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ORIGINAL PAPER

Geometric accuracy investigations of terrestrial laser scanner systems in the laboratory and in the field

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Abstract

This paper summarizes recent research into current terrestrial laser scanners undertaken by the HafenCity University Hamburg and gives an assessment of the geodetic accuracy of the latest generation of scanners. Three separate independent test methods are presented to investigate the geometric accuracy of terrestrial laser scanners under laboratory conditions: (a) distance measurement accuracy to b/w targets and spheres on the 20-m comparator track, (b) comparison of spatial distances in the 3D test field on b/w targets, and (c) investigation of the flatness deviation following the guideline VDI/VDE 2634 (VDI/VDE 2012) on a flat stone slab. The following laser scanners were tested in the lab: Leica BLK360 (2017), Leica RTC360 (2019), Z+F IMAGER 5016 (2019, 2020), Z+F IMAGER 5010 (2020), and Faro Focus^{3D} X330 (2020). The reference measurements were realised with the Leica Absolute Tracker AT960 (2017, 2020) and with the Leica TS60 total station (2019). The results of the geometric accuracy tests in the laboratory show very small deviations in the range of 1–2 mm for most of the scanners, thus corresponding to the manufacturer's specifications. In addition, five laser scanners were tested in accordance with instruction sheet 7-2014 of the German Society for Geodesy, Geoinformation and Land Management (DVW) for standardised testing of terrestrial laser scanners in the outdoor area of HafenCity University Hamburg. For the execution of the field test procedure, only the standard equipment and software of the respective manufacturers were used. The entire field test procedure, including data acquisition and evaluation, was completed within 4 to 5 h for each scanner. As expected, no significant distance or angle deviations were detected in any of the measurement systems, so that the tested laser scanners are ready-to-use, taking into account the measurement volume recorded.

Keywords 3D test field · Field test procedure · Flatness measurement error · Spatial distances · Terrestrial laser scanning

Introduction

The use of terrestrial laser scanners (TLS) has been established in the everyday work of geodesists for more than 15 years. The instruments currently available on the market now belong to the fourth generation of scanners and their precision can scarcely be improved. Nevertheless, the precision specified by the manufacturer should be checked from time to time in order to be able to guarantee a corresponding specification.

HafenCity University Hamburg (HCU) has been investigating terrestrial laser scanning systems for more than 15 years; since 2016, a more accurate test site has been established at the new building of HCU Hamburg, which can serve as a reference for the increased accuracy level of the new scanners. A new 3D test field and a 20-m comparator track in the laboratory are used to study and test various laser scanners. Institutions such as the Hamburg State Office of Criminal Investigation have their terrestrial laser scanners checked annually at HCU as part of their required quality management system certification. Besides HCU, other universities also investigate laser scanning systems. Holst et al. (2018) have compiled the diverse test scenarios of the various German universities.

In addition to the three investigations in the laboratory, the field test procedure of the DVW was also carried out in 2019 and 2020 in accordance with instruction sheet No. 7 (Neitzel et al. 2014), which originates with the publication of Gottwald (2008). This procedure has been published in its extension 2018 as ISO 17123-9, which now also considers

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test procedures for terrestrial laser scanners with this part 9. The results of the field test procedure for the five examined laser scanners Z+F IMAGER 5016 (three systems), Leica RTC 360, and Faro Focus^{3D} X330 are presented in "The field test procedure" section. In the opinion of the authors, there are only very early publications on the field test procedure (Gottwald 2008; Feldmann et al. 2011) according to the DVW instruction sheet.

Related work

Several authors have already reported on different approaches for investigating terrestrial laser scanning systems during the last two decades. Nevertheless, standardised tests and calibration methods of laser scanning systems do not yet exist for the user. Due to the huge variety of terrestrial laser scanners it is difficult for the user to find comparable information regarding the potential and precision of the laser scanning systems in the jungle of technical specifications and therefore to validate the technical specifications provided by the system manufacturers. It may thus be difficult for users to choose the right scanner for a specific application, emphasising the importance of comparative investigations into accuracy behaviour of terrestrial laser scanning systems.

Several groups, primarily university-based, have carried out geometrical investigations into laser scanning systems in order to derive comparable information about the potential of the laser scanners and develop practical testing and calibration methods. The first paper about terrestrial laser scanner evaluation was published by Boehler et al. (2003). Subsequent authors such as Ingensand et al. (2003), Johansson (2003), Schulz and Ingensand (2004), Tauber (2005), Heister (2006), Neitzel (2006), Büttner and Staiger (2007), Wehmann et al. (2007), Gordon (2008), Gottwald (2008), Feldmann et al. (2011), Muralikrishnan et al. (2017), Schmitz et al. (2019), and Schmitz et al. (2021) have focussed on geometrical investigations, whilst others have investigated in the influence of various materials and colours on laser scanning (Clark & Robson 2004; Sternberg et al. 2005; Voegtle et al. 2008; Yaman & Yılmaz 2017; Pawłowicz 2018) and yet others have reported on calibration methods for TLS (Lichti & Franke 2005; Rietdorf 2005; Reshetyuk 2006; Schulz 2007; Kern 2008; Kern & Huxhagen 2008; Gottwald et al. 2009; Abbas et al. 2013). A review about performance evaluation of terrestrial laser scanners was given recently by Muralikrishnan (2021). A quiet new approach is proposed by Wujanz et al. (2018) to improve the quality of TLS point clouds. They propose in their article two methodologies to compute intensity-based stochastic models based on capturing geometric primitives in the form of planar shapes utilising 3D point clouds, which were applied to phase shift and time-of-flight laser scanner.

The Laboratory for Photogrammetry and Laser Scanning of the HCU has been validating 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; Kersten et al. 2009; Lindstaedt et al. 2009, 2011, 2012), which allow statements about the accuracy behaviour and the application potential of terrestrial laser scanner systems to be made. Furthermore, the testing procedures are an essential part of practical teaching in the Geodesy and Geoinformatics master programme at the university.

