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Investigation on the influence of the incidence angle on the reflectorless distance measurement of a terrestrial laser scanner

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Abstract
Although the influence of incidence angle (IA) is one of the known error influence of terrestrial laser scanners (TLS), it is not taken into account in the evaluation of TLS-data. In this paper fundamental question is discussed, how the IA influences the TLS-distances, it is of stochastic or of systematic nature or of a combination of both. For this purpose, a new methodology has been developed. Its special feature is that the directly measured TLS-distances are compared with reference distances. It is optional for close range and for longer distances. The methodology was realised with a time of flight laser scanner. At close range of 3.5 to 5.2 m other error effects up to 4.4 mm are more pronounced than the influence of IA. At the distance of about 30 m, a systematic effect of the IA was found. The total variation of the distance difference with IA is of ca. 2.0 mm. The stochastic properties of the influence of IA could not be quantified. In future works the methodology will be improved with respect to the obtained knowledge and the error influence well be completely quantified.

Keywords
incidence angle, reflectorless distance measurement, laser scanner

1. Introduction

In general, the geometry of object surfaces is determined from terrestrial laser scanning (TLS) measurements under varying incidence angles (IA). In consequence, the laser spot is deformed so that less signal strength is reflected back in comparison to its perpendicular alignment. The IA of the laser can affect the reflectorless distance measurements (RL) and thus, the TLS-data. In order to consider this influence in the TLS-measurement's planning as well as in the evaluation of TLS-data and in the object modelling, the quantification of its impact is necessary.

Previous investigations of the influence of the IA on the distance measurement of TLS are characterized by three problems. First, it is not clear which character the error influence has. In some studies it has been described by a systematic measure like a correction term [1, 2, 3] and in others by a stochastic measure like a standard deviation [4, 5]. Secondly, the impact was assessed by indirectly derived parameters. These can also falsify the quantified influence of the error. For the third the impact of the IA was quantified only at close range.

In this paper the influence of IA on the RL measurement is quantified in such a way that in the mentioned problematic aspects are minimized. The aim is to answer the fundamental question, whether the influence of the IA is of stochastic or of systematic nature or of a combination of both.

A new methodology to investigate the error influence is introduced. Instead of deriving the parameters indirectly, the study is performed on the level of directly TLS-measured distances which are compared with reference distances. To investigate the error influence at greater distances, two variants of the method have been developed for close range and for longer distances. The method is suitable for scanning total stations (TLS+TS).

The proposed methodology is executed with a time of flight TLS. The realised measurement setups and measurement procedures are described in detail. After evaluation of the

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measured data, the results are analysed, evaluated and discussed in the framework of these research issue.

2. Methodology

Our investigations of the influence of IA are based on the direct comparison of the reference with the TLS-distance. The investigated TLS- distance DTLS is defined as the distance between the zero point of TLS+TS and the scanned point P_i.

