Investigating Laser Scanner Accuracy

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Abstract. In a research project, i3mainz has installed a number of different test targets that allow an investigation in the quality of measurements obtained with laser scanners. The standardized tests, carried out since 2003, also allow a comparison between instruments of different manufacturers for the first time. The test procedures include scans of plane surfaces of different reflectivity in different ranges to obtain information about the noise of the range measurements and about systematic offsets caused by different materials. Several test fields using white spheres as targets have been installed to get information about the accuracy of distances in scanning direction and across. Due to different angular increments and spot sizes, not all 3D scanners have the same abilities to resolve small object details. 3D scanners are also known to produce errors at edges. Both phenomena are tested with appropriate targets. The tests are still available and producers and users are invited to have their instruments examined.

1 Introduction

Surveying results must meet certain specifications in order to provide the necessary accuracy standards for a certain application. On the other hand, if instruments and methods are used which yield an accuracy far above the needed standard, this will result in unnecessary cost and expenditure. Therefore, any geometric surveying task comprises not only the derivation of the relative positions of points and objects but also an estimation of the accuracy of the results. In traditional surveying and photogrammetry where defined targets are observed, least squares adjustment based on overdetermination usually yields reliable information concerning the accuracy of the results as well as the accuracy of the observations. If the number of observations is not sufficient for an adjustment, one may estimate the accuracy of the results by propagating the errors of the observation instruments to the results. In this case, the accuracy of the measurement device has to be known. Furthermore, the results can be improved applying calibration values to correct systematic errors.

In the case of laser scanners, a large number of 3D coordinates on an object's surface is measured in a very short time. Relevant object features, such as corner points or edges, are not directly recorded; instead they have to be modeled from the point clouds in a separate process. While it is possible to record the same object several times from different observation points, it is impossible to record the very same points in these repeated surveys. Therefore, deviations can only be noticed after objects have been extracted from the point clouds and modeled. If the geometric properties of the objects are known, however, the deviation of single points from the object's surface may be an indication for the accuracy. Using a plane surface would be the simplest case, but cylinders or spheres can also be considered.

2 Accuracy of Laser Scanners

2.1 General Remarks

The accuracy specifications given by laser scanner producers in their publications and pamphlets are not comparable. Experience shows that sometimes these should not be trusted and that the accuracy of these instruments which are built in small series varies from instrument to instrument and depends on the individual calibration and the care that has been taken in handling the instrument since.

Every point cloud produced by a laser scanner contains a considerable number of points that show gross errors. If the point cloud is delivered as a result of surveying, a quality guarantee, as possible for other surveying instruments, methods, and results, cannot be given.

When the tests were initiated in 2003, some institutions had already published methods and results concerning accuracy tests with laser scanners (e.g. Balzani et. al., 2001, Johansson, 2002, Kern, 2003, Lichti et. al., 2000, 2002). Based on this knowledge a comprehensive test program was developed at i3mainz and as many different scanners as possible were compared since, using the same installations

2.2 Angular Accuracy

The laser pulse is deflected by a small rotating device (mirror, prism) and sent from there to the object. The second angle, perpendicular to the first, may be changed using a mechanical axis or another rotating optical device. The readings for these angles are used for the computation of the 3D point coordinates. Any errors caused by the axes/bearings or angular reading devices will result in errors perpendicular to the propagation path. Since the positions of single points are hard to be verified, few investigations of this problem are known. Errors can be detected by measuring short horizontal and vertical distances between objects (e.g. spheres) which are located at the same distance from the scanner and comparing those to measurements derived from more accurate surveying methods.

2.3 Range Accuracy

In the case of ranging scanners, range is computed using the time of flight or a phase comparison between the outgoing and the returning signal. Ranging scanners for distances up to 100 m show about the same range accuracy for any range. Triangulation scanners solve the range determination in a triangle formed by the instrument’s laser signal deflector, the reflection point on the object’s surface and the projection center of a camera, mounted at a certain distance from the deflector. The camera is used to determine the direction of the returning signal. In contrast to the ranging scanners, the accuracy of ranges acquired with triangulation scanners diminishes with the square of the distance between scanner and object (Boehler and Marbs, 2002).

Ranging errors can be observed when known distances in range direction are measured with the scanner. If scanners are not equipped with a defined reference point (such as forced centering), it is only possible to measure range *differences* between targets. Plane, cylindrical or spherical targets may be used if their precise positions are surveyed with instruments and methods more accurate than the laser scanner.

Whereas a systematic scale error will be present in any spatial distance measured, a systematic constant (zero) error will be eliminated when distance differences in range direction are determined. The constant error will influence distances between two points which are located in different directions as seen from the scanner, however. If both points are located in the same distance from the scanner, the deviation of their distance will amount to the zero error when the direction difference is 60°; it will amount to twice the zero error when the direction difference is 180° (e.g. when scanning all walls with a panoramic scanner from one single observation point in the center of a room). Since systematic range errors vary depending on the reflective material, a universal correction for a zero error cannot be determined (see sections 2.6 and 4.6). This is the main reason why a generally acceptable calibration and certification of laser scanners is not possible.

A very fast and easy check for the noise (accidental error, precision) of range measurements can be achieved when a plane target perpendicular to the observation direction is scanned and the standard deviation of the range differences of the points from an intermediate plane through the point cloud is computed. As an additional result, this test also detects if range is internally only provided with a certain resolution (e.g. 1 cm) which is the case for some instruments (Kern, 2003).

