Calibration of CCD sensors on geodetic measuring systems

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In different geodetic tasks, CCD sensors are used more and more instead of visual readings on different geodetic instruments. If the ocular lens of the telescope is replaced with a CCD sensor, the most important task is to calibrate the instrument. Calibration of CCD sensors is illustrated here by the example of calibration of the QDaedalus astrogeodetic measuring system.

QDaedalus system is a computer-controlled automated geodetic total station completed with GNSS technology which can be used mainly for astrogeodetic measurements. Before the measurements, the most important step is the calibration. Accordingly, it is necessary to establish a connection between the readings on the horizontal and vertical circle of the total station and the readings in the coordinate system of the CCD sensor. In our initial measurements the calibration procedure at night in field conditions was rather cumbersome and did not give the exact measurement accuracy. To solve this problem, we have developed a new method and tool for calibrating more easily and more accurately. Studies were performed on the optimal number of calibration measurements, and optimal raster size; additionally, the temperature dependence of the measurements was also investigated. Our experiences are useful in all cases when installing a CCD sensor for geodetic instruments.

Keywords: QDaedalus, total station, CCD sensor, collimator, astrogeodetic measurements, calibration matrix, temperature dependence.

Introduction

The QDaedalus system can be used primarily to determine deflection of the vertical using astrogeodetic measurements. Its base device is an appropriately modified Leica TCA1800 total station supplemented with GNSS (Völgyesi and Tóth, 2016; Tóth and Völgyesi, 2016). The modification of the total station affects the optical system, replacing the instrument's eyepiece with a high resolution and very high sensitivity CCD sensor (see Fig. 1). GNSS provides data in two directions: it provides accurate timestamps for astronomical recordings to the CCD sensor and the controller computer, and determines the WGS84 coordinates for calculating the vertical deflections. Controlling the whole system and data processing is done by the QDaedalus software. QDaedalus software controls the movement of the total station, focuses the telescope, receives and processes images of the CCD sensor, manages the GNSS data, determines the current topocentric coordinates of the stars, the Sun, the Moon, and the planets in the astrogeodetic measurements, sorts the initial data and the measured values into the database, and, on the spot, determines the vertical deflections or azimuth values. The sketched structure of the QDaedalus system is shown in Fig. 2.

Base principle of the calibration

At the beginning of the astrogeodetic measurements, the most important step is to calibrate the instrument (Völgyesi és Tóth, 2016). So, a connection should be established between the ℓ, z

readings on the horizontal and vertical circle of the total station, and the *x*, *y* coordinates on the CCD sensor (Fig. 3).

