



## On the Calibration of Angle Comparators (Autocollimators)

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**Abstract:-** Angle measurements are one of the main branches of production metrology. It includes measurements of angles in absolute values or deviations from specified reference angles. The angle comparators play important roles in the determination of small angles with high accuracy. Autocollimators are angle comparator type that can measure small angles with accuracy up to 0.05 arcs or better. Calibration of autocollimator becomes necessary demand not only for measurement of errors but also to ensure the traceability for other standards calibrated by them i.e. rotary tables, index tables, and angle blocks. In this paper, a proposed method based on laser interferometers is used for the calibration of a 0.05/±1000 arcs autocollimator system. The calibration is carried out for the axes X and Y of the autocollimator successively since the laser interferometer can calibrate one axis each time. The obtained results are analyzed and compared with tolerances according to predetermined tolerances and relevant standards

**Keywords:** *Laser Interferometer, Autocollimator, Angle, Small Angle Generators, Metrology*

### 1. Introduction

Angle Measurements are considered a main branch in dimensional metrology. Angles can be generated in a wide range of measurements from a full circle of 360° of rotary tables and total stations down to fractions of arc seconds of Angle comparators. Autocollimators are angle comparators that can measure precisely the angular deviation with accuracy up to 0.05 arcs or better. Autocollimators can be used in calibrations of angle instruments and small angular measurements in many scientific fields. Deflectometry measurements are a clear example of autocollimator applications [1–2]. Autocollimators are also used in the calibration of index tables, rotary tables, and rotary encoders with the aid of other optical elements [3–5]. Both rotary tables/encoders and index tables can be calibrated by using an autocollimator as an angle comparator with the aid of 12 faces reference polygon. The function of the autocollimator is to measure the angular differences between the table and polygon face at specified angle positions. By subtracting errors of the autocollimator and polygon from the measured errors, the angular errors of the table under calibration can be accurately determined. In addition to that, the polygons can be calibrated with experimental methods based on two or three autocollimators as in [4] and [5].

Errors measurement of autocollimators through their calibration become a necessary demand. The autocollimators should be calibrated by using reference angle measuring instruments/standards that are traceable to the SI units [6]. There are many methods and experimental setups that can be used in the calibration of autocollimators [7]. Angle comparators (Rotary tables fitted with angle encoders), Small angle generators (SAGs), Angular interferometers, Optical wedges, and Reference autocollimators are



the most common calibration methods for autocollimators [8–11]. Angle comparators of calibrated and fully investigated rotary tables equipped with angle encoders are used to calibrate autocollimators. Small angle generators (SAGs) are used in the calibration of autocollimators. These generators may be constructed and scientifically operated based on a sine bar or tangent arm [12–13]. SAGs based on sine bars generate angles by making height differences between the two rollers of the bar. A reflecting mirror is fixed at one end of the bar facing the autocollimator. The height difference can be made by reference gauge blocks or micrometer heads. A height difference of several microns divided by the length between the two rollers of the sine bar (ranges from 0.1 m upto 1m) can generate easily very small angles in a fraction of arc seconds, Figure (1).

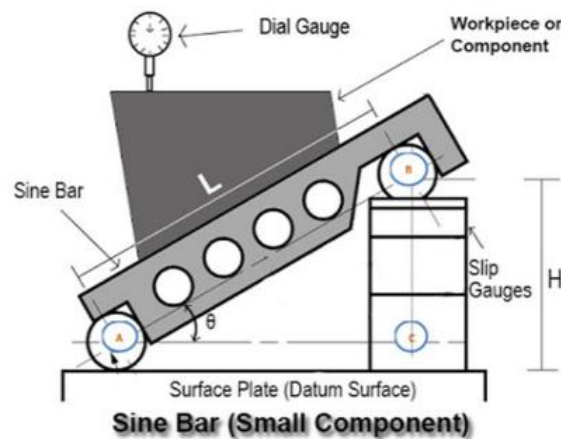


Figure 1. Angle generation by SineBars.

$$\text{Sine } (\theta) = \frac{H}{L} \quad (1)$$

SAGs based on tangent arms generate small angles with the aid of angular interferometers. Two retroreflectors are fixed at the two ends of the arm from one side while a reflecting mirror is fixed at the middle of the opposite side of the arm. Through a special setup of laser interferometer system, two interferometer beams are reflected by the fixed retroreflectors on the arm. Any arm rotation will change the path difference in the interferometer beams and can generate angles in very small values down to 0.001 arcs. Optical wedges can be used to generate small angles by using a precise rotating mechanism and arranging them in a suitable set-up. These wedges are usually called rotating wedge small angle generators. Traceable reference autocollimators are used with a suitable rotating/tilting mechanism in the calibration of low-accuracy autocollimators. A Rotary Table or piezo-driven tilting mechanism may be used when coupled with a suitable mirror and reference autocollimator. Most calibrations of autocollimators focus their efforts on error determinations of plane angles. However, some research works go toward the measurements of spatial angles [14–15].

