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EVALUATION OF THE QUALITY OF A CHECKERBOARD CAMERA CALIBRATION COMPARED TO A CALIBRATION ON A LABORATORY TEST FIELD

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Abstract

For photogrammetric works, a fundamental issue is the determination of camera internal orientation parameters (IOP). Without camera calibration, it is difficult to imagine a correct adjustment of the image network. Many industries use non-metric cameras, ranging from automatics and robotics, to heritage inventories, and the increasingly popular social mapping phenomenon uses low-budget cameras. Many different calibration methods exist, but dedicated calibration fields are commonly replaced by fast in-plane calibration with regular patterns. The main goal of this research is to verify the thesis that calibrating cameras on a checkerboard gives worse results in determining IOP than on a laboratory test field which may translate into the resulting model. For the purpose of this study, a special field was constructed, allowing calibration of the instruments on the basis of the network solution by the bundle adjustment. Unlike classical 2D fields, the field is equipped with a cork background providing a good base for matching and automatically detecting measurement marks. Calibration results were compared with calibration performed on a checkerboard implemented in MATLAB Camera Calibration Toolbox. In order to determine IOP in MATLAB, images of the checkerboard must be taken in such a way, that the whole pattern fits into the frame, otherwise toolbox defines the incorrectly coordinate system, which has a bad impact on calibration results. Moreover, the determined parameters have several times larger standard deviations than those determined in the laboratory test field, which confirms the thesis.

Key words: camera calibration, internal orientation parameters, checkerboard, test field.

Introduction

The camera internal orientation parameters (focal length and principal point coordinates) are an essential element in photogrammetric works. The calibration process is necessary to obtain metric information about three-dimensional reality using two-dimensional images. This process aims to describe a projection model that relates to both coordinate systems: the terrain system and the image system (Oniga et.al., 2018). Cameras can be calibrated for their geometric quality as well as their radiometric quality, and many times this process can be performed on a single calibration field.

Many calibration methods can be found in the literature (Remondino et.al., 2006; Zhang, 2004) divided by, for example, the functional model, estimation and optimization techniques, or the dimension of the calibration field. Laboratory calibration fields can be either internal or external. Photogrammetric solutions are largely based on the collinearity equation proposed by (Brown, 1968) while in computer vision techniques the use of homography is more popular (Kolecki et.al., 2020).

A mathematical interpretation of calibration based on the collinearity equation has been used for over 50 years. A perfect realization of the central projection is practically impossible due to systematic errors resulting from camera design (e.g., lens mounting errors). In order to minimize the influence of these errors, the Additional Parameters (AP) started to be determined (Brown, 1971), Considering the AP we obtain a collinearity equation with eight parameters (Luhmann et.al., 2016) form:

$$\begin{aligned} x' &= c_x - f * \frac{R_{11}(X-X_0)+R_{21}(Y-Y_0)+R_{31}(Z-Z_0)}{R_{13}(X-X_0)+R_{23}(Y-Y_0)+R_{33}(Z-Z_0)} + x(k_1r^2+k_2r^4+k_3r^6)+p_1(r^2+2x^2)+2p_2x \\ y' &= c_y - f * \frac{R_{12}(X-X_0)+R_{22}(Y-Y_0)+R_{32}(Z-Z_0)}{R_{13}(X-X_0)+R_{23}(Y-Y_0)+R_{33}(Z-Z_0)} + x(k_1r^2+k_2r^4+k_3r^6)+p_2(r^2+2y^2)+2p_1xy \end{aligned} \tag{1}$$

where:

c_x, c_y - coordinates of the principal point in the camera system

x,y - coordinates of the observed point in the camera system

f – focal length
R_{ij} – elements of the rotation matrix R
X_0,Y_0,Z_0 - coordinates of the principal point in the terrain system
X,Y,Z - coordinates of the observed point in the terrain system
k_1,k_2,k_3,p_1,p_2 - radial (k_i) and tangential (p_i) distortion parameters
r – radial radius

