On the Temperature Dependence of Gyroscopic Measurements Using the GYROMAT 2000

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Key words: Gyroscopic measurements, temperature correction, system calibration, Gyromat.

ABSTRACT

Precise azimuth measurements using gyroscopes have become indispensable for large underground construction projects. Currently, the most advanced gyroscope is the fully automatic DMT GYROMAT 2000 which is a very robust instrument, requiring a short measurement period (<10 minutes) and designed to yield high precision azimuths with a standard deviation (std) of 7^{cc}.

Several ongoing large tunnel projects are associated with high temperature differences up to 50°C between the surface and the tunnel. Investigations elsewhere have indicated that the results using the GYROMAT 2000 may be plagued by uncompensated temperature effects. This is a very critical issue for underground azimuth transfers.

Therefore the accuracy and the effectiveness of the temperature corrections of the GYROMAT 2000 were investigated. For this purpose we designed and built a calibration facility for the system calibration of gyroscopes. Using a climatic cell, test measurements were carried out in the temperature range from –10°C to 40°C. The azimuth variations over the whole temperature range were studied with these datasets. Using the standard temperature compensation provided in the GYROMAT 2000, a std of the azimuths of 11^{cc} was obtained. This corroborates the findings by other laboratories about the temperature dependence of the GYROMAT 2000 results.

We report the results of a system calibration during a five day period with temperature variations between -10°C and 40°C. The internal temperature corrections of the tested GYROMAT 2000 were disabled. Using this data set, we can show that a simple second order polynomial correction function already yields almost unbiased azimuth results for the full temperature range. The elimination of the first observations of every group of azimuth measurements leads to further accuracy improvement, with a std of 6.9^{cc}.

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1. INTRODUCTION

Azimuth measurements are indispensable for tunnel control surveys. The main applications are:

- achieving the direction transfer from the geodetic network into the tunnel network (underground), e.g. through a vertical shaft;
- reducing the error propagation and thus reducing the breakthrough error in the usually very long but narrow tunnel network which also is of unavoidable poor geometrical strength; and
- controlling lateral refraction effects.

In 1991 DMT (Deutsche Montan Technologie) introduced the most precise and (first) fully automatic gyroscope GYROMAT 2000. Recently the history of its development and principle of operation were summarized by Korritke (1997). The original design principles of the Gyromat were discussed by Eichholz and Schaefler (1978). The GYROMAT 2000 is specified in the DMT brochure with a nominal precision of 10^{cc} whilst Rommel (1991) states 7.5^{cc} for a latitude of 48°. It has been used very successfully for many tunneling projects, see Korittke (1997). A detailed explanation of the gyroscopic principles is beyond the scope of this paper and the reader is referred to the references made above, to Zanini (1992) and Grillmayer (2002).

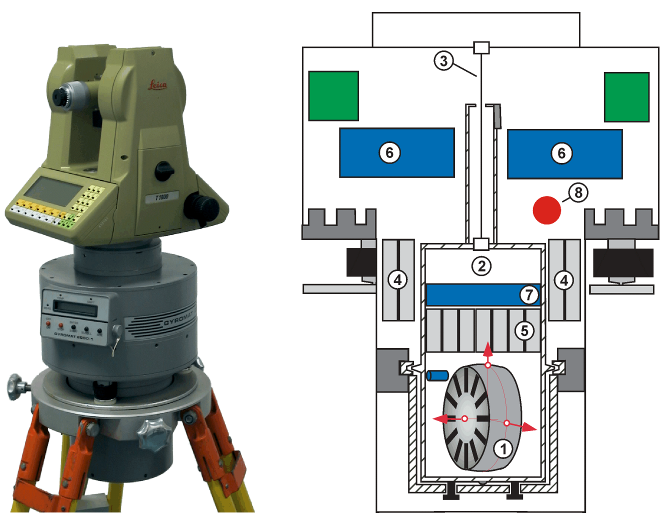

Figure 1: GYROMAT 2000 (a) with permanently mounted Leica T1800 theodolite; (b) schematic cross-section, for principal components see text

A GYROMAT 2000 is shown in fig. 1a with a permanently mounted theodolite Leica T1800, and fig. 1b shows its schematic cross-section. The rotor (1) with a mass of 2 kg is mounted in a cage (2), which contains the interior battery (5), and the electronics (7). The cage (2) is attached to a steel suspension tape (3). The exterior battery (4) and the computing unit (6) are also identified in fig. 1b. In the context of this paper, we report that the rotor is driven by a DC motor, developing a temperature increase of about 1°C by its operation. Furthermore, the tape´s zero position (rotor is not spinning) and the mean position of the oscillating rotor are temperature dependent. Therefore the proper acclimatisation of the gyroscope is crucial for the measurement of accurate azimuths and consequently an internal temperature sensor (8) is used.

