Calibration of Terrestrial Laser Scanners

Kalibrierung terrestrischer Laserscanner

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The calibration of a laser scanner is necessary to reduce systematic errors in the acquired point cloud. Furthermore, calibrating laser scanners is motivated by the need of users to access up-to-date quality information. For calibrating a terrestrial laser scanner, a functional calibration model needs to be set up. This functional calibration model is only partially comparable to the one of a total station. Complicating at setting up this complete calibration model is amongst others the fact that the manufacturers publish their calibration functions and procedures only sparsely. For calibrating a terrestrial laser scanner after delivery, the parameters of the functional calibration model can be estimated based on a self-calibration in a calibration point field. The development of an optimal calibration field has not yet been completed; its configuration is presently in the focus of several research institutions. This study gives an overview about the task of calibrating terrestrial laser scanners based on a description of laser scanner specifications, test procedures and their errors causing imperfections.

Keywords: Terrestrial laser scanning, error sources, systematic errors, laser scanner specifications, system calibration, test procedures

Die Kalibrierung von Laserscannern ist nötig, um systematische Abweichungen in aufgenommenen Punktwolken zu reduzieren. Außerdem kann die Kalibrierung von Laserscannern damit motiviert werden, dass Anwendern aktuelle Qualitätsinformationen zur Verfügung stehen sollten. Zur Kalibrierung eines terrestrischen Laserscanners muss ein funktionales Kalibriermodell aufgestellt werden. Dieses Kalibriermodell stimmt nur teilweise mit demjenigen eines Tachymeters überein, sodass eine Erweiterung der bekannten Kalibrierfunktionen nötig ist. Erschwerend bei dieser Erweiterung wirkt die Tatsache, dass die Instrumentenhersteller ihre Kalibrierfunktionen und Kalibrierverfahren nur bedingt mitteilen. Nach Auslieferung des Laserscanners an den Nutzer können die Parameter des funktionalen Kalibriermodells durch eine Selbstkalibrierung basierend auf einem Kalibrierpunktfeld geschätzt werden. Die Entwicklung einer optimalen Konfiguration dieses Kalibrierfelds steht derzeit im Fokus verschiedener Forschungseinrichtungen. Dieser Beitrag gibt einen aktuellen Überblick über die Kalibrierung terrestrischer Laserscanner, basierend auf einer Beschreibung von Laserscannerspezifikationen, Prüfverfahren und gerätespezifischen Unvollkommenheiten, die zu systematischen Abweichungen führen.

Schlüsselwörter: Terrestrisches Laserscanning, Abweichungsursachen, systematische Abweichungen, Spezifikationen von Laserscannern, Systemkalibrierung, Prüfverfahren

1 INTRODUCTION

Terrestrial laser scanners are now widely used in engineering geodesy both for documentation and for deformation monitoring. Analyzing area-based deformations of built structures e.g., of cooling towers /Ioannidis et al. 2006/, tunnels /van Gosliga et al. 2006/, dams /Eling 2009/, /Wang 2013/ or radio telescopes /Holst et al. 2015/, is an application case where the high sampling density and the potential to obtain higher accuracy for areal information than for individual points motivate the use of scanners. However, the methods and procedures of quality management as established for other geodetic instruments like levels, total stations or GPS-antennas have not yet been introduced for laser scanners. This can partially be explained by the fact that a laser scanner samples the surfaces quasi-randomly, in particular without any object signalization, and without specific significance of the individual measured points. Hence, strategies for quality management and calibration cannot be simply transferred from total stations to laser scanners. On the other hand, the quality management is difficult since it depends on the measurement process but the measurement process of a laser scanner is related to the specific construction of the respective instrument which is mostly hidden from the users. The instruments need to be regarded as black boxes /Walser & Gordon 2013/: the internal error sources and the pre-processing steps of the measurements are not known to the operator.

Thus, although quality management and calibration of laser scanners are crucial – especially for area-based deformation analysis with high demands regarding accuracy –, the required methods have not yet been fully developed and appropriate procedures are not yet established. Relevant aspects regarding this quality management, i. e., the error sources of laser scans and the aims of scanner calibration, are explained in more detail in the following sections.

1.1 Error sources of laser scans

When sampling an object by a terrestrial laser scanner, the accuracy of the laser scans depends on the following four groups of impacts /Soudarissanane et al. 2011/, /Zogg 2008/:

- Instrumental imperfections;
- atmospheric effects;
- scanning geometry or measurement configuration, respectively;
- object properties or surface related effects, respectively.

The imperfections of the instrument, i. e. the laser scanner, comprise (i) deviations in its mechanical construction leading to deviations during the polar beam deflection and (ii) deviations in the electro-optical distance measurements. An example of the first group is, e. g., the inclination error of the mirror, and of the second group, e. g., an uncompensated offset. While some of these errors are similar to the ones of a total station, also significant differences exist /Holst & Kuhlmann 2014, 2016/. This will be discussed in Section 3.2.

While the imperfections of the instrument affect all measured polar elements of a laser scanner, the other impacts listed above affect typically only the electro-optical distance measurements. The influence of atmospheric conditions onto the distance measurement is, in principle, similar to the one when using total stations. Nevertheless, since the measured distances are often smaller than 100 m, acquired in a short time period and of less precision, the impact of the atmospheric conditions can be neglected in many applications. By choosing the laser scanner station, a certain scanning geometry is fixed. The accuracy of the laser scan depends among others on the resulting incidence angle and the scanning distances. Since laser scanners sample the surface reflectorlessly, object properties, e. g., shape and reflectivity, influence the accuracy of the distance measurement. These statements regarding the electro-optical distance measurement will be given in Section 3.1 in more detail.

All of these error sources lead to random as well as to systematic errors that can only be identified, separated and eliminated to a certain amount during a common scan project. This especially holds for the errors due to object properties that highly depend on the specific object. This present study considering the calibration of a terrestrial laser scanner mainly covers or helps mitigating, respectively, the first error source dealing with the imperfections of the laser scanner.

1.2 Aim of calibration

There are two aims of calibrating a terrestrial laser scanner. Firstly, a calibration helps at reducing the systematic errors occurring at laser scanning. The remaining systematic errors need to be incorporated into a stochastic model of the point cloud. This stochastic model is, e. g., needed in order to perform a sophisticated deformation analysis. Therefore, we need to understand all single phenomena at laser scanning, i. e., the sources of the TLS uncertainty listed in Section 1.1.

Secondly, calibration of laser scanners is motivated by the need of users to access up-to-date quality information, possibly independent from or in addition to information provided by the manufacturer. Ideally the users are provided with strategies for testing or verifying, respectively, and for calibrating their laser scanners.

The topic of testing, which is only considered briefly in this paper, aims at proving whether the laser scanner's accuracy equals certain specifications or not. Contrary, calibrating a laser scanner aims at assuring that the error contribution from the instrument remains (over time) within these specifications. Furthermore, calibration can help to improve these specifications. In detail, calibration needs (i) to be carried out under controlled, known and reproducible conditions and (ii) to be practically relevant also for use under other conditions. The laser scanner tests/verifications are, therefore, required before calibration to understand what these "conditions" are and afterwards or independently to check whether the calibration was successful.

