Optical modeling combining geometrical ray tracing and physical-optics software

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Abstract. The exercise given demonstrates the construction of a diffraction-limited transmission sphere for interferometry in a geometrical ray-tracing program, followed by an analysis of its performance in a physical-optics program. [S0091-3286(00)01507-5]

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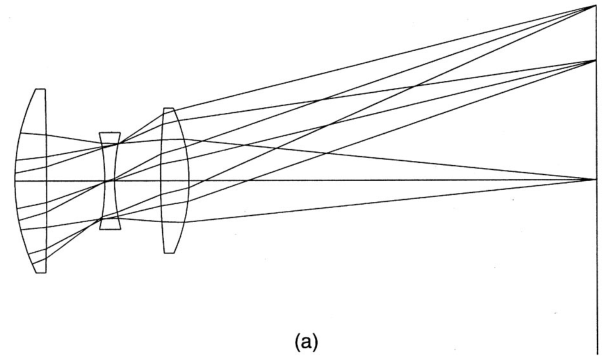
1 Introduction

The recognized forms in optical design, the triplet and double Gauss in particular, owe their existence to early photographic lens designers, and we are indebted to their efforts for the legacy. It is remarkable how often these forms hold up when applied to new problems, in spite of the computer power applied to the latter. When contemporary designers are faced with lens design problems, they often find it useful to start with known forms and move up in complexity only as necessary to solve a problem. For the optical designer, the first questions to ask regard the magnification, fields, conjugate distances, speed required, and so on. If at first glance the conditions are not too difficult, the first candidate to use as a reference design is the Cooke triplet,[1] the three-legged stool of optical design, simple and stable. Many variations of this nineteenth-century design can be found in the literature. But if the three-lens form is not up to the task, more complex forms are readily available. In fact, commercial optical design software packages include variations of the triplet, the double Gauss—the *planar*[2] in Zeiss terminology, and wide-angle lenses. They are included by software companies not just as examples of how lenses look and work in a software model, but to use as a starting point in problem solving.

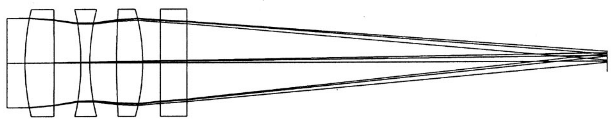
We use such a design, the Cooke triplet, in the construction of a transmission sphere for an interferometer and show how this modest form begins to solve a problem and then signals us when it is time for help. The first major departure for this form from its photographic roots to this new application is the requirement for correction of only a single wavelength, 0.6328 μm. So the glass selection requirements for polychromatic correction disappear. However, there are glass selection issues in transmission spheres. First and most important is the marketplace requirement of fused silica for the front element. All of the other elements contemplated can be a single material. Often this material is BK7, due to its low cost and good working properties, but for this problem we will choose LAF2 for its higher index. In ZEMAX®, the optical design software package used in the first part of this article, we will start by creating a copy of the Cooke triplet found in the sample folder and shown in Fig. 1(a).

After changing the design wavelengths from visible to monochromatic, we change the off-axis fields to very small departures from the optical axis, 0.3 and 0.7 deg. ZEMAX contains a keystroke function /P that, when used in the glass column of the Lens Data Editor, will allow the user to change one glass to another and keep the power constant. The original prescription used SK16 and F2, and we can change these glasses to LAF2 by typing LAF2/P. Much like using a close-up lens with photographic lens, we assume that we will need an additional element, and here we will use fused silica. From our perspective this is the last element of the system, but to the user it will be the first element of his transmission sphere. Next we arbitrarily move the stop to a small distance in front of the front element. The resulting lens appears in Fig. 1(b). Our starting point is an f/5 Cooke; our goal will be a much faster system, f/1.4. In light-gathering power this is an increase of approximately 35 times. It is this radical change in f number that is the principal issue in this example. To produce the final design for interferometer transmission we will use an entrance pupil of 20 mm, reduce the focal length in a series of steps, and then scale the entrance pupil diameter back up as performance improves. In the final design the entrance pupil will be 100 mm, corresponding to the beam diameter of commercially available interferometers.

