

Calibration of Optical Rotary Tables using Autocollimators and Laser Interferometer Systems

Prof. **S. Zahwi**, Prof. **M. Amer**, National Institute for Standard, Egypt;

Prof. **M. A. Abdo**, Al-Azhar University, Faculty of Engineering, Egypt;

Researcher Assistance **A. El-Melegy**, National Institute for Standard, Egypt

Keywords:

Angle, Measurement, Rotary table.

Abstract:

Calibration of rotary tables can be performed using autocollimators or laser interferometer systems. In this investigation a comparison between these two methods of calibration as applied on an optical rotary table has been carried out. The calibrated table is a Carl Zeiss optical rotary table of resolution 30 arcsecond. An Elcomat[®] 3000 autocollimator system and an Agilent[®] 5529A laser interferometer system have been used in this calibration. A precise indexing table of 360 serrations with accuracy of ± 0.5 arcsecond manufactured by Davis[®] and a glass polygon of 12 faces with accuracy of ± 0.3 arcsecond delivered by MOLLER WEDEL GmbH has been used. The indexing table is used in co-operation with the laser system while both of the polygon and the indexing table are used with autocollimator system. Repeated results from the different methods of calibration were carried out and presented in the paper. Uncertainties associated with the measurement results for each method have been estimated using the procedures mentioned in GUM. The paper discusses the accuracies as well as difficulties and ease associated with each method.

Introduction:

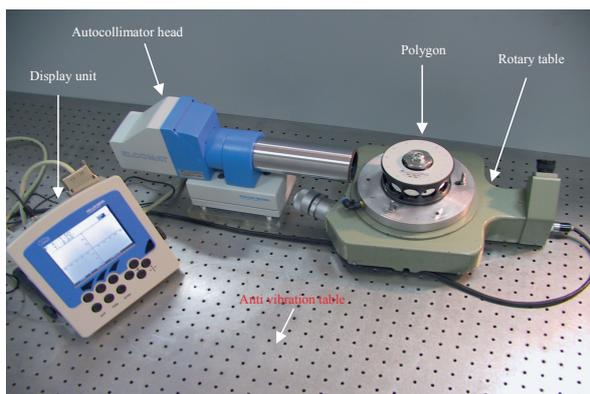
Engineering measuring devices, such as rotary and indexing tables are used for angle measurement carried out in industry [1]. Calibration of rotary tables requires two basic components, a reference standard such as a precise polygon or a precision reference indexing table for generating a reference angle nominally equal to the angle being calibrated and an angle measuring instrument used as an angle comparator such as an autocollimator or laser interferometer system to measure small deviations in the measured angle from the reference angle [2]. Autocollimators have a long history of being used in metrology laboratories for calibration of angle standards, such as polygons, indexing tables, rotary tables and angle gauge blocks [2]. Rotary tables can be calibrated by autocollimator against a precision polygon; or against a precise indexing table using a reflecting mirror on the top of the table. Laser interferometer system can

also be used to calibrate rotary tables against precise indexing table with retroreflectors optics. In this investigation, a comparison of calibration results on an optical rotary table by the two systems is carried out. Associated uncertainties are estimated according to GUM [4] and [5].

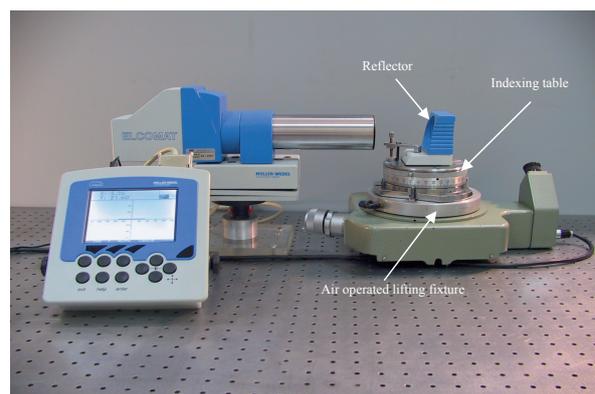
Experimental Setup:

An optical rotary table having a measuring range of 360° and a resolution of 30 arcsecond is calibrated. This table is calibrated using two measuring systems, laser interferometer system and autocollimator system. Each of the two systems has a 0.05 arcsecond resolution. The calibration of rotary tables is based on angle standards, two angle standards, namely polygon and an indexing table has been used. A calibrated precision optical Polygon of 12 faces calibrated with uncertainty of 0.03 arcsecond has been used. An indexing table of 360° range, angle step of 1° and calibrated with uncertainty of ± 0.6 arcsecond.

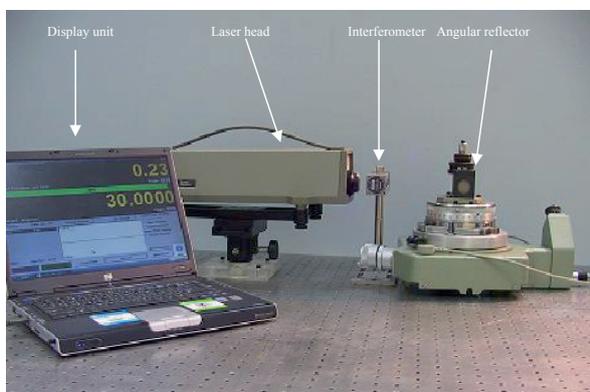
The rotary table is calibrated at steps of 30° throughout its full range 360° . The results of calibration are corrected for the errors of angle standards used. Error charts are drawn in each case showing the error at each calibrated angle (steps). The calibrations are carried under environmental conditions of $20^\circ\text{C} \pm 1^\circ\text{C}$. Figure 1 shows the different experimental setups used.



a) Autocollimator with the aid of polygon



b) Autocollimator with the aid of indexing table



c) Laser interferometer with the aid of indexing table

Fig. 1: Calibration of rotary tables using different systems

Results:

An example of rotary table calibration result and associated error charts is shown in figure 2. The total error $T_{\Delta\theta}$ of the rotary table is determined in each case. The calibration is repeated 10 times by each system on the same rotary table. The standard deviations of the repeated results at each measured angle are shown in figure 3. Table 1 shows the average total error $T_{\Delta\theta}$ and the standard deviation of the scatter of results $S(T_{\Delta\theta})$ as obtained from the repeated calibrations using each method. Figure 4 represents such results represents such results.

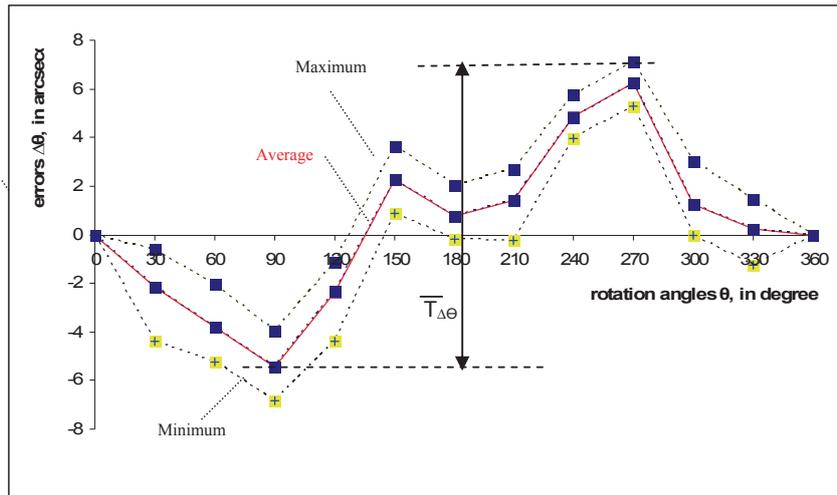


Fig. 2: An example of an error chart.

