Impact of Prism Type and Prism Orientation on the Accuracy of Automated Total Station Measurements

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Abstract. Automated total stations are a core element of today's monitoring installations and are used for dam monitoring, landslide monitoring and for the stability assessment of tunnel constructions. The achievable accuracy always depends on the instrument, the atmospheric conditions along the measurement path and the used target.

From investigations performed several years ago it is known, that certain configurations and prism types are not suitable for high-accurate applications. E.g. 360° prisms are not recommendable because horizontal and vertical angles and also the slope distances vary depending on the orientation of the prism.

In recent years, manufacturers redesigned some of their prisms and new total stations with improved distance measurement capabilities and better automated target aiming systems were released.

In this paper we demonstrate which effects have been mitigated and which prisms and configurations can still degrade the achievable accuracy. For instance the results of our laboratory investigations show that newer EDM technologies can reduce the distance errors on 360° prisms. However, also circular prisms can adversely influence angle and distance measurements. A special situation arises when a circular prism is perfectly aligned to the instrument. In this case front reflections caused by the front surface can cause errors in the range of several millimeters. Finally we also investigate the different behavior of prisms when used in an active and passive mode.

Keywords. Total station, circular prism, 360° prism, active target

1 Introduction

Investigations performed several years ago showed that for high-accurate surveying tasks it is indispensable to use circular prisms instead of 360° prisms. The deviations depending on the orientation of the 360° prism can rise up to several millimeters, which was demonstrated in several tests at different research institutions, see e.g. Favre & Hennes (1999), Stempfhuber & Maurer (2001), Ingensand (2001) or Krickel (2004).

Mao & Nindl (2009) give an overview of possible measurement errors when using different prisms types and describe the sources of these errors. Relevant factors are the prism construction (glass quality, geometry, coatings), the prism alignment with respect to the line of sight of an instrument and the used electronic distance measurement (EDM) unit.

In this paper we present the results of detailed prism investigations focusing on

- newer Prisms (e.g. the Leica GRZ122 prism which is the successor of the GRZ4 prism)
- the impact of different EDM types (e.g. the Trimble DR 300+ compared to the Trimble DR Plus)
- the influence of prism orientation and prism coating

2 Measurement Setup

To ensure comparable results all investigations were carried out under stable meteorological conditions in the IGMS measurement laboratory. The prisms were mounted on an adapted total station Leica TM1100 (see Figure 1). We developed a program based on Leica GeoCOM commands to turn the instrument and thus the attached prism horizontally in predefined steps.

Fig. 1 Measurement setup for prism investigations: adapted Leica TM1100 with rotating 360° prism

The TM1100 was mounted on an industrial tripod to vary the measurement distance and to adjust the prism height in order to ensure a horizontal line of sight. The second total station (Leica TS15, 1”, R1000) which performed the angle and distance measurements was mounted on a pillar. The same setup was also used for investigations of Trimble total stations (S6, S8) and the corresponding Trimble prisms.

Before each test started the prisms had to be aligned perfectly to the line of sight of the instrument. This was achieved by auto-collimation. Therefore, an auto-collimation mirror was placed on the prism front surface (for circular prisms) or at the edge of the prism housing (for 360° prisms). For all 360° prisms the same type of prism facet was chosen for the initial alignment.

At each rotation steps, up to 40 single automated angle and distance measurements were executed. The horizontal step size was 1° or 3° in most investigations and was reduced to 0.05° and 0.005° for detailed investigations.

3 Results using Leica 360° Prisms

Four types of Leica 360° prisms were chosen for the horizontal rotation tests. Figure 2 shows these prisms in the initial alignment (0° orientation) position with 1 facet leaning backwards. The GRZ122 is the upgraded version of GRZ4, whereas the GRZ101 mini prism was designed for special applications at short ranges and the MPR122 for machine guidance.

Fig. 2 Leica 360° prisms (not to scale, from left to right): GRZ4, GRZ122, GRZ101 (360° mini prism), MPR122 (for machine guidance)

To identify a possible distance dependence of occurring measurement errors the experiments were performed at various distances between the instrument and prism. In this paper we focus on the results of the 5m (close-up range) and the 26m (longest possible distance when using a pillar in our laboratory) experiments.

