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Design of a calibration machine for optical two-dimensional length standards

Björn Hemming, Ilkka Palosuo, Antti Lassila
Centre for Metrology and Accreditation (MIKES)
Metallimiehenkj. 6 Espoo, FIN-02150, Finland
Phone: +358 9 616 761, Fax: +358 9 616 7467
E-mail Ilkka.Palosuo@mikes.fi, Bjorn.Hemming@mikes.fi, Antti.Lassila@mikes.fi

ABSTRACT

Optical measurements with coordinate measurement machines equipped with optical sensors, and video measurement machines, are clearly increasing in industry. Accurately manufactured two-dimensional standards, with a precision typically between 0.05 μm and 5 μm, are used to check and calibrate these measuring machines. In order to start a calibration service for two-dimensional standards, a new calibration machine is currently under development at the Centre for Metrology and Accreditation (MIKES). In this paper we describe the mechanical design, properties and present a detailed uncertainty analysis of position measurement. By modeling and compensating mechanical error sources the required standard uncertainty level of 50 nm is achievable.

Keywords: Calibration, 2D coordinate measurements, two-dimensional standard

1. INTRODUCTION

The last few years have seen a rapid growth in the use of machine vision in measurement equipment in length metrology. Optical coordinate measurement machines and video measurement machines are widely used, for example, in plastic industry. These measurement machines are very versatile, but on the other hand have several subjects fo calibration. One straightforward method to check and calibrate optical coordinate measuring machines is to use two-dimensional standards (figure 1). These reference standards have a precision typically between 0.05 μm and 5 μm. In order to achieve traceability, also these two-dimensional standards should be calibrated.

A design and development project aiming at a new calibration service for two-dimensional length standards was started in 2000 at MIKES. The technical requirements for the new calibration machine are an expanded uncertainty in calibrations 0.1 μm (at 95% confidence level) over the measuring range of 150 mm x 150 mm. The principle of operation of the device is similar to instruments used to measure photolithographic masks

In recent years calibration machines have also been developed at several National Measurement Institutes [1, 2, 3, 4, 5, 6]. The measurement principle is usually to measure movements of standard with laser interferometers and then to measure the position of the dot or grid on the standard with CCD camera and machine vision methods. In NPL a photomask comparator is also used to measure the relative displacement of commonly placed features between a pair of photomasks. Typical expanded uncertainties for the x-y coordinate measurement are 50 - 120 nm ($k=2$). Error separation or self-calibration methods have been presented especially by authors affiliated with the microlithographic industry [7, 8, 9]. In these methods it is assumed that the artifact is rigid and is measured in three or four different orientations. Much of the mathematical research in this field is concerned with how to deal with fourfold rotational symmetric errors [8].

In this paper we describe the mechanical and optical design of the developed instrument. Systematic error sources ar measured and modeled for on-line compensation. Also a detailed uncertainty analysis of position measurement is presented. Although the equipment is under development and the presented numerical results are preliminary, the uncertainty analysis is useful for future improvement of the instrument.

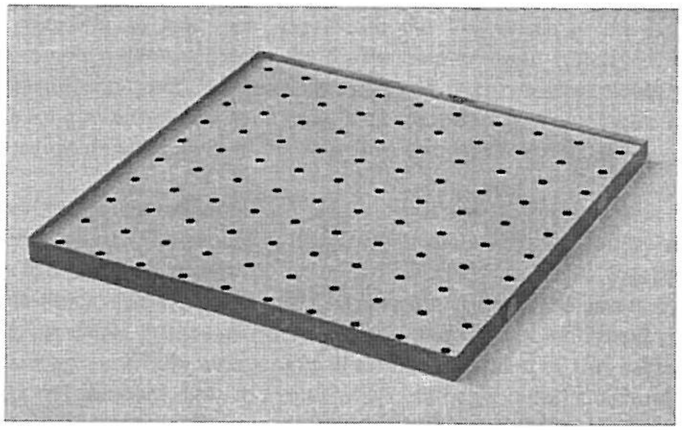

Figure 1. Example of a two-dimensional standard with dots (Photo: R. Rajala).