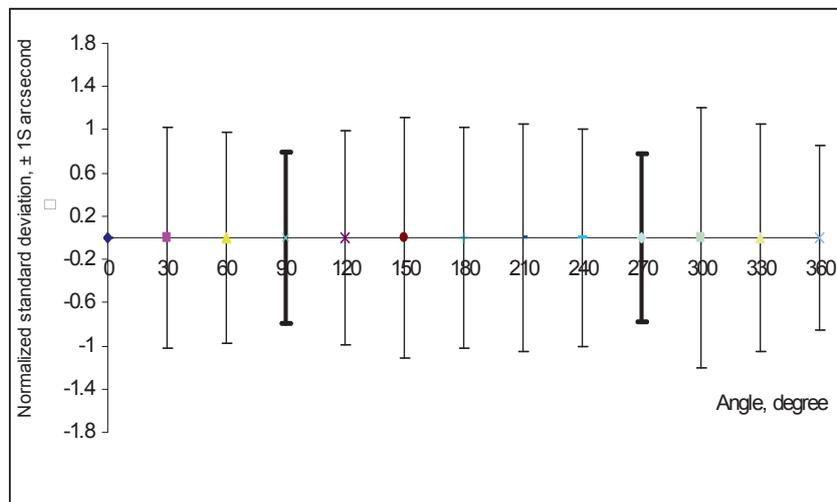
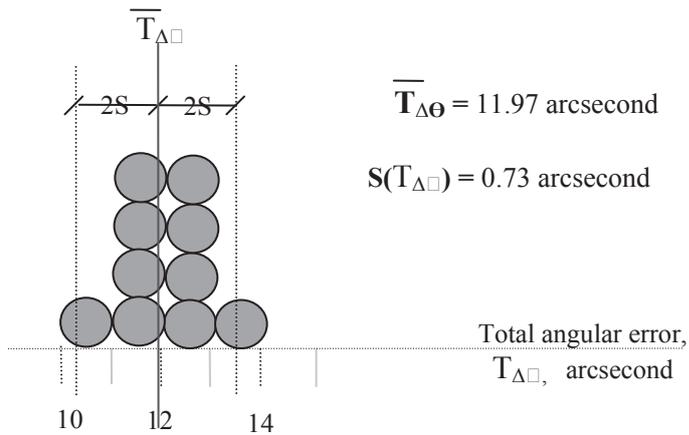


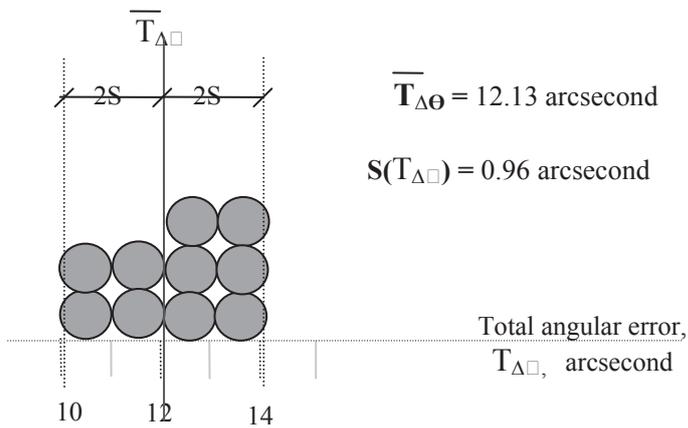
Fig. 3: Associated standard deviation at the calibrated angles.