The results are presented as differences of the measured horizontal and vertical angles to the initial measurement at 0° rotation. The size of these differences is numbered in mm on the left axis scale and in mgon on the right axis scale. Additionally the variation of the slope distance is shown in a separate figure.

3.1 Measurements to Leica 360° Prisms at 5m Distance

In case of 360° prisms measurements can be performed at any horizontal orientation of the prisms. Therefore a full 360° turn was carried out in the experiments. The results at a 5m distance are shown in the Figures 3 to 5.

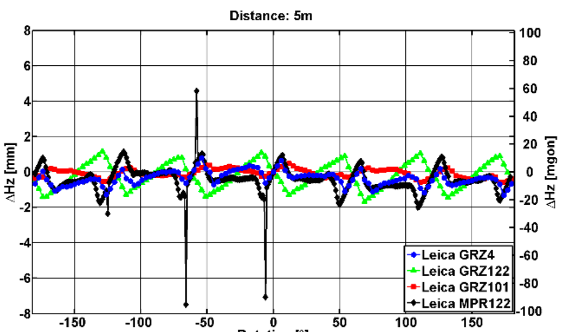

Fig. 3 Deviations of automated horizontal angle measurements to 360° prisms at 5m distance at different prism orientations

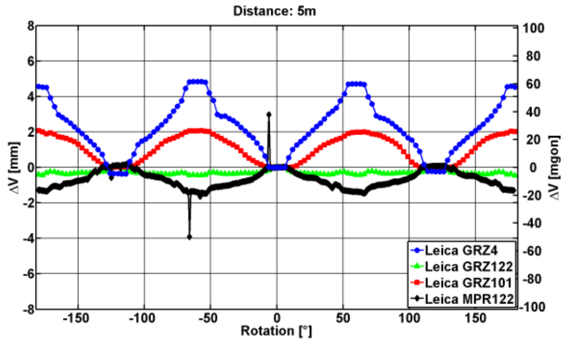

Fig. 4 Deviations of automated vertical angle measurements to 360° prisms at 5m distance at different prism orientations

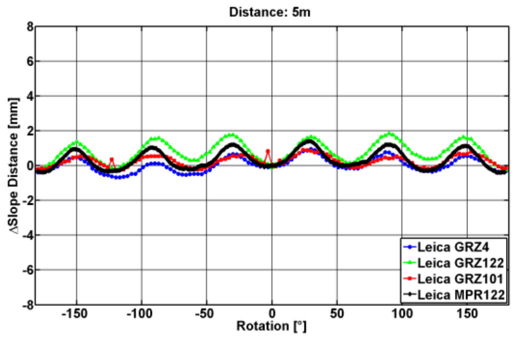

Fig. 5 Deviations of slope distance measurements to 360° prisms at 5m distance at different prism orientations

For all 360° prisms the cyclic error pattern due to the six prism facets can be depicted clearly, e.g. Figure 5. With respect to distance variations all prisms behave similar. Approximate amplitudes were be calculated by dividing the range of the deviations without outliers by two.

Concerning vertical angle measurements (Figure 4) it can be seen that the GRZ4 prism has the largest variations and a cyclic error with about 2.5mm amplitude. These variations almost vanish for the GRZ122 prism which is the improved of the GRZ4 prism. The prism behavior of the GRZ101 and the MPR122 is between the two other prisms with amplitudes of about 1mm.

The amplitudes of the vertical angle variations are less than 2mm for all prisms.

Table 1. Measurement variations of Leica 360° prisms at 5m distance

	Amplitude of cyclic error [mm]		
Prism	Hz	V	D
GRZ4	1.3	2.5	0.8
GRZ122	1.7	0.2	1.1
GRZ101	0.6	1.0	0.6
MPR122	1.8	0.8	0.9

The values of the typical cyclic error are summarized in Table 1.

Additionally to the cyclic variations single outliers occurred when measuring to the 360° prims (e.g. Figure 3, MPR122). These will be further discussed in section 3.3.

