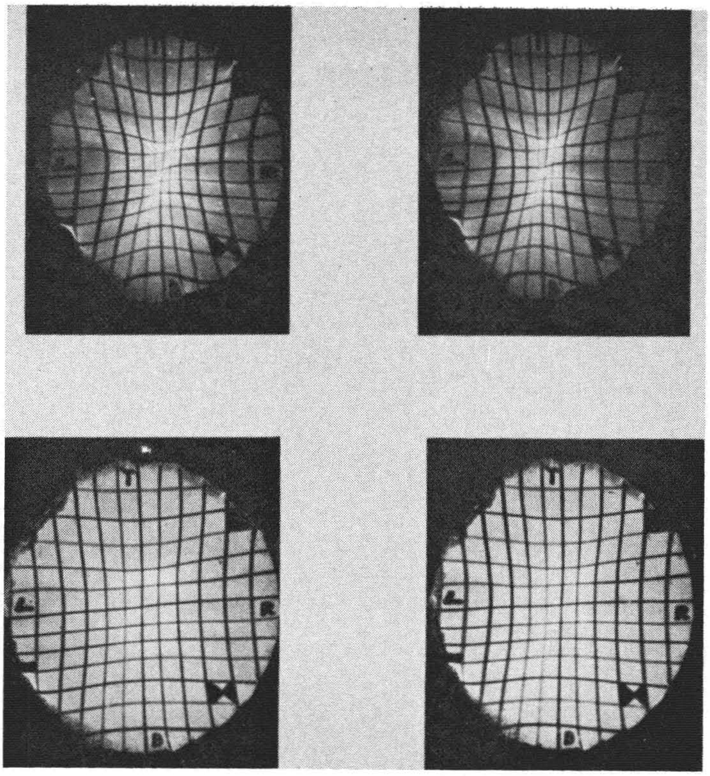


FRONTISPIECE. Stereo-Foucault results. See page 624.

R. J. ONDREJKA*
Itek Corporation
Lexington, Mass.

Optical Aberration in Stereo

The results of the Hartman Plate and the Foucault Knife-Edge tests are displayed stereoscopically and evaluated photogrammetrically.

INTRODUCTION

AN IDEAL photographic optical system should have the following characteristics:

- No chromatic aberration
- No spherical aberration
- No coma
- No astigmatism
- No distortion
- A perfectly flat field
- Rapidity of exposure (i.e., small F/ratio)
- Large depth of focus
- Large angular field of view.

It can be unconditionally stated that it is impossible to design a lens which will satisfy all of these conditions simultaneously; and indeed, it is difficult to correct more than a

---

* Presented at the Semi-Annual Convention of the American Society of Photogrammetry, Los Angeles, Calif., September 1966 under the title, "The Evaluation of Optical Aberrations with Stereophotogrammetric Techniques."

few of these aberrations at one time. In recent years the use of rare-earth element glass and the employment of aspheric surfaces in high quality air survey and reconnaissance lenses has brought us a long way in our attempts to achieve an ideal lens, but nevertheless, some of the above stated requirements, such as rapidity of exposure and large depth of focus, are physically opposed to one another.

When selecting a lens for mapping and other precise photogrammetric practices, we are all familiar with the requirements for the large angular field, elimination of distortion and rapidity of exposure (the latter being necessary to minimize image motion or eliminate the need for image motion compensation). We may approve the choice of a lens or lens design based primarily on these requirements and make the assumption that the remaining optical requirements have been optimized for our purpose and that the lens will provide us with a high quality final photographic image. These photogrammetric lens characteristics are quite firmly fixed at the completion of lens design and remain relatively unchanged after optical element fabrication and assembly (although poor optical assembly can result in serious tangential lens distortions). This is not true, however, for the requirement of eliminating or limiting lens aberrations. No matter how idealized the lens design may be, the care with which the lens elements are fabricated and the techniques and controls of the lens assembly are the primary factors contributing to a high quality lens or a lens which may, at its completion, be unacceptable for our purpose.

ABSTRACT: *Two techniques—the Hartmann Plate and Foucault Knife-Edge—are presented stereoscopically and evaluated photogrammetrically. In the Hartmann test for Spherical Aberration, the collimated light presented to the lens under test is divided into "bundles of rays" by passing it through a symmetrical array of holes in an opaque plate. The two photographs, viewed stereoscopically, visually display the different focus positions of rays passed through the various zones of the lens. In the Foucault Knife-Edge test, the pinhole and knife-edge stations are separated and interchanged, photographically recording the illumination front at each of the knife-edge locations. When the photographic images are viewed stereoscopically, a three-dimensional "impression" of the optical wave front can be observed.*

OPTICAL TEST AND EVALUATION

The key to the production of a lens which meets the design specifications, or to the production of an acceptable lens, is of course, precise testing. Testing begins with the glass material itself to determine the refractive index, homogeneity, and the presence of internal stresses and imperfections. Various tests are also performed during the grinding, rough polishing and edging of the lens elements; but, the testing of the *finished optical surfaces* or of the *finished lens assembly* indicates the acceptability of the optical component and the imaging quality of the system.

