Proc. of SPIE Vol. 0483, Optical Alignment II, ed. M.C. Ruda (Jan 1984) Copyright SPIE

Techniques for characterizing optical system fabrication

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Abstract

A theory has been developed for representing fabricated optical components by a set of easily identified local coordinate systems linked by physically relevant stationary pivot points. The use of stationary pivot modeling has many advantages when attempting to make performance predictions on complex optical systems during the fabrication and assembly process. In this paper, the basic techniques for modeling fabricated optical components by stationary pivots are developed and some applications discussed.

Introduction

There is a substantial difference between investigating and predicting the performance of an ideal "paper" optical design and that of an assembled optical system. The basic reason for this is that a paper optical design neglects the mechanical properties of the optical elements and their interactions with the mounting hardware. A fabricated lens may be thought of as a mechanical environment which orients a set of optical properties. Although all major optical design codes provide the degrees of freedom necessary to model assembled optical systems, they do not provide a user environment that is conducive to direct analysis. This situation severely limits the ability to provide computer-assisted analytical support during the fabrication, assembly, and testing of an optical system.

An assembled optical system may be characterized by four areas. The first two are optical elements and mechanical spacers. A spacer, by definition, is anything that separates two optical elements. These will be termed collectively optical components. The second two are the mechanical barrels and the optical tests used in assembling the system. These constrain the location of the optical components laterally and as such will be referred to as constraint spaces.

The purpose of this paper is to develop the properties of two of these areas and techniques for their characterization. In these developments a different philosophy has been pursued for constructing a working reference axis for defining the placement of the optical components. Rather than choosing a straight-line reference axis, a series of physically significant local coordinate systems are developed. These local coordinate systems are linked by a set of stationary pivot points whose position is defined by the basic element data. This provides a continuous model for an assembled optical system without resorting to a reference axis. This is important as there are very few cases where a true straight-line reference axis exists for any assembled optical system.

The goal of these developments is to provide a capability to accept, manufacture and test data from the optical shop and generate a meaningful vector set that reflects the true properties of the assembled optical system, in both static and dynamic environments. In establishing the various relevant coordinate systems a series of abbreviations will be defined. These are summarized in Table 1 for easy reference throughout the paper.

Local coordinate axes

To properly characterize an assembled set of fabricated optical components, it is necessary to define two sets of local coordinate axes, both of which are physically significant. These are the local optical axis and the local mechanical axis. Both are defined by basic physical operations that occur during the fabrication process. These will be introduced and discussed for optical elements and then extended to apply to spacers.

The local element optical axis (LEOA) is defined as the line that connects the two centers of curvature of an optical element. In the case where one surface is plano, the LEOA is the line through the remaining center of curvature that is normal to the plano surface. This axis is created when the two radii are placed on the element using a diamond generator. All of the optical properties of an element are rotationally symmetric about this axis. In the LEOA coordinate system, only errors in radii, thickness and index occur.

The local element mechanical axis (LEMA) is defined to be the central axis of the cylinder (or cone) which represents the outer envelope of the fabricated optical element. This axis is created by the edging operation which is typically the last glass removal operation vacuum chamber. Fields of view are chosen by a selection of optics that can be introduced into the line of sight and the resulting images are focused on the focal plane of a CID video camera.

All ten beams can be observed with one target plane imager. The Nova system beamlines enter the chamber in two groups of five. Each group of beams is included in a 100° cone with one cone of beams entering on the left in Fig. 4 and one group entering on the right. The target is introduced from the top of the chamber and the target plane imager is inserted on the axis of one of the cones of five beams. Therefore, five of the beams are observed in reflection from the ground glass reticle and five are observed in transmission. Using this viewing capability, a focal pattern is established by translating the target chamber focusing lenses.

A second viewing mode exists with the target plane imager. Figure 4 shows an adjustable mirror in the figure insert. All the beams can be reflected directly into the sensor by tipping the mirror and rotating the optical periscope. In this mode the beams can be viewed directly in near-field and far-field. This is useful for viewing alignment references in the beam, diagnosing beam quality, and making quantitative transmission measurements. At shot time the entire optical periscope is retracted about a meter and protected behind a closed vacuum valve.