Hence, this study slightly discusses the topics of laser scanner specifications and testing of laser scanners (Section 2) since these topics are highly correlated with the imperfections of the laser scanner (Section 3) and the task of calibrating a laser scanner (Section 4).

2 SPECIFICATIONS AND TESTING

As written in the previous section, the calibration of laser scanners is directly linked by specifying their quality (Section 2.1) and by proving their performance in field tests (Section 2.2) and laboratory tests (Section 2.3).

2.1 Specifications

In contrast to classic geodetic instruments, there are still no standardized specifications for laser scanners. So, every manufacturer points out the dominant features of its instruments based on proprietary terms and procedures such that the specifications cannot be compared directly and easily among instruments provided by different manufacturers. E. g., different manufacturers tend to use different grey values or criteria to specify maximum range. In general, the original polar observation quantities cannot be accessed and have to be reconstructed from the cartesian coordinates of the point cloud in order to assess the accuracy of slope distance, horizontal and vertical angles. Moreover, the impact of different scan quality settings and import filters has to be taken into account (*Fig. 1*). The various combinations make it considerably laborious to derive sets of objective and comparable accuracy measures /Wunderlich et al. 2013a/. The different settings also command other scanner features as scanning time and range. As a result, featured optimum specifications will typically not be valid simultaneously e. g., highest range and speed of data capture will not be possible if lowest noise level was selected.

For several years the geodetic community has been putting effort into establishing scientific and practical test procedures. The goals are on the one hand to check specifications and to make different scanner products objectively comparable, and on the other hand to enable users to verify proper instrument behaviour according to expected quality before and after a survey job, see e. g. the code of practice proposed by /Neitzel et al. 2014/. At geodetic laboratories in Austria, Germany and Switzerland, numerous investigations have been completed in the course of PhD theses, dedicated lab work and joint initiatives, e. g. of the GKGM e. V. (Society for Calibration of Geodetic Devices).

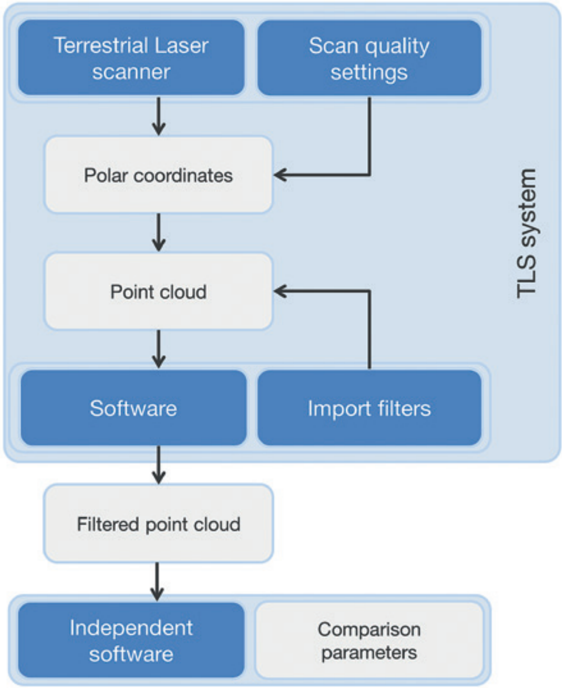

Fig. 1 | Quality settings and import filters influencing scanning features /Wunderlich et al. 2013a/

2.2 Field tests

Field tests are indispensable for checking maximum range (with respect to objects of different reflectivity and chosen instrument mode settings) and for basic checking whether a scanner delivers results compliant to its specifications. The former purpose is valuable for comparing competing products. It is often carried out at open-air branches of geodetic laboratories. The second purpose should be achievable both near the surveying office and also at or near the project location to ensure proper instrument function after transport and expected data quality before returning from the remote job site. After several initiatives /Gottwald et al. 2008/, /Feldmann et al. 2011/, /Neitzel et al. 2014/ succeeded in adopting an instruction sheet which enables a practitioner to carry out a reproducible field test clearly indicating whether the scanner meets the required quality demands or not. The instruction includes a clearly defined configuration, defines explicitly which measurements need to be performed and explains the simple evaluation of the results. The configuration (*Fig. 2*) consists of four targets forming both a vertical and a horizontal triangle sharing one side to which the two TLS stations are aligned. The dimensions of the triangles and the distances to the stations depend on the maximum range of the scanner.

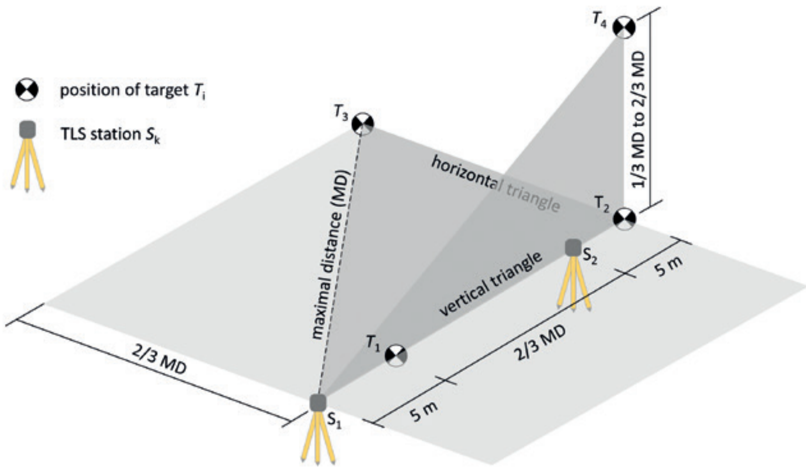

Fig. 2 | Configuration of the field test by /Neitzel et al. 2014/

2.3 Lab tests

Lab tests either focus on checking the accuracy of specific observation quantities or of certain scanner performance declarations under controlled testing conditions, sometimes within pre-surveyed point fields of superior accuracy, tailored to the investigation. Dependent on lab size, shape and facilities, every lab developed processes of its own. Some are renowned for continuous checking of a great variety of scanners delivered to the lab, also in repeated tests, e. g. /Böhler & Marbs 2003/. Others lay emphasis on detailed investigation of a particular scanner including different geometric configurations, surfaces and object materials, e. g. /Schulz 2007/. Other labs have focussed on developing and using processes to compare different scanners with respect to certain capabilities. /Wunderlich et al. 2013a/ pursue such comparisons, e. g. regarding edge behaviour and form truth when scanning challenging test objects. *Fig. 3* shows one of the experiments using a breaker plate to investigate the influence of edges on the geometric truth for different scanners and distances. With the known object geometries and with respect to the scanner's specific distance noise level, points can be classified as geometrically correct (green) or wrong (red). The same tests are repeated with different filter settings (see Section 2.1) to study the effect of the unspecified filters. A brief description of the field and lab test facilities can be found in /Wunderlich et al. 2013b/.