Various means exist for executing these tests and variations of these techniques are almost as numerous as the laboratories which perform the testing. The basic techniques may include:

- ★ Spherometers—usually applied to spherical surfaces over two inches in diameter. This is a direct physical measurement.
- ★ Illuminated Microscope—for testing of small concave or convex surfaces by through-focus observation.
- ★ Foucault Knife-Edge—for evaluating the surface of long radius concave elements.
- ★ Kohlrausch Illuminated Slits—for evaluating the surface of long radius convex elements.
- ★ Optical Flat Test Plate—evaluation by observing and measuring Newton rings.
- ★ Fitted Test Plate—evaluation of interference fringes between the element under test and a test element having the surface desired.
- ★ Interferometer Tests—visual evaluation of interference fringes produced by the coincidence of optical wave fronts.
- ★ Hartmann Test for Spherical Aberration—for the evaluation of aberrations in a lens element or assembly of elements by division of the optical path.

Almost all lens elements to be tested, whether the optical system be refractive or reflective, have a physical shape which is three-dimensional. It is also true that the aberrations being evaluated have effects which are physically three-dimensional, but it

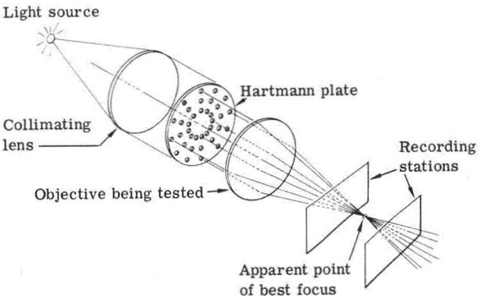


FIG. 1. Laboratory setup for the Hartmann test.

is interesting to note therefore, that all of the conventional testing techniques either visually or graphically present the test medium and results in a two-dimensional form. Where a three-dimensional analysis is needed, a series of two-dimensional observations (such as a through-focus run with a microscope) are required. In most instances these test results, which are abstract impressions of the phenomena which is occurring, require skilled specialists for their interpretation and evaluation. It would seem highly desirable that anyone understanding the relatively simple written definitions of the various aberrations being tested, might also be able to view and evaluate these effects under test in a natural, "real life" form. It would also seem desirable to employ the accuracies of stereophotogrammetric measurement and control of interpretation errors afforded by a true perspective of the aberration being tested.

STEREOPHOTOGRAMMETRIC OPTICAL TESTS

Only a few of the before mentioned tests and evaluations lend themselves to stereophotogrammetric techniques. Optical tolerances and obvious operational advantages still take precedence over ease of understanding and control of "possible" errors in interpretation.

In the optical laboratories of Itek Corporation the optical engineers and photogrammetric engineers have, over the past few years, been combining knowledge in their technical disciplines in attempts to improve optical testing techniques or at least, provide additional testing tools. One development concerned with the Hartmann Test has met with considerable success and another, a variation of the Foucault Test, shows some measure of promise.

HARTMANN TEST

In the Hartmann test for Spherical Aberration, the collimated light presented to the lens under test is divided into "bundles of rays" by passing it through a symmetrical array of holes in an opaque plate or diaphragm. The plate is placed over the front of the collimator or the back of the objective as illustrated in Figure 1.

The number and size of the holes is dependent upon the size of the objective and the number of aberration samplings desired, nevertheless the hole pattern should cover the entire aperture and the holes should be large enough so that no additional aberrations are introduced by them. Preferably the holes should be of uniform size and quality and should permit the transmission of sufficient light. The radial "clock" pattern illustrated in Figure 1 with a reference hole, was found to be very satisfactory.

The collimated rays are converged, i.e. focussed, by the objective being tested and are photographically recorded equal distances before and after the apparent "point" of best focus. The distance between the recording locations and their distance from the "point" of best focus should be accurately measured to enable quantitative values to be later determined, but the actual choice of locations for the photographic samplings should be based on the desired scale of the pattern and on the quality of the out-of-focus diffraction discs formed by the holes.

The resultant photographic records are illustrated in Figure 2, arranged as a stereogram with one of the two useful stereo "base" orientations. Note that one of the records is rotated 180 degrees with respect to its exposed position. This of course is necessary for positioning of both images of the same ray at the same location in the stereo image which will then allow their direct visual comparison.

