Geometric Accuracy Investigations of the Latest Terrestrial Laser Scanning Systems

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Key words: accuracy, evaluation, laser scanning, positioning, standards

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 offers 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, 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 3D laser scanning systems, accuracy tests of distance measurements in comparison to reference distances, accuracy tests of inclination compensation, and influence of the laser beam's angle of incidence on 3D accuracy.

ZUSAMMENFASSUNG

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 der baugleiche 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.

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1. INTRODUCTION

Terrestrial laser scanning systems have been available on the market for about ten years and in the last five years laser scanning is on the way to becoming accepted as a common method of 3D data acquisition, finding its position on the market beside established methods like tacheometry, photogrammetry and GPS. Terrestrial laser scanning stands also 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 like 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 authors 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 methods (Boehler et al. 2003; Ingensand et al. 2003; Clark & Robson 2004). 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 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 (Fig. 1).

Figure 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.

Scanner/Criterion		**Trimble GX**	**Leica ScanStation 1**	**Leica ScanStation 2**	**Riegl LMS-Z420i**	**FARO LS 880 HE**	**Z+F IMAGER 5006**
Scan method		Time-of-flight	Time-of-flight	Time-of-flight	Time-of-flight	Phase difference	Phase difference
Field of view [°]		360 x 60	360 x 270	360 x 270	360 x 80	360 x 320	360 x 310
Scan distance [m]		350	300	300	1000	< 76	< 79
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
3D scan precision		12mm/100m	6mm/50m	6mm/50m	10mm/50m	3mm/25m	10mm/50m
Camera		integrated	integrated	integrated	add-on option	add-on option	add-on option
Inclination sensor		compensator	compensator	compensator	compensator	yes	yes

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

The technical specifications and the important features of these laser scanners are summarised in Table 1. The tested scanners 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 Table 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.

Most of the presented investigations use spheres as test bodies to obtain the reference positions. The diameters of the used spheres were 76.2mm, 145mm, and 199mm, respectively. The spheres were of matt white colour and were checked for eccentricity and diameter. To obtain centre positions of the spheres, the point clouds representing the sphere were manually corrected for outliers. The fitting of the sphere geometry was performed using algorithms in the Trimble software RealWorks Survey and 3Dipsos.

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. 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 separately, which is not useful due to test the whole system (hard- and software).

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

A durable established 3D test field was used in the hall of building D at the HCU campus (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 30x20x12m^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 0.5mm, while the standard deviation of the coordinates of the reference points is less than 1mm (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 145mm (in March 2007) and 199mm (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 at the ground floor, two at 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 centre of the fitted sphere derived from the 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. The minimum distance is 1.5m and the maximum distance is 33.1m in the test field, which is within the scanning range of each tested scanner.

Scanner	**# 3D points**	**# distances**	**Δl min [mm]**	**Δl max [mm]**	**span min/max [mm]**	**syst. shift [mm]**
Leica ScanStation 1	38	703	-2,3	9,2	**11,5**	3,6
Z+F IMAGER 5006	38	703	-7,4	6,6	**14,0**	-0,3
Trimble GX	38	703	-16,0	27,6	**43,6**	6,0
Faro LS 880 HE	38	703	-41,1	30,7	**71,8**	0.1

Table 2: Comparison of 3D distances between laser scanner and reference in the 3D test field (test campaign March 2007)

