

WARM-UP EFFECT AND WARM-UP TIME OF A LASER TRACKER

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Abstract: The warm-up effect is a well-known phenomenon, which occurs in all types of laser trackers. The series of experiments was performed to determine the influence of warm-up effect on measurement and a warm-up time of device – the time after the temperature inside the tracker is stable. In this paper, the tested tracker was Leica AT960-MR. Results showed that the warm-up effect could cause errors up to tenths of millimeters, and a warm-up time of instrument is around two hours, which is similar to the other researches.

Keywords: Absolute tracker, Testing, Precision, Performance

1. Introduction

Providing high precision measurement of three-dimensional points coordinates in situ is crucial in many industrial applications. For achieving precision up to tens of micrometers, a Laser Tracker (LT) is often used. LT is a coordinate measuring system in which a cooperative target is continuously followed with a laser beam, and its location is determined in terms of distance and two angles [1]. Position determination is based on a well-known spatial polar method frequently used in geodesy. LTs are mainly used in the shop floor environment to determine the position of characteristic points of large objects and machines. Because of their high precision, portability, and relatively simple usage, they have been used in every type of industry for example automobile,

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aircraft, ship, airspace). Application is similar to laser scanning [2], [3], but with higher measurement accuracy.

There are many factors to consider when using the LT that can affect the measurement. One of these factors is a phenomenon called the warm-up effect. After the LT is turned on (during the initialization phase), the laser source is raising its temperature so that it can be used for measurement. During this process, the other parts of the LT are heating up as well. Due to the thermal expansion of the components inside the tracker, various shifts and misalignments occur, which causes numerous uncertainties. For the reduction of the warm-up effect, the measurement should be performed after the temperature inside the device has stabilized. The time interval, after which the temperature stabilizes, is called the warm-up time.

This paper aims to determine the warm-up time of the absolute tracker Leica AT 960-MR and the impact of the warm-up effect on the measurement. Uncertainties made by the warm-up effect have a significant impact on results, so knowledge of this phenomenon is essential. A detailed description of the warm-up effect is provided in the text below, together with performed experiments.

2. Warm-up effect

The warm-up effect should not be confused with a common adaptation of the device with ambient temperature. Standard acclimatization of LT is a process when the tracker needs to adapt to temperature change when it is moved from different temperature environments. The warm-up effect is caused by internal heating of the laser source used in the ranging unit. Thermal expansion caused by the process of internal heating has a significant impact on the measurement. There is also information from the Leica geosystem given in [4] that the inclination sensor in the oil bath suffers from heating as well and changes its zero position. According to the manufacturer, this is the major contributor to the warm-up effect. However, when measuring with the Leica AT 960-MR, it is possible to turn off the inclination function (measurement is performed in a local system of the LT), and thus this effect may be reduced.

In general, the warm-up effect may vary among different manufacturers because of their individual design of LT and technologies used. Three main manufacturers today are Automated Precision Incorporated (API), Faro technologies, and Leica geosystems (Hexagon). Each manufacturer has several models of LT, which can differ too. Therefore, the warm-up effect should be considered individually.

The essential thing related to the warm-up effect is warm-up time. It specifies a period after which LT reaches a stable internal temperature level. This value also depends on the model of LT, but research has shown that it takes around two hours to reach a stable temperature for different LT [4], [5], [6]. Manufacturers are providing more optimistic information. For example, Faro technologies recommend on their web page one-hour warm-up time [7]. The same time recommends API in their tracker manual [8]. Leica geosystems provided information that achieving specified precision for Leica AT960-MR should be after 30-40 minutes of warming-up. In addition, after 3-4 hours should be the performance of LT even 50% better that is specified.

The impact of the warm-up effect on the measurement is described in several ways. Some authors are calculating the impact on measured angles and distances [4], [5], [6], the others are evaluating changes in the position of LT (translation, rotation) or impact on scale factor and offset of distance measurement [6], [9]. Exact values are not given because there are changing/depending on the model of LT, but they always exceed the manufacturer declared precision. Besides, the vertical angle is often more affected than horizontal angle and distance. One possible explanation is that the laser source is placed near the vertical encoder circle and therefore is more susceptible to temperature changes.