3.2 Measurements to Leica 360° Prisms at 26m Distance

The same rotation test was also performed at 26m distance. The results are shown in Figures 6 to 8.

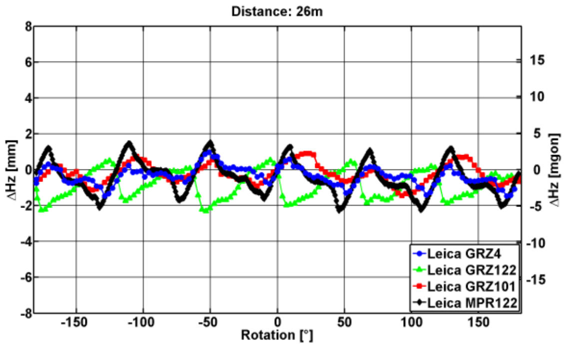

Fig. 6 Deviations of automated horizontal angle measurements to 360° prisms at 26m distance at different prism orientations

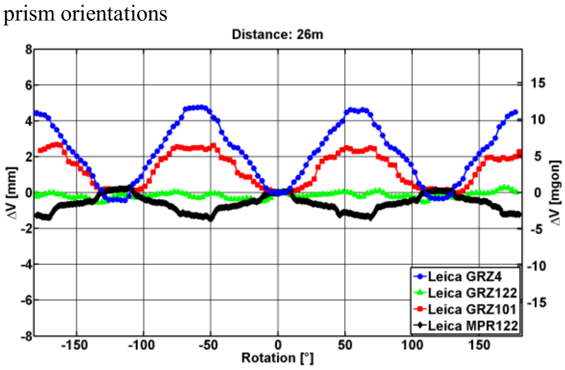

Fig. 7 Deviations of automated vertical angle measurements to 360° prisms at 26m distance at different prism orientations

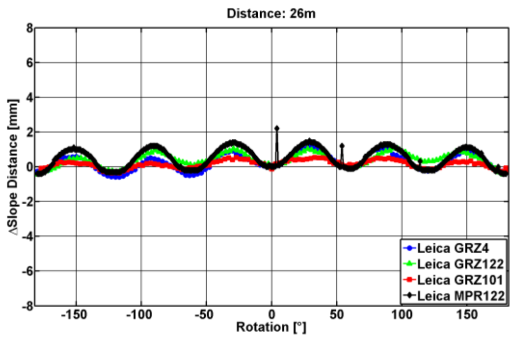

Fig. 8 Deviations of slope distance measurements to 360° prisms at 26m distance at different prism orientations

When comparing the results of the 5m and 26m experiments (Table 1 and Table 2) it can be seen that the deviations in millimeters are almost the same. The patterns are slightly less distinct at 26m (compare Figures 5 and 7) but otherwise no distance dependency could be detected.

Table 2. Measurement variations of Leica 360° prisms at 26m distance

	Amplitude of cyclic error [mm]		
Prism	Hz	V	D
GRZ4	1.2	2.6	0.9
GRZ122	1.4	0.4	0.7
GRZ101	1.2	1.4	0.5
MPR122	1.8	0.9	0.9

3.3 Detailed Measurements to Leica 360° Prisms at 5m Distance

For detailed investigations of the outliers described in section 3.1 the step width of the prism rotation was reduced to 0.05° for a rotation angle of ±20° around the initial alignment. The results of the angle measurements of these investigations are shown in Figure 9 and Figure 10.

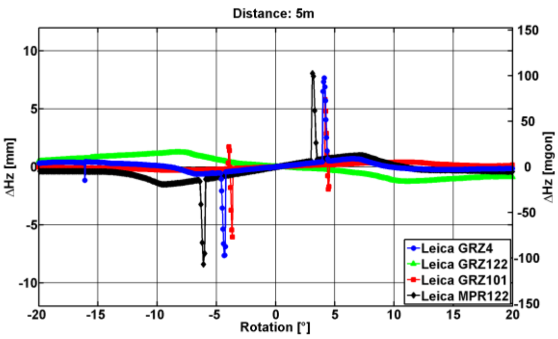

Fig. 9 Detailed investigations of automated horizontal angle measurements to 360° prisms at 5m distance