Table 1: Calibration results of the rotary table

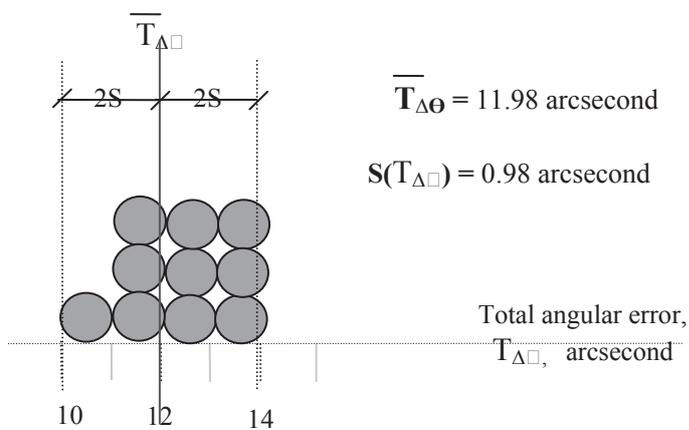
Calibration of rotary table by	Average total error of table, $\overline{T_{\Delta\theta}}$, arcsecond	Standard deviation, $S(T_{\Delta\theta})$, arcsecond
Autocollimator with polygon	11.97	0.73
Autocollimator with indexing table	12.13	0.96
Laser interferometer system	11.98	0.98



a)



b)



c)

Fig. 4: Results of rotary table as calibrated by;
 a) Autocollimator system with polygon
 b) Autocollimator system with indexing table
 c) Laser interferometer system with indexing table

Uncertainty Estimation:

The main factors affecting the calibration results and contributing to the uncertainty are mainly; uncertainty in the reference standard angle, accuracy of the angle comparators, uncertainty due to instabilities in environmental conditions, uncertainty due to eccentricity; uncertainty due to flatness of reflectors and uncertainty due to pyramidal effect.

Mathematical Model;

The measurand is the angles on the table under test (rotary table):

$$\theta = \Delta\theta + \theta_s + \Delta_m + \Delta_i + \Delta_e + \Delta_f + \Delta_p \quad \text{----- (1)}$$

Where;

- θ is angle on the rotary table (measurand).
- θ_s is angle on the reference standard.
- $\Delta\theta$ is the difference between the measurand and the angle standard as measured by the angle comparator.
- Δ_m is the correction due to inaccuracy of the angle comparator
- Δ_i is the correction due to instabilities due to environmental conditions on the measurements
- Δ_e is the correction due to eccentricity in fixing the angle standard to the table under test.
- Δ_f is the correction due to flatness deviation of reflectors and polygon faces.
- Δ_p is the correction due to pyramidal error.

The uncertainty at any angle based on GUM [4] and according to the mathematical model of equation 1, is: (by differentiation)

$$u^2(\theta) = [\partial(\theta)/\partial(\Delta\theta)]^2 u^2(\Delta\theta) + [\partial(\theta)/\partial(\theta_s)]^2 u^2(\theta_s) + [\partial(\theta)/\partial(\Delta_m)]^2 u^2(\Delta_m) + [\partial(\theta)/\partial(\Delta_i)]^2 u^2(\Delta_i) + [\partial(\theta)/\partial(\Delta_e)]^2 u^2(\Delta_e) + [\partial(\theta)/\partial(\Delta_f)]^2 u^2(\Delta_f) + [\partial(\theta)/\partial(\Delta_p)]^2 u^2(\Delta_p) \quad \text{.....(2)}$$

$$u^2(\theta) = c_1^2 u^2(\theta_s) + c_2^2 u^2(\Delta\theta) + c_3^2 u^2(\Delta_m) + c_4^2 u^2(\Delta_i) + c_5^2 u^2(\Delta_e) + c_6^2 u^2(\Delta_f) + c_7^2 u^2(\Delta_p) \quad \text{.....(3)}$$

Where,

$$C_i = 1$$

$$u^2(\theta) = u^2(\theta_s) + u^2(\Delta\theta) + u^2(\Delta_m) + u^2(\Delta_i) + u^2(\Delta_e) + u^2(\Delta_f) + u^2(\Delta_p) \quad \text{so;(4)}$$

The total error of the rotary table;

$$T_{\Delta\theta} = \Delta\theta_{\max} - \Delta\theta_{\min} \quad \text{..... (5)}$$

Where;

- $T_{\Delta\theta}$ is the total error of the rotary table.
- $\Delta\theta_{\max}$ is the maximum error during calibration of the rotary table.
- $\Delta\theta_{\min}$ is the minimum error during calibration of the rotary table.

