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Article

Accuracy of Laser Scanners for Measuring Surfaces made of Synthetic Materials

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Keywords: terrestrial lidar, measurement error, material tests

Summary: Synthetics are a group of materials which, when observed using laser scanners, may cause additional measurement errors. These errors result from optical permeability, which may vary depending on the structure of the synthetic material. A laser beam which penetrates the material can be subject to numerous physical phenomena such as absorption, dispersion, full or partial reflection, refraction at the interface between two media, diffraction and interference that change the measured distance. As a result, additional measurement errors occur, independent of the known errors, when the beam is reflected from the outer surface of the material. Their occurrence is influenced by light transmission, density and internal structure of the synthetic material, its colour and thickness. The distance from the scanner, laser beam angle of incidence, temperature, scanner type (carrier wavelength), or even the distance between the synthetic material and its background are important as well. This study is devoted to examining these dependencies. Currently there are no studies distinguishing and examining synthetic materials as a separate group of materials that may interfere with distance measurements due to the phenomena that occur in their structure.

Zusammenfassung: *Genauigkeit von Laser-Scannern bei der Oberflächenmessung von synthetischen Materialien.* Synthetische Materialien können bei der Erfassung von Oberflächen mit Laserscannern zu zusätzlichen Messfehlern führen. Diese Fehler ergeben sich aus der optischen Durchlässigkeit, die in Abhängigkeit von der Struktur des synthetischen Materials variieren kann. Ein Laserstrahl, der in das Material eindringt, kann mehreren physikalischen Phänomenen, z. B. Absorption, Streuung, vollständige oder teilweise Reflexion, Refraktion an Grenzflächen zwischen zwei Medien, Beugung oder Überlagerung, unterworfen sein, welche die gemessene Distanz verändern. Als Ergebnis erhält man zusätzliche und von bisher bekannten Fehlerursachen unabhängige Messfehler, wenn der Strahl an einer aus synthetischem Material bestehenden Oberfläche reflektiert wird. Diese werden von der Lichtdurchlässigkeit, der Dichte und der inneren Struktur des synthetischen Materials beeinflusst. Die Distanz vom Scanner, der Auftreffwinkel des Laserstrahls, die Temperatur, der Scannertyp (Trägerfrequenz des Lasers) oder auch die Distanz der gescannten Oberfläche von Objekten, die sich aus Sicht des Sensors im Hintergrund befinden, sind ebenfalls von Bedeutung. Dieser Beitrag widmet sich der Untersuchung dieser Einflüsse. Bisher gibt es keine Studien, welche synthetische Materialien als eigene Gruppe von Materialen unterscheiden, welche in spezifischer Weise die Distanzmessung auf Grund ihrer inneren Struktur beeinflussen.

1 Introduction

Synthetic materials (materials consisting of synthetic polymers) are a group of materials which, when observed using laser scanners, may cause additional measurement errors. These errors result from the optical permeability, which may vary depending on the structure of the synthetic material. Existence of this phenomenon may be proved by the following experiment. One can measure a distance to a synthetic element, for example 2 mm – 3 mm thick, consisting of white

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Plexiglas or polystyrene, using any type of reflectorless range finder, then measure it again without changing the position of the element but with an identical element adhered to its back surface. The observed distance will be greater due to laser beam penetration through added layers of material. On the other hand, covering the front surface with a sheet of paper will prevent the laser beam from penetrating and result in a shorter measured distance. A laser beam penetrating the material may initiate a number of physical phenomena, changing the measured distance. As a result, additional measurement errors occur, independent of the already familiar errors that occur when the beam is reflected from the outer surface of the material. Even cursory tests of selected materials demonstrate that in some cases these errors can appear much bigger than the assumed accuracy of the scanner. Due to the growing use of synthetic elements in various branches of technology and construction, as well as the high prevalence of scanning techniques for the measurements of all types of structures (Berenyi et al. 2010, Hiremagalur et al. 2007, Holst et al. 2012, Johnson & Johnson 2012, Monserrat & Crosetto 2008, Salemi et al. 2008), a need arises to investigate the influence of these materials on errors of measured distances.

In the literature on examining the accuracy of laser scanners there have been no studies that address measurements to synthetic materials, although some of them indicate potential problems associated with measuring materials having a certain degree of transparency (Eren et al. 2009, Salemi et al. 2008, Voegtle et al. 2008). Generally, on the basis of several laser scanning studies (Abbas et al. 2013, Eren et al. 2009, Gottwald 2008, Kaasalainen et al. 2011, Kersten et al. 2009, Lee et al. 2010, Lichti & Jamtsho 2006, Polo et al. 2012, Soudarissanane et al. 2007) and those given below, it is known that the measurement accuracy is affected by several factors, including: the type of a scanner (pulse-based, phase-based), the precision of a scanning mechanism (laser footprint, accuracy and resolution of the horizontal and vertical angular encoders, the eccentricity of the scanning system), scanning geometry (beam angle of incidence, scanning distance), external conditions (lighting, humidity, temperature), and the properties of the scanned surface.

Considering the properties of the material, which this article focuses on, the research work carried out by Boehler et al. (2003) is worth mentioning. Their paper includes a series of tests for checking the quantitative and qualitative accuracy of points measured using nine laser scanners selected from different manufacturers. Among other things, the relation between surfaces of varying reflectivity and the accuracy of the acquired information was tested. The following samples made of various materials and in different colours were used: white paint (90 % and 80 % reflective), grey paint (40 % reflective), black paint (8 % reflective), metallic paint, various kinds of films. Measurements of different colour surfaces yielded good accuracy results. For the white surfaces, a deviation of zero was obtained. Also, the grey and black colours brought zero errors for most scanners. The situation was much worse in the case of different types of films, where errors from a few up to tens of millimetres occurred. Contradictory results were shown in Bucksch et al. (2007), where the bright surfaces gave much greater accuracy than the dark ones. The problem associated with material reflectance has been analysed in Clark & Robson (2004). The authors selected materials of standardized colours and textures, and scan them from various distances (4 m – 24 m) at the angles of 20°, 40° and 60°. The experimental results revealed systematic discrepancies in the recorded distances, depending on the type of the scanned surface. Colours which exhibit low reflectance, such as black or red, lead to longer distance measurements than the reference distance. The authors proposed a correction factor, reducing these systematic errors. A similar problem was presented in Pfeifer et al. (2008), where the authors focused on the signal energy returning to the receiver. It was hypothesized that this energy can be determined based on the observed range and intensity value. It was proven that it was possible to reproduce the reflectance of a given surface with the accuracy at the level of 6 %. Surface reflectance is also dealt with in Zámečníková et al. (2014b). The authors used the standard white colour (spectralon), which is the material of almost perfect Lambertian reflectance, as well as cardboard boxes in varied colours. The materials were moved on a specially constructed trolley in the range of 1.1 m to 29.7 m at every 7.5 cm. The authors found that the obtained deviations depend not only on the range, but also on the signal strength.

Another study of the properties of the scanned objects was performed by Voegtle et al. (2008). This study used materials commonly applied on the façades of buildings, having different properties: colourful sheets and shades of gray, different kinds of wood, metal elements, plaster of various granularity, transparent films and materials with varying degrees of moisture. The authors' attention was drawn to the tests of partly transparent materials: errors ranged from 15 mm (for 35 % transparency) to 34 mm (for 5 % transparency).