When stereoscopically viewing this stereogram, you will observe that the discs appear at different "elevations." This is a direct visual observation of one component of the Spherical Aberration in the lens being tested. A rotation of the stereo "base" through 90 degrees will visually illustrate the second component of this aberration. The "elevation" differences result from observed parallaxes, which in turn are created by non-equal linear separations (or displacements) of the disc images of identical rays in the two photographic records. As with most optical disturbances, the effect is quite systematic and this can be observed in the example where the discs on the perimeter of the pattern are considerably lower than the average reference plane formed by the center images in the pattern. Subtle "elevation" differences

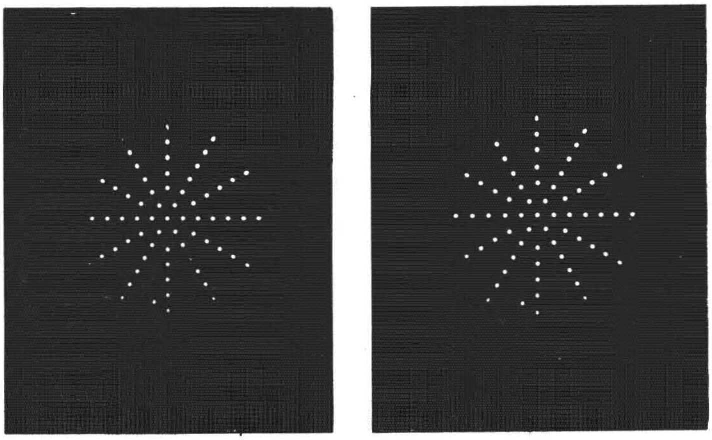


FIG. 2. Stereogram of the Hartmann test.

throughout the pattern illustrate the sensitivity of this visual technique even when applied to high quality lenses such as the one being tested in this example.

Visual observation of an aberration was the original intention of this experiment, but it is quite obvious that simple parallax measurements will provide a value for a mean reference plane which can then be combined with the exposure station measurements to provide a computed position of best focus. If a parallax bar is used, the mean of the two values determined from the two base orientations would be used. If a stereocomparator is used, the *x*, *y*, *px*, and *py* values are determined in the same coordinate reference system and one value can be directly computed.

Either measurement technique would require an expanded version of the original Hartmann formula which states that:

$$A = A_1 + \frac{l_1}{l_1 + l_2} \cdot (A_1 - A_2)$$

as illustrated in Figure 3:

A = the position of best focus

A_1 = measured value of one exposure location

A_2 = measured value of the second exposure location

l_1 = distance between two image discs at exposure location A_1 (usually two points falling in the same radial zone of the lens)

l_2 = distance between the two image discs defined by l_1, but at exposure location A_2

If a diagram of aberration effects is the desired end-product, it will first be necessary to do a least squares transformation of the coordinates of the discs of one pattern to the coordinates of the other. After the transformation, based on the formulas:

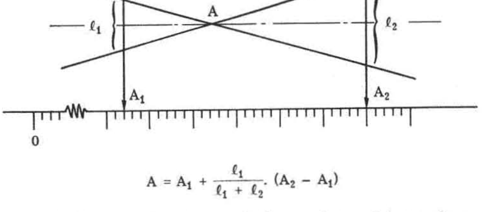
$$X = ax + by + C_X$$
$$Y = -bx + ay + C_Y$$

the residuals in *x* and *y* can be used to determine error vectors which, when plotted against a representation of the original pattern, and its orientation with respect to the lens, can be used to illustrate the positional effects of the optical aberration. The transformation scale factor determined from the computation can be used for the determination of the position of best focus.

FOUCAULT KNIFE-EDGE TEST

Traditionally, the wave front produced by a concave optical surface is evaluated by means of the Foucault Knife-Edge test. The illuminated wave front is, of course, a signature of the quality and uniformity of the desired surface characteristics of the optical element. The laboratory setup for the Foucault test is illustrated in Figure 4.

Light from the pinhole, which is in the same vertical plane as the moveable knife-



$$A = A_1 + \frac{\ell_1}{\ell_1 + \ell_2} \cdot (A_2 - A_1)$$

FIG. 3. Determination of the point of best focus.

