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Some Applications of the Wave Front Shearing Interferometer

James B. Saunders

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This paper gives the results of several applications of the wave front shearing prism interferometer. The instrument is very compact and easy to apply. It is applied to the testing of chromatic aberration of simple and compound lenses; and to the testing of wave forms that characterize the monochromatic aberrations (spherical, coma, and astigmatism). Results are shown for several different type lenses. This interferometer is equally applicable to the testing of small lenses and large telescope objectives.

Key Words: Interferometer, testing of lenses, lens aberrations, aberrations, prism interferometer, chromatic aberration of lenses.

Previous applications of lens testing interferometers have been limited because of the difficulties associated with their use. The Twyman lens testing interferometer, for instance, requires several precision elements that have apertures equal to or exceeding that of the lens to be tested. The curvature of the convex reference mirror should match the back focus of the lens to a reasonable approximation, thus necessitating the use of a different reference mirror for lenses of different focal lengths. The relatively large separation of the elements invites vibrations and is vulnerable to temperature and atmospheric disturbances. Several modifications of the wave front shearing prism interferometer (abbreviated to WFSPI), that are small and relatively free from some of the above mentioned objections, have been described by Saunders [1].[1]

All the elements of the WFSPI are combined into one small compound prism. Since it operates at a point of convergence of the light beam (fig. 1) it can be very small. A small prism can be made so that imperfections in it are quite negligible. A prism 2.5 cm in length will accommodate any lens that provides a working distance (image point to back surface of lens) in excess of 1.7 cm if its aperture does not exceed this distance.

[1] Figures in brackets indicate the literature references at the end of this paper.

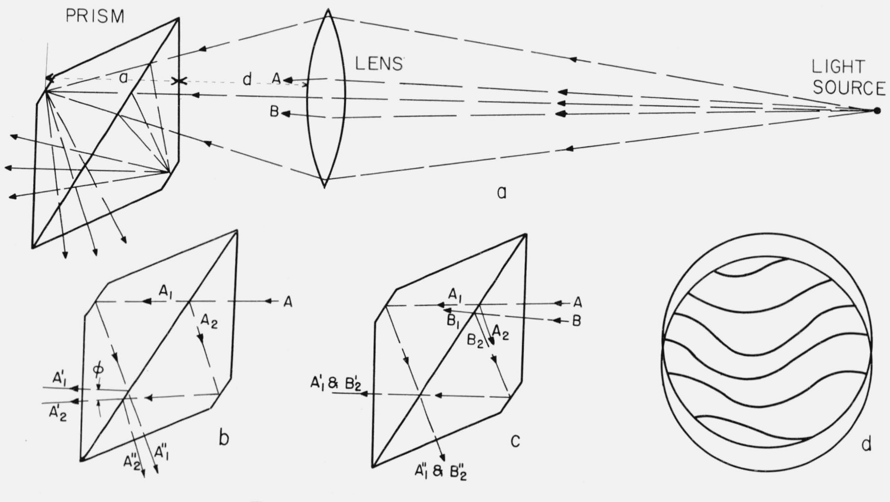


FIGURE 1. *Optics of the interferometer.*
Interference is obtained by the combination of one component, $A'_1(A''_1)$, of ray A with one component, $B'_2(B''_2)$, of ray B that leave the source in different directions.

The maximum separation of any two interfering beams is the lateral shear, S, which is usually a small fraction of the diameter of the lens being tested. Thus, the effects of temperature and atmospheric disturbances are easily suppressed.

Interference fringes may be obtained with white light. However, a narrow band interference filter is preferred for most wórk.