The uncertainty in the total error of the rotary table;

$$u^2(T_{\Delta\theta}) = 2 u^2(\theta) \quad \text{.....(6)}$$

Substituting from equations 4 & 6, the uncertainty $u(T_{\Delta\theta})$:

$$u^2(T_{\Delta\theta}) = 2 [u^2(\Delta\theta) + u^2(\theta_s) + u^2(\Delta_m) + u^2(\Delta_i) + u^2(\Delta_e) + u^2(\Delta_f) + u^2(\Delta_p)] \quad \text{.....(7)}$$

This equation is used in calculating the combined uncertainty of the total error in calibration of the rotary table. $u(\Delta\theta)$ can be obtained from the repeatability observed in the calibration at each angle. The maximum standard deviation during the 10 repeated calibrations is taken to represent $s(\Delta\theta)$ of individual measurement results. The standard deviation of the mean $[s(\Delta\theta)/\sqrt{10}]$ is taken to represent repeatability in angle measurements.

A summary of uncertainty budget in each case are shown in tables 2; 3 and 4

Table 2: Uncertainty budget for rotary table calibration by autocollimator system with the aid of polygon

Quantity x_i	Type	$U(x_i)$ arcsecond \pm	Distribution.	Standard Uncertainty $u(x_i)$ arcsecond \pm	Sensitivity Coefficient c_i	$[c_i u(x_i)]^2$	Degree of freedom ν_i
Repeatability of measurements; $\Delta\theta$	A	0.82	Normal	0.41	1	$(0.41)^2$	9
Uncertainty in polygon; θ_s	B	0.30	Normal	0.15	1	$(0.15)^2$	∞
Autocollimator accuracy; Δ_m	B	0.05	Rectangular	0.03	1	$(0.03)^2$	∞
Environmental instability; Δ_i	B	0.10	Normal	0.05	1	$(0.05)^2$	59
Flatness of polygon s mirrors; Δ_f	B	0.05	Rectangular	0.03	1	$(0.03)^2$	∞
Pyramidal error; Δ_p	B	0.31	Normal	0.16	1	$(0.16)^2$	27
Combined Standard Uncertainty (u_c)						$(0.47)^2$	$\nu_{eff} = 16$
Expanded Uncertainty (U): $U = k \times u_c = 2 \times 0.47 = 0.94$ arcsecond							
Where, k is a coverage factor providing a level of confidence of approximately 95 %. For a normal distribution, $k=2$							

Uncertainty in the total error of the rotary table ($U_{T\Delta\theta}$):

According to equation (7);

$$U_{T\Delta\theta} = (\sqrt{2}) \times U(\theta) = (\sqrt{2}) \times (0.94) = 1.33 \text{ arcsecond}$$

Table 3: Uncertainty budget for rotary table calibration by autocollimator system with the aid of the indexing table

Quantity x_i	Type	$U(x_i)$ arcsecond \pm	Distribution	Standard Uncertainty $u(x_i)$ arcsecond \pm	Sensitivity Coefficient c_i	$[c_i u(x_i)]^2$	Degree of freedom ν_i
Repeatability of measurements; $\Delta\theta$	A	1.02	Normal	0.51	1	$(0.51)^2$	9
Uncertainty in Indexing table; θ_s	B	0.60	Normal	0.30	1	$(0.30)^2$	∞
Autocollimator accuracy; Δ_m	B	0.05	Rectangular	0.03	1	$(0.03)^2$	∞
Environmental instability; Δ_i	B	0.10	Normal	0.05	1	$(0.05)^2$	59
Flatness of reflecting mirror; Δ_f	B	0.05	Normal	0.025	1	$(0.025)^2$	∞
Eccentricity; Δ_e	B	0.23	Normal	0.12	1	$(0.12)^2$	19
Pyramidal error; Δ_p	B	0.31	Normal	0.16	1	$(0.16)^2$	27
Combined Standard Uncertainty (u_c)						$(0.63)^2$	$\nu_{eff} = 21$
Expanded Uncertainty (U): $U = k \times u_c = 2 \times 0.63 = 1.26$ arcsecond							
Where, k is a coverage factor providing a level of confidence of approximately 95 %. For a normal distribution, $k=2$							