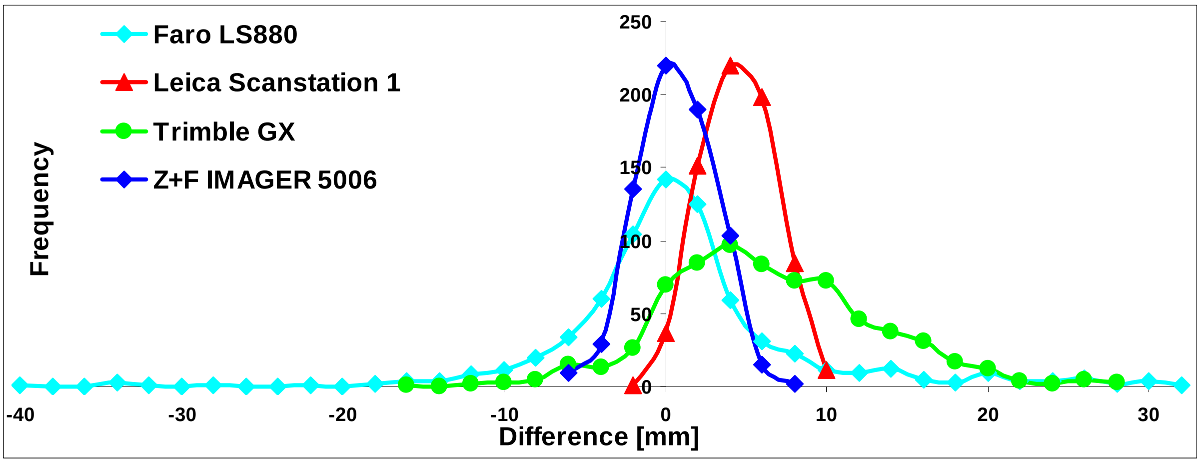

Figure 3: Distribution of differences between scanned distances and reference distances for four tested terrestrial laser scanner (campaign March 2007)

The results of the 3D test field investigations of test campaign March 2007 are shown in Table 2, where all differences between scanned and reference distances for all stations are summarised as the range (span) Δl from minimum to maximum deviation value as an indication for the accuracy of each system. This range value is influenced by the measurement precision of the instrument and by the algorithm for the fitting of the sphere. The centre coordinates of all spheres were computed with the Trimble software RealWorks Survey after manual cleaning of the outliers. The best result was a range from minimum to maximum of 11.5mm, which was achieved with the Leica ScanStation 1 (see Table 2). The result of the IMAGER 5006 at 14mm is slightly worse. In contrast to these good results the span of the Trimble GX and faro scanner shows a huge value of 43,6mm and 71,8mm, respectively (Table 2), 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 = 17,3mm) was achieved with the Trimble GS100, the predecessor model of the GX. The average value of all differences was less than +1mm for Faro and Z+F scanner, while this value was +4mm for Leica ScanStation 1 and +6mm for Trimble GX scanner, which yields a systematic shift and which is clearly illustrated in Fig. 3.

Scanner	**test campaign**	**# 3D points**	**# distances**	**Δl min [mm]**	**Δl max [mm]**	**span min/max [mm]**	**syst. shift [mm]**
Leica ScanStation 1	Oct. 2007	29	351	-5,4	6,5	**11,9**	0,7
Leica ScanStation 2	Oct. 2007	29	351	-5,4	6,5	**11,9**	2,2
Leica HDS6000	Oct. 2007	30	406	-6,7	6,3	**13,0**	-0,2
Z+F IMAGER 5006	Oct. 2007	30	406	-5,7	7,7	**13,4**	0,4
Riegl LMS420i	Dec. 2007	29	351	-19,8	6,5	**26,3**	-6,3

Table 3: Comparison of 3D distances between laser scanner and reference in the 3D test field