## 2. Objectives

In this study, a proposed method is used to calibrate a 0.05 arcs autocollimator based on a laser interferometer of heterodyne 5529A type. Both reflecting mirror and retroreflector optic are sited



centrally back-to-back on the same rotary table. Each axis of the autocollimators is calibrated in a separate setup for both directions positive and negative. The next section describes the measuring instrument, the autocollimator, and the measurement method. In section 3, the measurement results are presented. In section 4, the results are analyzed and discussed for different measurement modes. In section 5, the main conclusions are outlined.

### 3. Methods

In this work, a proposed method based on a laser interferometer system is used to calibrate an angle comparator (autocollimator system). Each axis of the autocollimator is calibrated in a separate setup one after one. The calibration is carried out for a range of  $\pm 1000$  arcs with a rotation step of 100 arcs.

#### 3.1. Laser Interferometer System

A heterodyne He-Ne laser interferometer system of Agilent 5529A model type is used. Its working principle is based on the Michelson interferometer which consists of two mirrors, M1 and M2 arranged as shown in Figure (2) with a beamsplitter inclined at  $45^\circ$  to the mirrors. The output laser beam is split into two beams; one beam is a moving arm “measurement retroreflector” and the other is a fixed arm “reference retroreflector”. As the moving mirror moves, several fringes are constructed. By multiplying the number of the fringes ( $n$ ) by half of the wavelength ( $\lambda$ ) of the laser beam, the path difference between the two beams is calculated. This path difference represents the linear displacement ( $d$ ) that the moveable arm is moved. This optical setup is used for linear measurements.

$$\text{Displacement } (d) = n \times \frac{\lambda}{2} \quad (2)$$

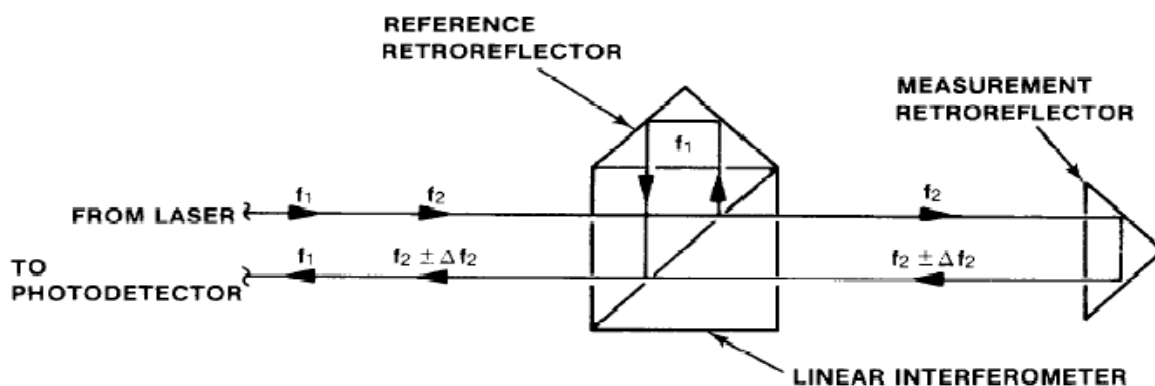


Figure 2. Linear measurements by laser interferometer system.

For the measurement of angle positioning, Figure 3, the angular optics creates two parallel beam paths between the Angular Interferometer and the Angular Reflector; one path's frequency  $f_1$ , and the second path's frequency  $f_2$ . The distance between the two paths is precisely known since the two reflectors are precisely positioned within the Angular Reflector. Initially, the angle between the Angular Interferometer and the Angular Reflector is assumed to be “0”, and the two paths between them have



some relative length. If either the Angular Interferometer or the Angular Reflector is rotated  $\Delta\theta$ , the relative lengths of the two paths will change; this change will cause a Doppler-shifted frequency change in the beam that is returned from the Angular Interferometer to the laser head. The laser measurement system's electronics hardware will calculate and display the angular change, using the new frequency count data and the spacing between the optical paths.

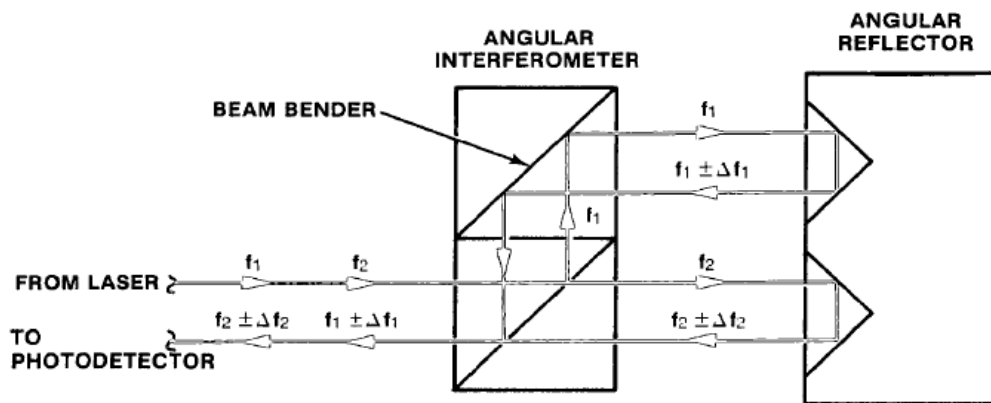


Figure 3. Angular measurements by heterodyne He-Ne laser interferometer system.