The terrestrial laser scanners investigated

For the laboratory and field investigations, a selection of current and innovative laser scanning systems were available from 2017 to 2020 (Fig. 1): the Z+F IMAGER 5016 (2019) from the Hamburg State Office of Criminal Investigation (LKA), the Leica BLK360 (2017), and the Leica RTC360 (2019) from the German engineering company Dr. Hesse und Partner Ingenieure (dhp:i). Both scanners (IMAGER 5016 and RTC360) have a specified distance measurement accuracy of 1 mm + 10 ppm and an angular accuracy of 0.004° and 0.005°, respectively. Whilst the distance measurement of the IMAGER 5016 is based on the phase difference method, the Leica RTC360 uses a combination of phase difference and time-of-flight methods. Additional integrated sensors such as an inclination compensator and camera, as well as extensive software, make the systems flexible and efficient to use. In 2020, three additional IMAGER 5016s (2× LKA and 1× HCU) were tested in addition to HCU's two older Faro Focus3D X330 and IMAGER 5010 laser scanners. Compared to all above-mentioned scanners, the

Fig. 1 Terrestrial laser scanner investigated (f.l.t.r.): Leica BLK360, Leica RTC360, Z+F IMAGER 5010, Z+F IMAGER 5016, and Faro Focus^{3D} X330

Leica BLK360 is a low-cost scanner with minor precision. The technical specifications of all tested scanners are summarised in Table 1.

Geometric accuracy tests in the laboratory

The 3D test field

The test field used was set up in 2016 in the geodetic laboratory of the new building of HCU Hamburg. The initial results of the investigations of the Leica BLK360 on this test field have already been published by Blaskow et al. (2018). In contrast to the test field at the old location (see publication of Kersten et al. 2009; Lindstaedt et al. 2009; Lindstaedt et al. 2011; Lindstaedt et al. 2012), it has a significantly smaller measurement volume and extends over only one floor. However, the length of the laboratory results in reference distances up to 35 m. The test field consists of 20 signalised b/w targets distributed on walls and ceiling in the laboratory (Fig. 2), where each target is installed as a so-called "point nest" to adapt a corner cube reflector CCR for highly accurate reference measurements with a laser tracker. However, for testing laser scanning systems, these special adapters allow the installation of a b/w target on each point nest (Fig. 3 right). The investigations in the 3D test field provide information about several error components of a laser scanning system, which cannot be determined separately in this test. In addition to the distance and angular precision of the scanner, the algorithm for target fitting in the respective

Table 1 Technical specifications of the laser scanners tested

Specification	Leica BLK360	Leica RTC360	Z+F IMAGER 5016 /5010	Faro Focus^{3D} X330
Measuring procedure	ToF with WFD	ToF and phase	Phase	Phase
Field of view H/V (°)	360/300	360/300	360/320	360/300
Range (m)	0.6–60	0.5–130	0.3–365/0.3–187	0.6–330
Measurement rate (pts/s)	360,000	<2,000,000	Maximum 1,100,000	<1,000,000
Angular precision H/V (°)	No data	0.005	0.004/0.007	0.009/0.009
Ranging precision	4 mm at 10 m	1 mm + 10 ppm	1 mm + 10 ppm	2 mm + 0.3 mm at 25 m
Scan resolution	3 selectable resolution settings	3 selectable resolution settings, 3/6/12 mm at 10 m	6 selectable resolution settings, 1 … 12 mm at 10 m	1/1–1/32, 1.5–49 mm at 10 m
Distance measurement noise	0.3–0.5 mm at 10 m	0.4 mm at 10 m	0.3–0.5 mm at 10 m	0.3 mm at 10 m
3D point precision	6 mm at 10 m	5.3 mm at 40 m	No data	No data
Camera	Integrated	Integrated	Optional add-on	Integrated
Inclination sensor	No data	Visual inertial system	Dynamic compensator	Two-axis compensator
Dimension ($B \times T \times H$) (mm)	165 × 100 (H/D)	120 × 240 × 230	150 × 258 × 328/170 × 286 × 395	240 × 200 × 100
Weight + battery (kg)	1.0	6.0	6.5/9.8	5.2
Market launch	2017	2018	2016/2010	2013

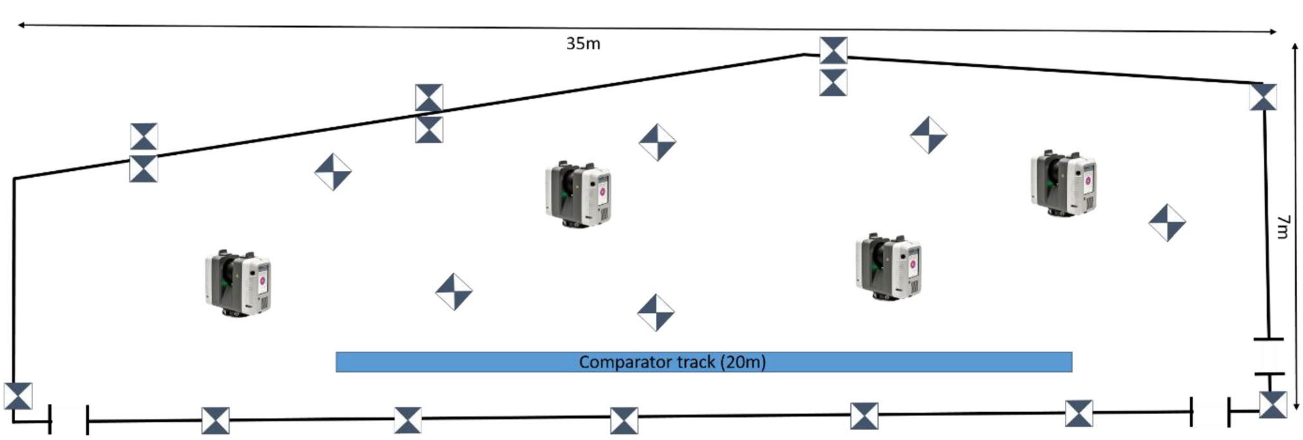


Fig. 2 Dimensions of the 3D test field of the HCU Hamburg including distribution of the b/w targets and four scanner positions

Fig. 3 F.l.t.r.: terrestrial laser scanner Leica BLK360, Leica RTC360, Z+F IMAGER 5010, Z+F IMAGER 5016 in the 3D test field, and b/w target installation

software also influences the result. Therefore, it is important to use the software associated with the scanner for the target measurements in order to be able to assess the overall system (hardware and software).