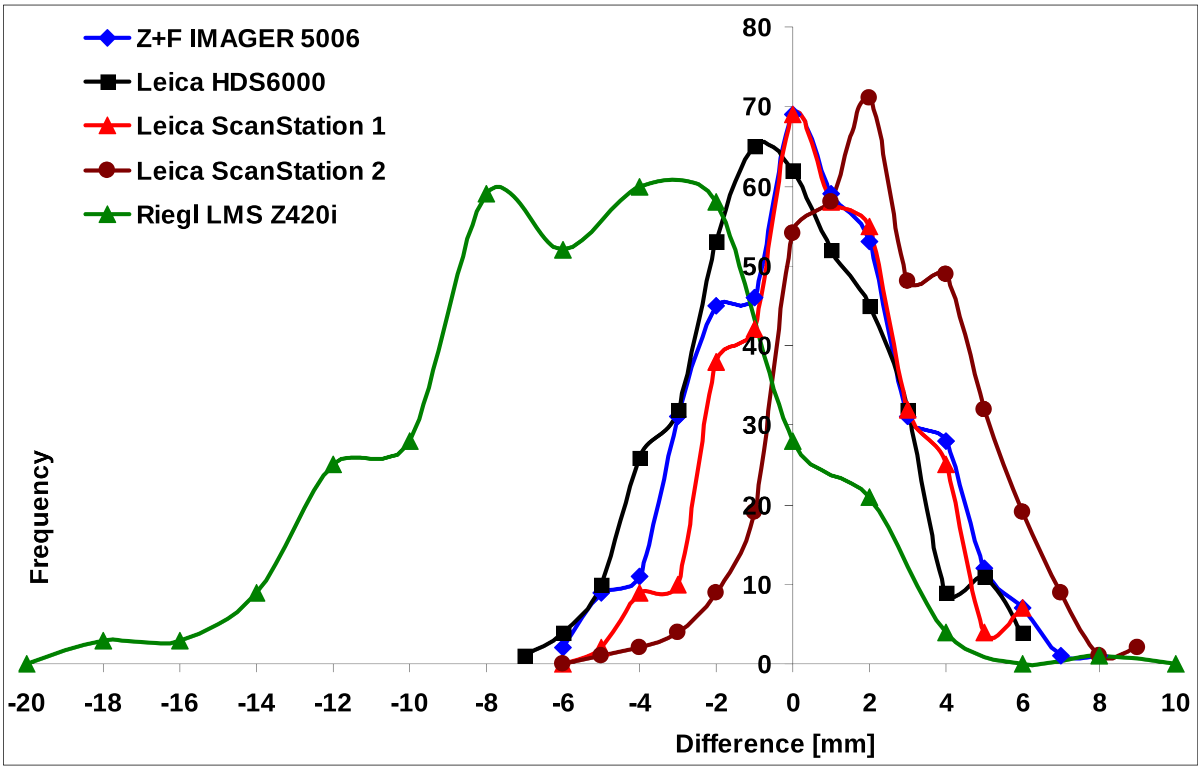

Figure 4: Distribution of differences between scanned distances and reference distances for five tested terrestrial laser scanner (campaign October and December 2007)

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 Table 3. In these test field investigations just 29 or 30 spheres with a diameter of 199mm were used. These results confirm the previous results from March 2007, whereas the span (sum of Δl min + Δl max), which 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 (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 (Table 2), could not be confirmed with a different Leica ScanStation 1 in the investigation of October 2007 (Table 3).

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 in distance ranges from 10m to 100m in steps of 10m 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 0.3mm. A standard deviation of 0.1mm 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

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All scanning distances of Faro LS880 and IMAGER 5006 were derived from scanned spheres with a diameter of 145mm, 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 distance of 60m and IMAGER 5006 scans to 75m. All major results of this accuracy test are illustrated in Fig. 4. There it is clearly indicated that the differences between the Leica ScanStation and IMAGER 5006 and the references distances are always less than 2mm, while for the Trimble GX the differences are also less than 2mm between 10-60m, but from 70 to 100m distance the differences increased to a systematic effect of 3-5mm. The differences between the Faro LS880 scans and the reference were in the range of 1-5mm. Although Faro LS880 and Z+F IMAGER 5006 are capable of measuring up to 80m, it must be stated that even with the highest resolution the number of ‘hits’ on the 145mm sphere is not high enough for distances beyond 50m to allow a precise fitting of sphere geometry. Additionally, it could be seen in several practical outdoor tests 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 on the official baseline of the city of Hamburg, which consists of seven granite columns and covers a distance range up to 430m. For these investigations additional points in 10m interval were integrated for the distance range up to 75m. All reference distances were measured by a precision total station Leica TCA2003. These determined reference distances deviated on average by ± 0.5mm from distances which were measured with a high precision Kern Mekometer 5000 before these investigations.

