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High precision calibration of polygons for emerging demands

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High precision calibration of polygons for emerging demands

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Abstract. The polygons are basic angle standards that are still considered as one of the most precise-robust references for establishment of traceability in angle measurements. Investigations for high precision calibration of polygons to answer new demands (expanded uncertainties less than 0.1") were carried out. Three high precision 36 sided polygons were calibrated using the primary angle measuring system of TUBITAK UME. Agreement of TUBITAK UME's and polygon manufacturer Möller-Wedel Optical (MWO)'s results was better than 0.1". Reproducibility of 0.043" as peak-to-valley (pv) and 0.013" as root mean square (rms) value was achieved for successive calibration of polygons. The results are reported with descriptions of our high precision calibration system and the process.

1. Introduction

Precision angle measurement is a continuing research topic [1] and an important enabling technology with a wide range of scientific and industrial applications e.g. in precision engineering, aerospace, geodesy, navigation, astronomy and synchrotron beamline metrology. Polygons are basic standards for angle measurement and are still considered to be one of the most precise and robust references in angle metrology. They are mostly calibrated by National Metrology Institutes (NMIs) and used for establishment of traceability. Additionaly, NMIs and accredited laboratories use polygons for interlaboratory comparisons as transfer standards to evaluate their capabilities.

The uncertainty attainable with polygons largely depends on the geometry (flatness and squareness) of their reflecting faces and also on optical errors of the autocollimator and alignment errors occurring during sensing of the faces. The current capabilities of NMIs can be obtained from the Calibration Measurement Capabilities (CMC) database of the BIPM [2]. According to current CMC data, uncertainty values mostly range between 0.1" and 1". But, emerging demands [1] require uncertainties less than 0.1", particularly for calibration of rotary tables fitted with precise angle encoders, since their use as a primary angle measuring system is increasing. However, previous interlaboratory comparisons [2] produced unsatisfactory results due to above issues and the measurement differences turned out to be much greater than uncertainties estimated by the participants. Therefore, evaluation of the uncertainty of angle measurement by polygons remains a difficult problem.

Angle measurement by polygons is on-going research topic at TUBITAK UME and the investigations for achieving uncertainties less than 0.1" is in progress. This paper gives highlights about high precision calibration facilities at TUBITAK UME and presents the recent results obtained by 3 high precision 36 sided polygons using the primary angle measuring system. It is shown that reproducibility of 0.043" as peak to valley (pv) and 0.013" as root mean square (rms) value was achieved and agreement of TUBITAK UME and polygon manufacturer's results was better than 0.1".

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2. Calibration set-up and equipment for precise polygon calibration

The angle comparator, an air-bearing rotary table specifically developed for TUBITAK UME by KUNZ, is used as a primary standard for high-accuracy calibrations of angle measuring systems and standards at TUBITAK UME [3]. The comparator is based on a subdivision of the natural and error-free standard of the full circle, 360° = 2π rad. For calibration of high precision polygons, we use our primary angle measuring system with the calibration set-up shown in figure 1. To achieve ultimate precision, we apply well known cross calibration method [4, 5] utilising full closure principle and minimize error sources disturbing the calibration results. Our comparator is installed in the dimensional laboratory of TUBITAK UME at a constant ambient temperature ($\Delta T < 0.3$ K). The device stands on a massive hard stone plate, which is isolated from vibration using passive vibration pads (compact air mount) and also located on a concrete block (1.5×1.5×1) m separated from the floor of the building. Additionally, the calibration set-up is entirely shielded with a foam box to reach more stable ambient conditions (e.g. $\Delta T < 0.05$ K) (Figure 2).

In the cross calibration method, a pre-selected number of n partial comparator angles, each $360/n$ in size, is compared with a second measuring system, e.g. a 36 sided polygon. This comparison is made in a total of $n \times n$ measurements (36 × 36 = 1296) with the polygon being successively set to these n angular positions in relation to the comparator's angular scale. For precise setting, we use a Moore indexing table [6], an intermediate table located between the polygon and our angle comparator (Figure 1). For each n angular position setting, the Moore table is manually used to set the relevant polygon face for optical probing of the autocollimator (see Figure 3). An adjustable mounting device is used for precise levelling of the polygon to minimize the pyramid error prior to the measurement.