Each scanner investigated scanned the test field at the same four scan stations (Fig. 2). The resolution for the IMAGER 5016 and 5010 was set to high (6 mm at 10 m) with quality balanced and normal, respectively, whilst for the Faro Focus the resolution was set to 1/5 (7.7 mm at 10 m) with quality 3×. For both Leica scanner, RTC360 and BLK360, the highest possible scan resolution was selected (3 mm at 10 m and 5 mm at 10 m, respectively). Due to occlusions in the test field, not all targets could always be scanned in each scan, but in general there were between 16 and 18 targets visible in the scans. The reference measurements of the targets were performed using a Leica AT 960 laser tracker in 2017 and 2019. The targets were each measured from three different stations, transformed, and then averaged. According to the manufacturer's specifications, the angular accuracy of the Leica Absolute Tracker AT960 is ±15 µm + 6 µm/m, whilst the distance accuracy is 10 µm (Hexagon 2021). Thus, reference coordinates with superior accuracy were available for the comparison of reference and scanned spatial distances in the test field.

Subsequent data processing (here comprising of target measurements) was performed in the respective manufacturer software Z+F LaserControl, Leica Cyclone Register 360, and Faro Scene. Target fitting was implemented in all programs and was performed automatically for the data of the Z+F and Faro scanners, whilst the targets of the RTC360 had to be partially adjusted or corrected subsequently. Of the maximum 760 distances for four viewpoints, 613 distances were evaluated for the IMAGER 5016 and 666 distances for the RTC360. For the BLK360 scans, the ReCap Pro software from Autodesk, which is part of the scanning system, was used to measure the centre of the scanned targets at each scan position using the target fitting function of the software. Although 18 targets were always visible in each scan, only a number between 11 and 13 targets could be fitted per scan station, which resulted in 326 distance combinations. The remaining targets could not be successfully fitted due to the scan resolution and the long distances in the test field.

The distances calculated from the centre coordinates were compared with the spatial distances of the reference measurement and the differences were plotted in a frequency diagram (Fig. 4). For both IMAGER 5016, a maximum shift from 0.0 to +0.5 mm is obtained with an almost ideal and identical normal distribution; the span (as the sum of the absolute maximum negative and positive deviation) of the values is 3.9 mm and 3.8 mm, respectively. In contrast, the curve of the RTC360 is somewhat flatter and wider, and the span is twice as large at 8.0 mm. On the other hand, the maximum is not shifted from zero, 160 values were classified to zero here. However, the span determined for the scanner Faro Focus and Leica BLK360 demonstrate that the accuracy of the spatial distances in the 3D test field is much worse than the other laser scanners. This aspect is also obvious for these two laser scanners in the spatial distance deviation in the range of ±1 mm. A deviation of maximum ±1 mm was observed for the IMAGER 5016 in 93.1% and 92.4%, for the RTC360 in 77.6%, for the IMAGER 5010 in 75.7%, for the Faro Focus in 40.5%, and in only 21.2% of all values for the Leica BLK360 (Table 2). The mean value calculated from the distance differences (scanned vs. reference) indicates only a small systematic measurement deviation for each scanner (accept BLK360 with 5.0 mm) in the investigated measurement range of the reference distances (Table 2). The reference distances are in a range between 1.8 m and 35.9 m (minimum and maximum 3D distances). The scanners measure the spatial distances between 0.3 mm longer and −0.6 mm shorter on average, whilst the BLK360 shows a systematic effect and scans the distances 5 mm shorter on average (Table 2).

The 20-m comparator track

The distance accuracy of terrestrial laser scanning systems was investigated on the 20-m comparator track in the geodetic laboratory at HCU Hamburg. On the track, any distances up to 20 m in length can be realised and determined for measurement from one direction with the laser scanner and from the other direction with the reference measurement system (Leica AT960 laser tracker or Leica TS60 total station). The b/w target or sphere (199-mm diameter) is mounted on a carriage together with a corner cube reflector for the reference measurements. With this movable sledge, distances of 1 to 20 m in meter intervals are realised. The measurement setup for checking the distance measurement accuracy of terrestrial laser scanning systems is illustrated in Fig. 5 and Fig. 6.

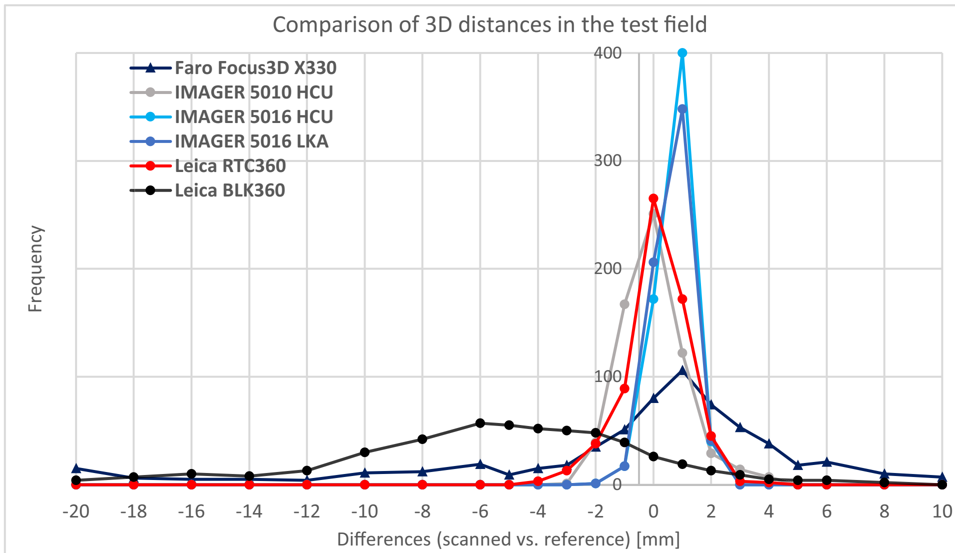


Fig. 4 Results of the comparison of spatial distances in the test field

Table 2 Results of the comparison of spatial distances in the 3D test field for six laser scanners

Comparison of spatial distances (3D)	Z+F 5016 LKA	Faro Focus	Z+F 5010 HCU	Z+F 5016 HCU	RTC360	BLK360
Number of distances	613	630	630	630	666	326
Minimum deviation (mm)	−2.1	−33.4	−3.1	−2.1	−4.5	−26.5
Maximum deviation (mm)	1.8	23.9	3.7	1.7	3.5	9.8
Span (mm)	3.9	57.3	6.8	3.8	8.0	36.3
Mean value (mm)	0.2	−0.6	−0.4	0.3	−0.3	−0.5
Standard deviation mean value (mm)	0.4	4.0	0.8	0.4	0.8	4.2
S^{3D} in −1 … +1 mm (%)	93.1	40.5	75.7	92.4	77.6	21.2