2.4 Resolution

The term "resolution" is used in different contexts when the performance of laser scanners is discussed. From a user's point of view, resolution describes the ability to detect small objects or object features in the point cloud. Technically, two different laser scanner specifications contribute to this ability, the smallest possible increment of the angle between two successive points and the size of the laser spot itself on the object. Most scanners allow manual settings of the increment by the user.

Since the combined effects of increments and spot size determine object resolution, a test object comprising small elements or small slots can serve to determine feature related resolution information.

2.5 Edge Effects

Even when well focused, the laser spot on the object will have a certain size. When the spot hits an object edge, only a part of it will be reflected there. The rest may be reflected from the adjacent surface, a different surface behind the edge, or not at all (when no further object is present within the possible range of the scanner). Both, ranging scanners and triangulation scanners produce a variety of wrong points in the vicinity of edges. The wrong points (artifacts, phantom points) are usually to be found on the ray from the laser deflection point in the instrument through the edge point, behind the edges (when looking from the scanner). The range error may vary from just a fraction of a millimeter to values of several decimeters. In addition, the object representation in the point cloud is larger than reality since the point will be recorded at the angular position of the *center* of the ray even if the object is hit only with the *edge* of the ray.

Obviously, wrong points are inevitable since the laser "spot" cannot be focused to point size. It can be assumed that well focused lasers will show better results. When using a standard target with different types of edges, the performance of different types of scanners can be compared.

A systematic effect can be observed when cylindrical and spherical targets are observed (Lichti et. al., 2002). In this case, especially at the peripheral parts of the object, the center of the reflecting surface area is not identical with the center of the transmitted beam.

2.6 Influence of Surface Reflectivity

Laser scanners have to rely on a signal reflected back from the object surface to the receiving unit in case of ranging scanners and to the camera in case of triangulation scanners. In either case, the strength of the returning signal is influenced (among other facts such as distance, atmospheric conditions, incidence angle) by the reflective abilities of the surface (albedo). White surfaces will yield strong reflections whereas reflection is weak from black surfaces. The effects of colored surfaces depend on the spectral characteristics of the laser (green, red, near infrared). Shiny surfaces usually are not easy to record.

It has been observed that surfaces of different reflectivity result in systematic errors in range. For some materials these errors may reach amounts several times larger than the standard deviation of a single range measurement. Some scanners which provide some type of aperture adjustment show errors in the first points after the laser spot has reached an area of a reflectivity differing considerably from the previous area, and it can be observed that the correct range is achieved only after a few points have been measured. For objects consisting of different materials or differently painted or coated surfaces, one has always to expect serious errors. These can only be avoided if the object is temporarily coated with a unique material which, of course, is not applicable in most cases.

If the effect has to be examined and evaluated, one may use plane white targets and apply the material in question to the center part of the target. When the intermediate planes are computed for the coated center part only and then for the rest of the (white) target without using the center part, the difference between those planes will give an indication of this effect.

2.7 Environmental Conditions

Temperature. Any scanner will only function properly when used in a certain temperature range. Even within this range, deviations may be observed, however, especially in the distance measurement. It should be noted that the temperature inside the scanner may be far above the temperature of the surrounding atmosphere due to internal heating or heating resulting from external radiation (sun). Obviously, temperature effects may show systematic changes over time.

Atmosphere. As in any optical distance measurement, the change of the propagation speed of light due to temperature and pressure variations affects the results. For short ranges this is often neglected. Also, many users report that measurements in surroundings where dust or steam is present lead to effects similar to the edge effects described above.

Interfering radiation. Lasers operate in a very limited frequency band. Therefore filters can be applied in the receiving unit allowing only this frequency to reach the receiver resp. the camera. If the radiation of the illumination source (sunlight, lamps) is strong as compared to the signal, enough of this ambient radiation will pass the filter and influence the accuracy or prevent any measurements at all.

2.8 Specifications and Considerations Besides Accuracy

This article concentrates on accuracy considerations. Of course, other scanner specifications influence their applicability as well (Boehler and Marbs, 2002). Among these are measuring speed, range limits, field of view, laser class, registration devices for the combination of several scans and the transformation to a control network, the availability of imaging cameras which can work in combination with the scanner, weight and ease of transportation, power supply (battery operation), ruggedness when operated in bad weather or hostile environments, availability and quality of software.

Besides, the quality of the user support and the guarantee conditions are not the same for all manufacturers. These should be checked carefully in addition to the technical specifications before a decision is made to favor one product or another.

3 Testing Installations at i3mainz

3.1 General Remarks

When the decision was made to start a research program with the aim to compare the accuracy and performance of different types of laser scanners, new testing installations had to be developed. In order to reduce measuring time and expenses, a set of targets was designed using standard materials, and all experiments were installed in two buildings of FH Mainz, University of Applied Sciences. Most experiments can be repeated at any other location provided the same type of targets and surface paints are used.

Since single points of scans cannot be analyzed and compared, ball type targets (white spheres with a diameter of 76.2 mm on a magnetic ground plate as produced by Mensi) are used for most distance determinations. Scanners proposed for a variety of different application tasks should be able to detect and model a sphere of this size. Plane boards are used for experiments concerning range noise and investigations concerning the behavior of surfaces with different reflectivities. Some additional special objects, described below, were constructed for further investigations.