The GYROMAT 2000 measures the internal temperature drift in order to limit azimuth observations to drift-free periods. Furthermore, an azimuth correction (ΔA) based on the internal temperature is automatically applied (Rommel, 1991):

$$\Delta A = \beta_1 \, \Delta_B \, dT + \beta_2 \, T_i \tag{1}$$

where Δ_B is the angle between the gyroscopic reference mark and the zero position of the tape, dT is the temperature difference between the start and end time of the gyroscopic measurement, and T_i is the average internal temperature of the gyroscope. The coefficients β_1 and β_2 are determined by a factory calibration.

Heister (1992) reported about systematic residual azimuth errors of about 20^{cc} for the temperature range of –5°C to 30°C. Carosio and Ebneter (1998) corroborated this result with their own experiments on the temperature dependence of azimuths of about 30^{cc} for a temperature range of –10°C to 40°C. They suggested that the development of a new calibration function might be benefitial.

There are several reasons why this temperature related residual azimuth effect has recently become a rather critical issue. Currently several large tunnel projects are in progress where azimuth transfers have to be used through several 100m deep shafts, e.g. Sedrun of the Gotthardt tunnel (Carosio and Ebneter, 1998). The huge, overburden rock massif causes underground temperatures of more than 40°C whilst surface temperatures might be as low as -10°C. Thus a temperature difference of nearly 50°C could exist between the measurements of the gyroscopic calibration values at the surface stations and the underground azimuth measurements. Possible systematic azimuth errors caused by this temperature difference would remain undetected as there is no alternative technique available to check the gyroscopic azimuths.

This is the main reason why we decided to investigate the temperature dependence of azimuth measurements using our GYROMAT 2000 instrument (fig. 1a). For this purpose we developed a climatic cell (section 2) and carried out several calibration runs, with and without the application of the internal temperature corrections (section 3). In section 4 we discuss the results and the development of an appropriate calibration function.

2. CALIBRATION FACILITIES

In our geodetic metrology laboratory (GML) we have built two calibration facilities for gyroscopes. The GML is climatised at a temperature of (22.0 ± 0.5)°C. Details about the design and the equipment which was specially built for these facilities, e.g. brackets, targets, autocollimation, are described in Grillmayer (2002).

The first calibration facility is used to determine the stability of the azimuth measurements over time at a constant environmental temperature. A constant azimuth can be defined either by the normal of a stable mirror surface or by a line between two precise targets. Therefore the first facility consists of a pillar for the gyroscope and three autocollimation prisms which are nearly equally distributed over 360°. In addition, two illuminated targets are used which are aligned with the pillar.

The second facility was developed to investigate the temperature dependence of a gyroscope and is basically a climatic cell. The design principle was to mount the gyroscope on a very solid pillar and have only the gyroscope inside a small climatic cell, see fig. 2. Thus temperature induced pillar motions should not occur. The thermal barrier between the pillar and the climatic cell was built of carbon fibre reinforced plastics with a very low thermal conduction coefficient. Rubber rings are used as a seal and to mechanically separate the climatic cell from the pillar, see fig. 2.

The air-conditioning unit is housed outside the GML and connected by induction and extraction ducts to the climatic cell. The temperature can be selected between –10°C and

Figure 2: View of the climatic cell with door, and one of two observation windows

Figure 3: Handling of gyroscope inside the climatic cell

40°C and is kept constant at the selected value. The theodolite T1800 and the gyroscope can manually be operated inside the climatic cell using heavy duty rubber gloves, see fig. 3.

The variation of the azimuths is determined using direction measurements (nearly horizontal) to two autocollimation mirrors mounted on steel pillars. For the observations to the autocollimation mirrors, special glass windows (fig. 2) were inserted in the insulation walls of the cell. The autocollimation eyepiece was improved with a powerful LED. For the remote observation of the two autocollimated crosshairs, a CCD camera is used. An attachment to the telescope of the theodolite was built to house the CCD camera, the mirror to deflect the image, and the battery for the LED as counterweight. Fig. 4 shows the crossbar form of this attachment which is necessary to permit observations on both faces with the theodolite inside the cell, see fig. 3. The CCD image is viewed by the observer on an outside PC screen.