It is not possible to analyse properties of the scanned material separately from the scanning geometry. Both the angle of the beam incidence and the distance have a significant effect on the resulting accuracy. In Soudarissanane et al. (2007) it was found that the measurement noise for a fibreboard and plywood painted white increases with increasing angles. The effect of the scanning angle on the resulting accuracy was also analysed in Soudarissanane et al. (2009) and Soudarissanane et al. (2011). An increase in the measurement noise with the increasing scanning angle was identified. The authors proposed a model which optimized the point position and corrected the influence of the angle. There was a significant improvement in the standard deviation, from the value of 3.25 mm to 2.55 mm. The influence of the scanning angle on the final accuracy was also presented in Zámečníková et al. (2014a). For the angles 100° – 65° and 50° – 45° the measured distances were longer than the reference distance, while in the range of 65° – 50° they were shorter. The authors did not explain the specific character of this phenomenon. Having eliminated the systematic factor, using a polynomial model, the values of standard deviations were significantly reduced.

From the point of view of the research results presented in our study, experiments with a metal plate were interesting. In Voegtle et al. (2008) the effect of the beam angle of incidence on the resulting accuracy was analyzed. Considering the values of the mean square errors, the following relation was noted: for the perpendicular direction of the beam incidence the errors are significantly larger than for smaller angles. A metal plate (aluminium, high reflectance) also appears in Zámečníková et al. (2014b). The authors noticed that small changes in the scanning angle (0.1°) result in 20 % changes in the signal strength, and thus to changes in the recorded deviations. The results presented in that paper confirmed that a higher reflectance results in larger errors for short distances, and for the distances exceeding 20 m their value decreases.

In conclusion, it can be said that the research hitherto conducted mainly analyzed the errors caused by the reflection of a laser beam from the outer surface of a material. Synthetic materials were neither tested nor distinguished as a separate group of materials which might distort the measurements of a distance due to their internal structure. Therefore, this work presents error analysis for distance measurements of the elements of this type.

The authors initially studied measurements to synthetic materials in Lenda & Marmol (2010) by testing the distance measurement deviations of reflectorless range finders for a few selected materials. It enabled the first conclusions on the factors influencing the distance measurement errors of synthetic materials, as well as to plan appropriate methodology for the implementation of research studies, taking into account a wider range of materials for laser scanners. The studies carried out in this paper present a wide range of issues. From the point of view of the users, this paper allows for a sufficient assessment of the impact of synthetic materials on the laser scanners' distance measurements.

2 Research Methodology

A laser beam in the structure of a synthetic material may be subject to a series of phenomena, such as absorption, dispersion, full or partial reflection, diffraction and interference, and refraction at the interface between two media (Feynman et al. 2001, Fowles 1989, Rees 1990, Trager 2007, Wandachowicz

2000). Depending on the type of the material, the influence of each of these properties varies with respect to the errors of the measured distance. On the basis of the tests carried out in Lenda & Marmol (2010), it was observed that the magnitude of these phenomena is affected mainly by factors such as the degree of light transmission, type of the synthetic material (chemical composition), density, thickness and the temperature of the material. The colour of the material is of some importance as well, which, however, was not included in the previously conducted research. According to these observations, a group of 16 materials was selected for testing. The analysis of 13 of these (Tab. 1), due to the similar properties of the materials and obtained results, turned out to be sufficient.

Plexiglas was the material with the biggest changes in measured distances during the range finder tests. Therefore, for this particular synthetic material, the most detailed tests were planned, taking into account its colour, thickness and light transmission. Other high density materials included: HIPS, Polystyrene and Polyolefin (rubber). Materials with low density were represented by foam synthetic materials: Styrofoam and Polyurethane foam. All tested materials, except for the coloured Plexiglas, were white or gray, which was favourable from the point of view of the range and accuracy of the reflectorless measurements. Plexiglas had a specified degree of light transmission. This parameter was unknown for the other materials. The tests associated with different thicknesses of the synthetic materials were performed for two materials: with high density, i.e. for Plexiglas, and with low density, i.e. for Styrofoam.

Temperature also influences the results of the reflectorless distance measurements. All materials were tested at two temperatures: at about 15 °C and at about 40 °C. The temperature of 15 °C (cold) was ambient temperature, and the temperature of 40 °C (warm) was reached by heating the materials with a portable heater. The temperature measurement was carried out using a Testo 830-T2 pyrometer.

The results of the reflectorless measurements are also affected by the incidence angle of the beam on the target. To assess the significance of this factor, basic tests were performed at the most favourable, normal incidence of the laser beam on the target (90°). For comparison, measurements were also carried out for the beam incidence at an angle of 45°. Materials with partial transparency placed at an angle increase the distance which the beam can travel within the structure of the material. Potentially, this could affect the increase in

Tab. 1: The materials tested.

No.	Material type	Colour	Thickness (mm)	Transparency (%)
1	Plexiglas (Polymethyl methacrylate)	red	5	30
2	Plexiglas	green	5	30
3	Plexiglas	blue	5	30
4	Plexiglas	white	5	30
5	Plexiglas	white	5	70
6	Plexiglas	black	5	30
7	Plexiglas	white	10	30
8	HIPS (High impact polystyrene)	white	5	-
9	Polystyrene	white	5	-
10	Styrofoam (Extruded polystyrene foam)	white	5	-
11	Styrofoam	white	10	-
12	Polyurethane foam	grey	10	-
13	Rubber (Polyolefin)	grey	5	-

the error values. On the other hand, due to the partial reflection of the beam from the surface of the material placed at an angle, the penetration of the interior of the material can be limited, which will reduce the value of the errors. For these reasons, it is difficult to find an analogy with other studies at varying angles of the beam incidence, contained in the existing literature.

Since our previous studies of reflectorless range finders presented the effect of a distance on the obtained errors associated with greater penetration of the material by the laser beam on shorter distances, tests of the scanners were carried out on the bases of three lengths: 5 m, 15 m and 50 m.

The procedure of determining the distance measurement deviations for each of the materials requires an explanation. We built a target of 20 cm × 30 cm for each material. Those targets were split into two halves of 20 cm × 15 cm each (Fig. 1). For the cardboard, which served as a reference, the distance deviation in relation to the original Leica reflective tape target had been predetermined – it equals 0.6 mm – taking into account the difference in thickness of the cardboard and tape target (Leica 2015). It was decided not to stick the tape target directly on the tested synthetic materials, due to a possibility of it being transmitted by the laser beam, which would enable the penetration into the structure of the synthetic material, distorting the results. The tested synthetic materials adhered directly to the opaque background. The planar target was scanned at a high resolution (2 mm density). Points near the boundaries of the two halves of the targets were removed from the cloud of points in order to obtain homogeneous sets of points. Based on the filtered data, a regression plane was determined for each of the fields, and then the distance between them was compared, taking into account the thickness of the cardboard. The compared planes were created from two different point clouds, so they were not exactly parallel. The determination of the distance between them was carried out as follows: The regression planes have been fitted in the reference cloud and the test cloud. The dense point grid with a resolution of 1 point per 3 mm² has been interpolated on the test plane. Then the distances from all points of the sample of the reference plane have been determined, along the normal to that plane. Then the average distance has been calculated and taken as the distance between the planes. Such a method of determining the distance allowed eliminating inaccuracies associated with a slight rotation of both planes. The difference was the distance measurement deviation of the synthetic material with reference to the white cardboard, and, consequently, to the reflective tape. The deviation of the distance measurement of synthetic materials observed in this way (ΔD) is not an overall error of distance measurement. It is, however, an additional contribution, which should be added to the standard errors of a laser scanner, assuming reflection of a beam from the outer surface of the material. In addition, the precision (mp) of fitting the regression plane into a set of points representing the synthetic material, expressed by the RMS-error of the distances of the points from the regression plane was determined.

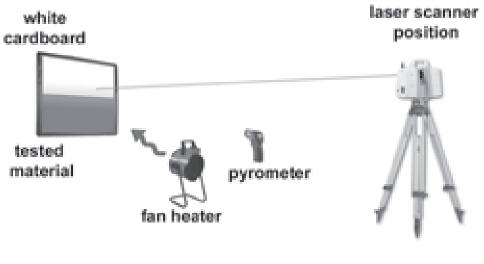


Fig. 1: Experimental setup.