In the opinion of the authors it is not possible to supply a calibration or certification for laser scanners since the parameters and procedures influencing the result of a measurement are too numerous. Therefore it should be noted that our experiments were not designed in order to find the mechanical, optical or electronic sources of errors in the instruments; instead they show the effects of such errors on a certain measurement under practical measurement conditions. When, for example, a short distance between two spheres which are at the same distance from the scanner, is derived after their center points have been modeled from the point clouds, this will give a general indication of the angular accuracy of the scanner but does not really tell everything about the accuracy of the angular position of a single point. Since the same procedures and targets were used for all instruments examined, this provides a reliable method to compare the performance of those instruments under practical application conditions.

On spheres, a point grid of 4 mm spacing was aimed at. If this was not possible, a value as close as possible was chosen. Accordingly, the grid spacing for planes was 5 mm or as close to this value as possible. Tests concerning resolution and edge effects were carried out with 1 mm grids, if possible. All objects were recorded once, using one measurement per point and recording tenths of millimeters (if possible).

Modeling planes and spheres was accomplished using least squares adjustment. Known geometric object properties (planarity of planes, diameter of spheres) were introduced as fixed values. Mensi's 3Dipsos software was used after it was verified that it yields the same results for these tasks as other software.

When modeling intermediate planes, points near the edges were manually removed. When spheres were modeled for distance evaluations in range direction, points near the circumference were also removed manually (they were kept, however, when distances orthogonal to range direction were determined). All modeling and computation tasks were carried out by the same person.

3.2 Angular Accuracy

Errors in the angles between two rays can be detected when a short distance between two spheres located at equal distances from the scanner is determined. Modeling the spheres will result in a low pass filtering. Therefore the results will not allow detecting small arbitrary angular variations.

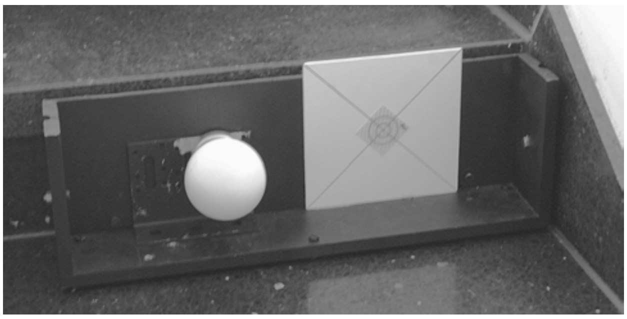


Figure 1. Box for positioning spheres at defined locations on steps.

A first test installation uses white spheres in a box that can be positioned at well defined points on a stone stairway at the end of a 60 m corridor. The box (Figure 1) allows repositioning the spheres within some tenths of millimeters with respect to the stone steps when the tips of six bolts protruding from the bottom and the sides are brought into contact with the stone faces of the steps. Thus, the precise position, acquired with geodetic methods can be re-established any time. The targets are used on either side of six steps, a distance of about 1 meter (Figure 2). This allows the calculation of six independent short distances in horizontal and six in vertical direction.

In a different room, four spheres are installed at a vertical wall at the corners of a rectangle 3.5 m high and 5 m wide. Since special steel plates with two defined mechanical contacts for the magnetic ground plates of the spheres are used (Figure 3), the spheres can be re-positioned precisely to the original position which was determined by geodetic methods. This arrangement is scanned from a distance of up to 15 m from three observation points as indicated in Figure 4. This again yields six independent distances in horizontal and six in vertical direction.

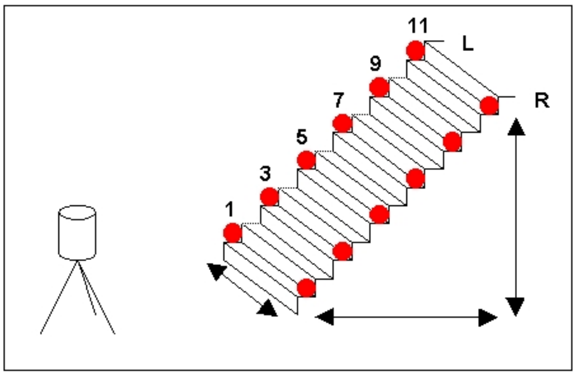


Figure 2. Sphere positions on the stairway.

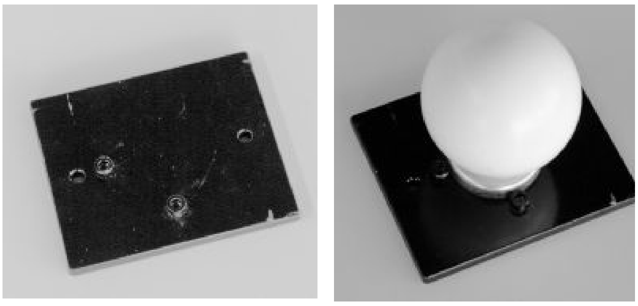


Figure 3. Steel plate for positioning a sphere at a wall.

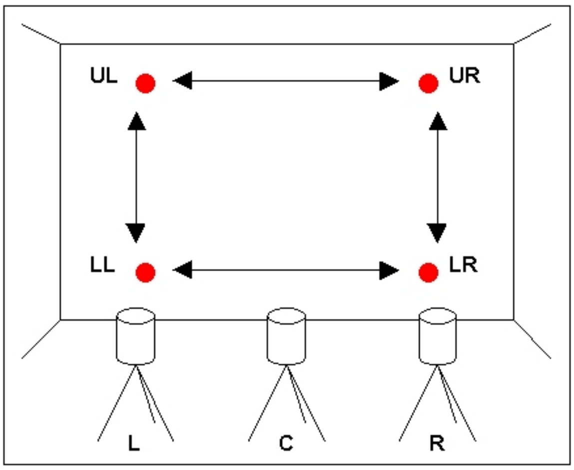


Figure 4. Location of spheres at a wall and observation stations.