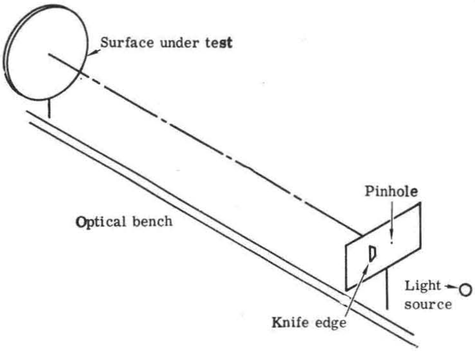


FIG. 4. Laboratory setup for the Foucault test.

edge, is sent toward the concave mirror surface and is reflected back so that it comes to a focus in the plane of the knife-edge. The test engineer places his eye close against the knife-edge and while viewing the illuminated surface, moves the knife-edge slowly across the eye. If, when doing this, the surface darkens uniformly or to some desired pattern, the knife-edge is precisely at the focus of the pinhole and therefore at the center of curvature of the surface. If the pinhole/knife-edge combination is at the center of curvature of a spherical surface, the darkening should be uniform and complete. If the combination is used with a parabolic surface, a characteristic "donut" image will appear because all portion of the surface do not have the same center of curvature. Figure 5 is a photograph of the illuminated wave front of a spherical mirror. The non-uniform tone near the center would indicate a "non-perfect" sphere. This tested optical component will either continue being polished or will be evaluated for the surface quality needed for the particular purpose.

In a recent experiment in the optical laboratories of Itek the Foucault test laboratory setup was modified in an attempt to produce a new testing technique based on three-dimensional observation of the wave front produced by concave optical surfaces. In the method developed, the pinhole and knife-edge stations are separated and interchanged, photographically recording the illuminated wave front at each of the knife-edge locations. This is illustrated in Figure 6.

The experiment was performed on a very poor quality spherical shaving mirror to exaggerate the phenomena, and a square grid was placed over the mirror to monitor the gross aberrational effects. The result was the images shown in the Frontispiece, arranged as stereo pairs. The three dimensional "impression" is very easily observed and the topographic characteristics can be closely correlated with a conventional, two-dimensional definition of the surface. The stereo pairs illustrate two station separations or base to height ratios, but the bases which yield a usable "model" are considerably less than that considered optimum in stereo aerial photography.

This modified Foucault technique is in its very early stages of development and its

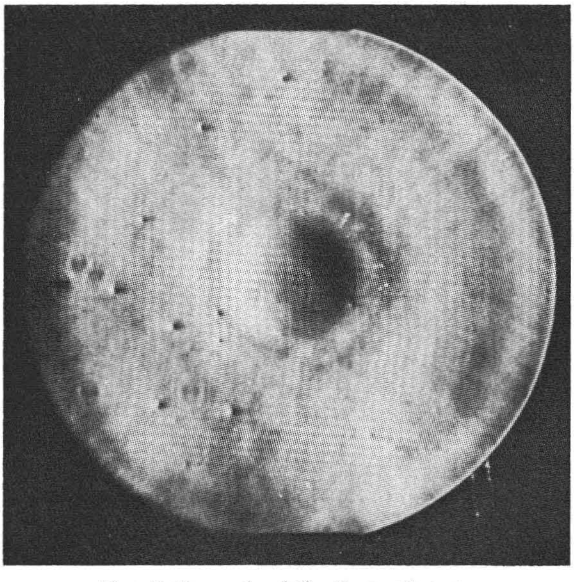


FIG. 5. Example of the Foucault test.

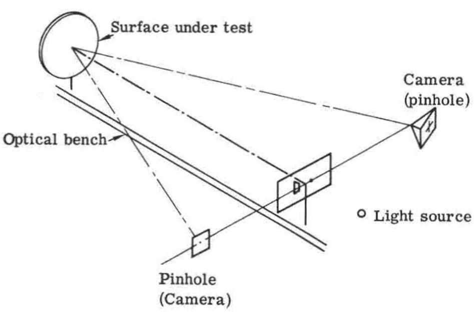


FIG. 6. Stereo-Foucault setup.

validity for use in the evaluation of high quality optical surfaces has still to be proven. Quantitative expressions such as contours, form lines and profiles have been obtained, but only on the highly deformed, exaggerated surface. The potential of this testing tool, particularly in the working evaluation of aspheric surfaces in apparent and therefore experiments with this method are continuing.

SUMMARY

The ability to observe optical aberrations in an understandable three-dimensional way provides considerable advantages over abstract impression of the disturbances. The two techniques discussed not only provide this possibility, but introduce the potential of accurate stereo interpretation and precise stereophotogrammetric mensuration possibilities. With the increasing complexity of optical surfaces, closer surface tolerances, wider variety of component materials, and larger sized elements comes the requirement for the development of improved testing techniques. This requirement can be met by problem understanding and technical imagination.

ACKNOWLEDGEMENTS

I would like to acknowledge the efforts of Ronald Aspden and Edward Fitzgerald for their theoretical and experimental work leading to the Stereo-Foucault test possibilities.

See announcement of 1968 Congress in Switzerland on page 658.