Novel Technique for Measurement of Centration Errors of Complex, Completely Mounted Multi--Element Objective Lenses

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ABSTRACT

The size and the focal length of camera objectives (e.g. cell phones or digital cameras) are becoming smaller and smaller. At the same time the quality requirements are increasing. Besides surface accuracy, the imaging quality of the complete optics is mainly influenced by the alignment errors of the single elements. TRIOPTICS has developed a new technology called MultiLens® in order to measure the centering errors of all single surfaces within an objective lens with up to 40 surfaces or more. We achieve accuracies in the range of an arc second. During the measurement the deviation of each center or curvature with respect to a reference axis is measured. These data are further processed in order to provide the shift and tilt of an individual lens or group of lenses in respect to a given reference axis (Patent pending Ref. 1).

Applications mainly include the measurement of cell phone and digital camera lenses. However, any type of objective lens from endoscope up to very complex objective lenses used in microlithography can be measured with highest accuracy. The method has been extended to measure also the aspherical axis of lenses.

Keywords: centering, centration, lens, optical surface, objective, aspherical axis, digital camera, cell phone camera, tilt, shift

1. INTRODUCTION

Driven by the new types of objectives used for digital cameras or cell phone cameras the focal lengths of objective lenses are becoming smaller and smaller. A Smaller focal length is related to a smaller radius of curvature. The knowledge of the true centering error of individual optical surfaces inside of a mounted objective is becoming an important factor for the manufacturing of high quality miniature objectives. TRIOPTICS developed a measurement device to measure the individual centering errors of completely assembled optics. Based on these measurements it is possible to calculate the shift and tilt of different optical elements with respect to a given reference axis. The reference axis can be a mechanical axis (sample mount), it can be a best fit axis through all centers of curvature or it can be the optical axis of a single optical element.

The measurement is made on a vertical optical bench. The sample is placed on a high precision air bearing. The axis of rotation of the air bearing is the reference of measurement. The basic measurement results are provided with respect to this axis of rotation.

1.1 Principle of measurement

For the measurement of the centring error an electronic autocollimator is used for non contact measurement. This autocollimator is equipped with a set of focusing optics to provide a wide focusing range. In case the light emerging from the autocollimator enters the surface under test almost perpendicular a fraction of light will be reflected back. This happens when the focus point of the focusing autocollimator reaches the plane of curvature of the surface under test. The light will be focused on a CCD-camera. An autocollimation image of the autocollimator target (usually a cross hair) can be seen. If the surface is tilted with respect to the axis of rotation the image of the cross will be shifted. This can be seen when turning the sample around the axis of rotation. In this case the cross hair image turns on a circle. The diameter of the circle is related to the tilt of the surface (see Fig. 1).

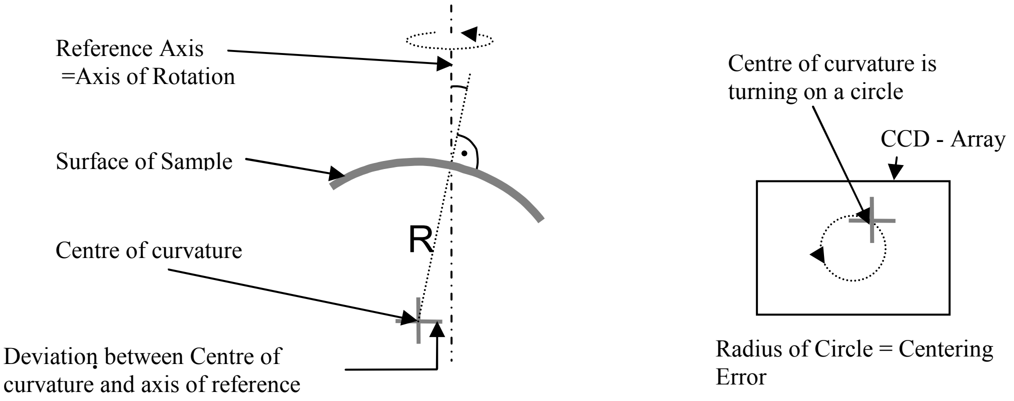

Fig. 1. A spherical surface is tilted with respect to the axis of rotation. By use of a focusing electronic autocollimator the center of curvature can be visualized on a CCD by using an illuminated cross hair target. While rotating the sample the image of the cross hair target moves on a circle. The diameter of the circle is proportional to the tilt of sphere.