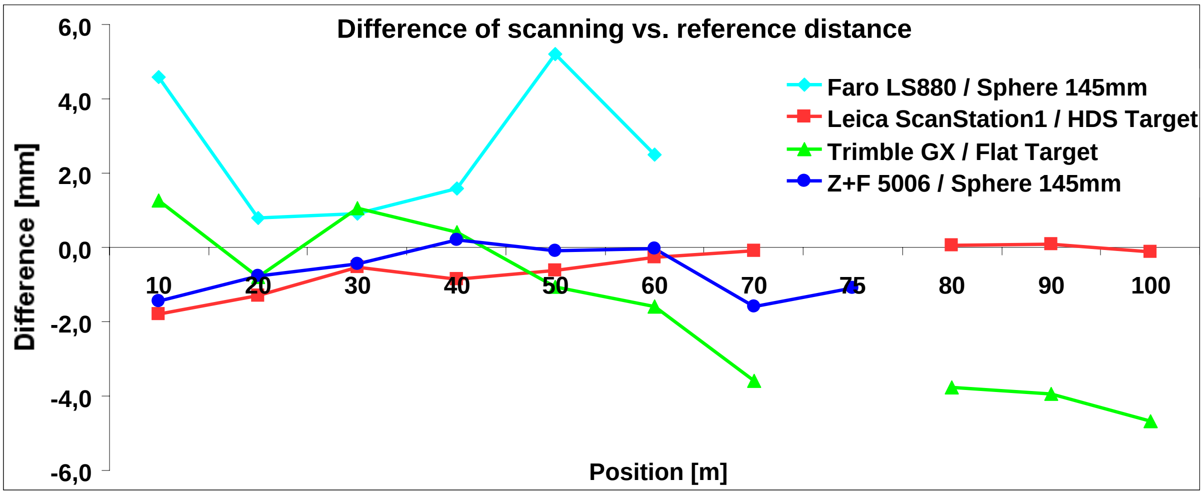

Figure 5: Comparison of the differences between scanning and reference distances (campaign March 2007)