### 3.2. Autocollimator System

An autocollimator is an instrument that can measure optically small angular displacements, inclinations, and deviations with high precision. It can measure the angular displacements of a reflecting mirror or multi-faces optical polygon in two perpendicular axes in fractions of arc-second (arcs). A mirror in the optical path reflects beam back into autocollimator, Figure (4).

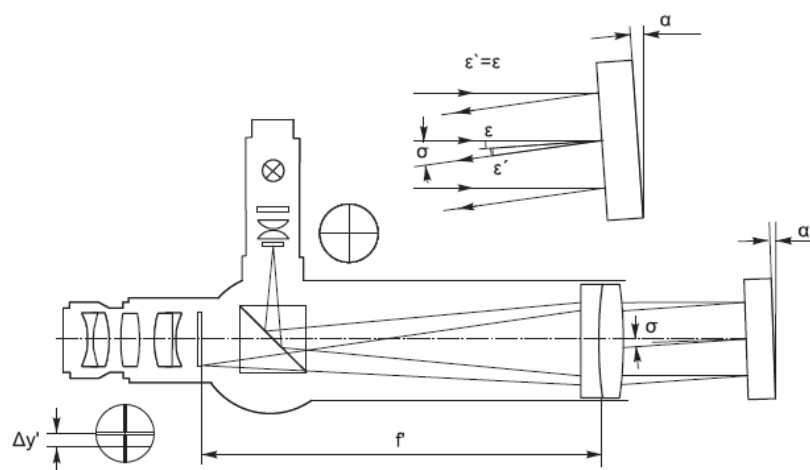


Figure 4. Measurements by autocollimator system.

The reflected beam generates the autocollimation image [16]. When the mirror is perpendicular to the optical axis, the beam is reflected into itself. When the mirror is tilted with an angle  $\alpha$ , the incident angle of the beam on the mirror is  $\epsilon = \alpha$ . After reflection the beam enters the objective obliquely with an angle of  $\alpha = 2\epsilon$ . Depending on the angle of the ray bundle to the optical axis, the autocollimation image is



shifted from the centre. The shift of the autocollimation image from the centre in both  $x'$  and  $y'$  directions is a measure for the tilt of the mirror. Autocollimators that are calibrated to tilting angle show half the angle of the reflected beam to the optical axis on their reading and therefore directly the tilting angle  $\alpha$  of the mirror. Under the assumption that the tilt occurs only in  $y'$ -direction, the angular reading  $\Delta\theta_y$  on the reticle is equal to  $\sigma/2$ :

$$\alpha = \frac{\sigma}{2} = \Delta\theta_y \quad (3)$$

The tilting angle can also be calculated directly from the shift of the reticle image  $\Delta y'$ :

$$\alpha = \frac{\sigma}{2} = \frac{\Delta y'}{2f'} \quad (4)$$

where;  $\alpha$  is tilting angle of the mirror,  $\sigma$  is angle of the beam with respect to the optical axis of the autocollimator,  $\Delta y'$  is shift of the reticle image,  $f'$  is focal length of the autocollimator.

In this study, an Elcomat 3000 autocollimator system autocollimator of 0.05 arcs resolution and  $\pm 1000$  arcs inclination range are calibrated.

### 3.3. Measurement Method

The proposed method for calibration of autocollimators as illustrated in Figure (5), depends on the experimental setup “back-to-back” reflectors. Both the setups of the laser interferometer system and autocollimator are carried out for angular measurements mode. The retroreflector and reflecting mirror are fixed on a rotary table back-to-back while the laser and autocollimator heads are aligned as accurate as possible in the same line. As the table is rotated, the generated angle ( $\Theta$ ) is measured and detected by the two systems.

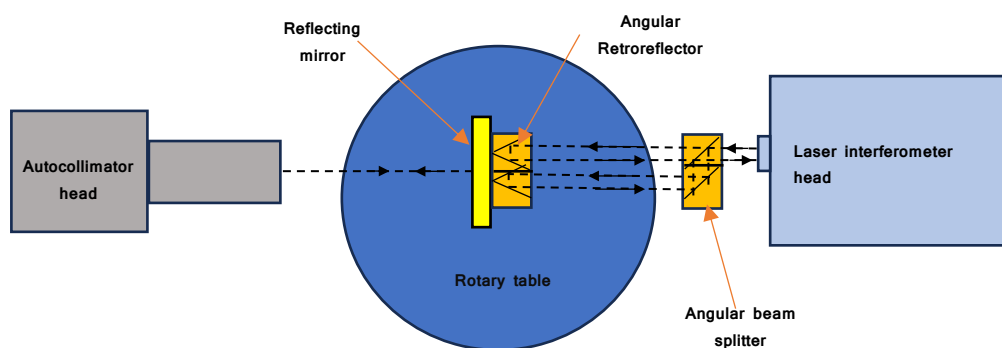


Figure 5. Experimental setup for calibration of an autocollimator by a laser interferometer.