3.3 Range Accuracy

Measuring noise. A very simple test to get an indication of the arbitrary range deviations can be performed when a plane surface is scanned and modeled. The resulting deviations of the single points are a reliable source of information for the precision of range measurements. Three different surfaces are used: white, gray and black with reflectivities of about 80, 40 and 8 %.

Known range differences. Three different experiments are installed in order to compare known range differences with the ones measured by the scanners. Spheres are used in either case for the end points of the distances. In the set-up shown in Figure 2, where small range differences can be measured from observation stations up to 60 m away, the horizontal components in range direction are used to form six independent distances. In addition, the faces of steel lockers in this long corridor were used to place spheres at well defined known locations thus allowing the comparison of 4 range differences in mid-range. Finally, for close ranges between 3 and 8 m, a sphere is placed on an interferometric comparator and moved to six positions with 1 m spacing, thus providing another 3 independent range differences. Since all these measurements concern differences in range direction, a systematic constant (zero) error would not be detected. This error will show up in the measurements of longer distances orthogonal to range direction, as the set-up shown in Figure 4. Distance deviations in this case would be caused by both, an angular and a constant range error.

3.4 Resolution

Since values for increments and spot sizes in the manufacturer's specifications do not give much indication about the ability of a scanner to reach a certain resolution, a practical approach is chosen in order to achieve resolution information. A box about 300 mm x 300 mm was constructed (Figure 5). The front panel has slots which are about 30 mm wide at the outside becoming smaller towards the center. If a scanner has a high resolution (small angular increments and a small laser spot) there should be reflections not only from the front panel but also from the bottom of the box which is about 55 mm behind the front panel. If the resolution is very good, these reflections from the bottom should not only be present in the outer regions but also near the center.

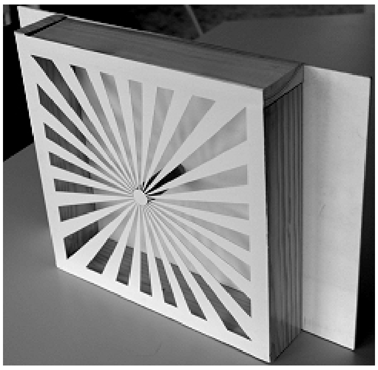


Figure 5. Target with slots of varying widths for resolution tests.

3.5 Edge Effects

Edges. A board (Figure 6) is used to get an indication how many points are recorded at wrong locations due to edge effects. The board is placed against a sky background when scanned. Thus, the measurement of the outer edges will not be influenced by objects behind the board whereas the front edges of the attached smaller board simulate the effect of reflections from two different objects. The evaluation is based on a plot of the resulting point cloud (see Figure 10).

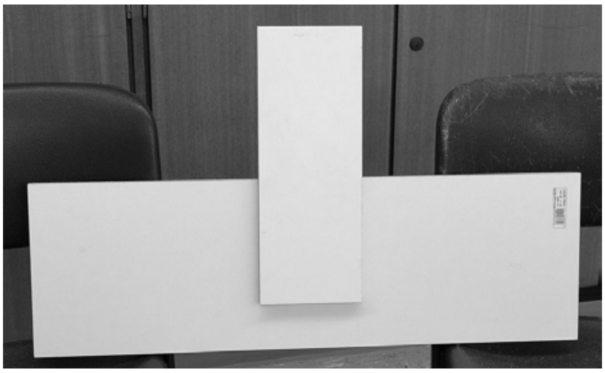


Figure 6. Board used to study edge effects.

Cylinder. A vertical pipe with a diameter of 200 mm is scanned from a distance of 3 m. A cylinder is modeled from the point cloud and its diameter compared to the known value. Also, to visualize the effect, the resulting point cloud is plotted and compared graphically with the known diameter.

3.6 Influence of Surface Reflectivity

Boards showing a wide white frame and a square center part of different reflectivity (Figure 7) are scanned. Separate planes are modeled through the frame and the center part (excluding points at the edges). The range difference between the two planes indicates the error which has to be expected in similar cases. The following colors and materials are used:

- White dull spray paint, reflectivity 90%
- White dull spray paint, reflectivity 80%
- Gray dull spray paint, reflectivity 40%
- Black dull spray paint, reflectivity 8%
- Spray paint with metallic appearance
- Polished aluminum foil
- Blue retro foil, as used on Leica targets

Since large deviations were observed on the orange parts of a rubber traffic cone with alternating orange and white sections, this object (not a plane) was also added to the test procedure. Similar effects can be observed when range poles coated with “warning” color are scanned.

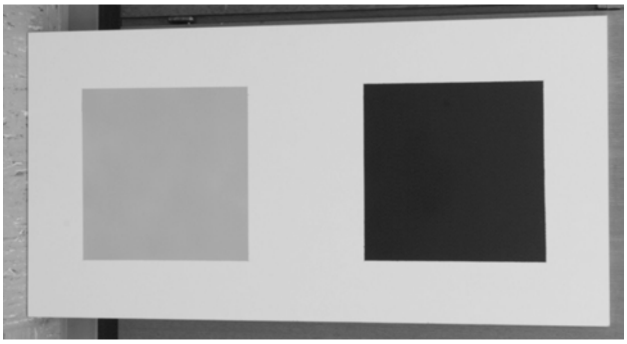


Figure 7. Board with white frame and different surface coatings.