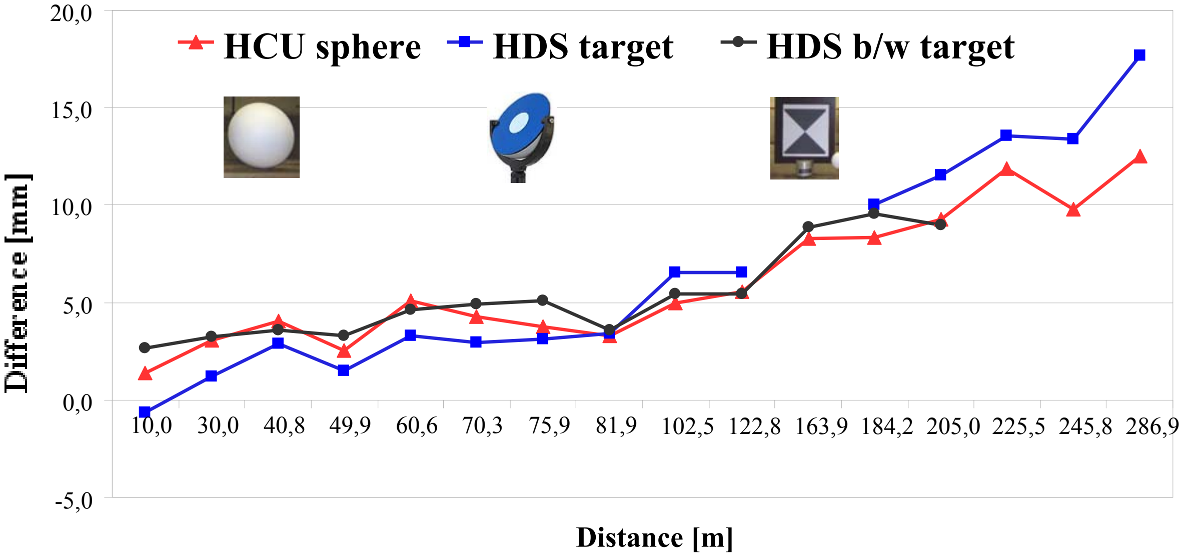

Figure 6: Comparison of the differences between scanning and reference distances for the Leica ScanStation 2 (campaign October 2007)

The scans of the ScanStation2 to different targets (HDS Flat target, HDS black/white target as well as spheres with a diameter of 199mm) were controlled using the software Leica Cyclone 5.8. The spheres used are plastic hollow balls with 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 (Fig. 6).

As a result indicated in Fig. 6 a scale factor of approx. +65ppm can be derived for the ScanStation 2. In the scan range under 100m measurements to the HDS flat target show the smallest residuals (< 5mm), while over 100m distance the measurements to the spheres indicate the best results (residual of max. 12.5mm to a distance of 287m). It can be assumed that the fitting algorithm is positive affected by the larger sphere surface compared to the HDS flat target. For the measurements to black/white targets the fitting algorithm of Cyclone could only supply a result up to a distance of 205m.

The results of the investigations into the scanning accuracy of the Riegl LMS-Z420i using the reflective target, 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 ±5mm for distances up to 205m, but for distances from 205m up to 430m the accuracy decreases significantly with the distance due to the decreasing ratio of distance and target size. Better results might be obtained if the target size was larger for longer distances. Tauber (2005) could achieve similar results on the baseline of the Leibniz University Hanover using the Riegl LMS 360i.

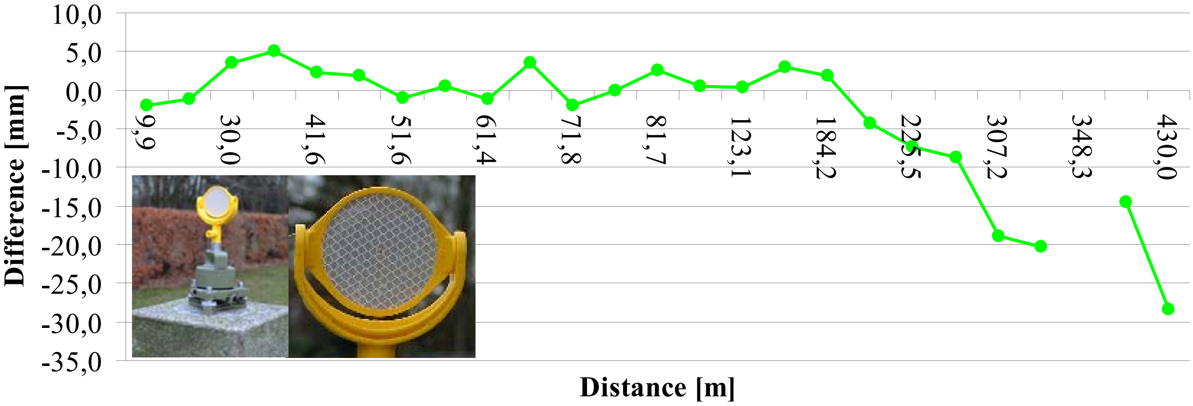

Figure 7: Comparison of the differences between scanning and reference distances for the Riegl LMS 420i using the reflective target (campaign December 2007)

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 200m.

3.3 Accuracy Tests of Inclination Compensation

All scanners in the test programme are equipped with an inclination sensor (see also Table 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 in-

clination 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 50m. 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 (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 seconds. The recordings of the Nivel20 showed no significant movements of the tripod during scanning (Fig. 8).