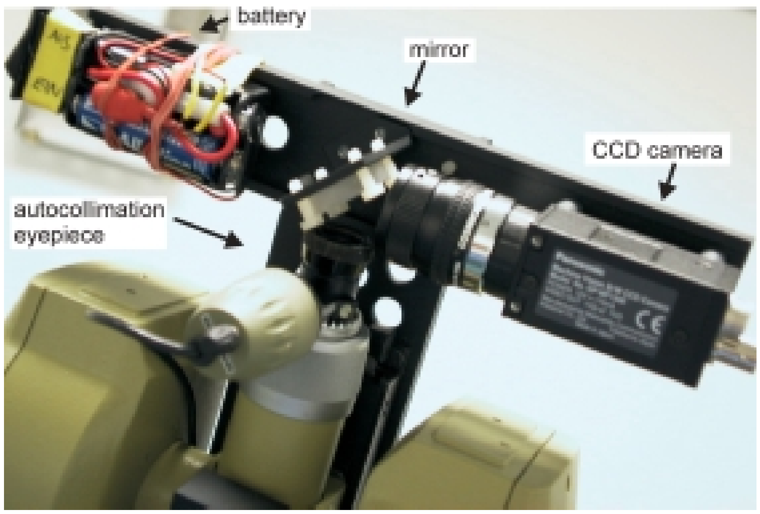

Figure 4: The autocollimation attachment

3. INVESTIGATIONS AND RESULTS

3.1 Preamble

Using the calibration facilities in our GML (section 2), investigations were carried out about the stability of the azimuth observations with time, the influence of mislevelling of the gyroscope, and the temperature dependency. In all investigations only one GYROMAT 2000 (S.No. 221) was used; from now on called GYR-IVM. As mentioned before the GYR-IVM uses a permanently fixed Leica T1800 theodolite. The T1800 was chosen, as it uses (diametrically opposed) indices to eliminate the eccentricity effects of the coded circle.

In all investigations we used the method of system calibration, Brunner and Woschitz (2001). In essence, system calibration means to compare the results obtained by the instrument including the factory corrections and data processing by the firmware against the ´true` values of the measurements. In our calibration facilities the ´true` values are, for example, the directions of the normals to the autocollimation mirror surfaces which are constructed to remain constant during the time of a calibration run.

In the following, we will present the results of our investigations of the temperature dependence of the GYR-IVM measurements. The results of other experiments are described by Grillmayer (2002). In our investigations of the temperature effects, the system calibration yields residual deviations which are the variations of the observed azimuths in comparison to the constant mirror normals.

3.2 Temperature Dependence of Azimuth Measurements

Carosio and Ebneter (1998) reported about their investigations of the temperature dependent azimuth variations using the GYROMAT 2000 with a permanently attached Leica T1600 of the ETH-Z. They observed a 50^{cc} variation for a temperature difference of 50°C using an acclimatisation period of 2 h after each change of the ambient temperature in the ETH-Z climatic room. An increase of the acclimatisation period to 4 h reduced the variability of the azimuths by a small amount. They obtained different azimuths, depending on the sign of the temperature change, i.e. cooling down or warming up.

Desiderio and Koch (1998) used the ETH-Z GYROMAT 2000 for more detailed investigations. They found a hysteresis in all measurement cycles between -10°C and 40°C. The residual azimuth deviations could be modeled by a simple regression line of a slope of 0.62^{cc}/°C. The application of the linear regression model reduced the standard error from 15^{cc} to 11^{cc} for one azimuth measurement.