Critical in the sphere's use is the relationship between the radius of curvature of the last surface and the working distance. They must be the same. That last surface will be uncoated and will be the reference; it should contain the focus of the sphere. We will force the radius of the surface and the back focus to be the same in the merit function of the design program. After several minutes of iterative optimization the code halts for some human intervention. The latter is a series of judgment calls. For example, we may walk the design up to a faster condition in steps, say four, at focal ratios 2.8, 2, 1.2, and finally 1.4. The initial Cooke design operated at f/5, but the reduction of fields, the change to a single wavelength, and the addition of fused-silica plate simplified the problem. Moving the design to a speed of f/2.8 is straightforward. The design rapidly improves but does not yet approach the diffraction limit. At f/2.8, with an entrance pupil of 20 mm, the most important



(a)

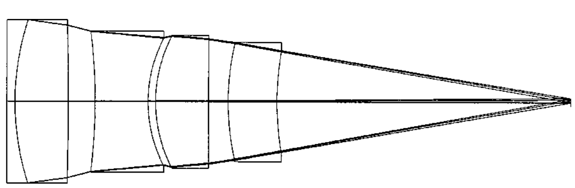


(b)

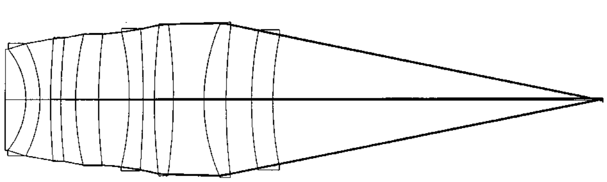
Fig. 1 50-mm f/5 Cooke triplet used as the starting point in the design (a) and modified (b) with reduced fields, monochromatic light, stop moved, and fused-silica plate added.

issue is the relative thickness of the elements. The lenses rapidly rose to the maximum allowed in the merit function. See Fig. 2(a). This was a clue that we needed to split elements, and at this point the global search algorithm was used to see if better results could be obtained. After an hour the form in Fig. 2(b) was chosen for further work. A distance of 375 mm was chosen as a challenging working distance for a f/1.4 Fizeau interferometer, and after an overnight run the design in Fig. 3 resulted.

The performance of the design, as shown in Figs. 4(a) and 4(b), reveals high theoretical performance in terms of MTF and spot size. Further work would be required to remove ghosts that will surely be present and to reduce the elements to a practical size. However, as an exercise in geometrical lens design a useful model has been produced



(a)



(b)

Fig. 2 (a) The f/2.8 form shows a tendency in the lens design program to want fatter elements. In (b) the elements have been split and begin to show new forms such that the beam path encounters negative powers early on.

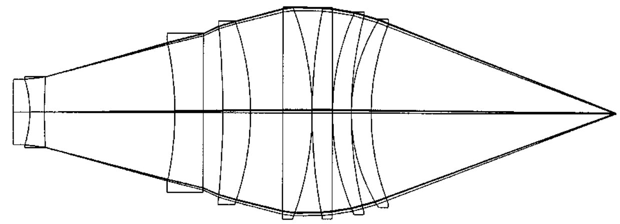


Fig. 3 Fizeau transmission sphere operating at f/1.4 with a distance to focus of 375 mm.

to demonstrate a handoff between a ray-tracing program and a physical-optics program.

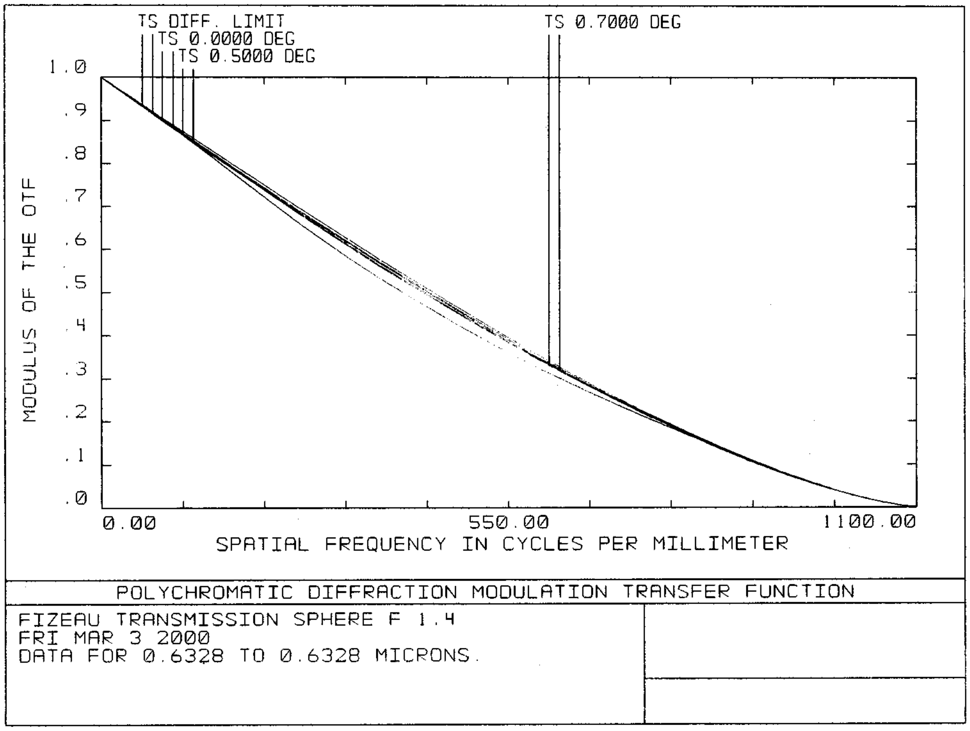
In the next section we will model the transmission sphere designed in ZEMAX with DIFFRACT™.