The measured error ( $\epsilon$ ) is identified by;

$$\epsilon = \theta_A - \theta_L \quad (5)$$

Where is measured angular error,  $\theta_A$  is measured angle by autocollimator,  $\theta_L$  measured angle by laser interferometer. The angular errors are measured in X and Y axes of the autocollimator.



In X axis;

$$\epsilon_x = \theta_{A,x} - \theta_L \quad (6)$$

In Y axis;

$$\epsilon_y = \theta_{A,y} - \theta_L \quad (7)$$

The calibration is carried out for an angle range of 1000 arcs clockwise and anticlockwise. The experiment is sited firstly for the X axis of the autocollimator and then the autocollimator is laterally tilted 90° to calibrate the Y axis of the autocollimator.

## 4. Results

### 4.1. Calibration of X axis

The angular errors in the X axis of the autocollimator are measured in 10 runs of measurements, 5 runs in the clockwise direction, and 5 runs in the anti-clockwise direction Tables (1) and (2), Figure (6). The angular rotation in a clockwise direction acts as the positive direction of the X axis (+X). The angular rotation in the anti-clock direction acts as the negative direction of the X axis (-X).

**Table 1. Recorded angular errors (in arcs) in the +X axis (clockwise direction).**

Run Nr. Nominal angle, arcs	1	2	3	4	5	Average error, arcs	Stdev, arcs
0	0.00	0.00	0.00	0.00	0.00	<b>0.00</b>	<b>0.00</b>
100	-0.02	0.05	-0.04	-0.07	-0.10	<b>-0.02</b>	<b>0.05</b>
200	-0.06	0.17	0.11	-0.07	-0.10	<b>0.04</b>	<b>0.12</b>
300	0.03	0.30	0.19	-0.23	-0.20	<b>0.07</b>	<b>0.23</b>
400	0.08	0.42	0.35	0.40	0.40	<b>0.31</b>	<b>0.16</b>
500	0.17	0.48	0.52	0.57	0.60	<b>0.44</b>	<b>0.18</b>
600	0.25	0.62	0.61	0.50	0.50	<b>0.50</b>	<b>0.17</b>
700	0.32	0.69	0.76	0.30	0.40	<b>0.52</b>	<b>0.24</b>
800	0.25	0.84	1.01	0.23	0.20	<b>0.58</b>	<b>0.40</b>
900	0.43	0.96	1.25	0.50	0.50	<b>0.79</b>	<b>0.39</b>
1000	0.49	1.00	1.23	0.67	0.70	<b>0.85</b>	<b>0.33</b>
<b>Total error, arcs</b>	<b>0.55</b>	<b>1.00</b>	<b>1.29</b>	<b>0.90</b>	<b>0.90</b>	<b>0.94</b>	<b>0.30</b>

**Table 2. Recorded angular errors (in arcs) in the -X axis (anti-clockwise direction).**

Run Nr. Nominal angle, arcs	1	2	3	4	5	Average error, arcs	Stdev, arcs
0	0.00	0.00	0.00	0.00	0.00	<b>0.00</b>	<b>0.00</b>
-100	-0.09	-0.06	0.15	0.07	0.10	<b>0.02</b>	<b>0.11</b>
-200	-0.18	-0.12	0.00	-0.07	-0.10	<b>-0.09</b>	<b>0.08</b>
-300	-0.32	-0.26	-0.04	-0.20	-0.20	<b>-0.21</b>	<b>0.12</b>
-400	-0.37	-0.19	-0.05	-0.17	-0.10	<b>-0.20</b>	<b>0.13</b>
-500	-0.56	-0.30	-0.28	0.07	0.10	<b>-0.27</b>	<b>0.26</b>
-600	-0.40	-0.23	-0.39	-0.37	-0.40	<b>-0.35</b>	<b>0.08</b>
-700	-0.64	-0.33	-0.33	-0.53	-0.50	<b>-0.46</b>	<b>0.15</b>
-800	-0.73	-0.32	-0.38	-0.60	-0.70	<b>-0.51</b>	<b>0.19</b>
-900	-0.57	-0.31	-0.39	-0.87	-0.80	<b>-0.53</b>	<b>0.25</b>
-1000	-0.57	-0.31	-0.41	-0.60	-0.60	<b>-0.48</b>	<b>0.14</b>
<b>Total error, arcs</b>	<b>0.73</b>	<b>0.33</b>	<b>0.57</b>	<b>0.93</b>	<b>0.90</b>	<b>0.64</b>	<b>0.26</b>