The best thing about how to deal with the warm-up effect is to wait until the temperature stabilizes. But this process usually takes two hours or more and can be unsatisfactory in some cases. Manufacturers recommend doing the re-initialization process every fifteen minutes during the first two hours of measurement in this case. This process should calibrate LT parameters to achieve declared precision. On the other hand, research [4] shows that the calibration of Faro LT was not very useful because of the instability of the system.

3. Experiments

To evaluate warm-up time and warm-up effect a series of experiments were made. All experiments were performed in Hexagon office in Bratislava. Hexagon office is located at ground floor with robust foundation and away from the main traffic. Although the stability of building is good, it can suffer from temperature change during the day. Unfortunately, laboratory with stable temperature was unavailable during the experiments. However, the reaction of the LT on external temperature change can be also tested.

3.1. Tested Leica AT960-MR and used equipment

Tested instrument was Leica AT960-MR (*Fig. 1*) with maximum range of 20 m with declared precision. Controller, external temperature sensor and computer with software are part of the system as well. In this case software Tracker Pilot and Polyworks were used.



Fig. 1. Leica AT960-MR

Domain of the Leica LT is distance measurement technology called Absolute InterFeroMeter (AIFM). It combines a heterodyne InterFeroMeter (IFM) for dynamic measurement with an Absolute Distance Meter (ADM) to set the absolute reference distance. The functional principles of mentioned methods of distance determination are given, for instance, in [10], [11], [12]. Angle encoders, inclination sensor, motorization and other components are similar or same as are used in high accuracy total stations. More detailed description of components and functions can be found in [13].

Basic accuracy characteristics are calculated per standards [1], [14] and are shown in *Table I*. It is important to properly understand values given by manufacturer. In three-dimensional point coordinate accuracy are included uncertainties made by distance and angle measurement and uncertainty made by retroreflector. This coordinate uncertainty is defined as the deviation between a measured coordinate and the nominal coordinate of the measured point. Orient to Gravity (OtG) accuracy means accuracy of 3D point coordinate when the inclination sensor is turned on. Distance accuracy is divided into two parts. Dynamic lock on is accuracy for ADM absolute distance determination (when setting reference distance for IFM). On the other hand, AIFM accuracy only shows IFM relative distance determination. These two values are indistinguishable because both modules measure simultaneously and contribute to the resulting accuracy of distance measurement. Angle measurement accuracy is the biggest contributor to uncertainty of measurement. *Table I* shows, that angle accuracy is same as 3D point coordinate accuracy (distance accuracy is neglected).

Table I

Basic accuracy characteristics of Leica AT960-MR

Accuracy characteristics	Standard deviation (1σ)	Maximum permissible error (MPE) (2σ)
3D point coordinates	$7.5 \mu\text{m} + 3 \mu\text{m/m}$	$\pm 15 \mu\text{m} + 6 \mu\text{m/m}$
Angle accuracy	$7.5 \mu\text{m} + 3 \mu\text{m/m}$	$\pm 15 \mu\text{m} + 6 \mu\text{m/m}$
Distance accuracy AIFM	$0.25 \mu\text{m/m}$	$\pm 0.5 \mu\text{m/m}$
Dynamic lock on	$\pm 5 \mu\text{m}$	$\pm 10 \mu\text{m}$
Orient to Gravity (OTG)	$7.5 \mu\text{m} + 4 \mu\text{m/m}$	$\pm 15 \mu\text{m} + 8 \mu\text{m/m}$

Among other tools a reflector was used during experiments. Traditionally, these reflectors are embedded in a spherical housing and there are several types and sizes of them. A Red Ring Reflector 1.5" type was used in the experiments. This type of reflector has a protective ring attached to it to prevent aiming at a large angle, causing an error in measured distance.

The ambient temperature during the experiment was measured near the instrument and at the reflector using non-contact temperature sensors. Data registration was ensured using the Comet MS6D datalogger with a recording interval of 1 s.