2 Modeling with DIFFRACT: Testing Optical Surfaces

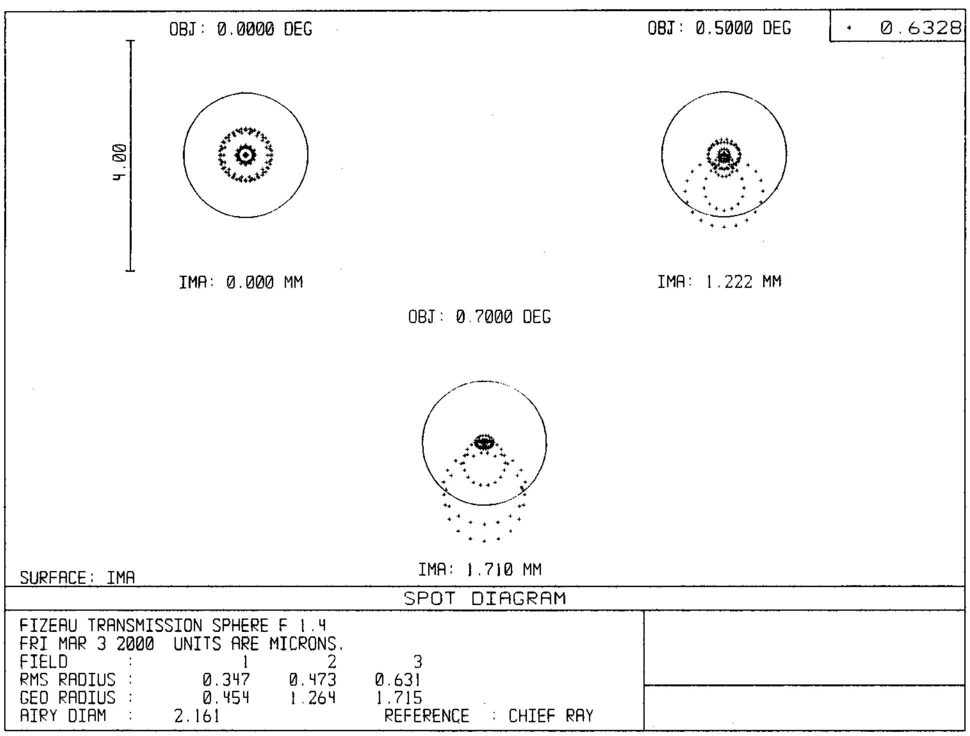
DIFFRACT is a commercial program developed for simulating optical systems consisting of a sequence of discrete elements, such as lenses, polarizers, waveplates, gratings, multilayer stacks, and so on. The program can handle uniform, Gaussian, and diode laser beams, as well as arbitrary wavefronts defined by the user. It allows wavefront propagation in Fresnel and Fraunhofer regimes, conversions back and forth between wavefronts and geometric-optical rays, and polarized ray tracing. Several different kinds of lenses (including graded-refractive-index lenses) can be placed in the optical path, as well as mirrors, prisms, waveplates, polarizers, birefringent crystals, optically active materials, optical-disk surfaces, diffraction gratings, multilayer stacks, Fabry-Perot etalons, phase/amplitude masks, photodetectors, and more. DIFFRACT has provisions for interferometry, Seidel and Zernike aberrations, coherent and incoherent imaging, etc., and can handle physical-optics problems as diverse as holography, the Talbot effect, internal and external conical refraction, various kinds of microscopy, evanescent coupling, and optical-disk readout.

