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Methods for the control of centering error in the fabrication and assembly of optical elements

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ABSTRACT

In modern optical systems precise lens centering requirements must be achieved to minimize non-symmetrical aberrations. In this paper, several traditional and unique methods and their application of optical element centering in fabrication and assembly are presented and analyzed.

INTRODUCTION

The measurement and control of centering error in the fabrication of optical components, assembly of doublets and assembly of optical elements in their mechanical mounts is critical in meeting system performance (resolution, MTF, etc.) requirements in modern electro-optical systems. Decentered optical elements, whether at the component level or in mechanical mounts and elements tilted during assembly are typically the greatest contributing factors to image degredation in an optical system.

Once the need for controlling and measuring centering error is defined and understood, one must determine the most appropriate method. In order to select the appropriate method, one must understand the basic calculations of centering error and the parameters which have the greatest influence. In the following pages the basic calculations for centering error and the concepts, methods and instrumentation associated with the measurement of centering error will be discussed.

GENERAL DEFINITIONS

Optical Axis (OA)

(1) Simple Optical Component (Single Lens or Two Spherical Mirrors)

--The straight line passing through the centers of curvature of the spherical surfaces composing a rotationally symmetrical optical component.

(2) Compound Optical Component (System)

--The straight line connecting the two principal points of a rotationally symmetrical optical system.

Mechanical Axis (MA)

--The axis of rotational symmetry of the periphery of a single lens or of the barrel in the case of a lens assembly.

Centering Error

--The relationship between the MA and the OA expressed in terms of angular tilt or linear displacement.

CALCULATION OF CENTERING ERROR

The calculation of centering error can be performed from either the geometrial or aberrational points of view.

The geometrical approach is used in various methods of measurement of centering error to analyze the accuracies and sensitivites of measurements. The use of different basic parameters results in different methods of measurement. The relationship between these parameters can be found from elementary geometric correlations evident from Fig. 1a, b and is shown in Table 1. Here we assume that decentrations Δ_1, Δ_2 and image displacement e are relatively small and that standard sign convention is used.

In the aberrational approach, a system of centering tolerances is formulated by analysing the influence of centering error on the wave aberration. In present work the coma of the axial image resulting from a surface tilt is analysed and used to determine the proper formulae for linear and angular centering error.

In Fig. 1c. a decentered lens is shown as a centered lens and an extra wedge with spherical surfaces. The justification of such an assumption is based on the optical effect a decentered lens has on an optical system which results in bending of the optical axis and introduction of coma aberration.

Coma (in angular measure) initiated by the wedge and computed in the image plane of the optical system behind the wedge is determined as

$$\Delta\alpha'_{k+1} = -3\Theta_k u^2 \frac{n^2-1}{2n} M \qquad (1)$$

where $\Delta\alpha'_{k+1}$ actually is the angle under which coma δW_k is viewed through the system behind the wedge.

$M = \frac{\Delta\alpha'_{k+1}}{\Delta\alpha'_k} = \frac{S'_k}{S_{k+1}}$ angular magnification of the optical system behind the wedge.

Then coma in the image plane of the surface "k" is

$$\Delta\alpha'_{k+1} S_{k+1} = \delta W_k = -3\Theta_k u^2 \frac{n^2-1}{2n} S'_k \qquad (2)$$

Assuming that angle Θ_k at the apex of the wedge is small and S'_k is relatively large we can state $S'_k = \frac{y_k}{u}$, then $\delta W_k = -3\Theta_k \frac{n^2-1}{2n} \frac{y_k^2}{S'_k}$ and for the image plane of the system containing number "p" of surfaces coma caused by decentration of the surface number "k" can be found as

$$\delta W'_k = \delta W_k m = -3\Theta_k \frac{n^2-1}{2n} \frac{y_k^2}{S'_k} m \qquad (3)$$

where $m = \frac{S'_{k+1}}{S_{k+1}} \cdots \frac{S'_p}{S_p}$ magnification of the optical system behind the wedge.

This formula can be used for the calculation of either coma or decentration of a particular surface depending on which parameters are known. To determine the permissible centering error of the surfaces of an optical system it seems reasonable to use the Rayleigh quarter-wave limit for image quality by assuming that coma caused by decentration shall not exceed the value $\Delta W'_k = \frac{\lambda}{2n \sin u}$ corresponding to OPD $= \frac{\lambda}{4}$.