The tests were performed using two laser scanners with similar accuracy, but with a different carrier wavelength: Leica C10 and Riegl VZ-400. Basic data of these scanners with reference to the subject in question were presented in Tab. 2. The carrier wavelength is important especially when measuring targets of varying colours since spectral curves may differ even in the case of very similar materials (Toś 2014). The colour of the material may influence the absorption of beams with different wavelengths. It can also affect the measurement accuracy of synthetic materials in a varied manner, depending on the size of the inhomogeneity in their structure.

In the production process it is not always possible to obtain a uniform chemical composition and repetitive structure of synthetic ma-

Tab. 2: Selected parameters of the tested laser scanners.

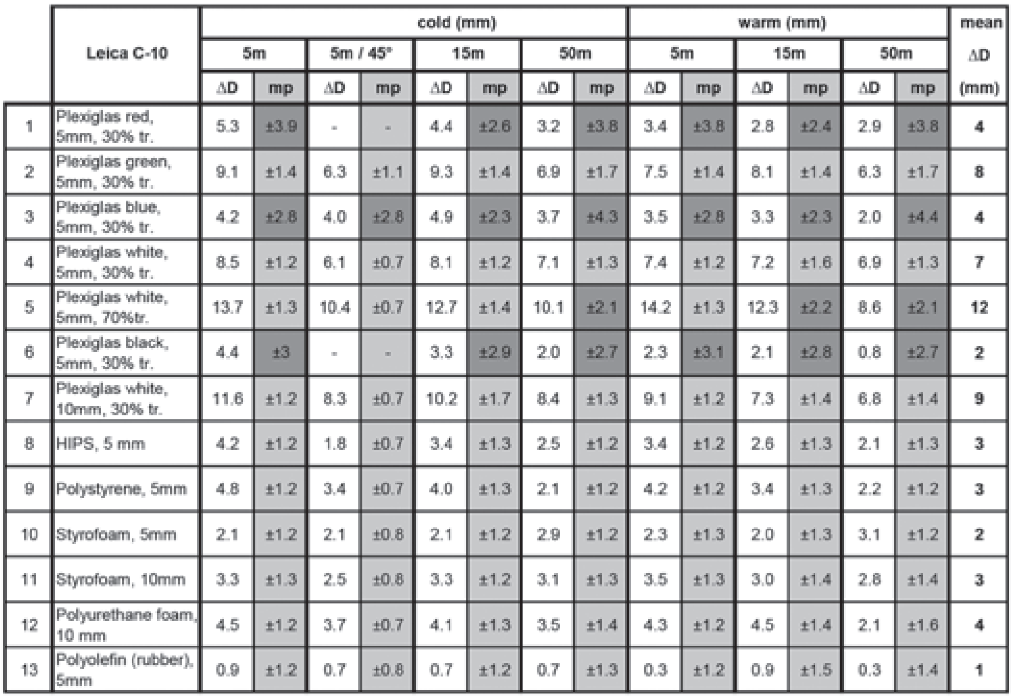
	Leica C-10	Riegl VZ-400
Type	pulse-based	pulse-based
Accuracy of length measurement	4 mm (up to 50 m)	5 mm (up to 100 m)
Range	up to 350 m	up to 600 m
Carrier wavelength	532 nm	1550 nm
Beam divergence	0.24 mrad	0.35 mrad

terials. For this reason, comparative tests were performed for several materials (Plexiglas white, 5 mm thickness and 30 % transparency (hereinafter briefly stated with x mm/Y %), Polystyrene 5 mm, and Styrofoam 10 mm), taking into account the measurement of three samples of the same production lot, as well as the measurement to three samples of unknown origin. The tests were performed using the Leica C-10 scanner, at the baseline of 5 m, the distance between the laser scanner and the test material.

3 Results of Test Measurements

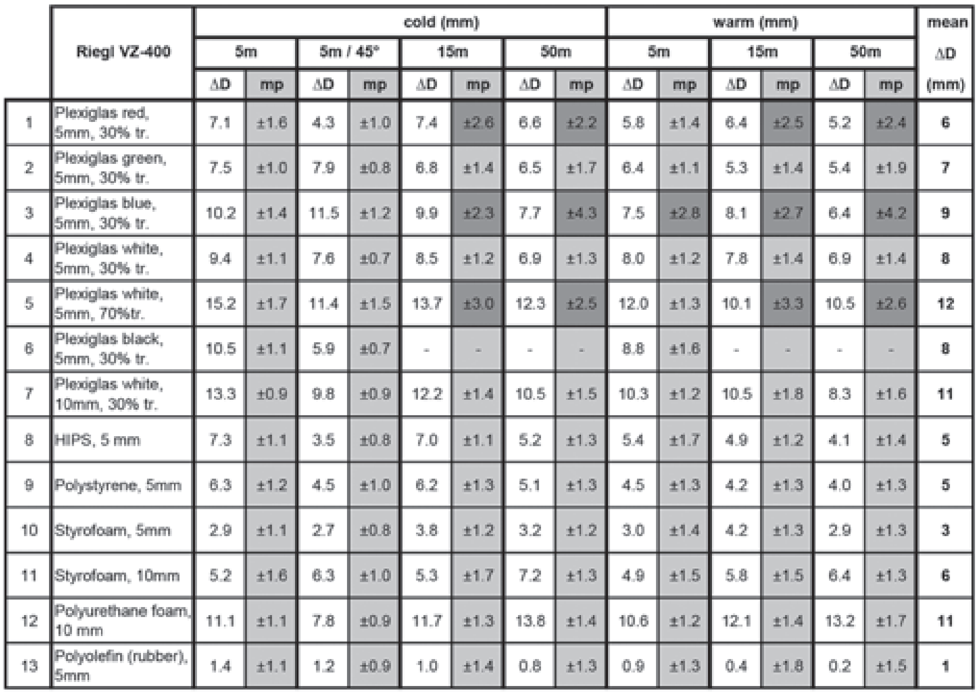
The results obtained from the conducted tests are shown in Tab. 3 (Leica C-10 scanner) and Tab. 4 (Riegl VZ-400 scanner). Due to highly ambiguous results (scattered data) of the measurements performed at the angle of 45° at the distances of 15 m and 50 m, they are not presented here. The diagrams presented in Figs. 2 and 3 were drawn based on these Tables. The measurement results of different samples of the same materials are included in

Tab. 3: Distance measurement deviations of the Leica C-10 scanner (ΔD = distance measurement deviations relative to the comparative model, mp = precision of fitting the regression plane for a synthetic material, tr. = transparency).