For an independent check of the ETH-Z results, we tested the GYR-IVM by a temperature cycle (-10°C to 40°C) during 5 days, starting and ending at 20°C. In this test the internal temperature corrections of the GYR-IVM were used. The temperatures in the climatic cell were changed in 5° steps using a 2 h acclimatisation period before the start of a gyroscopic measurement. The batteries of the GYR-IVM were continuously charged. Fig. 5 shows the results (azimuth changes) as a function of the internal temperature, T_i, with different colors for the warming and cooling sequences of the ambient temperatures, T_a. The

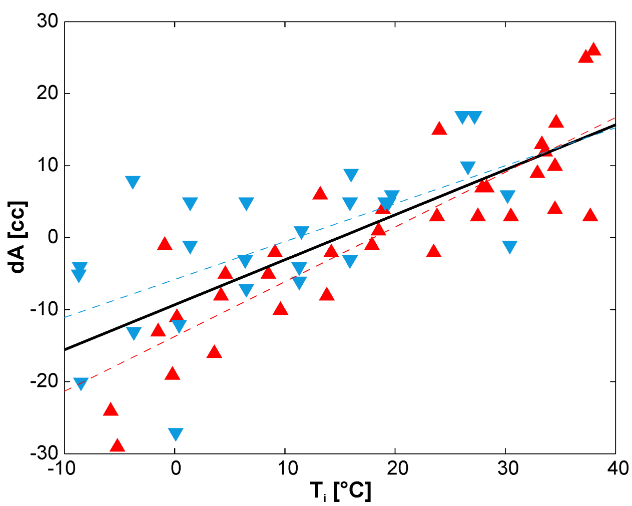

Figure 5: Temperature (T_i) dependence of the GYR-IVM azimuth measurements; red triangles refer to warming and blue triangles refer to cooling sequences; the black regression line uses all data

standard deviation (std) about the mean of all data is 11^{cc}. The appropriate regression lines indicate a small difference between the different sequences, see fig. 5. The linear regression of all data points yields

$$dA = -9.3 + 0.62\ T_i \qquad [in\ ^{cc}] \tag{2}$$

with a std of 7.5^{cc} which now is in full agreement with the instrument´s specification. The std of the slope is 0.62 ± 0.13 in eq. (2) and indicates that the slope is statistically significant.

Now, it is interesting to compare our results with those of Desiderio and Koch (1998). In both cases the range of ambient temperatures was –10°C to 40°C, and the DMT internal temperature corrections were used, see eq. (1). However, the climate room at the ETH-Z and our climatic cell, the theodolites and the measurement techniques used for the direction measurements are different. Therefore, it is quite a surprise that the slopes of the regression lines for the residual azimuth variations turn out to be identical, 0.62 [^{cc}/°C].

3.3 Calibration of the GYR-IVM without Internal Temperature Correction

For the temperature calibration measurements at the factory, DMT sets the internal temperature corrections to zero. With the help of DMT we brought the GYR-IVM into the same condition and measured a full temperature cycle during 5 days starting on 13.11.2000.

