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# Methods for quantification of systematic distance deviations under incidence angle with scanning total stations

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ABSTRACT

If scanning total stations (TLS + TS) are used in scanning mode for high accurate engineering applications, the systematic influence of the incidence angle (IA) on the reflectorless distance measurement has to be eliminated. At present, methods for quantifying the systematic distance deviations under IA are missing because the measured points are not reproducible. In this paper, three such methods are presented. They are conditional on the used instruments and the required accuracy. These methods are validated with respect to specified framework conditions. The distance deviations are derived in all three methods as difference between the distance measured with TLS + TS in the scanning mode ($D_{TLS}$) and the corresponding reference distance ($D_{ref}$). The $D_{ref}$ is determined in three steps: measurement of a high accuracy network, measurement for determining the starting point of the $D_{ref}$; object measurement to determine the endpoints of $D_{ref}$. The corresponding $D_{TLS}$ and $D_{ref}$ are identified by means of the horizontal direction Hz ($Hz_{TLS}$ and $Hz_{ref}$) and the vertical angle V ($V_{TLS}$ and $V_{ref}$), both pairs of angles referring to the same origin marked by the axis of the common coordinate system. Depending on the used method, the $D_{ref}$ is determined with a standard uncertainty of 0.1–0.3 mm (at a distance of 30 m). The quantified influence of IA on the distance measurement of the Leica MS50 at a distance of 30 m to a granite plate varies in the interval of 0.8 mm. The strong variation due to the IA occurs from 0 to 20 gon, its effect is stable from 20 to 60 gon.

## 1. Introduction

If known and unknown influences affect measured quantities, systematic measurement deviations can occur. They bias measurement data, such that they deviate from true values (Niemeier, 2008, pp. 10–12). In order to eliminate them, the measurement process has to be analyzed, influences have to be investigated and their correlations determined. Thereafter, they can be compensated by appropriate measurement strategies (by averaging or differentiating), by applying corrections determined in the calibration, or by implementing the systematic parameter as unknown in evaluation models. The elimination of the systematic deviations is essential for exploiting the accuracy potential of measuring instruments.

The scan data (point cloud) measured by terrestrial laser scanners (TLS) are influenced by instrumental imperfections, atmospheric effects, scanning geometry, object properties or surface related effects and georeferencing, e.g. (Soudarissanane et al., 2011; Boehler et al., 2003; Zogg, 2008, pp. 49–75; Ge, 2016, pp. 63–90). These error sources are partially investigated in the component calibration (Dorninger et al., 2008; Zámečníková et al., 2014b; Schulz, 2007, pp. 23–72) and estimated in the functional model of the system calibration (Lichti, 2007; Lichti et al., 2011; Gordon, 2008, pp. 50–57; Reshetyuk, 2009, pp. 66–114; Holst and Kuhlmann, 2014). The quantified calibration parameters are usually related to the frame conditions of the study. The properties are not generalized and no generally valid complete models are set up. It is caused by the specific design of each TLS as a black box that evokes other systematic errors, by the variety of combinations of scanning geometry and object properties (e.g. radiometric properties) and other behavior of each scanner to the complexity of the measurement conditions.

The non-considered systematic deviations of the measured data can lead to feigning rigid body movements, feigning object deformations or a combination of both. In order to use the TLS for measurements with an accuracy level of 1–2 mm (documentation, deformation monitoring it is necessary to develop the strategies for the elimination of the systematic deviations (Holst and Kuhlmann, 2014; Eling, 2009, p. 99; Wang, 2013, p. 52; Sarti et al., 2009).

The mentioned influence of the scanning geometry includes the IA of the laser beam. The IA is defined as the angle between the measuring beam and the normal to the plane, which locally approximates the

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measured area during the scanning process. The laser beam falls on surfaces of different orientation, i.e. the IA changes. The variation of the IA causes systematic distance deviations, e.g. (Zámečníková et al., 2015; Zámečníková and Neuner, 2017a, 2017b).

The measurement deviations due to the influence of IA are explained in two ways in the geodetic expert group. In a first way, the laser footprint is deformed by the resulting geometry. Under IA are different distances in the beam path, which are within a certain distance interval, which depends on the size of the beam diameter on the surface and the orientation of the surface (Jutzi, 2007, p. 13). Thus, the center point of the laser spot does not coincide with the endpoint of the distance. Furthermore, the average value of the distances within the laser spot is longer than the distance corresponding to the measured horizontal direction and vertical angle (Schulz, 2007; Gordon, 2008, pp. 30–31; Linstaedt et al., 2009). In the second way, under higher IA, the reflected signal strength is reduced (Schäfer and Schulz, 2005; Kersten at al., 2008; Wujanz et al., 2017). The intensity of the reflected signal strength in the nearer part of the laser spot dominates in the measurement signal and leads to shorter distances (Kern, 2003, p. 41–42; Joeckel et al., 2008, pp. 10–12; Schäfer, 2017, pp. 78–81). There is no weighting process in signal processing yet the parts of the signal have a higher impact onto the distance. According to previous explanations, the distances with increasing IA may become shorter or longer.