	Leica C-10	cold (mm)								warm (mm)						mean
		5m		5m / 45°		15m		50m		5m		15m		50m		ΔD
		ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	(mm)
1	Plexiglas red, 5mm, 30% tr.	5.3	±3.9	-	-	4.4	±2.6	3.2	±3.8	3.4	±3.8	2.8	±2.4	2.9	±3.8	**4**
2	Plexiglas green, 5mm, 30% tr.	9.1	±1.4	6.3	±1.1	9.3	±1.4	6.9	±1.7	7.5	±1.4	8.1	±1.4	6.3	±1.7	**8**
3	Plexiglas blue, 5mm, 30% tr.	4.2	±2.8	4.0	±2.8	4.9	±2.3	3.7	±4.3	3.5	±2.8	3.3	±2.3	2.0	±4.4	**4**
4	Plexiglas white, 5mm, 30% tr.	8.5	±1.2	6.1	±0.7	8.1	±1.2	7.1	±1.3	7.4	±1.2	7.2	±1.6	6.9	±1.3	**7**
5	Plexiglas white, 5mm, 70%tr.	13.7	±1.3	10.4	±0.7	12.7	±1.4	10.1	±2.1	14.2	±1.3	12.3	±2.2	8.6	±2.1	**12**
6	Plexiglas black, 5mm, 30% tr.	4.4	±3	-	-	3.3	±2.9	2.0	±2.7	2.3	±3.1	2.1	±2.8	0.8	±2.7	**2**
7	Plexiglas white, 10mm, 30% tr.	11.6	±1.2	8.3	±0.7	10.2	±1.7	8.4	±1.3	9.1	±1.2	7.3	±1.4	6.8	±1.4	**9**
8	HIPS, 5 mm	4.2	±1.2	1.8	±0.7	3.4	±1.3	2.5	±1.2	3.4	±1.2	2.6	±1.3	2.1	±1.3	**3**
9	Polystyrene, 5mm	4.8	±1.2	3.4	±0.7	4.0	±1.3	2.1	±1.2	4.2	±1.2	3.4	±1.3	2.2	±1.2	**3**
10	Styrofoam, 5mm	2.1	±1.2	2.1	±0.8	2.1	±1.2	2.9	±1.2	2.3	±1.3	2.0	±1.3	3.1	±1.2	**2**
11	Styrofoam, 10mm	3.3	±1.3	2.5	±0.8	3.3	±1.2	3.1	±1.3	3.5	±1.3	3.0	±1.4	2.8	±1.4	**3**
12	Polyurethane foam, 10 mm	4.5	±1.2	3.7	±0.7	4.1	±1.3	3.5	±1.4	4.3	±1.2	4.5	±1.4	2.1	±1.6	**4**
13	Polyolefin (rubber), 5mm	0.9	±1.2	0.7	±0.8	0.7	±1.2	0.7	±1.3	0.3	±1.2	0.9	±1.5	0.3	±1.4	**1**

Tab. 4: Distance measurement deviations for the Riegl VZ-400 scanner.



	Riegl VZ-400	cold (mm)								warm (mm)						mean
		5m		5m / 45°		15m		50m		5m		15m		50m		ΔD
		ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	ΔD	mp	(mm)
1	Plexiglas red, 5mm, 30% tr.	7.1	±1.6	4.3	±1.0	7.4	±2.6	6.6	±2.2	5.8	±1.4	6.4	±2.5	5.2	±2.4	**6**
2	Plexiglas green, 5mm, 30% tr.	7.5	±1.0	7.9	±0.8	6.8	±1.4	6.5	±1.7	6.4	±1.1	5.3	±1.4	5.4	±1.9	**7**
3	Plexiglas blue, 5mm, 30% tr.	10.2	±1.4	11.5	±1.2	9.9	±2.3	7.7	±4.3	7.5	±2.8	8.1	±2.7	6.4	±4.2	**9**
4	Plexiglas white, 5mm, 30% tr.	9.4	±1.1	7.6	±0.7	8.5	±1.2	6.9	±1.3	8.0	±1.2	7.8	±1.4	6.9	±1.4	**8**
5	Plexiglas white, 5mm, 70%tr.	15.2	±1.7	11.4	±1.5	13.7	±3.0	12.3	±2.5	12.0	±1.3	10.1	±3.3	10.5	±2.6	**12**
6	Plexiglas black, 5mm, 30% tr.	10.5	±1.1	5.9	±0.7	-	-	-	-	8.8	±1.6	-	-	-	-	**8**
7	Plexiglas white, 10mm, 30% tr.	13.3	±0.9	9.8	±0.9	12.2	±1.4	10.5	±1.5	10.3	±1.2	10.5	±1.8	8.3	±1.6	**11**
8	HIPS, 5 mm	7.3	±1.1	3.5	±0.8	7.0	±1.1	5.2	±1.3	5.4	±1.7	4.9	±1.2	4.1	±1.4	**5**
9	Polystyrene, 5mm	6.3	±1.2	4.5	±1.0	6.2	±1.3	5.1	±1.3	4.5	±1.3	4.2	±1.3	4.0	±1.3	**5**
10	Styrofoam, 5mm	2.9	±1.1	2.7	±0.8	3.8	±1.2	3.2	±1.2	3.0	±1.4	4.2	±1.3	2.9	±1.3	**3**
11	Styrofoam, 10mm	5.2	±1.6	6.3	±1.0	5.3	±1.7	7.2	±1.3	4.9	±1.5	5.8	±1.5	6.4	±1.3	**6**
12	Polyurethane foam, 10 mm	11.1	±1.1	7.8	±0.9	11.7	±1.3	13.8	±1.4	10.6	±1.2	12.1	±1.4	13.2	±1.7	**11**
13	Polyolefin (rubber), 5mm	1.4	±1.1	1.2	±0.9	1.0	±1.4	0.8	±1.3	0.9	±1.3	0.4	±1.8	0.2	±1.5	**1**

Tab. 5. During the tests with the VZ-400 scanner, it was noticed that synthetic materials were not directly adhering to the background, but they stood out approximately 2 cm – 3 cm behind it. This resulted in a significant deterioration in the distance measurement deviation for some materials. The measurements were repeated and, for comparison, Tab. 6 shows the results for the background adhering and not adhering to the synthetic material.

The precision of fitting the regression plane for the reference cardboard was similar for both scanners and it was ± 1.2 mm for 90° beam incidence angles, and ± 0.8 mm for the 45° incidence angles, with the scatter for these values reaching a maximum of ± 0.2 mm.

Tab. 5: Distance measurement deviations of the samples for selected materials: A1–A3 – sample material from the same production lot, B1–B3 – sample material from unknown production lots, Leica C-10 scanner, distance 5 m.

	Plexiglas white, 5 mm, 30% transparency (mm)	Polystyrene, 5 mm (mm)	Styrofoam 10 mm (mm)
A 1	8.5	4.8	3.3
A 2	8.1	4.6	3.9
A 3	8.8	5.1	4.2
B 1	8.5	4.8	3.3
B 2	6.9	4.7	5.2
B 3	11.8	6.4	2.8

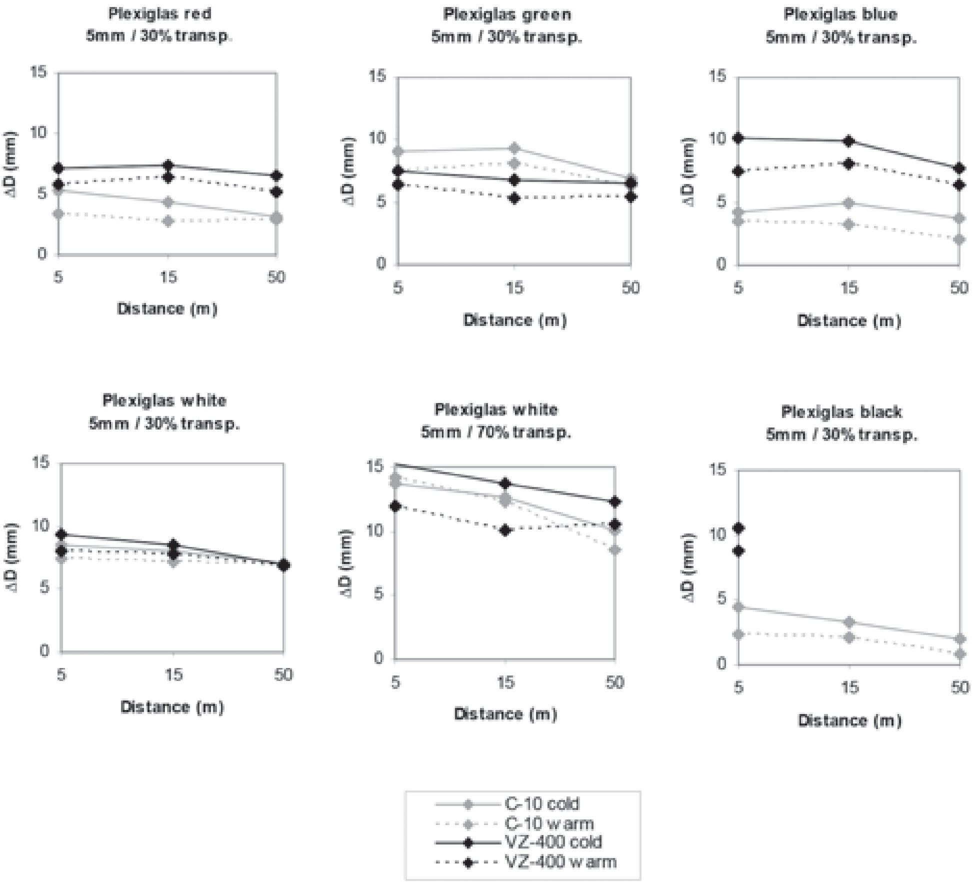


Fig. 2: Distance measurement deviations for the materials 1–6, ΔD – distance measurement deviations relative to the comparative model.