Alignment of the Nova laser system is an exacting task. It is particularly complicated by the requirement to operate at harmonic wavelengths. Design of the subsystems described here owes a great deal to experience gained from engineering and operating previous large laser systems. We have developed sensors that not only satisfy the requirements but that accomplish this in a cost effective way as well.

Table 1. Summary of Abbreviations Established in the Text

LEOA	Local element optical axis	LSCA	Local surface coordinate axes
LEMA	Local element mechanical axis	LSP	Local surface plane
MCA	Mechanical clear aperture	LSXA	Local surface x axis
LSOA	Local Spacer optical axis	LSYA	Local surface y axis
LSMA	Local spacer mechanical axis	LSZA	Local surface z axis

on an element. The introduction of this second coordinate axis is the key to modeling the mechanical properties associated with a fabricated optical element.

It is important to realize the significance of the two choices that have been made for coordinate axes. In the manufacture of any optical element there are only two operations that define the geometry of the element. These are:

(1) The generation of the radius of curvature on each surface with the simultaneous establishment of the thickness of the element.

(2) The edging operation to provide a well defined mechanical aperture for assembly.
The local coordinate axes that have been selected, LEOA and LEMA, are uniquely defined by these two operations. These axes are an inherent property of the element. In a perfect optical element the LEOA and LEMA are coincident.

Optical element units

A drawing of an optical element with arbitrary fabrication errors can be constructed (Figure 1) as follows:

(1) Draw a line representing the LEOA axis;

(2) Draw a line representing the LEMA axis and the accompanying cylinder boundaries that represent the generated mechanical clear aperture (MCA);

(3) With a compass, draw surface one with its center of curvature on the LEOA axis and limited to lie within the MCA boundaries;

(4) Draw surface two with its center of curvature on the LEOA axis and lying within the MCA.

To simplify all of the drawings, the LEOA and LEMA axes are shown to be coplanar and to intersect. The developments to follow, however, are not dependent on either of these conditions.

The element in Figure 1 may be separated in four distinct optical units: a spherical refracting cap with center c_1, a tilted plane parallel block, an oriented wedge, and a second spherical refracting cap with center c_2 as in Figure 2. They represent the only fundamental units required to form a complete theory of optical systems with spherical refracting surfaces. Each unit is characterized by a parameter set which will now be developed.

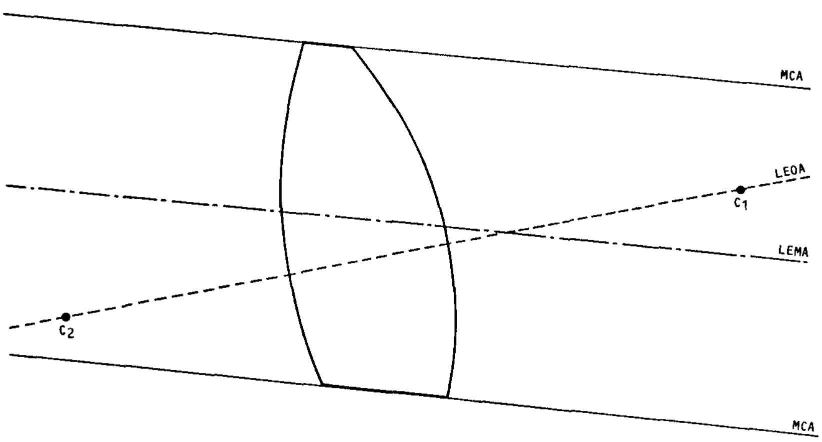

Figure 1. Local axes for a fabricated optical component. The LEOA (Local Element Optical Axis) defines the axis of symmetry for the optical properties. The LEMA (Local Element Mechanical Axis), centered in the cylinder defined by the MCA (Mechanical Clear Aperture), defines the axis of symmetry for the mechanical properties.