DIFFRACT is designed in a modular fashion. The user first chooses an optical element from a list of available items, propagates the beam through that element, reorients the coordinate system of the emergent beam (if necessary), then proceeds to the next element, and continues in this fashion until a complete system is built up. The elements of DIFFRACT and the rules for their sequential placement in a system are fairly straightforward. What makes the program powerful is the variety of combinations made possible by these simple elements and their rules of operation in tandem. In a way, working with DIFFRACT is reminiscent of playing a game of chess, where the pieces are few in number and the rules of moving them on the board are easy to master. Yet, the number of possible games is infinite, and the richness and complexity of the resulting patterns is truly astonishing.

Many articles have been published on various aspects of DIFFRACT; in particular we refer the interested reader to the Engineering column in *Optics & Photonics News*, starting with the February 1997 issue. In the present article we will focus on a specific application of this program, in testing optical surfaces.



(a)



(b)

Fig. 4 An MTF plot (a) and spot diagram (b) showing high performance in an f/1.4 Fizeau transmission sphere.

The left-hand side of Fig. 5 shows the cross section of a transmission sphere designed for optical testing, detailed in Sec. 1. This lens, consisting of fourteen spherical surfaces, brings a coherent and collimated input beam into sharp, diffraction-limited focus at its front focal point *F*. The first thirteen surfaces of the transmission sphere are antireflection-coated, but the last surface, referred to as the reference surface, is bare. The reference surface thus reflects about 4% of the incident optical power towards the entrance pupil of the lens. Because the reference surface is

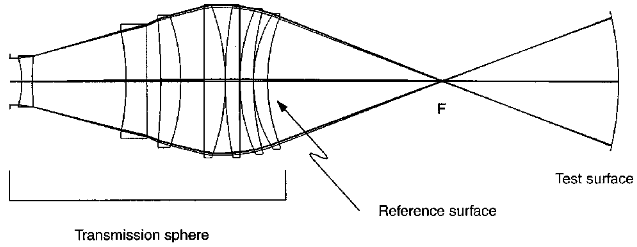


Fig. 5 A seven-element f/1.4 transmission sphere consisting of six elements of LaF2 and one element, containing the reference surface, of fused silica. The distance to the surface under test is twice the front focal length, which is 375 mm.

a perfectly spherical surface whose center of curvature (by design) coincides with F, the back-propagating reference beam appears to originate at the focus of the lens.[3,4] The net result is that the 4% of the light reflected from the reference surface returns perfectly collimated to the entrance pupil, capable of acting as a reference beam for interferometric measurements.

The test surface is typically placed in front of the transmission sphere,[5–7] as shown in Fig. 5. If the test surface happens to be perfectly spherical with a center of curvature also at F, then, in the absence of aberrations and mounting errors, the light reflected from the test surface returns to F and emerges as a perfectly collimated beam at the entrance pupil of the lens. Under these circumstances no interference fringes will be observed between the test beam and the reference beam. Any mounting errors or deviations from sphericity introduce phase variations across the test beam, which then result in interference fringes.

In Fig. 6 we present the fringe patterns observed for several placement errors of the spherical test surface shown in Fig. 5. A 20-μm defocus (i.e., longitudinal displacement along the optic axis Z) yields the circular fringes of Fig. 6(a), while a 50-μm lateral shift along the X axis yields the straight-line fringes of Fig. 6(b). Figure 6(c) shows the fringe pattern observed when the test mirror is tilted by 0.1 deg. The fringes in Fig. 6(d) correspond to 20 μm of defocus plus 0.1 deg of tilt, while those in Fig. 6(e) represent the combined effects of 20 μm of defocus, 0.1 deg of tilt, and 50 μm of lateral shift along the X axis.[1] For best fringe contrast the test surface should be uncoated and have more or less the same refractive index as the last element of the transmission sphere. The amplitudes of the test and reference beams thus become comparable, whereby fringe contrast is maximized.