It is possible to extend the above model with two components (b_1,b_2) related to the non-orthogonality of the image layout axis. One direction of scale change must be chosen to go from a rectangular pixel to a square one. Structure-from-Motion (SfM) is a relatively low-cost method used in photogrammetric software whose main task is to reconstruct the photographed scene. It is based on the basic idea of stereoscopy, that is, the reconstruction of three-dimensional reality from a series of overlapping and shifted images (Westoby et.al., 2012). The main advantage of SfM is that it does not require knowledge of the IOP of successive images , the internal orientation of the camera (including distortion), and Ground Control Points (GCP) are only responsible for giving scale and georeferencing to the model. This is due to the implemented SIFT algorithm, which is responsible for detecting similarities in images burdened by longitudinal and transverse parallax. Moreover, as a result of SfM, the camera parameters are determined. An analysis of the successive steps of the method along with their mathematical aspect was presented by (Schonberger, Frham, 2016). First, consecutive images are analyzed for overlap. Then similarities are searched for in three steps. Extraction involves the detection of local image features. They should be radiometrically as well as geometrically invariant so that it is possible to recognize them on many frames. In the next step, matching is performed, which is a search of the images to find a match of features between them. Then, potential overlapping images are verified, since the matching is based on appearance, it is necessary to check whether the same features are definitely related to the same points in the scene. This involves trying to estimate a transformation that would provide a mapping of feature points between images using projective geometry. The result of this step is a so-called scene graph with frames as nodes and verified pairs of photos as edges.
As proposed by (Zhang, 2000), checkerboard-based calibration has been implemented by implementing this solution in many software such as MATLAB or OpenCV. Due to its low cost and availability, it has become a widely used method displacing the classical approach. Unlike the methods based on the collinearity equation, it is not necessary to know any terrain coordinates; the system is determined based on the arrangement of squares in a chessboard.
Due to the differences in the two methods, it was decided to calibrate the same instrument by two methods, compare and evaluate the calibration results.

Methodology of research and materials

The main step was to analyze the literature on available calibration methods. On the basis of the gained knowledge, it was decided to construct a special two-dimensional calibration field, which allowed to determine the camera calibration based on the solution of the image network using the bundle adjustment method and Structure from Motion (SfM) strategy. A Nikon D5200 camera with a 20 mm lens was tested during the study. Given the characteristics of the SfM strategy, the primary goal was to find a suitable background that would make a good matching base. Many materials were tested: topographic maps, fabrics with characteristic weave, and cork, which finally turned out to be the best and, at the same time, relatively cheap solution. Due to the least regular and repeating structure, several photographs of cork provide an adequate number of ties and, consequently, a high overabundance of observations in the adjustment.
The calibration space was created from two mirror-like zones. Each of them consists of a cork sheet of dimensions about 2m x 1m with a grid of 11 x 4 points. Between them, there is an additional narrow space enriched with a column of markers. To optimize the calibration process, markers automatically detected in Agisoft Metashape software were used. Finally, the field took the form of an almost regular 11 x 9 grid with an additional 8 markers on each diagonal (Figure 1).
The research tested what minimum size of markers can be used for the algorithm to be able to identify them in images taken at a certain distance from the field.
To ensure adequate accuracy of the photogrammetric grid, it was assumed that the determination of spatial coordinates of all markers in the local system would be performed in such a way that the average error of their

position in space would not exceed ±0.3 mm. The geodetic survey scheme is discussed in chapter 3.2 of the publication (Kolecki et.al., 2020). constituted the basis for the target measurement.
Photographs of the field were originally planned based on the proposal (Acka, Gruen 2009,) with a slight modification - it was assumed that in the case of the tested camera the pixels of the matrix are square and there is no non-orthogonality of the image axes, so the central images rotated successively by 90° were abandoned. Originally it was assumed that 3 images would be taken in 3 rows, but this option proved to be ineffective due to too low mutual coverage of the images. Therefore, the central image was replaced by two images taken straight ahead, each covering about 70% of the field width. Finally, a registration scheme of 12 images (3 series of 4 images each) was worked out, in the order of left, center left, center right, and right.