2. CURRENT DESIGN

The mechanics of the equipment consists of two linear granite rails, two linear stepping motor actuators and ten air bearings (figure 2 and figure 3). The type of air bearings used is vacuum preloaded. Vacuum preloaded bearings hold themselves down and lift themselves off a guide surface at the same time. The benefit of this bearing type is that only one guide surface is needed and the air gap is very stable. With these parts the mirror block can be moved on the granite block via two perpendicular movement axes. Together with linear actuators, piezo actuators are also installed to facilitate movements smaller than the resolution of the stepping motor-type actuators.

The two-dimensional standard under calibration is fastened to the zerodur mirror block using three suction pads. A three-axis plane-mirror interferometer system measures the position of the mirror block. The optical components are fixed to a large zerodur plate. The laser, which is of heterodyne type, measures axes denoted X, Y1 and Y2. Using the difference between Y1- and Y2-axis measurement results, angular yaw movement along the x-axis can be calculated. The optical components of an old lithography machine were used. Due to its original design Abbe's principle cannot be followed.

The position of the feature in the standard is detected with a ½ " CCD- camera, equipped with a high-magnification telecentric lens. In this project a 1024 x 768 square pixel camera with digital output according to the new IEEE 1394 standard was chosen. A far more critical decision is the type of lighting. Currently a fiber ring light is being tested, but coaxial light is also considered. The illumination will of course be dependent on the type of standard being calibrated.

The air temperature is measured with two Pt-100 sensors. Atmospheric air pressure and humidity are measured with capacitive sensors. The environmental measurement data is used to calculate the refractive index of air [10, 11].

The calibration of a two-dimensional standard is briefly a series of movements from one measurement mark to another using stepping motors and piezo actuators. The position of each mark within the camera field of view is measured using pattern matching correlation techniques. Using the two piezo actuators the measurement mark (i.e. two-dimensional standard) is positioned at the center of the field of view. Next the position given by the lasers is read and appropriate corrections are applied.

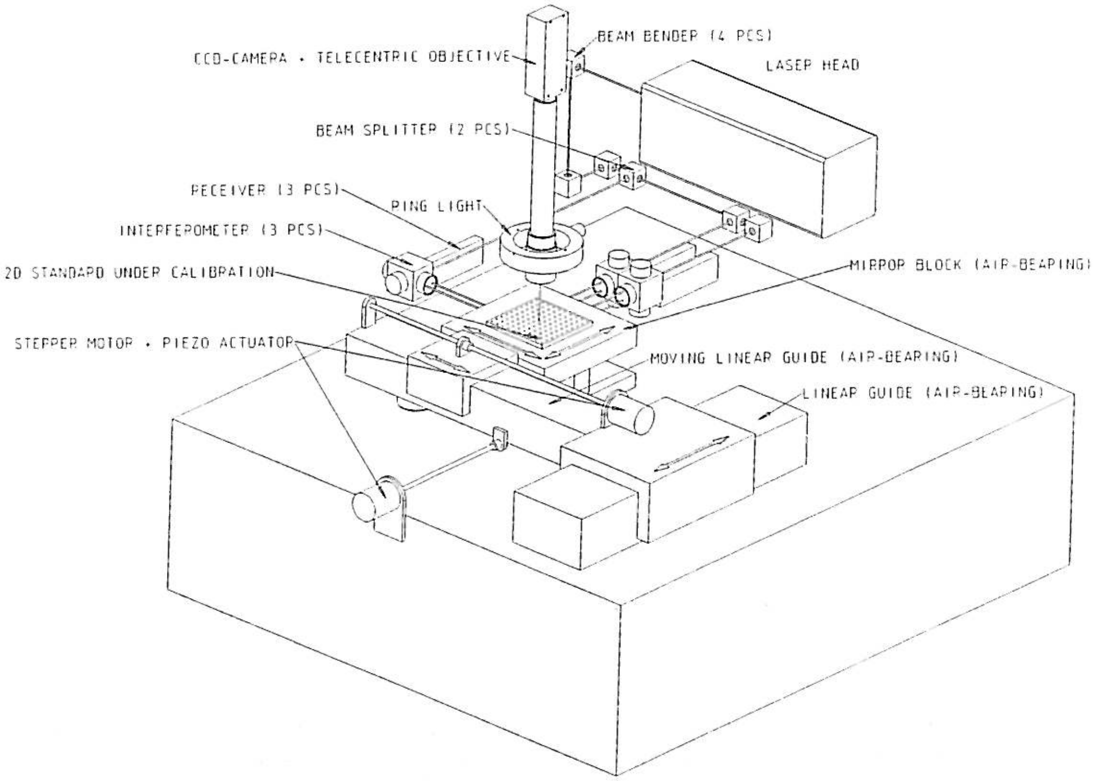

Figure 2. Schematics of the developed calibration machine.