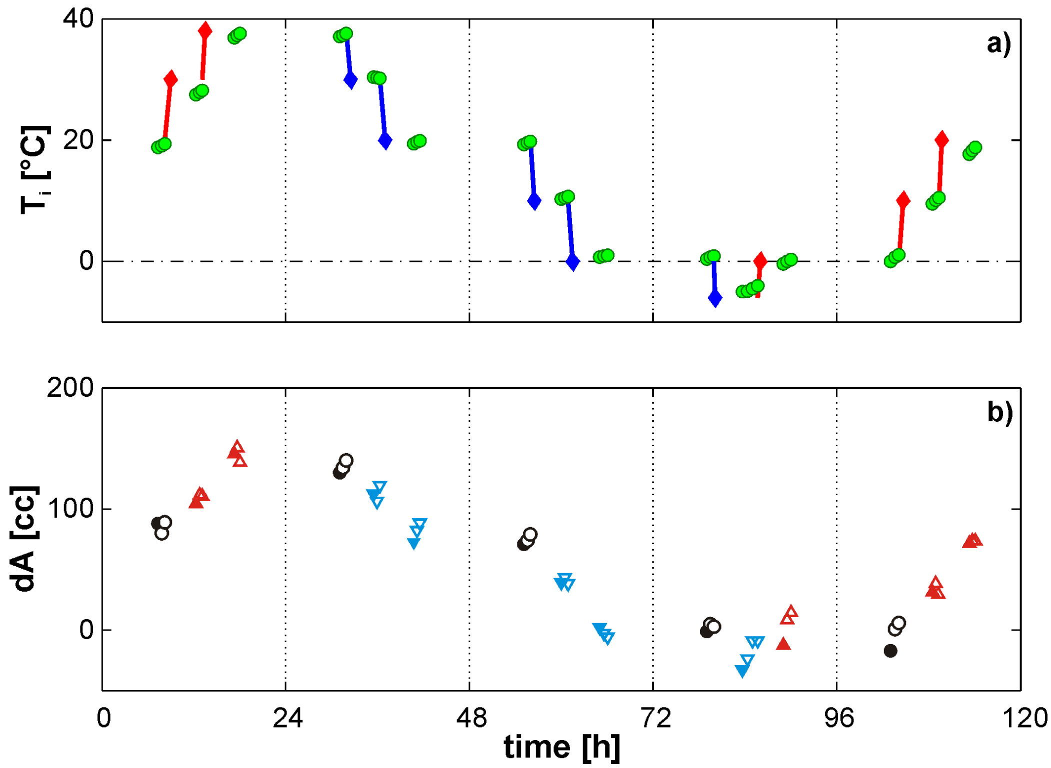

Figure 6: Five day temperature test: (a) measured internal temperatures, T_i, and sequences of warming (red) or cooling (blue); (b) measured changes in azimuth, dA, with color coding of the symbols; the black circles refer to stable thermal periods; full symbols indicate the first of a group of measurements.

Table 1: Results of the polynomial fits for reference temperature 0°C

Thermal regime	n	a_1 [^{cc}/°C]	a_2 [^{cc}/°C^2]	σ [^{cc}]
static	15	5.04 ± 0.41	$- .036 \pm .011$	6.9
cooling	16	4.25 ± 0.39	$- .015 \pm .015$	7.4
warming	15	3.63 ± 0.50	$.006 \pm .013$	7.3
all	46	4.32 ± 0.23	$- .014 \pm .006$	7.4
all minus first obs of a group	31	4.07 ± 0.26	$- .009 \pm .007$	6.9

Before and after the five day temperature test, the GYR-IVM was used on the static calibration facility to prove its unaltered accuracy. The batteries of the gyroscope were continuously charged and therefore the gyroscope was always inside the climatic cell during the five day long test period. Fig. 6a shows the cooling and warming sequences, and the measured internal temperatures, T_i, during the azimuth measurements. Fig. 6b shows the variation of the azimuths, dA with time.

In fig. 7 the azimuth variations are plotted against T_i, but separately for the three thermal conditions before each azimuth measurement: (a) static ambient temperature (during night time), (b) cooling period, and (c) warming period. An acclimatisation period of nearly 4 h was allowed before the measurements after any temperature change and, of course, the temperature drift of the GYR-IVM was observed to be zero. Table 1 lists the computed

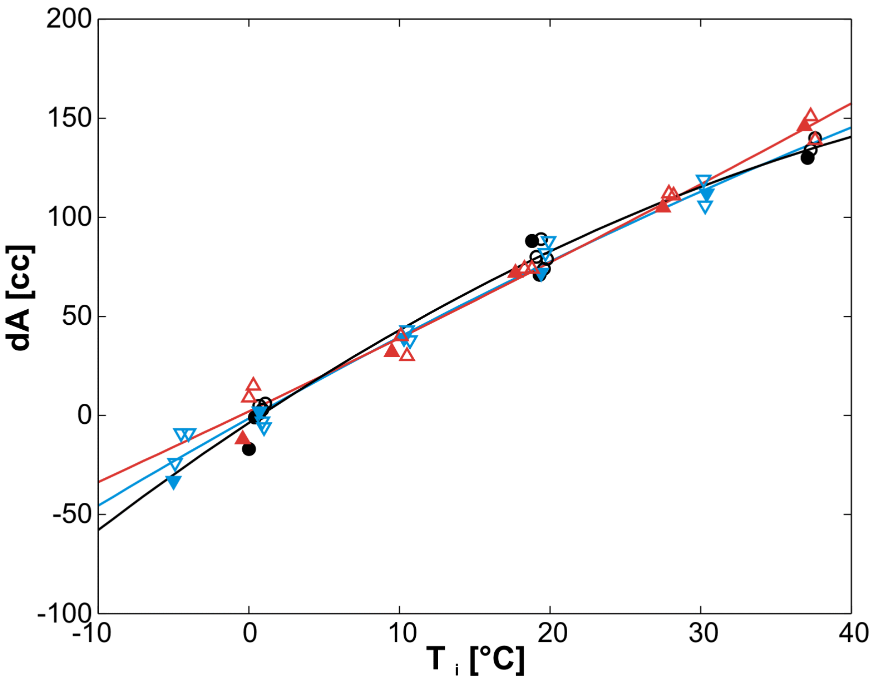

Figure 7: Five day temperature test: azimuth variations dA vs internal temperature T_i; thermal conditions: static (black), warming (red), cooling (blue); and related polynomial curves