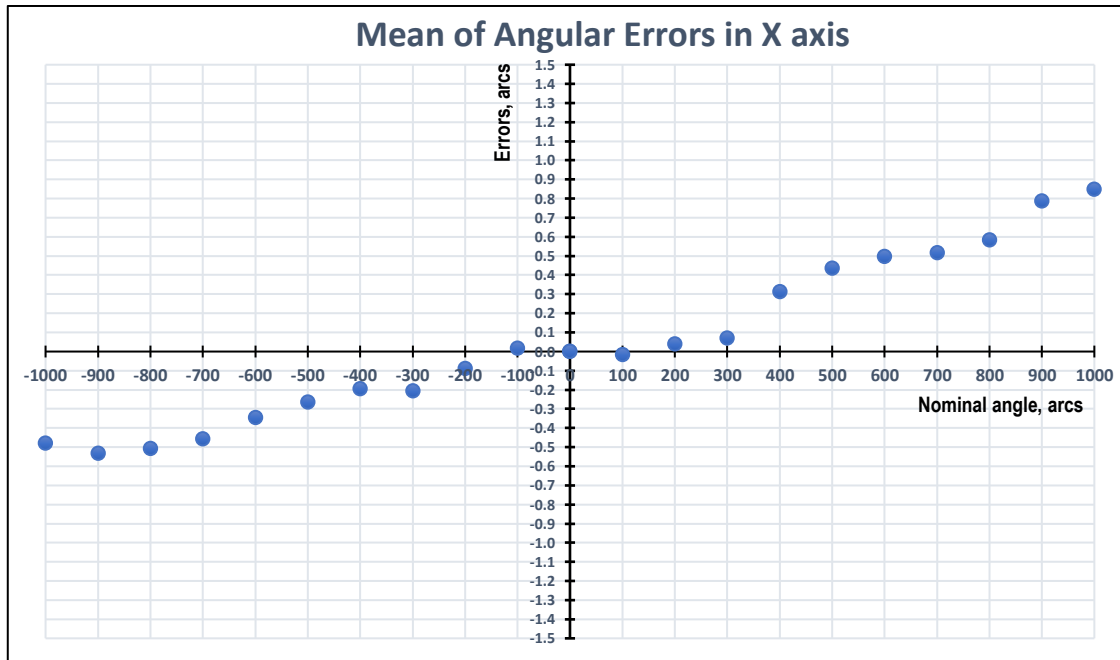


Figure 6. Mean angular errors (in arcs) for the 10 runs in the X-axis.

#### 4.2. Calibration of Y axis

The angular errors in the Y-axis of the autocollimator are measured in 10 runs of measurements, 5 runs in the clockwise direction, and 5 runs in the anti-clockwise direction Tables (3) and (4), Figure (7). The angular rotation in a clockwise direction acts as the negative direction of the Y axis (+Y). The angular rotation in the anti-clock direction acts as the positive direction of the Y axis (-Y).

Table 3. Recorded angular errors (in arcs) in the +Y axis (clockwise direction).

Run Nr. Nominal angle, arcs	1	2	3	4	5	Average error, arcs	Stdev, arcs
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-100	-0.06	-0.02	0.14	0.07	0.10	0.03	0.09
-200	0.01	-0.22	-0.18	-0.30	-0.40	-0.17	0.13
-300	0.30	-0.49	-0.35	-0.40	-0.50	-0.23	0.36
-400	0.23	-0.65	-0.48	-0.43	-0.40	-0.33	0.39
-500	0.26	-0.89	-0.63	-0.57	-0.50	-0.46	0.50
-600	0.28	-0.93	-0.82	-0.60	-0.60	-0.52	0.55
-700	0.27	-1.11	-1.01	-0.83	-0.90	-0.67	0.64
-800	0.22	-1.39	-1.11	-0.87	-0.90	-0.78	0.71
-900	0.05	-1.65	-1.12	-1.07	-1.10	-0.95	0.72
-1000	0.03	-1.68	-1.37	-1.10	-1.10	-1.03	0.74
Total error, arcs	0.36	1.68	1.51	1.17	1.20	1.18	0.58



**Table 4. Recorded angular errors (in arcs) in the -Y axis (anti-clockwise direction).**

Run Nr. Nominal angle, arcs	1	2	3	4	5	Average error, arcs	Stdev, arcs
0	0.00	0.00	0.00	0.00	0.00	<b>0.00</b>	<b>0.00</b>
100	-0.08	0.03	0.13	-0.57	-0.50	<b>-0.12</b>	<b>0.31</b>
200	0.03	-0.31	0.19	-0.43	-0.40	<b>-0.13</b>	<b>0.29</b>
300	-0.07	-0.38	0.29	0.10	0.10	<b>-0.02</b>	<b>0.28</b>
400	0.08	-0.50	0.30	-0.07	0.00	<b>-0.05</b>	<b>0.34</b>
500	0.26	-0.59	0.42	0.17	0.20	<b>0.06</b>	<b>0.45</b>
600	0.26	-0.35	0.53	0.23	0.20	<b>0.17</b>	<b>0.37</b>
700	0.19	-0.41	0.46	0.30	0.30	<b>0.13</b>	<b>0.38</b>
800	0.32	-0.48	0.80	0.20	0.20	<b>0.21</b>	<b>0.53</b>
900	0.30	-0.42	1.37	0.43	0.40	<b>0.42</b>	<b>0.74</b>
1000	0.51	-0.49	2.07	0.40	0.40	<b>0.62</b>	<b>1.06</b>
<b>Total error, arcs</b>	<b>0.58</b>	<b>0.62</b>	<b>2.07</b>	<b>1.00</b>	<b>0.90</b>	<b>1.07</b>	<b>0.69</b>