The WFSPI divides a wave front into two components, shears one component relative to the other, and recombines the two beams of light so as to produce interference in the overlapping area. Each ray that enters the prism is divided into four components, two emerging from one face and two from another, as shown in figure 1b. None of these four components are recombined and, therefore, do not interfere with each other. Interference is obtained by the combination of one component of each of two rays that leave the source in different directions (rays A and B) and are subsequently recombined by the prism, as shown in figure 1c. An observer's eye, receiving either pair of the recombined rays, sees interference fringes in whatever plane it is focused on. When the eye is focused on the lens, it sees fringes in the plane of the lens (fig. 1d).

A reference surface, such as is required in the Twyman interferometer, is not used since this interferometer yields results by comparing a wave front with an image of itself. The shape and width of the fringes are measures of the deviation of the original wave front from a sphere. A simple mathematical operation [2] has been described that permits a computation of the wave front from observations of a single fringe pattern.

The fringe configuration produced by a lens that is afflicted with chromatic aberration will change with change in the wavelength of the light source. Figure 2 shows a plot of image distance (focal length of the lens if the source is at infinity) versus wavelength for a single element lens that has a focal length of approximately 42 cm and an aperture of 9 cm. The slit of a prism monochromator was used, with a zirconium arc, as the light source. A small filament [3], mounted on a milling machine table and applied as described by Platzeck [4] and Gaviola, was also used to locate the

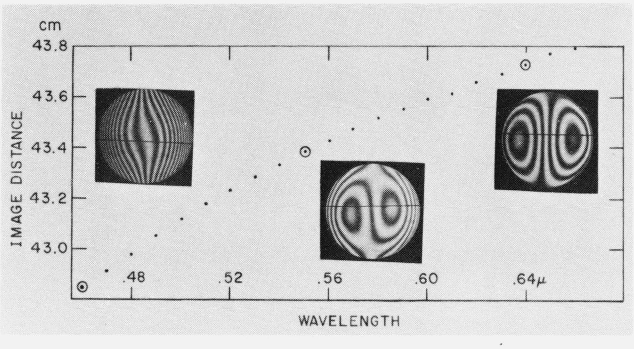


FIGURE 2. *Image distance versus wavelength.*
Plano-convex lens, focal length 42 cm, aperture 9 cm. The inserted photographs are the fringe patterns for the indicated wavelengths.

focal positions. The photographs inserted in figure 2 represent the fringe configurations for the three indicated wavelengths.

It can be shown by ray tracings that the image distance, q_ν, corresponding to any wavelength, λ_ν, is given by the formula

$$q_\nu = d + a n_\nu^{-1} - \lambda_\nu N_\nu d / \phi b n_\nu,$$

where d is the distance from the lens to the prism (fig. 1a); a is the distance from the entrance face of the prism to the point where the principal ray suffers total internal reflection; n_ν is the refractive index of the prism; N_ν and b are, respectively, the number of fringes and distance between the two reference points, P_1'' and P_2' (fig. 3). The sign of N_ν is chosen so that it increases when d is increased. The angle ϕ is the relative deviation, inside the prism, of any two components of an original ray that emerges from the same face of the prism (such as rays A_1' and A_2' of fig. 1b). The difference in focal distance, Δq_{12}, for any two wavelengths, λ_1 and λ_2, is given by

$$\Delta q_{12} = a(n_1^{-1} - n_2^{-1}) - d(\lambda_1 N_1 n_1^{-1} - \lambda_2 N_2 n_2^{-1})/\phi b.$$

A change of one in the value of N corresponds to approximately 0.5 mm in the focal distance for the prism used while obtaining the data for figure 2. This prism produces a shear of 0.006 radians.

When the chromatic aberration is small, a prism of high sensitivity (large shear angle) should be used. Figure 4 is a plot of image distance versus wavelength for an air spaced doublet (focal length = 463 mm, aperture = 64 mm). The shear is approximately 0.047 radians. One fringe corresponds to approximately 0.1 mm shift in the image point. The photographs from which the data were obtained are shown in figure 5.

