"zero-length" tracking edit ahead of each effect.

We have intended to bring to the surface only some of the problems encountered in today's computerized editing. Probably, a book could be written about problems editors have to face as they build their edit lists.

To sum it up, edit list management is not as difficult as it may appear. Four most important factors must always be remembered: (1) the editor must thoroughly know the system he is working with; (2) he must understand the relationship of the instruction numbers in the list to the edits they will produce; (3) he must never be in too much of a hurry; and (4) finally, he must check and make sure that all edits in the completed list are listed by consecutive record times. If the system in use is not capable of reordering edits in the list by record times, the list must be submitted to a firm that provides software for the "cleanup" of edit lists. Such a service is normally provided at a small cost and will yield a well-organized list, ready for auto-assembly. Edit list management is not difficult if time and care are applied.

Effects of Aspheric Surfaces on Optical Performance and Their Application to Lenses for 35mm Cinematography

By J. MUKAI, Y. MATSUI, and I. HARUMOTO

The practical use of aspheric surfaces in optical devices, such as parabolic mirrors or illuminating condensers, is well-known. Technical problems in the design and manufacture of such surfaces had to be overcome before the incorporation of aspheric surfaces into the construction of high precision optics, such as camera lenses for motion pictures and television, could be attempted. An overview of the performance of aspheric surfaces is given, and their limitations are mentioned. Spherical aberration, distortion, and astigmatism can be controlled by their use. The introduction of an aspheric surface into the design of a lens produces two types of effects: direct effects permit controlling of a specific aberration, and indirect or secondary effects may allow for the simultaneous control of another aberration. Greater lens compactness and reduction of the number of required lens elements may result. Three fundamental parameters for the measurement and evaluation of an aspheric surface are explained. A short description of various possible grinding and polishing methods is given. The accuracy of the surfaces obtained can be measured by the use of interference fringes or by means of a feeler in combination with a laser. Canon designed their first aspheric lens in 1971. It is shown that the aspheric design reduces aberration fringes, gives greater freedom from flare, and improves contrast. A series of four aspheric high speed lenses for motion-picture use was created. Some details of their design and contruction, including the "floating" focusing mechanism, are mentioned. A Class III Scientific or Technical Award from the Academy of Motion Picture Arts and Sciences resulted from this technological achievement.

The use of aspheric surfaces to improve the performance of optical systems has long been known and there have been a number of cases where such surfaces have been used in practical applications. We may cite as an example of their use in high performance systems, parabolic mirrors used in astronomical observation systems and as an example for low precision systems, aspheric condenser lenses. However, for many years aspheric surfaces were not practically applied to high precision optical systems such as camera lenses for still photography, motion pictures, and television. Technical problems in both design and production limited the use of aspheric surfaces in optical products like these, but advances in production engineering and also in computer-aided design technology have gradually removed these restraints, and several new objectives in which aspheric surfaces are used are now available.

Effects of Aspheric Surfaces and Their Limitations (Problems in Design Technology)

As is described below, processing of aspheric surfaces is much more difficult than that of spherical surfaces and therefore involves higher cost. The increased cost limits the number of aspheric surfaces which may be used in any given optical product to only one or two. This makes the design of aspheric optical systems more difficult than that of conventional spherical systems. First, the designer must determine which of the surfaces in the system will be most effective in aspheric form, and then he must endeavor to make the improvements gained by the use of an aspheric surface worth the cost. It is obvious from these considerations that one must know for which purpose an aspheric surface can be quite effective and for which purposes it is ineffective. This is of basic importance for any decision on whether or not an aspheric surface should be used in an optical system. Aspects of lens performance which can be improved by the use of aspheric surfaces are the following.

1. The image formation of a specific point in the focal plane can be made free from aberration. (Correction of spherical aberration in a parabolic mirror is an example.)
2. A specific aberration curve can be controlled as desired. (An example of this is the control of distortion in a retrofocus lens.)
3. The surface has different sagittal and meridional curvatures for an off-axis pencil of rays. This facilitates the control of astigmatism.

However, an aspheric surface is ineffective with regard to the control of the following parameters.

1. Dimensional characteristics of an optical system such as focal length and back focal distance.
2. Petzval curvature.
3. Primary chromatic aberrations such as longitudinal and lateral chromatic aberration of the first order.

The application of aspheric surfaces with these characteristics in an optical system will produce direct and indirect effects. By direct effect, we mean the improvement of aberration which can be expected by the introduction of an aspheric surface specifically for the purpose. By indirect effects, we mean certain secondary effects which can be attained simultaneously with the direct effect. The following is an example of indirect effects.