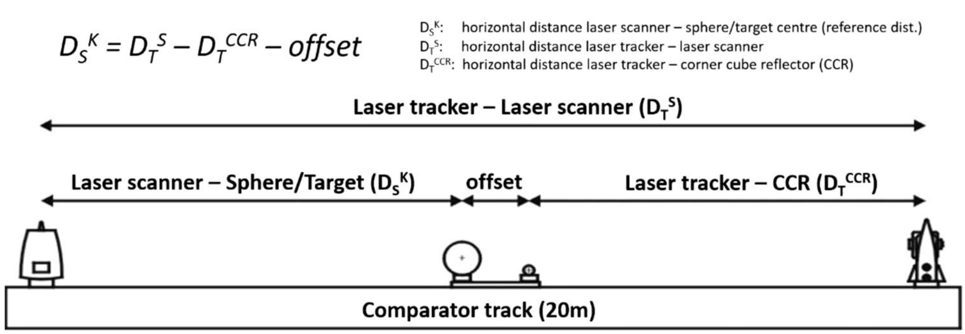


Fig. 5 Measurement setup of the 20-m comparator track in the laboratory of HCU Hamburg

Fig. 6 Terrestrial laser scanner at the comparator track (f.l.t.r.): Leica BLK360, Leica RTC360, Z+F IMAGER 5016, Leica Absolute Tracker AT960 (reference system 2017, 2020), and b/w target and sphere mounted on a metallic sledge

First, the position of the laser scanner is determined in the coordinate system of the laser tracker to derive the distance DTS between laser tracker and laser scanner. For quality control this measurement has to be conducted before and after the scanning of the targets and spheres. Secondly, the offset between CCR and sphere or target on the carriage has to be determined by measurements to the position of the target/sphere and the CCR point nest. Furthermore, the target thickness of 2.03 mm and the radius of the CCR — 19.05 mm — must be taken into account and added to the offset calculated from the measurements. The offset between CCR and sphere centre is 300.21 mm, whilst the offset between CCR and target is 129.06 mm. In 2019, the reference distances were measured with a Leica TS60 total station, with an accuracy of 0.6 mm + 2 ppm according to the manufacturer specification when measured on a corner cube reflector. In 2017 and 2020, the reference distances were measured with the Leica AT960 laser tracker.

Two passes were scanned for each of the scanners on the comparator track, one to the target and one to the sphere. The first scan was started at a distance of 1 m from the scanner position and then continued at intervals of 1 to 20 m each. The scan resolution of each of the IMAGER 5016 and 5010 was set to high with quality normal (6 mm at 10 m), for the Faro Focus the resolution was 1/5 with quality 3× (7.7 mm at 10 m), and for the BLK360 and RTC360 the highest level was chosen (5 mm at 10 m and 3 mm at 10 m, respectively). Whilst with the IMAGER scanners and the Faro Focus only a small section to the target/sphere was scanned each time, a complete panoramic scan had to be scanned each time with the two Leica scanner due to the non-existing functionality of a section scan. Due to the high scanning speed, this did not result in a significantly longer scanning time, but the data volume of the RTC360 acquired in all three tests in the lab was more than 100 times larger than that of the IMAGER scanners. This large data volume then inevitably entailed longer data processing.

Both targets and spheres could be measured in the software ReCap Pro for all scans of the BLK360. However, the fitting of the target was only possible up to a distance of 15 m, whilst the fitting of the sphere could only be performed up to a distance of 18 m due to an insufficient scan resolution. Furthermore, the sphere fitting failed at a distance of only 1 m, presumably due to the short distance. The fitting of the spheres was conducted in ReCap Pro with a free radius. The manufacturer's specified distance measurement accuracy for this BLK360 is 4 mm at 10 m or 7 mm at 20 m. Thus, accuracy for measurement on targets is expected to be in this range or even slightly better. But, not all of the scanned distances are within this specification as illustrated in Fig. 7. However, it was not possible to judge whether the poor target fitting in the software is directly responsible for the inaccurate distance determination or whether there are instruments errors. For reliable analysis, further investigations should be carried out. Nevertheless, it is noticeable in this investigation that all distances were determined too short. Sphere fitting, on the other hand, caused fewer problems in ReCap Pro than target fitting and it was always successful except for the measurement of the shortest distance. A check of the free radius sphere fitting in another software (Geomagic) gave similar results, but with a relatively constant offset of about 4 mm up to the distance of 16 m (Fig. 7).

The diagram in Fig. 8 shows the results of the scans to the b/w target. In contrast to the BLK360, all scanners show small deviations from the reference between −1.0 mm and +1.6 mm. The deviations of the IMAGER 5016 (LKA) are around zero in both the positive and negative range, which is confirmed by the mean value of −0.07 mm. In contrast, the deviations of the RTC360 (mean value +0.5 mm), the IMAGER 5016 (HCU) (mean value +0.2 mm), and the Faro Focus (mean value +0.7 mm) are all positive with 1–2 exceptions; i.e. the distances are generally minimally too short. Only the IMAGER 5010 tends to show deviations in the negative range (mean value −0.5 mm); i.e. the distances are then measured minimally too long.

For the measurements to the spheres, the result looks a bit different (Fig. 9), because the deviations tend to be negative for all but a few scanners. For the IMAGER 5016 (LKA) all deviations are negative, but less than 1 mm; i.e. the distances

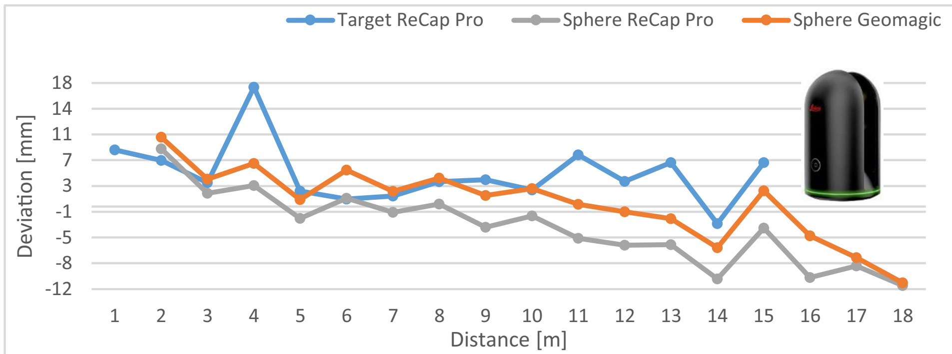


Fig. 7 Distance measurement accuracy on the 20-m comparator track for Leica BLK360 scans to both b/w target and sphere