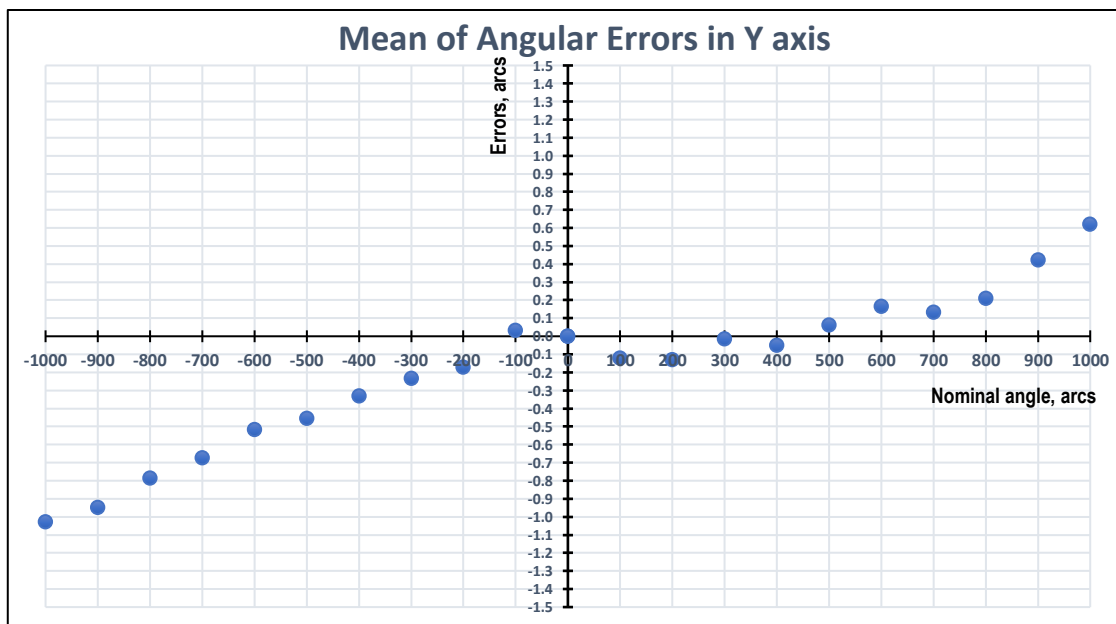


Figure 7. Mean angular errors (in arcs) for the 10 runs in the Y-axis.

## 5. Discussion

The results for error measurements through the calibration of the autocollimator are evaluated in three ways. The errors are first compared with those obtained during the autocollimator calibration by the manufacturer. Then the errors are compared with the specified tolerances of the manufacturers and the standard DIN1319. Lastly, the related parameters of the angular positioning of the autocollimator i.e. mean positional deviation, systematic positional deviation, repeatability, and accuracy are identified and determined.



## 5.1. Errors vs manufacturer calibration

The manufacturer calibrated the autocollimator by a special type of angle generator. A precision round table and a reference reflecting polygon are used in this calibration. The autocollimator is calibrated in the axes X and Y for a range of  $\pm 1000$  arcs. Figure (8) and Figure (9) show the measured errors in the X and Y axes for the calibration process. The resulting maximum error in the X axis are about 0.03 arcs while the errors in the Y axis are about 0.09 arcs. By comparing the errors in Figure (5) and Figure (7); the results of new calibration in the X axis show an agreement for a range of  $\pm 200$  arcs while the errors are propagated for the other range of upto 1000 arcs on both sides. For the Y axis, Figure (6) and Figure (8) a kind of consistency is existed for a range of  $\pm 100$  arcs and then the errors rise upto 0.6 arcs in +Y and 1.0 arcs in -Y. The interpretation for this error difference can be due to the annual drift for a long time of autocollimator usage. The manufacturer calibration happened 17 years ago before the delivery of the instrument. Supposing a drift of 0.025 per year, the error propagation can be imagined. The errors in the autocollimator due to the new calibration should be considered in each application and error compensation shall be performed

