Evaluation of the Credibility of Reflectorless Distance Measurement

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Abstract: Reflectorless distance measurement provides the ability to easily make quick measurements saving time and labor for surveyors. The precision and accuracy of these types of measurements are under discussion because of the variety of parameters that can affect these measurements that are not well-understood. This paper attempts to answer some of the questions that have arisen about the credibility of reflectorless distance measurements ranging up to 50 m. An experiment was carried out using 26 different materials as the reflecting surface (these materials were also of differing colors). Additionally, the experiment used three different angles of incidence of the incoming electromagnetic energy with three different types of reflectorless total stations over a variety of ranges. A further experiment was conducted with an additional total station using 11 different materials at different ranges. To properly evaluate the results, a special supporting base was manufactured for holding the reflecting surface to ensure accuracy in the evaluation. The results are presented in tables and the conclusions that are derived indicate that further investigation is needed, especially at longer distances, as the parameters that influence reflectorless distance measurement in those situations are many more, and more important than at short ranges.

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Introduction

The evolution of distance measurement during the past 50 years has contributed to the amelioration of this process, especially with respect to the accuracy and credibility of measurements made with this method and to increase the reliability of setting out of construction points and stakes for engineering projects. The tape was replaced by electromagnetic distance measurement (EDM) for long distances, subsequently improvements in range, mass, and speed of operation of this technology eventually enabled the integration of EDM into electronic theodolites resulting in compact total stations. These total stations, which continued to require retroprisms for distance measurement solved many logistical issues in surveying and lightened the workload of surveyors. In the 1990s the use of a powerful visible laser beam was used for measurements to almost on any surface without the use of retroprisms. Many of today's total stations have integrated this reflectorless EDM technology (Paiva 2001a,b). As these instruments are widely used by surveyors (Mills and Barber 2004), they have an obvious interest in knowing the potential and limits of these modern reflectorless total stations. Recently published information surveying the total station market indicates that reflectorless total stations with a range of 2 km are not unusual. While outside the purview of this note, attention must be paid to the laser safety class of the instrument. Laser safety classes in Europe vary between 1 and 4. Most surveying instruments have a laser of class 2 or 2 M, but some of them are of class 3R (Leica Geosystems 2005), which requires careful use. Important parameters influencing the credibility of a reflectorless distance measurement are as follows:

1. The length of the distance measured;
2. The texture and the color of the surface to which the measurement is made;
3. The reflectivity of the surface to which the measurement is made;
4. The illumination of the surface;
5. The incidence angle of the laser beam with respect to the surface;
6. The position of the measured point when measuring to inner or outer corners;
7. The size and the shape of the footprint of the laser beam;
8. The area of the surface needed for reflection of the laser beam;
9. The laser class of the light beam used for the measurement; and
10. The type of electronic distance measurement technology used for the measurement (i.e., "time of flight" or "phase shift").

It should be noted that in addition to the well-known "time of flight" (Paiva 2001a,b) and "phase shift" method (Trimble 2005), there is also a new measurement method named "system analyzer," purported to improve the accuracy and the credibility of reflectorless measurements (Bayoud 2006).

This paper presents the results of a series of experimental measurements aimed at capturing the behavior of some reflectorless distance measurement devices. The purpose of the experiments is

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Fig. 1. Some of the materials: (a) Kodak gray card; (b) Kodak white card; (c) reflective tape target; (d) white cement; (e) black paper; (f) red plastic; (g) white foam; and (h) roof tile

to attempt to draw conclusions about the credibility of this technology by analyzing measurements made with four reflectorless total stations on the following:

1. 26 different materials;
2. Two color variations for four materials; and
3. Three different angles of incidence.

The measurements were carried out in a metrology tunnel, where a row of pillars was previously accurately arranged in order to ensure the exact placement of the instruments and materials to which measurements were made.

Instrumentation and Materials

For the total stations used in this experiment, salient details are listed in the following table. The selection of materials used in this study depended upon the frequency of their appearance in surveyors' field work, such as, for example cement, tile, wood, and marble. Certain special materials were also used just for checking the laser behavior, as for example gold and ice. Fig. 1 shows 8 out of the 26 materials. The list of the materials used in the study is as follows: Kodak gray card (18%), gray cement, Kodak white card (90%), gray paper, reflective tape target, black paper, self-adhesive aluminum target, white plastic, Sokkia's geodetic target, red plastic, white cement, gray floor tile, brown foam, flesh-colored floor tile, white foam, rock marble, particle board, iron, melamine, roof tile, nickel, asphalt, gold, wood, and ice.