Uncertainty in the total error of the rotary table ($U_{T\Delta\theta}$):

According to equation (7);

$$U_{T\Delta\theta} = (\sqrt{2}) \times U(\theta) = (\sqrt{2}) \times (1.26) = 1.78 \text{ arcsecond}$$

Table 4: Uncertainty budget for rotary table calibration by laser system with the aid of indexing table.

Quantity x_i	Type	$U(x_i)$ arcsecond \pm	Distribution.	Standard Uncertainty $u(x_i)$ arcsecond \pm	Sensitivity Coefficient c_i	$[c_i u(x_i)]^2$	Degree of freedom ν_i
Repeatability of measurements; $\Delta\theta$	A	0.76	Normal	0.38	1	$(0.38)^2$	9
Uncertainty in Indexing table; θ_s	B	0.60	Normal	0.30	1	$(0.30)^2$	∞
Laser system accuracy; Δ_m	B	0.05	Rectangular	0.03	1	$(0.03)^2$	∞
Environmental instability; Δ_i	B	0.10	Normal	0.05	1	$(0.05)^2$	59
Eccentricity; Δ_e	B	0.23	Normal	0.12	1	$(0.12)^2$	13
Combined Standard Uncertainty (u_c)						$(0.51)^2$	$\nu_{eff} = 29$
Expanded Uncertainty (U): $U = k \times u_c = 2 \times 0.51 = 1.02$ arcsecond							
Where, k is a coverage factor providing a level of confidence of approximately 95 %. For a normal distribution, $k=2$							

Uncertainty in the total error of the rotary table ($U_{T\Delta\theta}$):

According to equation (7);

$$U_{T\Delta\theta} = (\sqrt{2}) \times U(\theta) = (\sqrt{2}) \times (1.02) = 1.44 \text{ arcsecond}$$

Discussion:

A summary of the average total error in the rotary table $T\Delta\theta$ and the uncertainty associated in each case are shown in figures 5.