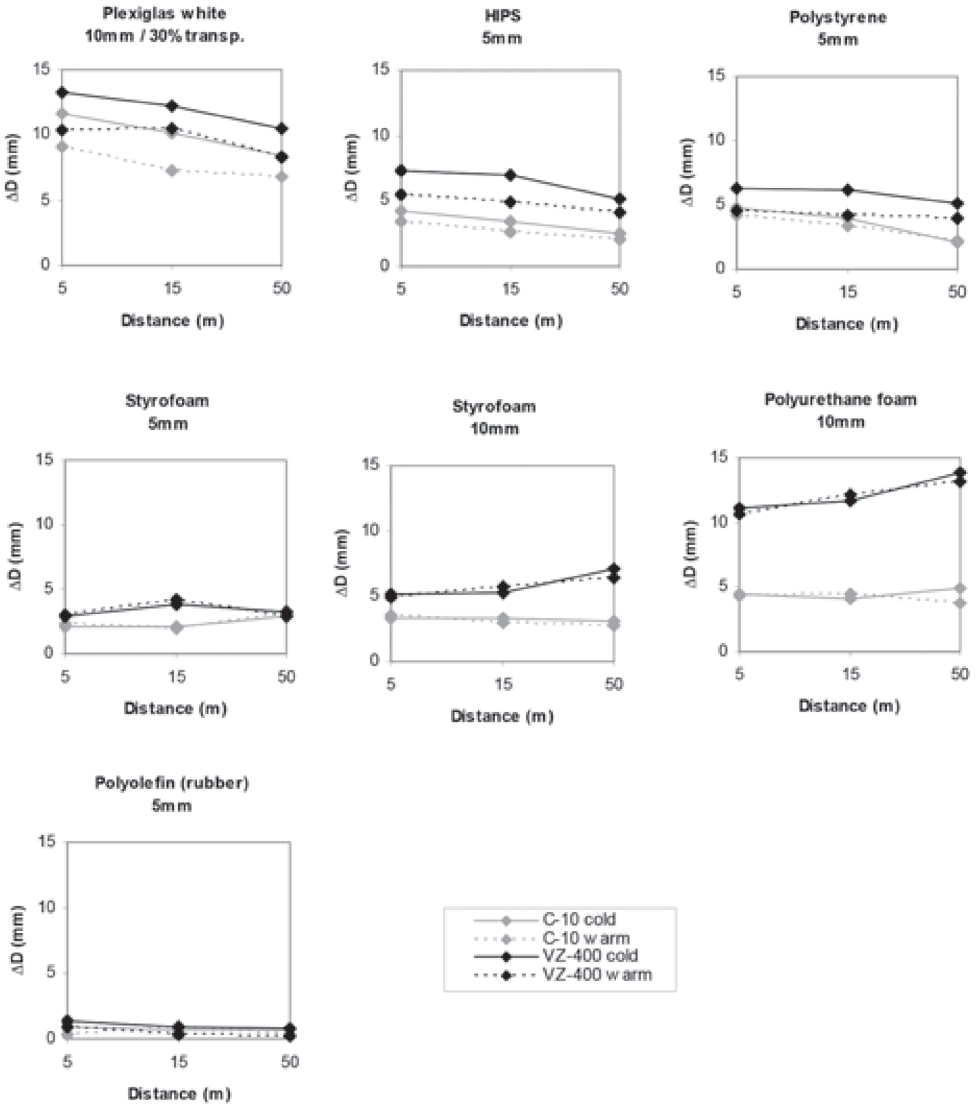
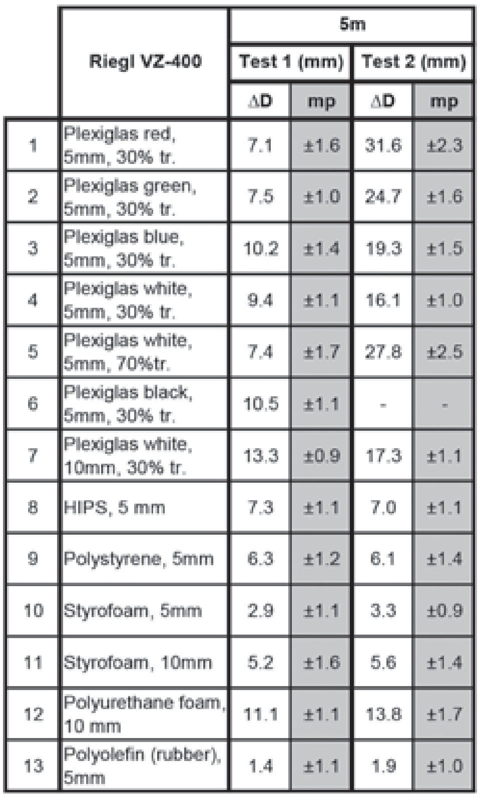


Fig. 3: Distance measurement deviations for the materials 7–13, ΔD – distance measurement deviations relative to the comparative model.

Tab. 6: Comparison of the distance measurement deviations of the VZ-400 scanner for various locations of the synthetic material background. Test 1: The background adhering to the rear surface of the synthetic material. Test 2: The background placed approximately 2 cm – 3 cm behind the synthetic material. Comparison for the 5 m distance (tr. – transparency).



	Riegl VZ-400	5m			
		Test 1 (mm)		Test 2 (mm)	
		ΔD	mp	ΔD	mp
1	Plexiglas red, 5mm, 30% tr.	7.1	±1.6	31.6	±2.3
2	Plexiglas green, 5mm, 30% tr.	7.5	±1.0	24.7	±1.6
3	Plexiglas blue, 5mm, 30% tr.	10.2	±1.4	19.3	±1.5
4	Plexiglas white, 5mm, 30% tr.	9.4	±1.1	16.1	±1.0
5	Plexiglas white, 5mm, 70%tr.	7.4	±1.7	27.8	±2.5
6	Plexiglas black, 5mm, 30% tr.	10.5	±1.1	-	-
7	Plexiglas white, 10mm, 30% tr.	13.3	±0.9	17.3	±1.1
8	HIPS, 5 mm	7.3	±1.1	7.0	±1.1
9	Polystyrene, 5mm	6.3	±1.2	6.1	±1.4
10	Styrofoam, 5mm	2.9	±1.1	3.3	±0.9
11	Styrofoam, 10mm	5.2	±1.6	5.6	±1.4
12	Polyurethane foam, 10 mm	11.1	±1.1	13.8	±1.7
13	Polyolefin (rubber), 5mm	1.4	±1.1	1.9	±1.0

4 Analysis of the Results

The assessment of the results was divided into several categories, resulting from the properties of the material itself, the conditions in which it was found, and the tested instrument. The analyses included the following categories: type of material (light transmission, density and internal structure, colour, thickness), distance, angle of incidence, temperature, type of scanner (carrier wavelength), and distance of the synthetic material from the background. Some phenomena were especially noticeable for the shortest measurement distance (5 m), at low temperature of the material (15 °C), which is explained later in the text. Therefore, during the comparisons, we will frequently refer to the results obtained under such conditions as the "basic" conditions.