Special Supporting Base

A special supporting base was indispensable so that the materials could be properly and accurately placed. It has two vertical support forks and screws on the rear so that the fastening materials to it are facilitated. It is made by aluminum (Fig. 2).

The base was manufactured to achieve the following goals:

1. The center of the screw on its bottom must be on the same plane, as it is defined by the internal surface of both the support forks.

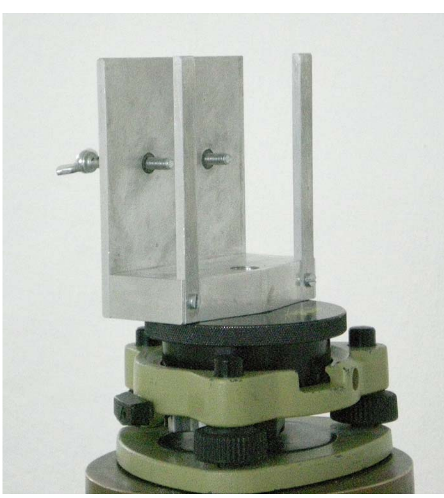

Fig. 2. Special base for supporting the target materials

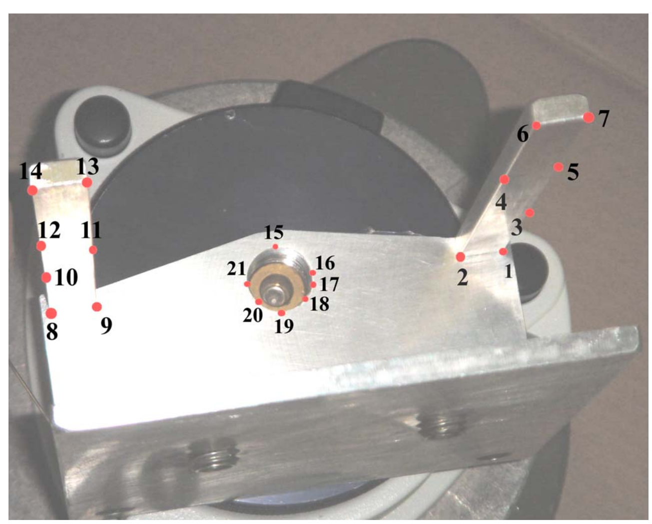

Fig. 3. Base with measuring points shown

Fig. 4. Metrology tunnel

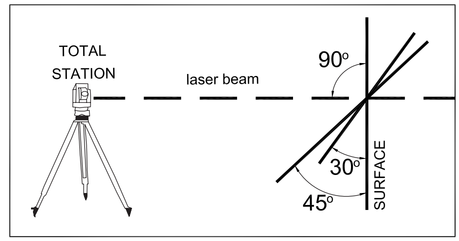

Fig. 6. Different incidence angles of the laser beam on the material's surface

2. The support forks must be vertical and perpendicular to the plane of the bottom of the base.

These goals are intended to enable the placement of the front surface of each material installed in the base, at the same position of the retroprism. Thus comparable measurements are enabled.

The validation of the design of the base was checked by measurements of key points on the base's body (Mavrakis 2008). Seven points were measured on the circumference of the screw, on the base's bottom, and 14 points were measured on both its support forks (Fig. 3). These measurements were made using high accuracy total stations (Leica TDM 5000 and Leica TDA 5005), both of which have a stated accuracy of ± 0.5 arc sec per DIN18723 for angle measurements. Furthermore, the measurements were made using intersections of the lines of sight of the totals stations, to insure adequate accuracy in the coordinate's determination. During the measurements, the points on the base's body were marked by a pin edge to assure unique targeting for each one due to the very close distance about 3 m between the base and the instruments. The coordinates x, y, and z of the measured points were calculated in a local arbitrary Cartesian system with an accuracy of ± 0.1 mm. The well known general equation of the circle is used

$$A \cdot x + B \cdot y + C = -x^2 - y^2 \quad (1)$$

The coefficients A, B, and C are calculated by solving the system of seven equations (as many as the measured points on the circumference of the screw).