Fig. 1 Modified Leica TCA1800 total station with CCD sensor

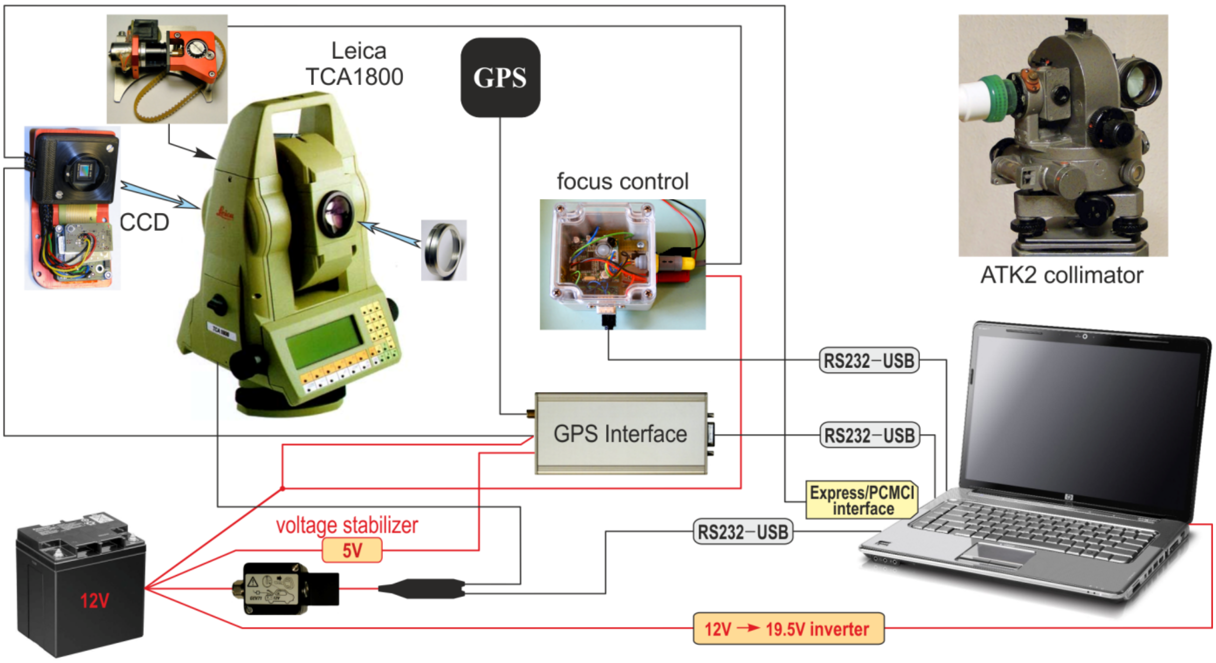

Fig. 2 Schematic structure of the QDaedalus system

For calibration, the total station's servomotor moves the instrument's telescope in small steps around the target point selected for calibration, and records the horizontal and zenith angles while the CCD sensor registers the *x*, *y* coordinates of points simultaneously. To eliminate possible instrumental errors and to achieve the expected accuracy, we carry out the calibration measurements in different points ($i = 1, 2, ..., n$) and different face position of the telescope ($j = 1, 2$), and record the horizontal and the zenith angle readings ℓ_{ij}, z_{ij} on the total station while from image processing the values x_{ij}, y_{ij} in the coordinate system $\vec{e}_x, \vec{e}_y$ of the CCD sensor are record too (see on the left side of Fig. 3). The starting point of the coordinate system fixed for the CCD sensor is the centre of the pixel point in the upper left corner of the image, while the axes $\vec{e}_x, \vec{e}_y$ are perpendicular to each other and parallel to the edge of the CCD sensor.

Using equations

$$\left.\begin{aligned} \bar{x} &= \frac{1}{n}\sum_{i=1}^{n}\frac{x_{i1}+x_{i2}}{2} \\ \bar{y} &= \frac{1}{n}\sum_{i=1}^{n}\frac{y_{i1}+y_{i2}}{2} \end{aligned}\right\} \tag{1}$$

the $\bar{x}, \bar{y}$ mean can be computed from the x_{ij}, y_{ij} values, ($\bar{x}, \bar{y}$ are the coordinates of the principle point (the point of the optical axis of the telescope on the CCD sensor). Using $\bar{x}, \bar{y}$ values the differences $\delta x_{ij} = x_{ij} - \bar{x}$ and $\delta y_{ij} = y_{ij} - \bar{y}$ can be computed (see on the left side of Fig. 3)

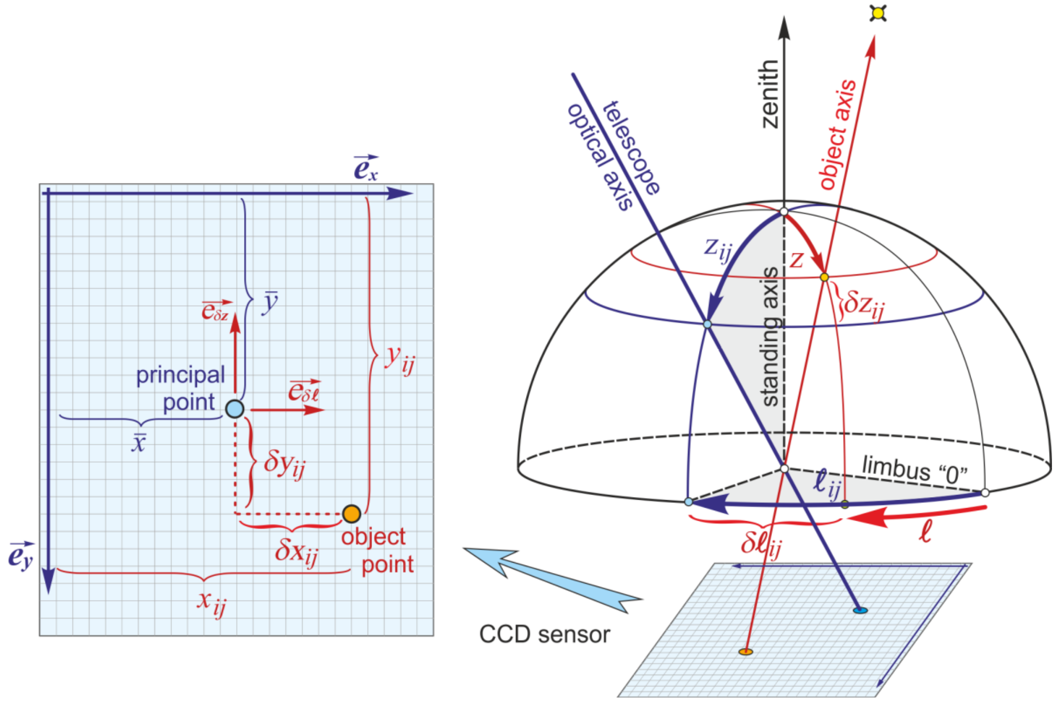

Fig. 3 The principle of calibration

The relationship between the coordinate system of the CCD sensor and the angle readings on the total station can be given by the relations

$$\ell_{ij} = \ell + \delta\ell_{ij} = \ell + \frac{1}{\sin z_{ij}}\left(a_{11}(x_{ij}-\bar{x}) + a_{12}(y_{ij}-\bar{y})\right) \tag{2}$$

$$z_{ij} = z + \delta z_{ij} = z + \left(a_{21}(x_{ij}-\bar{x}) + a_{22}(y_{ij}-\bar{y})\right) \tag{3}$$

(Bürki et al, 2010). This is a simple 6-parameter affine transformation between the two systems. If we know the ℓ_{ij}, z_{ij} readings and the x_{ij}, y_{ij} values determined by the CCD sensor, the six unknowns, ℓ, z, a_{11}, a_{12}, a_{21}, a_{22} can be determined based on Equations (2) and (3), taking into account (1), using the least squares adjustment. The calibration must be performed after each new assembly of the system, or in any case, whenever the position of the CCD sensor is changed. Since the calibration parameters can also be changed when focusing the telescope or changing the temperature (Knoblach, 2009; Bürki et al., 2010), we are planning to investigate for the determination of the calibration parameters simultaneously with the actual measurements.

