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Methods for Geometric Accuracy Investigations of Terrestrial Laser Scanning Systems

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Summary: Currently the second, or for some manufacturers even the third, generation of terrestrial laser scanning systems is available on the market. Although the new generation of terrestrial 3D laser scanning systems offer several new (geodetic) features and better performance, it is still essential to test the accuracy behaviour of the new systems for optimised use in each application. As a continuation of previously published investigations the Department Geomatics of the HafenCity University Hamburg (HCU Hamburg) carried out comparative investigations into the accuracy behaviour of the new generation of terrestrial laser scanning systems (Trimble GX, Leica ScanStation 1 and 2, and Riegl LMS420i using time-of-flight method and Leica HDS6000, Z+F IMAGER 5006, and Faro LS880 HE using phase difference method). The results of the following tests are presented and discussed in this paper: test field for 3D accuracy evaluation of laser scanning systems, accuracy tests of distance measurements in comparison with reference distances, accuracy tests of inclination compensation, and influence of the laser beam's angle of incidence on 3D accuracy.

Zusammenfassung: *Methoden für geometrische Genauigkeitsuntersuchungen terrestrischer Laserscanningsysteme.* Die neueste Generation der terrestrischen 3D-Laserscanner bietet einige neue geodätische Eigenschaften und bessere Leistung. Dennoch ist es weiterhin sehr wichtig, das Genauigkeitsverhalten auch neuer Systeme zu testen, um sie optimal in verschiedenen Anwendungen einsetzen zu können. Standardisierte Prüfverfahren für terrestrische Laserscanner gibt es jedoch bisher heute noch nicht. Das Department Geomatik der HafenCity Universität Hamburg (HCU Hamburg) hat eigene Prüfverfahren entwickelt, die Aussagen über das Genauigkeitsverhalten terrestrischer Laserscannersysteme (TLS) erlauben. In diesem Beitrag werden Untersuchungen mit den Systemen Trimble GX, der Leica ScanStation 1 und 2, dem Riegl LMS-Z420i (alle mit Impulslaufzeitverfahren), sowie Faro LS880, Leica HSD 6000 und dem baugleichen IMAGER 5006 von Zoller + Fröhlich (alle mit Phasendifferenzverfahren) vorgestellt. Streckenvergleiche im 3D-Testfeld und auf einer Vergleichsstrecke, sowie Genauigkeitstests der Neigungssensoren und Untersuchungen zum Einfluss des Auftreffwinkels des Laserstrahles auf die 3D-Punktgenauigkeit wurden durchgeführt. Die erzielten Ergebnisse bestätigen weitestgehend die technischen Spezifikationen der Systemhersteller.

1 Introduction

Terrestrial laser scanning (TLS) systems have been available on the market for about ten years and within the last five years the technology has become accepted as a standard method of 3D data acquisition, finding its position on the market beside established methods such as tacheometry, photogrammetry and GPS. Terrestrial laser scanning also stands for a paradigm change "from the representative single point to the exact and highly detailed 3D point cloud" (Staiger & Wunderlich 2006). Advanced technology and new features of 3D laser scanners have been developed in the past two years, introducing additional instrument features such as electronic levels, inclination compensation, forced-centring, on the spot geo-referencing, and sensor fusion (e. g., digital camera and GPS). Most of these elements are obviously equivalent to features that can be seen in total stations. Several au-

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thors have already reported on different approaches for investigations into terrestrial laser scanning systems. Nevertheless, standardized test and calibration methods of laser scanning systems do not yet exist for the user.

Due to the huge variety of types of terrestrial laser scanners it is difficult for the user to find comparable information about potential and precision of the laser scanning systems in the jungle of technical specifications and to be able to validate the technical specifications, which are provided by the system manufacturers. Thus, it may be difficult for users to choose the right scanner for a specific application, which emphasises the importance of comparative investigations into accuracy behaviour of terrestrial laser scanning systems.

Therefore several groups, primarily university-based, carried out geometrical investigations into laser scanning systems in order to derive comparable information about the potential of the laser scanners and to find practical testing and calibration methods (Boehler et al. 2003, Ingensand et al. 2003, Johansson 2003, Clark & Robson 2004, Schulz & Ingensand 2004, Lichti & Franke 2005, Rietdorf 2005, Neitzel 2006, Reshetyuk 2006, Büttner & Staiger 2007, Schulz 2007, Wehmann et al. 2007, Gordon 2008, Gottwald 2008, Kern 2008, Gottwald et al. 2009). The department Geomatics of the HafenCity University Hamburg (HCU Hamburg) validates terrestrial laser scanners since 2004, in order to develop their own testing and evaluation methods (Kersten et al. 2004, Kersten et al. 2005, Sternberg et al. 2005, Mechelke et al. 2007, Mechelke et al. 2008), which allow statements about the accuracy behaviour and about the application potential of terrestrial laser scanner systems to be made.

2 The Terrestrial Laser Scanning Systems Used

The investigations into the accuracy behaviour of terrestrial laser scanners were carried out by using the following laser scanning systems: Trimble GX, Leica ScanStation 1, Leica ScanStation 2, Leica HDS 6000, Faro LS 880, IMAGER 5006 from Zoller & Fröhlich, and RIEGL LMS-Z420i (cf. Fig. 1).

The technical specifications and the important features of these laser scanners are summarised in Tab. 1. The tested scanners are panoramic scanners, but they represent two different distance measurement principles: Faro LS880, Z+F IMAGER 5006, and Leica HDS6000, which is structurally identical with the IMAGER 5006, use phase difference method, while Leica ScanStation 1/2, Trimble GX, and Riegl LMS-Z420i scan with the time-of-flight method. In general it can be stated that phase difference method is fast, but signal to noise ratio depends on distance range and lighting conditions. If one compares scan distance and scanning speed in Tab. 1, it can be clearly seen, that scanners using the time-of-flight method measure longer distances but are relatively slow compared to the phase difference scanners. Trimble GX and both Leica ScanStation instruments scan with a green laser beam (532 nm), while the other three scanners use laser light with wavelengths at near infrared. The precision (internal accuracy) of the scanning instrument is not unitarily specified in the specifications of the manufacturer, i. e., some uses the 3D position and some the distance as a precision criterion.