3.7 Environmental Conditions

All tests were conducted under favorable conditions, predominantly inside of buildings at temperatures around 20°C.

4 Results

4.1 Important Preliminary Remarks

Accuracy tests comparing different instruments have to be standardized in some way. We chose the approach to measure objects once with a defined point density. (Alternatively, considering the fact that some scanners record a much larger number of points in a certain time period, one could also use this time as a standard and allow a certain time period to achieve an object scan. Even more realistic, a relation between accuracy and cost could be used, considering different purchase and operating costs in addition.)

The following results were achieved solving certain tasks under certain preconditions as described above.

If a scanner shows “better” results than another one, this does not necessarily mean that it is the better instrument for a certain task different from the ones performed in our tests!

For example, the fine point grids of 4 resp. 5 mm could not be achieved with some instruments, therefore the results in our tests look poor, although these instruments would be perfectly suitable for certain other tasks (see also sections 2.8 and 4.8).

For the tests we tried to evaluate all laser scanners (working either on the time-of-flight, modulation or triangulation principle) that are able to record points at a 10 m range and claim to be applicable for different scanning tasks. According to the list supplied by our web site (WWW, 2003) this comprises about one dozen different instruments. Manufacturers and users were asked to co-operate in the tests. We are very grateful that many gave us the opportunity to test their instruments and others promised to co-operate in the near future. The following list shows the instruments tested so far. Updates will be published on our WEB site when additional scanners are examined.

Table 1. Scanners tested at i3mainz. Years indicate: year of production / year of test.

	Supplied by manufacturer	Supplied by users	Owned by i3mainz	Total tested
Callidus Precision Systems		2000/2003 2001/2003		2
Leica HDS2500	-/2003		2001/2003	2
Leica HDS3000	2004/2005	2004/2005		2
Mensi S25			2001/2003	1
Mensi GS100	2002/2003			1
Mensi GS200		2003/2004		1
Riegl LMS-Z210		2001/2003		1
Riegl LMS-Z420i	2003/2003			1
Riegl LPM-25HA		2004/2004		1
Zoller+Froehlich Imager 5003	2003/2003			1
			Total:	13

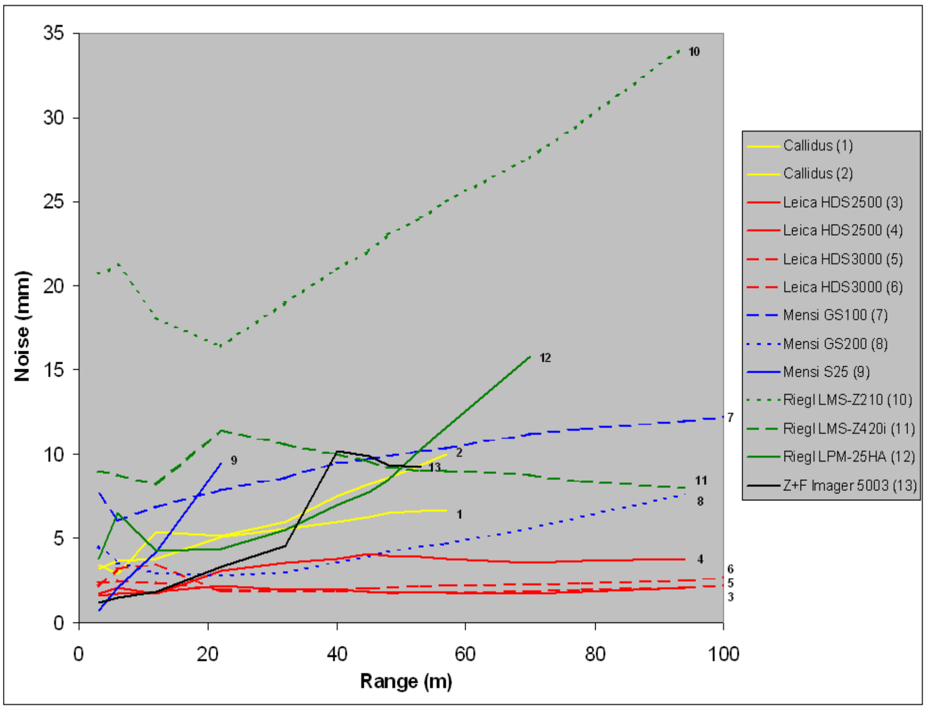


Figure 8. Measuring noise in range direction (standard deviation for a single point) for different scanners on a gray surface (40% reflectivity).

4.2 Distances Orthogonal to Range

Most distances are relatively short. When differences between the true values and the values derived from scanning occur, they can be related to inaccurate measurements of angles in the scanner. The spatial distances are those between the centers of two spheres which have been modeled from a large number of scanned points on the spheres' surfaces. The modeling can be considered as a low pass filtering process. The deviations of single scanned points may be considerably larger. Although it could be expected that distance errors caused by angles grow with range, this could not be observed in most cases. Therefore distance errors are shown as results (Table 2) instead of angular errors.