This is valid for single surfaces. If the sphere under test is inside of an optical system the measurement has to take care about other surfaces within the optical path. To get an autocollimation image of the target, the light entering the surface under test has to be almost perpendicular. This is the same condition as before. But now the focusing autocollimator has to focus into a different plane. Due to refraction on surfaces in front of the surface under test the image of the centre of curvature will be shifted to a different plane (see Fig. 2a). This position can be easily calculated if the basic parameters of the sample are known. Following design parameters of all surfaces are required: the radius of curvature, refractive index and thickness.

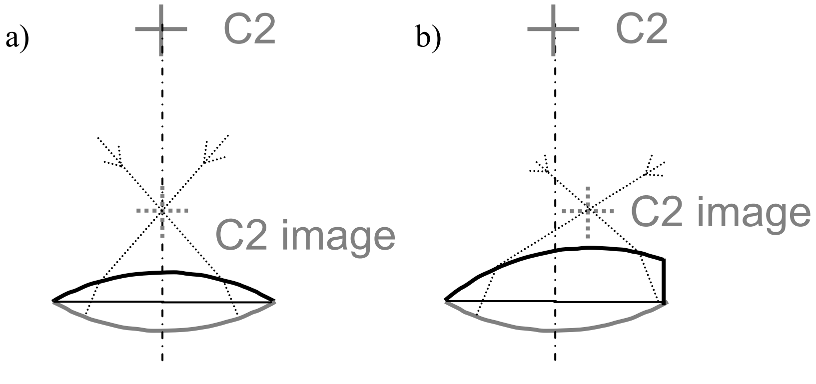

Fig. 2. To mesaure the centering error of an inner surface of an optical system the calculation has to consider refraction (Fig. a) and centering error (Fig.b) of surfaces in front of the surface under test. The figure shows the surface under test (grey color). The light (dotted lines) has to pass through the first surface (black color). The image of the center of curvature of the second surface (C2) appears on a different position due to the refraction and centering error of the first surface.

A second problem is connected to the centering error of surfaces in front of the surface under test. See Figure 2b. Imagine the tilt of the second surface is Zero, but the light has to pass through the top surface which is tilted. In this case the image of the centre of curvature of surface two seems to be shifted too. This will result in a centering error for surface number two. But if the centering error of surface number 1 is known, the influence of surface 1 can be removed by optical calculation. Succeeding surfaces can be measured in an iterative way. We have measured successfully optical systems with up to 40 surfaces. It is also possible to measure plane surfaces.

1.2 Spherical optics

After the measurement is finished, the true cartesian coordinates of all centers of curvatures with respect to the coordinate system of the measurement device can be calculated (Fig. 3a). This set of data can be further used for a more detailed analysis of the sample:

After calculation of the cartesian coordinates of the set of centre of curvatures, it is possible to fit a line connecting the centres of curvature. E.g. if the first lens is a singlet, a line can be drawn through the centre of curvatures of surface one and surface two. This line refers to the optical axis of the first lens (see following figure). The procedure can be repeated with other lenses or groups of lenses too. Now it is possible to calculate the shift or the tilt of this lens or group of lenses with respect to different references: the reference can be the axis of rotation (see figure 3b), the mechanical axis of a lens mount, a reference surface of a lens mount, etc. The figure shows the definition of the shift and tilt of the lenses.