The shape of a wave front, produced by a lens, is representative of all monochromatic aberrations of the lens in whatever manner it is used when producing this wave form. The interferometer of figure 1a produces a set of interference fringes that is characteristic of the shape of the wave front. The photograph shown in figure 6 depicts fringes produced by an f/2 camera lens with the source located 20 m from the lens. The curve marked f/2 in figure 7 is a plot of the deviations of the corresponding wave front from a best fitting reference sphere. It is apparent that if the between-the-lens diaphragm had been adjusted to an f/3 system the fringe pattern would have been reduced in area to that of the overlapping area of the two inserted circles in figure 6. When this reduced fringe pattern is analyzed by the method described in reference 2, the computed deviations from a best fitting sphere are found to be represented by curve f/3 in figure 7.

Since the curve that represents the deviation of the wave front from a best fitting sphere also represents the image forming characteristics of the lens, it is suggested that the quality of any lens may be represented by a relatively simple number. The manner of

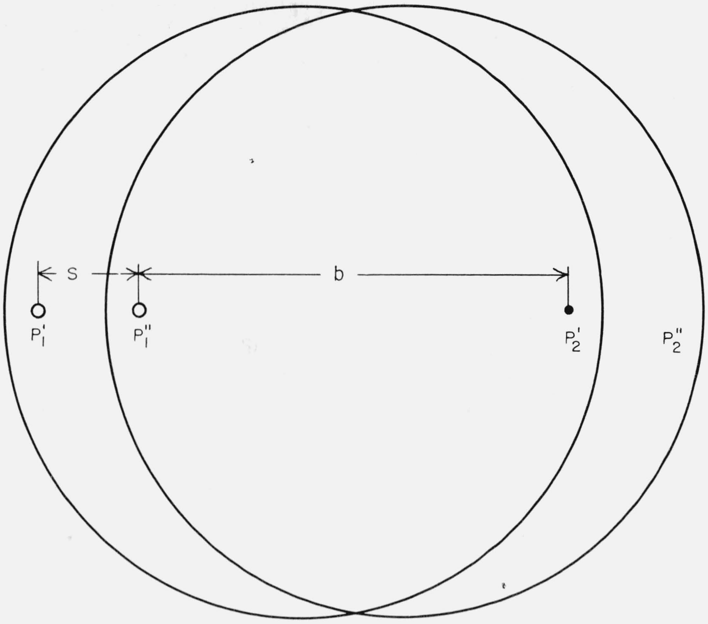


FIGURE 3. *Reference points P_1'' and P_2' are used for measuring change in focus.*

Points P_1' and P_1'' (P_2' and P_2'') are the two sheared images of a reference point $P_1(P_2)$. The separation of reference points P_1 and P_2 equals $(S+b)$, where S is the lateral shear of the beam in the plane of the lens. The reference points may be marked on the surface of the lens.