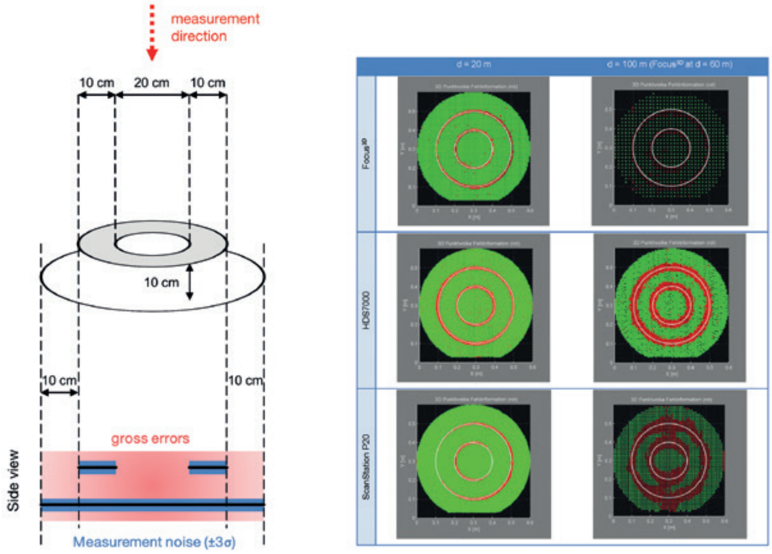

Fig. 3 | Test object and some comparative test series /Wunderlich et al. 2013a/

3 IMPERFECTIONS OF THE LASER SCANNER

The imperfections of the laser scanner can be divided into the ones of the distance measurement component (Section 3.1) and the ones due to the polar deflection (Section 3.2).

3.1 Deviations of the distance measurement component

Terrestrial laser scanners use similar distance measuring principles as conventional electronic distance measurement (EDM) devices. Thus, modelling the uncertainties and deviations of laser scanner distance measurements should follow the well-established error budget of EDM. The latter can be divided into four distinct groups of contributions (see also Section 1.1):

- Instrumental imperfections, in particular additive constant, scale factor and cyclic deviations (only for the continuous-wave (CW) measuring principle);
- atmospheric effects, primarily a temporally and spatially varying scale factor due to varying density of the air;
- scanning geometry, in particular angle of incidence;
- object properties, in particular reflectivity, roughness and surface penetration.

3.1.1 Instrumental imperfections

First studies on the calibration of terrestrial laser scanners already considered the instrumental imperfections. /Schulz & Ingensand 2004/ derive the additive constant from the comparison of scanned and interferometric distance measurements to planar targets and spheres, performed on a calibration track line with a length of about 50 m. They found an additive constant of a few mm, independent of the scanning mode of the chosen scanner. /Zhangmillim et al. 2008/ determine an additive constant of the same order of magnitude from measurements performed in all combinations between the pillars of a calibration baseline for EDM with a total length of approx. 800 m. In the near-field domain the additive constant can exhibit strong variations, as shown in /Zhang et al. 2008/.

Frequency deviations of the oscillator lead to scale errors. /Schulz 2007/ investigated the temporal variation of these errors for a particular scanner by directly measuring the CW modulation frequency using a diode and a frequency measuring system connected to an international frequency standard. He found a scale error of about 3 ppm at the beginning of the warm-up phase of the scanner; the error changed significantly during the first hour of operation and then settled at about –1 ppm for the remainder of the operation phase. Though, every measured distance is influenced by the frequency deviation, its impact on derived object geometry is usually very limited with TLS because of the typically short distances and the fact that several other sources contribute more to the deviations of the measurements.

The calibration of cyclic errors typically requires a dedicated measurement setup which allows shifting a target over a distance corresponding to the modulation wavelength. The differences between the displacements obtained by laser scanning and by laser-interferometry are analysed with respect to the phase residuals. An alternative approach is proposed by /Dorninger et al. 2008/. It comprises the identification of strictly planar patches within the measured point clouds and uses the residuals of the distance measurements obtained with respect to the respective best fit planes in order to estimate the parameters modelling the distance deviations. Using this procedure, cyclic components with wavelengths corresponding to the scale of the instrument (half modulation wavelength), half scale and quarter scale could be detected in the case when the internal calibration of the scanner was deactivated. The amplitude of the estimated cyclic deviations was on the order of 5 mm. The instrumental deviations of the distance measurement component are well understood and parameterized along with eccentricities, misalignments and other imperfections (see Section 3.2 and 4.2) for mitigation after calibration.

3.1.2 Atmospheric effects

The equations for refractive index calculation from atmospheric parameters are known with sufficient precision /Ciddor 1996/, /Ciddor & Hill 1999/, and refer to TLS just as to EDM. Modeling the refraction effect is still a difficult problem for lines of sight exceeding a few hundred meters in length and if mm accuracy is required because the meteorological parameters cannot be measured or predicted with sufficient accuracy along the entire line of sight, and because the spatial gradient of the refractive index may cause significant ray bending for lines-of-sight in the vicinity of the ground. However, for terrestrial laser scanning, the lines of sight are typically short enough and only few lines-of-sight are close to the ground such that atmospheric refraction is often negligible or can be accounted for with sufficient accuracy.

3.1.3 Scanning geometry and object properties

With increased precision of the instruments and increased accuracy of scanner calibration, biases and noise caused by the sampling of a natural surface rather than a precisely manufactured artificial target become a significant limitation for applications requiring high and known or predictable accuracy. The problem is associated with the finite beam width of the reflectorless distance measurement. The signal received by the instrument is the superposition of the signals received via all possible signal paths within the beamwidth. Conceptually, the distance measurement can be thought of as a weighted average of all distances between the instrument and the footprint of the laser beam on the scanned surface where the weight depends on the respective (local) reflectivity and on the measurement principle. Thus, the measured distance depends in particular on the material, orientation and roughness of the surface. /Schäfer 2014/ has succeeded in explaining edge effects by numeric simulation using a model based on that idea. However, experiments (e.g., /Schulz 2007/, /Zámečníková et al. 2014, 2015/) have shown that there are also biases related to subsurface reflection of signal com-

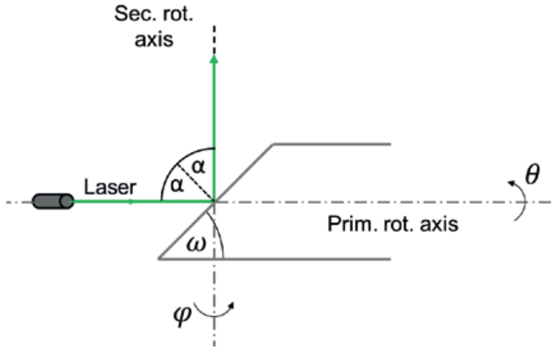

Fig. 4 | Ideal axis alignment of a panoramic terrestrial laser scanner leading to the green laser beam deflection /Holst & Kuhlmann 2016/

ponents with apparent signal penetration depths which can reach a few mm for certain materials and even exceed a cm, and biases related to the angle of incidence. Furthermore, the measurement noise was found to depend on the received signal power (e.g., /Zámečníková et al. 2014/).

So far, neither simple models for computationally predicting these effects nor standardized test procedures for assessing them experimentally are available (see also Section 2) but research efforts are undertaken at various institutions. With respect to scanner calibration this means that the calibration for compensation of instrumental imperfections should be carried out in a way such as to minimize detrimental effects from surface and material properties by using suitable calibration configuration and targets (e.g., diffuse planar targets with sufficiently high surface reflectivity).