Finally the following expressions indicate the linear and angular amount of centering error.

$$\Theta_k = -\frac{2}{3} \Delta W'_k \frac{n}{n^2-1} \frac{S'_k}{y_k^2 m} \qquad (4)$$

$$\Delta_k = \Theta_k R_k \qquad (5)$$

Utilizing these equations and ray tracing y'_k, S'_k data one can easily determine which surfaces of the optical system are more sensitive to decentration and therefore require higher accuracy centering.

PURPOSE AND APPLICATION OF METHODS FOR CONTROLLING CENTERING ERROR

Modern electro optical systems place demanding requirements on the control and measurement of centering error. The application of control and measurement methods of centering error will be divided into three categories: component fabrication, doublet assembly, and system assembly.

Component Fabrication

The first opportunity in the manufacturing process for the control of centering error occurs during the component centering operation. At this point, choosing the appropriate method and instrumentation requires an analysis of the specific optical requirements and the compatibility with the centering machinery to be used. Failure to control centering error at the component level can cause significant problems at higher levels of assembly.

Doublet Assembly

The doublet is the first level of assembly for many optical components and one that requires the control of centering error. The choice of an appropriate method and instrumentation requires an analysis of centering requirements, doublet and component configuration, and volume of doublets to be assembled. Again, failure to control centering error can cause significant problems at higher levels of assembly.

NOTE: One must review the centering specifications of the individual components to insure consistancy with the requirement of the doublet. In many cases centering error at the doublet level can be simplified and controlled more readily when the components are centered to tighten tolerances. (Lenses with very thin edges, doublets with critical central thickness tolerances, doublets where diameter is critical and individual components have identical diameter tolerance requirements should be reviewed carefully.)

System Assembly

System assembly can often require very demanding control of centering error especially when traditional lens/mount assemblies where centering is controlled by dimensional control of mating surfaces have been replaced by assemblies requiring centering at the assembly level. Modern optical systems and the hostile environments in which they must perform and often render tradtional assembly techniques unsuitable. Environmental requirements (temperature, vibration, shock), weight, cost and use of fragile infrared materials often require optical elements to be centered in assembly and potted in place. Instances also occur where elements must be completely suspended in potting compound which requires not only lateral centering of the element to the mechanical axis of the mount but the control of position and tilt to a plane perpendicular to the mechanical axis. Again the method and instrumentation must be selected on the basis of tolerance and sensitivity requirements, volume, and versitility.

The control of centering error wherever possible during fabrication and assembly will minimize the possibility of a decentration induced performance degredation at high levels of assembly and maximize product consistency, maintainability while minimizing costly rework and troubleshooting.

METHODS FOR CONTROLLING CENTERING ERROR

Because of the dual definition of the Optical Axis (OA), there are two different concepts on which the various methods for the measurement of centering error are based.

Concept A - Determines the displacement of the curvature centers of the lens surfaces by the use of reflected light.

Concept B - Determines the displacement of the principal points of the optical system by the use of transmitted light.

The methods utilizing Concept A are usually more accurate and would typically be applied in the assembly of optical elements with stringent tolerances for decentration. While more accurate, these methods are more complex and require more complex instrumentation and calibration. On the other hand, they supply more information (i.e. which element of a multiple element system is causing the system centering error.

Most of the traditional methods for the measurement and control of centering error are based on Concept B. They are typically simple and ideal for production applications where tolerances are not critical.

The following descriptions of traditional and unique methods for the measurement and control of centering error utilize the concepts described above.

A.1.1 Method Utilizing Laser and Telescope

The method can be applied to control centering error of components with anti-reflection coatings in assembly.The Laser is used as a high radiance source. The image reflected from the surface of the lens under test is observed through an alignment telescope. The displacement of the image compared with the reticle of the telescope determines the centering error of the surface. Two rotatable polarizers are intended for the control of irradiance to protect the observer's eyes from injury.

A.1.2 Method Using Reflected Light

The idea of this method is to use the reticle which can be positioned at any place between two lenses in the projection section of instrument. The image of the reticle reflected from one of the surfaces of the elements being cemented is observed through the beamsplitter and microscope which has an angular spaced reticle and focusing mechanism.