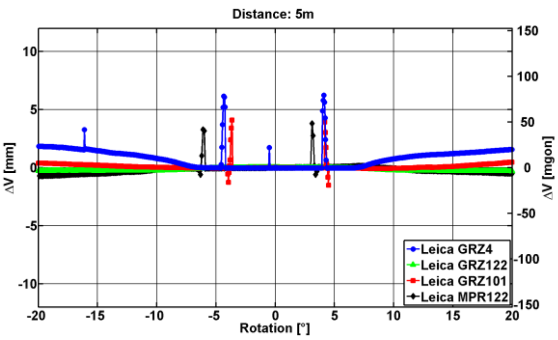

Fig. 9 Detailed investigations of automated vertical angle measurements to 360° prisms at 5m distance

All 360° prisms except the GRZ122 show deviations of up to 8mm nearly at the same rotation position. It can be concluded that these deviations are not arbitrary outliers but reproducible systematic effects. A possible reason for these systematic could be, that in some rotation positions the automated target recognition (ATR) system detects a mixture of two nearby prism facets and calculates the "wrong" prism center. Because of the different sizes and assembly of the GRZ4, GRZ101 and MPR122 prims these effects occur on slightly different rotation positions. The maximum size of the systematic single outliers of our experiments is given for a distance of 5m in Table 3 and a distance of 26m in Table 4. It has to be noted that even larger errors may occur at orientations not present in our experiments.

Table 3. Single deviations of Leica 360° prisms at 5m distance

	Maximum size of systematic errors [mm]		
Prism	Hz	V	D
GRZ4	7.7	6.2	5.0
GRZ122	- *	- *	- *
GRZ101	6.0	4.1	1.5
MPR122	8.2	3.8	- *

* no systematic effect except cyclic error pattern

Table 4. Single deviations of Leica 360° prisms at 26m distance

	Amplitude of systematic errors [mm]		
Prism	Hz	V	D
GRZ4	7.6	6.0	1.0
GRZ122	- *	- *	- *
GRZ101	6.3	4.0	1.5
MPR122	8.5	3.8	1.8

* no systematic effect except cyclic error pattern

4 Results using Leica Circular Prisms

4.1 Measurements to Leica Circular Prisms at 5m distance

For the experiments with the circular prisms a step width of 3° within the measurable rotation range (about ±50°) was chosen. Additionally a step width of 0.005° was selected in the vicinity of 0° orientation to investigate systematic effects.

Fig. 9 Leica circular prisms (from left to right): GPH1P precision prism, GPR121 precision circular prism (Professional Series 5000), GPR111 circular prism (Professional Series 3000)

The result of the horizontal variations is displayed in Figure 10. It can be seen that the horizontal deviations are less than 1mm at orientations within ±30° to the line of sight. Remarkable are the large deviations in the vicinity of 0° orientation.

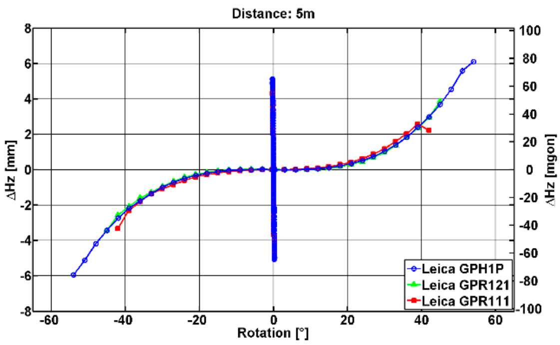

Fig. 10 Deviations of automated horizontal angle measurements to circular prisms at 5m distance at different prism orientations

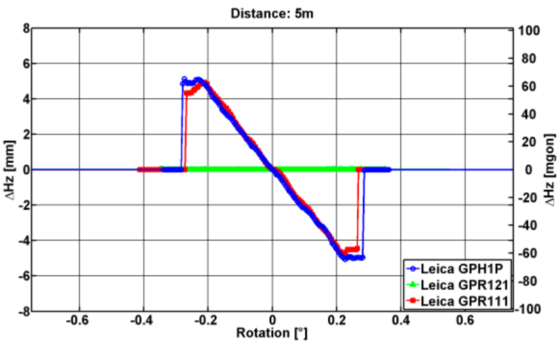

Fig. 11 Detail view of the deviations of automated horizontal angle measurements to circular prisms at 5m distance in the vicinity of 0° orientation