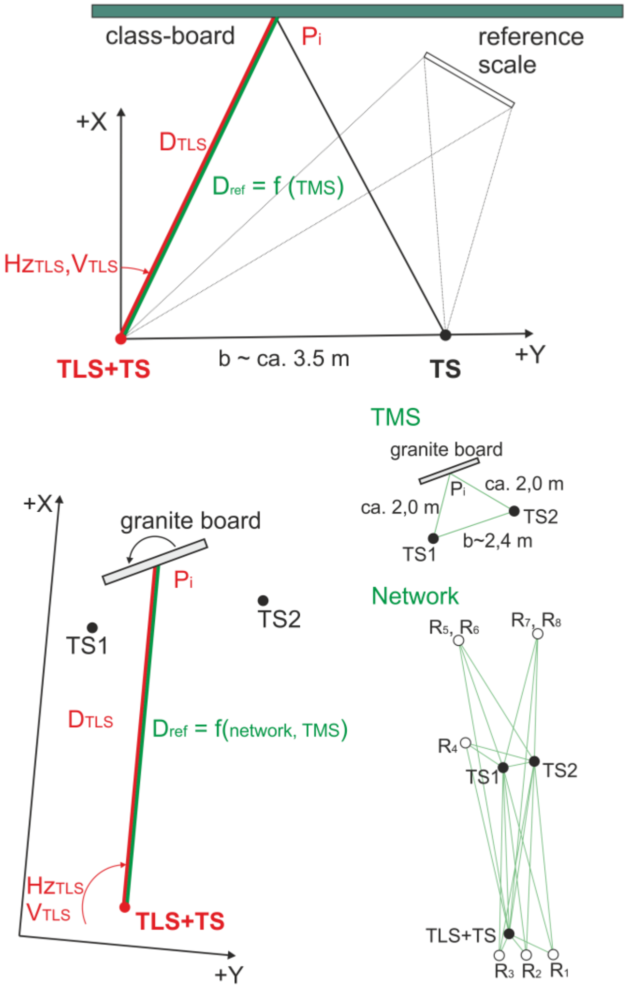

Fig. 1: Measurement setup a) for close range, b) for longer distance

The methodology consists of the following steps (Fig. 1):
1)A planar object is scanned from a standpoint of TLS+TS. The coordinates Y_{TLS}, X_{TLS}, Z_{TLS} of the point cloud are converted into polar coordinates Hz_{TLS}, V_{TLS}, D_{TLS}.
2)The point on the object P_i is staked out via Hz_{TLS}, V_{TLS} using the tachometric part of the instrument and signalised. The fundamental condition must be fulfilled, that TLS and TS work in the same coordinate system.
3)The end points of the studied distance are determined with a theodolite measurement system (TMS). Subsequently, the reference distance DRef is calculated from the determined coordinates.
The TMS consists of TLS+TS and another TS instrument (Fig. 1a)).
For the investigation of the error influence at longer distances e. g. 30 m it is not possible to use only the TMS due to the decrease of the accuracy and the spatial limitations in the laboratory. In this case, the object point P_i is determined with the TMS from a base (TS1-TS2) which is located at a short distance to the planar object (approx. 2.5 m) (Fig. 1b)). The base points and the reference point of the scanner are determined in a geodetic precision network.
The variant for determining the reference distance is selected according to the a priori accuracy analysis. The reference should be at least one order of magnitude more accurate than the investigated distance.
Steps 2 and 3 are repeated for distances under different IA.
4)On the basis of the differences between the TMS- and TLS-distances the character of the influence of IA will be investigated.

3. Measurements

The study was carried out with a Leica MultiStation MS50. It is characterized by the accuracy of the RL-distance measurement of 2 mm + 2 ppm, a distance measurement noise of 0.4 mm up to 10 m, 0.5 mm up to 25 m at measurement frequency of 62 Hz and the angular accuracy of 0.3 mgon. The spot size is 7x10 mm at 30 m.
The MS50 was used at close range (3.5 to 5.2 m) as well as at a distance of ca. 30 m under laboratory conditions. The near field was chosen because instruments have special behaviour in this range. The distance of 30 m belongs to usually measured distances at scanning of structures. Scanning was performed with the measuring rate of 62 Hz. The resolution was set to be larger than the diameter of the laser spot, so that correlations between adjacent distances are avoided.
The measurement process is automated predominantly via GeoCOM control. In the following sub-sections the measurement setup and the measurement procedure of the two cases of investigations are described.

a.Experiment at close range

A wooden class-board was used as a test object (Fig. 1a)). It has dark green color, dimensions of 5 m x 1.5 m x 0.025 m (width x height x depth) and is almost vertically fixed to the wall. The two station-points of the TMS were placed at 3.5 m from the object. In this measurement setup the MS50 was simultaneously used as a theodolite within the TMS configuration. The base between the theodolites (TLS+TS, TS) was 3.5 m long. For the basis determination a reference scale of 0.8 m was positioned horizontally.
Different IAs of the laser beam are obtained by the rotation

of instrument’s collimation axis in horizontal and vertical direction. In this measurement setup the TLS-distances vary from 3.5 m at IA of 0 gon to 5.2 m at IA of 55 gon.

In the measurement procedure first preparation steps were performed for TMS - mutual orientation of the horizontal circle of the theodolite and base determination. The mutual orientation was determined by collimation in two faces. Both instruments are specified with the same angular accuracy of $\square_{\mathrm{Hz}}$ = 0.3 mgon. The base was indirectly determined by solving the Hansen problem. The length of the reference scale was measured with the laser interferometer Agilent 5530 with $\square_{\mathrm{ref.\ scale}}$ = 0.4 ppm. The pointing accuracy to targets of the reference scale with MS50 is 0.3 mgon and with TS 0.3 mgon at the first and 0.7 mgon at the second end point (from 10 repetitions).

Subsequently, the board was scanned in one face with a resolution of 0.37 gon. The atmospheric corrections were applied to the distance measurement.

