in the $\Delta\phi$ (boresight pitch angle) and $\Delta\kappa$ (boresight yaw angle) will introduce artificial Y-parallax. These findings reveal the possibility of estimating biases in the boresight pitch and yaw angles using a control-free stereo pair.

To evaluate the impact of the mounting parameters biases on the reconstructed object space, one can introduce the displacements caused by each of these biases to the normalized coordinates from the left and right images. Using such coordinates from the left and right normalized images, the biased object space coordinates can be derived. By performing such analysis, one can devise the optimum flight configuration that maximizes the impact of biases in the mounting parameters. The impact of the pitch and the yaw bias in the object space reveals the possibility of estimating this parameter from a single flight line, or even a single stereo image pair since an artificial Y-parallax is introduced in the object space. However, having opposite flight lines with almost 100% side lap allows for a better estimate of the boresight pitch angle and having parallel flight lines would allow for a more reliable estimate of the boresight yaw angle. Strips captured in opposite directions with 100% side lap are also optimal for the recovery of the planimetric lever-arm offsets as well as the boresight roll biases. Only a vertical bias in the lever-arm offset parameters cannot be detected by observing discrepancies between conjugate surface elements in adjacent flight strips. Such inability is caused by the fact that a vertical bias in the lever-arm offset parameters produces the same effect regardless of the flying direction, flying height, or image point coordinates. Therefore, at least one vertical ground control point would be required to estimate the vertical component of the lever-arm offset vector.

4. EXPERIMENTAL RESULTS

The objectives of the experimental results section can be summarized as follows:

(1) Analyze the distortion model adequacy: the minimum number of parameters that is adequate/sufficient to properly model the distortions of the implemented camera will be investigated. In this work, the Brown-Conrady model is employed. It is usually assumed that K_1 is sufficient to describe the Radial Lens Distortion (RLD) in Medium-Format/Normal-Angle Digital Cameras. The experimental results will check whether this is valid or not for the MFDC under investigation.

(2) Test the equivalency of the calibration procedures: the equivalency of the indoor, in-situ, and the Camera Calibration Certificate – CCC (available through the data provider) calibration parameters will be verified.

(3) Verify the minimum control and flight configuration requirements for the system mounting parameters calibration.

To carry out investigations 1) and 2), the methodology described in section 2 will be utilized. Investigation 3) will be carried out by performing the system mounting parameters calibration using the devised optimal configuration while increasing the number of utilized ground control points to check whether significant changes in the estimated parameters take place.

4.1 Dataset description

The dataset tested in this research work was acquired by a MFDC Rollei P-65. The utilized camera has an array dimension of 8984x6732 pixels and a focal length of 60 mm. A total of eighteen convergent images were taken for the indoor camera calibration experiments. The GPS/INS-assisted flight mission configuration consists of a total of six flight lines, where four were flown in the E-W direction and two in the N-S direction, (in opposite directions) with 60% overlap. The flight lines flown in the E-W direction were acquired from a flying height of ~550 m (above MSL) and 80% side lap. The flight lines flown in the N-S direction were obtained from a flying height of ~1200 m (above MSL) and 100% side lap. The given GPS and INS accuracy by the data provider is ±10 cm and ±10 sec, respectively. In the surveyed area, thirty-seven control points were established. Although this dataset was not acquired for use in an in-situ calibration, which would require significant terrain height variation and/or oblique imagery, it was used for that purpose.

4.2 Calibration Results

The indoor and the in-situ camera calibration were performed using bundle adjustment with self-calibration under an indirect georeferencing procedure. Three different distortion models are investigated in this paper. The first model denoted in this paper as *A* includes the parameter K_1 only. The second model is denoted as *B* and includes the parameters K_1 and K_2. Finally, the third model, denoted as *C* includes the parameters K_1, K_2, P_1, P_2, A_1,and A_2. Table 1 reports the calibration results for the indoor and in-situ techniques using the three different distortion models. In the in-situ calibration, for all three distortion models, correlations between c and Z_o, and Z_o among images were found to be higher than 0.99. As mentioned earlier, the utilized test field was not designed for an in-situ calibration. More specifically, the utilized test field is relatively flat (i.e., no significant height variation). Furthermore, almost vertical images were taken instead of oblique images and therefore, c and Z_o could not be decoupled. The correlations between these parameters significantly reduce the reliability of the IOP acquired by this in-situ camera calibration. This is also expressed by the higher standard deviation of the estimated parameters when compared to the indoor cases. Therefore, only the indoor calibration will be considered for testing the adequacy of the distortion models.