4.1 *Light Transmission*

This is the primary factor affecting the distance measurement of synthetic materials. If the laser beam is not able to penetrate into the structure of the synthetic material, there are no changes in the measured distance in comparison with the reference cardboard. Such a situation can be observed only for one of the tested materials, i.e. opaque rubber (Polyolefin). Regardless of the conditions, the distance measurement error for this material did not exceed the value of 2 mm, usually remaining at the level of about 1 mm, unlike other materials, where a certain degree of transparency allowed for the occurrence of additional phenomena affecting the distance measurement. The changes in the distance observed for them ranged from about 2 mm to 15 mm. The influence of transmission was clearly visible when comparing the two samples of Plexiglas white, with a transmission of 30 % and 70 %. Mean deviations for the material with lower transmission were approximately 7 mm (C10) and 8 mm (VZ400), and 12 mm for larger transmission (C10 and VZ400). For both scanners, taking into account comparable materials (5 mm thickness, white colour), the largest deviations occurred for Plexiglas, which had a significant light transmission. Other materials were measured with mean deviations within the range of 1 mm – 3 mm (C10) and 1 mm – 5 mm (VZ400). For the C10 scanner, Plexiglas with 70 % transmission caused a slight deterioration in the precision of fitting the regression plane relative to other materials (up to ca. ±2 mm). For the VZ400 scanner, the fitting precision for this material decreased in some cases to ca. ±3 mm.

4.2 *Density and Internal Structure*

The studies covered two groups of materials with large differences in density and internal structure. The first one included materials with a continuous structure (Plexiglas, HIPS, Polystyrene, Polyolefin), and the second one included foamed materials (Styrofoam, Polyurethane Foam). In the foamed materials the beam was subject to changes, alternately in fragments of the material and in air chambers. Foamed materials were measured with smaller deviations in relation to the thickness of the material than their continuous counterparts. This could be assessed by comparing the measurement deviations of Polystyrene and Polystyrene Foam (Styrofoam) (5 mm) in basic conditions: Polystyrene: 4.8 mm (C10), 6.3 mm (VZ400) and Styrofoam: 2.1 mm (C10), 2.9 mm (VZ400). The foamed material achieved deviations of approximately half that size. It is interesting that for some materials, especially for Plexiglas, the measurement deviations were larger than the thickness of the material itself. Examples under basic conditions were Plexiglas white 5 mm / 30 % – 8.5 mm (C10), 9.4 mm (VZ400), Plexiglas white 5 mm / 70 % – 13.7 mm (C10), 15.2 mm (VZ400). During the tests, the materials adhered directly to the opaque background, so that the beam, having passed through the material, did not have a possibility of incidence on other targets. The values of the deviations, therefore, must have resulted from additional phenomena associated with the beam propagation in the structure of the material. They might be related, among others, to the repeated refraction or the reflection of a beam. In addition, the refractive index depends on the internal structure of materials. If it is not homogeneous, and the inhomogeneity has dimensions greater than the wavelength, the refractive index will be subject to changes. Comparing the measurements results performed with the C10 scanner to various samples of materials from the same production lot (Tab. 5), a stable level of deviations for Plexiglas white 5 mm / 30 % – (8.1 mm – 8.8 mm) and Polystyrene 5 mm / 30 % – (4.6 mm – 5.1 mm) is noticeable. For the foamed material, 10 mm Styrofoam, the relative differences are larger – (3.3 mm – 4.2 mm). When comparing samples of these materials originating from different production lots, possibly from different manufacturers, the results look somewhat different. Differences for 5 mm Polystyrene increased to 4.7 mm – 6.4 mm. For other materials, the relative differences were nearly doubled: 10 mm Styrofoam: 2.8 mm – 5.2 mm, Plexiglas white 5 mm/30 %: 6.9 mm – 11.8 mm. Therefore, the type of a material and its internal structure have a significant impact on the level of the measurement deviations. At the same time, this influence is difficult to determine accurately due to variations in the production.

4.3 *Colour*

The colour of the synthetic material significantly influences the measurement deviations. A sample Plexiglas was tested under basic conditions using the same parameters regarding thickness and permeability. Then, the deviations resulting from the changing colour of the material were within 4.2 mm – 9.1 mm (C10) and 7.1 mm – 10.5 mm (VZ400). For both scanners, the differences between the extreme values of the deviations had a factor of 1.5 to 2. As only a few selected colours were tested, a discrepancy may be even larger under real conditions. The colour of the material strongly influenced the absorption of beams with different wavelengths. Due to the fact that two scanners emitting laser radiation of different carrier wavelengths, 532 nm (C 10) and 1550 nm (VZ400), were selected for this experiment, the differences in the values of the deviations for the same colours were clearly noticeable. Under basic conditions, for the C10 scanner, the smallest deviations were observed for the following colours: blue: 4.2 mm, black: 4.4 mm, and red: 5.3 mm. It is interesting that, at the same time, for those colours the lowest precision of fitting a regression plane were obtained: blue: ±2.8 mm, black: ±3.0 mm, red: ±3.9 mm. Larger deviations were observed for white (8.5 mm) and green (9.1 mm), with better precision of fitting the plane: white ±1.2 mm, green ±1.4 mm. The VZ400 scanner demonstrated the smallest deviations for red (7.1 mm) and green (7.5 mm), and the largest for the blue (10.2 mm) and black (10.5 mm) colours. Therefore, for green, blue and black, the dependencies observed for the C10 scanner were inverted. In basic conditions, the precision of fitting the regression plane were at a low level for all colours (±1.0 mm – ±1.6 mm). For the test configurations other than the basic ones, the deviations for red and blue increased. The colour of the synthetic material in combination with its light transmittance is therefore a very important factor determining the value of the distance measurement deviations.

4.4 *Thickness*

The effect of the thickness of the synthetic material was assessed based on two samples of materials (Plexiglas 30 %, 5 mm and 10 mm, and Styrofoam, 5 mm and 10 mm). Under basic conditions, the measurement deviations using the C10 scanner for Plexiglas ranged from 8.5 mm to 11.6 mm, and for the VZ400 scanner from 9.4 mm to 13.3 mm. For Styrofoam, the deviations for the C10 scanner ranged from 2.1 mm to 3.3 mm, and for the VZ400 scanner from 2.9 to 5.2 mm. The deviations were different for each sample and scanner, and were within the limits of 36 % – 79 %, at 100 % change in thickness of the material. Greater differences were observed for the foamed material of low density, i.e. for Styrofoam 57 % – 79 %, while for Plexiglas they amounted to 36 % – 41 %. As Styrofoam in practice had a thickness greater than 5 mm or 10 mm, this could translate into relatively large measurement deviations. In view of the fact that colour has also a strong influence on the deviations of the measurements on Plexiglas the deviations could reach values higher than the thickness of the material itself. This happened in more than half of the cases for the C10 scanner and all of the cases for the VZ400. This could also be recognized with other synthetic materials measured with the VZ400 scanner, e.g. HIPS and Polystyrene. The dependencies related to the thickness of the synthetic material are therefore significant, nonlinear, and for better assessment it would be advisable to carry out more extensive tests.