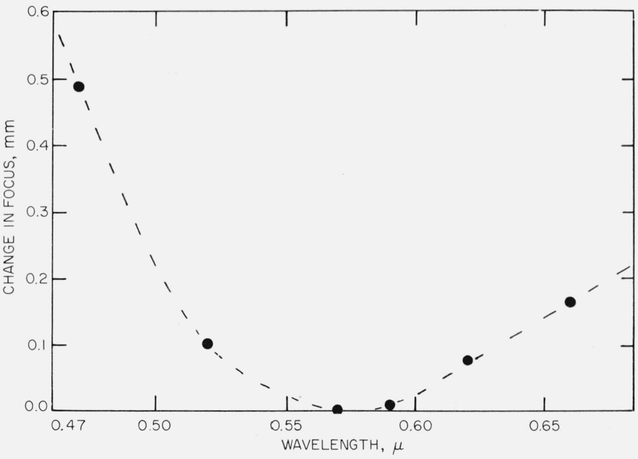


FIGURE 4. *Image distance versus wavelength for a 2-element achromatic lens.*

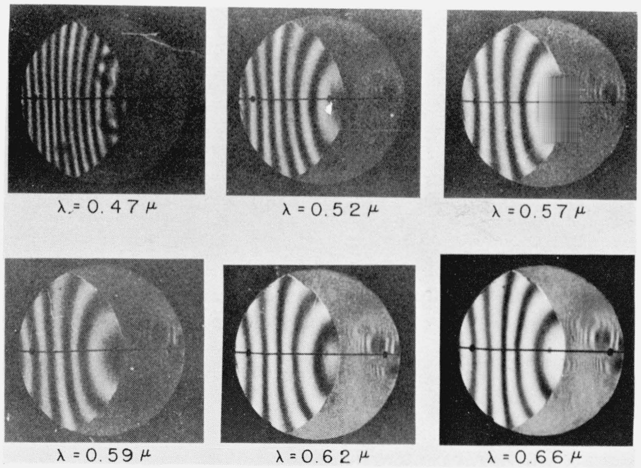


FIGURE 5. *Photograph of interference fringes for different wavelengths.*

selecting this number may be best decided later, but it appears that the weighted arithmetical mean deviation of the wave front from a statistically chosen best fitting sphere might represent the image forming characteristics of the lens. This number would vary with the position of the object, relative to the lens and its axis; however, so does the quality of the image. The weights should be chosen so as to give equal weight per unit area over the whole lens. The chosen number should also include other factors, such as aperture for instance, and might therefore be a compound number.

The weighted mean deviations of wave fronts are readily obtained from the corresponding fringe patterns produced by this interferometer. The weighted arithmetical mean deviation for curve f/2 in figure 7 is 2.1λ and for f/3 it is 0.1λ. The relative magnitude of these two numbers is believed to represent, to a close approximation, the corresponding relative image forming qualities.

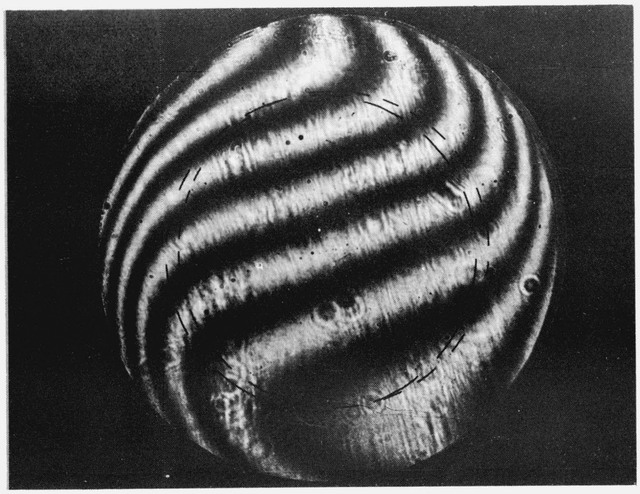


FIGURE 6. *Interference fringes in a f/2 camera lens.*
The inserted circles represent the edge of an iris diaphragm when adjusted to transmit an f/3 beam of light.