Most of the presented investigations use spheres as test bodies to obtain the reference positions. The diameters of the used spheres

Fig. 1: Terrestrial laser scanning systems for investigation at HafenCity University Hamburg: Trimble GX, Leica ScanStation 1 and 2, Riegl LMS-Z420i, Faro LS 880HE, IMAGER 5006 from Zoller & Fröhlich, and Leica HDS6000.

are 76.2 mm, 145 mm, and 199 mm, respectively. The materials in the spheres are solid plastic for the small diameter (76.2 mm) and hollow plastic with a special surface coating and centring option for the larger spheres (145 mm & 199 mm). These spheres are of matt white colour and are checked for eccentricity and exact diameter. To obtain centre positions of the spheres, each point cloud representing the sphere was manually corrected for outliers. The fitting of the sphere geometry was performed for each scanner station using algorithms in the Trimble software RealWorks Survey and 3Dipsos, where the radius of the sphere was fixed with the known value. The algorithm for sphere fitting used by the Trim-

Tab. 1: Summary of technical specifications (according to system manufacturer) of the tested laser scanning systems.

Scanner/Criterion		**Trimble GX**	**Leica ScanStation 1**	**Leica ScanStation 2**	**Riegl LMS-Z420i**	**FARO LS 880 HE**	**Z+F IMAGER 5006 / HDS 6000**
Scan method		Time-of-flight				Phase difference	
Field of view [°]		360×60	360×270	360×270	360×80	360×320	360×310
Scan distance [m]		350	300	300	2–1000	0,6–76	< 79
Wavelength [nm]		532	532	532	~1500	785	658
Scanning speed [pts/sec]		≤ 5000	≤ 4000	≤ 50000	≤ 11000	120000	≤ 500000
Angular resolution [°]	V	0,0018	0,0023	0,0023	0,0020	0,00900	0,0018
	H	0,0018	0,0023	0,0023	0,0025	0,00076	0,0018
Spot size at 10 m		0,6 mm	4,0 mm	4,0 mm	2,5 mm	2,5 mm	3,2 mm
Precision	position	12 mm/ 100m	6 mm/ 50 m	6 mm/ 50 m	–	–	10 mm/ 50m
	distance	7 mm/ 100 m	4 mm/ 50 m	4 mm/ 50 m	10 mm/ 50 m	3 mm/ 25 m	6 mm/ 50 m
Camera		integrated			add-on option		
Inclination sensor		compensator				yes	yes

Fig. 2: 3D test field at the HafenCity University Hamburg for geometrical investigations into TLS systems.

ble software has not been published. These results of the fitting were compared to results of a MATLAB routine on a random basis. The programmed MATLAB software uses the sphere fitting algorithm as described by Drixler (1993). Since there were no differences in the centre coordinates of the spheres, the Trimble software continued to be used for all fitting tasks due to simplified data handling. The standard deviation for sphere fitting was in the range of 0.4 – 1.0 mm for the test field investigations (cf. Section 3.1), although some deviations increased to 6.0 mm dependent on distance length and sphere diameter.

3 Geometric Investigations

3.1 *3D Test Field for Accuracy Evaluation of 3D Laser Scanning Systems*

Referring to the guidelines in part 2 and part 3 of the VDI/VDE 2634 (VDI/VDE 2634 2002) the accuracy of 3D optical measuring systems based on area scanning shall be evaluated by checking the equipment at regular intervals. This can be achieved by means of length standards and artefacts, which are measured or scanned in the same way as typical measurement objects. One important quality parameter can be defined as sphere spacing error similar to that in ISO 10 360 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 2007). Instead of calibrated artefacts in object space reference distances between spheres were used for the accuracy evaluation at HCU Hamburg. However, the precision of 3D laser scanning systems is composed of a combination of errors in distance and angle measurements, and in the algorithm for fitting the spheres/targets in the point cloud. The influence of these errors is difficult to determine independently and this causes issues when the goal is the testing of the whole system (hard- and software). However, in metrology, the accuracy of measurements is affected by the impacts of all random components and systematic errors. For the following evaluations accuracy is defined as a measure to an independent reference.

A durable established 3D test field was used in the hall of building D at the HCU campus (cf. Fig. 2) for test campaigns in March, October and December 2007. This was used in order to evaluate the 3D accuracy of distance measurements derived from the sphere coordinates and of point cloud registration regarding the practical acceptance and verification methods of VDI/VDE 2634. The volume of the test field is 30×20×12 m^3, including 53 reference points, which can be set up with prisms, spheres or targets. Just 38 (in March) and 30 points (in October/December) were used for these investigations. The points are distributed over three hall levels on the floor, on walls or on concrete pillars using M8 thread holes. The reference points were measured from four stations with a Leica TCRP 1201 total station. In a 3D network adjustment using the software Leica GeoOffice the station coordinates were determined with a standard deviation of less than 0.5 mm, while the standard deviation of

Tab. 2: Comparison of 3D distances (all in all combination (left) and seven selected distances (right)) between laser scanner and reference in the 3D test field (tests in March 2007).