It can be noticed in Table 1 that there is a significant improvement in the a-posteriori variance factor $(\hat{\sigma}_o)^2$ when utilizing the distortion model *B* instead of model *A*. In other words, model *B* leads to a better fit between the observations and the estimated parameters, including the IOP, more than that resulting from model *A*. The same significant improvement can be observed in the standard deviations of the estimated parameters in model *A* and *B*. The improvement in the a-posteriori variance factor $(\hat{\sigma}_o)^2$, on the other hand, is less significant when using the distortion model *C* instead of model *B*. A closer look at the indoor results also reveals that even though the a-posteriori variance factor $(\hat{\sigma}_o)^2$of model *C* is slightly better than that in model *B*, the standard deviation of some of the estimated parameters (e.g., x_p, y_p) using model *B* is better than that in model *C*. This is explained by the over-parameterization in model *C* that leads to correlation among the IOP and among the IOP and EOP. The correlation within the IOP is mainly between the x_p, y_p and P_1, P_2 (note the significant deviations between the estimates of x_p, y_p in models *B* and *C*). As a result, model *B* leads to better estimate of the IOP when compared with model *C*. Based on these results, the following conclusions can be made:

- Model *A* is an **inadequate** model for representing the inherent distortions in the implemented camera.
- Model *B* is an **adequate** model for representing the inherent distortions in the implemented camera. Therefore, differently from what is usually assumed for MFDCs, K_1 is not sufficient to model the lens distortion of the MFDC used in this research work.
- Model *C* is an **over-parameterized** model that leads to correlation among the elements of the IOP as well as correlation between the IOP and EOP.

Now, it will be verified whether we can use the bundle similarity approach to prove the adequacy of model *B*. The computed $RMSE_{offset}$ value for models *A* and *B* was found to be larger than ½ pixel (1.466 pixel). Therefore, these models define two different bundles. The computed $RMSE_{offset}$ value for models *B* and *C*, on the other hand, was smaller than ½ pixel (0.251 pixel). As a result, these bundles are deemed similar. In other words, model *C* does not lead to variation in the shape of the bundle when compared with model *B*. These results confirm the adequacy of the model *B* to represent the distortions inherent in the implemented camera.

So far, the focus was on the analysis of the distortion model adequacy. Now, the bundle similarity approach will be used to check the equivalence of the calibration parameters from the indoor and from the CCC. In this comparative analysis, only model *B* is used since it has already been proven that this is the adequate model. The computed $RMSE_{offset}$ value was smaller then ½ pixel (0.238 pixel), which demonstrates the equivalency between the indoor and the CCC calibration parameters are deemed equivalent.

Now, the impact of the utilized distortion model and the equivalency of the calibration procedures/datasets on the indirect georeferencing procedure will be verified. Table 2 presents the indirect georeferencing results using various calibration datasets. It can be noted in the reported values in this table that the inadequacy of model *A* in describing the inherent distortions in the involved camera is manifested in the worst a-posteriori variance factor among the tested models. As expected, the $(\hat{\sigma}_o)^2$ and the RMSE for the indoor models *A* and *B* are quite different given that these two models were deemed different. On the other hand, similar $(\hat{\sigma}_o)^2$ and RMSE values for the indoor models *B* and *C* can be observed, thus confirming the adequacy of the model *B*. Also, note that the $(\hat{\sigma}_o)^2$ and the RMSE of the in-indoor model *B* is close to the camera calibration certificate model *B* results. This similarity is also expected since these two calibration datasets were deemed equivalent.

Table 3 presents the GPS/INS-assisted aerial triangulation results using different calibration datasets for the estimation of the system mounting parameters. In the performed experiments, it could be verified that the given a-priori standard deviation of the available attitude (±10sec) was too optimistic in the adjustment procedure. Therefore, ±100sec was employed instead. As in the indirect georeferencing case, it can be observed in the reported values in Table 3 that model *A* leads to the worst a-posteriori variance factor among the tested models, verifying its inadequacy for representing the inherent distortions in the involved camera. Moreover, the inadequacy of model *A* results in unrealistic estimate of the lever arm components when compared with the physically measured ones. The indoor calibration (model *B*) leads to the closest estimate of the lever arm components when compared to the physically measured ones. It also leads to the best RMSE results when compared with the other tested models (highlighted cells in Table 3). On the other hand, the over-parameterized model *C* leads to unrealistic estimate of the lever-arm components as well as worse estimate of the RMSE values when compared with the outcome from the indoor calibration (model *B*). In terms of equivalency of the calibration procedures, it can be observed in Table 3 that, in spite of the fact that the indoor and the CCC have almost equivalent RMSE values, the later produces less realistic estimates of the lever-arm components. Therefore, the indoor calibration produces the most faithful description of the inherent distortions in the involved camera.

Another conclusion that can be drawn from Table 3 is that the estimated lever-arm components for a given calibration technique and distortion model (e.g., indoor model *B* – highlighted cells) do not significantly change with the increase in the number of utilized GCP. Hence, one can conclude that a single vertical GCP is sufficient for the estimation of the mounting parameters given that an appropriate flight configuration was utilized.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This paper has investigated the impact of the camera and system mounting parameters calibration on photogrammetric reconstruction. First, a methodology for testing the adequacy of the distortion models and the equivalency of the calibration techniques/datasets was presented. Then, the aspects involved in the design and implementation of an in-flight mounting parameters calibration, as they relate to control and flight configuration requirements were investigated through mathematical analysis of the GPS/INS assisted camera point-positioning equation. This analysis has led to the optimum flight configuration for the estimation of biases in the system mounting parameters. The experimental results section demonstrated that differently from what is usually presumed for MFDCs, K_1 is not sufficient to model the lens distortion of the MFDC used in this research work. Instead, the distortion model including the parameters K_1, K_2 is the adequate model to represent the IOP of the involved camera. Also, it was verified that the indoor calibration provides reliable estimate of the internal camera characteristics and leads to accurate system calibration and object space reconstruction. It was proven that a single vertical GCP is sufficient for the estimation of the mounting parameters given that an appropriate flight configuration was used. Future work will focus on performing more tests with other datasets including imagery suitable for in-situ calibration. Moreover, the achievable accuracy of the implemented camera using the estimated mounting parameters in a direct georeferencing will be investigated.