With the calibration parameters a_{11}, a_{12}, a_{21}, a_{22} and the coordinates of the principle point $\bar{x}, \bar{y}$, the values of ℓ^*, z^* are specified by the readings on the CCD sensor:

$$\ell^* = \ell_i - \frac{1}{\sin z_i}\left[a_{11}(x_i - \bar{x}) + a_{12}(y_i - \bar{y})\right], \tag{4}$$

$$z^* = z_i - \left[a_{21}(x_i - \bar{x}) + a_{22}(y_i - \bar{y})\right], \tag{5}$$

where readings ℓ_i, z_i are recorded on the horizontal and vertical circle of the total station and x_i, y_i are values defined in the coordinate system of the CCD sensor.

Technical solution of calibration

A new calibration must be performed in each case when the CCD sensor is refixed on the total station, moved or changed its position. In the case of astronomical measurements, the parallax of the total station must be set to infinity, so the calibration must be performed in this position as the CCD sensor can only produce sharp images from infinite objects. In the beginning, we used motionless LED diodes at a distance of one or two hundred meters, but at night, in field conditions, their use and handling were very difficult, and even the hundreds of meters distance of light sources did not produce a sharp image on the CCD sensor. We tried to use the Alpha Ursae Minoris (Polaris) star for calibration, but it was not suitable for accurate calibration because the position of the Polaris cannot be found exactly in the direction of the rotation axis of the Earth, and during the calibration, the position of the Polaris is moving a little bit. After that, we had to look for a solution that is suitable for simple and accurate calibration at night even in field conditions.

The problem was solved using a collimator, the principle of this tool is shown in Fig. 4.

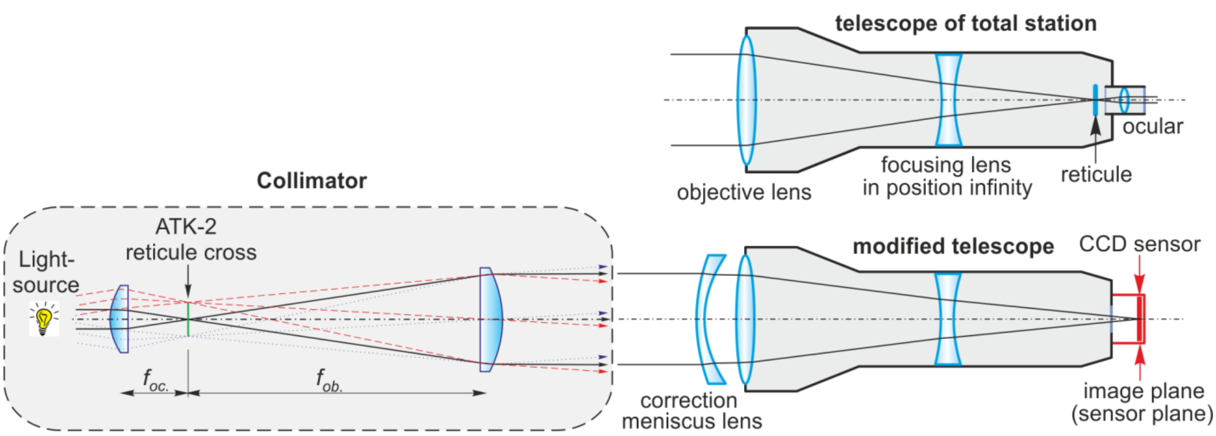

Fig. 4 The principle and application of the collimator for calibration

Our collimator is an auxiliary tool (telescope) that produces parallel beams of light from the object located at the focal point of the eyepiece – just as parallel beams of light coming from infinite distant objects (stars). Our collimator made for the calibration measurements shown in Fig. 5, is a properly modified ATK-2 astronomical instrument whose parallax had been fixed to infinity. An object which is suitable for calibration inside the ATK-2 instrument is the reticule cross in the focal point. We made a special LED light for the illumination of this reticule cross. Fig. 6 shows the picture of the reticule cross of the ATK-2 instrument as a calibration signal in the calibration window of the Qdaedalus software.