Parameter sets

The spherical refracting caps of an optical element are defined by the intersection of a sphere with a cylinder (or cone). The resulting plane of intersection is the local surface plane (LSP). Here, an orthogonal set of axes--the local surface coordinate axes (LSCA)--are defined. The y and z axes, LSYA and LSZA, lie in the LSP plane. The origin of the LSCA system is the center of the circle, in the LSP plane, defined by the intersection of the sphere with the cylinder. For more general cases, the origin is taken as the centroid of the two-dimensional figure in the LSP plane that describes the intersection of the generated spherical surface with the surface created by the edging operation. The x-axis, LXSA, is normal to the LSP plane and passes through the origin. These axes are shown in Figure 3.

The LSCA coordinate system associated with each optical surface represents the fundamental unit of an optical system. Any assembled optical system is simply a conglomeration of LSCA systems. By beginning with this basic unit, an exceptionally dynamic environment develops for emulating the fabrication and assembly process as it evolves from the paper design.

A spherical refracting cap is represented in the LSCA coordinate system, in the simplest case, by three values, two of which are independent:

r The radius of the spherical surface

ρ The radius of the circle defined by the intersection of the generated spherical surface with the cylinder defined by the edging operation measured in the LSP plane

δx The distance between the LSP plane and the spherical surface measured along the LSXA axis

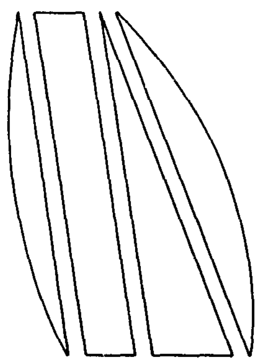

Figure 2. The basic optical units of a fabricated optical component. Any fabricated component can be represented by a pair of spherical refracting caps, a tipped parallel plate and a wedge.

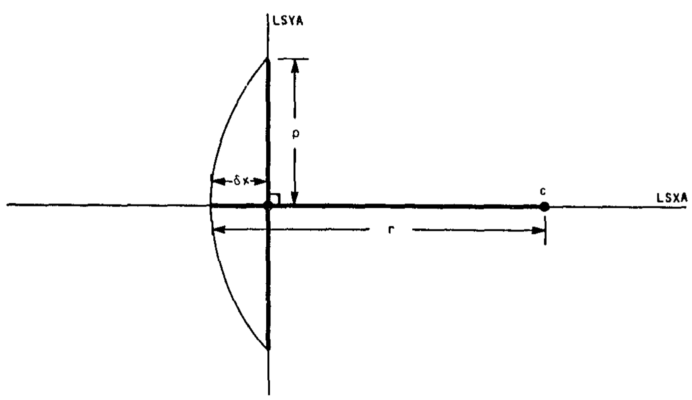

Figure 3. The LSCA (Local Surface Coordinate Axes). The basic building block for representing fabricated optical components. Any unconstrained optical system can be modeled by a series of LSCAs linked to each other by well defined (and easily identified) stationary pivot points.

These parameters are related through the sag equation for spherical surfaces

$$\delta x = \frac{\rho^2/r}{1 + \sqrt{1 + (\rho^2/r^2)}} \tag{1}$$

This parameter set is illustrated in Figure 3. More generally, the intersection of the spherical surface with the edging envelope will deviate from a circle as a function of azimuth in the LSP plane. In these cases, ρ is replaced by $\bar{\rho}$, which is the average value of the function $\rho(\phi)$, where ϕ is the azimuth angle.

An optical element contains two LSCA coordinate systems. Each LSCA system is characterized by a radius r and an aperture ρ. The linking of two systems may be specified by three parameters:

t_ρ The distance between the origins of the two LSCA systems.

θ_t The angle between the line that connects the origins of the two LSCA systems and the LSXA axis for the first surface (this represents the tilt of the plane parallel block unit).

θ_w The angle between the LSP planes associated with each surface (this is the angle of the wedge unit).

These definitions continue to be valid in the general case where the LSXA axes of each surface are not coplanar and do not intersect. In these cases, θ_t and θ_w lie in different azimuthal planes. These parameters are illustrated in Figure 4.

Vector representation of an optical element

A fabricated optical element that contains compound angular errors in tilt and wedge is completely specified by a set of three vectors and three associated scalars. These are:

$(\vec{t}_p, \rho_{MCA})$ $\vec{t}_p$ is the vector between the origins of the LSCA coordinate systems of each surface. This vector always lies along the LEMA axis.
ρ_{MCA} is the mechanical clear aperture, measured normal to the LEMA axis, generated by the edging operation.