A.1.3-A.1.7, Autocollimation With Different Optical Arrangements.

A.1.3 With the Sliding Objective

The autocollimation image of the crosshair projected at the center of curvature of the external surface of the lens under test, is viewed through the eyepiece (or microscope) with graduated reticle.

This image can be found by sliding the objective or the entire instrument along the optical axis.

The total image run-out as the lens is rotated represents the centering error of of the upper lens surface.

A.1.4 With Interchangeable Objectives

Additional set of interchangeable objectives is provided to broaden the range of measurement. In this schematic the sliding objective is in fixed position and change of magnification in each interchangeable objective can be obtained by moving one of its components along OA.

A.1.5 With Divided Objective

Divided objective is added to A.1.3. schematic to provide observer with opportunity to view the autocollimation images from two lens surfaces at the same time. The two halves of the front objective are independently movable along OA of the instrument. Therefore, the image of the crosshair can be projected into the centers of curvature of the surfaces of the lens under test.

A.1.6 With the Hole in External Objective

The objective with hole (called external objective) is added to A.1.3 schematic to provide in combination with sliding objective the autocollimation from two surfaces at the same time. If used in doublets cementing it provides optical monitoring of assembly process without rotation of the elements being cemented.

To obtain autocollimation images each objective can be independently focused by sliding it along OA.

A.1.7 Two Microscopes with Divided Objective

Two autocollimation microscopes based on the schematic A.1.5. can be utilized to control centering error in assembly of complex optical components. By positioning two instruments on each side of the lens under test one can control up to four surfaces at one time, providing the microscopes OAs are initially aligned with MA of lens mount.

A.1.8 Photo-Electric Method

The centering process is conducted by non-contact photo-electric error detectors and the centering error is measured using precision electro-mechanical trans-ducers contacting the outside diameter of the lens.

The lens under test forms two images of a collimated pinhole: one by reflection at the upper surface of the lens, and one by transmission through the lens. Each of these images is focused upon the position-sensitive photo cell by means of additional optics. The output voltages from each photo cell together with appropriate logic are used for centering process. These voltages become constant when the lens is centered and rotated.

B.1.1 - B.1.4 Traditional Methods Utilizing Collimated Light

B.1.1 Using Collimator and Microscope

The image of the collimator crosshair formed by the lens under test is observed through the microscope objective and viewing unit that together serve as a microscope. If the principal point of the lens does not coincide with its MA, the image of the collimator reticle pattern will revolve in a circle in the microscope field of view when the lens is rotated. A graduted reticle is used to measure the displacement of the principal point. For focusing, the microscope has a longitudinal adjustment.

B.1.2 Large Focal Length Microscope

The microscope has an objective with a focusing component which can combine the objective plane of the microscope with the image plane of collimator crosshair formed by the lens under test.

B.1.3 Using Collimator and Telescope

The lens under test serves as an objective and with a viewing unit forms a telescope. For lenses with a long focal lengths an extra lens can be introduced. For focusing, the viewing unit shall have longitudinal adjustment. The placement of a calibrated target in the focal plane of the collimator provided the constant angular spacing in the target pattern in the telescope focal plane regardless of the lens under test magnification.

B.1.4 Method Using Autocollimator and Mirror

The crosshair of the autocollimation eyepiece is projected to infinity through the lens under test, extra lens and objective. The two last lenses can be moved along the optical axis to create collimated light at the mirror surface. The reflected image is used for measurement of the centering error of the lens under test while it is rotated.

B.1.5. Telescope Method

The objective of the projection optical system forms the image of the crosshair in the focal plane of the lens which is being tested. This image can be observed through the telescope. The focusing range of the objective in the reticle projection optical system allows the measurement of centering error of negative and positive lenses with large focal lengths.

B.1.6 Laser Method

A narrow, low power laser beam can be used to control centering error of optical systems by measurement of the deviation of the beam transmitted through the optical system. The beam deviation is observed on the screen with the set of circles (graduated in arc minutes) placed behind the optical system under test.

To provide higher accuracy of measurement the system of mirrors for optical leverage is positioned between the system under test and the screen.

SUMMARY

The methods for controlling centering error described in this paper are not meant to be all inclusive. They are presented to identify possible methods from which to choose for a given application.