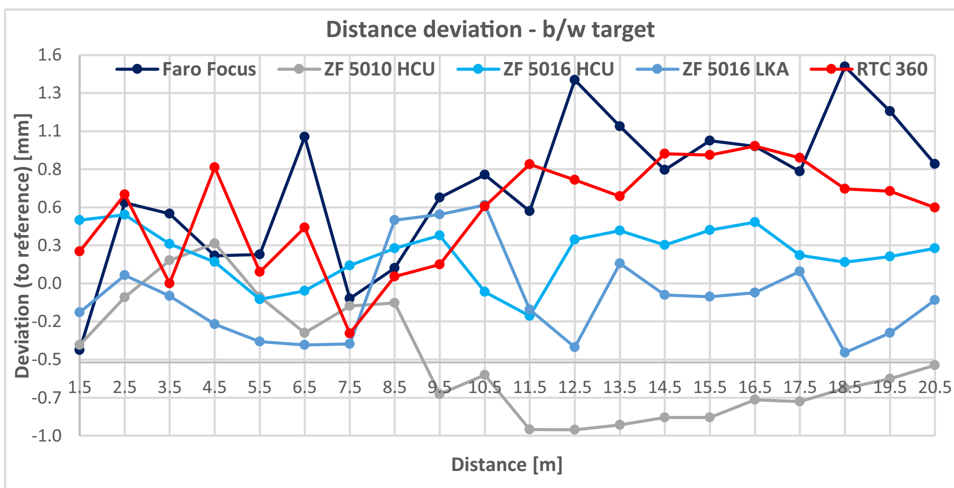


Fig. 8 Distance measurement accuracy on the 20-m comparator track for scans to a b/w target

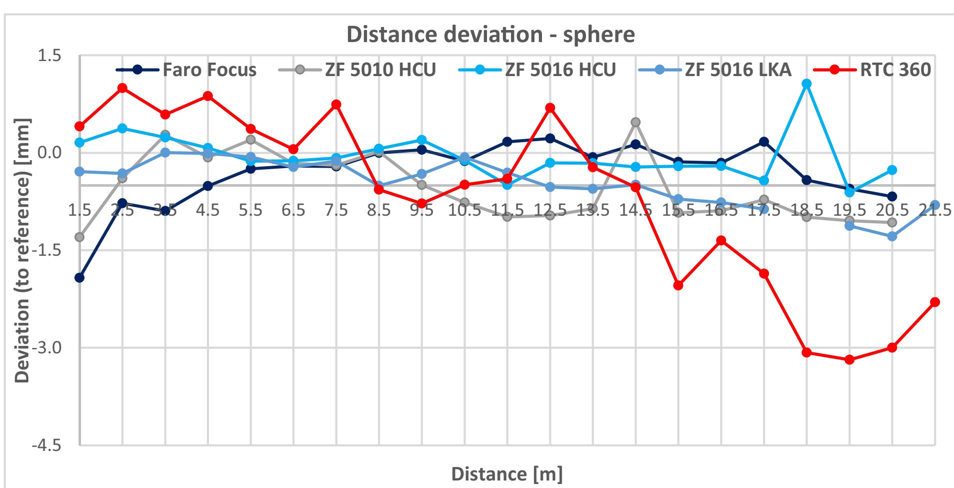


Fig. 9 Distance measurement accuracy on the 20-m comparator track for scans to a sphere

are measured slightly too long. The other IMAGER 5016 (HCU), the IMAGER 5010, and the Faro Focus confirm good results with distance deviation less than 1 mm. The results of the RTC360 are significantly worse starting at a distance of 15 m with deviations up to −3.2 mm, but for shorter distances the deviations are in the similar range of ±1 mm. It can be assumed that these larger deviations at longer distances are caused by an insufficiently precise target fitting of the spheres, since this in part had to be applied several times due to fluctuating results.

The planar stone slab

With the measurement on the planar stone slab, the quality parameter “flatness measurement error” can be determined according to the guideline VDI/VDE 2634 (part 2, VDI/VDE 2012). The guideline VDI/VDE 2634, parts 2 and 3, is an accredited standard for acceptance tests (verifying the specified accuracy) and re-verification (to ensure long-term compliance) of optical measurement systems based on area scanning (VDI/VDE 2012, 2008). Using the framework of well-defined test scenarios, suitable test objects (artefacts) are employed to determine quality parameters. The flatness measurement error is defined as the range of the signed distances of the measurement point from the best-fit plane calculated according to the least-squares method. The result is a statement about the measurement noise of the laser scanning system.

The terrestrial laser scanners were placed in front of a stone slab at a distance of approximately 10 m to scan the planar surface under constant laboratory conditions at different resolutions (Fig. 10 left). The scanned points belonging to the slab were cropped and a best-fit plane was calculated through all unfiltered point clouds using GOM Inspect software (V8 SR1).

The diagram in Fig. 10 shows a clear linear relationship between increasing scan resolution (or number of points) and flatness measurement error for the IMAGER 5016 (LKA). The absolute deviation (span of signed distances between the scanned points on the stone slab) increases from 1.1 mm for the lowest resolution to 3.3 mm for the highest resolution. Since the temperature in the instrument remained constant, the span represents the measurement noise of the instrument, which increases slightly with increasing resolution. A very similar behaviour, but with a slightly better result, was confirmed for the IMAGER 5016 (HCU) and for the IMAGER 5010 with the span of 0.7 mm/0.6 mm for middle resolution and 1.5 mm for ultrahigh resolution and 0.9 mm for superhigh resolution, respectively, in 2020. However, these results are not included in Fig. 10. For the RTC360, on the other hand, the three results of the span between 4.3 mm and 4.6 mm are almost identical or systematically constant (Fig. 10). The higher number of points for the RTC360 is probably due to the combined measurement procedure of time-of-flight and phase shift. The standard deviation of the Z+F IMAGER 5016 with maximum 0.36 mm is lower than that of the RTC360 with maximum 0.65 mm, but both scanner are well below 1 mm.