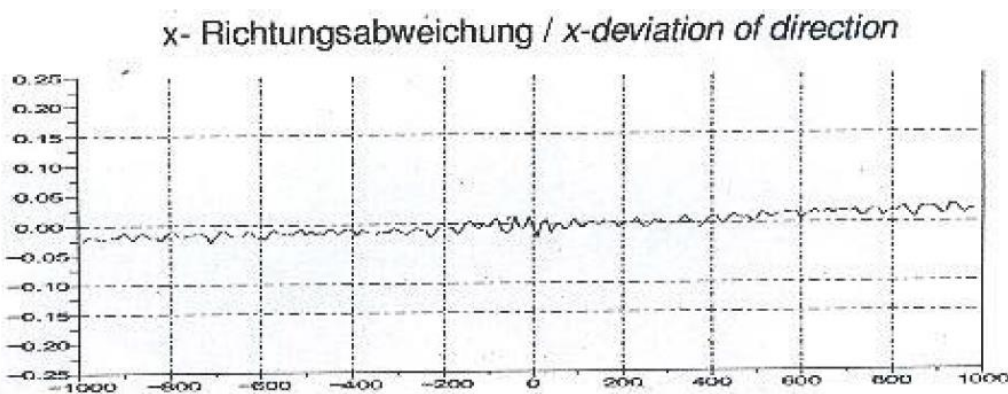


Figure 8. Angular errors (in arcs) in the X-axis for the autocollimator calibration by the manufacturer.

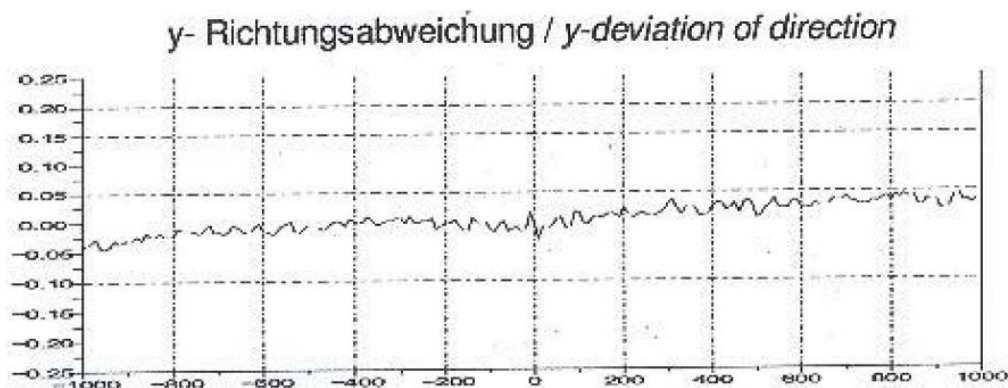


Figure 9. Angular errors (in arcs) in the Y-axis for the autocollimator calibration by the manufacturer.

## 5.2. Errors vs manufacturer tolerances

The autocollimator performance is evaluated by comparing the measured errors of each arm with the specified tolerance determined by the manufacturer. The manufacturer determines these tolerances



based on the standard DIN 1319 as: 0.2" over any 20" range and 0.5" for 1000" range. Table (5) shows the status of the measured errors in the X and Y axes of the autocollimator. The measured errors in the X axis comply with tolerances for the range of  $\pm 1000$  arcs at all angles except for 800, 900, and 1000 arcs in the positive direction (+X), the errors do not comply. The measured errors in the Y axis comply with tolerances for the range of  $\pm 1000$  arcs at all angles except for -700, -800, -900, and -1000 arcs in the negative direction (-Y) and for 1000 arcs in the positive direction (+Y), the errors do not comply. In general, the autocollimator's performance has an accepted quality for enough range in both X and Y axes which satisfy most measurement applications and can do its function in a good way.

**Table 5. Evaluation of the autocollimator performance**

Axis	Nominal Angle, arcs	Errors, arcs	Status	Axis	Nominal Angle, arcs	Errors, arcs	Status
	-100	0.02	Ok		-100	0.03	Ok
	-200	-0.09	Ok		-200	-0.17	Ok
	-300	-0.21	Ok		-300	-0.23	Ok
	-400	-0.20	Ok		-400	-0.33	Ok
	-500	-0.27	Ok		-500	-0.46	Ok
	-600	-0.35	Ok		-600	-0.52	Ok
	-700	-0.46	Ok		-700	-0.67	No
	-800	-0.51	Ok		-800	-0.78	No
	-900	-0.53	Ok		-900	-0.95	No
	-1000	-0.48	Ok		-1000	-1.03	No
	100	-0.02	Ok		100	-0.12	Ok
	200	0.04	Ok		200	-0.13	Ok
	300	0.07	Ok		300	-0.02	Ok
	400	0.31	Ok		400	-0.05	Ok
	500	0.44	Ok		500	0.06	Ok
	600	0.50	Ok		600	0.17	Ok
	700	0.52	Ok		700	0.13	Ok
	800	0.58	No		800	0.21	Ok
	900	0.79	No		900	0.42	Ok
X axis	1000	0.85	No	Y axis	1000	0.62	No

### 5.3. Determination of related parameters of the angular positioning

The related parameters of the autocollimator angular positioning i.e. mean positional deviation, systematic positional deviation, repeatability, and accuracy are identified based on the standard ISO 230-2 [17].