3.2. Testing of warm-up effect with two-face measurement

When designing the experiment, it is necessary to take into consideration the technology for measuring distances because of their different working principles. Tested

LT uses AIFM technology. Therefore, when aiming at target (reflector), the absolute distance is determined using ADM, which serves as a reference for the interferometer. Subsequently, all other distances are determined using an interferometer. However, if the laser beam is interrupted, the absolute distance is determined again by ADM. It follows that if the laser beam is not interrupted during the whole experiment, the warm-up effect on the interferometer is tested. On the other hand, if the laser beam before each measurement (two-face measurements) is interrupted, the warm-up effect on ADM is test.

The first experiment was performed by measuring reflector in two-face mode continuously for approximately four hours. The reflector was placed around three meters away from the tracker and in the approximately same height. The inclination sensor was turned off during the measurement. The software Polyworks was used because the Tracker Pilot did not allow two-face measurement. Measurement was controlled manually, and the time interval between single measurements was around one minute.

The experiment was performed in the Hexagon office. LT was placed in room whole night to stabilize with ambient temperature. The temperature in the room was measured during the whole experiment by non-contact temperature sensors: one placed near LT and the other one near the reflector.

With this type of experiment, the impact of the warm-up effect on measured distances and angles is evaluated. Because of the two-face measurement, only the ADM performance is tested. One problem with software Polyworks is that it provides only coordinates of measured points and not the measured values. Therefore, it is necessary to calculate the measured angles and distances to process the data.

After calculating angles and distances, it was necessary to express their change over time. The last measured point, which should be least influenced by a possible warm-up effect, served as a reference point in this case. The changes in the measured quantities are expressed as the difference between the measured values and the last measured value. The variations in the measured distance are shown in (*Fig. 2*), differences in the measured horizontal angle in (*Fig. 3*) and the differences in vertical angle in (*Fig. 4*). The temperature at the instrument (sensor 1) and the reflector (sensor 2) was measured during the experiment.

The best way to identify warm-up time is in the graph of the differences in distance (*Fig. 2*). During the measurement, there were step changes in the measured distances at the level of several micrometers in both instrument faces. The maximum step of almost ten micrometers occurred during the first 15 minutes, but this is still in the manufacturer's declared accuracy. A similar thing happened to another author as well [4], but without any explanation of this behavior. Step changes in the measured distance ceased to occur approximately 1 hour and 45 minutes after the start of the measurement, and the warm-up time can be confirmed. Changes in the distance are in the range of circa 14 micrometers during this time interval. After approximately another half an hour, it can be seen that the differences in the measured distance increased again. However, if these data are compared with the measured temperature, their correlation can be identified. After approximately 2 hours and 15 minutes, the room temperature began to rise (by almost 2 °C until the end of the experiment), which affected the measurement.