Thus the best fitting circle to the measured points on the screw circumference was determined. The center K of this circle is given by the following equation:

$$K\left(-\frac{A}{2}, -\frac{B}{2}\right) = K(3.0896 \text{ m}, 0.9856 \text{ m}) \quad (2)$$

The radius R of this circle is calculated as well

$$R = \frac{\sqrt{A^2 + B^2 - 4 \cdot C}}{2} = 7.1 \text{ mm} \quad (3)$$

The best fitting vertical plane to the 14 points measured on the base's support forks was calculated by means of the following:

$$A_1 \cdot x + B_1 \cdot y + C_1 = z \quad (4)$$

The coefficients A_1, B_1, and C_1 are calculated by means of the system of fourteen equations solution (as many as the measured points on both the support forks).

This plane defines the position of the front surface of each material when it is placed correctly on the base. The equation of the line defined by the intersection of the above vertical plane and the circumference of the screw is calculated using a system of Eqs. (1) and (4).

The distance between this line and the center of the circle is calculated and found to be 0.7 mm. This means that the surface of each material has a systematic deviation of 0.7 mm, on the sight direction, from the corresponding point of the retroprism center.

Fig. 5. Reflectorless measurement on marble, black paper, and wood

Table 1. Characteristics of Total Stations Used in This Study

Manufacturer	Model	Accuracy (standard deviation) in reflectorless mode (mm)	Accuracy (standard deviation) using retroprism (mm)	Range in reflectorless mode (m)	Used laser class	
					With retroprism	Reflectorless
Leica	TCR 303	±3	±2	100	2	2
Trimble	5605 DR+	±3	±3	600	2	2
Topcon	GPT 3003 LN	±5	±3	1,200	2	2
Leica	TCRM 1201+	±2	±1	400	1	3R

Note: Most instruments have an accuracy specification that includes the constant uncertainty stated above as well as a scale value, usually given in parts per million. As the distances measured are short in this experiment, the scale value when expressed as a distance is insignificant and thus not included.

This value must be subtracted from each measured distance before its comparison to the measured distance on the retroprism. Consequently, after the above metrological check of the special supporting base, the latter could be used for the experiments, as distances measured to the prism could be compared with those measured to any other material.

Experimental Procedure

The procedure that was applied using three out of the four total stations is the following:

1. The instrument is put on the first pillar of the metrology tunnel on a heavy forced centering base and also another centering base bearing a prism is put on the last pillar, 50 m away. The distance between the instrument and the prism is measured after setting the instrument in prism mode.
2. The prism is removed from the tribrach and the special base is installed on it (Fig. 4). The instrument's telescope is not moved during these changes. All materials used in the experiment are in turn installed on the base and the distance to each one measured after setting the instrument in reflectorless mode.

When a material is put on the special base its front surface is aligned with the optical point on the prism to which a distance measurement is made, except for the 0.7-mm difference described above (Fig. 5).

The reflectorless distance measurements were carried out at three different incidence angles of the laser beam on the surface

Table 2. Deviations between the Five Repeated Measurements

Materials	Deviations (mm)								
	Leica TCR 303			Trimble 5605DR+			Topcon GPT3003LN		
	90°	30°	45°	90°	30°	45°	90°	30°	45°
Kodak gray card (18%)	—	—	—	0	2	2	0	2	1
Kodak white card (90%)	1	1	1	1	1	1	1	1	2
Reflective tape target	0	0	0	1	1	1	2	2	2
Self-adhesive aluminum target	0	—	—	2	2	4	1	1	—
Sokkia's geodetic target	2	—	—	1	2	2	2	1	1
White cement	1	1	2	4	1	1	1	2	4
Gray cement	2	1	2	1	2	0	1	2	2
Gray paper	1	0	2	2	1	1	1	1	2
Black paper	—	—	—	0	1	3	2	2	2
White plastic	1	2	2	1	1	1	1	1	0
Red plastic	1	2	1	1	2	1	2	2	1
Gray floor tile	2	2	1	2	1	2	1	2	0
Flesh-colored floor tile	1	1	2	2	2	1	1	2	1
Brown foam	—	—	—	2	2	2	2	0	1
White foam	1	1	2	1	1	1	1	1	3
Marble	1	2	1	0	1	1	1	1	1
Iron	3	—	—	1	3	2	3	2	—
Roof tile	—	—	—	2	2	3	1	1	1
Asphalt	—	—	—	1	6	3	1	1	1
Wood	1	1	1	2	0	1	1	2	1
Rock	—	—	—	1	3	1	1	1	1
Particle board	2	1	1	2	1	1	4	0	1
Melamine	1	1	1	1	1	2	1	2	2
Nickel	0	3	0	1	0	1	1	1	***33***
Gold	1	—	—	1	0	1	3	1	2
Ice	5	—	—	7	1	1	1	1	4

