QUANTITATIVE MEASURES FOR THE EVALUATION OF CAMERA STABILITY

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ABSTRACT:

Increasing resolution and reducing costs of off-the-shelf digital cameras are giving rise to their utilization in traditional and new photogrammetric applications, and allowing amateur users to generate high-quality photogrammetric products. For most, if not all photogrammetric applications, the internal metric characteristics of such cameras need to be determined and analyzed. This is achieved by going through a camera calibration and stability analysis process using a specific test field configuration. In a traditional test field, precisely surveyed ground control points (GCPs) are used as control information. The proposed test field in this research involves the utilization of linear features. Two quantitative methods for testing camera stability are introduced, where the degree of similarity between reconstructed bundles from two sets of Interior Orientation Parameters (IOP) is evaluated. In addition, an illustration of the test field created for the experiments as well as a few technical details on each camera used in the calibrations are presented. Through experimentation, the stability of the estimated IOP of each camera over a period of eight months is quantified and analyzed.

1. INTRODUCTION

The primary objective of photogrammetry is to generate spatial and descriptive information from two-dimensional imagery. Since its inception, the use of film metric cameras has been the norm in photogrammetric projects. However, the role of digital cameras in such projects has been rising along with its rapid development, ease of use and availability.

In order to generate reliable and accurate three-dimensional information using such cameras, their internal characteristics, which are customarily known as the Interior Orientation Parameters (IOP), have to be modelled and carefully estimated. To determine the IOP, camera calibration is the universally-employed technique. Camera calibration requires control information, which is usually available in the form of a test field. Traditional calibration test fields consist of distinct and specifically marked points or targets (Fryer, 1996). Establishing and maintaining a conventional test field, as well as carrying out the calibration procedure, require professional surveyors and photogrammetrists. Such requirements limit the potential use of high quality and low cost digital cameras, and hence, a calibration test field consisting of straight lines and tie points can be adopted as an alternative for representing control information.

For calibration, images covering the test field are acquired and incorporated in a bundle adjustment with self-calibration procedure to simultaneously estimate the IOP of the implemented camera and the Exterior Orientation Parameters (EOP) of the exposure stations. The results from different calibration sessions are then used in an IOP comparison procedure to check the stability of the implemented camera. Statistical testing is a possible methodology that can be utilized to accept or reject the hypothesis that the estimated IOP from these calibration sessions are equivalent. However, this methodology makes a number of idealized assumptions and does not provide a meaningful measure to show the differences between bundles or other possible discrepancies in the object space that could arise from using different IOP. Therefore, the methodology used in this research is a bundle comparison procedure that quantifies the degree of similarity between reconstructed bundles from two sets of IOP. In this research, there are two methods of quantifying this similarity, which are an Image Space comparison and an Object Space comparison. The methodology behind these calibration and stability analysis procedures was proposed by Habib et al (2002-a) and Habib and Morgan (2004).

A number of amateur and professional cameras ranging in price from $500 to $6000 USD are used in the calibration and stability analysis. For each camera, a number of calibration datasets are produced. Each calibration dataset provides a set of IOP that is used to reconstruct a bundle of light rays where one bundle from one set of IOP is compared to another bundle from another set of IOP. By quantifying the difference between the two sets, an inference can be made on how similar the two sets are.

The paper is organized in the following manner:

- Section 2 provides a concise description of the calibration math model as well as the advantages and various approaches for utilizing straight lines in the calibration procedure.
- Section 3 outlines the methodology for stability analysis using statistical testing, as well as the two proposed methodologies where the degree of similarity is evaluated between reconstructed bundles using two sets of IOP.
- Section 4 provides a description of the test field and the cameras employed in the experiments.
- Section 5 primarily focuses on the experimentation results including an analysis of the results.
- Section 6 concludes with a brief summary and recommendations for future work.