Fig. 5 The ATK-2 collimator and the laboratory test of the calibration with ATK-2 collimator

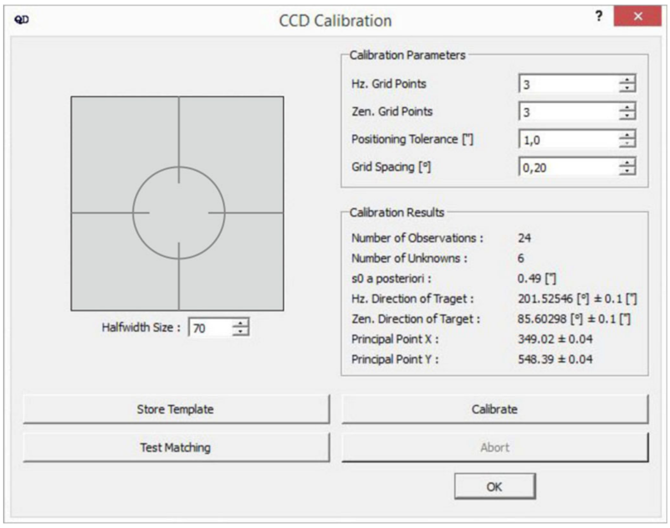

Fig. 6 The calibration window of the control software and the reticule cross of the collimator as a calibration signal

The optimal number of calibration measurements

The most important question of calibration is the optimal number of calibration measurements. With increasing the number of measurements, the accuracy of the $\bar{x}, \bar{y}$ coordinates of the principle point and the accuracy of the calibration parameters a_{11}, a_{12}, a_{21}, a_{22} are increasing, but at the same time we need to pay longer measurement time for the greater accuracy. So the question is how much calibration measurements need to do to get the required accuracy in the shortest possible time? Minimum three measurements have surely to be made, because if two measurements are significantly different from each other, it is not possible to decide which the wrong one is.

For the tests, 50 calibration measurements were performed on the collimator's reticule cross in unchanged fixed position of the CCD sensor with unchanged optical alignment (parallax) at the same temperature, using 3×3 calibration matrix points. The coordinates of the principle points on the CCD sensor were determined for all the 50 measurements, and the coordinates of the mean principle point is determined too. Fig. 7 shows the distribution of principle points and their error ellipse while the cross in the centre of the figure shows the average position of the principle points. Based on the mean errors of the calibration measurements, the mean error of the average position of the principle point from the 50 measurements is ±0.02 pixels in x and y directions.

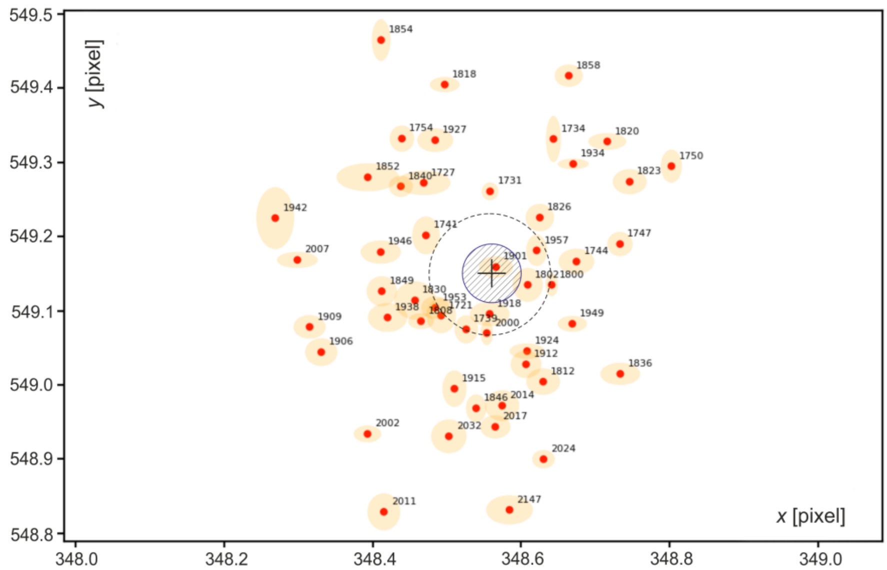

Fig. 7 Distribution of principle points and their mean errors on the CCD sensor. The middle cross is the average position of the principle point.

From the 50 calibration measurements we randomly select groups of 25, 10, 5 and 3 measurements in 10 different combinations to determine the optimal number of measurements, and in each group the average position of the principle point were compared with the average position of the principle point resulting from the 50 measurements. We also calculated the mean errors of the coordinates of the principle point determined for each group, which are summarized in Table 1. Based on the data in the table, the increase in the number of errors can be seen by decreasing the number of measurements.

Table 1 Changes of the mean errors of the principle points depending on the number of measurements

number of measurements	Δx [pixel]	Δy [pixel]
50	0.02	0.02
25	0.02	0.03
10	0.04	0.04
5	0.05	0.05

3	0.06	0.08

For determining the optimal number of calibration measurements, it is important to know how much are the greatest positive and negative differences of the coordinates of the principle point between in each measurement groups and the 50 measurements. The diagram in Fig. 8 shows that as the number of calibration measurements decreases, the differences of the coordinates of the principle points increases in relation to the coordinates of the principle point determined from the 50 measurements.