The obtained point cloud of the object was approximated by a plain. Hence, for each point the IA was calculated as the angle between the normal vector of the plain and the sighting line under HzTLS and VTLS. The IA calculated in this way range from 0 to 55 gon. The point cloud was divided in 5-gon zones of IA and 7 points per zone were selected for further study of the distance.

Each selected point was staked out, the RL distance in the single mode DRL was measured and the point was signalised with a needle. Its position was determined from Hz, V measurements performed in two faces from the two TMS-stations. The points located in two zones were determined twice, in order to empirically determine the accuracy of the stacking out and of the reference measurement. A maximum deviation of the reference distance of 0.4 mm was obtained by this procedure.

The stability of the stations was monitored during the measurement process; first by collimation, secondly by repeated measurements to surrounding prisms, and third by repeated base determination.

Within a time interval of 2 months the measurements were performed with two different TLS+TS instruments using the same measuring setup and another measuring arrangement with a longer base of about 7 m as well.

b.Experiment at 30 m-long distance

The test object used in this case was a granite board with dimensions 0.40 x 0.40 x 0.03 m (width x height x depth), that has a smooth and a rough side (Fig. 2). It was placed nearly vertically on a Thorlabs board and fixed laterally. The Thorlabs board with weight of 30 kg and dimensions of 0.60 x 0.60 x 0.06 m is sufficiently stable for the granite board.

The different IAs were obtained by rotating the object around its vertical axis. For this purpose, an angular scale was used. The TLS+TS was installed on a pillar about 30 m away from the test object. The distance between the two theodolites (TS1 and TS2) forming the TMS was 2.4 m. The basis was placed at a distance of ca. 2 m from the object. The three instrument stations and the surrounding 8 prisms (Ri) mounted on consoles and pillars built the geodetic precision network.

The measurement campaign started with the determination of the precise network. During the entire campaign the three instruments remained mounted in tribrachs to avoid centering errors. Therefore, with each instrument (TLS+TS, TS1, TS2) the elements Hz, V, D were measured to the prisms while only Hz, V were measured to the other instruments by the collimation in 3 sets. TS1 and TS2 have a specified angular accuracy of 0.3 mgon, TS1 the distance accuracy of 2 mm + 2 ppm and TS2 1 mm + 1.5 ppm.

For each IA the granite board was scanned with a resolution of 0.0212 gon in one face. Just as in close range it was then approximated by a plain. At each IA among all scanned points 5 per position were selected on the basis of their distance to the adjusted plain. Each selected point was staked out and signalised in the HzTLS, VTLS direction. The 3D-position of the signalised point was determined in two faces with TMS. The granite board was aligned in steps of 10 gons in order to get IA between 0 and 60 gons. The influence of the IA was studied on both sides of the granite board. At IAs of 0, 45, 55 gons staking out and TMS-measurements were realised twice, in order to quantify the accuracy.

By means of measuring 4 points on the board before and after staking out it was verified if the position of the board remained unchanged during the staking out and reference measurement process (Fig. 2).

The stability of three stations was controlled by polar measurements to prisms and the Hz, V directions measurements between stations.

4. Post processing and results

The reference distances were determined from the highly accurate measurements. They meet the high precision requirement that is necessary in order to quantify the influence of the IA. Any systematic deviation affecting these measurements was first analysed. Based on this assessment the accuracy achieved for the reference range could be expressed. Furthermore, reference and TLS-distances were compared, the resulting distance differences were analysed and conclusions were drawn.

4.1.Investigation at close range

The reference distances are determined from the coordinates of the TLS+TS-zero point and of the selected object points. Errors that could possibly affect the obtained reference distance are listed in the Tab. 1. They were methodically eliminated or quantified and their impact was evaluated. Based on this research we conclude that the reference distance could be distorted systematically up to ca. 0.2 mm.

Tab. 1: Error influences on the reference distance determination in close range

Influence	Impact/Elimination
Stability of the theodolite	1.Repeated measurement of 5 prisms max. coordinate difference of 0.5 mm – within the accuracy of the measurement method; 2.Repeated collimation – emp. σ of 0.5 mgon 3.Repeated base determination σ of 0.1 mm, max. deviation of 0.3 mm Stable stations
Axes errors, eccentricity errors	Eliminated by measurements in two faces
Skewness of the trunnion axis	Min. impact at V directions from 95 to 105 gon
Collimation	emp. σ of 0.5 mgon, max. dev.1.2 mgon Max. impact on the reference distance 0.2 mm
Base determination	σ of 0.1 mm, max. dev. 0.3 mm
Hz, V – Scanning/Staking out	Max. dev. in Hz und V of 0.8 mgon Max. impact on the reference distance 0.02 mm no influence
Intersection angle	45-58 gon Measurement with another configuration with doubled base length no influence
Staking out/TMS	repeatability of reference distance σ of 0.2 mm

The a priori accuracy of the reference distance of 0.2 mm was obtained by simulation studies. This value conforms exactly to the empirical standard deviation of the reference distance, obtained from two independent repeated determinations of the reference distance in two zones.