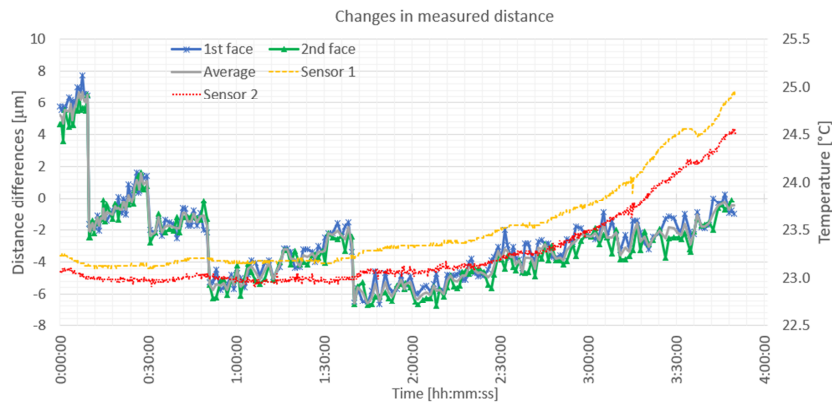


Fig. 2. Differences in measured distance

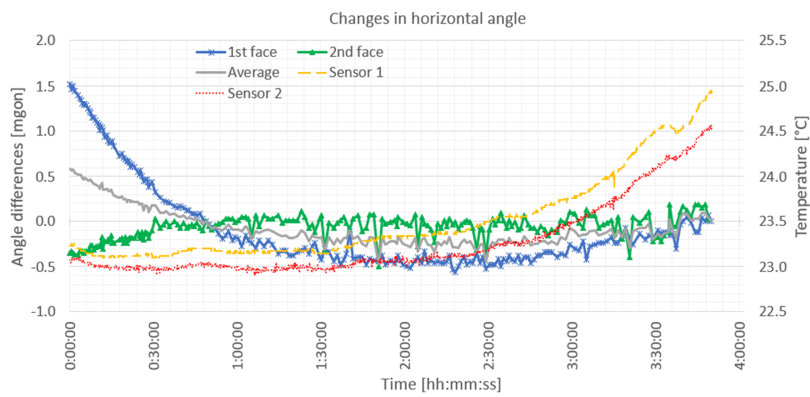


Fig. 3. Differences in measured horizontal angle

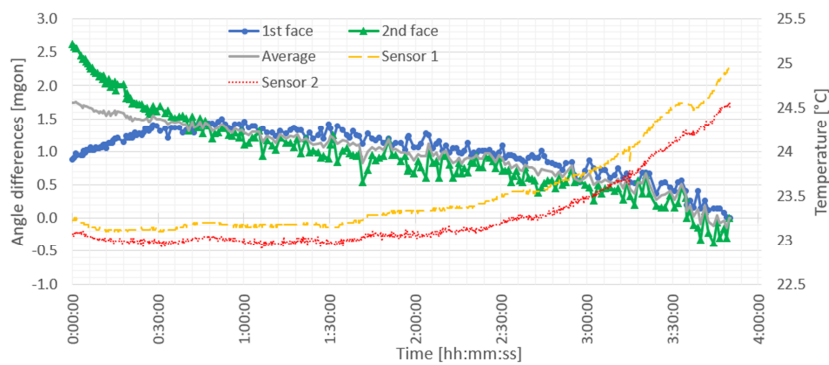


Fig. 4. Differences in measured vertical angle

The strange thing is that LT should internally compensate for this rise in temperature. Device manual states that a 1 °C change in temperature can cause 1 ppm change in distance. For three meters long distance is this value 6 micrometers (in this case), which is in congruence with *Fig. 2*. It is unknown fact why the LT is not compensating the temperature changes.

Similar conclusions can be made based on the graph of differences in the horizontal angle (*Fig. 3*). When measured in the 1st face, the values stabilize as well as the distances after approximately 1 hour and 45 minutes. The maximum difference in angle changes during this time interval is about 2.0 mgon. This value causes almost 0.1 mm deviation in a direction perpendicular to the laser beam (at 3 m distance). With a maximum instrument range of 20 m, this is approximately 0.6 mm, which is not negligible. There is also a similar phenomenon of gradual increase in differences as in the determination of distance. However, this is again caused by the rising temperature in the room. The two-face measurement can partially reduce the impact of the warm-up effect, but this type of measurement is very rarely used in practice.

When determining changes in the vertical angle (*Fig. 4*), the situation is a bit different. Steady-state conditions in the second face occur after approximately 1 hour and 45 minutes (the same time as in the previous cases). However, measurements in the 1st face stabilize earlier, approximately after an hour of measurement. Again, it is possible to see the impact of the temperature change in the room. The maximum difference in measured vertical angles during warm-up time is about 0.5 mgon for the first face and 2.0 mgon for the second face.

3.3. Testing of warm-up effect with measurement in 1st face (without laser beam breaking)

The next experiment was similar to the previous one, with only a few changes. The reflector placed at three meters distance from the LT was measured only in the 1st face and without interrupting the laser beam during the experiment. This means that the impact of the warm-up effect on distance measured with IFM was tested. Software Tracker Pilot was used to collect the data (angles and distances) with fifteen seconds time interval between measurements. The variations in the measured distance are shown in (*Fig. 5*), differences in the measured horizontal angle in (*Fig. 6*) and the differences in vertical angle in (*Fig. 7*). Similarly, to the previous experiment, the temperature at the instrument (sensor 1) and the reflector (sensor 2) was measured during the experiment.