Table 2. Differences between known and scanned distances between two spheres orthogonal to range. Standard deviations (mm) based on 12 independent vertical and 12 independent horizontal spatial distances.
[a] Because of limited angular increment tested for short ranges only.
[b] Influenced by low range accuracy due to triangulation principle at far range; much better for close ranges (e.g. 0.8 mm vert. and 0.2 mm horiz. at 4 m range)

	Vertical distances (std. dev.)	Horizontal distances (std. dev.)	Maximal absolute difference
Callidus Precision Systems (1)	5.6[a]	4.3[a]	12.2[a]
Callidus Precision Systems (2)	9.9[a]	2.5[a]	18.3[a]
Leica HDS2500 (1)	0.8	0.8	1.6
Leica HDS2500 (2)	0.5	0.5	1.1
Leica HDS3000 (1)	1.3	1.1	2.9
Leica HDS3000 (2)	1.1	1.8	2.8
Mensi S25	3.8[b]	3.4[b]	9.2[b]
Mensi GS100	1.9	2.3	3.3
Mensi GS200	4.7	2.2	8.3
Riegl LMS-Z210	10.2[a]	16.8[a]	27.1[a]
Riegl LMS-Z420i	1.7	2.1	4.1
Riegl LPM-25HA	2.5	3.9	6.5
Zoller+Froehlich Imager 5003	2.9	7.5	11.1

The standard deviations for different instruments vary considerably. Even at close range some scanners (marked with "[a]" in Table 2) have problems to resolve the spheres due to large laser spots and coarse angular increments. This results in poor "angular" performance although the angular positioning of the center of the laser beam itself may be much more accurate. Also, it should be noted that some instruments have different accuracies in vertical and horizontal directions.

4.3 Distances in Range Direction

As a general principle, distance *differences* between two spheres nearly in line with the scanner were measured. Because of the filtering effect described in section 4.2, deviations of single points may be considerably larger.

Table 3. Differences between known and scanned spatial distances between two spheres in range direction. Standard deviations (mm) based on at least 12 independent short distances in close range and 14 independent distances in far range.
[a] Modeling of spheres not possible for far ranges due to limited angular increment.
[b] But 0.2 mm at 4 m range and 0.5 mm at 6 m range.
[c] At 22m range. [d] Only 4 measurements at far range.
[e] Only 3 measurements at far range. [f] Only 2 measurements at far range.

	Close range < 10 m (std. dev.)	Far range 10 – 50 m (std. dev.)	Maximal absolute difference
Callidus Precision Systems (1)	1.5	-[a]	2.6
Callidus Precision Systems (2)	2.8	-[a]	5.9
Leica HDS2500 (1)	0.6	1.1	2.3
Leica HDS2500 (2)	0.4	0.5	0.9
Leica HDS3000 (1)	0.8	1.0	2.0
Leica HDS3000 (2)	1.2	0.7	2.3
Mensi S25	1.4[b]	4.6[c]	7.7[c]
Mensi GS100	2.6	2.0	8.2
Mensi GS200	1.1	1.1	2.7
Riegl LMS-Z210	19.7	-[a]	40.4
Riegl LMS-Z420i	2.6	2.7[d]	5.9
Riegl LPM-25HA	3.5	5.7[e]	6.4
Zoller+Froehlich Imager 5003	1.6	0.7[f]	12.3

As the spatial location of points rely on range as well as on angles, the results in Table 2 and in Table 3 should be considered in combination for a complete assessment of spatial accuracy.

4.4 Resolution

In order to judge the ability of a scanner to resolve small objects, the target shown in Figure 5 was scanned from two different ranges with small grid increments (1 mm if possible). Ideally, points should be recorded on the front panel as well as on the rear panel. In either case, the star type pattern should be clearly distinguishable. The resulting point clouds for scans from 6 m range (Figure 9a) and from 22 m range (Figure 9b) give a good indication of the object resolution that can be achieved.