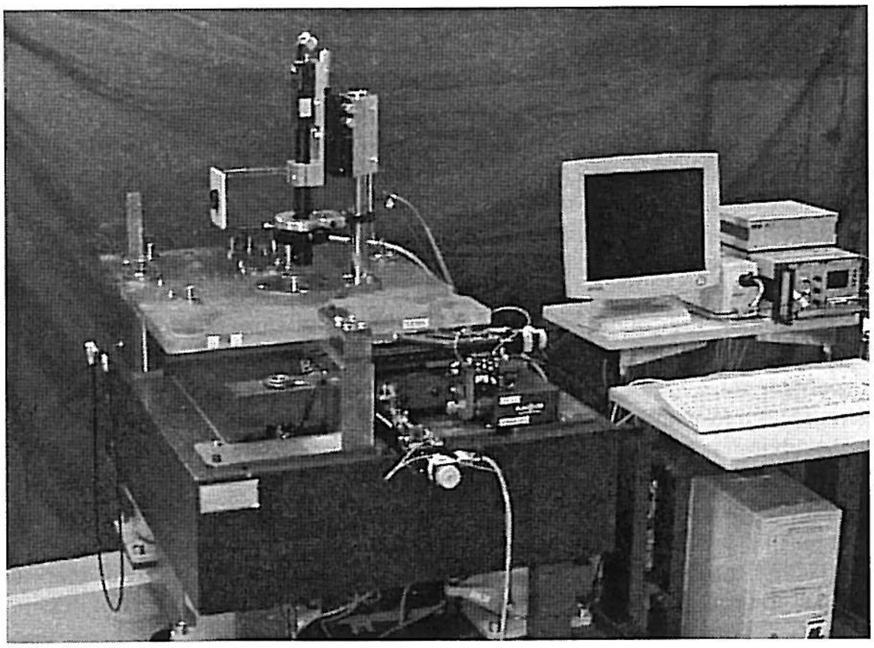

Figure 3. The developed calibration machine.

3. UNCERTAINTY ANALYSIS

To evaluate the achievable precision an approach described in the ISO Guide to the Expression of Uncertainty in Measurement is used [12]. A simple mathematical model for the measurement is derived. Each variable in the model is associated with a standard uncertainty, which should be evaluated from measurements, experiments, data sheets or experience. Numerical values for correction of systematic errors are used when available. The uncertainty budget in this paper is made only for the position measurement of the two-dimensional standard.

Factors affecting accuracy of the movements are straightness of the movement axis, roll, pitch, yaw and perpendicularity of the movement axis. The accuracy of the XY stage was evaluated by measuring the straightness of both axis and roll, pitch, yaw and perpendicularity of the axis. These measurements together with the measured flatness and squareness of the mirror block (see figure 4) and alignment errors of the lasers give input data for the error compensation and uncertainty analysis. Although operating in a temperature stabilized room, also temperature effects should be considered as correction for laser wavelength, thermal expansion of the calibration machine and thermal expansion of the two-dimensional standard. Due to limitations in the calibration machine the measurements cannot be done fully according to Abbe's principle, with a vertical Abbe offset of about 15 mm. This forms the largest error source. However, the Abbe error is measured and modeled, and it is described how this estimate is used to correct the measurement results (figure 5).

The model for the position measurement of x- and y-coordinates is:

$$x_0 = \frac{f_x \lambda_0}{4n(t,p,h)} + h_x \tan(\beta_x(L_x, L_y)) + L_y \tan(\varepsilon) + \delta x_{yaw} + F_x(L_y) + \delta x_{\cos} \tag{1}$$

$$y_0 = \frac{f_y \lambda_0}{4n(t,p,h)} + h_y \tan(\beta_y(L_x, L_y)) + \delta y_{yaw} + F_y(L_x) + \delta y_{\cos} \tag{2}$$

where:

f_x	fringe count for x-axis interferomete
f_y	fringe count for y-axis interferomete
λ_o	vacuum wavelength for laser
$n(t, p, h)$	refractive index of air as function of air temperature, pressure and humidit
h_x	effective distance for Abbe correction for x-axis due to pitch
h_y	effective distance for Abbe correction for y-axis due to pitch
$\beta_x(L_x, L_y)$	pitch angle of x-axis movement as function of position (L_x, L_y)
$\beta_y(L_x, L_y)$	pitch angle of y-axis movement as function of position (L_x, L_y)
ε	orthogonality deviation between plane mirrors
δx_{yaw}	correction for Abbe error in x-axis due to ya
δy_{yaw}	correction for Abbe error in y-axis due to ya
$F_x(L_y)$	flatness correction as function of position L_y
$F_y(L_x)$	flatness correction as function of position L_x
$\delta x_{\cos}$	correction for cosine error of laser alignment
$\delta y_{\cos}$	correction for cosine error of laser alignment

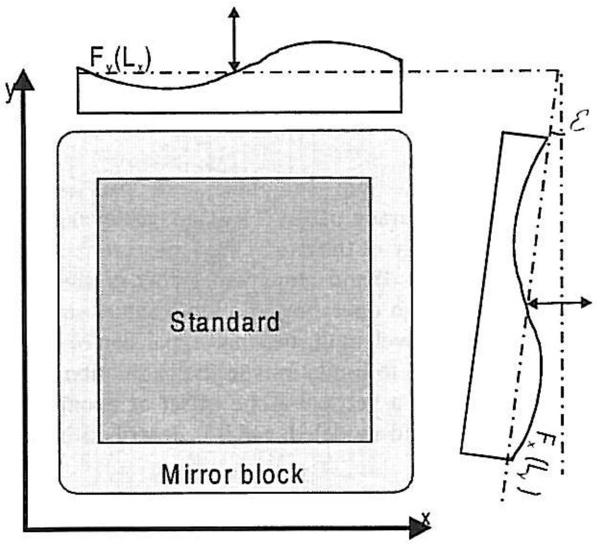

Figure 4. Effects of flatness error of mirror faces and orthogonality error on position measurement.

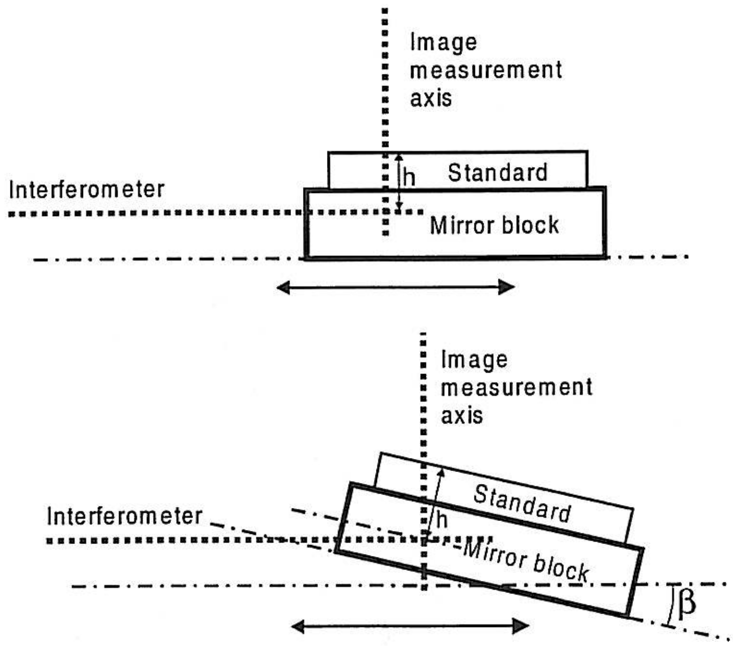

Figure 5. Effect of pitch angle and Abbe error.

In the following the components are described together with estimated standard uncertainties. In many cases a rectangular distribution is assumed and the standard uncertainty k=1) is simply the limits divided b $\sqrt{3}$ [12]. The emphasis is on the description of mechanical errors and uncertainties.

Fringe count, f_x, f_y

The uncertainty of the fringe count consists of optical and electronic non-linearity and resolution of the laser interferometer. When the resolution is 5 nm and the non-linearity of similar devices is approximately 10 nm (peak to peak) the total uncertainty is 3.2 nm.

Vacuum wavelength of laser, λ_o

Based on experience for similar Zeeman stabilized lasers, the relative uncertainty for laser vacuum wavelength is estimated to be 5×10^{-9}.