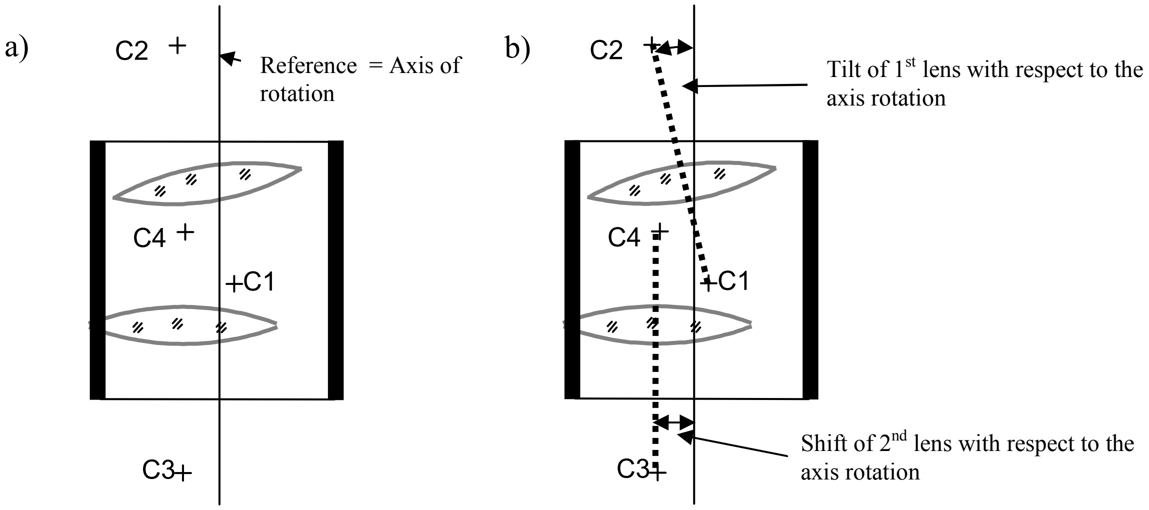

Fig. 3. The diagram shows an optical system consisting of two singlets. a) The measurement result provides the centers of curvature of each surface (indicated by “C” and number of surface). The optical axis of each lens results as a connection of the centers of curvature. b) Now tilt and shift of each single lens in respect to the reference axis can be calculated.

Figure 4 shows the shift and tilt of lens 2 with respect to lens 1.The reference can also be the axis of the mechanical lens mount. In this case an electronic indicator is used to measure the axis of the mount in respect to the axis of rotation.

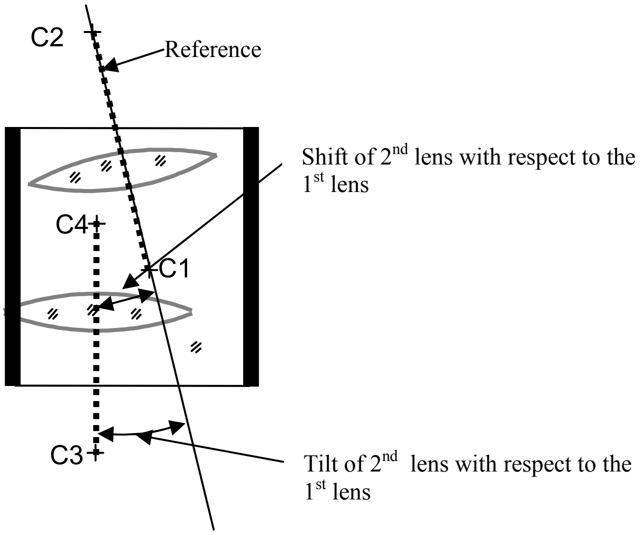

Fig. 4. Shift and Tilt of lens #2 in respect to lens #1.

1.3 Aspherical Optics

This measurement technique can be also used to measure the tilt and shift of cell phone lenses as well as endoscope optics or any other type of small optics. It is possible to measure surfaces with an radius below 1mm as well as surfaces with antireflection coatings. Like other types of plastic optics cell phone lenses usually have strong aspherical surfaces (Ref. 2). In spite of this fact, it is possible to measure the shift and the tilt of the single elements of this kind of samples. In order to accomplish this task, the measurement is done using only the paraxial area of the sample. This is shown in the following sketch. In the paraxial region the aspherical surface can be approximated by a best fit sphere.