The distance deviations could be investigated at the level of the received signal strength (radiometric level) or/and at the distance level. Outgoing from the known received signal strength, a model for the transfer of the received signal strength to the distance under IA is missing. Also, the transmitted and received waveform is not present over time, so the approach for airborne laser scanner (Roncat, 2014, pp. 10–26; Jutzi, 2007, pp. 32–48) cannot be applied. Basically, if the investigation existed on the radiometric or/and distance level, the validation of the approach would be necessary also on the distance level. In this paper, the systematic distance deviations are investigated only on the distance level.

A general problem makes the quantification of the systematic distance deviations due to the influence of the IA in the scanning mode more difficult. The endpoints of the measured distances are not signalized and reproducible. In Mechelke et al. (2007) a plane under IA is scanned with four spheres as reference points. The variation of the distance offset between the approximated plane through the point clouds and center points of approximated reference points respectively was observed and set as a measure for the effect of the IA. If the geometry of the measuring object deviates, the influence of the IA is not correctly quantified by the indirect derivation (Wujanz et al., 2017). Typically, this influence is not included in the functional model of the measured distance for a system calibration (Lichti, 2007; Lichti et al., 2011; Gordon, 2008, pp. 50–57; Reshetyuk, 2009, pp. 66–114; Holst and Kuhlmann, 2014). In order to tackle this influence, methods for its quantification are required.

The aim of the paper is to introduce novel metrological methodologies, which are focused on the direct comparison of distances measured in scanning mode under laboratory condition with reference distances in order to assess the influence of the IA. Three methods for quantification of the systematic deviations under IA are presented, validated and critically compared. Two of the methods were partly published in the context of different research questions (Zámečníková et al., 2015; Zámečníková and Neuner, 2017a, 2017b). They serve as a developed tool that research institutions can use.

Currently, the methods are suitable for scanning total stations (TLS + TS) operated in scanning mode, as they use the total station part of TLS + TS. The use of TLS + TS constitutes a bridging solution towards applicability for usual TLS. The methods are based on individually measured distances, i.e. circumventing indirect derivation by the modeling of the measured object (Wujanz et al., 2017). The application of these methods is given by the available instruments and by the required accuracy of the reference distance.

The proposed methodological approach is regarded as one step forward towards the complex investigation of the scanning geometry on the reflectorless distance measurement. The quantified systematic distance deviations contribute to the understanding of the influences and enable to select their compensation strategy, e.g. the derivation of the term for the functional model of the measured distances in the system calibration.

The paper is structured as follows: in the second chapter, the concepts common to all three methods for the quantification of systematic distance deviations under IA are introduced. In the 3rd chapter the framework conditions of the experiments are given for all methods, the measuring setup, the measurement process and the evaluation of each method are described. In the 4th chapter, the results of all experiments are shown and analyzed for validation of the methods. Finally, the paper is summarized and an outlook is given.

## 2. Methodology

The quantification of the systematic distance deviations is based in all three methods on the comparison of the distance measured by a total station in the scanning mode ($D_{TLS}$) with the corresponding reference distance ($D_{ref}$) (Fig. 1).

### 2.1. Reflectorless distance $D_{TLS}$

The investigated reflectorless distance $D_{TLS}$ is defined by the distance between the zero point of the TLS + TS ($P_0$) and the object point (P) under measured $Hz_{TLS}$, $V_{TLS}$ (Fig. 1).

As the measurement result of TLS + TS, the rectangular coordinates of the measured point cloud ($y_{TLS}$, $x_{TLS}$, $z_{TLS}$) refer to the TLS + TS coordinate system (CS). Its origin is located in $P_0$, the x-axis corresponds to the zero direction of the Hz-circle and the z-axis to the vertical axis of the instrument. It is assumed that the polar elements $Hz_{TLS}$, $V_{TLS}$, $D_{TLS}$ calculated from the obtained rectangular coordinates correspond to the measured ones. Furthermore, it is assumed that in case of the TLS + TS the angles of the scanner component ($Hz_{TLS}$, $V_{TLS}$) and of the total station component ($Hz_{TS}$, $V_{TS}$) are equal ($Hz_{TLS} = Hz_{TS}$, $V_{TLS} = V_{TS}$).

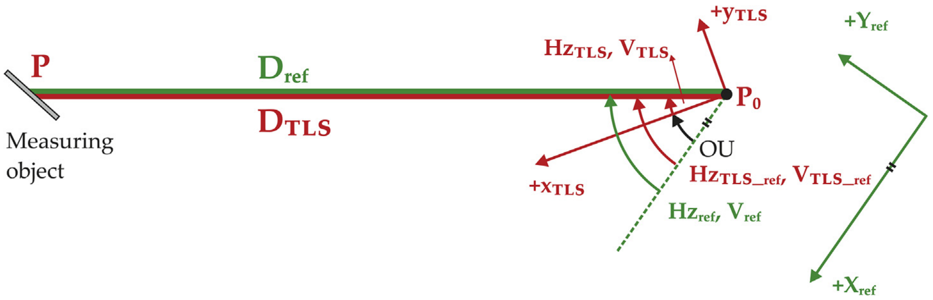

**Fig. 1.** The common principle of the three methods.