Scanner	# 3D points	# dist.	Δl_{min} [mm]	Δl_{max} [mm]	span [mm]	syst. shift [mm]	$\lvert\Delta l\rvert$ [mm]	# dist.	Δl_{min} [mm]	Δl_{max} [mm]	span [mm]
Leica ScanStation 1	38	703	− 9.2	2.3	11.5	−3.6	**3.6**	7	−5.6	1.6	7.2
Trimble GX	38	703	−27.6	16	43.6	−5.5	**6.5**	7	−5.9	−1.8	7.7
Z+F IMAGER 5006	38	703	− 6.6	7.4	14.0	0.3	**1.8**	7	−2.1	3.3	5.4
Faro LS 880 HE	38	703	−30.7	41.1	71.8	0.1	**5.0**	7	−3.5	29.9	33.4

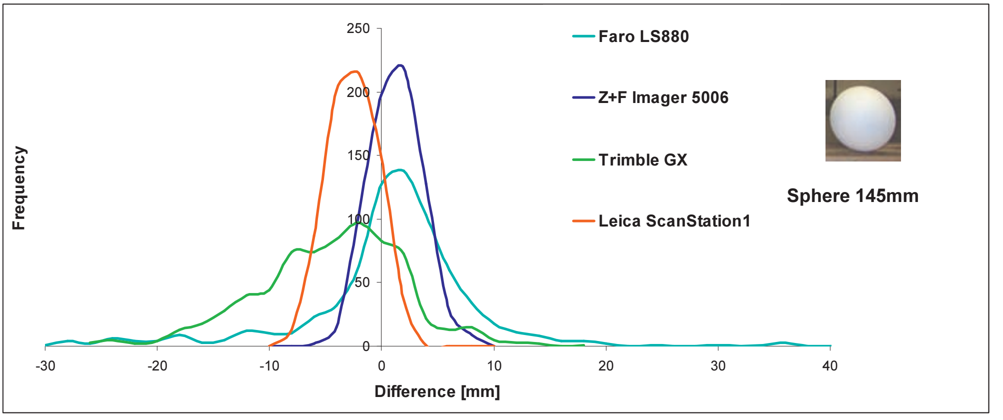

Fig. 3: Distribution of differences (2 mm interval) between scanned distances and reference distances for four tested terrestrial laser scanner (test campaign in March 2007).

the coordinates of the reference points is less than 1 mm (local network). Specially built adapters of the same length as those used with the prisms guaranteed a precise, stable and repeatable set up of spheres. Thereafter, spheres with a diameter of 145 mm (in March 2007) and 199 mm (in October and December 2007) were installed on these reference points. These spheres were scanned with all tested scanners from five scan stations for each system, where two scan stations were located on the ground floor, two on the first floor and the fifth station was placed on the second floor, so that a good geometric configuration for point determination could be guaranteed. For evaluation, all combinations of distances between all reference points were compared to those obtained from the centres of the fitted spheres derived from the registered point cloud. In accordance with the guidelines of VDI/VDE 2634 part III all scan stations were transformed into one common object coordinate system for each laser scanner using the determined coordinates of each sphere centre. The sphere-spacing error Δl is determined by $\Delta l = lm - lk$, where m is measured and k is the reference distance. Additionally, the mean value of all absolute values $|\Delta l|$ (sphere spacing error) has been determined according to Heister (2006). The minimum distance is 1.5 m and the maximum distance is 33.1 m in the test field, which is within the scanning range of each tested scanner.

Two results of the 3D test field investigations from the March 2007 test campaign are shown in Tab. 2: (a) all differences between scanned and reference distances for all stations (registered in one common object coordinate system using the sphere centre coordinates for transformation), and (b) the differences between scanning and reference of seven selected well-distributed distances (same distances for all scanners) are summarised as the span ($\Delta l_{max} - \Delta l_{min}$) from minimum to maximum deviation value as an indication of the accuracy of each system. The differences between the distances in case (a) are highly correlated, while the distances in case (b) were selected as proposed in the VDI/VDE 2634, and to avoid these correlations. Instead of seven distances, Heister (2006) proposed eight spatial distances in the object for this test. This range value Δl is influenced by the measurement precision of the instrument and by the algorithm for the fitting of the sphere. Since the fitting with the Trimble software has been checked as previously mentioned, errors in sphere fitting can be excluded. The best result was a range from minimum to maximum of 11.5 mm for all differences, which was achieved with the Leica ScanStation 1, while for the IMAGER 5006 a span of 5.4 mm was obtained using the seven differences of distances (see Tab. 2). The three scanners ScanStation 1, GX und IMAGER 5006 show similar accuracy behaviour (between 5 and 8 mm) using the same seven distances, while the Faro

Tab. 3: Comparison of 3D distances (all in all combination (left) and seven selected distances (right)) between laser scanner and reference in the 3D test field (Oct./Dec. 2007).

Scanner	# 3D points	# dist.	Δl_{min} [mm]	Δl_{max} [mm]	span [mm]	syst. shift [mm]	$\|\Delta l\|$ [mm]	# dist.	Δl_{min} [mm]	Δl_{max} [mm]	span [mm]
Leica ScanStation 1	27	351	−6.4	5.4	11.8	−0.7	**1.8**	7	−3.1	1.6	4.8
Leica ScanStation 2	28	378	−8.6	4.8	13.4	−2.2	**2.6**	7	−4.3	−2.3	6.6
Riegl LMS420i	27	351	−6.5	19.8	26.3	6.3	**6.5**	7	2.5	12.8	10.3
Leica HDS6000	29	406	−6.3	6.7	13.0	0.2	**2.0**	7	−2.4	2.4	4.8
Z+F IMAGER 5006	29	406	−7.7	5.7	13.4	−0.4	**2.1**	7	−4.4	1.6	6.0