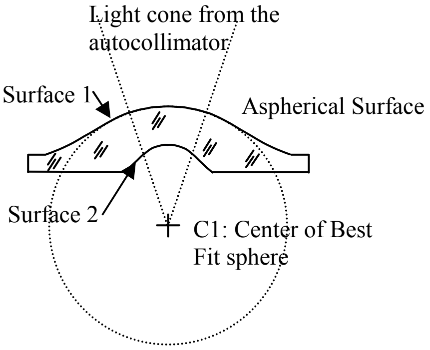

Fig. 5. Principal sketch of a single element of a cell phone lens. The surfaces are strongly aspherical. “C1” refers to the best fit sphere of the center of curvature of the first surface.

2. MEASUREMENT RESULTS

2.1 Measurement setup

The measurement device has two basic components: A) An electronic autocollimator mounted on a stepper motor driven linear stage B) High precision rotary stage (air bearing). Additionally a second autocollimator can be mounted on the bottom side of the air bearing. The following sketch shows the side view of a system with two autocollimators. This system has been used for the measurements described in this paper.

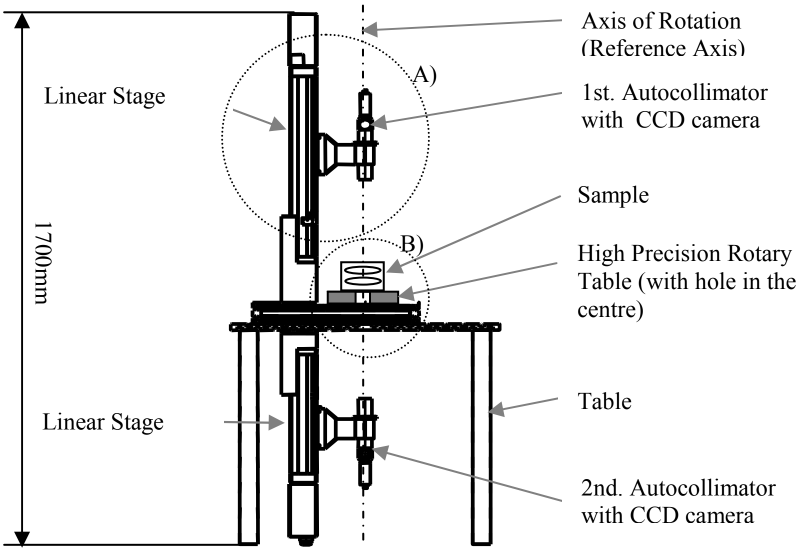

Fig. 6. Side view of the device to measure the centering error of complete optics.

The air bearing is used to provide a reference axis with highest accuracy. The radial run out of the air bearing is below 0.05µm. For the measurement of a single surface the air bearing makes one revolution and stops always at the same reference position. The plane of the table is the x-y plane The basic centering error is provided with x-y components. The z-direction is pointing down and coincides with the axis of rotation (=reference axis).

2.2 Measurement of an objective

For a typical measurement, an objective consisting of two doublets has been selected. See Fig. 7.

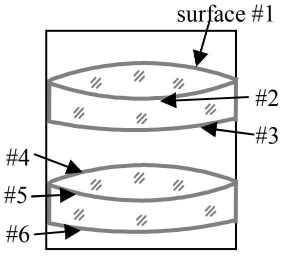

Fig. 7. Sketch of the sample used for measurement. Two similar doublets are mounted together in a housing.

The sample has been measured 4 times. After each single measurement the sample has been removed, turned around the azimuth (approx. 90°) and placed again on the air bearing. Due to this procedure the centering error results of each measurement in respect to air bearing are quite different. The raw data can be, however, used for the calculation of the Cartesian coordinates of the centres of curvature (as shown above), for definition of the optical axes of the optical elements and finally to unveil the centering properties of the sample.