Refractive index of air, $n(t, p, h)$

The refractive index of air is related to the determination of the laser wavelength in air. The uncertainty of the refractive index is caused mainly by inaccuracy in the measurement of the environmental parameters and the updated Edlen's formula itself [11]. Relying on experience the estimated standard uncertainties are 0.05 K for air temperature, 8 Pa fo air pressure, 2.9% for humidity and 10^{-8} for the formula.

Orthogonality deviation between plane mirrors, ε

The orthogonality of the plane mirrors was measured with an autocollimator and a rotary table. The measured angle was 89°59' 59.82" equaling an orthogonality deviation of 0.87 μrad. The uncertainty of this measurement was 0.73 μrad. The uncertainty of the orthogonality would result as a large uncertainty contribution for the x- and y-coordinates if measured by an autocollimator only. In the future, orthogonality deviation will be measured using diagonal measurements of glass scales [3]. The standard uncertainty of the orthogonality correction is estimated to be 0.02 μrad.

Abbe error due to yaw, $\delta x_{yaw}, \delta y_{yaw}$

The yaw angle of the movements was measured with a laser interferometer. For both axes the yaw angle was below 14.5 μrad, equaling the standard uncertainty of 8.4 μrad. The CCD camera is aligned close to the crossing of the laser beams; however, an Abbe offset distance of approximately 0.5 mm is difficult to avoid. This corresponds to a standard uncertainty of 0.004 μm. There is no need to compensate for the yaw angle, but the magnitude 8.4 μrad is used as a uncertainty for yaw Abbe error on both axis.

Flatness correction for mirror block, $F_x(L_y)$, $F_y(L_x)$

Flatness deviations of the mirror surfaces are 0.048 μm for the x-face and 0.041 μm for the y-face, measured with a Zygo GPI Fizeau interferometer (figure 6). The uncertainty of these measurements is 0.018 μm (k=1). The data is used for correction of the flatness error. The uncertainty of correction is estimated to be 0.010 μm. The combined uncertaint of the flatness correction is 0.021 μm.

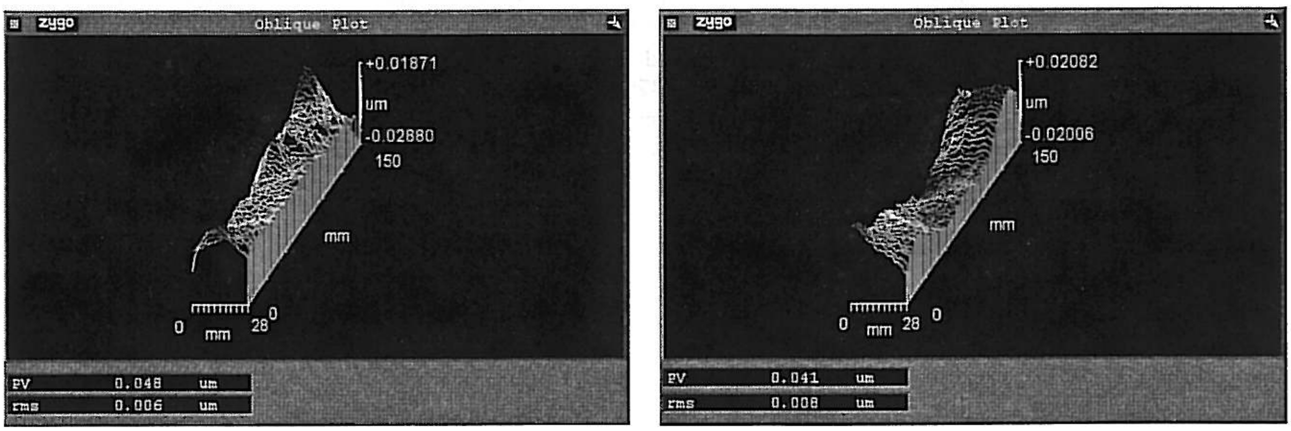

Figure 6. Flatness deviations of the mirror surfaces (left x-axis mirror surface, right y-axis mirror surface).

Correction for cosine error for laser alignment, $\delta x_{\cos}, \delta y_{\cos}$

The standard uncertainty for the uncompensated cosine error is estimated to be 200 µrad.