Once an application is identified (parameters and requirements defined), the methods must be reviewed and an appropriate method chosen. The mathematics associated with the chosen method must be performed to determine the parameters of the instrumentation. Due to the expense of design, fabrication and purchasing of instrumentation, one must analyze the trade-offs in instrumentation selection. Volume of work to be done, single purpose vs. versatile, accuracy required, set-up required, calibration ease, etc., must be evaluated to insure the proper method and instrumentation are chosen.

Hybrids of methods presented, the use of video displays, computerized calibration and display, etc., are alternatives and expansions upon the presented methods that have not been discussed, but remain as options in selecting a method for a particular application.

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TABLE 1

PARAMETERS TO BE MEASURED	PARAMETER TO BE DETERMINED	BASIC FORMULA FOR CALCULATION	METHOD OF MEASUREMENT
α -Angular image displacement	α -Angular image displacement	-	Control in Transmitted Light
t_{max} -Max edge thickness t_{min} -Min edge thickness D -¶ Outside diameter	σ -Wedge angle of element	$\sigma \approx \frac{t_{max} - t_{min}}{D}$	Mechanical Measurement
σ -Wedge angle of element n -Refractive index	α -Angular image displacement	$\alpha = (n - 1)\sigma$	Mechanical Measurement
e -Lateral image displacement f' -Focal length of element	α -Angular image displacement	$\alpha = \frac{e}{f'}$	Control in transmitted light
R_1, R_2-Radii of curvatures of element spherical surfaces d -Axial thickness of element Δ_1, Δ_2-Lateral displacements of centers of curvature	Δ_0 -Lateral displacement of nodal point of the element Θ_0 -Angular tilt of optical axis of the element	$\Delta_0 \approx \frac{\Delta_2 R_1 - \Delta_1 R_2}{R_1 - R_2 - d}$ $\Theta_0 \approx \frac{\Delta_2 + \Delta_1}{R_1 - R_2 - d}$	Control in transmitted or reflected light Control in transmitted or reflected light
Δ_1 -Lateral displacement of center of curvature of the surface R_1 -Radius of curvature of spherical surface	Θ_1 -Angular tilt of spherical surface	$\Theta_1 = \frac{\Delta_1}{R_1}$	Control in reflected light

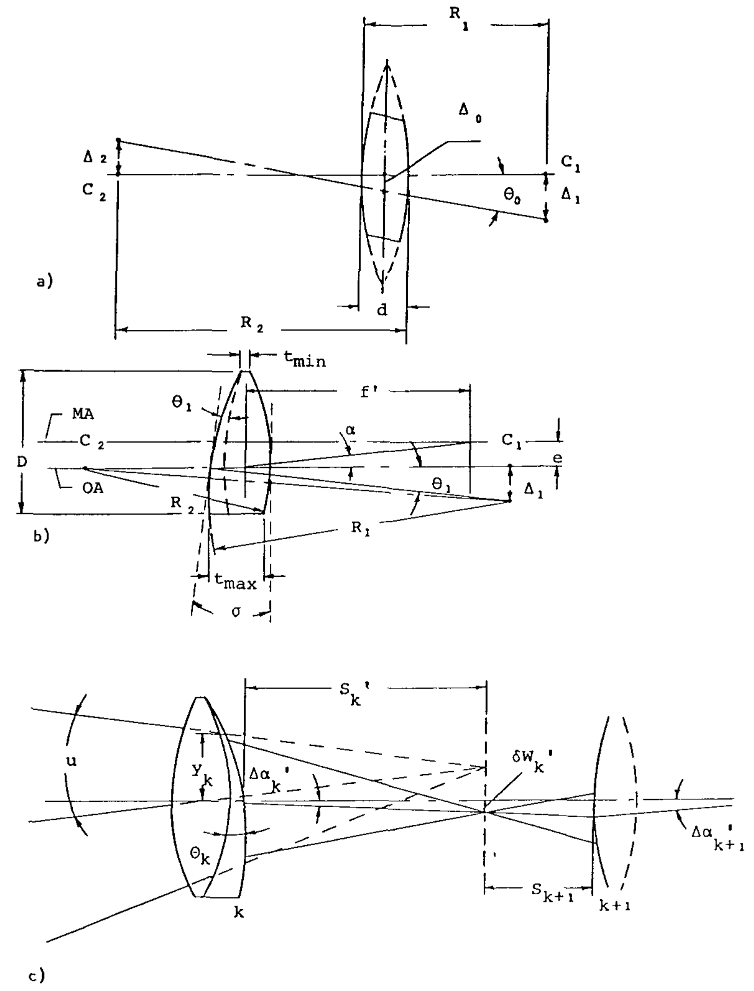
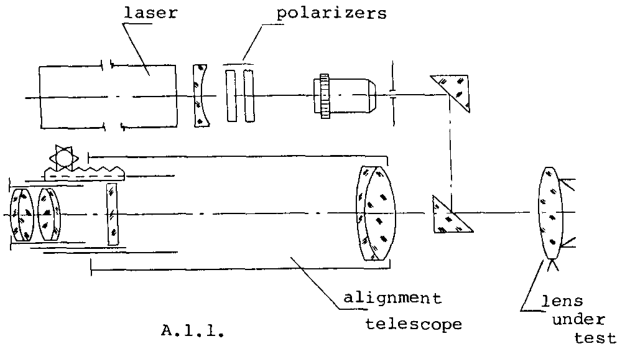