4.5 *Distance*

Dependencies resulting from the variable distance of the target are easiest to evaluate from the diagrams in Figs. 2 and 3. For most materials, the deviations are reduced with increasing distance. The differences between the results for the distances of 5 m and 15 m do not exhibit this phenomenon clearly, i.e. sometimes the deviations even increase. However, the differences between the results at the distances of 5 m and 50 m exhibit a certain tendency and reach the values of up to 3.5 mm. The increasing tendency of the deviations was observed for two foamed materials: Styrofoam (10 mm) and Polyurethane Foam for the VZ400 scanner. Deviations decreasing with distance are contrary to current experiments for reflectorless instruments. Moreover, the equipment manufacturers themselves inform about increasing deviations with increasing distance. However, this phenomenon can be explained by a reduced ability of radiation to penetrate the material which, at the larger distance, has a lower energy density at the surface of the synthetic material. In this way, the scale of the phenomena described above is limited. Due to the fact that the largest deviations were observed at short distances, the 5-meter baseline was set as the "basic" condition. With the increasing distance there was no significant increase in the precision of fitting the regression plane.

4.6 *Incidence Angle*

Studies related to the varying incidence angles of the beam yielded inconclusive results. The tests were carried out at the angle of 45° without the materials being heated. The results for the distances of 15 m and 50 m did not demonstrate any systematic order, the measurement deviations just increased or decreased in a random manner. This was associated with significant decrease of precision of fitting the regression planes with up to several millimetres.

The ambiguous test results at greater distances could have resulted from the variable reaction of fragments of the materials to the illumination at an angle. At a greater distance where the density of the radiation energy at the sample surface is smaller, the non-homogeneity of the material could have determined the phenomenon of partial reflection from the surface of the inclined sample, changing the degree of the material penetration by the beam. This is particularly visible for the blue Plexiglas measured with the C10 scanner at a distance of 15 m (Fig. 4). The left figure presents a sample scanned at the angle of 90°, and the right one at the angle of 45°. Significant losses in the point cloud (front view, right side) together with highly scattered individual points (top view, right side) are visible in the latter case.

For this reason, only the results for the distance of 5 m are presented, because they seemed not to be subject to blunders. With the decreasing angle of the beam incidence (from the standard 90° to 45°), for the C10 scanner, a decreasing measurement deviation of up to about 3 mm in almost all the cases was observed. This was related to the decrease in the deviations of fitting the regression plane from about ± 1.2 mm to ± 0.7 mm on an average. Similar observations were made in Voegtle et al. (2008), where it was also found that with a decreasing incidence angle, the deviation decreased. However, in Soudarissanane et al. (2007), for some materials an opposite tendency was observed. It was also confirmed by the previous research of the authors associated with the tests of reflectorless range finders (Lenda & Marmol 2010). Similar relations were observed for the instrument VZ400, where the deviations decreased by more than 4 mm. However, for some materials (Plexiglas green and blue, 10 mm Styrofoam), a slight, about 1 mm increase in the deviations occurred. The precision of fitting the regression plane were also subject to a decrease an average of about ± 1.2 mm to ± 1.0 mm. In our experiments, at the angle of incidence of 45°, the materials Plexiglas red and black were immeasurable for the Leica scanner. Based on the obtained results and the results of other researchers, it was apparent that the angles of incidence affect the measured distance. The tests exhibited a decrease in the deviations at more acute angles of the beam incidence – which may be the result of reduced penetration by laser beam due to partial reflection from the surface of the sample at incidence angle of 45°.

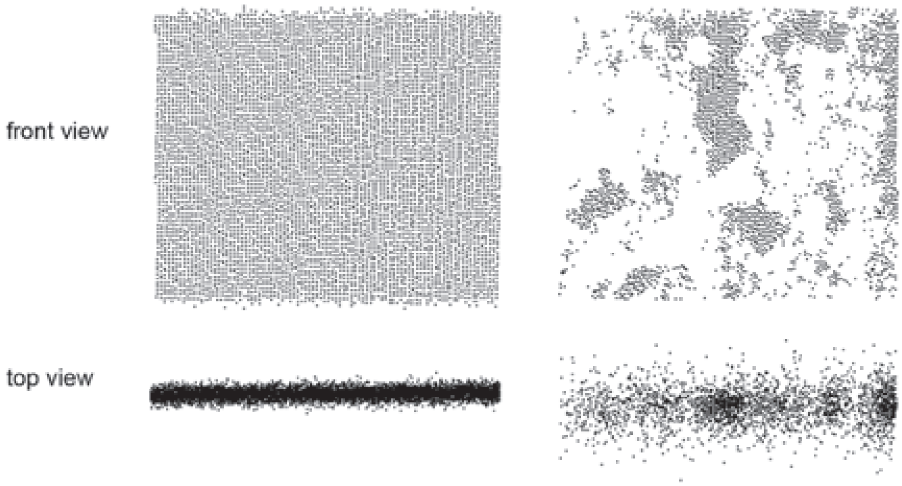


Fig. 4: Point clouds obtained from blue Plexiglas with the C10 laser scanner at 15 m distance. Sample scanned at 90° incidence angle on the left and 45° incidence angle on the right; above: front views of the materials, below: top views of the materials.

4.7 *Temperature of the Material*

The influence of the temperature is easiest to assess from the diagrams contained in Figs. 2 and 3. A decrease in the deviations for the non-foamed materials (except rubber) related to the temperature growth is quite clear, as well as its lack for the foamed materials. Non-foamed synthetic materials, when heated, generate deviations that are smaller by about 1 mm – 3 mm (C10) and by about 1 mm – 4 mm (VZ400) than cold ones. Continuous materials, having no air bubbles in their structures, exhibited susceptibility to heat. This phenomenon could be explained by the thermal expansion of materials and the related lower density of synthetic materials, reducing the refractive index value. However, since the change in the volume of the synthetic materials when heated was negligible, other factors related to temperature, unnoticed by the authors, must have affected the reduction of the measurement deviations. Due to the fact that larger deviations were observed for cold targets, low temperature was adopted as another "basic" conditions.

4.8 *Scanner Type*

In this category, the carrier wavelength of the laser, different for the two scanners (532 nm (C10) and 1550 nm (VZ400)) should be distinguished. The light of various wavelengths is absorbed in a different manner by the colours and materials of a different size and ordering of the molecules. Taking into account all 13 tested materials, almost all of the tests demonstrated slightly higher deviation values for the VZ400 scanner. This dependency could have been expected when comparing the precision parameters of both instruments.

4.9 *Distance between Synthetic Material and the Background*

The location of the background of the tested material is of great importance to the measured distance of some synthetic materials. If it is close, just a few centimetres from the synthetic material, a laser beam, after being transmitted through the material, can be reflected by the background, causing significant changes to the obtained results, of up to several centimetres. For some synthetic materials it does not really matter (HIPS, Polystyrene, Styrofoam, Polyolefin), for others these changes may be small (Polyurethane foam). For some of the materials (Plexiglas, especially with small thickness) it may, however, result in very significant discrepancies. The observed increase in the deviations for different colours of 5 mm Plexiglas, under basic conditions, ranged from 71 % (white) to as much as 345 % (red), reaching the values of up to 32 mm. It was combined with a slight increase in the plane fitting precision. The dependencies associated with the colours were quite different from the ones observed for the background adhering to the synthetic material. The loss of accuracy related to a complete passage of light through the synthetic material may thus result in obtaining significant, unpredictable values. Further studies, taking into account various distances between the synthetic material and the background, may foster interesting results.