3.2 Deviations due to polar beam deflection

A panoramic laser scanner is constructed by three main axes (*Fig. 4*), i.e., primary rotation axis, secondary rotation axis, and collimation axis. The first and second one are similar to the trunnion

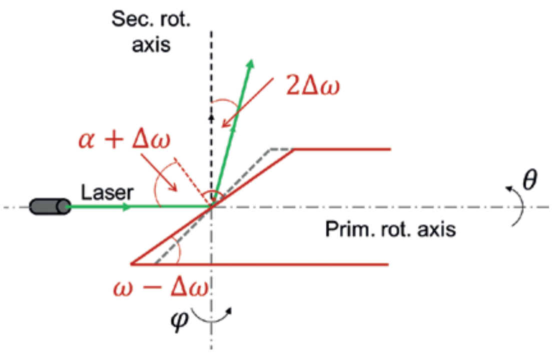

Fig. 5 | Effect on the green laser beam deflection due to an inclination error of the mirror $\Delta\omega$ and the resulting deviations shown in red /Holst & Kuhlmann 2016/

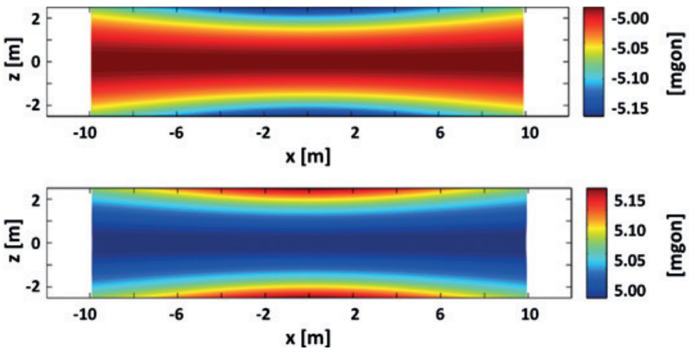

Fig. 6 | Error of horizontal angle φ due to an inclination error of the mirror of $\Delta\omega = 2.5$ mgon (top) and due to a collimation error of a total station of $c = 5.0$ mgon (bottom) /Holst & Kuhlmann 2016/

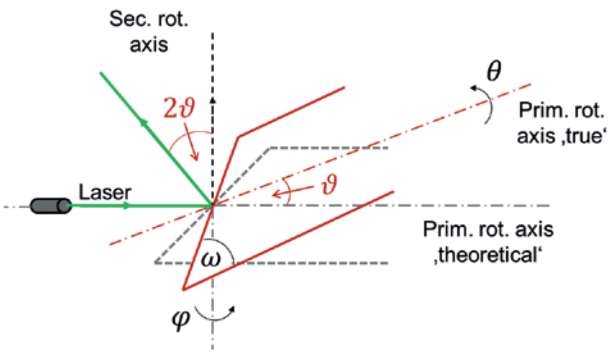

Fig. 7 | Effect on the green laser beam deflection due to a vertical misalignment of the primary rotation axis υ and the resulting deviations shown in red /Holst et al. 2014/

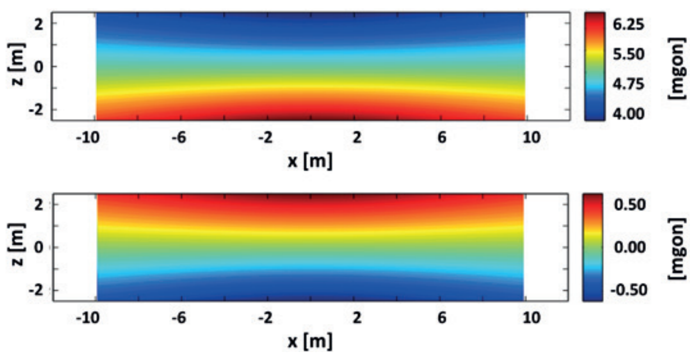

Fig. 8 | Error of horizontal angle φ due to a vertical misalignment of the primary rotation axis of $\upsilon = 2.5$ mgon (top) and due to a trunnion axis error of a total station of $i = 2.5$ mgon (bottom) /Holst et al. 2014/

axis and the vertical axis of a total station, respectively. The collimation axis is defined by the laser beam vector after reflection at the mirror. A beam steering model for scanners with two mirrors can be found in /Wunderlich 2001/.

At an ideal laser scanner construction, a laser beam is aligned to the center of a mirror whose reflecting surface is inclined to the laser beam axis by $\omega = 50$ gon. The primary rotation axis is defined by the longitudinal axis of this mirror whose rotation around this axis leads to the deflection θ of the laser beam. Due to this parallelism of laser beam vector and primary rotation axis, the laser beam is deflected by an angle of 100 gon following the equality of incidence angle α and emergent angle α. This whole construction rotates around the secondary rotation axis that deflects the laser beam by the angle φ.

Hence, the polar elements comprise the distance, the rotation angle about the primary rotation axis and the rotation angle about the secondary rotation axis. If the scanner is set up vertically, its primary rotation axis is horizontal and the secondary is vertical. In this case, the rotation angle θ about the primary rotation axis corresponds to the vertical angle and the angle α about the secondary rotation axis to the horizontal angle. For clarity, we will henceforth use these expressions even if the scanner may actually be set up with arbitrary orientation; „vertical" and „horizontal" is thus to be understood within the coordinate system of the scanner.

Similar to the construction of a total station, the three axes – i.e., primary rotation axis, secondary rotation axis, collimation axis – are assumed to be orthogonal to each other and to coincide in one point. Also similar to the construction of a total station, all of these physical assumptions can only be met to a certain level of accuracy. Hence, deviations from these assumptions lead to systematic measurement errors. These errors do only partially coincide with the ones of total station /Gordon 2008/, /Holst et al. 2014/, /Holst & Kuhlmann 2016/.

In principle, the deviations can be grouped in three categories (for a definition and a delineation of these errors, see /Holst et al. 2014/:

- Laser: horizontal and vertical eccentricities, horizontal and vertical misalignments, etc.
- Mirror: inclination error, etc.
- Axes: vertical index error, horizontal and vertical eccentricities of secondary rotation axis, horizontal and vertical misalignments of primary rotation axis, etc.

As indicated in the enumeration, the list of error sources is not exhaustive /Holst et al. 2014/. A fourth category would deal with the errors due to the electro-optical distance measurement (see Section 3.1).

For a better understanding of these deviations, the polar beam deflection of the laser scanner is simulated in a forward model. By incorporating a specific deviation into this forward model, the effect on the point cloud when scanning an object can be observed. In this study, this procedure is processed for two types of deviations: the inclination error of the mirror and the vertical misalignment of the primary rotation axis.

Using a simple example by the sampling of a plane of 20 m width and 5 m height in 10 m distance, the resulting effects are studied and compared to the ones that would appear when using a total station (Holst et al. 2014). This measurement configuration leads to vertical angles θ between 84 gon and 116 gon, hence, a variation of 32 gon.

3.2.1 Inclination error of the mirror

Fig. 5 shows the effect of the inclination error of the mirror: Due to the error of $\Delta\omega$, the laser beam vector is deflected by an error of $2\Delta\omega$ leading to errors in the horizontal direction. The resulting systematic error of the horizontal angle φ when simulating an inclination error of $\Delta\omega = 2.5$ mgon is shown in *Fig. 6*. Additionally, *Fig. 6* reveals the systematic error of the horizontal angle φ when simulating a total station with a collimation axis error of $c = 5.0$ mgon using the same scanning geometry. The figures indicate that the inclination error $\Delta\omega$ of the mirror corresponds (except for the sign convention) to a collimation axis error of a total station of $2\Delta\omega$.