Fig. 1



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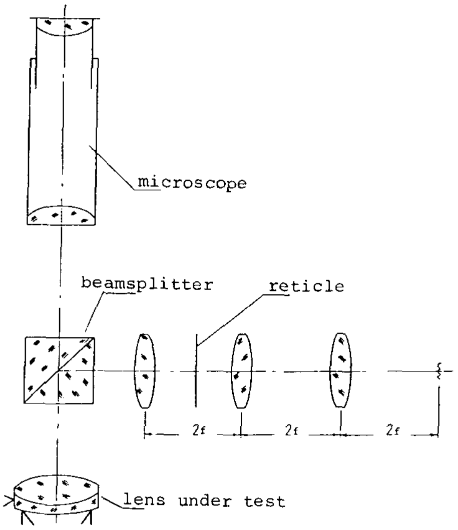

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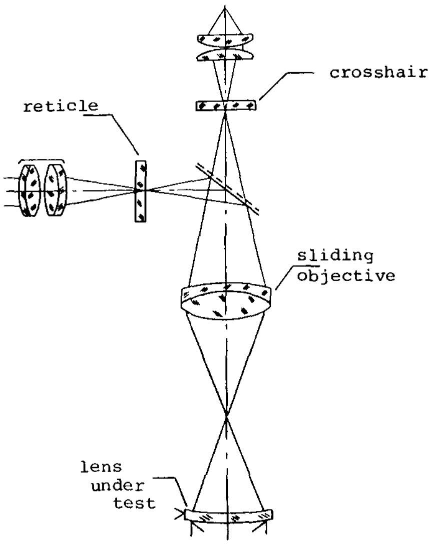

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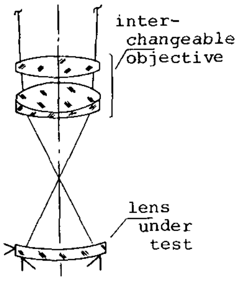

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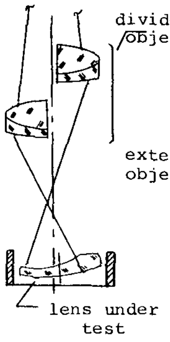

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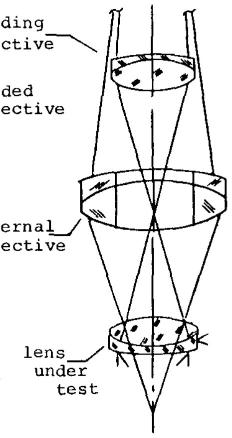