2. CAMERA CALIBRATION

The purpose of camera calibration is to determine numerical estimates of the IOP of the implemented camera. The IOP comprises the focal length (c), location of the principal point (x_p, y_p) and image coordinate corrections that compensate for various deviations from the assumed perspective geometry. The perspective geometry is established by the collinearity condition, which states that the perspective center, the object point and the corresponding image point must be collinear. A distortion in the image signifies that there is a deviation from collinearity. The collinearity equations, which define the relationship between image and ground coordinates of a point in the image, are:

$$x_a = x_p - c\frac{r_{11}(X_A - X_O) + r_{21}(Y_A - Y_O) + r_{31}(Z_A - Z_O)}{r_{13}(X_A - X_O) + r_{23}(Y_A - Y_O) + r_{33}(Z_A - Z_O)} + \Delta x$$
$$y_a = y_p - c\frac{r_{12}(X_A - X_O) + r_{22}(Y_A - Y_O) + r_{32}(Z_A - Z_O)}{r_{13}(X_A - X_O) + r_{23}(Y_A - Y_O) + r_{33}(Z_A - Z_O)} + \Delta y \quad (1)$$

Where:

x_a and y_a	are the image coordinates
X_A, Y_A and Z_A	are the ground coordinates
Δx and Δy	are compensations for the deviations from collinearity
x_p, y_p and c	are the IOP of the camera
X_O, Y_O, Z_O	are the ground coordinates of the exposure station (perspective center)
$r_{11}, r_{12}, \ldots, r_{33}$	are the elements of a rotation matrix that are a function of ω, φ and κ

Potential sources of the deviation from collinearity are the radial lens distortion, de-centric lens distortion, atmospheric refraction, affine deformations and out-of-plane deformations (Fraser, 1997). These distortions are represented by explicit mathematical models whose coefficients are called the distortion parameters. The relative magnitude of these distortions is an indication of the condition and quality of the camera.

In order to determine the IOP of the camera, including the distortion parameters, calibration is done with the use of control information in the form of a test field. In a traditional calibration test field, numerous control points are precisely surveyed prior to the calibration process. Image and object coordinate measurements are used in a bundle adjustment with self-calibration procedure to solve for the IOP of the involved camera, EOP of the imagery and object coordinates of the tie points. As mentioned earlier, establishing a traditional calibration test field is not a trivial task and it requires professional surveyors. Therefore, an alternative approach for camera calibration using an easy-to-establish test field comprised of a group of straight lines is implemented in this research.

Object space straight lines prove to be the least difficult and most suitable feature to use for calibration. They are easy to establish in a calibration test field. Linear features, which essentially consist of a set of connected points, increase the system redundancy and consequently enhance the geometric strength and robustness in terms of the ability to detect blunders. Corresponding lines in the image space can be easily extracted using image-processing techniques such as image resampling and application of edge detection filters. Moreover, automation of the linear feature extraction process can be a reliable and time-saving approach. For camera calibration purposes, object space straight lines will project into the image space as straight lines in the absence of distortion. Therefore, deviations from straightness in the image space can be modelled and attributed to various distortion parameters in a near continuous way along the line.

Several approaches for the representation and utilization of straight lines have been proposed in literature and all suffer from a few drawbacks. In these approaches, the IOP estimation follows a sequential procedure (Brown, 1971; Guoqing et al, 1998; Prescott and McLean, 1997; and Heuvel, 1999). First, linear features are used to derive an estimate of the radial and de-centric lens distortions, which is then followed by a traditional calibration to determine the principal distance and principal point coordinates. The estimated parameters in the calibration will be contaminated by uncorrected systematic errors such as affine deformations, which are not compensated for during the first step. Another approach by Bräuer-Burchardt and Voss (2001) assumed that distorted lines can be modelled as circular curves, which might not always be the case. Chen and Tsai (1990) introduced another method that requires the knowledge of the parametric equations of the object space straight lines, which mandates additional fieldwork.

In this research, Habib et al (2002-a, 2002-b) proposed a calibration test field consisting of straight lines that are represented by two points along the line in the object space. Acquired imagery over the test field is used in a bundle adjustment with self-calibration procedure to simultaneously estimate the IOP of the implemented camera and the EOP of the exposure stations. For a detailed explanation of the bundle adjustment procedure, the representation, selection and optimal configuration of straight lines in imagery, and the automated linear feature extraction process, refer to Habib et al (2002-b) and Habib et al (2004). Once the calibration procedure has been carried out, the IOP of the camera that are derived from two different calibration sessions can be inspected.