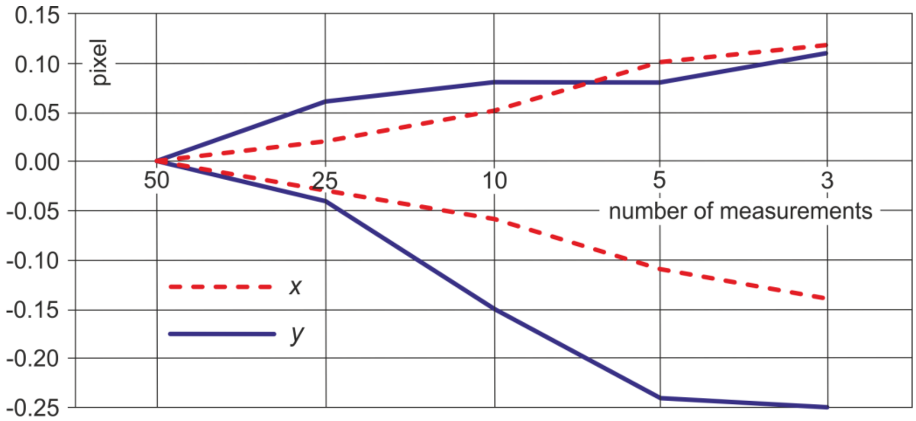

Fig. 8 Growth of the largest positive and negative differences in x and y direction relative to the principle point of the 50 calibration measurements when decreasing the calibration number.

Based on our investigations can be concluded that for less than five calibration measurements, accuracy below 0.05 pixels is no longer expected. Fig. 7 shows that the principle points are expected within the hatched inner circle for 10 or more repetitions, while 5 repetitions may have a high chance of falling points outside the dotted circle.

Similar results can be obtained when examining calibration parameters a_{11}, a_{12}, a_{21}, a_{22}. The QDaedalus software also determines the calibration parameters a_{11}, a_{12}, a_{21}, a_{22} in Eq. (2) and (3) beside the $\overline{x}, \overline{y}$ coordinates of the principle point. We have separately examined the change in the value and error of each calibration parameter a_{ij} depending on the number of calibration measurements. Fig. 9 illustrates the change in value and error of parameter a_{11} by increasing the number of calibrations from 1 to 50.

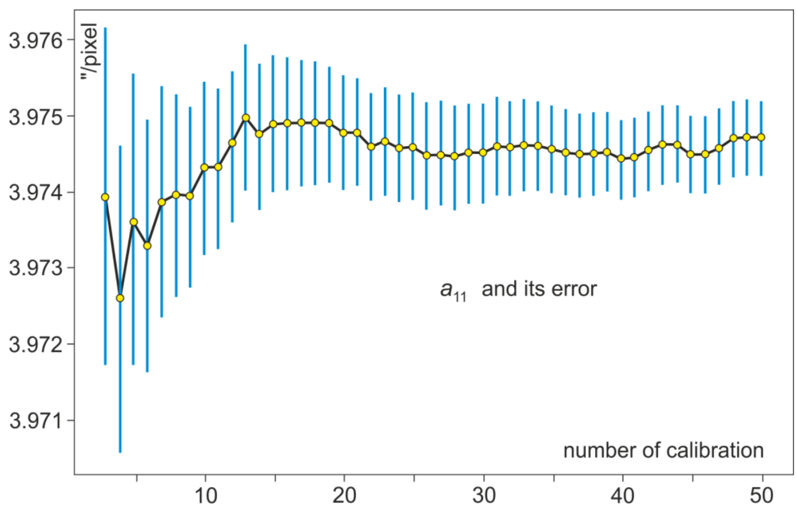

Fig. 9 Change of the value and error of the calibration parameter a_{11} in the function of the number of calibrations

From our examinations, can be concluded that the calibration parameters change significantly with large errors at the beginning, however, approx. from the 12th – 13th measurements they are already reach a value that will hardly change later, and from here the error of a_{11} is getting smaller with very little improvement. Almost the same is true for calibration parameters a a_{12}, a_{21}, a_{22}.

In summary, using the QDaedalus system it can be concluded from our investigations that minimum 10 calibration measurements should be made, but more than 15 measurements will not significantly improve the results. So the calibration measurement between 10 and 15 is the best compromise in terms of accuracy and measurement time.

The optimal size of the calibration matrix

For calibration, the total station's servomotor moves the telescope of the instrument in small steps of a special order in the vicinity of the target point of the calibration. The calibrated area of the CCD sensor can be varied depending on the size of the calibration matrix and the grid spacing. By default, QDaedalus software moves the instrument in the first and second telescope positions along the points of the 3×3 calibration matrix as it is shown in the middle of Fig. 10. By default, the grid spacing is 0.2 degrees which covers a larger area of the CCD sensor during calibration. But we can also choose another grid spacing, for example at 0.05 degrees, only the smallest centre area of the CCD sensor is included in the study, whereto the stars are usually projected during the measurements.