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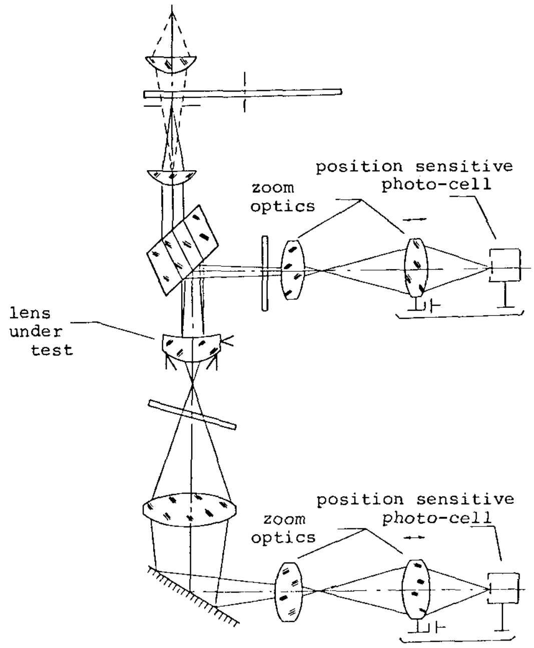

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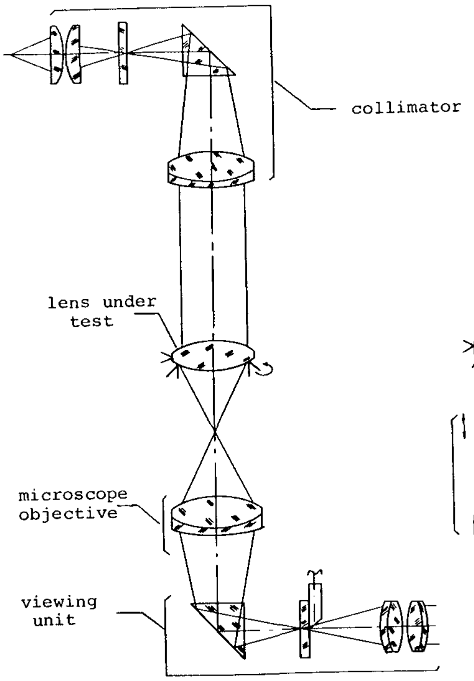

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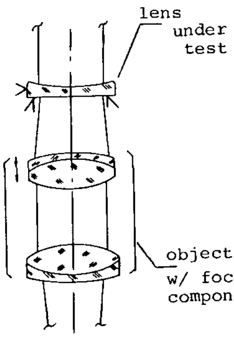

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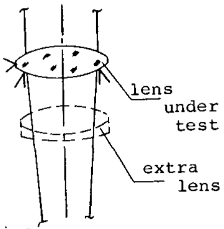

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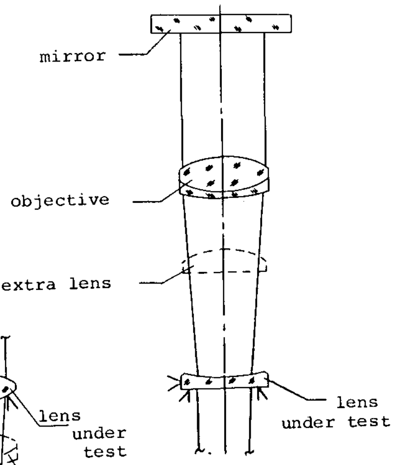

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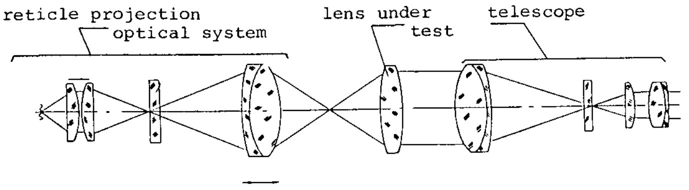

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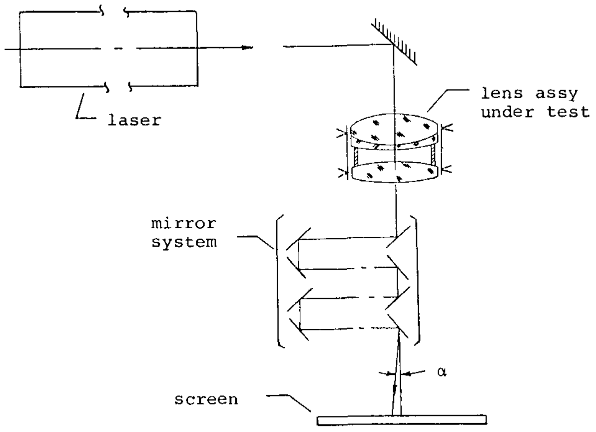

B.1.6.