When looking at this area in more detail (Figure 11) it becomes apparent that the large deviations only occur when using the GPH1P or GPR111 prism. The measurements to the GPR121 are not affected. Furthermore, the angle deviations suddenly increase at an orientation of about -0.3° to up 60mgon and then decrease linearly to -60mgon at +0.3° orientation. The reasons for this behavior are reflections of the front surface of the GPH1P and GPR111 prisms. The design of Leica Geosystems prisms is explained by Mao & Nindl (2009). The prisms are coated with copper to increase the degree of reflection up to 75% and to raise the EDM performance up to 30%. When there is a very accurate alignment of the prism front surface orthogonal to the line of sight, measurement errors can occur due to direct reflections of the ATR or EDM signal on the front surface, like shown in Figure 12 and Figure 13.

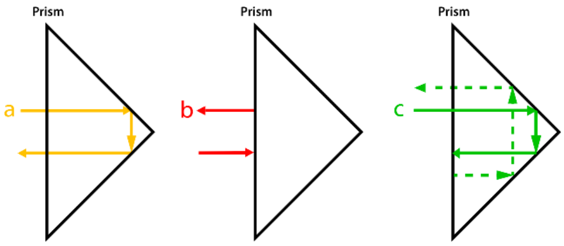

Fig. 12 Orthogonal alignment of the prism front surface (no anti-reflex coating) to the line of sight leading to different reflections at the prism: (a) Signal going through the glass body, (b) Reflection at the front surface, (c) Reflection at the inner surface (after Mao & Nindl, 2009).

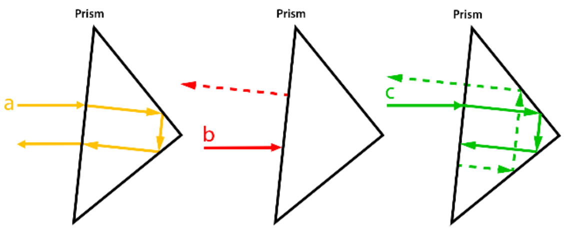

Fig. 13 Slightly misaligned prism front surface: only the signal going through the glass body (a) is received by the total station.

As also shown by Mao & Nindl (2009) this effect mainly arises at close-up ranges and can cause measurement errors of several mm.

The GPR121 has an anti-reflex coating and therefore the measurements to this prism type are not affected. To avoid reflections on the prism front surface when using the GPH1P prism, Leica Geosystems applies a slightly tilted diopter on the prism (Leica Geosystems AG, 2015).

4.2 Measurements to Leica Circular Prisms at 26m distance

The rotation measurements to the circular prisms were also repeated at a distance of 26m. It can be seen that the pattern is similar as at a distance of 5m, compare Figure 10 and Figure 14.

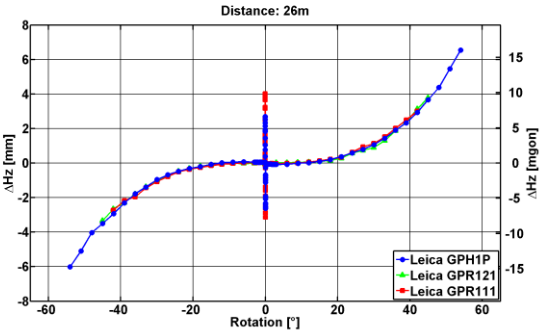

Fig. 14 Deviations of automated horizontal angle measurements to circular prisms at 26m distance at different prism orientations

As expected at 26m distance the measurements are influenced by front reflections in a much smaller range compared to measurements at 5m orientation. At 26m the prism has to be almost perfectly aligned to about ±0.06°, see Figure 15.