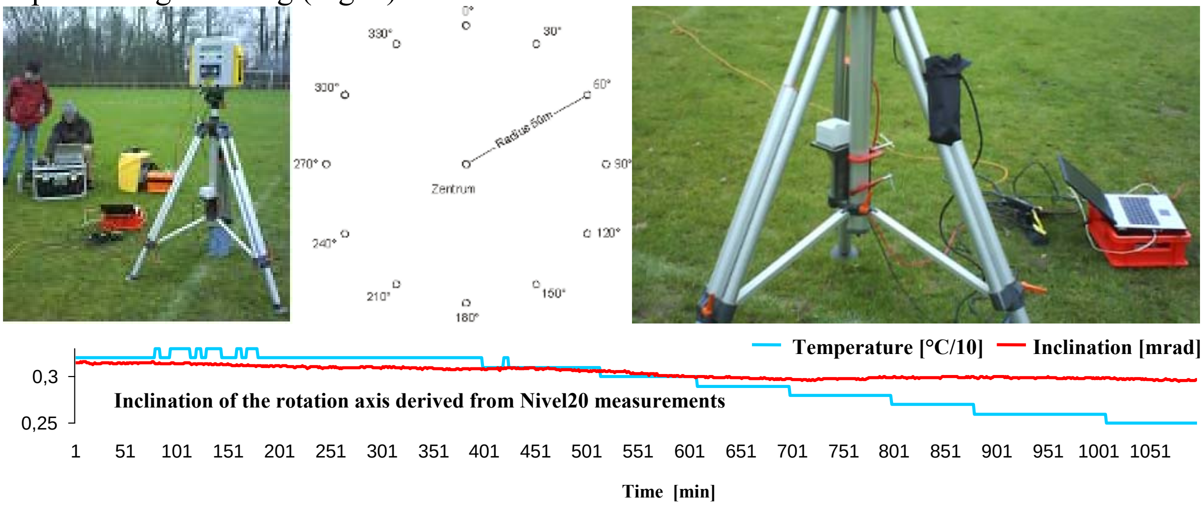

Figure 8: Test field for inclination compensator of the terrestrial laser scanner: scanner on solid tripod (left), schematic test configuration for scanner and spheres (centre), inclination sensor Leica Nivel20 fixed at the scanner tripod (right) and illustration of tripod movement derived from Nivel20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

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 scanner show maximum deviations of 2mm with a very minor sine oscillation, probably resulting from calibration error of the inclination sensor (Fig. 9 top). Faro LS880 shows huge differences up to 15mm, which may be influenced by the comparably low resolution (8mm / 50m) 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 145mm and in October

2007 with spheres with a diameter of 199mm, is almost identical and is very similar to the Faro LS880. These effects are influenced by an 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.