Calibration is performed by direct comparison of polygon intervals with the angle comparator using a computer programme. Once the process is started, the computer programme takes care of the process and collects readings of the angle comparator and the autocollimator for each n angular position. For data acquisition, 50 single values of the two measuring systems are read out in each interval. The measurements performed in the range of 360 degrees with steps of 10 degrees (for a 36 sided polygon) take approximately 30 minutes. To eliminate drift influences during calibration, two measurement series are consecutively carried out in both rotational directions (CW and CCW) of the comparator. Finally, 50+50 autocollimator readings are taken for each polygon face and recorded.

After the first series of measurement, the second face of the polygon is set and then the second series of measurement starts. This continues up to the last polygon face. The raw data recorded in the text file is transferred to an excel template created for calculation of angular deviations. Pitch angle and cumulative pitch angle deviations are calculated using the mean values of taken in both directions.

2.1. TUBITAK UME angle comparator

TUBITAK UME's primary angle measurement system is an air-bearing rotary table fitted with a precise angle encoder [3]. As a measuring system, a high precision encoder of HEIDENHAIN (ERP 880) is used with a resolution of ~0.0009". The drive system of the comparator consists of 4 piezo-electric motors working against a ceramic ring (drive strip) that is fixed on the rotor. Nanomotion's HR Series piezo-electric motors are used with amplifiers facilitating additional ultra high resolution capabilities, down to 1 nanometer step, using the unique DC mode. This corresponds to ~0.001" angular value with 340 mm diameter ceramic ring (drive strip). For static measurements, DC mode allows fine positioning with repeatability better than 0.005".

2.2. High precision electronic autocollimator

A high precision electronic autocollimator of MOELLER-WEDEL OPTICAL (MWO), type Elcomat 3000 was used for calibration of polygons [7]. The device was calibrated at TUBITAK UME with an expanded uncertainty of 0.01" for the range of ± 8". The deviation of the autocollimator was less than 0.05" (pv) for this range. A laser alignment kit accessory was used to centre the polygon faces up to 1 mm to the optical axis of the autocollimator. This provided precise optical probing of the polygon faces minimizing the angular errors due to flatness deviations.

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2.3. High precision indexing table as intermediate table for polygon settings

Changes of relative positions (i.e. settings) of the polygon in relation to the TUBITAK UME angle comparator was provided using the indexing table of Moore tool company [6]. The small error of the indexing table, (0.5" as pv) provides precise relative positioning of the polygon faces and results in use of almost the same range of the autocollimator during optical probing (i.e. comparison of the polygon and angle comparator intervals).

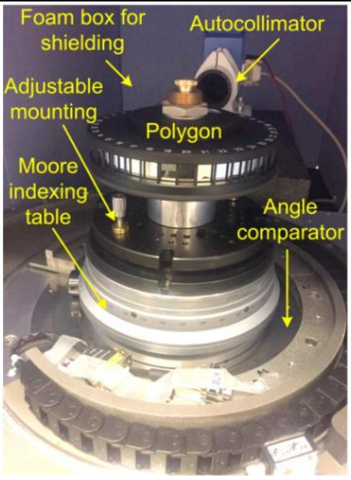

Figure 1. Calibration set-up

Figure 2. Calibration is performed automatically inside the foam box minimising environmental disturbances.

Figure 3. Setting of the relevant polygon face for optical probing of the autocollimator using the intermediate table (Moore indexing table) by manual adjustment. This is done for each *n* angular position setting.

3. Precise polygons for calibration

All of the polygons were manufactured by MWO using the material 'sital', a glass ceramic material with an ultra low coefficient of thermal expansion (similar to zerodur). They have central mounting holes and are accommodated in metal cases. The cases of the polygons were custom made according to specifications provided by TUBITAK UME. There is an additional step on top of the polygon case for convenient eccentricity adjustment. Concentricity of hole in the middle of the polygon to outer diameter of the plate (i.e. step for mechanical probing during eccentricity adjustment) is better than 25 micron. Detailed information on the technical specifications of the polygons is illustrated in table 1. The flatness of the polygon faces was measured at TUBITAK UME using a Zygo Verifire flatness interferometer and the pyramidality of faces were recorded during calibration using Elcomat 3000 autocollimator.