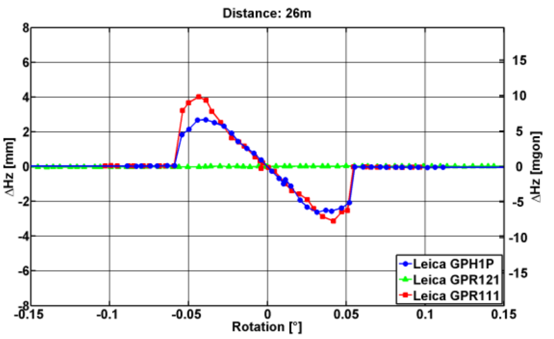

Fig. 15 Detail view of the deviations of automated horizontal angle measurements to circular prisms at 26m distance in the vicinity of 0° orientation

Table 5. Orientation range affected by front reflections

Circular prism	Anti-reflex coating	Influenced orientation range	
		5m distance	26m distance
GPH1P	No	± 0.28°	± 0.06°
GPR121	Yes	-	-
GPR111	No	± 0.28°	± 0.06°

The effect of the missing anti-reflex coating can be summarized in Table 5. Whereas the GPR121 is the only circular prism with an anti-reflex coating, the use of GPH1P and GPR111 can cause problems especially at short distances.

5 Measurements to a Trimble MultiTrack 1000 prism

Automated aiming of total stations is based on the emission and reception of infrared light. In a standard operation mode, the instrument transmits infrared light and detects the signal reflected by the prism either with an infrared camera sensor (Instruments by Leica Geosystems) or a quadrant detector (Instruments by Trimble). In such a setup the prism is only a passive element. Alternatively, active prisms can be used. These prisms actively send out infrared light which is received by the total station. An example of such a prism is the Trimble MultiTrack 1000 prism. This prism consists of eight single prisms arranged in a circle (see Figure 16 right) and two rings of 16 LEDs. If used in active mode, the LEDs of the prism emit an infrared signal in all directions (see Figure 16 left).

Fig. 16 Trimble MultiTrack (MT) 1000 in active (left) and passive (right) mode. Images captured with an infrared camera

When measuring to this MultiTrack target three different modes are possible. In the passive mode the prism diodes are switched off and the light source of the total station is on. In the active mode the aiming is only based on the light transmitted by the active target. Therefore, this mode is more robust in an environment with many reflecting surfaces. The third mode is called semi-active mode.

In this mode the Target ID which is also transmitted by the LEDs is used to track the prism but the instrument automatically switches to passive prism tracking mode when taking a standard measurement (Trimble, 2013, p. 425).

We performed experiments using all three modes with a Trimble S8 HP. The horizontal and vertical angle deviations are shown in Figure 17 and Figure 18. In passive mode a cyclic pattern with amplitudes of about 3mm is clearly visible. This pattern is caused by the 8 individual prisms. The semi-active mode delivers the same results as the passive mode because when taking a measurement the instrument switches to passive mode. In active mode a pattern with 16 cycles can be seen. The amplitude of this pattern is slightly smaller than in active mode. The situation is different with respect to vertical angle measurements. Whereas the vertical angle measurements are almost not influenced by the prism orientation in passive mode, significant variations occur in active mode.

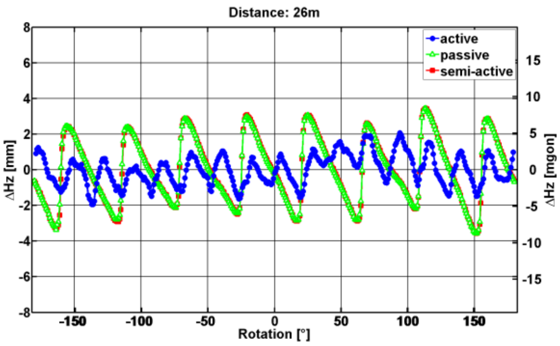

Fig. 17 Deviations of automated horizontal angle measurements to a MultiTrack 1000 prism at different prism orientations at a distance of 26m using a Trimble S8 HP