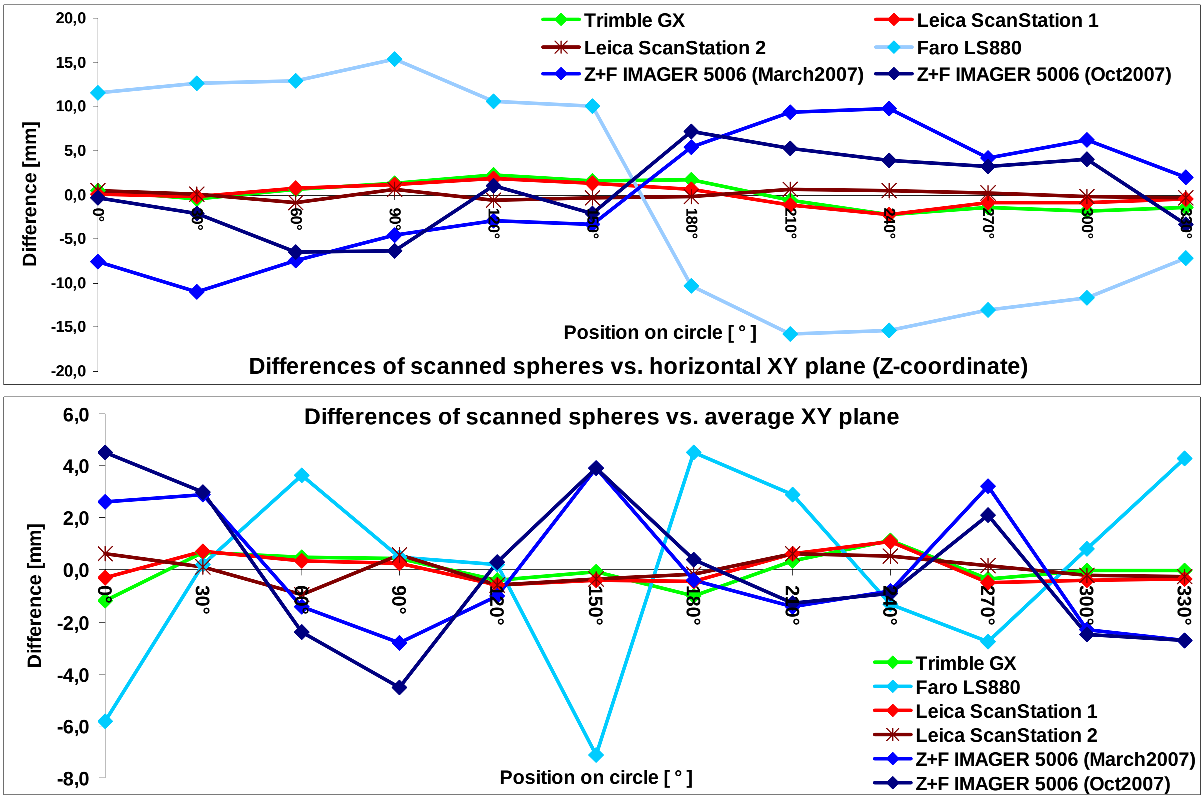

Figure 9: Test of inclination sensor in comparison: Differences between scanned spheres and horizontal XY plane (top), and average XY plane (bottom)

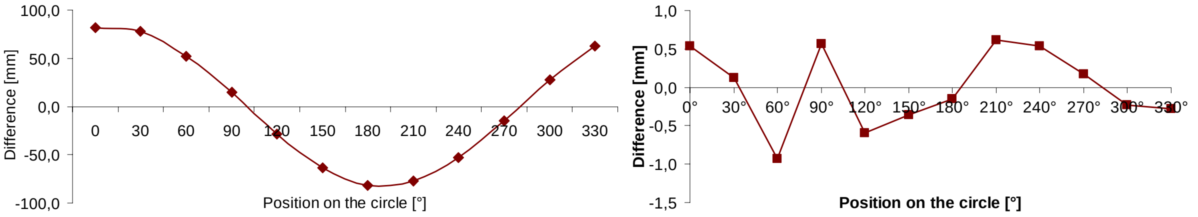

Figure 10: Leica ScanStation 2: Differences vs. horizontal plane (z-coordinate) for switched off compensator (left) and active inclination compensator (right). Note the difference in y-scale between the two graphs.

Fig. 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 are depending 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 (Fig. 10 right). Since these results are very similar to the previous tests using Leica ScanStation 1 and Trimble GX (Fig. 9 top), it can be stated that the dual axis (tilt) compensator of the scanners with the time-of-flight method adjusts changes of the inclination during scanning almost perfectly.

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

Among other effects the accuracy of a point cloud is dependant 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 x 79cm^2 (Fig. 11 centre) was mounted in a metal frame and could be swivelled in this 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 38.1mm) 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 3mm at an object distance of 10m. 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.

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

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 could 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 is increasing with the decreasing angle of incidence. The time-of-flight scanners show minor effects of up to 3mm for an angle of incidence of 5°-10°, while the phase difference scanners achieve difference values of up to 12mm for the same angle. But generally, it can be stated that if the angle of incidence is less than 45°, significant influence on the accuracy of the point cloud can be expected. Further investigations are still necessary to check the influence of larger object distances.