3. STABILITY ANALYSIS

The desired outcome of stability analysis is to determine whether two sets of IOP are equivalent to each other. The following sections describe possible approaches for comparing two IOP sets to analyze camera stability.

3.1 Statistical Testing

The statistical properties of two IOP sets can be described by an assumed normal distribution, which has a mean of the true IOP (IOP_T) of the implemented camera. For stability analysis, a null hypothesis (H_o) can be tested for possible rejection under the assumption that the two IOP sets are equivalent. Accepting the null hypothesis simply affirms that there is no significant difference between the two IOP sets and the internal characteristics of the camera are stable. Assuming that the two IOP sets are uncorrelated and that the true IOP of the camera does not change between the two calibration sessions, the null hypothesis is:

$$H_o: IOP_I = IOP_{II} \quad \text{or} \quad H_o: e = IOP_I - IOP_{II} \sim (0, \Sigma_I + \Sigma_{II})$$

Where: IOP_I and IOP_{II} are the estimated IOP sets from the two calibration sessions, and Σ_I and Σ_{II} are the corresponding variance-covariance matrices.

A test statistic (T), which is used to determine whether or not the null hypothesis is rejected, follows a χ^2 distribution with degrees of freedom that is equal to the rank of the matrix - $\Sigma_I + \Sigma_{II}$ (Koch, 1999). It is computed as:

$$T = e^T (\Sigma_I + \Sigma_{II})^{-1} e$$

The acceptance or rejection of the test statistic will partly depend on the assumed level of significance, which is the fixed probability of rejecting a true null hypothesis. Assuming a certain level of significance, if the computed value is greater than the critical value (T_c) of the test statistic (i.e., $T > T_c$), the null hypothesis is rejected and hence, the two IOP sets are deemed to be significantly different from each other.

Statistical testing for the purposes of evaluating camera stability includes a number of assumptions that make it impractical to use. It assumes a normal distribution for the estimated IOP without any biases; it assumes that the variance-covariance matrices associated with the IOP sets are available; and it does not take any possible correlation between IOP and EOP into consideration. Furthermore, Habib and Morgan (2004) demonstrated that statistical testing generally gives pessimistic results for stability analysis even though the two sets of IOP may be similar from a photogrammetric point of view. Lastly, the differences in IOP should be evaluated by quantifying the discrepancy between bundles of light rays, defined by the two IOP sets, in terms of the dissimilarity of the reconstructed object space. This will provide a more meaningful measure of the differences between the IOP sets. Due to these shortcomings of statistical testing, two alternative techniques for evaluating camera stability are utilized in this research and explained in the next section.

3.2 Similarity of Reconstructed Bundles

In this research, two methods for evaluating the similarity are used. One method is a comparison that is confined to the image space and the other is an object space comparison.

3.2.1 Image Space Comparison

In this method, two IOP sets define two bundles of light rays that share the same perspective center, *Figure 1*. The degree of similarity between these bundles can be evaluated by computing the mean spatial angle (angular offset) between conjugate light rays, while assuming that the image coordinate systems associated with the two bundles are parallel to each other.

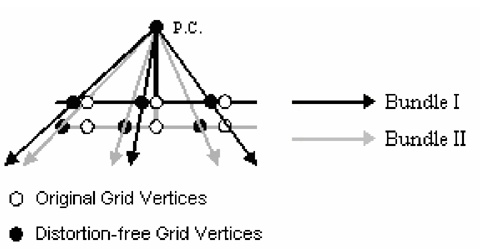

Figure 1 – Two bundles with same perspective center and parallel image coordinate systems

The steps to derive a quantitative measure for the degree of similarity between the two bundles can proceed as follows:

i. Define a synthetic regular grid in the image plane. The user can specify the size of the grid cells and the extent of the grid with respect to the image size. The extent of the grid should cover the entire image (i.e., 100% of the image).
ii. Remove various distortions at the defined grid vertices using the involved IOP from two calibration sets.
iii. Assuming the same perspective center, define two bundles of light rays using the principal distance, principal point coordinates and distortion-free coordinates of the grid vertices.
iv. Compute the spatial angle between conjugate light rays within the defined bundles.
v. Derive statistical measures (i.e., the mean and standard deviation) describing the magnitude and variation among the estimated spatial angles.