The differences between the reference distances D_{TMS} and the corresponding distances in the scanning mode D_{TLS} are shown in Fig. 3. The illustrated differences vary systematically with the IA. The scanned distances are up to 3.0 mm longer than D_{TMS} in two intervals: 0-35 and 50-55 gon. In contrast, the distances are up to 4.4 mm shorter within the interval 35-50 gon. The shown systematic effect is physically or geometrically not-explainable. It was therefore assumed, that the obtained effect results from a superposition of the influence of IA with other effects in close range.

The systematic difference between the reference and the scanned distances was reproduced 1.5 months later with another instrument of the same type using the same configuration as well as a slightly modified configuration with a longer base (Fig. 3 a)).

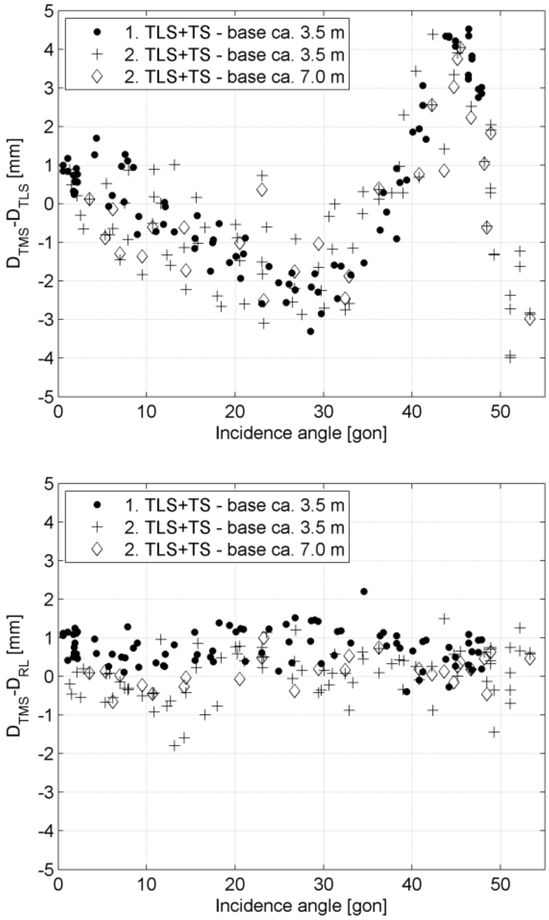

Fig. 3: Distance differences as function of the incidence angle
a) Differences between D_{TMS} and D_{TLS},
b) Differences between D_{TMS} –D_{RL}

If the systematic part of the distance deviation is split up using an appropriate approximating polynomial function, the stochastic properties in each zone of IA can be quantified. In this case, it is not relevant to express the precision as a function of the IA.

The differences D_{TMS}-D_{RL} show no systematic effects. The distance deviations are mainly in the interval of -1.0 mm to 1.5 mm, which corresponds to the manufacturer specification (Fig. 3b)).

To explain the occurred systematic effect in TLS-distance (Fig. 3a)) further analysis and experiments were performed. The conceptual connection of the investigations is:

a) Determination of the distance dependence.
b) Indication of the surface dependency.
c) Determination of the colour dependence.

In the experimental setup not only the IA varies, but also the distances. Therefore, the differences D_{TMS}-D_{TLS} were plotted as a function of distance in Fig. 4. Obvious distance dependence in the form of a cyclic oscillation can be noticed. However, this could not be a cyclic phase error because the instrument uses the time of flight method for distance measurements. To split up the influence of the distance a measuring arrangement with a fixed distance (minimal distance variation) and variable IA needs to be realised in the future.