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Table 1. Calibration results using indoor and in-situ techniques and the distortion models under investigation

	Indoor (*A*)	Indoor (*B*)	Indoor (*C*)	In-Situ (*A*)	In-Situ (*B*)	In-Situ (*C*)
$(\hat{\sigma}_o)^2$ (mm)^2	$(0.0019)^2$	$(0.0011)^2$	$(0.0010)^2$	$(0.0050)^2$	$(0.0020)^2$	$(0.0017)^2$
x_p (mm±mm)	0.0653 ±0.0050	0.0649 ±0.0028	0.0058 ±0.0069	0.0501 ±0.0406	0.0921 ±0.0167	-0.0029 ±0.0164
y_p (mm±mm)	0.1484 ±0.0049	0.1541 ±0.0027	0.0829 ±0.0069	0.1843 ±0.0413	0.1751 ±0.0170	0.1012 ±0.0164
c (mm±mm)	60.686 ±0.0123	60.678 ±0.0070	60.681 ±0.0065	60.713 ±0.3887	60.783 ±0.1598	60.672 ±0.1376
K_1 (mm^{-2}± mm^{-2})	-2.0137e-007 ±7.5957e-008	-4.2737e-006 ±9.5110e-008	-4.2090e-006 ±9.1696e-008	1.8516e-006 ±1.3248e-007	-3.9882e-006 ±1.1422e-007	-4.0168e-006 ±9.7047e-008
K_2 (mm^{-4}± mm^{-4})	-	5.5041e-009 ±1.1476e-010	5.4768e-009 ±1.0631e-010	-	5.4293e-009 ±9.3405e-011	5.4038e-009 ±7.9654e-011
P_1 (mm^{-1}± mm^{-1})	-	-	-5.4675e-006 ±6.0061e-007	-	-	-5.5541e-006 ±4.9130e-007
P_2 (mm^{-1}± mm^{-1})	-	-	-6.5251e-006 ±6.0055e-007	-	-	7.0255e-006 ±6.0257e-007
A_1	-	-	1.1723e-005 ±5.5275e-006	-	-	-1.7625e-006 ±9.7739e-006
A_2	-	-	-3.0024e-005 ±9.0786e-006	-	-	-6.5324e-005 ±1.7521e-005

Table 2. Indirect georeferencing results using different calibration datasets using ten GCPs and twenty-seven check points

	$(\hat{\sigma}_o)^2$ (mm)^2	RMSE_X(m)	RMSE_Y(m)	RMSE_Z(m)
Indoor (A)	$(0.0060)^2$	0.071	0.096	0.596
Indoor (B)	$(0.0021)^2$	0.051	0.047	0.103
Indoor (C)	$(0.0025)^2$	0.081	0.064	0.083
CCC (B)	$(0.0022)^2$	0.054	0.051	0.165

Table 3. Estimated a-posteriori variance factor, lever-arm components, boresight angles and RMSE values using GPS/INS-Assisted Integrated Sensor Orientation (ISO – ±10cm & ±100sec) and different IOP

Camera Calibration Datasets + GCP	$\hat{\sigma}_o^{\,2}$ (mm)^2	Lever-Arms			Boresight angles			RMSE_X (m)	RMSE_Y (m)	RMSE_Z (m)
		dx (m)	dy (m)	dz (m)	dω (º)	dφ (º)	dκ (º)			
Indoor (*A*) + 1 vertical GCP	$(0.0072)^2$	0.343	-0.141	0.505	-0.1123	0.8600	179.5792	0.201	0.223	0.175
Indoor (B) + 1 vertical GCP	$(0.0027)^2$	-0.039	-0.110	1.146	-0.1225	0.8418	179.5522	0.078	0.096	0.121
Indoor (B) + 37 vertical GCP	$(0.0026)^2$	-0.033	-0.128	1.123	-0.1186	0.8454	179.5511	0.085	0.099	NA
Indoor (B) + 37 full GCP	$(0.0026)^2$	-0.007	-0.144	1.232	-0.1203	0.8436	179.5449	NA	NA	NA
Indoor (*C*) + 1 vertical GCP	$(0.0033)^2$	0.301	-1.546	1.185	-0.0723	0.7977	179.5438	0.082	0.356	0.189
CCC (*B*) + 1 vertical GCP	$(0.0028)^2$	-0.121	-0.465	1.096	-0.1224	0.8433	179.5528	0.095	0.121	0.122
Physically measured values	-	-0.180	-0.170	1.065	-	-	-			