Table 3. Differences ΔD at a Distance of 50 m

Materials	Leica TCR303			Trimble 5605DR+			Topcon GPT3003LN		
	ΔD (mm)	ΔD (mm)	ΔD (mm)	ΔD (mm)	ΔD (mm)	ΔD (mm)	ΔD (mm)	ΔD (mm)	ΔD (mm)
	90°	30°	45°	90°	30°	45°	90°	30°	45°
Kodak gray card (18%)	—	—	—	1.0	4.0	**9.0**	2.0	2.0	3.0
Kodak white card (90%)	7.0	**11.0**	**18.0**	0.0	3.0	7.0	1.0	1.0	2.0
Reflective tape target	−1.0	−1.0	−1.0	−3.0	−2.0	0.0	2.0	3.0	3.0
Self-adhesive aluminum target	**8.0**	—	—	−2.0	5.0	**17.0**	1.0	−7.0	—
Sokkia's geodetic target	**37.0**	—	—	0.0	7.0	**9.0**	0.0	4.0	2.0
White cement	**11.0**	**11.0**	**14.0**	**−17.0**	2.0	5.0	−4.0	1.0	2.0
Gray cement	**19.0**	**22.0**	**24.0**	**−25.0**	3.0	7.0	−2.0	1.0	3.0
Gray paper	**15.0**	**10.0**	**26.0**	0.0	4.0	**9.0**	0.0	1.0	3.0
Black paper	—	—	—	−1.0	4.0	6.0	−1.0	−1.0	0.0
White plastic	2.4	**9.0**	**12.0**	−4.0	−7.0	−2.0	−2.0	−7.0	−6.0
Red plastic	4.8	**14.0**	**17.0**	−1.0	0.0	4.0	1.0	−1.0	−4.0
Gray floor tile	**12.2**	**19.0**	**25.0**	0.0	4.0	8.0	−2.0	0.0	2.0
Flesh-colored floor tile	**8.0**	**17.0**	**22.0**	0.0	2.0	7.0	0.0	0.0	3.0
Brown foam	—	—	—	0.0	3.0	**9.0**	0.0	1.0	**−9.0**
White foam	3	6.0	**14.0**	**−9.0**	−8.0	−1.0	**−10.0**	**−8.0**	**−9.0**
Marble	**7.8**	**13.0**	**17.0**	−6.0	−2.0	2.0	−4.0	1.0	1.0
Iron	**26**	—	—	1.0	**16.0**	**33.0**	11.0	2.0	—
Roof tile	—	—	—	−2.0	2.0	6.0	0.0	−1.0	2.0
Asphalt	—	—	—	**−14.0**	−3.0	6.0	−4.0	−4.0	−3.0
Wood	**14.0**	**16.0**	**22.0**	0.0	3.0	7.0	1.0	1.0	2.0
Rock	—	—	—	−6.0	−1.0	6.0	1.0	0.0	0.0
Particle board	**17.2**	**21.0**	**27.0**	0.0	4.0	**9.0**	0.0	4.0	3.0
Melamine	4.2	**12.0**	**16.0**	−1.0	3.0	6.0	1.0	1.0	1.0
Nickel	2.0	**37.0**	—	0.0	1.0	3.0	0.0	1.0	**−62.0**
Gold	4.0	—	—	−2.0	3.0	7.0	0.0	0.0	0.0
Ice	3.0	**8.0**	—	**−15.0**	**−26.0**	**−14.0**	**−34.0**	**−36.0**	**−28.0**

of each material. First, the surface is put perpendicular to the laser beam (90°), second the surface is turned by 30° and third by 45° in relation to the direction of the laser beam (Fig. 6). Also, in order to evaluate the precision of the measurements, measurements to each material were made five times for each angle of incidence.