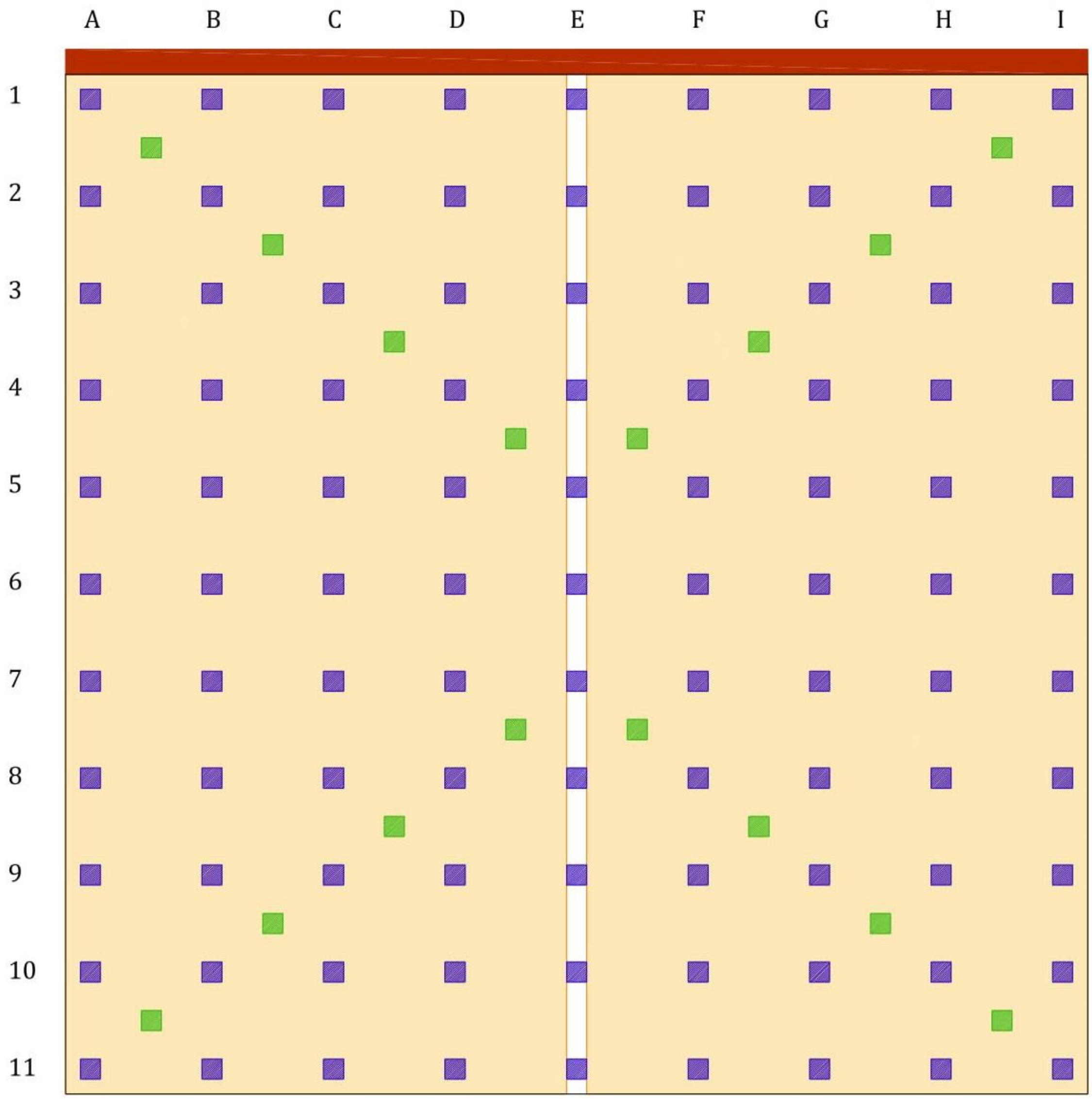

Fig. 1 Project of calibration field design: blue – markers network, green – additional markers, beige– cork sheet, brown – clamping strip

As the basis of the study, Agisoft Metashape Professional software was used. This tool is used for three-dimensional reconstruction from any set of photos provided that there is a mutual overlap between consecutive shots. Whether the final product is to be a textured object model or exterior block orientation elements, the first step is always to *Align photos*. This process consists of finding homology points in consecutive photos based on the SfM method. The result is a pre-aligned network of photos and a cloud of tie points which is the basis for the self-calibration of the camera. The program allows one to choose which lens distortion parameters are to be modeled during the adjustment. To finally align the image network using the bundle adjustment method, it is necessary to georeference the images by pointing to points with known field coordinates or by using the scale bars method. In the case of pointing, it is important to decide which points will be the Check Points (CHP), i.e. those that do not take part in the adjustment directly, but during calculations, spatial coordinates are determined for them. The differences between the aligned position of the points and their nominal coordinates are the real measure of the accuracy obtained at the site, and thus they constitute the quality of the whole aerotriangulation. In this study, the influence of the ratio of the number of Ground Control Points (GCP) to the number of CHP on the camera distortion parameters was analyzed.