Abbe error due to pitch angle, $h_x \tan \beta_x(L_x, L_y)$, $h_y\ \beta_y(L_x, L_y)$

The position of the normal to be calibrated is situated 15 mm above the measurement plane formed by the laser beams (figure 5). The pitches of the x- and y-axis axes are measured with a laser interferometer (figure 7). The uncertainty of these measurements is about 2 µrad (k=1). Polynoms are fitted to the pitch measurement data for x- and y- axes and used for calculation of correction. For both axes the standard uncertainty for the fit is estimated to be 2 µrad. The combined uncertainty for the measurement and the fit is 2.8 µrad (k=1).

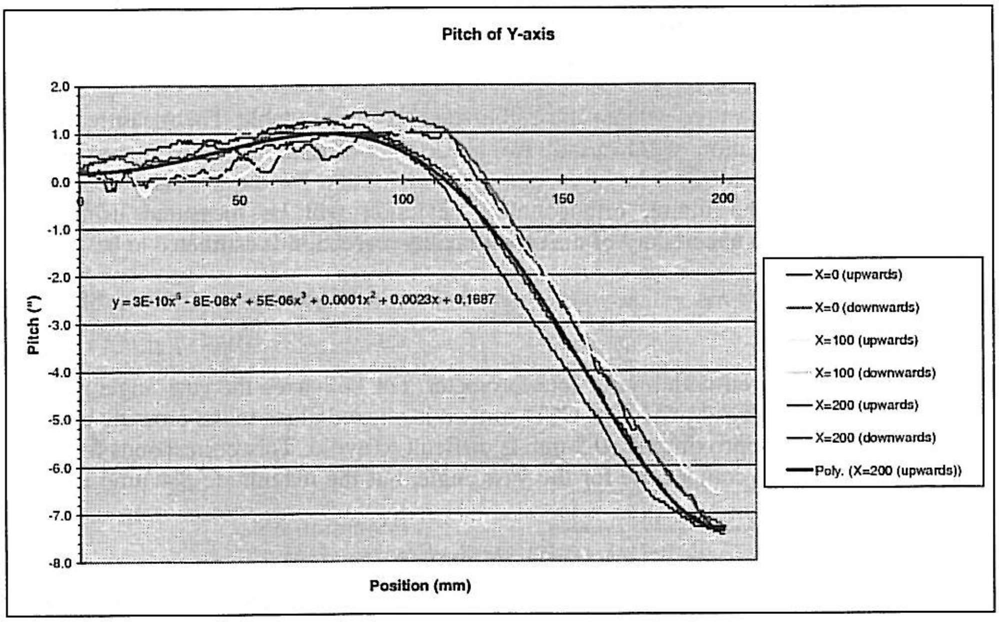

Figure 7. Pitch error of the y-axis modeled by a polynom as a function of the x-position.

None of the input quantities are considered to be correlated to any significant extent. The uncertainty sources for a measured and calculated x-axis coordinate are collected together in an uncertainty budget shown in table 1. The combined uncertainty ~~at 95% confidence level is~~ Q[0.047; 0.071 L][1] µm where $L = L_x$ is the position in m. For a position at 100 mm this equals the uncertainty of 0.048 µm (k=1) or 0.096 µm (k=2). The uncertainty budget for the y axis coordinate is similar to the x-axis coordinate; however, the orthogonality error is excluded.

[1] [1] $Q[A; B\,L] = (A^2 + (B\,L)^2)^{1/2}$

Table 1. Uncertainty budget for measurement of the x-coordinate. L is equal to measured x-coordinate, y is 150 mm.

Quantit		Estimate		Distri-bution	Standard uncertaint		Sensitivity factor		Uncertainty contribution	
Fringe count	f_x	$\cong 0.1$m		normal	0.0032	µm	1		0.0032	µm
Abbe correction due to pitch	$\beta(L_x, L_y)$	0	µrad	rectang.	2.800	µrad	1.5×10^{-8}	m/µrad	0.0420	µm
Orthogonality	ε	0.873	µrad	normal	0.02	µrad	1×10^{-7}	m/µrad	0.0020	µm
Flatness of mirror block	$F_x(L_y)$	0		rectang.	0.021	µm	1		0.0210	µm
Abbe correction due to yaw	δx_{yaw}	0		rectang.	0.004	µm	1		0.0041	
Vacuum wavelength	λ_0	0.633	µm	normal	5×10^{-9}		1	L	0.005 L	µm
Air temperature	t	20	°C	normal	0.05	K	9.6×10^{-7}	1/K L	0.048 L	µm
Air pressure	p	1013	Pa	normal	8.0	Pa	2.7×10^{-9}	1/Pa L	0.022 L	µm
Air humidity	h	50	%	normal	2.9	%	8.5×10^{-9}	L	0.025 L	µm
Edlen formula		1.000267		normal	1×10^{-8}		1	L	0.010 L	µm
Cosine correction	δx_{cos}	0	µrad	rectang.	200.000	µrad	2×10^{-10}	1/µrad L	0.040 L	µm