The field test procedure

The verification of terrestrial laser scanners in the laboratory or in the test field is a method of device verification that is not possible for every user. Especially test fields, which have an increased space requirement, are primarily found at universities and institutes; in smaller offices this possibility is often not available. Through the development of the DVW instruction sheet 07-2014, standardised field test procedures for the testing of laser scanners have been created, which are possible for all users and require a limited amount of time. This concerns systematic instrument deviations resulting from the distance measurement or the axis mechanics (Neitzel et al. 2014). These are partly identical to the deviations of a total station, but cannot be eliminated by a full set evaluation (Holst et al. 2018). Thus, the procedure according to DVW instruction sheet is manufacturer-independent and provides an opportunity to compare the manufacturer’s specifications with the accuracies achieved in the field test procedure. If excessive deviations are found,

Scanner	resolution	mm @ 10m	span [mm]	std.dev. (sigma)	# points
Z+F5016	middle	12	1,07	0,17	2.106
	high	6	1,84	0,23	8.374
	superhigh	3	2,37	0,29	33.180
	ultrahigh	1	3,29	0,36	132.404
RTC360	middle	12	4,30	0,65	4.611
	high	6	4,57	0,62	19.777
	superhigh	3	4,59	0,63	81.337

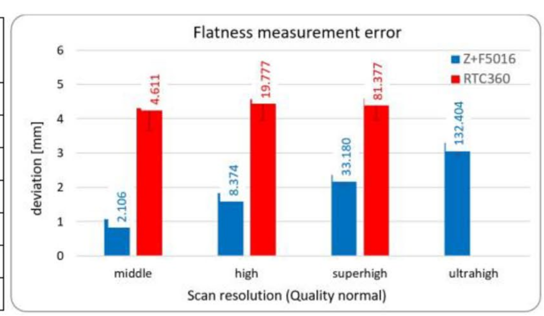


Fig. 10 Results (2019) of the flatness measurement error in a table (left) and in a diagram (right)

it is recommended to send in the instrument for calibration if the manufacturer has not already provided the possibility to enter correction values.

After the laboratory tests presented above, the two TLS systems (IMAGER 5016 and Leica RTC360) were subjected to the field test procedure in 2019, on the one hand to prove their suitability for use, and on the other hand to implement the field test method at the HCU Hamburg and to set up a suitable setup at a suitable location for future investigations. In September 2020, three additional scanners, two IMAGER 5016 and one Faro Focus3D X330, were tested by the field test method.

The measurement setup was carried out directly in front of the HCU Hamburg building on the Henning-Voscherau-Platz to the west. Here, the conditions are available to meet all the requirements specified in the DVW instruction sheet as far as possible (Fig. 11), because both the necessary space for longer horizontal sections and the possibility of an elevated target for the vertical triangle are given. An overview of the site with the installed targets (blue circles) and scanner stations (red circles) is illustrated in Fig. 12.

The measurements were performed for the scanners in 2019 in about 2 h each and in 2020 in about 3 h each, because six additional targets were scanned at right angles to scan station 1 at distances of 5 to 30 m for the determination of u_T. For each scan station, the targets were scanned four times each, taking into account the long distances for the resolution. Thus, with the Leica RTC360, the highest resolution level (3 mm at 10 m) was selected in each case and an all-round scan was performed; on the other hand with the IMAGER 5016, only section scans of the targets were scanned with the highest resolution of 1 mm at 10-m distance after a full panoramic scan.

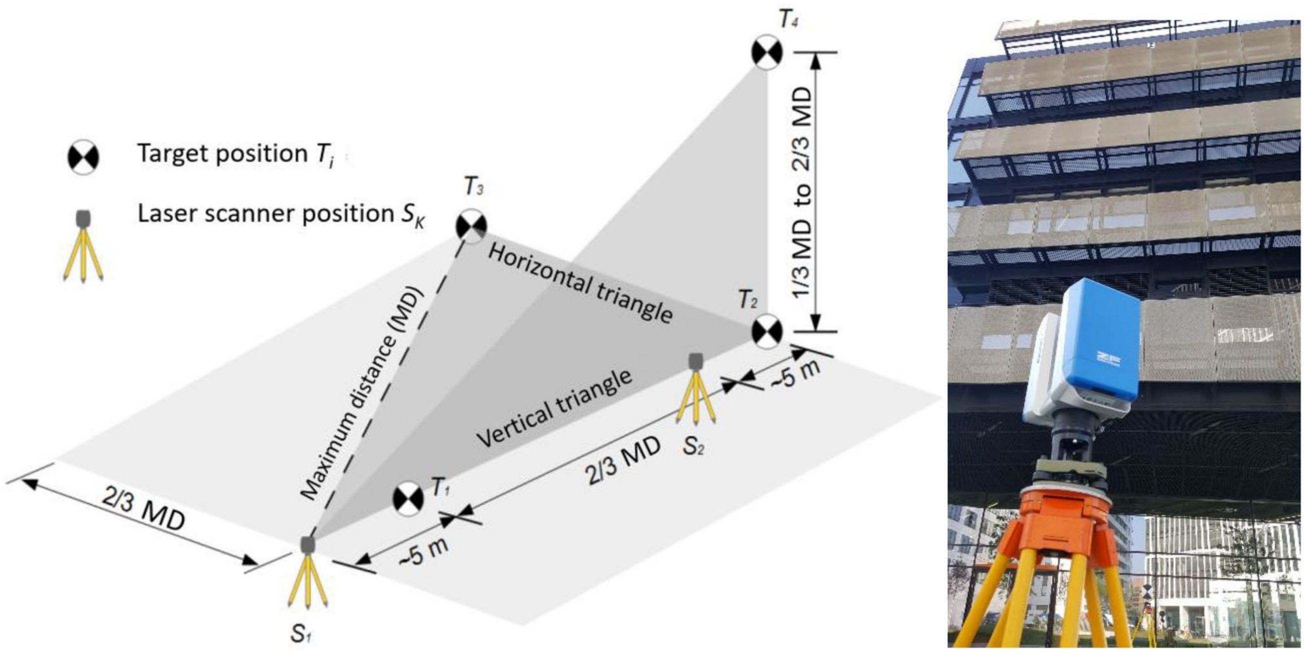
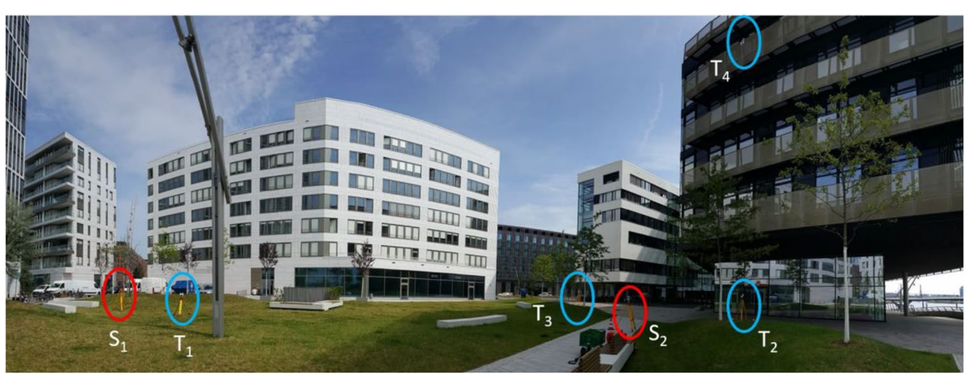