For this purpose, a fit line was generated through the first doublet, a second separate fit line through the second doublet. Eventually the tilt and shift of these fit lines have been calculated, as given in the table. The calculation has been made for all 4 measurements. Column 4 shows the shift between the first and the second doublet and column #7 shows the tilt between both doublets. From the x and y component of the shift it can be also seen that the sample has been turned clockwise roughly around 90° between the single measurements.

This can be seen in the following table of data.

Table 1. Shift and tilt of the first doublet in respect to the second doublet:

No. Measure.	**Shift X [µm]**	**Shift Y [µm]**	**Shift Total [µm]**	**Tilt X [arcmin]**	**Tilt Y [arcmin]**	**Tilt Total[arcmin]**
1	1.7961	-8.4130	**8.6026**	0.2644	4.0365	**4.0452**
2	-8.770	-1.8986	**8.9736**	4.0548	-0.0833	**4.0557**
3	-0.8953	8.7743	**8.8199**	-0.3458	-4.0351	**4.0498**
4	8.4513	1.9539	**8.6742**	-4.0579	0.0587	**4.0584**
Average			**8.768**			**4.052**
Std.Dev.			**0.164**			**0.006**

The data above illustrate the high accuracy and repeatability of the measurement. The shift between both doublets is 8.77µm with a standard deviation of 0.16µm. The tilt between the optical axis of both achromats is 4.05 arc minutes measured with a standard deviation of 0.006 arcmin (0.4 arcsec!).

It is possible to apply more analysis on the same set of measurement data. In the following data table the tilt of the 3rd surface in respect to surface #1 and #2 has been calculated. This is the error introduced while cementing the first doublet.

Table 2. Cementing error of the first doublet. (Tilt of 3rd surface in respect to surface #1 and #2)

No. Measure.	**Surface Total[arcmin]**
1	0.458
2	0.49
3	0.482
4	0.51
Average	0.485
Std.Dev.	0.022

2.3 Measurement of a cell phone lens

Following figure shows a typical sketch of cell phone lens consisting of 3 single lenses. Such type of lens has been used for measurement.

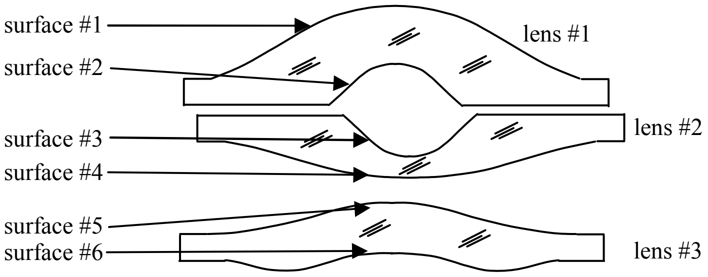

Fig. 8. Principal sketch of the sample used for measurement. The sample has 3 elements with strong aspherical surfaces

After finishing the measurement, the top lens #1 has been taken as a reference for the lenses #2 and #3. The shift and tilt of lens #2 and #3 were calculated in respect to the first lens. The measurement has been repeated two times. The results are displayed in table 4. The tilt of the second lens seems to be extraordinarily high. This is due to the fact that the center of curvature #3 and #4 are very close together. Therefore small changes in the measured position cause very big changes in the tilt angle. But in spite of this fact the value of the tilt and shift of all lenses could be measured with a good repeatability.

This can be seen in the following table of data.

Table 3. Shift and tilt of the first achromat in respect to the first lens.

First Measurement: Second Measurement:

Lens Number	**Shift Total [µm]**	**Tilt Total[arcmin]**		**Lens Number**	**Shift Total [µm]**	**Tilt Total[arcmin]**
1	0.0	0.0		**1**	0.0	0.0
2	106.180	591.1316		**2**	106.82	595.733
3	5.8558	7.1038		**3**	4.484	7.3454

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