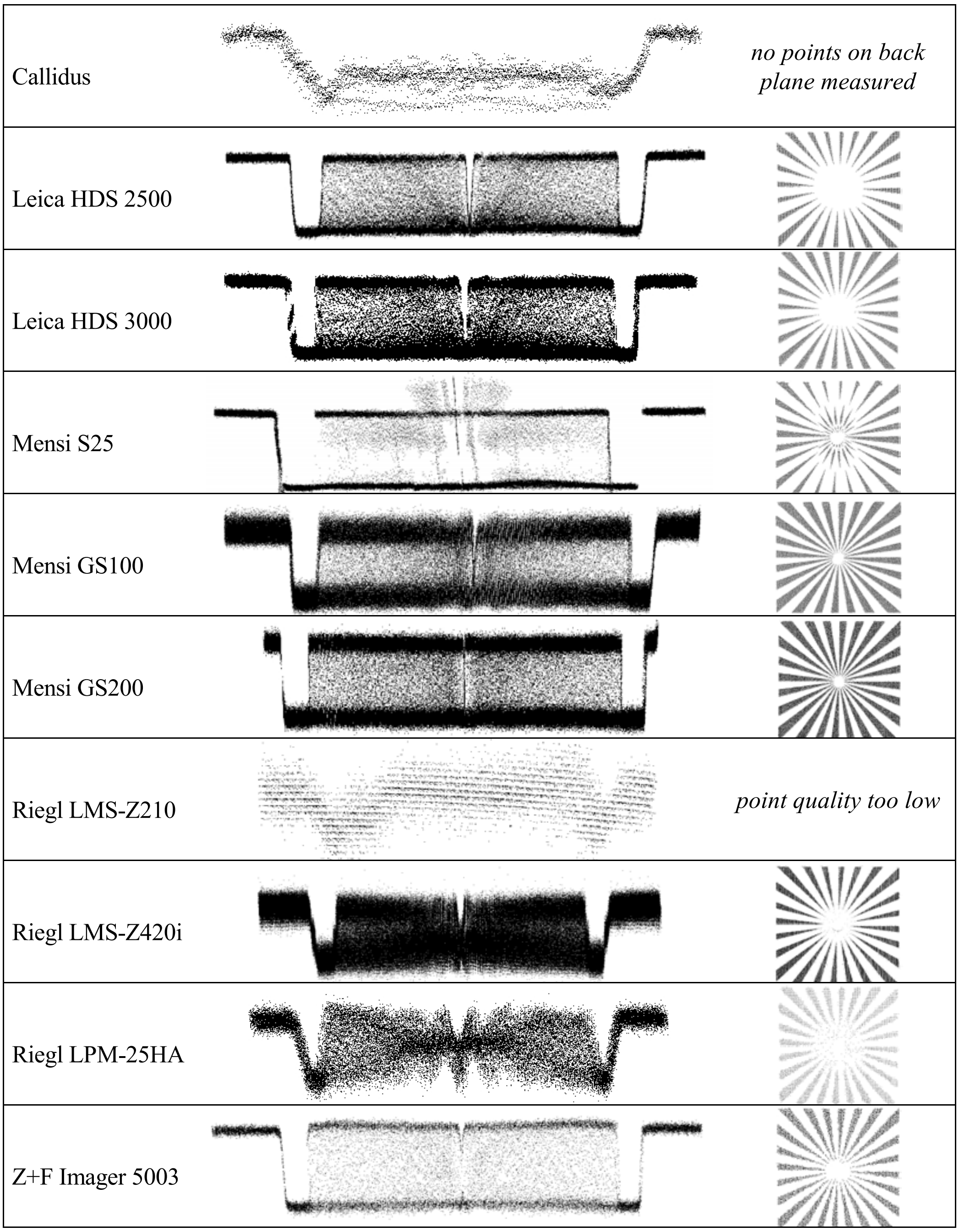


Figure 9a. Results of the resolution test using the target shown in Figure 5. Scanned at **6 m** range.
Left: Cross section of point cloud. Right: Points on back plane of target (in smaller scale).

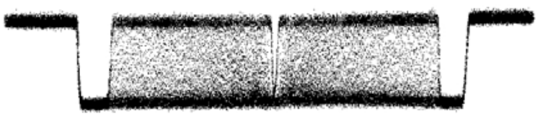
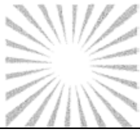
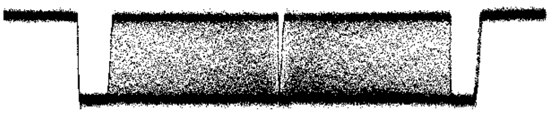
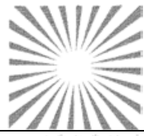
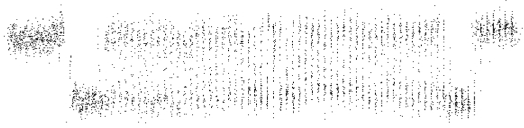
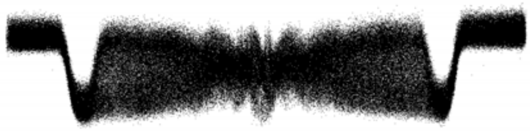
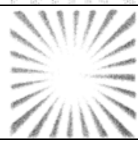
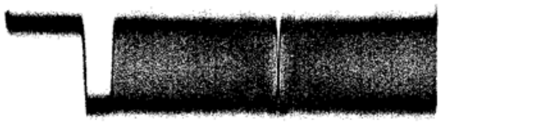
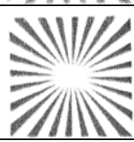
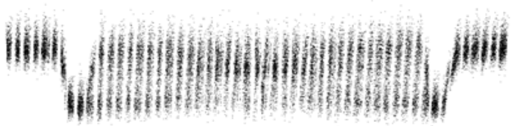
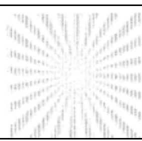
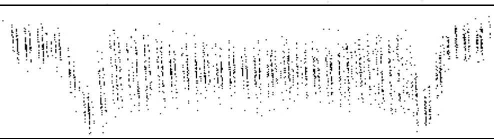
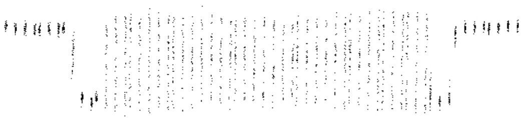
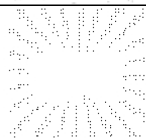
Callidus	*point density too low to resolve the object at this range*	
Leica HDS 3500		
Leica HDS 3000		
Mensi S25		
Mensi GS100		
Mensi GS200		
Riegl LMS-Z210	*point density too low to resolve the object at this range*	
Riegl LMS-Z420i		
Riegl LPM-25HA		
Z+F Imager 5003		

Figure 9b. Results of the resolution test using the target shown in Figure 5. Scanned at **22 m** range. Left: Cross section of point cloud. Right: Points on back plane of target (in smaller scale).

4.5 Edge Effects

Results for the edge detection device (Figure 6) are shown in Table 4. Typical examples are plotted in Figure 10. Edge quality can also be judged from the point clouds shown in Figures 9a/b.

Table 4. Evaluation of edge quality.