$(\vec{c}_1, r_1)$ $\vec{c}_1$ is the vector between the origin of the LSCA coordinate system and the center of curvature of surface 1. It defines the direction of the LSXA axis.
r_1 is the radius of surface 1.

$(\vec{c}_2, r_2)$ $\vec{c}_2$ is the vector between the origin of the LSCA coordinate system and the center of curvature of surface 2. It defines the direction of the LSXA axis.
r_2 is the radius of surface 2.

Figure 5 illustrates the vector representation of the element shown in Figure 2. Note that the vectors $\vec{c}_1$, $\vec{t}_p$, $\vec{c}_2$ need not be coplanar.

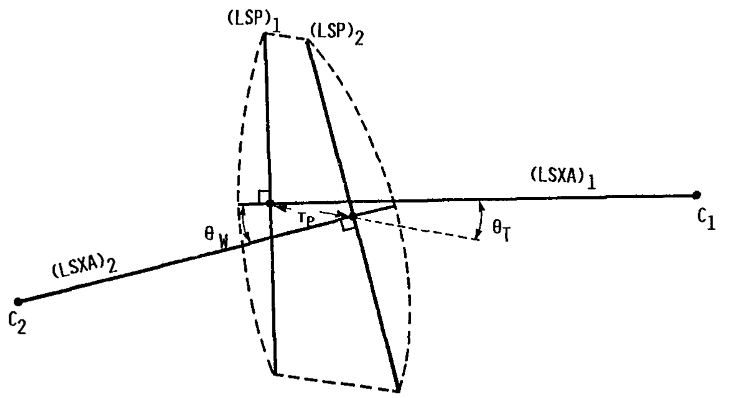

Figure 4. Representing a fabricated optical component with LSCAs. The conventional measures of error in radii, thickness and wedge are easily identified and applied through the use of stationary pivots.

The vector set shown in Figure 5 provides an excellent basis for modeling the mechanical properties associated with an optical element. A key feature of this set is that it provides an environment in which each of the characteristics errors of an optical element may be interpreted and applied independently. It allows for complete three-dimensional error modeling. It is physically relevant and interfaces into the conventional optical models. This generalization of the parameter set associated with optical elements is all that is required to incorporate the mechanical properties associated with optical elements. Its success is based on the fact that the origins of the LSCA systems are stationary pivot points. This property provides a means of linking the LEOA axis to the LEMA axis regardless of whether or not these two axes are coplanar or intersect. These pivot points completely decouple radius, thickness, tilt, and wedge errors, allowing them to be analyzed independently. This independence greatly enhances the ability to interpret the effect of fabrication and assembly errors on optical performance.

Spacers

A spacer separates two optical elements. For this discussion a ring spacer that contacts adjacent surfaces of two optical elements is used as a conceptual model. The results that are presented apply to a much more general class of spacers including, for example, lathe assemblies. As a model, an unconstrained "poker chip" assembly is used to represent the interface between the lenses and spacers. This consists of a vertical stack of alternating lens elements and ring spacers where all the element clear apertures are much larger than the spacer ring radius and no barrel is present.

In this configuration each spacer contacts an optical surface at three points, ideally located on a circle. The centroid of these points defines the origins of the two LSCA coordinate systems for the spacer. By associating the radius of curvature of the contacting optical surfaces with the spacers as well as the elements, the vector model illustrated in Figure 5 becomes equally valid for spacers and elements. A spacer is simply an optical element with an index of refraction of one. The vector model in Figure 5 then is a general representation of an optical component.