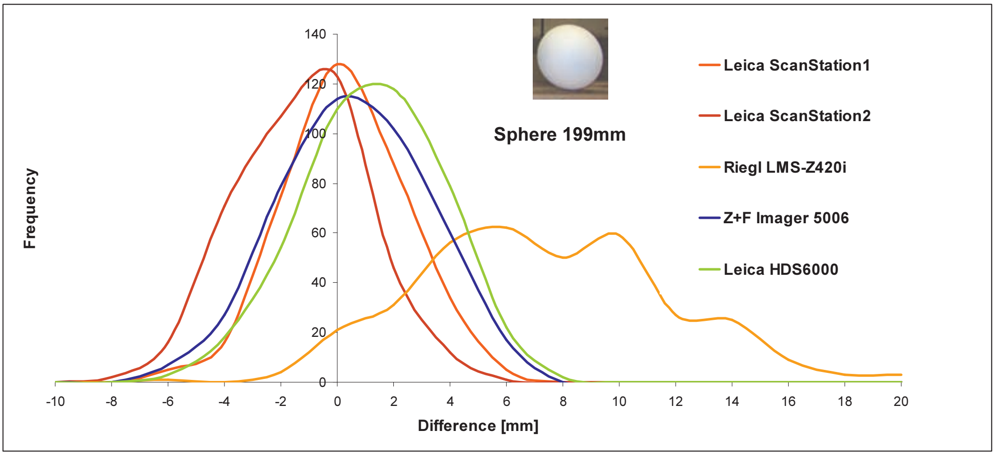

Fig. 4: Distribution of differences (2 mm interval) between scanned distances and reference distances for five tested terrestrial laser scanner (test campaign in October and in December 2007).

scanner is significantly worse. In contrast to these good results the spans of the Trimble GX and Faro scanners show huge values of 43.6 mm and 71.8 mm, respectively (cf. Tab. 2), using all differences, which demonstrates that these scanners obviously have problems with some 3D distances. In an earlier investigation, which is not published, a significantly better result (span min/max = 17.3 mm) was achieved with the Trimble GS100, the predecessor model of the GX. The average value of all differences was less than +1 mm for Faro and Z+F scanner, while this value was -3.6 mm for Leica ScanStation 1 and -5.5 mm for Trimble GX scanner, which indicates a systematic shift and which is clearly illustrated in Fig. 3. Currently, these systematic shifts cannot be explained. As demonstrated in Tab. 2 the sphere spacing error ($|\Delta l|$) is very good for IMAGER 5006 with 1.8mm, while this error is worse by a factor 3–4 for Faro LS880 (5.0 mm) and Trimble GX (6.5 mm).

The results of the subsequent 3D test field investigations in October and December 2007 for the five scanners Leica ScanStation 1 and 2, Leica HSD6000 and IMAGER 5006, and Riegl LMS-Z420i are summarised in Tab. 3. In these test field investigations spheres with a diameter of 199 mm were used since significantly more measured points were achieved on each sphere over longer distances when compared to the smaller spheres. These results confirm the previous results from March 2007, where the span ($\Delta l_{max} - \Delta l_{min}$), which was obtained with the Riegl scanner, is slightly worse, but better than the span for GX and Faro LS880. Again, two scanners (Leica ScanStation 2 and Riegl) show a systematic shift in the deviation from the reference (cf. Tab. 3), which is also illustrated in Fig. 4. On the other hand the systematic shift, which was computed for the Leica ScanStation 1 in March 2007 (cf. Tab. 2), could not be confirmed with a different Leica ScanStation 1 in the investigation of October 2007 (see Tab. 3). As shown in Tab. 3 the sphere spacing error |Δl| is very good for both ScanStations (1.8 mm/2.6 mm), for HDS6000 (2.0 mm) and for IMAGER 5006 (2.1 mm), while this error is worse by a factor 3 for Riegl LMS420 (6.5 mm). However, in general the results of the IMAGER 5006 (and HDS6000) are very similar for both independent test campaigns in March and October 2007, which is also a confirmation of the reliability of the approach used.

Better results of the span ($\Delta l_{max} - \Delta l_{min}$) and of the sphere spacing error have been achieved for Leica HDS6000 (3.5 mm/1.8 mm) and Faro LS880 (8.9 mm/2.0 mm) by Kern & Huxhagen (2008) using a test field with short distances between 0.9 m and 3.5 m for spheres with a diameter of 76.2 mm. The number of reference distances used for this test is not published. Gordon (2008) used a test field with the dimensions of 12.5 m×5 m×3.5 m with 37 spheres for the IMAGER 5003. In this test slightly worse results have been obtained for the span: 17.8 mm using 666 distances with 37 spheres and 15.6 mm for 8 sphere distances.

3.2 *Accuracy Tests of Distance Measurements in Comparison to Reference Distances*

Accuracy tests of distance measurements using reference distances derived from a precise total station were performed in an outdoor environment for distance ranges from 10 m to 100 m in steps of 10 m (targets on a tripod) for Trimble GX, Leica ScanStation 1, Faro LS 880HE and for Z+F IMAGER 5006 in March 2007. Reference distances were measured with a Leica TCRP1201 10 times before and 10 times after the scanning using averaging distance measurement mode. The differences between the first and second measurement sequences were less than 0.3 mm. A standard deviation of 0.1 mm was achieved for the reference distances. Since all tested scanners use Wild-type forced-centring, it was possible to exchange prisms for scanner targets. By using special adaptors the centre of the scanner target could be placed in the same position as the prism centre.

All scanning distances for Faro LS880 and IMAGER 5006 were derived from scanned spheres with a diameter of 145 mm, while for Leica ScanStation HDS targets and for Trimble GX green flat targets were used. For repeatability and reliability reasons each distance to sphere or target was scanned three times in the sequence forward-backward-forward with each scanner from the same position. Due to the limitation of scanning range Faro LS880 scans were checked to the dis-