The checkerboard calibration was performed using the Camera Calibration Toolbox in MATLAB. It is based on Zhang's solution (Zhang 2000) which assumes photographing an ideal plane, which is not always fulfilled in reality. The recommendation is to take 10-20 photos of the checkerboard (either printed or displayed on the screen) from different perspectives. While loading the photos into the toolbox, choose the parameters to be determined (distortion coefficients k_1, k_2, k_3 p_1, p_2). The algorithm searches for checkerboard corners on the photos and defines a coordinate system in one of them. Calibration results can be evaluated based on the determined parameters with standard deviations, as well as based on graphs.

Discussions and results

The core of the work was the installation of the field on the wall. An important aspect was to minimize the area occupied by the markers on the cork. It was decided that the markers with a center radius of 3.5 mm would be glued on 4 cm x 4 cm rubber pads. To provide them with greater stability each pad was fixed with screws (Figure 2).

Fig. 2. Example of marker stabilization

The next step involved determining the field coordinates of the markers. For this purpose, a classical tachymetric survey was performed from 2 stations parallel to the calibration field. The coordinates were determined using angular-linear intersection. The images were then registered and aligned using the bundle adjustment method. A tie point cloud containing more than 18,000 points (Figure 3) formed the basis for determining IOP along with standard deviations.