The above methodology for comparing the reconstructed bundles assumes the coincidence of the optical axes defined by the two IOP sets. However, stability analysis is concerned with determining whether the reconstructed bundles coincide with each other regardless of the orientation of the respective image coordinate systems. Therefore, there might be a unique set of three rotation angles (ω, φ, κ) that can be applied to the first bundle to produce the second one while maintaining the same perspective center, *Figure 2*.

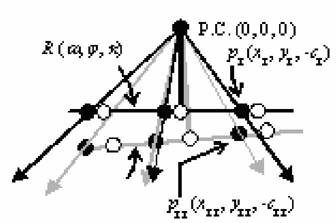

Figure 2 – Image Space Comparison where bundles are rotated to reduce the angular offset

As shown in *Figure 2*, (x_I, y_I, $-c_I$) and (x_{II}, y_{II}, $-c_{II}$) are the three-dimensional vectors connecting the perspective center and two conjugate distortion-free coordinates of the same grid vertex according to IOP_I and IOP_{II}, respectively. To make the two vectors coincide with each other, the first vector has to be rotated until it is aligned along the second vector. This coincidence of the two vectors after applying the rotation angles can be mathematically expressed as:

$$\begin{bmatrix} x_{II} \\ y_{II} \\ -c_{II} \end{bmatrix} = \lambda \ R(\omega,\phi,\kappa) \begin{bmatrix} x_I \\ y_I \\ -c_I \end{bmatrix} \qquad (2)$$

To eliminate the scale factor (λ), the first two rows in *Equation 2* are divided by the third one after multiplication with the transpose of the rotation matrix to give the following equations:

$$x_I = -c_I \frac{r_{11} x_{II} + r_{21} y_{II} - r_{31} c_{II}}{r_{13} x_{II} + r_{23} y_{II} - r_{33} c_{II}}$$
$$y_I = -c_I \frac{r_{12} x_{II} + r_{22} y_{II} - r_{32} c_{II}}{r_{13} x_{II} + r_{23} y_{II} - r_{33} c_{II}} \qquad (3)$$

Equation 3 represents the necessary constraints for making the two bundles defined by IOP_I and IOP_{II} coincide with each other. The rotation angles (ω, φ, κ) are estimated using a least squares adjustment. The variance component (σ_o^2), the variance of an observation of unit weight, resulting from the adjustment procedure represents the quality of the coincidence between the two bundles after applying the estimated rotation angles.

Assuming that (x_I, y_I) in *Equation 3* are the observed values, the corresponding residuals represent the spatial offset between the two bundles, after applying the rotation angles, along the image plane defined by the first IOP set. Therefore, assigning a unit weight to all the constraints resulting from various grid vertices yields a variance component that represents the variance of the spatial offset between the two bundles along the image plane. A relative comparison between the computed variance component and the expected variance of image coordinate measurements would reveal whether the two bundles are significantly different from each other or not. The above methodology is denoted as the rotation (ROT) method in image space comparison.

The comparison in image space provides meaningful measures of the degree of similarity between two bundles of light rays, defined by two sets of IOP, sharing the same origin (perspective center). However, it is possible that the IOP and EOP might be correlated. Therefore, the object space comparison method is an alternative technique for comparing the bundles in terms of their fit at a given object space.

3.2.2 Object Space Comparison

In contrast to the image space comparison method, two bundles of light rays are compared by permitting spatial and rotational offsets between them while observing their fit at a given object space. Hence, the two bundles might not share the same perspective center. The methodology for evaluating the degree of similarity between the two bundles in terms of their fit at a given object space can proceed as follows:

i. Define a regular grid in the image plane.
ii. Derive distortion-free coordinates of the grid vertices using two IOP sets.
iii. Define a bundle of light rays for the first IOP set using the perspective center together with the distortion-free grid vertices.
iv. Intersect the bundle of the first IOP set with an arbitrary object space to produce a set of object points, as shown in *Figure 3*.
v. Use the object points and the corresponding distortion-free grid vertices, according to the second set of IOP, in a Single Photo Resection (SPR) procedure to estimate the position and the attitude of the second bundle that fits the object space as defined by the given set of object points. The variance component resulting from the SPR procedure represents a quantitative measure of the spatial offset between the distortion-free grid vertices, defined by the second set of IOP, and the computed coordinates from back projecting the object points.