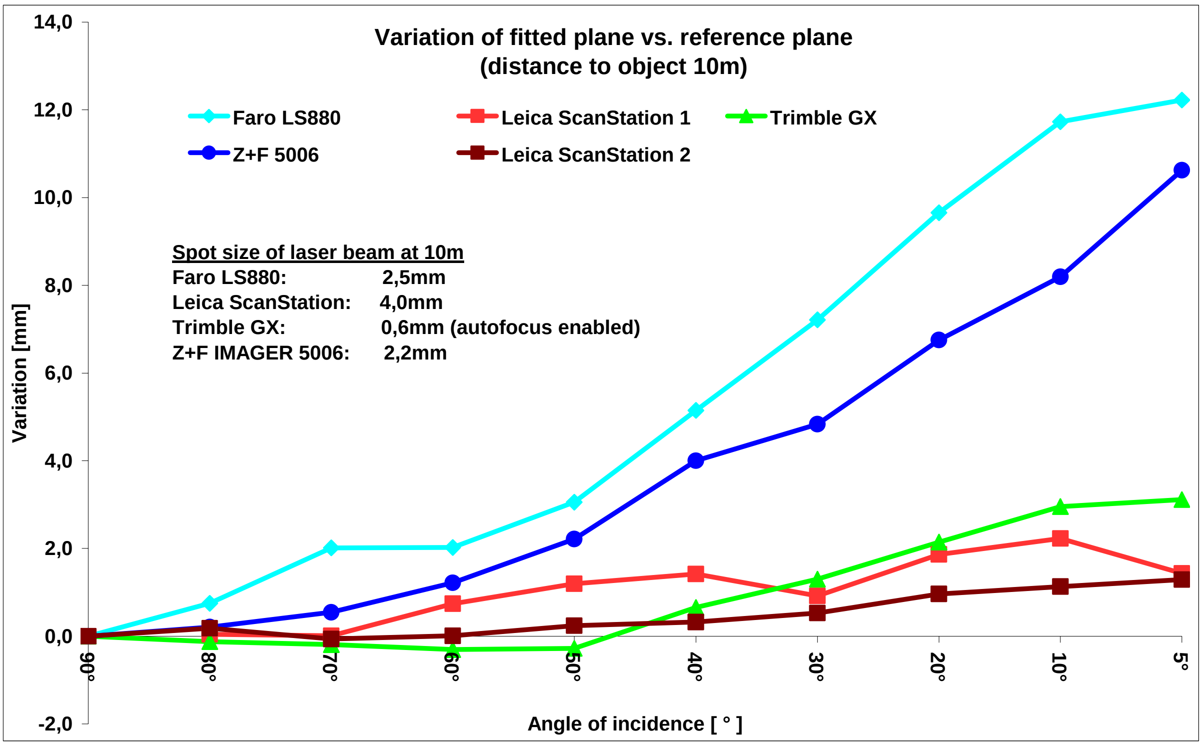

Figure 12: Influence of angle of incidence on 3D accuracy in comparison

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 this range value (from minimum to maximum deviation value), which is influenced by the measurement precision of the instrument and by the algorithm for the fitting of the sphere, varied from 11,5mm to 76mm for the tested scanners. In this test it could be demonstrated that only the time-of-flight scanners achieved a systematic shift of up to +6mm in the derived distances. The accuracy tests of distance measurements in comparison to reference distances showed clearly that the results met the accuracy specification of the manufacturer, although the accuracy is slightly different for each instrument. However, it could be seen in several practical outdoor tests that signal to noise ratio rises in daylight conditions for longer distances. In the accuracy tests of the inclination compensation it could be seen 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 less than 45°. The accuracy is also not influenced by the spot size of the laser with respect to the angle of incidence. In the previous investigations into the influence of object colour on the quality of laser distance measurements it could be shown that the Faro and Trimble scanners show significant effects of some object colours 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.

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