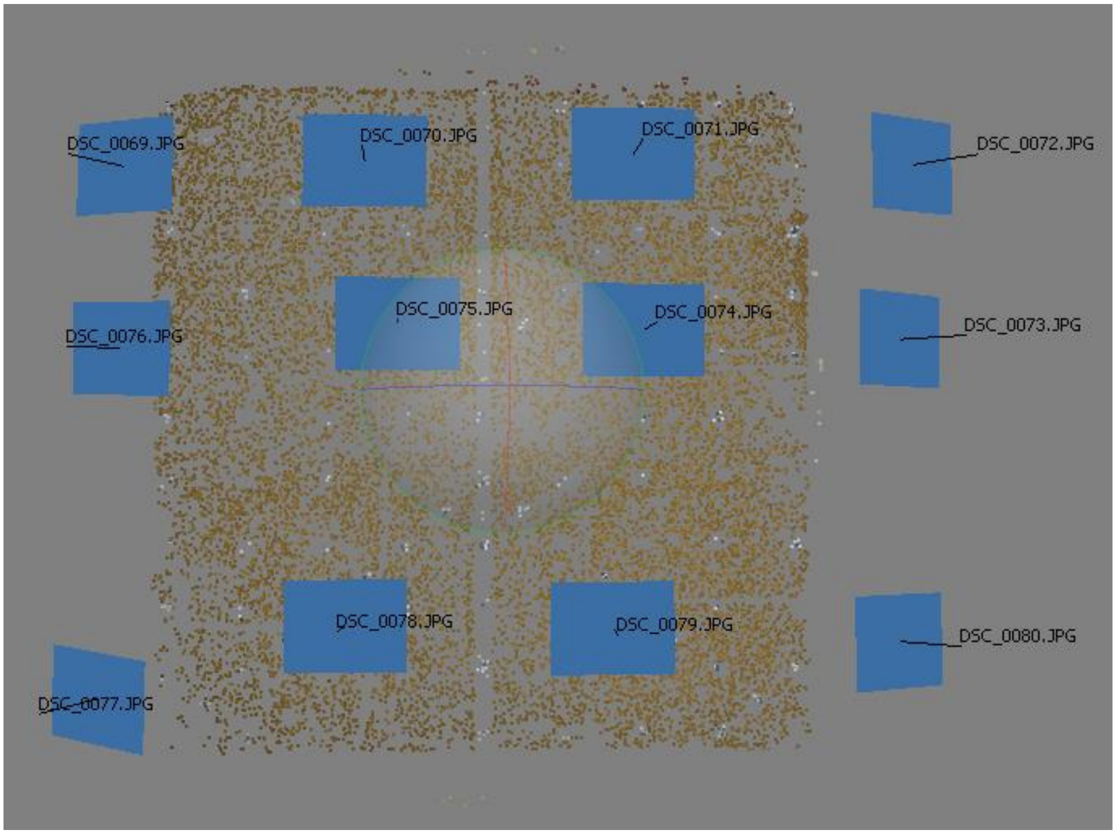

Fig. 3 Tie points cloud with the location of images.

The effect of a systematic reduction in the number of Ground Control Points on the determined IOP was analyzed in this study. Based on 9 variants, it was found that both at 90 GCP (25 CHP) and 15 GCP (100 CHP), results within 0.5 mm spatial error for CHP can be obtained. Therefore, it was decided to conduct analyses with a smaller number of GCP. Results are in (Table 1).

Table 1.

Interior orientation parameters from bundle adjustment with standard deviations.

IOP	Value [pix]	St. Dev. [pix]
f_y	5278.63	0.25
c_x	10.36	0.25
c_y	-17.79	0.22
k_1	-0.11460	0.0003
k_2	0.11150	0.0013
k_3	-0.04110	0.0019
p_1	0.00019	0.00001
p_2	-0.00011	0.00001

Calibration in MATLAB is very simple - it comes down to taking pictures of the checkerboard, loading them, and running the toolbox. The determination of camera parameters is done automatically and practically without any user intervention. The main problem of calibration in this program is the detection of the coordinate system. If the images of the checkerboard are taken at a too large angle, the algorithm misinterprets the origin of the coordinate system and the direction of its axis (Figure 4). During the research, this problem was encountered, so some of the images were excluded from the research.