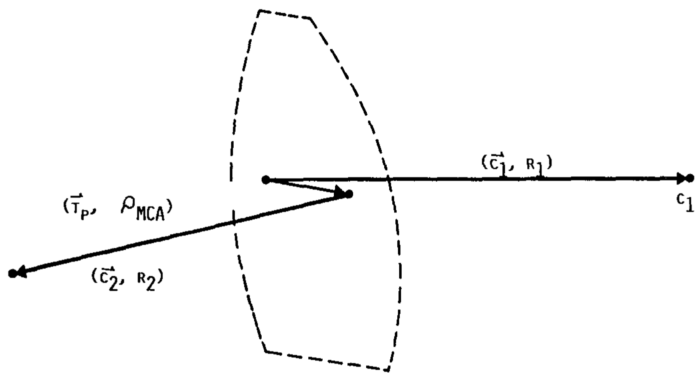

Figure 5. Vector representation of a fabricated optical component. A complete, decoupled, characterization of a fabricated optical component is provided by three vectors and three associated scalars. Two of the vectors ($\vec{c_1}$ and $\vec{c_2}$) connect the local surface planes (LSP) with the centers of curvature c_1 and c_2. And one ($\vec{t_p}$) connects the two local surface planes. The three associated scalars are the surface radii r_1 and r_2 and the mechanical clear aperture radius ρ_{MCA}.

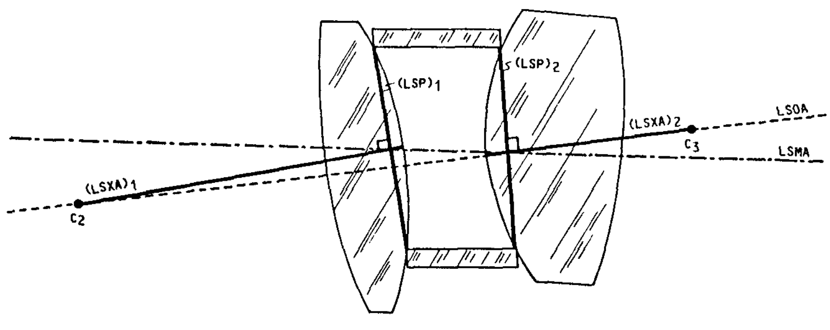

Figure 6. Representing a spacer as an optical component. By associating the radii of the contacting optical surfaces and considering the index to be 1.0, a spacer assumes all of the optical and mechanical properties of an optical element.

As with optical elements, the local spacer mechanical axis (LSMA) is defined to lie along along the line connecting the origins of the LSCA systems. Similarly, the local spacer optical axis (LSOA) is the line connecting the centers of curvature of the contacting optical surfaces. The optical properties of the spacer are rotationally symmetric about the LSOA axis. These are shown in Figure 6. It is important to note that the LSCA system for a spacer and the LSCA system for the contacting optical element are not coincident. However, they always have a common point at the center of curvature of the contacting optical surface. The center of curvature then is a stationary pivot point for the interface between elements and spacers.

This completes the first set of developments required to model assembled optical systems. The vector model described provides a means for representing fabricated optical components. It also may be used to model unconstrained optical assemblies. This represents a significant development in itself as it allows an optical designer to follow the evolution of an optical system from the paper design through sensitivity analysis and fabrication, two important areas. The model provides an unambiguous definition of the interpretation of errors in radius, thickness, tilt, and wedge and their interaction between surfaces and between components. It may be used in both deterministic and random modeling environments. It is a direct extension of the optical design parameter set and as such may be directly incorporated into the computer-assisted design environment.

Application to sensitivity analysis

One of the first tasks following the design of an optical system is the generation of a sensitivity table for use by other groups: mount designers, optical shop, metrology, etc. This is typically an ill-defined task, and techniques vary widely from designer to designer. At this stage of a project no information about mounting is available. A good modeling approach then is an unconstrained perturbation analysis. The linked vector models are superb for this application. They isolate the errors that are considered and provide an excellent efficient computing environment. By defining pivot points at the origins of the LSCA systems for fabrication errors in elements and spacers and at the centers of curvature for the interface between elements and spacers a very clear view of the modeling process is provided to the various groups who must interpret the data. The parameter decoupling provided by the pivot modeling makes implementation into an automatic computing environment a straightforward task.

Application to the fabrication process

In the fabrication of an optical element, there are four major operations, each of which generate characteristic errors. In the typical sequence, the first three operations determine the optical parameters defined by the ideal paper design. The last operation defines the mechanical environment, which will, in some cases, affect the final orientation of the optical properties in the assembly.