TABLE 2

CON-CEPT	NAME OF THE METHOD	METHOD APPLICATION				BASIC FORMULA	FOCUS RANGE	ACCURACY	ADVANTAGES	DISADVANTAGES
		FAB	DOUB.CEM.	COMP.ASSY	TEST					
A.1 1	Utilizing Laser & Telescope	XX	X	X	X	Direct Reading	250 mm to ∞	30 to 100 µm	Control of elements with anti-reflection coatings	Magnification of telescope varies while it is scanning its focal range
A 1.2	Using reflected Light	X	XX	X	X	Direct Reading	0-70mm	3 to 10 µm or 5 to 1' arc	Increase accuracy by change in microscope magnification	Focus Range is limited by microscope travel
A 1.3	With Sliding Objective	XX	XX	X	X	$\Delta_1 = \frac{cq}{2M}$	- ∞ to 50mm 100mm to + ∞	3 to 250 µm	Practically unlimited range of focus Control of compound systems	Magnitude of reticle division depends on position of sliding objective along OA
A 1 4	With interchangeable objectives	XX	X	X	X	$\Theta_1 = \frac{c}{2MR} q$ $\Delta_1 = \Theta_1 R$	- ∞ to -10mm 50mm to ∞	.5-1 arc min 3 to 300 µm	Set of objectives provides wide range of measurement	Requires calculation of centers of curvature positions for correct choice of objective
A.1 5	With divided objective	XX	X	XX	X	$\Delta_1 = \frac{c}{4M} q$	- ∞ to -10mm 30mm to ∞	.3 to 250 µm	Control of compound systems, wide range of focus	Variable magnitude of reticle division
A 1.6	With an opening in external objective	X	XX	X	X	$\Delta_1 = \frac{c}{2M} q$	same as A 1.3	3 to 250 µm	Doesn't require rotation of lens under test	Same as A.1.3
A 1.7	Using two microscopes with divided objectives		XX	X	X	$\Delta_1 = \frac{c}{2M} q$	Same as A.1 3	3 to 250 µm	Control of wedge of cement between lenses & centering error of lower lens	Same as A 1 3
A.1 8	Photo-electric method	XX			X	Direct Reading	± ∞	0 1 µm or 1 arc sec	Results of measurement do not depend on observer (good for automatic measurements)	Final accuracy depends on geometric errors of lens under test & centering fixture
B 1 1	Using collimator & microscope	XX	XX		X	$\Delta_0 = \frac{c}{2M} q$	0 to 300mm	5µto 10 µm or .5-1'arc	Traditional method	When used in assy., method cannot determine assy. with cement wedge.
B 1 2	Using collimator & large focal length microscope	XX	X		X	$\Delta_0 = \frac{f'_{foc}}{f'^2} cq$	0- to 600mm	5 to 50 µm	Examination of negative lenses	Variety of lenses to be checked is determined by the f'_{foc} of focusing component
B.1 3	Using collimator & telescope	XX	X		X	$\Theta_0 = \frac{cq}{f'_{col}}$	±150mm	5-1'arc	The angular spacing in target pattern will remain the same in telescope focal plane regardless of magnification of lens under test	Focus range is limited by lens under test travel
B 1 4	Using autocollimator & mirror	XX	X		X		± 120mm	5-1'arc	Twice the sensitivity of method B.1 3	Magnitude of reticle division is variable & depends on focal length of lens under test & extra objective
B 1 5	Telescope method	XX		X	X	$\Delta_0 = \frac{1}{2}\beta f'$	± 100mm	.5-1'arc	Control of centering error of negative and positive lenses with long focal length	Focus Range is limited by objective travel
B 1.6	Laser Method	X	X	XX	X	Direct Reading	± ∞	5-1'arc	Universal method, fast & accurate for production volumes	

NOTES:

c - number of reticle divisions in FOV of instrument

q - reticle increment

R - radius of curvature of surface under test

M - magnification of objective

f'_{foc} - EFL of focusing component

f'_o - EFL of main objective

f'_{col} - EFL of collimator objective

β - angular size of circle in which image revolves

f' - EFL of lens under test