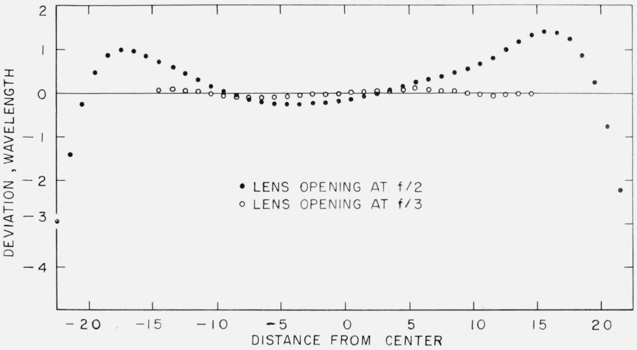
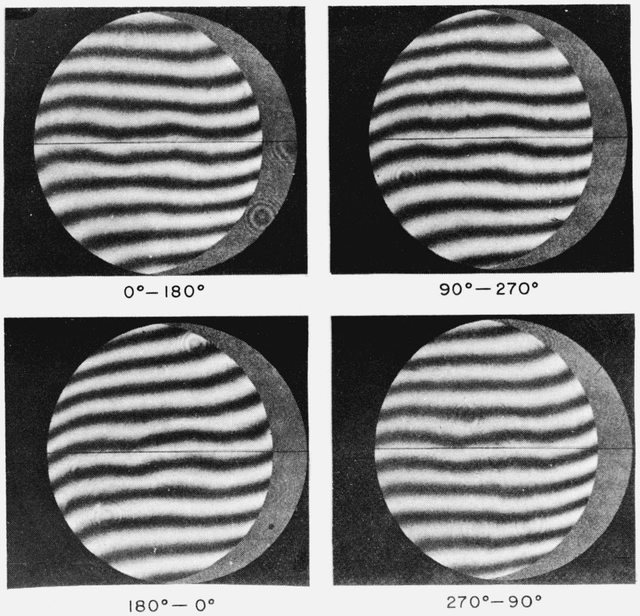


FIGURE 7. *Deviations of the wave front, produced by an f/2 lens when wide open and at f/3, from best fitting reference spheres.*



AERIAL CAMERA LENS FOCAL LENGTH 50" APERTURE 8"

FIGURE 8. *Interference fringes of a lens when sheared in opposite directions along two axes that are normal to each other.*

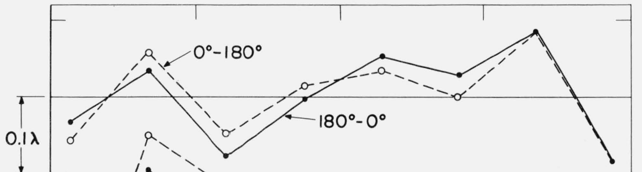


FIGURE 9. *Curves representing deviations of wave fronts from close fitting spheres.*
The direction of shear, relative to the initial position of the lens, was increased 45° between successive exposures for making the corresponding photographs.

The photographs of figure 8 are the fringes produced by an aerial camera lens of 8-in. aperture and 50-in. focal length that was designed and made at NBS. This lens has four air-spaced elements, and was designed to be used with another element—a concave lens near the focus—as an image flattener. The directions of shear are indicated for each photograph. Only four of the eight photographs that were made are shown here. Figure 9 shows the eight curves, representing the deviations from best fitting spheres along the indicated diameters. The eight equally spaced directions are indicated in the drawing. The abscissas of each of the four pairs of curves in figure 9 represent the same direction along the indicated diameter. The difference in wave front shape, for the several diameters, clearly indicates assymmetry in the wave front.

An astronomical objective may be tested in the laboratory by autocollimation if a sufficiently large optical flat is available. If such a flat is not available, it may be tested in the manner illustrated in figure 1a, by placing a small source at a considerable distance from the lens. Figure 10 shows the photographs of the fringes and figure 11 shows the corre-

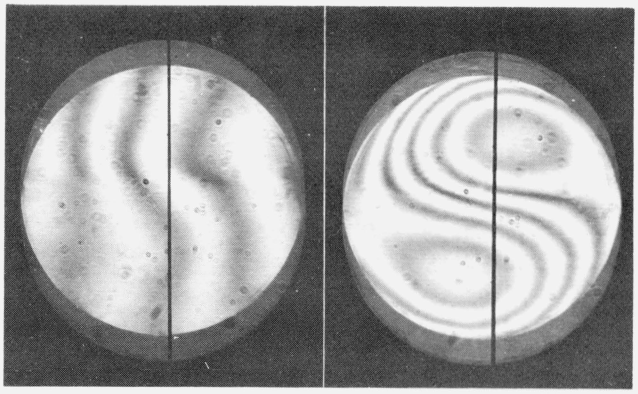


FIGURE 10. *Fringes produced by a lens when used properly,* a, *and when the axis is reversed,* b.