Differences in the distance are different in this case. There are no step changes during the measurement, and warm-up time can be set around 1 hour and 45 minutes. The measured distance is affected by warming-up of about 33 micrometers, which is way behind declared accuracy. Unfortunately, instability of ambient temperature can be observed again. The temperature in the room rose by 1.5 °C, and the difference between sensors is almost 1 °C at the end of the experiment. After 3 hours of measurement, it can be seen that differences in distance are rising together with the rising temperature in the room. However, distance should be automatically corrected by LT.

Evaluate the warm-up time from horizontal angle measurement is not easy because of instable temperature conditions (*Fig. 6*). Nevertheless, the angle changes are relatively stable around 2 hours after the experiment started. Differences reached values

of 2.5 mgon until 2 hours of experiment, which is almost 0.8 mm for a full 20 m range of LT.

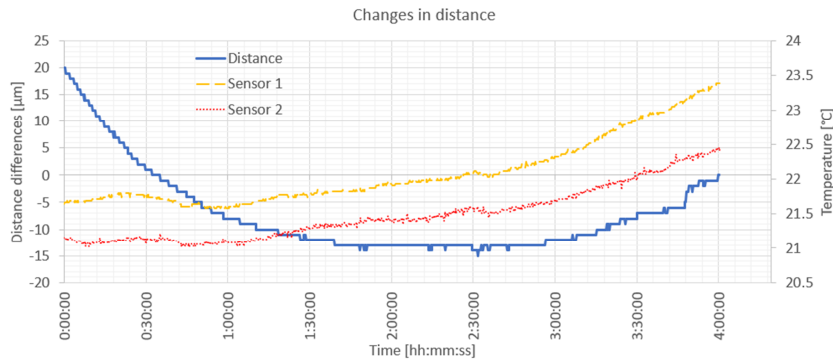


Fig. 5. Differences in measured distance

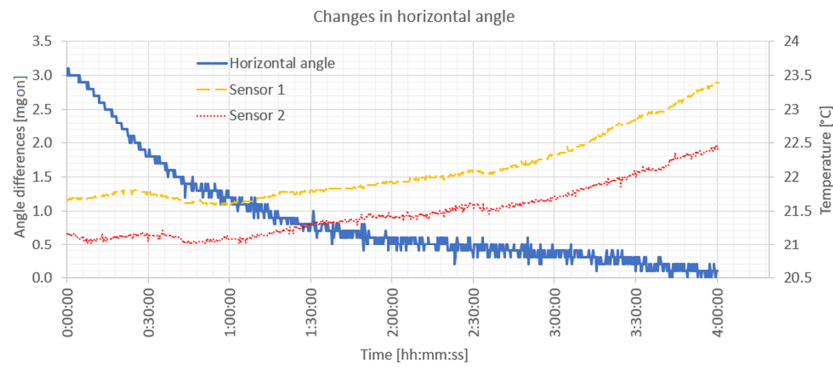


Fig. 6. Differences in measured horizontal angle

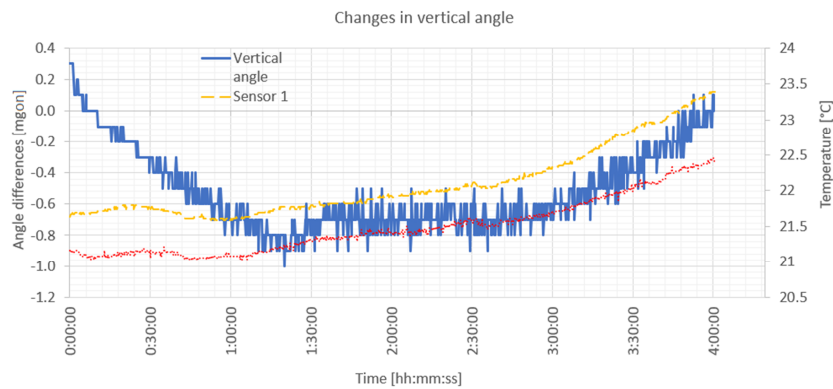


Fig. 7. Differences in measured vertical angle

Vertical angle differences reached values circa 1.2 mgon in this case (*Fig. 7*). Warm-up time can be set as 1 hour and 45 minutes, which is in congruence with the distance measurement. Vertical angle differences are also affected by external temperature, which can be observed after 3 hours of measurement. However, the temperature has an opposite effect on the vertical angle (differences are increasing) in contrast to the first experiment (differences are decreasing - *Fig. 4*). Conditions were almost the same during both experiments, therefore is this opposite behaving unclear. One possible explanation is different tripod reactions on temperature rising. However, the same equipment was used, and the temperature rose similarly, so that explanation is less likeable.