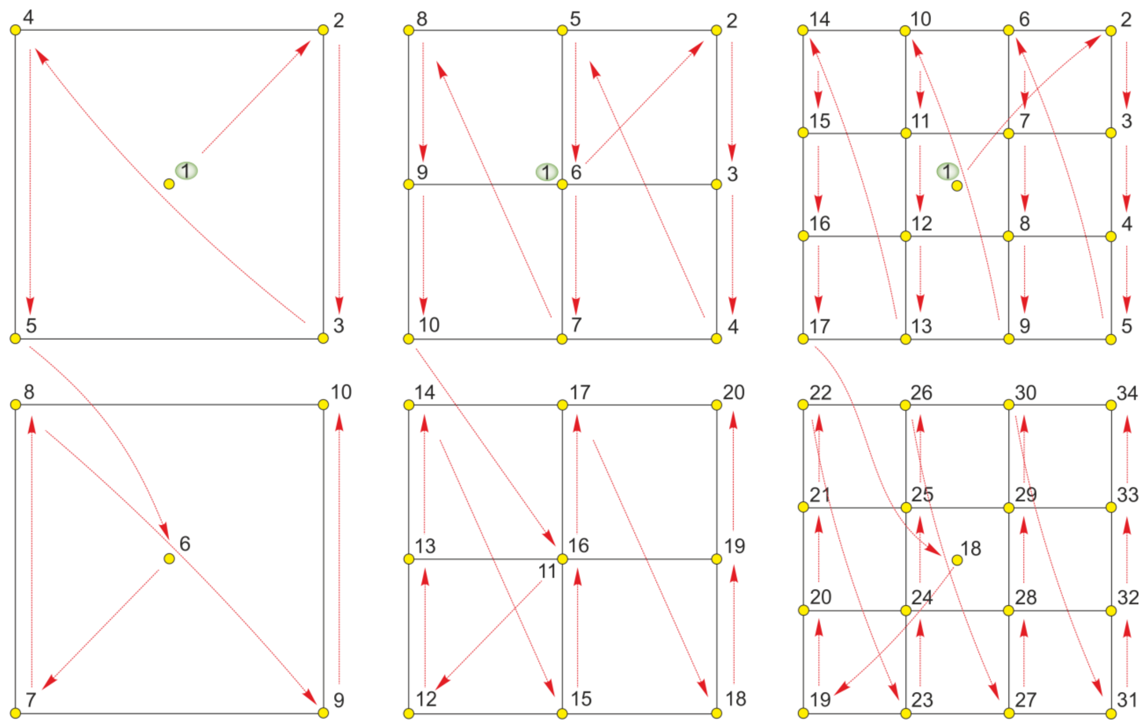

Fig. 10 Moving the telescope along the corner points of 2×2, 3×3 and 4×4 matrixes in I and II telescope position

It is also possible to perform a calibration for a finer resolution of the relevant area of the CCD sensor by increasing the size of the matrix and reducing the grid spacing. In the right part of Fig. 10, the location of the measuring points of the calibration matrix 4×4 and the order of movement of the telescope can be seen as an example.

During our investigations, we have been looked for the answer to the question whether we get better results using smaller (eg 2×2) calibration matrix with more repetition of measurements, or using larger (eg 4×4) calibration matrix with fewer repetition of measurements. Our measurements were performed on the calibration matrices of 2×2, 3×3, 4×4, 5×5 and 6×6, as shown in Fig. 10, while changing the grid spacing we have limited our measurements to the same area of the CCD sensor. While we measured along the 5×5 and 6×6 grid points quickly became apparent at the beginning of the measurements that only the measurement time would increase significantly without any positive results, so we do not have to deal with these possibilities.

Calibrations were performed by twelve measurements in each variant of matrix size in the order of 2×2, 3×3, 4×4 and then in the order of the 2×2, 3×3, 4×4 again (this is total of 72 measurements). Results for the various calibration matrices (spatial distribution of the principle points) are shown in Fig. 11 and the numerical results are summarized in Table 2.