When an aspheric surface is applied to control the distortion present in a wide angle lens of the inverted telephoto-lens type, improvements in other aberrations can sometimes be obtained at the same time. In some other cases, greater compactness of the overall system or a reduction in the number of lens elements can be attained together with the correction of aberrations.

When designing an aspherical optical system, it is difficult for a designer to determine in advance which of the various surfaces will be most effective by giving it an aspheric shape. Thus, the initial investigation must cover a much broader range than required for conventional optical systems. This is the major reason why the design of aspheric optical systems is difficult. Existing computer-aided design technology is a powerful tool for surmounting this diffi-

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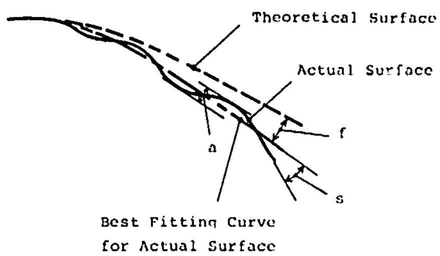

Fig. 1. **Representation of the accuracy of a fabricated aspheric surface.**

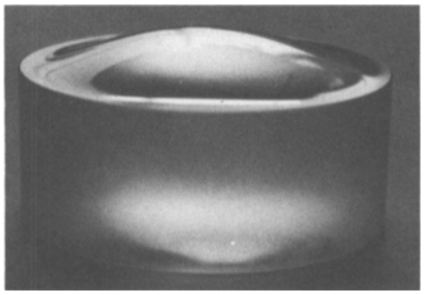

Fig. 2. **Example of an aspheric lens.**

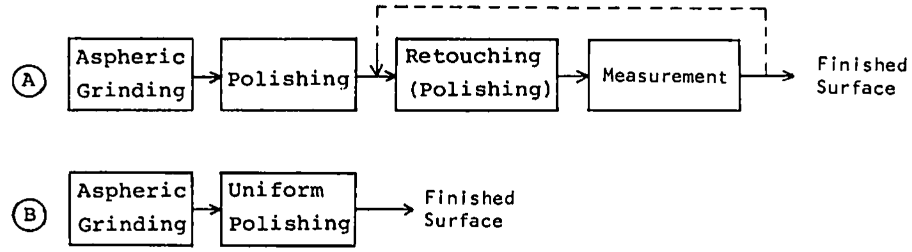

Fig. 3. **Block diagrams illustrating two typical processes for finishing an aspheric surface.**

culty. But it is merely a tool which cannot by itself eliminate a difficulty due to its very nature. The process of optimization by computer only progresses continuously, not by leaps and bounds. If the designing of a lens is compared to the task of climbing a mountain, by using the existing automated design technology we can only climb the peak nearest to our starting point. If there is a taller peak on the other side of the valley, we have to make a new start.

At present, almost all known optical systems are composed only of spherical surfaces, and have already been improved to a very high degree through the combined efforts of very many designers. However, the highest quality peak of an optical system could perhaps be achieved in a quite different way if aspheric surfaces were introduced into the system. If this indeed is done, it will be difficult for a designer to reach his ultimate goal, the highest peak, merely relying upon automated design technology. It can be said that the most reliable tool to achieve the desired quality level (disregarding the obvious solutions near at hand) is the designer's ingenuity, ability, and imagination.

Accuracy Required for Aspheric Surfaces, and Its Attainment (Problems of Production Engineering)

Even if an optical system incorporating an aspheric surface has excellent design values, it has no immediate practical value if it cannot be produced with the required precision. Precisely because there enter many more design variables in the shape of an aspheric surface, the control of its accuracy is much more difficult. Figure 1 illustrates the sectional view of an actually obtained aspheric surface. The deviation of the surface from the ideal shape can be expressed by three parameters: average shape deviation, technically called the figure f of the lens; accuracy a; and smoothness s. Of these, f represents the deviation of the surface shape obtained from the desired theoretical shape, after smoothening out small irregularities by averaging. This parameter influences the basic aberrations. Parameter a represents the depth of the irregularities in the processed surface, and s represents the local tilt in the irregular surface, both measured against the average shape. If these two parameters are of significant magnitude, they can cause a reduction in resolving power or a ring-like pattern in the defocused image. For lenses for still and motion-picture photography and for television, permissible limits for these three parameters are, for example, $\pm 1\ \mu$m for f, $\pm 0.1\ \mu$m for a, and $1/5000$ radian for s.

When processing spherical lenses in common use today, the work is first rough-ground to the approximate desired shape, and then it is rubbed with a polishing tool which has the desired final curvature, but in an opposite convex-concave relation to the work. Thus, in spherical lens making, the desired accuracy can be obtained with little difficulty.