Using the Leica TCRM 1201+ (Leica Geosystems 2007), 11 materials were measured according to the above-described procedure for incidence angles of 90° and 45° and for distances of 50 and 15 m (Iliodromitis 2008). The measured distance on the prism (D_p) was compared with the reflectorless measured distance on each material (D_m) at each incidence angle as follows:

The difference $\Delta D = D_p - D_m$ was calculated. The acceptable value of ΔD is given by the Eq. (5) for the desired confidence level

$$-z \cdot \sigma_{\Delta_D} \leq \Delta D \leq z \cdot \sigma_{\Delta_D} \quad (5)$$

where $\sigma_{\Delta_D} = \sqrt{\sigma^2_{D_{IR}} + \sigma^2_{D_{RL}}}$

$\sigma_{D_{IR}}$=error of the distance measurement on the retro prism according to the manufacturer; $\sigma_{D_{RL}}$=error of the reflectorless distance measurement according to the manufacturer (Table 1).

The acceptable values of the difference ΔD for confidence levels of 68 and 95%, respectively, for each instrument are

Leica TCR 303: $\pm 3.6 \cdot z_{95\%} = \pm 7.1$ mm

Trimble 5600 DR+: $\pm 4.2 \cdot z_{95\%} = \pm 8.2$ mm

Topcon GPT 3003 LN: $\pm 5.8 \cdot z_{95\%} = \pm 11.4$ mm

Leica TCRM 1201+: $\pm 2.2 \cdot z_{95\%} = \pm 4.3$ mm

Results

Tables 2–4 summarize the results. The symbol (–) means that the instrument did not measure the distance to the concrete sample target material. The values of the differences ΔD, which are unacceptable for confidence level 95%, appear in the gray cells. Table 2 displays the deviation (in millimeters) of the five repeated measurements from each other. These deviations express the precision of the instruments without taking into consideration their accuracy, namely, their comparison to retroprism measurement. The deviations fluctuate between 0 and 7 mm. Only one large deviation was observed (33 mm) to the nickel target, at an angle of 45°, using the Topcon GPT 3003 LN. The deviations of the repeated measurements show that these modern total stations are precise enough in the reflectorless mode. We should note that although their measurements are precise they are not always accurate.

The diagram (Fig. 7) shows that about 40% of the measurements have deviation greater than 1 mm at any incidence angle. It also shows that among all measurements those made on a perpendicular surface to the laser beam have the smallest deviations.

Table 4. Differences ΔD at 15 m and 50 m Using the Leica TCRM 1201+

Materials	ΔD (mm) 15 m 90°	15 m 45°	50 m 90°	50 m 45°
Kodak gray card (18%)	0	−1	0	−1
Kodak white card (90%)	+1	+1	−1	***−8***
Self-adhesive aluminum target	+1	+1	0	−2
Gray marble	0	−1	−1	***−8***
White marble	0	0	−2	***−8***
Wood	0	−1	−1	***−6***
Roof tile	0	−1	0	***−8***
Black paper	0	−1	0	***−8***
White paper	−1	−1	0	***−7***
Iron	+2	+2	−1	***−8***
Glass	***−11***	***−11***	***−13***	***−19***

Some dark colored materials as black paper, gray floor tile, brown foam, iron, and roof tile have the greater deviations in the repeated measurements.

Table 3 presents the differences ΔD in mm for the distance of 50 m. It shows that the Trimble 5605 DR+ and the Topcon GPT 3003LN measure exactly the same distance using a reflector or not in the case of about one-third of the materials at incidence angle of 90°. However, at an incidence angle of 45°, only the one-ninth of them has the same measurement. Both the Trimble 5605 DR+ and the Topcon GPT 3003 LN measure systematically longer distance on white materials such as white plastic, white foam, and marble, as well as on asphalt at every incidence angle.

The Leica TCR 303 measures systematically shorter distances in reflectorless mode. It was able to make measurements to only to 75% of the materials for incidence angle of 90° and to 50% of the materials at an incidence angle of 45°. It had less than 20% acceptable measurements at an incidence angle of 90°. It is very likely that the short range of the instrument is a crucial parameter but it is the only one that measures correctly to ice.

In the case of Kodak Gray Card (18%), the material to which the manufacturer accuracies are given. It was discovered in the experiment that the measurements are not independent of the incidence angle. However, it should be noted that it was impossible to measure to this material with the Leica TCR 303.