coefficients of second order polynomial fits to the data sets:

$$dA = a_0 + a_1 T_i + a_2 T_i^2 \qquad (3)$$

Eq. 3 implies that the reference temperature was chosen with 0°C in agreement with DMT´s choice. Table 1 lists the std of the coefficients for the assessment of their significance. The number n of data points and the standard deviation σ of the residuals after the polynomial fit are also listed. a_0 is not shown as it is a result of the choice of the reference temperature and thus absorbed in the calibration constant which is determined on field calibration lines before and after the azimuth measurements.

The second order polynomial fitted to all data points yields a std of 7.4^{cc} which is close to the nominal std of a GYROMAT. A slightly smaller std of 6.9^{cc} can be achieved using the data points during the static thermal conditions, i.e. the instrument was kept for a whole night at a constant ambient temperature. We conclude that the post-processing polynomial fit of the azimuth variations obtained with the GYR-IVM is more effective than using the internal temperature corrections, see section 3.2.

4. DISCUSSION

It is intriguing that the ETH-Z and our results using different GYROMATS and different experimental conditions show the same pattern of a residual temperature effect on the azimuth results, see section 3.1. It was suggested that the theodolite-gyroscope interface could be the reason for this pattern. However, the data of the 5 day temperature test prove that even a simple second order polynomial correction function would produce accurate results without a residual temperature effect. Furthermore, we have been able to verify that the temperature calibration data (measured by DMT) are almost identical to our data (fig. 7), (DMT, personal communication). Thus, the residual temperature effect seems to be an artifact of an incorrect internal temperature corrections.

In section 3.3 we showed that our GYR-IVM is capable of measuring azimuths in different thermal conditions (-10°C to 40°C) with a standard deviation (std) of 7.4^{cc} using a simple second order polynomial temperature correction function. Before embarking on a search for an even better temperature correction model, it would be sensible to assess the noise level of gyroscopic measurements. The repeatability of gyroscopic azimuth observations was determined on the test facility (see section 2) with 5.1^{cc} during conditions of stable ambient temperatures of 22°C (Grillmayer, 2002). The repeatability of the measurements in the climatic cell can be assessed by transforming the data taken to 20°C, to a reference temperature of 20°C using the polynomial curve (table 1). Then the std of these corrected data can be calculated, i.e. 6.3^{cc} which is in fair agreement with the above mentioned 5.1^{cc}, considering the poorer observing conditions inside of the climatic cell. Therefore, we may estimate a possible improvement in accuracy of about 1^{cc} to 2^{cc} before the noise limit of azimuth measurements using the GYR-IVM is reached.

Fig. 6a shows an increase in T_i for consecutive measurements which is caused by the internal heat generation through the operation of the gyroscope. This temperature effect is termed ´self-heating` and will occur superimposed on the temperature acclimatisation of the instrument due to a difference between the ambient and the internal temperature. This composite effect might be the same which was interpreted as a time-dependent azimuth variation effect by Desiderio and Koch (1998). Furthermore, it could be the reason for the slightly different curves during different thermal conditions in fig. 7. This ´self-heating` effect was experimentally investigated by Grillmayer (2002). However, a significant accuracy improvement was not achievable so far.

It is generally known that mechanical instruments of high precision show a ´start-up` effect in the result of the first measurement after an idle period. This ´start-up` effect can be attributed to settling of mechanical gears, release of stored strain due to the mechanical start-up process, and the acclimatisation of the instrument. Such effects have also been observed by other operators using the GYROMAT instruments (Heister, DMT; personal communication). Thus it is advisable to ignore the first gyroscopic measurement after transportation or a longer period of rest.

Consequently, we have investigated the five day data set for this effect. For all three thermal conditions, always the first measurement of each group of three (once four) observations was deleted and the remaining data were fitted by a second order polynomial. The coefficients with their std of this polynomial curve are listed in table 1. The std of this data is 6.9^{cc} about the polynomial fit. Fig. 8 shows the data set, the polynomial curve, and the data points of all first measurements of the 15 groups (full symbols). From fig. 8, a suggestion can be derived that the azimuth values of the first of a group of measurements tend to be too small. Other data sets (DMT, personal communication) support this conjecture.