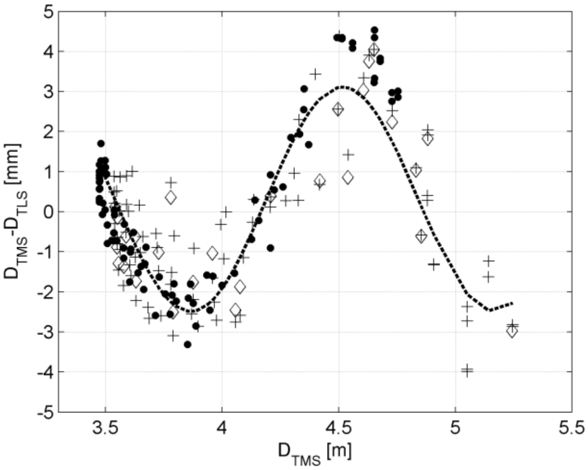

Fig. 4: Differences D_{TMS} - D_{TLS} as function of the distance

B) Material dependence

The RL-distances measured in the single mode showed a good agreement with the TMS-distances (Fig. 3b)). For this reason, the former are following used as a reference basis for comparison. The board and parts of the adjacent white concrete wall have been scanned.

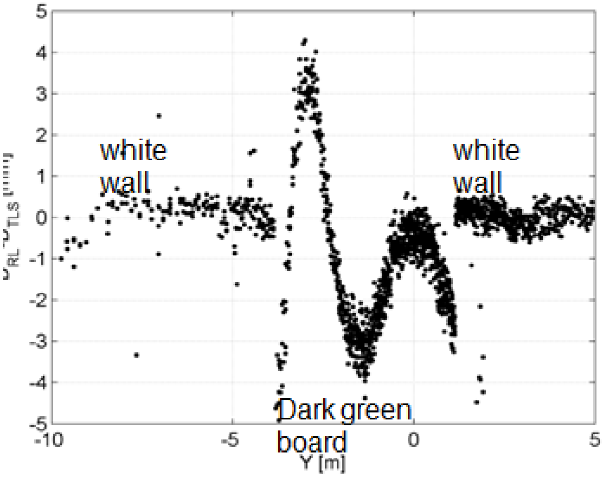

Fig. 5: Differences D_{TMS} - D_{TLS} as function of the material (Abscissa Y-coordinate, almost parallel to the board)

The distances to some points were measured in RL-modus. The differences between RL- and scanned distances are shown in Fig. 5 and indicate that the systematic effect is occurring only for the dark green board. Thus, the material dependence is evident. It should be noticed that the board has much lower reflectivity (8%) than thewall (90%) (empirically determined using Kodak gray card).

C) Dependency on the colour

Another board of the same colour and of another material consisting of a layer of glass and chipboard was examined as in the previous experiment. In addition, different light colours were applied with chalk. The systematic differences occur only in case of dark green surfaces (Fig. 6).

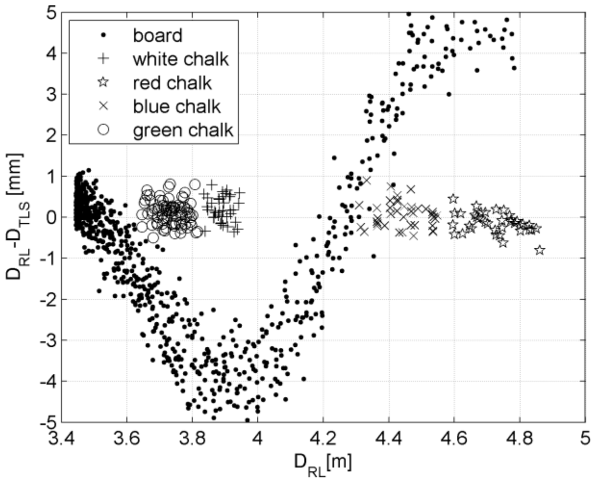

Fig. 6: Differences D_{TMS} - D_{TLS} as function of the distance, distances were measured to a surface of different colours

At the close range the systematic cyclic error effect influences TLS-distances. It occurs by scanning of dark green material.

4.2. Investigation at close range

The longer reference distances were determined in two steps. First the coordinates of the stations were determined by a free adjustment of the precision network. Actual instrumental parameters were considered, which were determined by the method of ISO17123-4 [7]. The accuracies obtained for the station positions are (maximum values) $\square_Y$ = 0.03 mm, $\square_X$ = 0.14 mm, $\square_Z$ = 0.02 mm. Secondly, the coordinates of object points were calculated using spatial forward intersection with the base formed by TS1 and TS2. The reference distances were obtained from the coordinates of the zero point of TLS+TS and the previously determined ones of the object points.