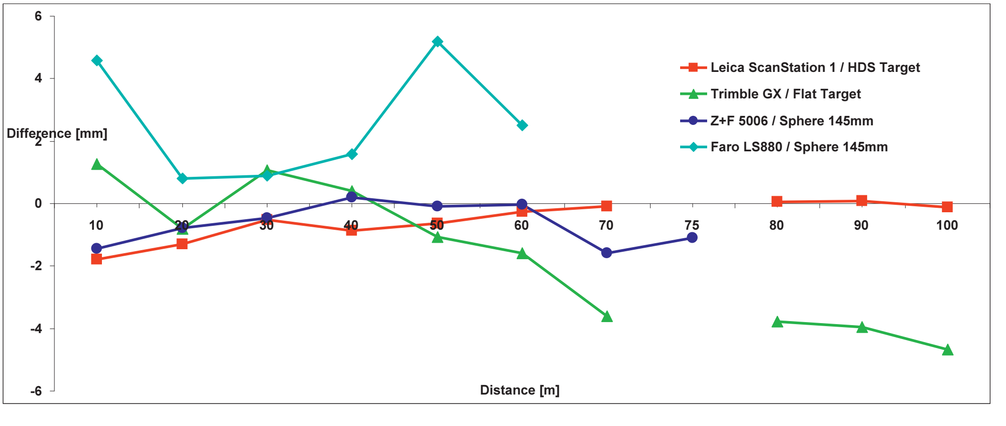

Fig. 5: Comparison of the differences between scanning and reference distances (campaign March 2007).

tance of 60 m and IMAGER 5006 scans to 75 m. All major results of this accuracy test are illustrated in Fig. 5. This figure clearly indicates that the differences between the Leica ScanStation and IMAGER 5006 and the references distances are always less than 2 mm, while for the Trimble GX the differences are also less than 2 mm between 10–60m, but from 70 to 100 m distance the differences increased to a systematic effect of 3–5 mm. The differences between the Faro LS880 scans and the reference were in the range of 1–5 mm. Although Faro LS880 and Z+F IMAGER 5006 are capable of measuring up to 80 m, it must be stated that even with the highest resolution the number of 'hits' on the 145 mm sphere is not high enough for distances beyond 50 m to allow precise fitting of sphere geometry. Additionally, in several practical outdoor tests it was notable that signal to noise ratio rises depending on daylight conditions for longer distances.

Due to the long range of the Leica ScanStation 2 and the Riegl LMS-Z420i the investigations into the accuracy of distance measurements were carried out with a different setup on the official baseline of the city of Hamburg in Ohlsdorf, which consists of seven granite columns and covers a distance range up to 430 m. For these investigations additional points in 10 m intervals were integrated on a tripod for the distance range up to 75 m. All reference distances were measured by a precision total station Leica TCA2003. These determined reference distances deviated on average by ± 0.5 mm from distances which were measured with a high precision Kern Mekometer 5000 before these investigations.

The scans of the ScanStation 2 to different targets (HDS flat blue target, HDS black/white target as well as spheres with a diameter of 199 mm) were controlled using the software Leica Cyclone 5.8. The spheres used are plastic hollow balls with a special surface coating and centring option, which were developed at the HCU. All scans were executed with active inclination compensation and distance corrections for atmospheric pressure and temperature, whereby each target was scanned four times. The respective sphere centre coordinates were computed automatically in Cyclone and averaged afterwards in order to compare the scanned horizontal distances with the reference distances (cf. Fig. 6).

As a result, indicated in Fig. 6, a scale factor of approx. +65 ppm can be derived for the ScanStation 2. In the scan range under 100m measurements to the HDS flat targets show the smallest residuals (< 5 mm), while over 100 m distance the measurements to the spheres indicate the best results (residual of max. 12.5 mm to a distance of 287 m). It can be

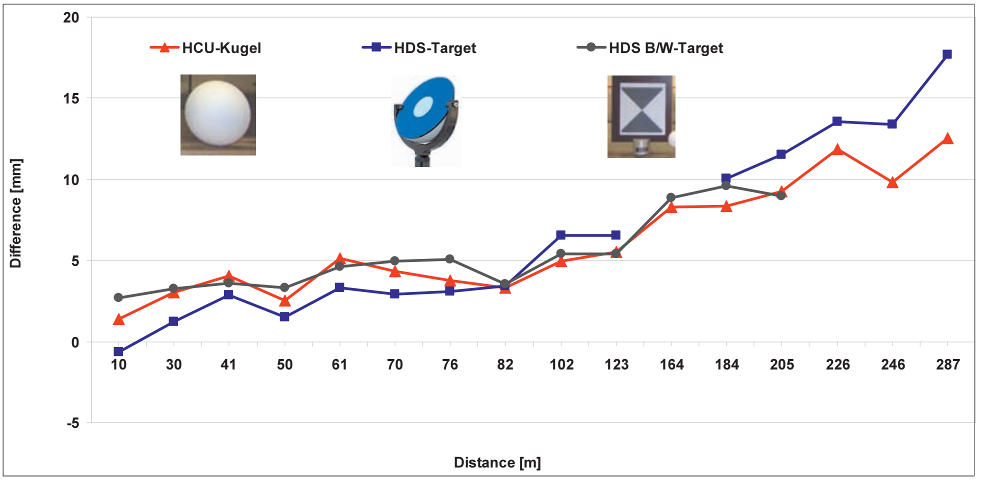

Fig. 6: Comparison of the differences between scanning and reference distances for the Leica ScanStation 2 (test campaign in October 2007).

Fig. 7: Comparison of the differences between scanning and reference distances for the Riegl LMS 420i using the reflective target (test campaign in December 2007).

assumed that the fitting algorithm is positive affected by the larger sphere surface compared to the HDS flat blue target. For the measurements to black/white targets the fitting algorithm of Cyclone could only supply a result up to a distance of 205 m. This scale factor is affected by the targets/spheres being too small in relation to the long scan distances (over 200 m). Larger targets/spheres would probably yield better results. Therefore other ScanStations 2 should be tested for the presence of the same problems.

The results of the investigations into the scanning accuracy of the Riegl LMS-Z420i scanner using the reflective target (size 50 mm), which was scanned three times for each position, are illustrated in Fig. 7. The differences between scanning distance and reference are in the range of ±5 mm for distances up to 205 m, but for distances over 205 m the target used was too small to derive reliable results from these scanned distances. Thus, the target size must be adapted to a larger size (e. g., 100 mm) for scanning longer distances in future tests. Tauber (2005) could achieve similar results on the baseline of the Leibniz University Hanover using the Riegl LMS 360i.