3.2.2 Vertical misalignment of the primary rotation axis

Fig. 7 shows the effect of the vertical misalignment of the primary rotation axis. When simulating an error of υ, the laser beam is again deflected by an error of twice the size, i.e., 2υ, leading to errors in the horizontal direction and in the vertical direction. However, only the horizontal deviation will be treated in this chapter. This time, the resulting error is not symmetric to the horizontal direction but increases towards nadir and decreases towards zenith. This is shown in *Fig. 8* by a simulated deviation of $\upsilon = 2.5$ mgon. Although this vertical alignment of the primary rotation axis seems to be similar to a trunnion axis error of $i = 2.5$ mgon of a total station, the comparison in *Fig. 8* reveals the different resulting errors in horizontal direction.

These two examples imply that the deviations of a terrestrial laser scanner due to the beam deflection are relevant when considering the error budget of a laser scanner and when trying to calibrate it. Furthermore, the examples reveal that these deviations cannot be simply transferred from the ones that are already known at total stations. Hence, the individual forward modeling of possible deviations in the beam deflection is crucial for the task of laser scanner calibration.

4 CALIBRATION OF TERRESTRIAL LASER SCANNERS

Usually, laser scanners are calibrated by the manufacturers directly after production (Section 4.1). After delivery of the laser scanner to the customer, a system calibration can be performed based on a calibration point field (Section 4.2). The installation of an optimal calibration point field is presently in the focus of several research institutions so that Section 4.3 provides future improvements for these calibration point fields.

4.1 Calibration by the manufacturers

All laser scanners produced by well-known manufacturers are subject to a calibration process prior to delivery. Additionally, the manufacturers offer the calibration also as a service. The factory calibration process is considered a sensitive issue by most manufacturers and the amount of information disclosed differs significantly, therefore. The strategy adopted by Leica Geosystems is worth being emphasized: the calibration process of their P- and C-series laser scanners is explained in a White Paper freely available for download /Walsh 2016/. The description in the next paragraphs is exclusively based on this White Paper and a patent document /Walsh & Leica 2014). Zoller+Fröhlich provides selected information upon request that we briefly summarize in the last paragraph /M. Mettenleiter, personal communication, March 4, 2016/. Most manufacturers treat such information as confidential, and thus the description within this section is unavoidably incomplete.

4.1.1 Calibration by Leica Geosystems

Prior to calibration, each Leica scanner of the P- or C-series is brought to the so-called neutral assembly state by exposing it to a range of temperatures over several days in environmental chambers. Additionally, each scanner is operated within the operating range during this period. This step is meant to release stresses accumulated during the assembly of the instrument.

As the components of the scanner are made of different materials with different thermal expansion coefficients, temperature variations lead to small changes in absolute and relative position of the components directing the laser beam. Thus, the angular calibration is performed over the entire span of environmental conditions according to the scanner specifications. This is accomplished by setting the scanner up in an environmental chamber with windows at specific locations. Leica uses pairs of collimated telescopes pointing at each other and placed outside the chamber in order to locate the laser beam. These telescopes can observe each other when the scanner is not placed between them so that the relative orientation of the axes of these telescopes is known with high accuracy.

For the calibration the laser scanner is placed on the collimated axis of a telescope pair. Knowing the nominal relative position of the collimated telescopes and the laser scanner, the actual angular location of a laser beam directed into one of the telescopes can be derived by image processing using a sensor placed in the focal plane of the telescopes. The sensing based on the collimation principle allows detecting deviations in the angular direction of the laser beam at the level of sub-arc-seconds. Measuring the angular location of the laser beam in two faces of the scanner for at least four directions allows to estimate the angular calibration parameters in a modified bundle adjustment. The parameters include an azimuth offset, an elevation offset, an elevation misalignment, the mirror misalignment and the laser misalignment (see also Section 3.2).

These parameters and their dependence on temperature are stored in the instrument. To apply the corrections, the actual temperature of the instrument is sensed during the measurements at various locations throughout the interior of the instrument. The validity of the parameters is restricted in time, and the calibration needs to be repeated at time intervals specified by the manufacturer.

The tilt correction is intrinsically related to the angular measurements. Therefore, the calibration of the corresponding sensors is relevant as well. Again it needs to be carried out in the environmental chamber in order to model the dependence on environmental conditions. The chamber includes a tilt table and a reference tilt sensor for this purpose. Additionally, a separate calibration stand is used for calibration at room temperature. In this stand the laser beam of the scanner points at a reference unit equipped with a camera which is able to sense the laser beam. The tilt table on which the scanner is mounted can perform different motions. Relating the output of the scanner's tilt sensor to the output of the reference sensor, one obtains the tilt adjustment parameters like offset and scale.

The calibration of the distance measurement unit aims at the determination of the additive constant and of the scale factor (see Section 3.1). Typically, these corrections are determined from measurements covering the entire domain of measurable distances. However, such classic procedures can hardly be automated. A different calibration, process is therefore adopted by Leica /Tuexsen 2016/. As in the case of the angular calibration, pairs of devices are arranged around the scanner, such that the devices point at each other while the scanner is placed in the middle. The devices used for calibrating the distance unit are fiber optical networks. They allow the realization of optical paths with different lengths while requiring very little space. In order to avoid temperature influences on the optical fibers, they are placed outside the environmental chamber. For the calibration, distance measurements are performed in two faces by the scanner to both fiber networks. Based on these measurements, carried out at different temperatures, the temperature-dependent calibration parameters are determined and stored in the scanner to later correct the raw measurements.

4.1.2 Calibration by Zoller+Fröhlich

Certain components of the Z+F laser scanners are calibrated individually, others are determined integrally through scans within a calibration test field. The temperature behavior of the distance measurement unit is investigated by means of environmental chambers. If an internal reference distance measurement is not performed in the scanner (this is the case for the Profiler series), the measured distances are corrected mathematically by the detected drifts. The deviations from linearity and the noise are determined on a distance measurement calibration baseline with respect to an interferometeric reference by using three targets of different reflectivity. The detected deviations from linearity are compensated mathematically. Also the intensity value is calibrated, such that one gets the same intensity value for an object regardless of its location in the domain of distance measurements.

Prior to the angular calibration the mechanical stability of the scanner is tested and ensured. For the angular calibration reference targets located with high accuracy are used. The discrepancies between the target centers extracted from the laser scan and their reference coordinates are used in a calibration model to estimate the correcting parameters for the deflection unit. The estimated parameters fit all resolution levels. Finally, prior to issuing a calibration certificate the 3D-point accuracy is estimated with respect to the targets of a reference field.

