# Nanometer Profile Measurement of Large Aspheric Optical Surface by Scanning Deflectometry with Rotatable Devices: Error Analysis and Experiments

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**Abstract**

Scanning deflectometry is used for measuring optical near flat surface with uncertainty of sub-nanometres [1]. However, for measuring aspheric surface with large departure from perfect spherical surface this method is difficult to use. The key problem for scanning deflectometry is that high accuracy autocollimators usually have limited measuring range which is less than 1000 arc-sec, so it cannot be used for measuring surface with large slope. We have proposed a new method for measuring large aspheric surface with large slope based on scanning deflectometry method. Rotatable devices are used to enlarge the measuring range of autocollimator. The uncertainty propagation analysis of our proposed method is done. The result shows that when measuring a large aspheric surface with a diameter over 300 mm and with a slope of 10 arc-deg the uncertainty is less than 30 nm. For the verification of our proposed method, experimental devices are set up. A spherical optical surface with diameter of 35 mm and curvature radius of 5000 mm is measured. Measuring range of autocollimator is successfully enlarged by our proposed method. Experimental result shows that the standard deviation of 10 repeated measurement is less than 30 nm which is larger than the analysis value. Random drift and systematic error is found in the experiment result. Temperature drift is considered to be the main reason for the systematic error.

## 1 Principle

The basic principle is shown in Fig.1. For this method, three modules are used: an autocollimator module, a mirror under measurement module and a scanning stage module. The autocollimator module and the surface under measurement module are unmovable while measuring. On the scanning stage there is a rotatable stage fixed on it. Two mirrors are fixed on the scanning stage. One is fixed directly on the scanning stage and the other is fixed on the rotatable stage. Laser beam from the autocollimator head is reflected twice by the two mirrors and then reflected from the mirror under measurement. By reflected twice again, the laser goes back to the autocollimator head. The angle of the mirror on this light spot is measured by the autocollimator. Then the scanning stage move a certain distance and get another angle. When the detected angle becomes close to exceeding the measuring range of the autocollimator, the rotatable mirror turns a certain angle by rotation stage. When the displayed value of the autocollimator returns, we continue to scan. Finally, the angle change of the surface normal is detected. To make an integral of the angle data, the profile of the aspheric mirror is known.

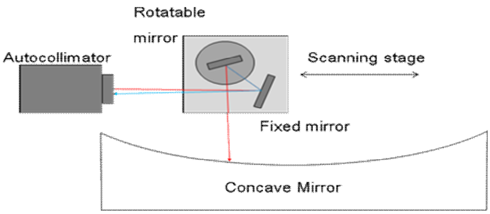
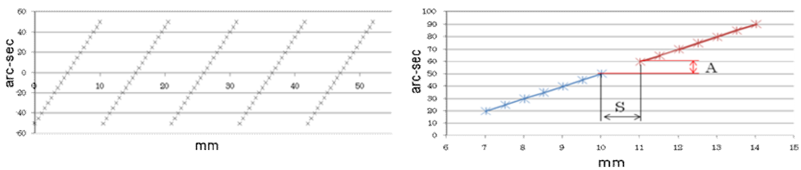



Fig.1 Principle of scanning deflectometry method with rotatable mirror

Because of the rotation of the mirror, the angle detected by the autocollimator is not continuous but interrupted as shown in Fig. 2(a). To connect the angle data we have to know the missed distance caused by rotation and the angle change caused by the distance change as shown in Fig. 2(b).




(a) (b)

Fig. 2 (a) Supposed angle data measured by autocollimator, (b) Connection of angle data which is interrupted by rotation

If the turned angle $\alpha$ and the distance between the rotation mirror and the mirror subject to measurement $D$ is known, the missed distance $S$ is calculated as $\alpha D$. The slope of these two points $K$ is assumed as slope of the least square line of angle data before the rotation is done. The according angle change $A$ is estimated as $KS$. As a result, the angle data is connected.

By making numerical integration of the connected angle data, we get the profile data $f_i$ of the surface as Eq. (1).

$$f_0 = 0,\ f_{i+1} = f_i + \frac{h}{2}(f_i' + f_{i+1}')$$
$$(i = 0,1,...,n-1)$$
$$f_i' = \tan(A_i) \tag{1}$$

In which, $f_0$ is the start point of the profile. The start point of profile is assumed as zero. $f_i$ is the displacement data of point $i$. $f'_i$ is the derivative of position $f_i$, which is equaled to the tangent of angle data $A_i$. The derivative is equaled to $h$ is the scanning interval.

## 2 Error Analysis

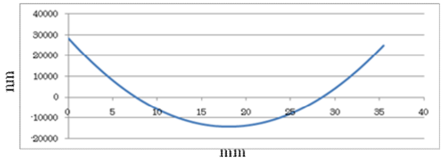
By numerical integration of angle data with the method introduced in Section 1**,** profile data is calculated. When the error of angle data is $E_a$, sampling interval is $h$, the number of sampling points is $N$, the length is $L$, the profile error of one line $\sigma$ can be expressed as Eq. (2). [2].

$$\sigma = \sqrt{N}hE_a = \sqrt{hL}E_a \tag{2}$$

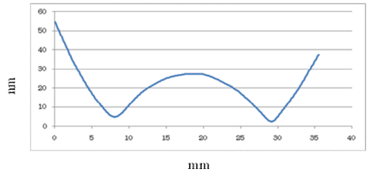
If a large optical surface with 300 mm length and 5000 mm concave radius is measured with an autocollimator with 1 μrad uncertainty, the uncertainty of the profile error is 12 nm. Here it is assumed that positioning uncertainty of scanning stage equals 5 μm and the scanning interval is 0.5 mm.

## 3 Experiments

An aluminum concave mirror with a diameter of 50 mm and the curvature radius of 5000 mm (±2%) is measured by the experiment setup. The mirror under measurement is not aspheric but spherical so that the further comparison with other method will be done easily. Because of the limitation of the moving range of scanning stage, only middle part of the mirror is measured.




(a)




(b)

Fig. 3 (a) Profile of concave mirror, (b) Standard deviation of profile data of 10 times

Measurement is repeated for 10 times. The average profile is shown as Fig. 3(a), and the standard deviation of 10 times measurement is shown in Fig. 3(b). The average of the standard deviation is 20.2 nm.

According to the error analysis in Section 2, the standard deviation of profile data $\sigma$ should be 6.2 nm. The temperature drift is considered to be the main factor which makes the difference between therotical analysis and experiment result.

## 4 Conclusion

Based on scanning deflectometry method with an autocollimator, we proposed a new method to measure large aspheric optical surface with rotatable devices. Error analysis is done to estimate the uncertainty propagated from angle data to profile data. A concave mirror is measured and the repeatability (standard deviation) of 10 times measurement is less than 30 nm.

**References:**

[1] Ralf D. Geckeler, Ingolf Weingaertner, Sub-nm topography measurement by deflectometry: flatness standard and wafer nanotopography, Proc. SPIE 4779, 1 (2002); doi:10.1117/12.451723

[2] Wei Gao, Peisen S. Huang, Tomohiko Yamada, Satoshi Kiyono, A compact and sensitive two-dimensional angle probe for flatness measurement of large silicon wafers, Precision Engineering, Volume 26, Issue 4, October 2002, Pages 396-404