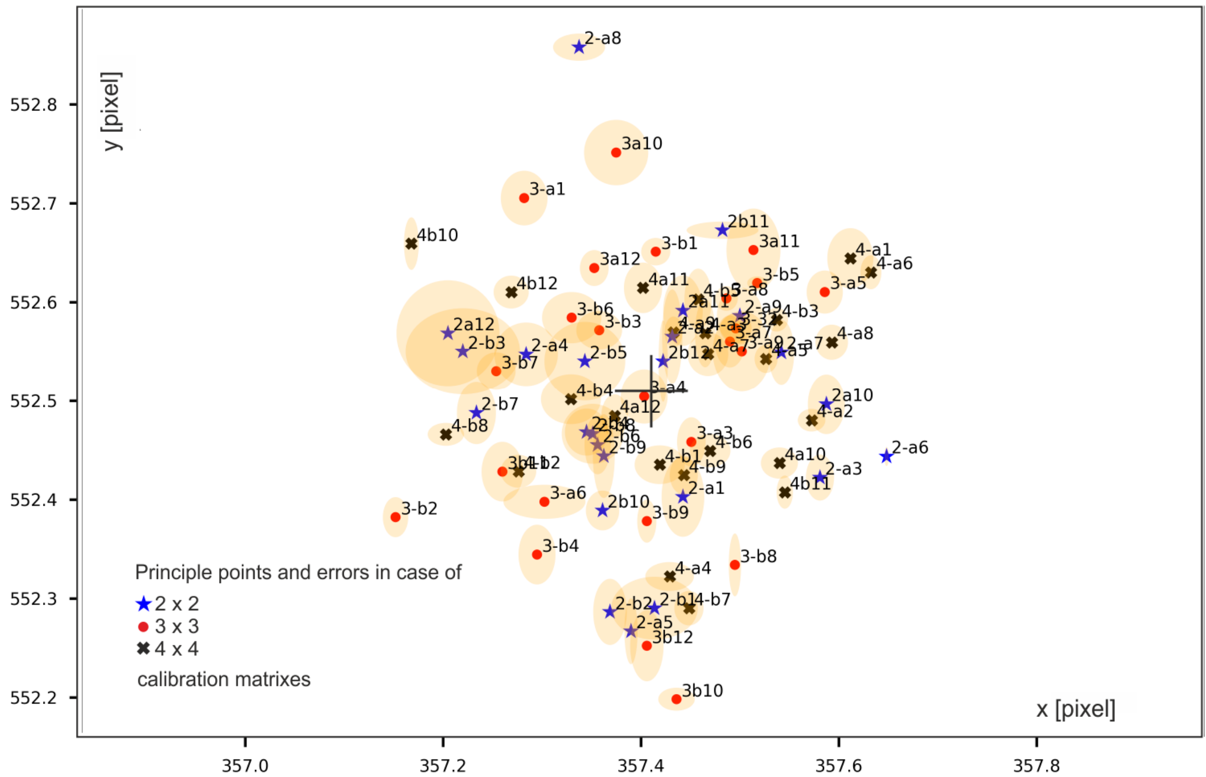

Fig. 11 Principle points and their errors in case of 2×2, 3×3 and 4×4 calibration matrixes.

Fig. 11 shows that there is no regularity in the arrangement of the principle points, the results of measurements for different calibration matrices are randomly mixed, the principle points scattered randomly around the mean principle point marked with the cross. This is also confirmed by the data in Table 2. Based on these data by increasing the size of the calibration matrix, the mean principle point changing its position only by hundredth pixel order of magnitude, and there are no significant deviations in the largest positive and negative differences in relation to the position of the mean principle point. However, there is a significant difference in the measurement time. The last column of the table shows the total duration of the different calibration measurements (the total duration includes adjusting and giving the parameters of the calibration, duration of the actual measurement, and saving the data by controlling them). It can be seen, that the total duration of the measurement is 1 minute 25 sec in the case of the 2×2 matrix, 2 minutes and 20 sec in the case of the 3×3 matrix, and 3 minutes in the case of the 4×4 matrix (the total duration is nearly 5 minutes in the case of the 5×5 matrix).

Table 2 The position and errors of the principle points depending on the size of the calibration matrix

	Position and errors of the princ. point				The biggest + and – differences				
	x[pixel]	mx	y[pixel]	my	Δx_{max}	Δx_{min}	Δy_{max}	Δy_{min}	t [sec]
All	357.41	±0.04	552.51	±0.05	0.26	–0.24	0.26	–0.24	–
2x2	357.40	±0.05	552.50	±0.05	0.20	–0.25	0.21	–0.17	85
3x3	357.43	±0.03	552.49	±0.04	0.28	–0.18	0.29	–0.16	140
4x4	357.44	±0.03	552.51	±0.04	0.24	–0.19	0.22	–0.15	180

Overall, it can be concluded that increasing the size of the calibration matrix, despite of the significant increase in the duration of the measurement does not result a significant increase in the accuracy of the position of the principle point. Therefore the calibration matrix size of 2×2 can be appropriate, but the size of 4×4 is surely superfluous. The optimal solution is to increase the number of measurements beside a smaller or middle matrix size.

Temperature dependence

The change of temperature, according to the theory of linear thermal expansion, causes small deformations of both the optical system and the position and fixation of the CCD sensor, which results the change in the position of the principle point. The question is the magnitude of change and how much error the temperature changing could be caused to the functionality of the measuring system? The measurements were carried out in a wide temperature range of −1 and +23°C while we have taken care of the unchanged position of the CCD sensor and we did not change the focusing to infinity. Our measurements were made on winter days, the calibration was started at a temperature of +23°C in a heated room, and then the measurements were continued outdoor at lower temperatures (+9, +8, +7, +6, +5, +4 and −1°C). It was important to have rested the measuring equipments for at least one hour before starting the outdoor measurements, because the instruments should be completely cooled to the lower outside temperature.

The measurement results are shown in Fig. 12, where the change in the position of the principle point can be seen as a function of the temperature change. The numbers next to the black (principle) points show the temperature values for that pixel position, and the temperature isolines encircles those areas where the principle points belong to the same given temperature.

It can be stated that, with decreasing the temperature, the position of the principle point on the CCD sensor is clearly shifted to the lower values in the x and y directions. The shift is significant, approx 1 pixel in case of a temperature difference of 20°C. However, it can be noticed in the middle of Fig. 12 that in case of smaller, 1-2°C temperature changes the principle points belonging to different temperatures are sliding into each another, that is, the error caused by a temperature change of 1-2°C is already slipping into the noise of other random measurement errors.

During the night astrogeodetic measurements, the high radiation and the quick decrease of temperature is an obvious consequence of the clear sky. Initially the decrease may be rapid it can reach several degrees per hour. During a shorter measurement period between the beginning of the calibration and the end of the astrogeodetic measurement, the decreasing small temperature change may not cause any significant problems (the error caused by the temperature change can lost in the unknown general measurement noise) however, longer measurement times or rapid temperature decrease may cause significant measurement errors that rises above the measurement noise.