The first operation is the selection of the glass blank that will be used. This sets the index of refraction n. The second operation is the generation of the first radius of curvature. This operation must meet one condition-to generate the correct radius r_1. The third operation must meet two conditions: it must generate the correct radius r_2 and the correct element thickness t, measured along the line connecting c_1 and c_2 (the LEOA). In a radius generating operation, the controls over radius and thickness are independent. An error in this operation may result in an error in the specified value for r_2 or t, or both. At the completion of these operations the parameters associated with the ideal paper optical design r_1, r_2, t, n, have been set. These parameters are completely independent and are an inherent property of the element. Although they may be fine-tuned during grinding and polishing, large modifications require performing the previous operation again or obtaining a new blank and starting over.

The reason for emphasizing the unalterable nature of the previous three operation is that the effects of the fourth operation, edging, may be modified by the mount type and/or the assembly process. The edging operation performs two functions; it generates the mechanical clear aperture ρ_{MCA}, and it establishes the local element mechanical axis, LEMA. The LEMA will completely specify the orientation of the element in the assembly if the mount provides no degrees of freedom. This occurs in the ideal case of a zero clearance lathe assembly in a perfect barrel. In cases where the LEMA does not establish orientation, it continues to be relevant in interactions with the constraint spaces.

Once an optical element has been fabricated, a series of measurements is made. It is important that the values are properly applied to the modeling environment. Of particular interest is the relation between the measured thickness and the distance between the origins of the LSCA systems, t_ρ. The parameter set that is typically measured consists of two radii, thickness, outer diameter, wedge, wedge orientation, and index. These may be applied in the modeling environment as follows

Radii

The measured radius of a surface simply defines the length of the LSXA axis r, for the surface.

Outer diameter

The outer diameter measurement sets directly the value for the ρ_{MCA}, as it is measured normal to the LEMA axis in most cases. This value may be used to compute the clear aperture radii for each surface:

$$\rho_1 = \rho_{MCA}/\cos\theta_t$$
$$\rho_2 = \rho_{MCA}/\cos(\theta_t-\theta_w) \qquad (2)$$

once θ_t and θ_w are known. With r and ρ specified, the remaining parameter δx, may be computed using Equation 1. This specifies the LSCA representation of each surface separately.

Plane parallel plate tilt

Typically, the value for the tilt orientation of the plane parallel plate unit, θ_t is not measured. This oversight is not significant in most situations. However, in high-precision, close-clearance barrel assemblies or with radial edge mounted elements, this parameter must be known. It is just as relevant as the wedge angle, especially in the limiting cases of a zero clearance lathe assembly.

Wedge

Wedge measurements are made by studying thickness variations at a zone near the edge of a rotating element. The orientation of the maximum/minimum orientation is marked, and the difference in thickness divided by the zone diameter gives the wedge angle θ_w. This is directly the value used in the model.

Thickness

The convention for measuring the thickness t_m of an optical element is to choose the maximum (or minimum) value of a gauge measurement obtained when scanning about the vertex. In the presence of wedge, this value should be corrected to obtain the distance between the origins of the LSCA system t_p. If the element is resting on a ring mount on surface 1 and has a wedge θ_w, the measured value t_m will have as a primary error term $\delta_m\theta_w$ and

$$t_\rho \approx t_m - \delta x_1 - \delta x_2 - \delta_m\theta_w$$

where (3)

$$\delta_m = \frac{r_1 r_2}{r_1+r_2}$$

The symbol δ_m represents the displacement of the location of the maximum from the center of the element. There are some circumstances, usually in high precision environments, where care is taken to make the thickness measurement along the LEOA axis. In these cases the correction term may be ignored.

Conclusion

A consistent set of models has been developed that greatly extends the field of computer-assisted analysis of optical system performance. Although the models were presented for spherical refracting surfaces only, reflecting, aspheric, off-axis components, and systems without rotational symmetry are not excluded. The basis is very general in nature and may be applied to a variety of environments. Through the use of these models the optical designer may continue to provide support and insights into the behavior of the optical system well beyond the design phase of a project.

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