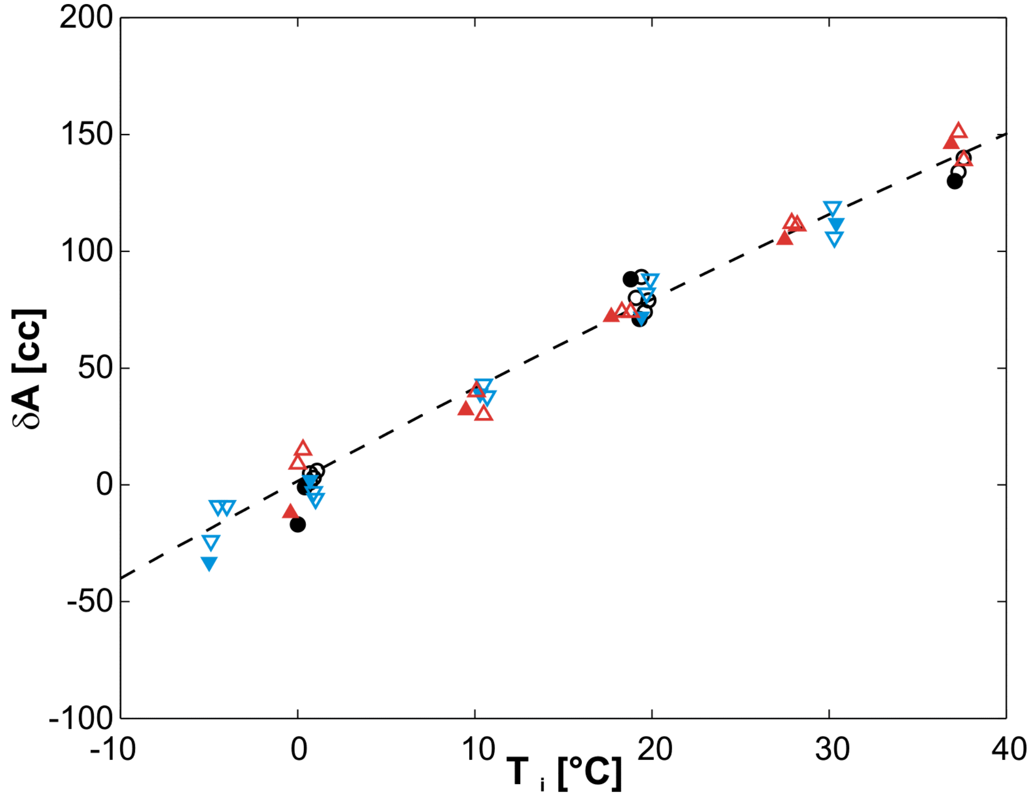

Figure 8: Five day temperature test: Residual azimuth deviation $\delta\ dA$ defined in eq. 4; first measurements (full symbols); other symbols see fig. 7

We were able to show that measurements with the GYROMAT can produce azimuths of an accuracy (std) of about 7^{cc} even under the extreme temperature variation of 50°C. A second order polynomial for the temperature corrections is applied instead of the internal temperature correction. A further improvement in accuracy can be achieved by not using the first gyroscopic observations of a group of measurements. The investigations about the ´self-heating` effect of gyroscopic measurements are still in progress.

ACKNOWLEDGEMENTS

We would like to thank R. Presl for cheerfully building the mechanical attachments, H. Heister (UniBW Munich) for many enlightening discussions, and the staff of DMT for providing information about the testing of the GYROMAT 2000.

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BIOGRAPHICAL NOTES

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Fritz K. Brunner received the degrees Dipl.-Ing. and Dr. techn. from the Technical University of Vienna in 1967 and 1972, respectively. During 1969-1974, he was an assistant at the TU Vienna. From 1974 to 1982, he was a lecturer at the University of New South Wales, Australia. During 1981, he was an A. v. Humboldt fellow at the Geodetic Institute, University of Stuttgart. From 1982 to 1986, he headed the Advanced Products Group at Wild Heerbrugg Ltd., Switzerland. In 1986 he was appointed Professor and Head, School of Surveying, University of New South Wales. In 1994 he received an A. v. Humboldt Research Award. Since October 1994 he is Professor of Engineering Geodesy, Graz University of Technology. From 1995 to 1999 he was President of Section I "Positioning" of IAG. In 2001, he was elected President of the Austrian Geodetic Commission.