Components independent of length	0.047	µm
Components dependent on length	0.071	µm
Standard uncertainty for L_x = 100 mm	0.048	µm

The complete uncertainty budget for the calibration of a two-dimensional normal will be reported in a future paper when data from repetitive tests and different measurement strategies are available. It is clear that thermal drift of both the equipment and typical error sources of machine vision such as pixel resolution, lens distortion, noise, and pattern-matching algorithms will be included.

4. CONCLUSIONS

The developed device and calculation of the error budget or uncertainty of measurement is presented. The combined uncertainty at 95% confidence level is Q[0.047; 0.071 L] µm where L is the position in m. This result is obtained b applying error compensation methods to pitch error of the movements and to flatness errors of the mirror block. The effect of pitch error could be reduced by a re-design of the mirror block to fulfill Abbe's principle. The measurement and correction of the orthogonality error can be done using a self-calibration method. The achievable accuracy of 0.1 µm (at 95 % confidence level) for a position at 150 mm is sufficient for many calibrations, but can be further reduced by error separation methods where the artifact is measured in several orientations.

5. REFERENCES

1 M. B. McCarthy, J. W. Nunn and G. N. Rodger, "NPL optical length scales in the range 300 nm to 400 mm", LAMDAMAP 97, 3rd International Conference on Laser Metrology and Machine Performance III. Computational Mechanics Publications, pp. 195-204.

2 M. McCarthy, *A rectilinear and area position calibration facility of sub- micrometre accuracy in the range 100-200 mm*. Ph.D. Thesis, Cranfield University, School of industrial manufacturing science, 260 p.

3 F. Meli, N. Jeanmonod, Ch. Thiess and R. Thalmann, "Calibration of a 2D reference mirror system of a photomask measuring instrument", Proceeding of the SPIE – The International Society for Optical Engineering (2001), Vol **4401**, pp. 227-233.

4 W. Häβler-Grohne and H.-H. Paul, "Two dimensional photomask standards calibration", 11 th Annual Symposium on Photomask Technology, BACUS, SPIE, Vol **1604**, pp. 212-223.

5 H. Bosse and W. Häβler-Grohne, "A New Instrument for Pattern Placement Calibration Using an Electron Beam Probe", Proceedings of the 9th International Precision Engineering Seminar, Braunschweig, Germany, 1997, pp. 148-152.

6 G. Schubert, H. Bosse and W. Häβler-Grohne, "Large X-Y-Stage for Nanometer Positioning in Electron Beam System", Proceedings of the 9th International Precision Engineering Seminar, Braunschweig, Germany, 1997, pp. 452-455.

7 M. R. Raugh, "Absolute two-dimensional sub-micron metrology for electron beam lithography, A theory of calibration with applications", *Precision Engineering*, **7**(1) Jan 1985, pp. 3-13.

8 M. T. Takac, J. Ye, M. R. Raugh, R. F. Pease, C. N. Berglund and G. Owen, "Self-calibration in two-dimensions: the experiment", Proceeding of the SPIE – The International Society for Optical Engineering (1996), Vol **2725**, pp. 130-146.

9 J. Ye, M. Takac, C. N. Berglund, G. Owen and R. F. Pease, "An exact algorithm for self-calibration of two-dimensional precision metrology stages", *Precision Engineering*, , nr 1, 1997, pp..

10 K. P. Birch , M. J. Downs , "An Updated Edlén Equation for the Refractive Index of Air" *Metrologia*, 1993, 30, n°3, 155-162

11 K.P. Birch and M. J. Downs, "Letter to the Editor: Correction to the Updated Edlén Equation for the Refractive Index of Air",*Metrologia*, 1994, 31, n°4, 315-316