The accuracy investigations into the tested laser scanning systems clearly demonstrated that the systems meet the technical specifications of the manufactures for distances up to 200 m.

3.3 *Accuracy Tests of Inclination Compensation*

All scanners in the test programme are equipped with an inclination sensor (see also Tab. 1), making it possible to level the scanner during measurements. Leica ScanStation 1/2 and Trimble GX are able to compensate for changes of main axis inclination during measurement, while Faro LS 880 uses corrections only for post-processing (in the registration of scans). The Z+F IMAGER 5006 uses the inclination sensor for gross error detection to indicate changes during the scanning, and for corrections of the scanned data in the post processing. If the inclination sensor is switched on during the scanning process, it is assumed for the time-of-flight scanners that the XY-plane of the scanner coordinate system is horizontal.

In order to check the accuracy of inclination compensation of each scanner, an outdoor test field was established using 12 spheres in steps of 30° on the circumference of a circle with a radius of 50 m. Each sphere was set up on a pole and was adjusted to the same height by using a Wild N3 high-precision level instrument, while the tested scanners were set up in the centre of the circle on a heavy-duty tripod (cf. Fig. 8). While scanning the spheres, it is assumed that the centre coordinates of the fitted geometries (spheres) lie in-plane and that this plane is horizontal (Z = constant). To check for movements of the scanner tripod during scanning, a Leica Nivel20 inclination sensor was fixed to the tripod, recording inclination in x and y direction in intervals of 5

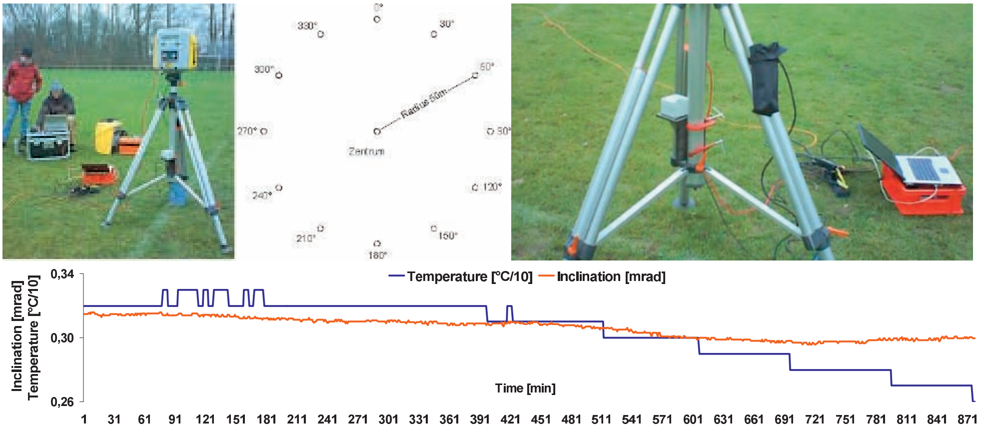

Fig. 8: Test field for inclination compensator of the terrestrial laser scanner: scanner on solid tripod (left), schematic test configuration for scanner and spheres (centre), inclination sensor Leica Nivel20 fixed at the scanner tripod (right) and illustration of tripod movement derived from Nivel20 measurements over the test period of more than 871 minutes (bottom).

seconds. The recordings of the Nivel20 showed no significant movements of the tripod during scanning (cf. Fig. 8).

Each sphere was scanned consecutively three times (March 2007) and five times (October and December 2007) with the highest possible resolution settings. The fitting of sphere geometries was performed using Trimble RealWorks Survey 5.1. Before sphere fitting, outliers were removed manually from the point cloud. The derived average Z-coordinates of all fitted spheres were compared to the reference horizontal plane for each scanner. Differences in Z vs. the reference plane were obtained from the average Z-coordinate of each position in the circle and are shown in Fig. 9. This is a clear indication that the compensation of inclination works almost perfectly for all tested time-of-flight scanners, while for the phase difference scanner it can be seen that scanning has been conducted in an inclined plane.

Leica and Trimble scanners show maximum deviations of 2 mm with a very minor sine oscillation, probably resulting from calibration error of the inclination sensor (cf. Fig. 9 top). Faro LS880 shows huge differences up to 15 mm, which may be influenced by the comparably low resolution (8 mm / 50 m) and the large signal to noise ratio of this scanner. The behaviour of the IMAGER 5006, tested in March with spheres with a diameter of 145 mm and in October 2007 with spheres with a diameter of 199 mm, is almost identical and is very similar to the Faro LS880. These effects are influenced by a slight inclination of the rotation axis. In Fig. 9 (bottom) differences from an average plane fitted through the centre coordinates of the spheres are shown. Since all spheres were positioned on a plane, differences should be zero. The resulting differences may be interpreted as effects of a tumbling error of the trunnion axis, but especially for the Faro and Z+F scanners the results are influenced by the sphere fitting error due to the scanning noise on the longer distances. Further investigations have to be performed with bigger targets and/or smaller radius of circle to guarantee sufficient numbers of scanned points on the spheres for reliable and precise sphere fitting, especially for phase difference scanners with limited scan distances.

Fig. 10 (left) shows a sine oscillation resulting from an inclined vertical axis when the inclination compensation of the Leica ScanStation 2 is switched off. The magnitudes of the amplitude following the 360° rotation depend on the inclination angle. When inclination compensation is switched on, the graph shows very minor deviations of better than 1mm for the z coordinate vs. the horizontal plane (cf. Fig. 10 right). Since these results are very similar to the previous tests using Leica ScanStation 1 and Trimble GX (cf. Fig. 9 top), it can be stated that the dual axis (tilt) compensator of the scanners with the time-of-flight method almost perfectly adjusts for changes of inclination during scanning.