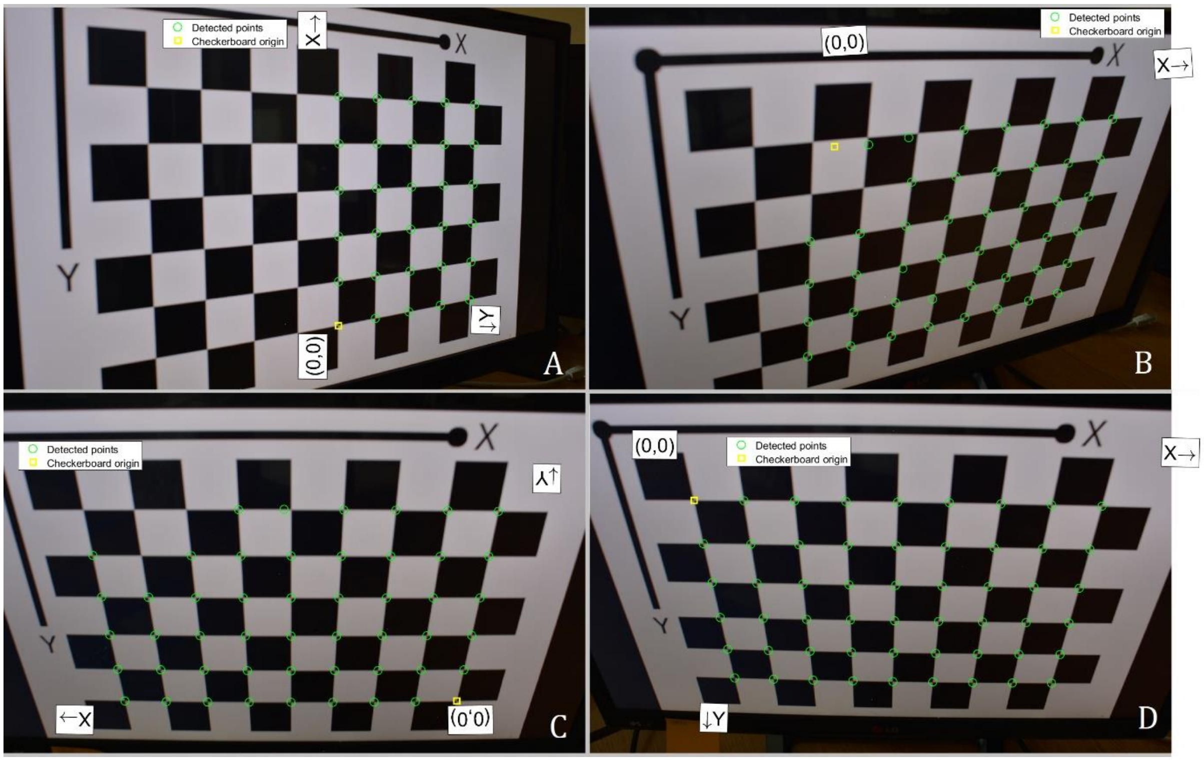

Fig. 4 Identification of coordinate system: A, B, C - incorrect, D – correct

Because the distortion depends on the radial radius (the longer the radius, the bigger the distortion), it is important that the pattern is on the whole surface of the photo, not only in its center. The program can deal mainly with photos where the checkerboard is located in the center of the frame. IOP estimation in such a case is deformed because it is based on smaller radial displacements located closer to the principal point. Because of that, the information about real distortion at the edges of the photo is lost.

Table 2.

Interior orientation parameters from MATLAB with standard deviations

IOP	Value [pix]	St. Dev. [pix]
f_x	5307.55	5.98
f_y	5306.95	6.00
c_x	3021.60	5.45
c_y	1987.57	3.95
k_1	-0.11919	0.008
k_2	0.13384	0.071
k_3	-0.11735	0.186
p_1	-0.00036	0.0002
p_2	0.00022	0.0003

Comparing the results from both solutions (Table 1, Table 2), the first thing that can be noticed is that the toolbox determines separately the focal length in the X and Y axis direction, while from the bundle solution we obtain only one overall focal length value.

The differences in the values of coordinates of the principal point are disturbing. They are the effect of differently hooked background coordinate systems in both programs. For the Agisoft system origin is located in the geometric center of the frame (X axis right, Y axis up) while in the MATLAB system is hooked in the upper left corner (X axis right, Y axis down). After conversion to a common coordinate system (Table 3), similar results are obtained.

Table 3.

Coordinates the principal point in the common coordinate system.

Principal point	Bundle adjustment		Checkerboard	
	Value [pix]	**St. Dev. [pix]**	**Value [pix]**	**St. Dev. [pix]**
c_x	10.36	0.25	21.60	5.45
c_y	-17.79	0.22	-12.43	3.95

Analyzing the radial distortion coefficients it is noticeable that the signs between the solutions are consistent. In the case of tangential distortion, the signs of coefficients are opposite, but due to the very small values of these parameters, it can be considered that their influence on the total distortion is minimal.

The main conclusion of the study proving the disadvantage of the results from MATLAB which are many times higher standard deviations than in the case of field calibration. This is true for all parameters determined. Note, however, that in the case of bundle adjustment there is a very large overabundance of observations relative to the unknowns due to SfM (each tie point in the image contributes 2 equations to the solution). In the case of the checkerboard, the number of observations is much smaller, and thus solving the equations is more difficult.

Conclusions and proposals

The resulting product of a photogrammetric study depends heavily on camera calibration. Introducing incorrect or questionable quality IOP can result in distorted adjustment and consequently incorrect scene reconstruction. Both methods used during the study have different characteristics. The calibration on the field is based on the use of the collinearity equation while the checkerboard is based on the use of homography.

However, based on the research performed, the widespread use of checkerboard calibration is risky. The obvious advantage is the ease and speed of performing such calibration. IOP determined by this method is characterized by much larger standard deviations than in the case of laboratory field calibration. Moreover, when taking checkerboard pictures, it is not possible to take them at a too big angle while keeping the pattern within the whole frame. Images with a checkerboard pattern only in the center of the shot may deform the results and lower the actual values of distortion coefficients.

Creating a laboratory test field is very time consuming, nevertheless calibration results from a bundle adjustment that takes into account SfM are far more reliable. The overwhelming advantage of this method is the huge number of observations included in the alignment. Due to the coded marks, the calibration process is greatly accelerated but still requires more user intervention than with the toolbox. When comparing the accuracy of the IOP's, it is clear that the effort put into a professional calibration on the test field results in more accurate values.

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