During the whole experiment, the laser beam was not interrupted. At the end of the experiment, several values were measured after breaking the line of sight on the reflector. Measured angles were not affected at all, but a step-change in the measured distance of 35 micrometers appeared. This high value can be explained by the accuracy of the dynamic lock-on of ADM, together with the impact of the warm-up effect on distance measured with ADM (*Fig. 2*). After the interruption of the laser beam, the IFM reference is reset, and measuring is started over.

3.4. Testing of warm-up effect with OtG function turned on

The last experiment was performed with the same conditions as the second experiment, but with OtG function turned on. When the OtG function is turned on, the inclination sensor is measuring the deviation between the vertical axis of the LT and the plumb line (gravity vector). Measured values are then automatically corrected of this deviation. Before the start of the measurement, the LT sets the initial value for compensation to align measurement to gravity. Inclination sensor should also be affected by the warm-up effect; therefore, the changes should be seen in the data. The variations in the measured distance are shown in (*Fig. 8*), differences in the measured horizontal angle in (*Fig. 9*) and the differences in vertical angle in (*Fig. 10*).

Despite the OtG function on, results are very similar to results in the second experiment. The temperature was stable during the whole experiment in this case, with the maximum difference of 0.3 °C, so it does not significantly affect the measurement. From distance measurement, the warm-up time can be set between 2 hours and 2 hours and 30 minutes. The change in distance during this time is around 38 micrometers.

Horizontal angle stabilized after approximately 1 hour and 40 minutes, with the maximum change of 2.3 mgon. It seems that the inclination sensor has no additional effect during warming-up because similar results were obtained from the previous experiment.

Vertical angle differences stabilized sooner than in the previous experiment (around 1 hour), and the differences are also smaller (around 0.8 mgon). The question is if this situation is caused by the OtG function because the inclination sensor should be affected by warming-up as well.

At the end of the experiment, the laser beam was interrupted, and the second initialization of the inclination sensor was made. After interrupting the laser beam, there was a change in measured distance of 30 micrometers (same situation as the previous experiment).