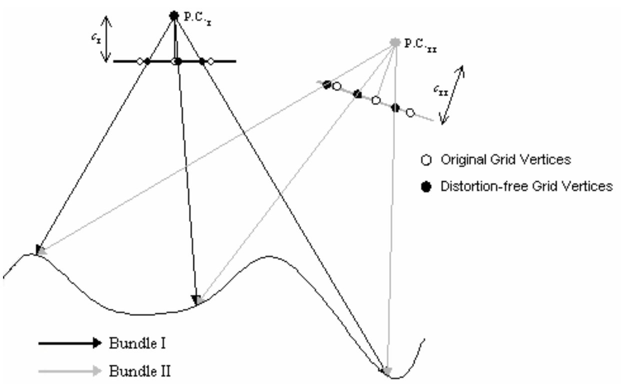

Figure 3 – Object Space Comparison between bundles by allowing spatial and rotational offsets

A relative comparison between the computed variance component and the expected variance of the image coordinate measurements will reveal whether the two bundles fit at the object space. A good fit signifies that the two bundles defined by the two sets of IOP are similar. The above methodology is denoted as the SPR method in this paper.

There is one factor in the SPR method that will affect the quality of fit of the object points, and that is the choice of the object space. A relatively flat terrain is expected to have high correlations between the IOP and EOP, and yield a better fit between the two bundles at the object space, even if the two IOP sets are significantly different from each other. On the other hand, a rugged terrain would allow for the de-correlation between the IOP and EOP, and give a more reliable measure for the degree of similarity between the two bundles. Therefore, the type of terrain must be chosen in such a way that it is similar to the expected object space to be photographed by the calibrated camera.

4. EXPERIMENT DESCRIPTION

To perform calibration and stability analysis on a camera, a specific detailed procedure is carried out. A two-dimensional test field consisting of straight lines and points was used for calibration, *Figure 4*. Lines and points were established on a 3.5 x 7.0 meter section of a white wall. The lines are thin, dark ropes that are stretched between nails on the wall, and the points are in the form of crosses that are signalized targets used as tie points in the calibration procedure. The datum for the calibration procedure is established by fixing six coordinates of three points as well as a few measured distances. For the conducted camera calibration experiments, eighteen converging and overlapping images are captured at locations that are roughly four to five meters away from the closest point on the test field. The position and orientation of each captured image are shown in *Figure 4*.

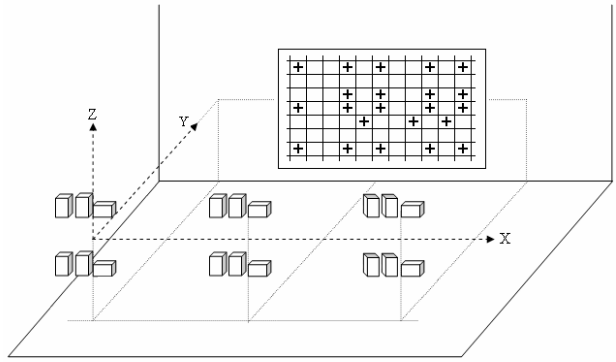

Figure 4 – Calibration Test Field and Position and orientation of 18 images captured for a calibration dataset

The cameras implemented for calibration and stability analysis are digital cameras ranging in price from $500 to $6000 USD. They are all Single-lens Reflex (SLR) cameras with Charged-coupled Device (CCD) sensors. *Table 1* summarizes the characteristics of the implemented cameras.

Camera	**Price Range ($ US)**	**Max. Output Resolution (pixels)**	**Pixel Size (mm/pixel)**	**Effective Pixels (MPixels)**
Canon EOS 1D	$5000	2464x1648	0.0115	4.15
Nikon 4500	$500 - $600	2272x1704	0.0031	3.87
Rollei d 7 metric	$6000	2552x1920	0.004	4.90
Sony DSC-F707	$650 - $800	2560x1920	0.004	4.92

Sony DSC-P9	$500	2272x1704	0.004	3.90

Table 1 – Characteristics of Implemented Cameras

5. EXPERIMENTAL RESULTS

A total of nine digital cameras were calibrated and evaluated for stability over an eight-month period. For each camera, with the exception of the four Nikon 4500 cameras, image datasets were acquired in two or more months. For the four Nikon 4500 cameras, two image datasets were captured on the same day by simply switching the camera off and on between datasets.