4. Calibration results and discussions

Three 36-sided polygons, specifications of which are given in table 1, were calibrated in the same set-up as shown in figure 1. Calibration of 36 sided polygon takes about 3 working days (3×8 working hours). Calibration results of TUBITAK UME were compared with the manufacturer MWO's results and the differences are illustrated in figure 4. MWO also uses their high precision angle comparator [8] for polygon calibration but they apply 3 measurements using their special method instead of 36 measurements as in the cross calibration done by TUBITAK UME. MWO gives an expanded uncertainty of 0.3" for these results while TUBITAK UME gives 0.12". The results shown in figure 4 show excellent agreement with a max deviation of ± 0.12" and 0.05" as rms.

TUBITAK UME also investigated the reproducibility of the polygon calibration results. Polygon-2 was calibrated at two different times. The difference between two successive calibration results of the same polygon is illustrated in figure 5. The agreement of the same polygon results by TUBITAK UME is 0.043" as pv and 0.013" as rms value. Since we use 36 sided polygons for the calibration of our angle comparator, investigation of the differences is one of our research topic in progress.

The autocollimator we use is a special version of the Elcomat 3000 and has an angle deviation of about 0.05" in the range of ±8" for reflective surfaces (%95) and about 0.01" for uncoated surfaces (reflectivity 5%). We think that using a different version of autocollimator or correcting the deviations, it will be possible to reach much better expanded uncertainties down to 0.05".

Table 1. Specifications for the 36 sided polygons

	Polygon-1	Polygon-2	Polygon-3
Size of reflecting faces	(12×15) mm	(15×25) mm	(15×25) mm
Angle deviations from nominal (max. - min.)	8"	5"	5"
Pyramidality of faces (max. - min.)	12.2"	11.9"	6.6"
Mean values for flatness of faces (as peak to valley, pv)	27.3 nm	28.3 nm	22.9 nm
Mean values for flatness of faces (as root mean square, rms)	3.6 nm	4.3 nm	3.9 nm

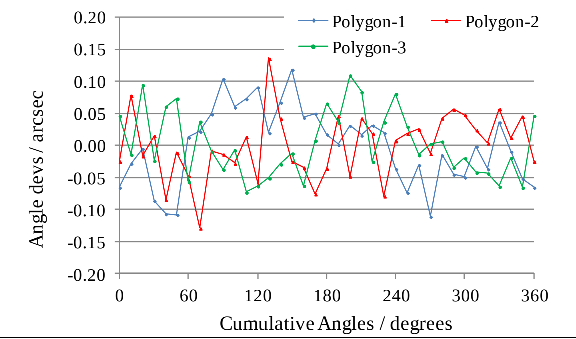

Figure 4. Differences between calibration results of TUBITAK UME and MWO.

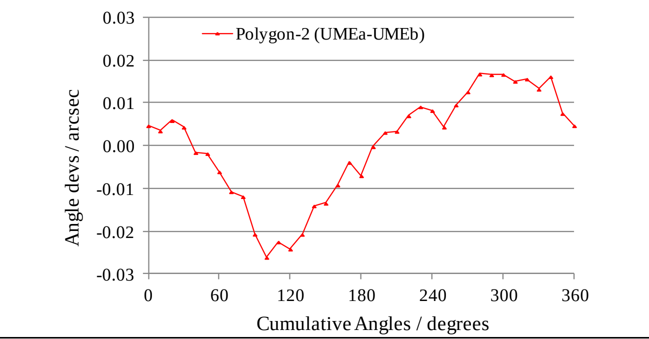

Figure 5. Difference between two successive calibration results of the same polygon by TUBITAK UME.

5. Conclusions

A precise angle measuring system, set-up and process for calibration of polygons used as precise angle reference standards, are presented. The results of three 36 sided polygons showed that it is possible to achieve expanded uncertainties less than 0.1" which is demanded particularly during calibration of primary reference angle comparators (Rotary Tables fitted with precise angle encoders). Comparison of calibration results with the manufacturer agreed within ± 0.12" and reproducibility was 0.043" as pv (peak to valley) and 0.013" as rms (root mean square). The investigations provide important information for National Metrology Institutes and calibration laboratories to evaluate their capabilities in angle metrology applying the full closure principle.

6. References

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