4.2 System calibration within a calibration point field

In order to mitigate the effects of scanner imperfections the latter need to be parameterized, and their impact on the coordinates output by the scanner must be modelled deterministically. Due to the polar measurement principle of the instrument it is advantageous to formulate this model in terms of polar coordinates $\boldsymbol{r}$ rather than Cartesian ones. One such model has been proposed by /Lichti 2007/:

$$\begin{aligned}\delta r_i^j &= a_0 + a_1 r_i^j + a_2 \sin\theta_i^j + a_3 \sin\frac{4\pi r_i^j}{U_1}\\ &\quad + a_4 \cos\frac{4\pi r_i^j}{U_1} + a_5 \sin\frac{4\pi r_i^j}{U_2} + a_6 \cos\frac{4\pi r_i^j}{U_2}\\ &\quad + a_7 \sin 4\varphi_i^j + a_8 \cos 4\varphi_i^j, \end{aligned} \tag{1}$$

$$\begin{aligned}\delta\varphi_i^j &= b_1 \sec\theta_i^j + b_2 \tan\theta_i^j + b_3 \sin 2\varphi_i^j + b_4 \cos 2\varphi_i^j\\ &\quad + b_5\, \varphi_i^j + b_6 \cos 3\theta_i^j + b_7 \sin 4\theta_i^j, \end{aligned} \tag{2}$$

$$\delta\theta_i^j = c_0 + c_1\theta_i^j + c_2 \sin\theta_i^j + c_3 \sin 3\varphi_i^j + c_4 \cos 3\varphi_i^j, \tag{3}$$

where $\boldsymbol{r}_i^j := \left[r_i^j,\ \varphi_i^j,\ \theta_i^j\right]$ is the i-th point within the j-th scan, r_i^j is the distance, φ_i^j the angle about the secondary rotation axis (i.e., the horizontal angle if this axis is vertical), and θ_i^j the angle about the primary rotation axis (i.e., the vertical angle in the above case). The quantities $a_0, a_1, \ldots, c_4$ are the parameters of this model; /Lichti 2007/ refers to them as additional parameters (APs). Finally, U_1 and U_2 are the shortest and second shortest modulation wavelengths in case of a phase based measurement principle.

Some of the terms in these equations follow directly from the forward modelling of the physical and geometrical properties of the instrument supposing an analogy with a total station, others were empirically found to represent systematic deviations identified with specific scanners. Depending on the scanner at hand some of the terms may have to be omitted right away (e.g. the cyclic distance deviations) or further terms may be needed. While the model is therefore somewhat arbitrary and it may be possible to find a more appropriate one for a given scanner (if its geometry and functionality is known, see Section 3.2) Eqs. (*1*) – (*3*) are sufficiently general to cover a wide variety of practical cases and have therefore been used successfully, see e.g. /Reshetyuk 2010/, /Lichti et al. 2011/.

The goal of scanner calibration is to estimate appropriate values of the APs such that the systematic deviations of the polar elements $\boldsymbol{r}_i^j$ produced by the scanner can subsequently be mitigated by

$$(\boldsymbol{r}_i^j)^c := \boldsymbol{r}_i^j - \left[\delta\hat{r}_i^j,\ \delta\hat{\varphi}_i^j,\ \delta\hat{\theta}_i^j\right]^T, \tag{4}$$

where the second vector on the right results from evaluating Eqs. (*1*) – (*3*) with $\boldsymbol{r}_i^j$ and with the estimated values of the required APs (very likely only a subset of the above). In this context it is very favourable that the above model is linear in the APs since the observed polar elements on the right hand side of Eqs. (*1*) – (*3*) can be introduced as fixed parameters into the adjustment without significantly changing the adjusted values. This means that the model can be used on top of the one implemented by the manufacturer and already applied to the raw scanner measurements before making them accessible as $\boldsymbol{r}_i^j$. Secondly, it also means that the observability of the APs (i.e., the precision with which they can be estimated) and their separability (i.e., the degree of correlations) do not depend on the value of the APs and can therefore be predicted before carrying out the calibration.

In order for the calibration to be useful the corrected polar elements as of Eq. (*4*) must be more accurate than the uncorrected ones, and the bias introduced into the corrected elements by deviations of the estimated APs from their true values should be negligible as compared to the standard deviation of the polar elements. This is particularly important in connection with deformation monitoring using TLS and in view of potential spatial filtering of the point clouds which reduces random noise but may cause unmitigated biases to become the dominant error source. For practical purposes an upper limit of the standard deviation of the estimates APs and an upper limit of the correlation between various parameters is suitable to judge the appropriateness of the APs. A paper presenting such an approach, a relation of these criteria to the specifications of the scanner and to the requirements of the applications, and discussing suitable configurations for calibration is in preparation by X. Ge, A. Wieser and Th. Wunderlich.

There are several possibilities to carry out the calibration, in particular component calibration and system calibration /Hennes & Ingensand 2000/. The former consists of separately calibrating the individual components of the instrument using dedicated equipment and procedures and then composing the individual results. Examples with respect to TLS calibration can be found in /Schulz 2007/, /Zogg 2008/, /Neitzel 2006a, b/. System calibration of TLS means estimating the parameters integrally from point cloud data. This approach is used e.g. by /Rietdorf 2005/, /Lichti 2007/, /Gordon 2008/, /Reshetyuk 2010/, /Holst 2015/, /Holst & Kuhlmann 2014/. Its potential advantages are (i) that precise knowledge of the components and their interaction is not needed, (ii) that it does not require special equipment or facilities, and (iii) that it can potentially even be carried out as self-calibration and thus on-the-job yielding accurate and up-to-date calibration parameters. Self-calibration is the focus of Lichti /2007/, /Reshetyuk 2010/, /Lichti & Licht 2006/, /Holst & Kuhlmann 2014/, /Al-Manasir & Lichti 2015/, and others.

System calibration of TLS can be carried out using signalised points or geometric features (e.g. linearity or planarity); both approaches can be found in the literature, e.g. in the publications cited above. The point-based approach requires that individual object points (OPs) are identified within the point clouds. If an established point field is (repeatedly) used for that purpose, the OPs may be realized using markers that can easily and accurately be located within the point cloud – ideally with a precision better than point density. In that case, the OPs can be placed in specific locations resulting from an optimization of the calibration configuration. If a self-calibration is carried out, the OPs may be special markers but they may also be characteristic natural points (point features) which can be detected and identified in several scans; in this case, the OPs will be quasi-randomly distributed as resulting from the characteristics of the scanned scene. Prior planning of the calibration is hardly feasible in this case. Using geometric features within the scanned scene instead of OPs is another option (see e.g., /Rietdorf 2005/, primarily attractive for the self-calibration case. E.g. /Holst & Kuhlmann 2014/ use a radio telescope for self-calibration which might be practicable due to its main reflectors smooth surface and the steep sighting during their laser scans.

We have carried out extensive numeric simulations for the case of point-field based system calibration with specially installed markers in an indoor environment in order to derive configuration requirements helping to plan or assess both a calibration point field and a calibration process (number of scans, scanner locations and orientations). We found that even in the idealistic case of a point field with known OP coordinates (e.g., previously measured with sub-mm accuracy using triangulation), known scanner location (e.g., setup on a pillar) and known scanner orientation angles, a very high number of OP measurements (on the order of 37 per AP, or higher) is required to estimate the APs with sufficient precision and separability such that their bias is negligible as compared to the standard deviation of the measurements. As an example, *Fig. 9* shows the configuration allowing to estimate a specific subset of 4 APs (a_0, b_1, b_2, c_0) with a single scan of a minimum number of OPs (86 in this case, 26 at the ceiling, 2.5 m above the scanner at an elevation angle of 80°, and 60 on the floor at an elevation angle of –70°).