3.4 *Influence of the Laser Beam's Angle of Incidence on 3D Accuracy*

Among other effects the accuracy of a point cloud is dependent on the angle of incidence of the laser beam. Reasons for this effect are the spot size and shape of the laser beam and the reflectivity of the object. The shape and its centre position influences the reflectance of the laser beam, which affects the precision of the scanned distance, and the 3D position of a scanned point within the point cloud. To evaluate the influence of the laser beam's angle of incidence on 3D accuracy of the point cloud a planar white stone slab with a dimension of 75×79 cm^2 (cf. Fig. 11 centre) was mounted in a metal frame and could be swivelled in this

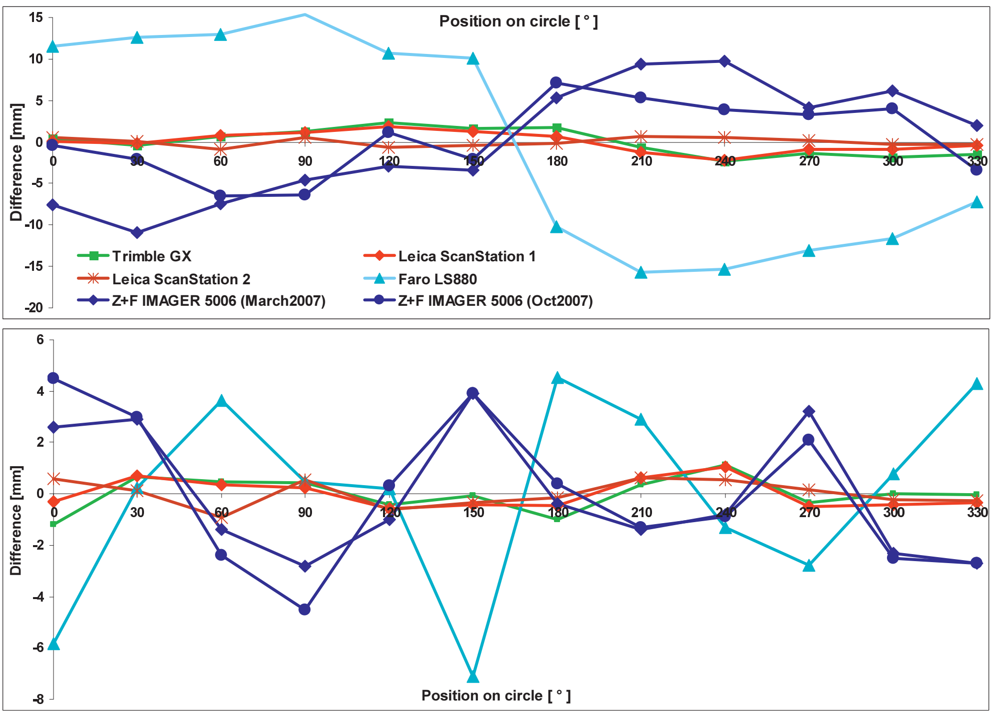

Fig. 9: Test of inclination sensor in comparison: Differences between scanned spheres and horizontal XY plane (top), and average XY plane (bottom).

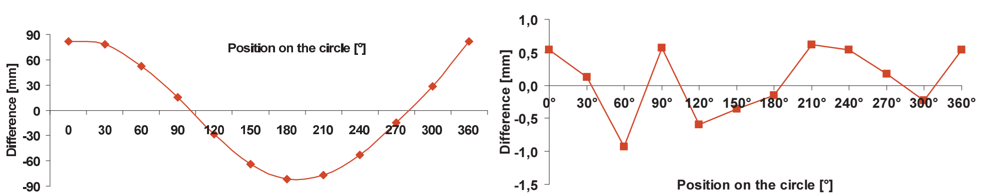

Fig. 10: Leica ScanStation 2: Differences vs. horizontal plane (z-coordinate) for switched off compensator (left) and active inclination compensator (right). Note the difference in y-scale between the two graphs.

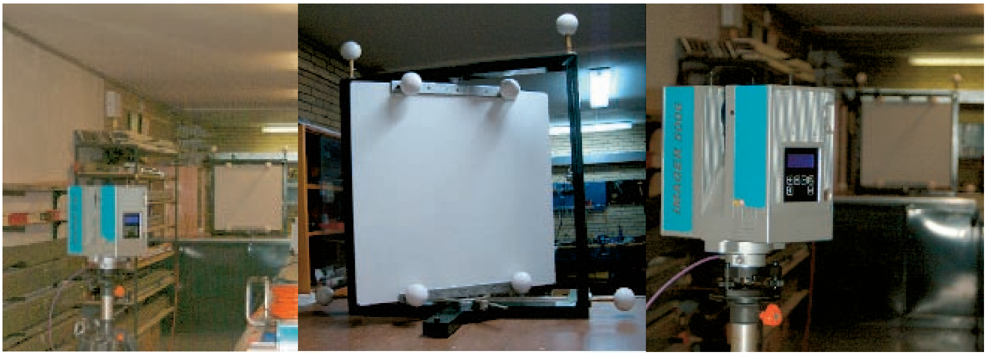

Fig. 11: Scanning set up for the investigations into the laser beams angle of incidence on 3D accuracy with swivelling planar white stone slab (centre).