As mentioned in *Section 3.2*, to check the stability of a camera, the estimated standard deviation (σ_o) component resulting from the adjustment procedure represents the spatial offset between the two bundles along the image plane. If this value is not significantly larger than the expected image coordinate measurement accuracy, which can be considered to be approximately two-thirds of a pixel, then the two IOP sets are deemed similar.

The stability results for the nine digital cameras (denoted by their experiment names) are listed below. The comparison method implemented is the ROT method with K1 estimated and four distances measured in the calibration procedure.

i. CanonOne – For the Canon camera, the standard deviation of the spatial offset (σ_o) must be less than 0.0077 mm, which corresponds to two-thirds of a pixel, for the IOP sets to be considered similar. From *Table 2*, it can be seen that all IOP set comparisons passed this test of similarity.

ID	***Date***		***σ_o (mm)***	***Similar***
	IOP Set I	***IOP Set II***		
1	**Jul 03**	**Oct 03**	**0.00385**	**Yes**
2	**Jul 03**	**Jan 04**	**0.00142**	**Yes**
3	**Oct 03**	**Jan 04**	**0.00469**	**Yes**

Table 2 – Stability Comparison of IOP sets for CanonOne
(Note: If $\sigma_o < 0.0077$, IOP sets considered similar)

ii. CanonTwo – From observing *Table 3*, all IOP set comparisons reveal that the IOP of this camera is stable over a short and long period of time since σ_o is less than 0.0077 mm.

ID	***Date***		***σ_o (mm)***	***Similar***
	IOP Set I	***IOP Set II***		
1	**Jul 03**	**Oct 03**	**0.00553**	**Yes**
2	**Jul 03**	**Jan 04**	**0.00480**	**Yes**
3	**Oct 03**	**Jan 04**	**0.00614**	**Yes**

Table 3 – Stability Comparison of IOP sets for CanonTwo
(Note: If $\sigma_o < 0.0077$, IOP sets considered similar)

iii. Rollei – The results in *Table 4* demonstrate that the IOP sets of the Rollei are similar for the six comparisons since σ_o is within the acceptable image coordinate measurement accuracy of 0.003 mm (⅔ of the Rollei pixel size).

ID	***Date***		***σ_o (mm)***	***Similar***
	IOP Set I	***IOP Set II***		
1	**Jul 03**	**Oct 03**	**0.00290**	**Yes**
2	**Jul 03**	**Jan 04**	**0.00147**	**Yes**
3	**Oct 03**	**Jan 04**	**0.00146**	**Yes**
4	**Jul 03**	**Feb 04**	**0.00201**	**Yes**
5	**Oct 03**	**Feb 04**	**0.00180**	**Yes**
6	**Jan 04**	**Feb 04**	**0.00103**	**Yes**

Table 4 – Stability Comparison of IOP sets for Rollei
(Note: If $\sigma_o < 0.003$, IOP sets considered similar)

iv. SonyF707 – For the SonyF707 experiment results given in *Table 5*, all comparisons of IOP sets indicate that the IOP of this camera remains stable since σ_o is within the acceptable image coordinate measurement accuracy of 0.003 mm.

ID	***Date***		***σ_o (mm)***	***Similar***
	IOP Set I	***IOP Set II***		
1	**Jul 03**	**Oct 03**	**0.00206**	**Yes**
2	**Jul 03**	**Feb 04**	**0.00176**	**Yes**
3	**Oct 03**	**Feb 04**	**0.00291**	**Yes**

Table 5 – Stability Comparison of IOP sets for SonyF707
(Note: If $\sigma_o < 0.003$, IOP sets considered similar)

v. SonyP9 – Image datasets were acquired only in the months of July and January, and as shown in *Table 6*, the IOP comparison of the SonyP9 gave a standard deviation component (σ_o) well below the required image coordinate measurement accuracy. However, more comparisons need to be made to determine how stable the camera really is.