Fig. 11 Schematic measurement setup of the field test procedure (left, according to DVW instruction sheet 07-2014 in Neitzel et al. (2014)) and Z+F IMAGER 5016 scanning T4 and T2 (right)

Fig. 12 Panoramic view of the measurement setup for the field test procedure at the Henning-Voscherau-Platz in front of the HCU building (right) according to the setup in Fig. 11. Red circles = scanner stations, blue circles = target positions



For the Faro scanner, all scans were performed as 360° scans with the scan parameter resolution 1/1 and quality 1× (which corresponds to 1.5 mm at 10-m distance and low measurement noise compression); each scan took approximately 15 min without colour acquisition.

After scanning in the field, only the 3D coordinates of each scanned target are required. Therefore, the target fitting was performed in the respective software and the determined target coordinates were exported and entered into the standardised Excel form, which is available with the DVW instruction sheet. From these target coordinates, distances and finally distance differences were calculated. In order to assess the significance of the differences that occurred, a measurement uncertainty u_T of the target centres had to be defined for each of the instruments investigated. Whilst this parameter was derived in 2019 for the two scanners investigated from the technical specification of the manufacturers, the measurement uncertainty u_T of the three scanners was determined in 2020 from multiple measurements of the target centres and a resulting standard deviation of each target centre coordinates (Table 3). From this measurement uncertainty u_T, the comparative quantity of the distance differences was derived according to Eq. (1) for the final evaluation of the instrument (Table 3).

$$u_\Delta = k \cdot u_\Delta = k \cdot 2 \cdot u_T = 4 \cdot u_T \tag{1}$$

Then, the coordinates of each measured target are averaged and the distances T_iT_j between the targets are calculated for both scan stations:

$$T_iT_j = \mathrm{sqrt}\left(\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2 + \left(z_j - z_i\right)^2\right) \tag{2}$$

Since all scanned distances are available twice due to two scan stations, differences Δ_{ij} can be calculated from each of the two distances, which were summarised in Table 3:

$$\Delta_{ij} = T_iT_j\left(S_1\right) - T_iT_j\left(S_2\right) \tag{3}$$

The results of the field test procedure are summarised in Table 3 for five laser scanners investigated in accordance with the calculation form of the DVW instruction sheet. For the three IMAGER 5016 scanners, the difference $\Delta_{1.2}$ is −1.7 mm, −2.4 mm, and −2.1 mm and is thus significantly below the reference value (2.3 mm/8.0 mm/4.4 mm) for all distances. Thus, no significant distance deviation can be detected. For the differences $\Delta_{1.4}$ and $\Delta_{3.4}$, only small deviations between −0.2 mm and −3.0 mm were determined and thus no significant errors in the angle measurements were detected.

The RTC360 delivers the highest value of all scanners for the distance difference $\Delta_{1.2}$ with 6.0 mm, but this value is still no indication of a distance deviation because the decisive comparison variable has the same value. The differences $\Delta_{1.4}$ and $\Delta_{3.4}$ are significantly lower at 3.0 mm and 0.2 mm and also do not indicate any errors in the angle measurement.

With the Faro X330, the distance differences $\Delta_{1.2}$ and $\Delta_{1.4}$ are in the level of the two IMAGER 5016 tested in 2020, but the difference $\Delta_{3.4}$ is the highest of all scanners at 11.1 mm. Nevertheless, the constant and systematic distance measurement deviation with 1.1 mm (1.2/2) does not give any indication of a distance deviation, since the comparison variable has a high value of 13.2 mm. In addition, no errors in the angle measurement are displayed in the calculation form.

The verification of the laser scanners by the field test procedure has shown that all scanners are suitable for use and that with the determined distance differences there are no significant distance and angle deviations in all instruments.

Conclusion and outlook

In this paper, successful laboratory and field investigations for current terrestrial laser scanners were presented. The results of the laboratory tests show a high level of accuracy for all scanners, which correspond to the manufacturer's specifications. For the first time, three laser scanners of the same type (Z+F IMAGER 5016) could be examined and compared. In the investigations, very good accuracies were achieved for all Z+F IMAGER 5016 tested, which also

Table 3 Results of the field test procedure of five different laser scanners according to the calculation form of the instruction sheet — uncertainty of measurement u_T, comparative value u_Δ, distance differences Δ_{ij}, and constant, systematic distance measurement deviation Δ_{Meadev}

Parameter (mm)	Z+F 5016 LKA (2019)	RTC360 (2019)	Faro Focus X330 (2020)	Z+F 5016 GT17 (2020)	Z+F 5016 GT18 (2020)
u_T	0.6	1.5	3.3	2.0	1.1
u_Δ	2.4	6.0	13.2	8.0	4.4
$\Delta_{1.2}$	−1.7	6.0	2.2	−2.4	−2.1
$\Delta_{1.3}$	0.1	5.2	3.1	−3.0	−2.0
$\Delta_{1.4}$	−0.2	3.0	3.1	−3.0	−1.5
$\Delta_{2.3}$	−6.2	0.8	2.6	−3.1	−3.7
$\Delta_{2.4}$	2.1	3.8	3.3	0.4	0.5
$\Delta_{3.4}$	−2.2	0.2	11.1	−2.9	0.5
Δ_{Meadev}	−0.8	3.0	1.1	−1.2	−1.1

performed slightly better than the Leica RTC360 in all 2019 test scenarios in the laboratory (3D test field, 20-m comparator track, and planar stone slab). Although the results apply only to the specific instruments in this investigations, they were confirmed in the case of the IMAGER 5016 (HCU) by the tests in 2020. The result of the Faro Focus^{3D} X330 scanner in the 3D test field is significantly worse compared to the other scanners. In general, the terrestrial laser scanning systems should be always considered as a complete system consisting of hardware and software (with the corresponding algorithms for point cloud processing).