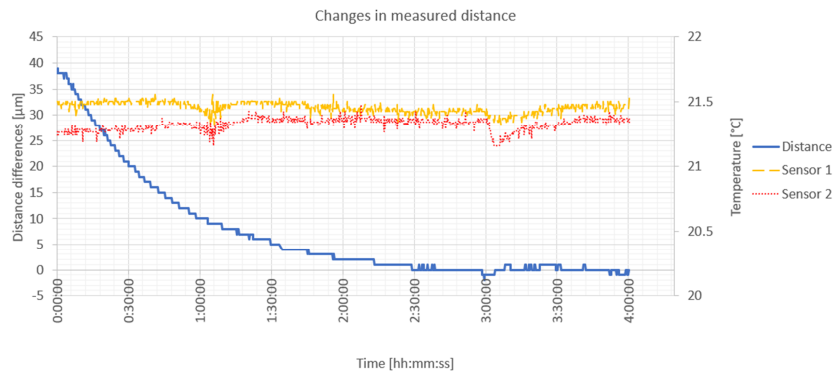


Fig. 8. Differences in measured distance

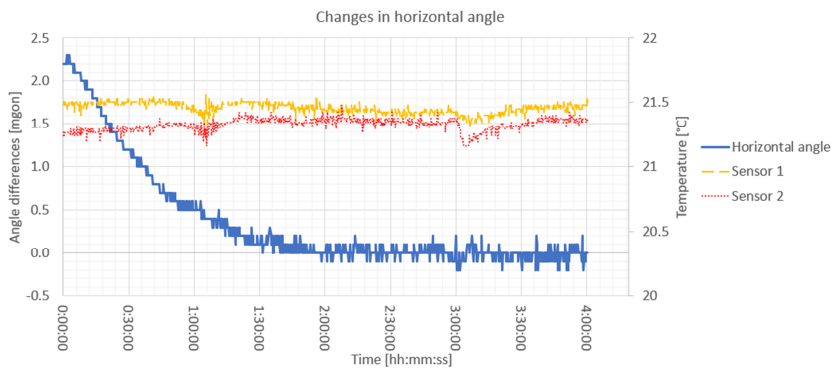


Fig. 9. Differences in measured horizontal angle

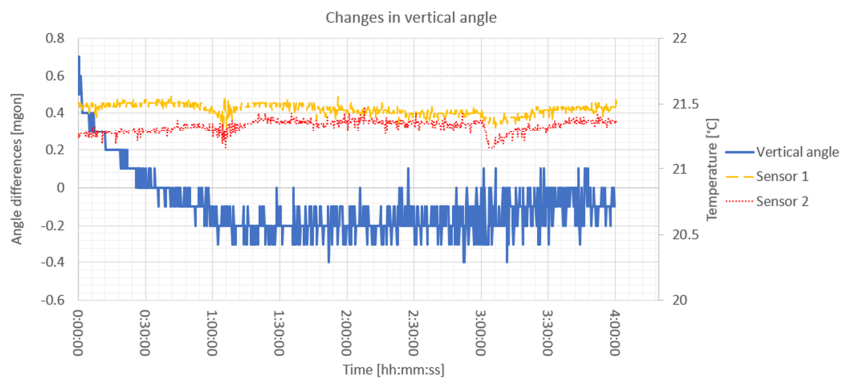


Fig. 10. Differences in measured vertical angle

After the second initialization of OtG, distance and horizontal angle were without change, but the vertical angle was affected. The difference rose by 0.5 mgon, so the

maximum difference of 1.3 mgon was observed, which is almost the same as in the previous experiment (*Fig. 7*).

The zero position of the inclination sensor was probably shifting during warming-up and after the re-initialization process was this position set back to zero. This caused the jump step in the vertical angle of 0.5 mgon. High accurate measurement is better to perform with OtG initialization after the warming-up procedure and not sooner.

From the presented experiments above, a 2-hour warm-up time can be set for Leica AT960-MR. However, according to manufacturers, approximately 1 hour of warming-up should be enough. If this statement is interpreted as a time after which LT fulfill declared accuracy, they are right or very close to it. For example, if differences in measured values after 1-hour in the last experiment are taken, uncertainty in the position of the measured point is around 35 μm (for 3 m long distance). The maximum permissible error declared by the manufacturer for this point is 33 μm , which is very close.

4. Conclusion

The paper describes the impact of the warm-up effect on measured distances and angles and the evaluation of warm-up time of LT Leica AT960-MR. Two-face measurement of distance has no significant effect during warming-up. On the other hand, a two-face measurement of angles can help to reduce the impact of the warm-up effect. In general, the distance measurement with ADM is less affected than measurement with IFM. When measuring with IFM, the laser beam should be interrupted after the warming-up to get the new reference from ADM. If this condition is not fulfilled (in same rare occasion) a jump step in the data will appear.

The impact of the warm-up effect on horizontal angles is between 2.0 and 2.5 mgon. For the maximum range of the LT (20 m), this angle deviation causes 0.6 to 0.8 mm in a direction perpendicular to the laser beam. Vertical angles are affected less than horizontal angles, from 0.5 to 1.2 mgon for all experiments. This is the opposite when compared with other researches. In various cases, the vertical angles were affected more than horizontal angles. The different design of the LT most likely causes this situation, but the further investigation needs to be made.

When the inclination sensor is turned on, differences in measured values seem to be minimal or any at all. However, if the re-initialization is made after warming-up, a jump in vertical angle by 0.5 mgon appeared. This means that the re-initialization process should be made again after warming-up or several times during warming-up.

There was also a problem with temperature compensation of measured distances when the ambient temperature changed. This is indicating the wrong reaction time of external LT temperature sensor or insufficient software compensation.

The warm-up time can be determined around 2 hours based on the presented data, which is in congruence with other publications. However, the influence of the warm-up effect on measured values needs to be considered individually for every LT model. Presented experiments showed interesting behaving of the LT on specific occasions, which should be taken into consideration during high accuracy measurements.

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