These parameters are calculated according to;

- **Angular positional deviation** [ $\epsilon$ ] is calculated as a result of subtracting the actual angular position value [ $\theta_A$ ] by the target position value [ $\theta_L$ ].

$$\epsilon = \theta_A - \theta_L \quad (8)$$

The calculation can be continued to obtain mean unidirectional ( $\bar{\epsilon}_{\uparrow}$  and  $\bar{\epsilon}_{\downarrow}$ ) or mean bidirectional  $\bar{\epsilon}_i$



$$\bar{\epsilon}_i \uparrow = \frac{1}{n} \sum_{j=1}^n \epsilon_{ij} \uparrow \quad (9)$$

$$\bar{\epsilon}_i \downarrow = \frac{1}{n} \sum_{j=1}^n \epsilon_{ij} \downarrow \quad (10)$$

- **Mean angular positional deviation** on a position is an arithmetic mean of the mean unidirectional angular positional deviations  $\epsilon_i \uparrow$  (clockwise direction) and  $\epsilon_i \downarrow$  (anti-clockwise direction). It is obtained from position  $\epsilon$  in the two measurement rotation directions.

$$\bar{\epsilon}_i = \frac{\bar{\epsilon}_i \uparrow + \bar{\epsilon}_i \downarrow}{2} \quad (11)$$

- **Systematic angular positional deviation** of an axis (E) is the difference between the algebraic maximum and minimum of the mean unidirectional positional deviations in an approach direction (clockwise  $\epsilon_i \uparrow$  or anti-clockwise  $\epsilon_i \downarrow$  direction) at any position  $\Theta_i$  along the axis.

$$E = \max. [\bar{\epsilon}_i \uparrow; \bar{\epsilon}_i \downarrow] - \min. [\bar{\epsilon}_i \uparrow; \bar{\epsilon}_i \downarrow] \quad (12)$$

- **Repeatability ( $s_i$ )**: It is an estimator of the standard uncertainty of the angular positional deviations obtained by a series of n unidirectional methods on a position  $\Theta_i$ .

$$S_i = \sqrt{\left[\left(\frac{1}{n} - 1\right) \sum_{j=1}^n (\epsilon_{ij} - \bar{\epsilon}_i)^2\right]} \quad (13)$$

- **Accuracy (A)**: It is the derived range from the combination of the bidirectional system deviation and the bidirectional angular positioning axis repeatability estimator using a coverage factor 2.

$$A = \max. [\epsilon_i \uparrow + 2S_i \uparrow; \epsilon_i \downarrow + 2S_i \downarrow] - \min. [\epsilon_i \uparrow + 2S_i \uparrow; \epsilon_i \downarrow + 2S_i \downarrow] \quad (14)$$

Table (6) shows the determined values of the parameters of angular positioning in the X and Y axes respectively. The presented values for the related parameters conform with the allowable tolerances for the range 1000" specified by the manufacturer. This appears good metrological capability of the autocollimator to be used.

**Table 6. Statistics of the parameters of angular positioning errors in the X and Y axes (in microns).**

Parameters/axis	Mean positional deviation	Systemic positional deviation	Repeatability	Accuracy
+X	0.41	0.35	0.23	0.4
-X	0.31	0.12	0.15	0.06
+Y	0.13	0.49	0.47	0.26
-Y	0.51	0.28	0.48	0.21
<b>Allowable tolerances for a range of 1000"</b>	0.5	0.5	0.5	0.5
<b>Status</b>	Ok	Ok	Ok	Ok

## 6. Conclusions

This study presents a proposed method based on laser interferometers for the calibration of autocollimators. A 0.05"/1000" electronic autocollimator is calibrated for its two axes X and Y with rotating step 100". The measured errors by the new calibration are compared with those of the



manufacturer calibration. The results in the X axis show an agreement between the two calibrations for a range of  $\pm 200$  arcs while the errors are propagated for the other range of upto 1000 arcs on both sides. For the Y axis, a kind of consistency is existed for a range of  $\pm 100$  arcs and then the errors rise upto 0.6 arcs in +Y and 1.0 arcs in -Y. The interpretation for this error difference can be due to the annual drift for a long time of autocollimator usage (17 years ago). The errors in the autocollimator due to the new calibration should be considered in each application. The autocollimator performance is evaluated by comparing the measured errors of each arm with the specified tolerance determined by the manufacturer and the standard DIN 1319. In general, the autocollimator's performance has accepted quality for enough range in both X and Y axes which satisfy most measurement applications and can do its function in a good way. The related parameters of the autocollimator angular positioning; mean positional deviation, systematic positional deviation, repeatability, and accuracy are identified. The presented values for the related parameters conform with the allowable tolerances for the range 1000" specified by the manufacturer.

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*Received: 06-07-2024*

*Revised: 15-08-2024*

*Accepted: 28-09-2024*

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