ID	***Date***		***σ_o (mm)***	***Similar***
	IOP Set I	***IOP Set II***		
1	**Jul 03**	**Jan 04**	**0.00145**	**Yes**

Table 6 – Stability Comparison of IOP sets for SonyP9
(Note: If $\sigma_o < 0.003$, IOP sets considered similar)

vi. Four Nikon Cameras – As mentioned earlier, the Nikon datasets are acquired on the same day by switching the camera off and on between dataset acquisitions. The results in *Table 7* indicate that all four Nikon cameras do not maintain the same IOP values and are considered unstable.

ID	***Camera***	***Set Number***		***σ_o (mm)***	***Similar***
		IOP Set I	***IOP Set II***		
1	Nikon288616	**Set 1**	**Set 2**	**0.00618**	**No**
2	Nikon288894	**Set 1**	**Set 2**	**0.00475**	**No**

3	Nikon288895	**Set 1**	**Set 2**	**0.00311**	**No**
4	Nikon288896	**Set 1**	**Set 2**	**0.01603**	**No**

Table 7 – Stability Comparison of IOP sets for Nikon cameras (Note: If σ_o < 0.0021, IOP sets considered similar)

As mentioned earlier, the ROT method is used to evaluate the similarity between the IOP sets. However, if the SPR method is used, the results differ depending on the type of terrain chosen. A comparison was done between a flat and hilly terrain using just the SPR method for the Nikon288616 camera. Two extreme object space configurations were used. The first object space represented a hilly terrain with a height variation of ± 800 m. The second object space represented a flat terrain with a height variation of ± 0 m. For the hilly terrain, the spatial offset standard deviation was 0.00619 mm, which is close to that estimated by the ROT method (0.00618 mm). These standard deviation values are similar because a hilly terrain would decouple any correlation between the IOP and EOP, thus yielding a reliable evaluation of the degree of similarity between the reconstructed bundles. On the other hand, using a flat terrain, the standard deviation of the spatial offset from the SPR procedure turned out to be 0.000087 mm (approximately 0.03 pixels), which indicates a good fit between the two bundles at a flat object space. However, this is a very optimistic and deceiving conclusion. In such a case, a flat terrain would lead to high correlation between the IOP and EOP. Therefore, although the two bundles are significantly different from each other, the EOP will adapt to absorb the differences between the two IOP sets to produce a good fit at the object space.

6. CONCLUSION AND RECOMMENDATIONS

The presented research outlined an efficient approach for calibration, and a meaningful measure for evaluating stability of off-the-shelf digital cameras. For calibration, an easy-to-establish test field consisting of straight line features and signalized points were used. Deviations from straightness in image space straight lines were attributed to various distortion parameters that were modelled using collinearity equations.

The two methods of evaluating camera stability, which quantitatively determined the degree of similarity between reconstructed bundles using two sets of IOP, were introduced. The ROT method is a comparison confined to the image space where the quality of the coincidence between conjugate light rays within two reconstructed bundles sharing the same perspective center is determined. The two bundles are allowed to rotate relative to each other until the best coincidence is achieved. The SPR method allows for spatial and rotational offsets between the two bundles while observing their quality of fit at a given object space. For both methods, the similarity measure was characterized by the standard deviation of the spatial offset between the two bundles. If the standard deviation was within the image coordinate measurement accuracy range (½ to ⅔ pixel size) of the implemented camera, then the two IOP sets were considered similar.

There were nine amateur and professional digital cameras tested in the experiments. Each type of camera had different characteristics and resolutions. The experimental analysis of the cameras revealed that the IOP remained stable over the eight-month period. The only exception was the stability of the Nikon cameras. The Nikons were just turned off and on between dataset acquisitions and this altered the IOP.

It should be noted that the calibration technique and stability measures described in this paper are general enough that they can be applied to digital as well as analogue cameras intended for mapping applications. The proposed stability measures would allow amateur users of digital cameras to evaluate their IOP and stability. A possible future initiative could be directed towards finding a way to compare more than two sets of IOP at one time. Current research will test additional new cameras and continue to focus on their short and long-term stability.

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