Errors in the network measurement, the staking out and the TMS measurement affect the determined reference distance. Their contribution to the accuracy of the reference distance is analysed and summarised in Tab. 2. The highest error influence is due to the stakeout. In our case, if the granite board rotates around the vertical axis, stakeout uncertainty in the horizontal direction directly affects the TLS-distance (e. g. a lateral deviation of 1 mm causes at an IA of 60 gon a distance error dD of 1.4 mm). This uncertainty is mainly caused by the thickness of the cross-hair and the magnification of the telescope. In future, the scale of the precise network e. g. the base should be controlled with high-precision measurement.

Tab. 2: Error influences on the reference distance at 30 m

	Influence		Impact/Elimination
Precision network	Points	Stability of stations	1.Repeated measurement of 8 prisms - max. deviation in a coordinate of 0.7 mm 2.Hz, V-measurement between instrument stations - max. V-deviation of 1.3 mgon - max. Hz- deviation from the sum of the interior angles of the triangle (TLS+TS, TS1, TS2) 1.1 mgon; - The individual Hz-directions vary within an interval of 2.5 mgon for TS1 and TS2, and of 0.9 mgon for TLS+ TS This results in a probable twisting of the Hz-circle (TS1 1.9 mgon, TS2 - 1.6 mgon); The internal geometry is preserved.
		Centering error - instruments	Instruments remain in tribraches, Hz and V-measurement through the collimation
		Centering error - prisms	Without removing
	Angle	Axes errors, eccentricity errors	Eliminated in two faces
		Skewness of the trunnion axis	Object points are measured under vertical angles of 111 - 116 gon Network points are measured under vertical angles of 83-102gon close to the horizon, lower impact
	Distance	Zero points errors	considered
		Scale error	potential for improvement
		Atmospheric corrections	considered
	Accuracy of station coordinate		max. σ_Y=0.03 mm, σ_X=0.14 mm, σ_Z=0.02 mm
Staking out		Hz, V – Scanning/Staking out	max. dev. 0.6 mgon, lateral deviation of 0.3 mm, distance deviation of 0.4 mm under IA of 60gon
		Repeatability of staked out and with TMS determined distance	One point was staked-out 12 times under an IA of 55 gon, and determined with TMS σ=0.29 mm
		Repeatability of staked out and with TMS determined distance	Twofold determination of the reference distances of 5 points under IA of 0,40,45,55,60 gon σ=0.05-0.51 mm
TMS		Accuracy of azimuth R_{TS1_TS2}	σ=0.1 mgon
		Accuracy of base	σ=0.07 mm
		Angle errors	As in the network
		Twisting of the Hz-circle at TS1 and TS2	Max. difference of the reference distance of 0.02 mm
		Board stability – before/after staking out	4 point were measured with TMS before and after staking out max. coordinate deviation of 0.05 mm
		Repeatability of the distance determination by TMS	1 point signalised with the needle once and measured 12 times by TMS σ=0.01 mm

The accuracy of the reference distance is calculated in the following way:

$$\sigma_{Ref} = \sqrt{\sigma^2_{Net\_TMS} + \sigma^2_{Stack}} \qquad (1)$$

, where

$$\sigma_{Stak} = \sqrt{\sigma^2_{Stack\_TMS} - \sigma^2_{TMS}} \qquad (2)$$

σ_{Net_TMS} – standard deviation of the reference distance (TLS+TS, Pi) derived with variance propagation law by taking into account full covariance matrix of the network adjustment (0.17 mm),
σ_{Stak} – empirical standard deviation of the staked out reference distance,
σ_{Stak_TMS} - empirical standard deviation of the repeatedly staked out and with TSM determined reference distance (0.05 – 0.51 mm),
σ_{TMS} – empirical standard deviation of the once signalised and repeatedly with TMS determined reference distance (0.01 mm);
The accuracy of the reference distance varies between 0.18 and 0.54 mm (Tab. 3)

Tab. 3: Standard deviation of the reference distance [mm]

IA [gon]	0	40	45	55	60
Rough surface	0.18	0.45		0.27	
Smooth surface	0.18	0.24	0.52	0.22	0.54

The individual distance differences for both sides of the granite board are shown in Fig. 7. In order to suppress the measurement noise, the distance differences per IA were averaged. The empirical standard deviations of a distance difference per IA reach values between 0.3 and 1.0 mm. The standard deviations of the mean values are between 0.1 to 0.4 mm. The averaged differences between the reference and TLS-distances at each IA are illustrated in Fig. 8. Comparing the mean values with their standard deviations we conclude according to the 3Sigma-rule (P = 95%) that the deviations are significant (Tab. 4).