The most important conclusion from our temperature studies is that, before the beginning of the field measurements when the instrument is transported from a heated room to the outdoor field measurement, we have to wait for the temperature of the instrument (including the inner optical structure too) having been the same as the outside temperature. In case of high temperature differences (mainly in winter), to achieve the full temperature equilibrium, it takes a longer time, which can be up to one hour.

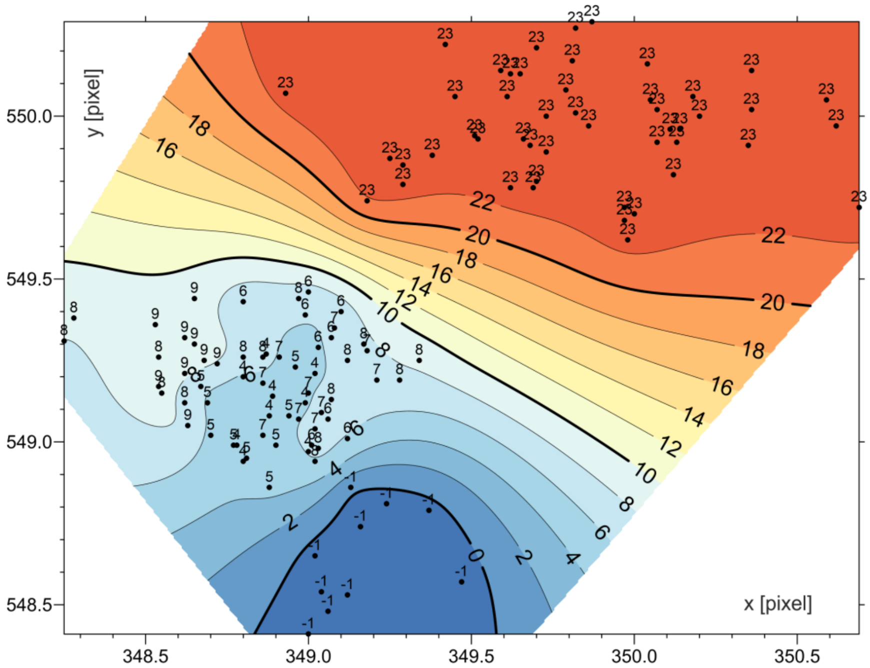

Fig. 12 Changing the position of the principle points as a function of the temperature change

At the same point between the beginning of the calibration and the end of the astrogeodetic measurement, the temperature change cannot exceed 1-2 degrees. In case of significant temperature decrease it is advisable to perform calibration measurements before and after the astrogeodetic measurement and calculate the mean position of the principle point and the average values of the a_{11}, a_{12}, a_{21}, a_{22} parameters. Therefore, continuous monitoring of the temperature change is important during the astrogeodetic measurements.

Summary

Using CCD sensors on geodetic instruments when the ocular lens of the telescope is replaced by a CCD sensor, the first important task is the calibration. This calibration was presented here through the example of calibration of the QDaedalus astrogeodetic measuring system.

The purpose of the calibration is to establish a connection between the readings on the horizontal and vertical circle of the instrument, and the readings in the coordinate system of the CCD sensor. For calibration, the servomotor of the instrument moves the telescope in small steps around a target point selected for calibration, and records the horizontal and zenith angles while the CCD sensor registers the coordinates simultaneously. Transformation parameters of the calibration can be computed from these measurements.

After discussing the principle of calibration, the practical solutions of the calibration was studied, and we have presented a new, simple and accurate technical solution by using a collimator. During our measurements and tests, the optimal number of calibration measurements, the determination of the optimal calibration matrix size and the effect of temperature change were examined.

An important question is the optimal number of the calibration measurements. Based on our investigations for the QDaedalus system, minimum 10 calibration measurements should be performed but more than 15 measurements do not significantly improve the results, so calibration measurement between 10 and 15 appears to be the best compromise in terms of accuracy and the required measurement time.

The calibrated area of the CCD sensor can be varied depending on the size of the calibration matrix and the grid spacing of matrix. It can be stated that increasing the size of the calibration matrix despite a significant increase in the duration of the measurement does not result a significant increase in the accuracy of the position of principle point. Therefore using the 2×2 or 3×3 matrix sizes is appropriate, but the 4×4 size is quite unnecessary waste of time. The optimal solution is to increase the number of measurements using small matrix size.

We have also examined at how much error have been caused by the temperature change. It was found that during the time between the start of the calibration and the end of the astrogeodetic measurement the temperature change cannot exceed 1-2°C. In case of significant temperature decrease mainly in the beginning of night it is advisable to perform calibration measurements before and after the astrogeodetic measurement and calculate the mean position of the principle point and the average values of the transformation parameters. The most important conclusion from our temperature studies is that, before the beginning of the measurements when the instrument is transported from a heated room to the outdoor field measurement, we have to wait for the full temperature equilibrium between the temperature of the instrument (including the inner optical structure too) and the outside temperature.

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