	Edge quality
Callidus Precision Systems	low
Leica HDS2500	average
Leica HDS3000	average
Mensi S25	average
Mensi GS100	average
Mensi GS200	average
Riegl LMS-Z210	low
Riegl LMS-Z420i	average
Riegl LPM-25HA	average
Zoller+Froehlich Imager 5003	low

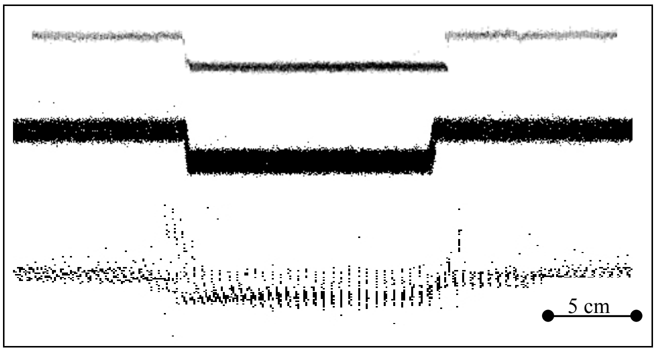


Figure 10. Typical examples for edge quality for the device shown in Figure 6.
Upper: High quality (not achieved with any scanner).
Center: Average quality. Lower: Low quality.

4.6 Influence of Surface Reflectivity

The results of the experiments described in section 3.6 are shown in Table 5. Whereas most instruments give reliable ranges for "normal" surfaces, some materials can produce systematic errors. Oblique incidence angles have not been tested and may result in other deviations. The variations prove that it is not possible to supply a general calibration for a scanner.

Table 5. Distance correction in mm due to different surface materials.
Positive sign = Distance is measured too short as compared to white surface.
[a] Scanner did not record any points on this surface.

	white 90%	white 80%	gray 40%	black 8%	metal paint	alu foil	blue foil	orange cone
Callidus (1)	0	0	0	0	0	0..-100	+7	-10
Callidus (2)	0	0	+4	+3	0..-10	0..-15	+5	-20
Leica HDS2500 (1)	0	0	0	0	0	0..+10	+22	-40
Leica HDS2500 (2)	0	0	0	0	0	0	+17	-70
Leica HDS3000 (1)	0	0	0	0	0	0..+15	+3	-25
Leica HDS3000 (2)	0	0	0	0	0	0	+3	-7
Mensi S25	0	0	0	0	0	0	0	0
Mensi GS100	0	0	0	+8	0	0	n.a.[a]	0
Mensi GS200	0	0	0	0	0	0	n.a.[a]	0
Riegl LMS-Z210	0	0	+13	+3	0..-100	0..-250	0	-100
Riegl LMS-Z420i	0	0	0	0	0	0	0	-20
Riegl LPM-25HA	0	0	+4	+5	0	0	-6	-20
Zoller+Froehlich	0	0	0	0	0	0..+30	-18m	-20

4.7 Environmental conditions

As mentioned above, all tests were conducted under favorable conditions, predominantly inside of buildings. Undoubtedly there are further conditions that will influence the accuracy of laser scanner measurements. These will have to be examined in separate investigations.

4.8 Specifications and Considerations Besides Accuracy

As pointed out in sections 2.8 and 4.1, accuracy is not the only fact that should be considered when selecting a laser scanner. Selling prices are important, too, and may depend on different specifications. Support and warranty conditions differ considerably! It should be checked how often the instrument has to be calibrated, where this has to be accomplished, how long this will take and what kind of expenses (service contracts, transportation, fees) this will cause for the user.

The quality of the included scanning software has to be considered, and it should be decided if modeling software has to be purchased separately from other companies (Boehler, Heinz, Marbs and Siebold, 2002).

In the following tables the authors report some major advantages and disadvantages of scanners. This is based on many reports from users, experience and subjective impressions and not on systematic research.

Table 6. Major advantages of some laser scanners.

Callidus Precision Systems	Very large field of view (full panorama)
Leica HDS2500	High accuracy.
Leica HDS3000	Very large field of view (full panorama). High accuracy.
Mensi S25	Very high accuracy for short ranges.
Mensi GS100	Large field of view.
Mensi GS200	High ranges possible. Large field of view. High resolution.
Riegl LMS-Z210	Very high ranges possible. Large field of view.
Riegl LMS-Z420i	Very high ranges possible. Large field of view.
Riegl LPM-25HA	Very large field of view. Similar to total station.
Zoller+Froehlich Imager 5003	Very high scanning speed. Large field of view.

Table 7. Major disadvantages of some laser scanners.

Callidus Precision Systems	Very coarse vertical angular increment (0.25°).
Leica HDS2500	Small scanning window (40° x 40°).
Leica HDS3000	-
Mensi S25	Fails in sunlight. Not suited for long ranges. Slow.
Mensi GS100	Large noise.
Mensi GS200	-
Riegl LMS-Z210	Low accuracy.
Riegl LMS-Z420i	Large noise.
Riegl LPM-25HA	Low scanning rate as compared to other Riegl scanners.
Zoller+Froehlich Imager 5003	Low edge quality. Limited angular increment (0.018°).

5 Conclusions

Laser scanners show considerable errors under certain conditions. Even when accuracy is not of much importance in certain applications, the resulting strain between neighboring points can be cumbersome when surfaces have to be modeled or when small details have to be detected. The results of our tests may help the producers to compare the performance of their instruments to those of their competitors. For the users, this publication and the associated web site (WWW 2003) may help to select the appropriate instruments for their projects.

6 Outlook

With the targets installed at FH Mainz, the authors are trying to test as many types of scanners as possible. Users and manufacturers are invited to have their instruments tested. Details about booking and fees can be found in the Internet (WWW, 2003).

7 Acknowledgements

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