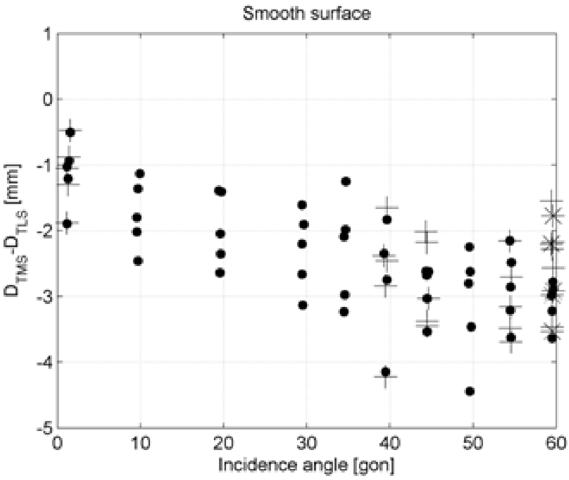

Fig. 7: Differences DTMS - DTLS as function of the incidence angle (repeated determination – cross, star)

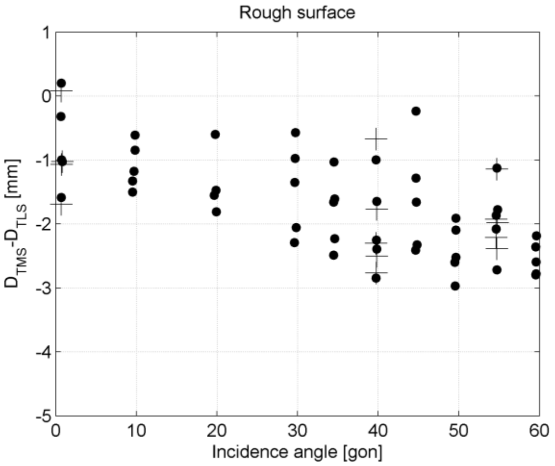

Fig. 8: Mean value of differences DTMS and DTLS per one incidence angle

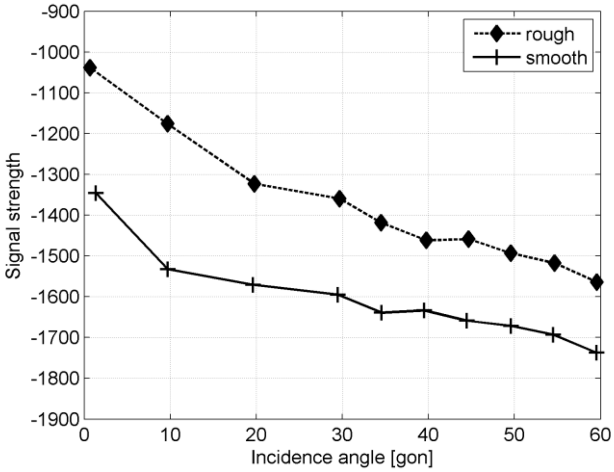

Fig. 9: Mean value of received signal strength by scanning to the rough and smooth surface of the granite board

The differences (Fig. 8) have a distance offset at IA 0 gon and vary systematically with the IA. At the rough surface of the granite board the TLS distance is 0.8 mm longer at IA 0 gon. This difference increases at larger IA up to 2.5 mm. The total variation of the distance difference with IA is of 1.7 mm. The smooth surface shows a similar behavior. At an IA of 0 gon the TLS distances are longer by 1.1 mm. At 60 gon the difference achieves 3.1 mm. Its total variation is of 2 mm. The significant offset (at the rough surface - not significant at P = 95%) in the case of IA=0 gon is surprising and needs further investigation. This IA is ideal for the RL measurement. The offset can be caused by other error influences on the RL distance measurement such as the reflectivity of the surface or the penetration of the laser [6].

Tab. 4: Mean value of distance differences DTMS and DTLS under a incidence angle and its standard deviation

IA [gon]	ΔD_{rough} [mm]	$\sigma_{\Delta Drough}$ [mm]	ΔD_{smooth} [mm]	$\sigma_{\Delta Dsmooth}$ [mm]
0	-0.7	0.3	-1.1	0.2
10	-1.1	0.2	-1.8	0.2
20	-1.4	0.2	-2.0	0.3
30	-1.4	0.3	-2.3	0.3
35	-1.8	0.3	-2.3	0.4
40	-2.0	0.3	-2.8	0.4
45	-1.6	0.4	-2.9	0.2
50	-2.4	0.2	-3.1	0.4
55	-1.9	0.3	-2.9	0.3
60	-2.5	0.1	-3.1	0.2

The obtained systematic variation of the distance differences is caused most probably by the influence of the IA on the TLS distance measurement. Higher IA lead to worse geometrical and physical conditions, resulting in greater distance distortion. As in the case of the close range investigation the variation of the differences is strongly correlated with the received signal strength (Fig. 9). Both, the distance differences and the received signal strengths are shifted (Fig. 8, Fig. 9). They also point to the influence of the surface roughness. The TLS-distances differences to the smooth surface are in average 0.7 mm longer than the ones for the rough surface.