If the scanner location and orientation are not known, finding configurations which yield sufficiently decorrelated APs is particularly difficult and is hardly achievable without using data from an inclination sensor within the scanner as direct observations of the scanner tilt. The numerical analysis shows that several scans and far more than 100 OPs may be required in such cases. With quasi-random OP distribution and unknown scanner location, as resulting during a self-calibration, we found that it may not be possible at all to estimate reasonable subsets of APs with sufficient precision and separability. Additionally, some of the parameters, e.g. the distance scale factor, cannot be usefully estimated from an indoor point field. So, careful planning and establishment of a dedicated point field for scanner calibration is indicated, along with an analysis of the observability and separability of the parameters, such that the

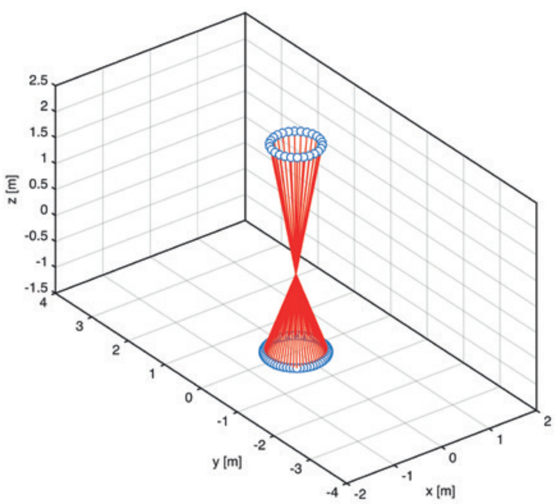

Fig. 9 | Minimum configuration of known OPs for estimating a_0, b_1, b_2, c_0 from known scanner setup using a single scan within a room of 4 m height (scanner at position [0, 0, 0], blue circles indicate OPs, red lines indicate respective line-of-sight) point field based calibration can be used to verify the temporal stability of the scanner with respect to some of the instrumental imperfections, while others will have to be monitored and calibrated by component calibration. Further research is needed to provide concrete guidelines for such a multi-modal calibration process.

4.3 Future improvements of system calibrations

As indicated in Section 3.2, the imperfections of a panoramic laser scanner do partly differ from the ones of a total station. However, current approaches for laser scanner calibration as written in Section 4.2 are based on modeling imperfections similar to the ones of a total station. Hence, this simplified functional model of a total station should be refined in future studies by a more realistic one similar to the suggestions in Section 3.2. This task is not trivial since only the forward model of the laser scanner imperfections has been investigated up to now /Holst et al. 2014/, /Holst & Kuhlmann 2016/. The resulting effects of this forward model, leading to systematic deviations in the point cloud, have not been parameterized yet. This parameterization would equal a backward model. For a total station, this backward model is long established, e.g., describing the systematic error of the horizontal direction due to the collimation axis error.

Furthermore, Section 4.2 insists that the development of an optimal calibration point field has not yet been finished. This calibration field should enable the estimation of calibration parameters with small correlations to separate the potential imperfections of the laser scanner. Therefore, varying distances in the point field and large height differences need to be incorporated. Furthermore, the external determination of the laser scanners inclination and orientation could possibly be helpful.

5 CONCLUSION AND OUTLOOK

The calibration of a laser scanner is necessary to reduce systematic errors in the acquired point cloud. Furthermore, the calibration provides the stochastic model of the observations. This is needed at laser scanner based deformation analyses for a realistic estimation of the deformation parameters' uncertainty. E.g. only based on this realistic uncertainty estimation, a meaningful significance test can be performed.

For calibrating a terrestrial laser scanner, a functional calibration model needs to be set up. Some of the corresponding calibration parameters are comparable to the ones of a total station, some are not. While especially the calibration parameters due to the polar beam deflection deviate from the calibration model known from a total station, the calibration parameters due to the electro-optical distance measurement are similar to the ones of a total station. Hence, we presently know more about the EDM errors than about the beam deflection errors. Complicating at setting up this complete calibration model is among others the fact that the manufacturers publish their calibration functions and procedures only sparsely.

For calibrating a terrestrial laser scanner, the parameters of the functional calibration model need to be estimated in a calibration point field. The development of an optimal calibration field has not yet been completed. Hence, we have to learn and improve each calibration field step by step, e.g. by starting interlaboratory tests between several calibration fields and laser scanners. Usually, calibration procedures should be carried out under accuracy conditions of at least 3 – 10 times better than the ones that are needed in the latter application. Whether this convention can be met at calibrating terrestrial laser scanners is questionable even if the tasks mentioned in this study are satisfactorily solved.

REFERENCES

Al-Manasir, K.; Lichti, D. D. (2015): Self-calibration of a Leica HDS7000 Scanner. FIG Working Week, May 17 – 21, 2015, Sofia, Bulgaria.

Böhler, W.; Marbs, A. (2003): Investigating laser scanner accuracy. Proceedings of the XIXth CIPA Symposium, Sept. 30 – Oct 4, 2015, Antalya, Turkey.

Ciddor, P. E. (1996): Refractive index of air: new equations for the visible and near infrared. In: Applied Optics 35(1996), 1566 – 1573.

Ciddor, P. E.; Hill, R. J. (1999): Refractive index of air. In: Applied Optics, 38(1999), 1663 – 1667.

Dorninger, P.; Nothegger, C.; Pfeifer, N.; Molnar, G. (2008): On-the-job detection and correction of systematic cyclic distance measurement errors of terrestrial laser scanners. In: Journal of Applied Geodesy, 2(2008), 191 – 204.

Eling, D. (2009): Terrestrisches Laserscanning für die Bauwerksüberwachung. Deutsche Geodätische Kommission, Reihe C, 641. Munich.

Feldmann, E.; Petersen, M.; Staiger, R. (2011): Erste Erfahrungen mit Feldprüfverfahren für terrestrische Laserscanner. In: Schriftenreihe DVW, 66 (Terrestrisches Laserscanning – TLS 2011). Wißner, Augsburg, 77 – 94.

Gordon, B. (2008): Zur Bestimmung von Messunsicherheiten terrestrischer Laserscanner. PhD Thesis, Fachbereich Bauingenieurwesen und Geodäsie, Technischen Universität Darmstadt, D 17.

Van Gosliga, R.; Lindenbergh, R.; Pfeifer, N. (2006): Deformation Analysis of a bored tunnel by means of Terrestrial Laser Scanning. In: ISPRS Volume XXXVI, Part 5.

Gottwald, R.; Heister, H.; Staiger, R. (2008): Zur Prüfung und Kalibrierung von terrestrischen Laserscannern – eine Standortbestimung. In: Schriftenreihe DVW, 54 (Terrestrisches Laserscanning – TLS 2008). Wißner, Augsburg, 91 – 110.

Hennes, M.; Ingensand, H. (2000): Komponentenkalibrierung versus Systemkalibrierung. Proceedings of the 13th International Course on Engineering Geodesy, March 13 – 17, 2000, Munich, Germany.

Holst, Ch. (2015): Analyse der Konfiguration bei der Approximation ungleichmäßig abgetasteter Oberflächen auf Basis von Nivellements und terrestrischen Laserscans. Deutsche Geodätische Kommission, Reihe C, 760. Munich.