Aperture equals 12 in.; focal length equals 15 ft.; air spaced, two element objective.

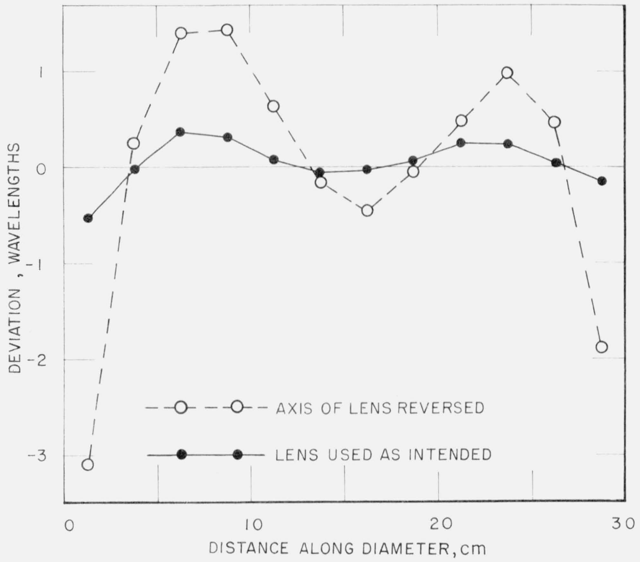


FIGURE 11. *Deviations of wave front versus distance along one diameter of an astronomical refractor.*

The two curves represent data computed from the two photographs of figure 10.

sponding deviation curves for a 12-in. aperture, 15-ft focal length refractor, when it is used as intended and when the axis is reversed.

Figure 12 shows interference fringes produced by the 32-in. aperture, 40-ft focal length reflecting telescope at the University of Virginia at Charlottesville, Va. The 12-sec exposure used for this photograph practically elimates the atmospheric effect by recording the average position of the fringes. The photograph is too recent to have permitted inclusion of the data analysis in this report.

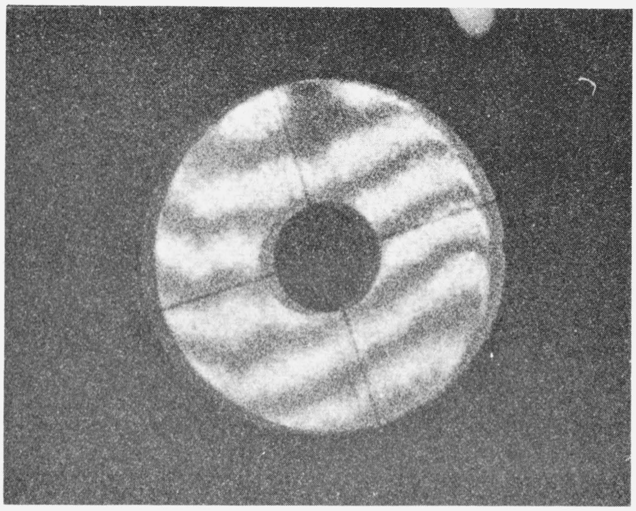


FIGURE 12. *First photograph of interference fringes produced by a star for testing an astronomical reflector.*

Aperture 32 in.; focal length equal 40 ft., Cassigrainian type telescope.

Test made with this interferometer show that it is as easy to assemble as a Foucault knife edge test. It gives quantitative results that are as accurate as other interferometer tests. The fringe pattern is practically independent of vibrations of the instrument. Technical personnel are not required for its use. It is relatively easy to make, the cost of material for it is negligible, and it is easy to reduce the effects of temperature gradients and atmospheric turbidity to negligible effects, and it is easy to reduce the effects of temperature gradients and atmospheric turbidity to negligible significance. Because of the simplicity of its operation, size, ruggedness and stability, this interferometer readily lends itself to combination with electronics for automatic testing for lenses.

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