In order to quantify the stochastic properties of the distances measured under various IA, we have assumed that the reference distances are more precise than DTLS. Under this condition, the systematic component should be separated and the standard deviations calculated with respect to the IA. However, in our experiment this basic assumption was not met. Thus, the stochastics of the distances among IA is not quantified. This lack of the presented methodology needs to be eliminated in future works.

5.Post processing and results

In this paper, a new method for investigation of the influence of IA on the TLS-distance measurement was presented. It is new and unique by comparing the directly measured TLS-distances to the reference in the areal acquisition. It is variable for distances of different lengths and was applied here for two ranges.

At close range of 3.5 to 5.2 m it was found out that other error effects are more pronounced than the influence of IA. A systematic cyclic distance-dependent effect up to 4.4 mm was detected at a material of dark green color with low reflectivity. Its physical cause needs to be clarified in the future. It has been shown that in the realised measurement arrangement with a fixed object, the variation of the investigated TLS-distances should be minimized or even eliminated. As a result, the object should not be fixed but rotatable.

At the distance of about 30 m, a systematic effect of the IA was found. For IA of 0 up to 60 gon, the TLS distances extend over 1.7 mm at the rough and 2 mm at the smooth surface of the granite board. The variation of the distance differences is closely related to the received signal strength. In addition, at IA of 0 gon a distance offset of -0.8 mm for rough surface and -1.1 mm for the smooth surface could be detected. The stochastic properties of the error influence could not be quantified because the reference distances are too noisy. From the realised investigation it can be concluded that the accuracy of the reference distance should be increased, especially the uncertainty of the staking-out should be minimized. For the determination of the stochastics the methodology could be added to repeat scanning of the object in the identical Hz and V grid. From the repeated distance measurements stochastic properties of the error influence can be obtained.

The first experiences show that the developed methodology for investigating the influence of the IA has great potential. In future works the methodology will be improved with respect to the above mentioned shortcomings. Only the complete answer to our research question enables a professionally competent handling of TLS-data.

References

[1] Kersten, T., Mechelke, K., Lindstaedt, M., Sternberg, H. (2008): Geometric Accuracy Investigations of the Latest Terrestrial Laser Scanning Systems. In: FIG Working Week, Stockholm.

[2] Lindstaedt, M., Kersten, T., Mechelke, K., Graeger, T., Sternberg, H. (2009): Phasen im Vergleich - Erste Untersuchungsergebnisse der Phasenvergleichsscanner FARO Photon und Trimble GX. In: Photogrammetrie, Laserscanning, Optische 3D-Messtechnik - Beiträge Der Oldenburger 3D-Tage 2009, Wichmann Verlag, Heidelberg, pp. 53–64.

[3] Mechelke, K., Kersten, T., Lindstaedt, M. (2007): Comparative Investigation into the Accuracy Behaviour of the New Generation of Terrestrial Laser Scanning Systems. In: Optical 3-D Measurement Techniques VIII., Zürich, pp. 319–327.

[4] Gordon, B. (2008a): Zur Bestimmung von Messunsicherheiten terrestrischer Laserscanner. Dissertation, Technische Universität Darmstadt.

[5] Gordon, B. (2008b): Diskussion von Feldprüfverfahren zur Messunsicherheitsbestimmung für terrestrische Laserscanner. In: Terrestrisches Laserscanning (TLS 2008), Schriftenreihe des DVW (54), Wißner Verlag, Augsburg, pp. 125–142.

[6] Zámečníková, M., Wieser, A., Woschitz, H., Ressl, C. (2014b): Influence of surface reflectivity on reflectorless electronic distance measurement and terrestrial laser scanning. Journal of Applied Geodesy, 8 (2014), 4, pp. 311–325.

[7] ISO17123-4 Optics and optical instruments - Field procedures for testing geodetic and surveying instruments - Part 4: Electro-optical distance meters (EDM measurements to reflectors)