Holst, Ch.; Kuhlmann, H. (2014): Aiming at self-calibration of terrestrial laser scanners using only one single object and one single scan. In: Journal of Applied Geodesy, 8(2014)4, 295 – 310.

Holst, Ch.; Kuhlmann, H. (2016): Challenges and Present Fields of Action at Laser Scanner Based Deformation Analyses. In: Journal of Applied Geodesy, 10(2016)1, 17 – 25.

Holst, Ch.; Nothnagel, A.; Blome, M.; Becker, P.; Eichborn, M.; Kuhlmann, H. (2015): Improved area-based deformation analysis of a radio telescope's main reflector based on terrestrial laser scanning. In: Journal of Applied Geodesy, 9(2015)1, 1 – 14.

Holst, Ch.; Tegelbeckers, J.; Kuhlmann, H. (2014): Erkennung und Erklärung von systematischen Effekten beim TLS. In: Schriftenreihe DVW, 78 (Terrestrisches Laserscanning 2014 – TLS 2014). Wißner, Augsburg, 51 – 68.

Ioannidis, C.; Valani, A.; Georgopoulus, A.; Tsiligiris, E. (2006): 3D Model generation for Deformation Analysis using Laser Scanning Data of a Cooling Tower. 3rd IAG/12th FIG Symposium, Baden, Germany.

Lichti, D.; Licht, M. (2006): Experiences with terrestrial laser scanner modelling and accuracy assessment. In: Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., 36(2006), 155 – 160.

Lichti, D. (2007): Error modelling, calibration and analysis of an AM-CW terrestrial laser scanner. In: ISPRS Journal of Photogrammetry and Remote Sensing, 61(2007), 307–324.

Lichti, D.; Chow, J.; Lahamya, H. (2011): Parameter de-correlation and model identification in hybrid-style terrestrial laser scanner self-calibration. In: ISPRS Journal of Photogrammetry and Remote Sensing, 66(2011), 317–326.

Neitzel, F. (2006a): Investigation of axes errors of terrestrial laser scanners, In: Gründig, L.; Altan, O. (Eds): 5th International Symposium Turkish-German Joint Geodetic Days, March 29–31, 2006, Berlin, Germany.

Neitzel, F. (2006b): Bestimmung von Ziel- und Kippachsenfehler polarer Messsysteme aus Minimalkonfigurationen und überbestimmten Konfigurationen. In: Zeitschrift für Geodäsie, Geoinformation und Landmanagement (zfv), 131(2006)3, 132–140.

Neitzel, F.; Gordon, B.; Wujanz, D. (2014): Verfahren zur standardisierten Überprüfung von terrestrischen Laserscannern. DVW-Merkblatt 7-2014. www.dvw.de.

Reshetyuk, Y. (2010): A unified approach to self-calibration of terrestrial laser scanners. In: ISPRS Journal of Photogrammetry and Remote Sensing, 65(2010), 445–456.

Rietdorf, A. (2005): Automatisierte Auswertung und Kalibrierung von scannenden Messsystemen mit tachymetrischem Messprinzip. Deutsche Geodätische Kommission, Reihe C, 582. Munich.

Schäfer, Th. (2014): Eine Simulationsumgebung zur Analyse berührungsloser Distanzmessungen unter Berücksichtigung der Interaktion zwischen Laserstrahl und Objekt. In: Wieser, A. (Ed.): Ingenieurvermessung 2014. Wichmann, Berlin/Offenbach, 27–36.

Schulz, T.; Ingensand, H. (2004): Influencing Variables, Precision and Accuracy of Terrestrial Laser Scanners. In: INGEO 2004 and FIG Regional Central and Eastern European Conference on Engineering Surveying, November 11–13, 2004, Bratislava, Slovakia.

Schulz, Th. (2007): Calibration of a terrestrial laser scanner for Engineering Geodesy. PhD Thesis, ETH Zürich, No. 17036.

Soudarissanane, S.; Lindenbergh, R.; Menenti, M.; Teunissen, P. (2011): Scanning geometry: influencing factor on the quality of terrestrial laser scanning points. In: ISPRS Journal of Photogrammetry and Remote Sensing, 66(2011), 389–399.

Tuexsen, H.-H. (2016): Werkskalibrierung und Überprüfung des Leica Scanners im Feld. In: VDVmagazin, (2016)1, 28–31.

Walser, B.; Gordon, B. (2013): Der Laserscanner, eine Black-Box? In: Schriftenreihe DVW, 72 (Terrestrisches Laserscanning 2013–TLS 2013). Wißner, Augsburg, 149–164.

Walsh, G. (2014): Telescope based calibration of a three dimensional optical scanner. Patent number: CA 2745807 C.

Walsh, G. (2016): Leica ScanStation P-Series – Details that matter. White Paper. http://leica-geosystems.com/-/media/files/products/white%20papers/leica_scanstation_p-series_details_that_matter_wp_en.ashx?la=en (01.03.2016).

Wang, J. (2013): Towards deformation monitoring with terrestrial laser scanning based on external calibration and feature matching methods. PhD Thesis, Wissenschaftliche Arbeiten der Fachrichtung Geodäsie und Geoinformatik, Leibniz Universität Hannover, No. 308.

Wunderlich, T. (2001): Operational and Economical Aspects of terrestrial Laser Scanning. In: Proceedings of 5th International Conference on Optical 3D Measurement Techniques, Vienna University of Technology, 18–25.

Wunderlich, T.; Wasmeier, P.; Ohlmann-Lauber, J.; Schäfer, Th.; Reidl, F. (2013a): Objective Specifications of Terrestrial Laser Scanners – A Contribution of the Geodetic Laboratory at the Technische Universität München. Research Report, Blue Series Books at the Chair of Geodesy, 21.

Wunderlich, T.; Wasmeier, P.; Ohlmann-Lauber, J.; Ge, X.; Reidl, F. (2013b): Ansätze und Einrichtungen des Geodätischen Prüflabors der TUM zur Untersuchung und Kalibrierung von Laserscannern. In: Schriftenreihe DVW, 72 (Terrestrisches Laserscanning 2013–TLS 2013). Wißner, Augsburg, 137–148.

Zhang, Y.; Wu, H.; Cheng, X.; Liu, C (2008): Accuracy Evaluation of Three Dimensional Laser Range Scanner Based on Field Calibration. In: Proceedings of the 8th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences, June 25–27, Shanghai, P. R. China, 2008, 119–126.

Zámečníková, M.; Wieser, A.; Woschitz, H.; Ressl, C. (2014): Influence of surface reflectivity on reflectorless electronic distance measurement and terrestrial laser scanning. In: Journal of Applied Geodesy, 8(2014), 311–326.

Zámečníková, M.; Neuner, H.; Pegritz, S.; Sonnleitner, R. (2015): Investigation on the influence of the incidence angle on the reflectorless distance measurement of a terrestrial laser scanner. In: Österreichische Zeitschrift für Vermessung & Geoinformation (vgi), 103(2015)2+3, 208–218.

Zogg, H. M. (2008): Investigations of high precision terrestrial laser scanning with emphasis on the development of a robust close-range 3D-laser scanning system. PhD thesis, ETH Zürich, No. 18013.

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Manuskript eingereicht: 08.04.2016 | Im Peer-Review-Verfahren begutachtet