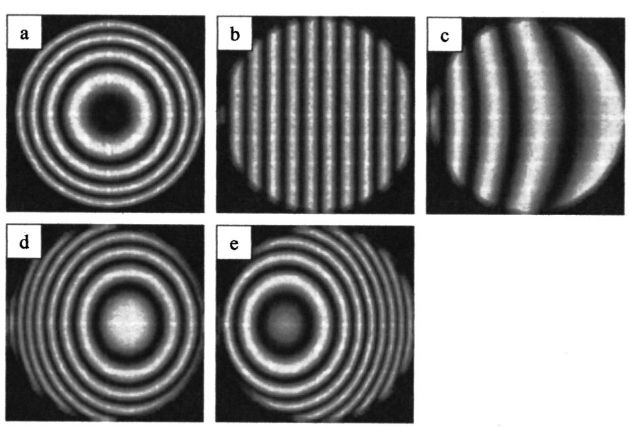


Fig. 6 Interferograms obtained with the system of Fig. 5 when the test item is an aberration-free, spherical, uncoated glass mirror having $R_c = -625$ mm. The fringe patterns shown are obtained with (a) 20 μm of defocus, (b) 50 μm of lateral shift, (c) 0.1 deg of tilt, (d) 20 μm of defocus plus 0.1 deg of tilt, (e) 20 μm of defocus, 0.1 deg of tilt, and 50 μm of lateral shift.

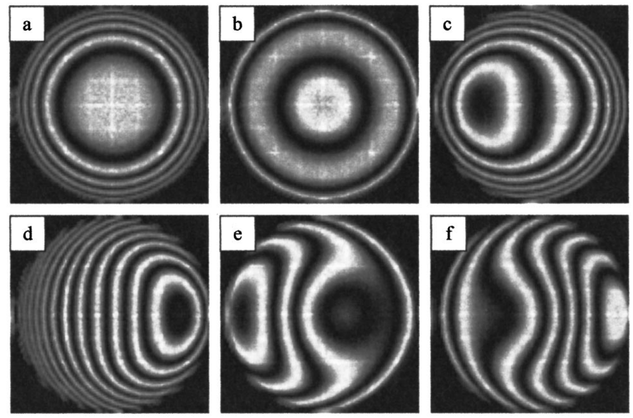


Fig. 7 Interferograms obtained with the system of Fig. 5 when the test item is a conic mirror of radius of curvature $R_c = -625$ mm and conic constant $k = 0.001$, located a distance of 1000 mm from the reference surface. (a) In the absence of positioning errors the only aberration contributing to the fringe pattern is $W_{040} = 5.77\lambda$ of spherical aberration. (b) Fringe pattern observed when the test surface is shifted out of focus by 20 μm. (c) Fringe pattern corresponding to 50 μm of lateral shift. (d) Fringe pattern corresponding to 0.1 deg of tilt. (e) The result of 20 μm of defocus plus 0.1 deg of tilt. (f) Fringe pattern observed when the positioning error consists of 20 μm of defocus, 0.1 deg of tilt, and 50 μm of lateral shift.

Another set of examples may be obtained for a conical test mirror (radius of curvature $R_c = -625$ mm, conic constant $k = 0.001$). Figure 7(a) shows the spherical aberrations of this conical mirror in the absence of defocus and other mounting errors. With 20 μm of defocus the fringes of Fig. 7(b) are obtained. Figure 7(c) corresponds to 50 μm of lateral shift in the X direction, while Fig. 7(d) represents the result of tilting the conical mirror by 0.1 deg. The fringes produced by the combination of 20 μm of defocus plus 0.1 deg of tilt are shown in Fig. 7(e), while those corresponding to 20 μm of defocus, 0.1 deg of tilt, and 50 μm of lateral shift along the X axis appear in Fig. 7(f).[1]

In all the above calculations the incident beam was first converted to a set of rays along the direction of the local Poynting vector. The rays were then traced through the lens, reflected at the reference surface, and traced back to the entrance pupil, at which point the emergent reference wavefront was reconstructed from the information available in the traced rays (namely, magnitude, phase, and polarization state). The same procedure was followed for the beam that exits the lens, reaches the test surface, and then returns through the lens to its entrance pupil. Finally, the test and reference wavefronts were combined interferometrically to create the fringe patterns.

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John Tesar: Biography appears with the paper ''Using small glass catalogs,'' in this issue.

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