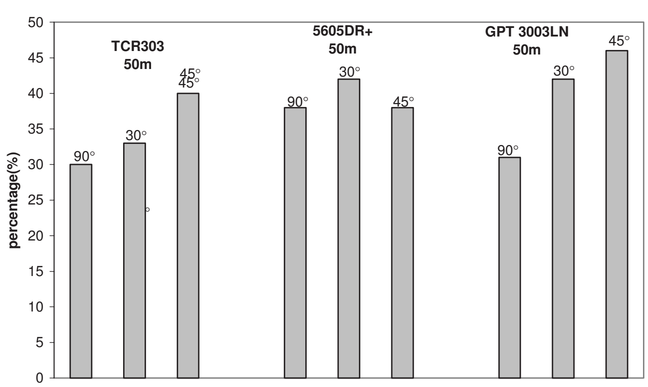

Fig. 7. Percentage of deviations >1 mm of the five repeated measurements

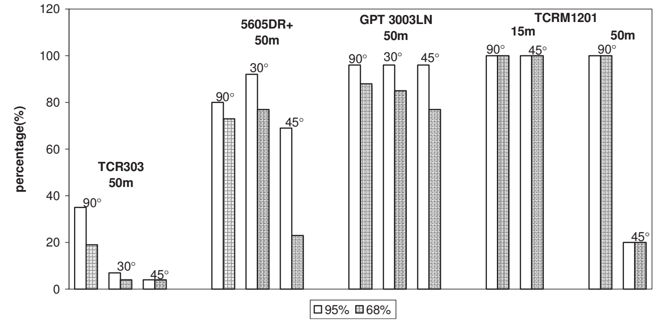

Fig. 8. Percentage of successful measurements for confidence levels of 68 and 95%

Only the reflective tape target out of the 26 materials has precise and accurate measurements using all instruments at every incidence angle. The measurement to ice using the Trimble 5605 DR+ and the Topcon GPT 3003 LN was not possible as the laser beam penetrates 2–3 cm into the ice.

The Topcon GPT 3003 LN has the maximum percentage of successful measurements for both confidence levels of 68 and 95% (Fig. 8) and for the three incidence angles. Probably this happens as this instrument has the longer range, which gives the possibility of more correct measurements in short distances.

Fig. 8 illustrates the results: (a) the acceptable measurements for incidence angle of 90° that fluctuate between 70 and 100% (except the TCR 303) and (b) the acceptable measurements for incidence angle of 45° that fluctuate between 20 and 100%.

The incidence angle is a parameter that strongly influences the accuracy of the reflectorless measurement. As it increases, so the observed differences from the true value of the distance also increase. The white foam was the most difficult material. The white cement and the iron give great deviations or they cannot be measured.

Table 4 presents the results for the Leica TCRM 1201+ at distances of 15 and 50 m. The Leica TCRM 1201+ measures exactly ($\Delta D=0$) the same distance for the two-thirds of the used materials for incidence angle of 90° either at 15 or 50 m. It also measures beyond the error limits and systematically longer distances for the most materials at incidence angle of 45° and distance of 50 m (Table 4). The check for two different distances by using the Leica TCRM 1201+, which today provides the best reflectorless accuracy of ±2 mm worldwide, according to the manufacture, shows that this accuracy is achieved in all cases, namely all materials at both 15 and 50 m at the perpendicular measurements. On the contrary, at 50 m and 45° incidence angle only two measurements were correct. The measurement on the glass is not possible by reflectorless measurement as the beam penetrates into the material.

Conclusions

1. It was realized that the experiment could not have been done without the use of the supporting base, which is manufactured under the indispensable presuppositions. It assures the correct placement of all materials and the possibility to compare the measured distances each other.
2. The majority of the reflectorless measurements are shorter than the true distance (Table 3).
3. The differences ΔD at a distance of 50 m are not systematic, as shown in Table 3; as many parameters influence the result.

4. With high incidence angles (i.e., not perpendicular to the incident beam), the performance of the EDM varies greatly with the distance being measured (Table 4).
5. Further investigation is needed for distances longer than 50 m; first in order to evaluate the credibility at the limit of the instruments' range, especially in case of measurements at difficult incidence angles-and second, to determine the surface area needed for such a measurement.
6. The total station with the longer range (GPT 3003LN) gives correct measurements even at incidence angle of 45°.
7. The percentage of the correct measurements fluctuates between 20 and 85% for a distance of 50 m, as illustrated in Fig. 3. This means that further improvement of reflectorless total station technology is needed.

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