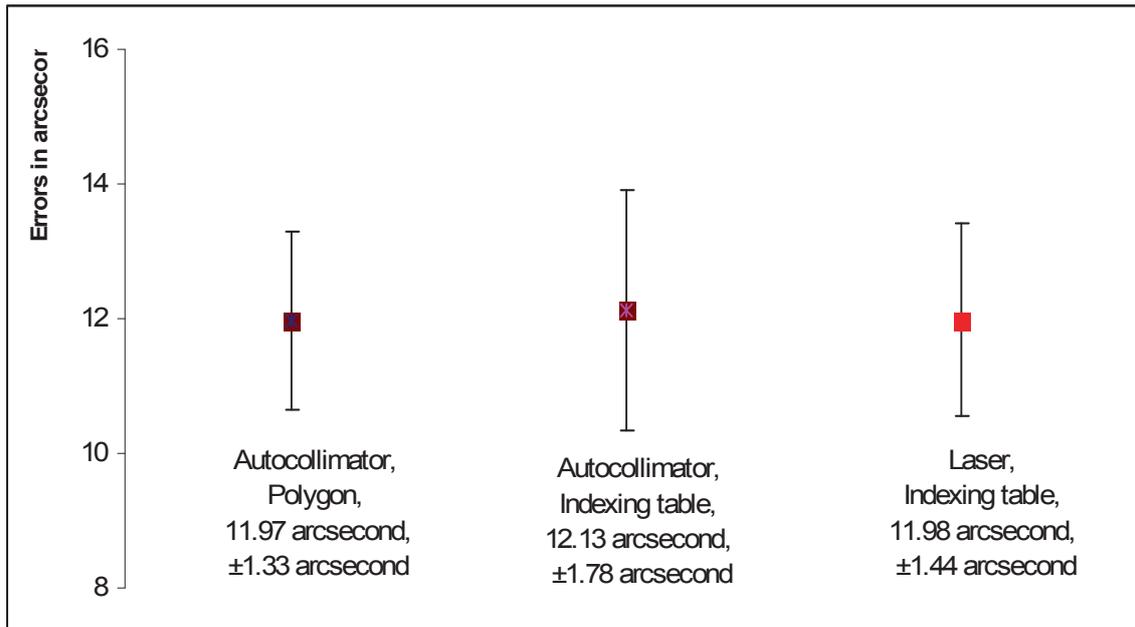


Fig. 5: Comparison of the average results of the rotary table error and associated uncertainties.

The normalizing error E_n (number of consistency) compares between measurement average values [6]. E_n values for the results of the rotary table calibration by the different methods investigated are shown in table 5. It is found that $E_n < 1$ in all cases. It could be said that according to the obtained results no significant differences were noticed between the average total errors of rotary table calibration by the two methods investigated.

Table 5: E_n values for the rotary table

Comparison between results of	E_n values
Laser with indexing <i>against</i> Autocollimator with indexing	0.07
Laser with indexing <i>against</i> Autocollimator with polygon	0.01
Autocollimator with indexing <i>against</i> Autocollimator with polygon	0.07

The uncertainty contributors are divided into two types of uncertainties, type A (repeatability) and type B (other contributors) as shown in figure 6. Type A (repeatability) is estimated to be (58% – 76%) of $U(T_{\Delta\Theta})$. The scale division of the rotary table under test is 30 arcsecond and by estimation one can estimate up to 6 arcsecond. High repeatability error could be due to this low resolution. The state of art of making rotary tables has improved a lot due to the use of rotary encoders and improving manufacturing techniques. It is now available in the market to get rotary tables used in workshop with resolution of about or less than 1 arcsecond.

Analysis of the relative influences of the factors affecting type B evaluation of uncertainty is shown in figure 7. The uncertainty due to accuracy of reference standard accuracy affects type B in the range (49% – 79%). The effect due to uncertainty of pyramidal error ranges up to 42%.

The effect due to eccentricity error ranges up to 17%. Other uncertainties (include instabilities, accuracy of instrument used and flatness deviation of reference angle) are relatively small.

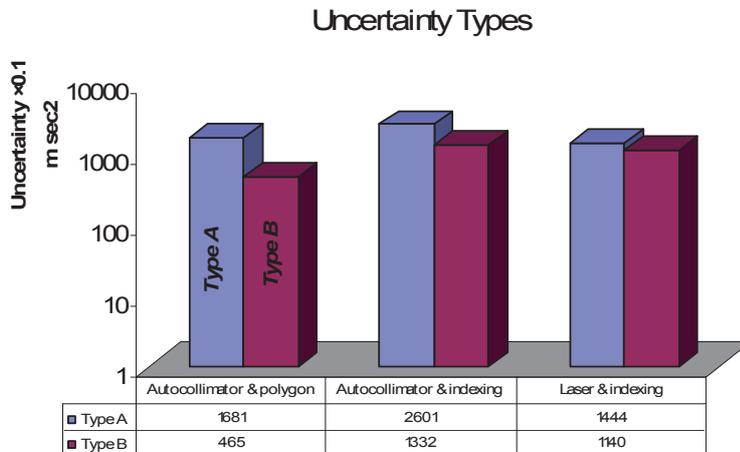


Fig. 6: Types of uncertainties components associated by each method.