5 Summary

The paper analyses a number of factors affecting the distance measurement of synthetic materials. The most important of these is optical permeability, which induces other phenomena occurring within the material structure. Some of them may have a significant impact on the obtained results, e.g. degree of permeability, type of material, colour in combination with a carrier wavelength of the laser radiation, and thickness. The effects of other factors seem to be less significant, but noticeable and systematic such as distance and temperature of the material. The angle of the beam incidence is also relevant. Synthetic elements may therefore exhibit shifts of several, sometimes over a dozen millimetres in the point cloud relative to other objects. Especially when they not adhere to the other materials, shifts in some cases (Plexiglas) may increase to several centimetres. In some cases, measurement deviation of the synthetic material can affect the accuracy of the entire scanned structure. This may happen when spatial markers in the form of Styrofoam balls are used to connect neighbouring scans. As it was demonstrated by our experiments, the error for Styrofoam increases significantly with its thickness, and therefore covering such balls with opaque lacquer should be considered. Some of the tests yielded inconclusive or questionable results (incidence angle), which may have resulted from the methodology, dependent upon the occurrence of additional phenomena, which the authors had not anticipated. The factors that interfere with the results of the research studies may include for example: additional lighting, reflections of the beam from the surrounding elements, type of the synthetic material background and the manner of its adherence to the sample. The deviations resulting from a complete passage of light through the synthetic material and the reflection of a beam from the background located at a certain distance from the material may reach significant values. In general, due to a large number of factors affecting the distance measurements and their mutual configurations, it is difficult to tabulate distance measurement deviations for specific synthetic materials. The situation is made worse by an average repeatability of their production. This study draws attention to the problem, allowing estimating the scale of the existing dependencies.

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References

Abbas, M.A., Setan, H., Majid, Z., Chong, A.K., Idris, K.M. & Aspuri, A., 2013: Calibration and Accuracy Assessment of Leica ScanStation C10 Terrestrial Laser Scanner. Developments in Multidimensional Spatial Data Models. – Lecture Notes in Geoinformation and Cartography **10:** 33–47.

Berenyi, A., Lovas, T. & Barsi, A., 2010: Terrestrial laser scanning – civil engineering applications. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Commission V Symposium **38** (5): 80–85, Newcastle, United Kingdom.

Boehler, W., Bordas, V.M. & Marbs, A., 2003: Investigating laser scanner accuracy. – 19th CIPA International Symposium, Antalya, Turkey.

Bucksch, A., Lindenbergh, R. & van Ree, J., 2007: Error budget of terrestrial laserscanning: Influence of the intensity remission of the scan quality. – III International Scientific Congress Geo-Siberia, Novosibirsk, Russia.

Clark, J. & Robson, S., 2004: Accuracy of measurements made with a CYRAX 2500 laser scanner against surfaces of known color. – Survey Review **37** (294): 626–638.

Eren, G., Aubreton, O., Meriaudeau, F., Secades, S., Fofi, D., Naskali, A.T., Truchetet, F. & Ercil, A., 2009: A 3D Scanner for Transparent Glass. Image Analysis and Processing. – International Conference on Image Analysis and Processing (ICIAP) 2009, Lecture Notes in Computer Science (LNCS) **5716:** 519–527.

Feynman, R.P., Leighton, R.B. & Sands, M., 2001: The Feynman Lectures on Physics. – PWN, Warszawa, Poland.

Fowles, G.R., 1989: Introduction to Modern Optics. – Dover Publications, Mineola, NY, USA.

Gottwald, R., 2008: Field Procedures for Testing Terrestrial Laser Scanners (TLS) – A Contribution to a Future ISO Standard. – Integrating Generations, FIG Working Week **2008:** 1–14, Stockholm, Sweden.

Hiremagalur, J., Yen, K., Akin, K., Bui, T., Lasky, T. & Ravani, B., 2007: Creating standards and specifications for the use of laser scanning in caltrans projects. – AHMCT (Advanced Highway Maintenance & Construction Technology Research Center) Research Report, University of California at Davis, California Department of Transportation, Davis, CA, USA.

Holst, C., Zeimetz, P., Nothnagel, A., Schauerte, W. & Kuhlmann, H., 2012: Estimation of Focal Length Variations of a 100-m Radio Telescope's Main Reflector by Laser Scanner Measurements. – Journal of Surveying Engineering **138** (3): 126–135.

Johnson, W. & Johnson, A., 2012: Operational Considerations for Terrestrial Laser Scanner Use in Highway Construction Applications. – Journal of Surveying Engineering **138** (4): 214–222.

Kaasalainen, S., Jaakkola, A., Kaasalainen, M., Krooks, A. & Kukko, A., 2011: Analysis of Incidence Angle and Distance Effects on Terrestrial Laser Scanner Intensity: Search for Correction Methods. – Remote Sensing **3** (10): 2207–2221.

Kersten, T.P., Mechelke, K., Lindstaedt, M. & Sternberg, H., 2009: Methods for Geometric Accuracy Investigations of Terrestrial Laser

Scanning Systems. – PFG – Photogrammetrie, Fernerkundung, Geoinformation **2009** (4): 301–315.

Lee, I.S., Lee, J.O., Park, H.J. & Bae, K.H., 2010: Investigations into the influence of object characteristics on the quality of terrestrial laser scanner data. – KSCE Journal of Civil Engineering **14** (6): 905–913.

Leica, 2015: http://www.allenprecision.com/survey/robotic-total-stations/accessories/prisms/60x60mm-reflective-tape-20-pack/ (19.7.2015).

Lenda, G. & Marmol, U., 2010: Accuracy of reflectorless range finders for the measurements of objects made form synthetic materials (polish). – Pomiary Automatyka Kontrola **11:** 1280–1286.

Lichti, D.D. & Jamtsho, S., 2006: Angular resolution of terrestrial laser scanners. – The Photogrammetric Record **21** (114): 141–160.

Monserrat, O. & Crosetto, M., 2008: Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching. – ISPRS Journal of Phtotogrammetry & Remote Sensing **63:** 142–154.

Pfeifer, N., Höfle, B., Briese, C., Rutzinger, M. & Haring, A. 2008: Analysis of the backscattered energy in terrestrial laser scanning data. – International Archives of the Photogrammetry and Remote Sensing and Spatial Information Science (IAPRS) **37** (B5): 1045–1051.

Polo, M.E., Felicísimo, A.M., Villanueva, A.G. & Martínez-del-Pozo, J.A., 2012: Estimating the Uncertainty of Terrestrial Laser Scanner Measurements. – IEEE Transactions on Geoscience and Remote Sensing **50** (11): 4804–4808.

Rees, W., 1990: Physical principles of remote sensing. – Cambridge University Press, UK.

Salemi, G., Achilli, V. & Boatt, G., 2008: 3D virtual modelling of a gothic stained-glass panel. – The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **37** (B5): 297–302.

Soudarissanane, S., van Ree, J., Bucksch, A. & Lindenbergh, R., 2007: Error budget of terrestrial laser scanning: influence of the incidence angle on the scan quality. – 3D-NordOst, Berlin.

Soudarissanane, S., Lindenbergh, R., Menenti, M. & Teunissen, P.J.G., 2009: Incidence angle influence on the quality of terrestrial laser scanning points. – ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **38-3/W8:** 183–188.

Soudarissanane, S., Lindenbergh, R., Menenti, M., Teunissen, P.J.G., 2011: Scanning geometry: Influencing factor on the quality of terrestrial laser scanning points. – ISPRS Journal of Photogrammetry and Remote Sensing **66** (4): 389–399.

Toś, C., 2014: The possibilities of using the terrestial scanning data for classification of rocks in limestone mine 'Czatkowice'. – Reports on Geodesy and Geoinformatics **97:** 80–90.

Trager, F., 2007: Springer Handbook of Lasers and Optics. – Springer.

Voegtle, T., Schwab, I. & Landes, T., 2008: Influence of different materials on the measurements of terrestrial laser scanner. – The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **37** (B5): 1061–1066.

Wandachowicz, K., 2000: Wyznaczanie rozkładu luminancji we wnętrzach z uwzględnieniem kierunkowo-rozproszonych charakterystyk odbiciowych materiałów (Determination of the luminance distribution in the interiors taking into account the characteristics of the directional--diffuse reflectance materials). – doctoral dissertation, Poznań, Poland.

Zámečníková, M., Neuner, H. & Pegritz, S., 2014a: Influence of the Incidence Angle on the Reflectorless Distance Measurement in Close Range. – INGEO 2014 – 6th International Conference on Engineering Surveying: 257–262, Prague, Czech Republic.

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

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