For the Leica BLK360, the manufacturer claims a 3D point accuracy of 8 mm at a distance of 20 m, which is lower than other, usually more expensive scanner. The investigations in the distance measurement accuracy of the Leica BLK360 showed that the manufacturer's specifications could be met in most of the scanned distances. However, both the comparison of the spatial distances in the test field and horizontal distances at the comparator track with references demonstrated that outliers are in the scanned data set. These outliers could be addressed to an unreliable automatic target fitting in the ReCap Pro software or errors in the scanning instrument. Nevertheless, a systematic effect could be detected, since the scanned distances of the BLK360 were too short in both, in the test field and at the comparator track. Finally, it must be mentioned that the investigations took place at a very early stage of software (ReCap Pro) and hardware (Leica BLK360) development. For this reason, further investigations should be carried out with other scanners of the same type in order to validate the results obtained here. Schmitz et al. (2021) already determined the magnitude and spatial expansion of the resolution capability of the BLK360 amongst nine other TLS.

In the field test procedure, two additional Z+F IMAGER 5016 and a Faro Focus^{3D} X330 were tested in 2020, in addition to the Z+F IMAGER 5016 and Leica RTC360 terrestrial laser scanners in 2019. The field test procedure took half a day for each of the scanners. The Henning-Voscherau-Platz in front of the HCU building was a suitable environment for the required measurement setup according to the DVW instruction sheet (horizontal and vertical triangle; see Fig. 13), but this may not be the case everywhere in practice. The measurement setup for the field test procedure could be largely adhered to at this location except for the parameters a_2 and a_3, as can be seen from the derived parameters of the scan data of the IMAGER 5016 (2019) in Table 4. The results of the field test procedure showed no significant distance or angular deviations for any of the scanners, thus demonstrating suitability for use. However, since the results of the field test procedure depend on the measurement uncertainty u_T or on the reference quantity u_Δ, it would be desirable if the system manufacturers would clearly specify this value in their technical specifications.

Critical aspects were also identified during the investigations. It was possible to export the determined target

Table 4 Review of the measurement setup for the field test procedure using the scan data from the IMAGER 5016 (2019)

Requirements according to instruction sheet		Value	Check
Straight line	S1, T1, S2, T2 in alignment (gon)	0.61	✓
Horizontal triangle	Right angle β in T2 (gon)	105.0	✓
Vertical triangle	Right angle β in T2 (gon)	98.5	✓
($\beta \approx 90°$, $\zeta \approx 30°$)	Tilt angle (ζ) in S2 to T4 (gon)	27.8	✓
a_1	Approximately 5 m	5.3	✓
a_2	2/3 c (m) = 31.7 m	21.6	(✓)
a_3	Approximately 5 m	8.6	(✓)
b	2/3 c (m) = 31.7 m	29.2	✓
c	Maximum distance (m)	47.6	-
d	1/3 to 2/3 c (m) = 15.9–31.7 m	17.6	✓

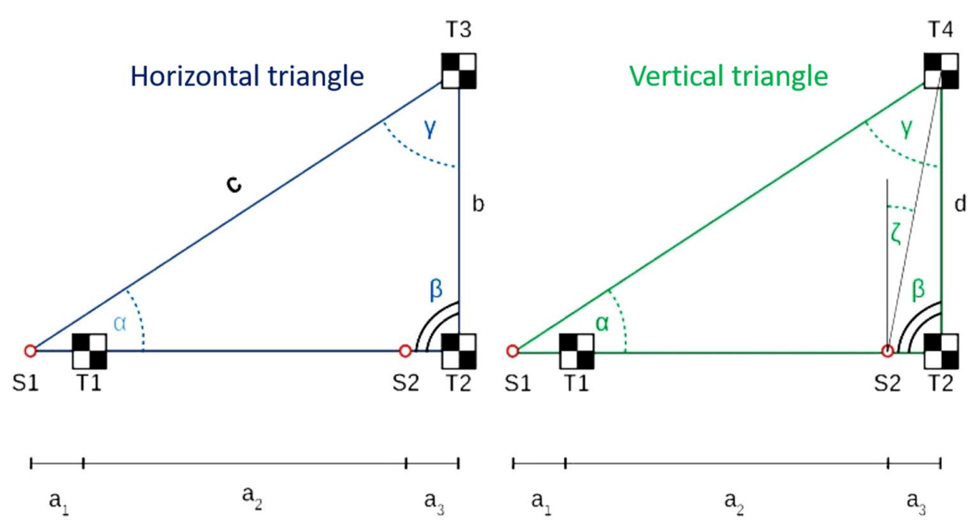


Fig. 13 Parameter of the two triangles according the setup of the field test procedure (see Fig. 11)

Table 5 Comparison of the amount of data generated during the four Z+F IMAGER 5016 and Leica RTC360 scanners

Scanner	test	# station	# scans	scan time [min]	data [GB]
Z+F5016 Zoller+Fröhlich	20m track, b/w target	1	20	56	0,3
	20m track, sphere	1	21	29	0,4
	3D test field	4	4	34	0,5
	Stone slab	1	4	8	0,1
RTC360 Leica Geosystems	20m track, b/w target	21	21	49	59,7
	20m track, sphere	21	21	48	59,7
	3D test field	4	4	36	14,2
	Stone slab	1	3	5	3,7

coordinates in Z+F LaserControl and in Faro Scene, whilst this option was not available in Leica Cyclone Register 360. In addition, different amounts of data were generated in the various test scenarios (Table 5). Whilst the IMAGER 5016 generated a data volume of 1.3 GB, the Leica RTC360 generated a data volume of 137.3 GB, which was larger by a factor of 100.

The investigations of terrestrial laser scanners will also be carried out in the future at the HCU Hamburg, since the tests can also be integrated very well into the course "Terrestrial Laser Scanning 2" of the Geodesy and Geoinformatics master degree program. A regular examination of the same scanners will then also allow statements to be made about the long-term stability of the scanners examined.

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Declarations

Conflict of interest The authors declare no competing interests.

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