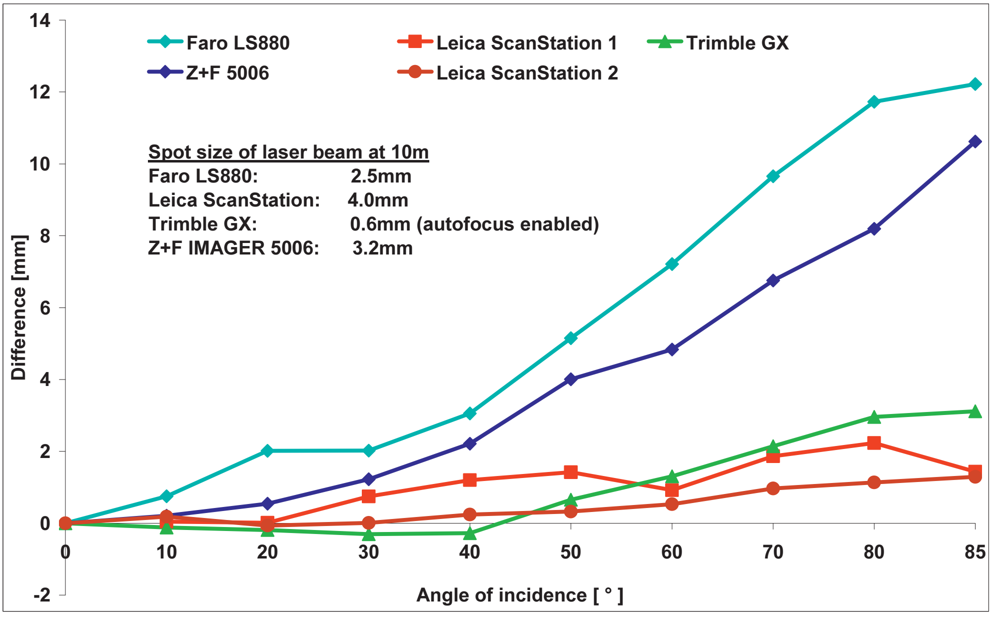

Fig. 12: Influence of angle of incidence on 3D accuracy in comparison.

frame. The frame was equipped with a reading device to set the stone slab at defined angular positions with a precision of 5'. Additionally, four spheres (radius 38.1 mm) were fixed on the stone slab, thus swivelling together with the stone slab. The stone slab and the spheres were scanned with a resolution of 3 mm at an object distance of 10 m. In total, ten scans were acquired in angular positions of the stone slab from 90° to 5°. Each plane, which was fitted in the resulting point cloud of the stone slab, was compared to reference points.

Since the angular position of the stone slab has no effect on the point cloud of the spheres, the centres of the spheres were selected as reference points for each position. Thus, the distance between the centre of the sphere and an average plane fitted through the point cloud representing the stone slab should be constant in an ideal case for each angular position of the stone slab. Nevertheless, it can be observed in Fig. 12 that the distance between the centres of the spheres and the computed plane increases with an increasing angle of incidence. The time-of-flight scanners show minor effects of up to 3 mm for an angle of incidence of 80°–85°, while the phase difference scanners achieve difference values of up to 12 mm for the same angle. But generally, it can be stated that if the angle of incidence is more than 45°, significant influence on the accuracy of the point cloud can be expected. The conditions in the test environment were the same for all scanning systems. But to achieve results for comparison with other test environments, the spectral reflectance of the stone slab should be determined in relation to the wavelength of the laser beam. Additionally, further investigations are still necessary to check the influence of angle of incidence for longer object distances.

4 Conclusions and Outlook

The major results of different tests using the current instruments of the new generation of terrestrial laser scanners are summarised in this paper. The investigations in the 3D test field showed that the range value (span), which is influenced by the measurement precision of the instrument and by the algorithm for the fitting of the sphere, varied from 11.5 mm to 71.8 mm for the tested scanners. It must be stated that these results are derived from highly correlated differences between scanned and reference distances. According to the proposal of Heister (2006) and the VDI/VDE 2634 (2002) a span from 4.8–10.3 mm (exceptional case 33.4 mm for Faro) has been achieved in the test field using just seven selected well-distributed distances for comparison. However, the influence of errors in distance and angle measurements have not been determined separately due to the purpose of testing the complete laser scanning system (hard- and software). In this test it could be demonstrated that only the time-of-flight scanners achieved a systematic shift of up to +6 mm in the derived distances. The sphere spacing error was better than 3mm for most of the scanners, exceptions were Trimble GX, Riegl LMS420 and Faro LS880.

The accuracy tests of distance measurements in comparison to reference distances showed clearly that the results of most of the scanners met the accuracy specification of the manufacturer, although the accuracy (defined as measured versus reference distance) is slightly different for each instrument. As shown in Tab. 5 only the Faro scanner has slight problems meeting the accuracy specification. Furthermore, the accuracy is decreasing significantly for increasing distances longer than 200 m. It can be assumed that the targets/spheres used for these longer distances were too small. Consequentely, the target/sphere size must be adapted to the scanning distance. However, it could be seen in several practical outdoor tests that signal to noise ratio rises in daylight conditions for longer distances.

The accuracy tests of the inclination compensation show that the inclination of the time-of-flight scanners is successfully compensated, while the phase difference scanners show effects (not errors) resulting from inclination of the vertical axis. A trunnion axis error could not be proven. The influence of angle of incidence on 3D accuracy can be neglected for time-of-flight scanners, while phase difference scanners show significant deviations, if the angle of incidence is more than 45°. The accuracy is also not influenced by the spot size of the laser with respect to the angle of incidence. Nevertheless, previous investigations into the influence of object colour on the quality of laser distance measurements showed that for the Faro and Trimble scanners some object colours cause significant effects on the accuracy of the scanning distance (Mechelke et al. 2007).

All investigations showed clearly that the tested scanners are still influenced by instrumental errors, which might be reduced by instrument calibration. Therefore, it is necessary to define standards for investigations and tests of laser scanning systems to derive simple calibration methods for the scanners as is usual for total stations and which can be applied by the user. These presented test procedures may be taken into consideration for future discussions on the implementation of standardized test procedures. A valuable proposal for the definition of standardised quality parameters for the investigation of terrestrial laser scanning systems is already summarised by HEISTER (2006) and practically tested by KERN & HUXHAGEN (2008). Future investigations in TLS should refer to these definitions.

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