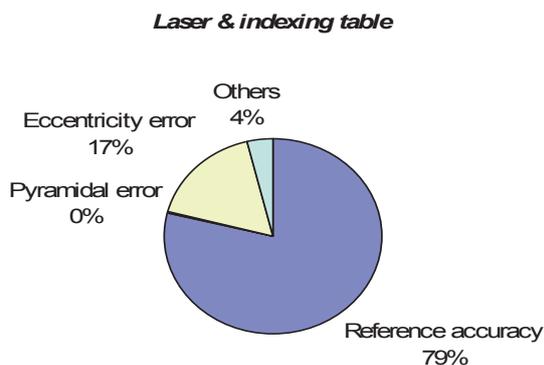
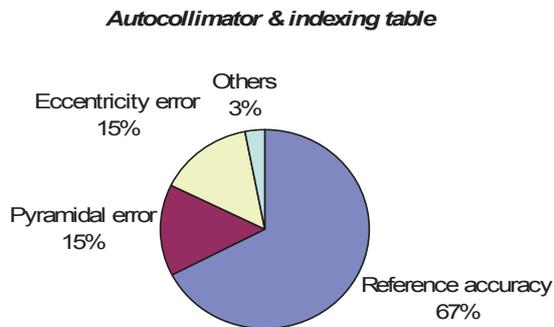
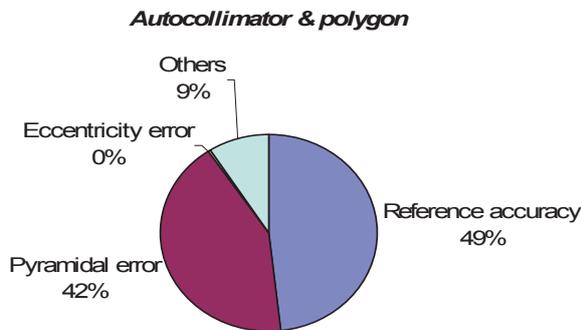


Fig. 7: Pie charts for different contributors of type B evaluation of uncertainty in calibration.

All of the investigated methods (systems) are portable. The calibration of rotary tables by autocollimator system with the aid of polygon comes faster and less time consuming than the other two methods. On the other hand, the angle step of calibration of the rotary table by autocollimator system with the aid of polygon is limited by the number of polygon faces.

Conclusion:

1. The averages of the results of the rotary table as obtained by different methods investigated are found to be statistically insignificant.
2. Either of laser interferometer system or autocollimator system is portable. So calibration of rotary table can be performed in calibration site.
3. The calibration of rotary tables by autocollimator system with the aid of polygon comes the easiest; require less time and less experience in application. However the angle step of calibration of the rotary table by autocollimator system with the aid of polygon is limited by the number of polygon faces.

References:

- [1] J. F. W. Galyer, C. R. Shotbolt, 'Metrology for Engineers', Cassell, London, third edition, ISBN 0 304 93434 8, 1974.
- [2] J. C. Evans and C. O. Taylerson, 'Measurement of angle in engineering', HMSO, second edition, 1964
- [3] Jack A. Stone, Mohamed Amer, Bryon Faust, and Jay Zimmerman, 'Uncertainties in Small-Angle Measurement Systems Used to Calibrate Angle Artifacts', Journal of Research of the National Institute of Standards and Technology, vol. 109 (3), pp. 319-333, 2004.
- [4] ISO/IEC Guide 98-3, 'Uncertainty of Measurement – Part 3: Guide to the Expression of Uncertainty in Measurement (GUM: 1995)', 2008.
- [5] Ted Doiron and John Stoup, 'Uncertainty and Dimensional Calibrations', Journal of Research of the National Institute of Standards and Technology, vol. 102 (6), pp. 647-675, 1997.
- [6] ISO 13528, 'Statistical Methods for use in Proficiency Testing by Interlaboratory Comparisons'.