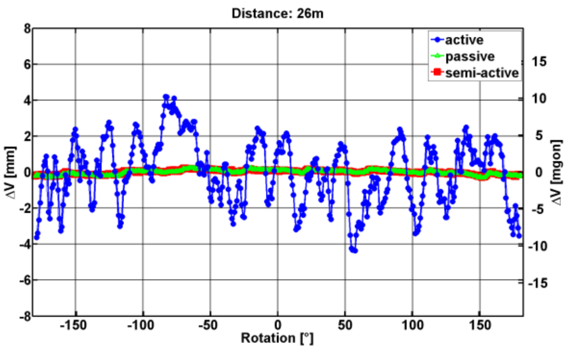

Fig. 18 Deviations of automated veritical angle measurements to a MultiTrack 1000 prism at different prism orientations at a distance of 26m using a Trimble S8 HP

Distance measurements are always based on light transmitted from the total station. Therefore, the LED rings of the MultiTrack 1000 target do not have an influence on the EDM measurement performance. However, the distance measurement results depend on the properties of the used EDM unit (wavelength of light source, beam shape and divergence, measurement principle etc.). Trimble integrates two different measurement principles in the total stations. The EDM measurements of the high precision (HP) models (e.g. S8 HP, S9 HP) are based on phase measurements whereas the direct reflex (DR) models use time of flight measurements. Older versions of the Trimble S6 have the DR 300+ EDM unit and newer version the enhanced DR Plus (Trimble, 2007 and Trimble, 2009).

The variations of the distance measurements of all three EDM units to the MultiTrack 1000 target are shown in Figure 19. It can be seen, that the variations of the Trimble S8 HP phase shift measurements are much smaller than the variations of the Trimble S6 DR 300+ time of flight measurements. However, it also can be seen that the variations the newer DR Plus time of flight unit are almost as small as the deviations of the phase shift measurements.

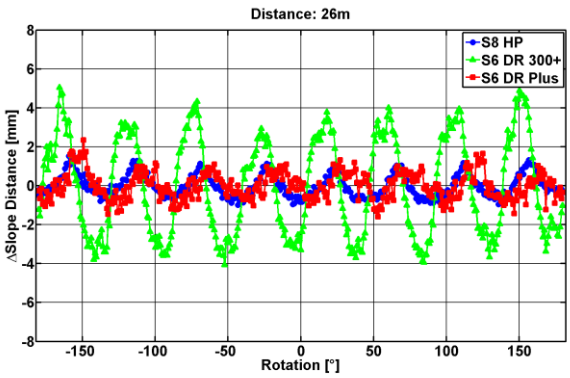

Fig. 19 Deviations of distance measurements to MultiTrack 1000 target at 26m distance at different prism orientations using different total stations

7 Summary and Conclusions

The motivation of the performed experiments was to give an overview of the impact of prism type and prism orientation when using state of the art prisms and instruments. Our results demonstrate that vertical angle variations can significantly be reduced when using the new GRZ122 360° prism instead of the GRZ4 prism. However, cyclic errors of more than 1mm still remain. Furthermore, many 360° prisms showed systematic large single deviations of several millimeters at specific prism orientations. Therefore, for applications with high accuracy demands it is still advisable to use circular prisms.

In our experiments the measurement deviations of circular prisms were less than 1mm when the prisms were orientated within ±30° to the line of sight. However, as was demonstrated in this paper a "perfect" alignment of the prism front surface to the line of sight can cause problems if the prism is not equipped with an anti-reflex coating. Obviously, the probability to receive direct reflections from the prism front surface is higher at close ranges. In order to avoid front reflections prisms with anti-reflex coatings can be used. Alternatively, like in case of the GPH1P prism, slightly tilted diopters can be used for prism alignment. This approach can still result in critical prism orientations for instance in rail track measurements using rail trolleys, where the distance between total station and prism is short and the prism orientation may slightly change during the measurements, e.g. due to a curve of the tracks. In these situations front reflections can only be avoided with prisms with anti-reflex coatings.

When using the Trimble MultiTrack 1000 the prism mode selection has a crucial impact on the horizontal and vertical angle variations. Although, the active prism mode is more robust in a high reflective environment, it significantly degrades the accuracy of the vertical angle measurements.

Considering distance variations we noticed significant improvements of measurements with newer time of flight EDM units.

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