However, for an aspheric lens (Fig. 2) the necessary accuracy cannot be obtained by the method described. Many proposals have been offered for the processing of aspheric sufaces, but most of them advocate a method composed of processing by an orthodox mechanical device and some kind of supplemental hand polishing work. Not only are these methods incapable of providing the required accuracy, but their low efficiency increases costs. They are also unsuitable for large-scale production. For these reasons, it has been generally difficult in the past to use aspheric surfaces in lenses for photography and television. However, through continued efforts for developing methods to produce aspheric surfaces in large quantities and at a relatively low price, it can now be said that the long-held dream about objectives incorporating aspheric surfaces has been realized, even though within a somewhat restricted range.

Typical procedures for the production of aspheric surfaces now used at Canon Inc. are shown in Fig 3. In this figure, A represents the process used when the accuracy of aspheric grinding is insufficient. In that case, the final accuracy is attained by "retouching." Retouching means a corrective polishing, performed after measuring the processed surface and finding the deviation to be corrected. In this case, a single retouching stage is rarely sufficient to obtain the required accuracy. Thus, retouching is repeated until measurement indicates that the aspheric surface has reached the required accuracy. Although it cannot be said that this process is highly efficient, it is often very effective, as the obtainment of almost any form is possible by use of a general-purpose three-dimensional grinding machine with medium precision.

Method B is a process whereby the surface is first ground to the desired accuracy, and then the entire surface is polished uniformly and consistently without causing any change in form. The desired aspheric surface is thus obtained with the required precision. This process is suited for mass production in the true sense of the term, because the technician is not required to make any adjustment in the course of the work, and it is possible to produce aspheric surfaces in series. After lengthy experimentation, Canon Inc. has succeeded in setting up standard production processes for both of these methods.

To establish the technology needed for the described high precision processing of aspheric surfaces, it was also necessary to have a means of measuring accurately the shape of the finished aspheric surface. As already stated, the accuracy we seek in aspheric surfaces is exceedingly high. Hence, ordinary measuring instruments, such as gauges with engraved scales, or devices which change measured electric capacities into dimensional values, are not appropriate. This made it necessary to use wavelengths of light as standards of measurement. For this, two methods of measurement are available. In one method, the distorted wave front of a light beam which has been transmitted through, or reflected by, the aspheric surface is combined with a reference wave front to generate interference fringes which can then be interpreted to determine the shape of the surface to be evaluated. In the other method, a feeler traces along the aspheric surface and the movement of the feeler is measured by a laser interference-measuring device. These methods must be used selectively according to the shape of the aspheric surface, the required accuracy, and the purpose of the measurement. With the aid of these measuring devices we have achieved the efficient production of high precision aspheric lenses.

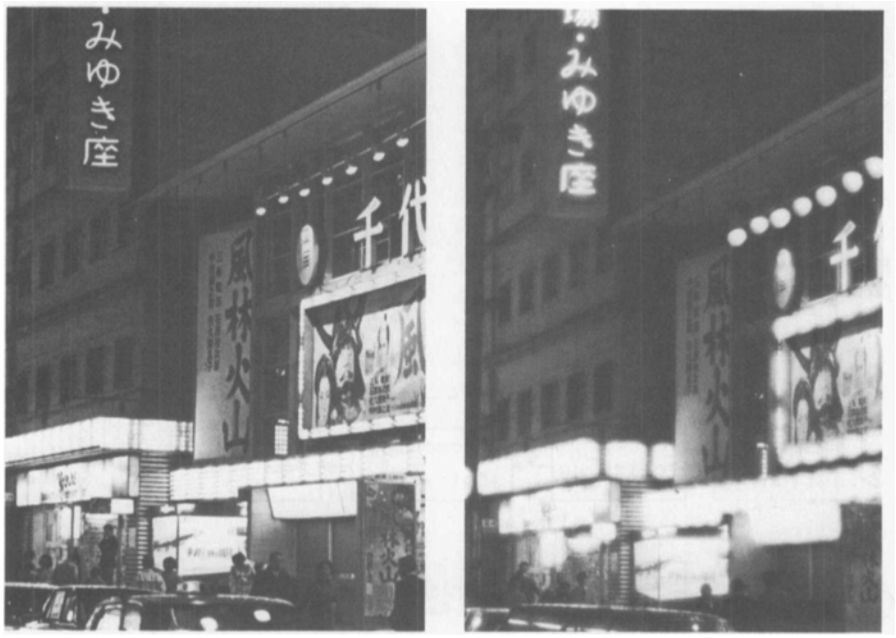

Fig. 4. Enlarged portions of photographs taken with an aspheric lens (left) and with an ordinary spherical lens of the same focal length and general specifications (right).

Fig. 5. High speed X35 series of Canon lenses for 35mm cinematography: (A) 85 mm *T*/1.4 (*f* /1.2); (B) 55 mm *T*/1.4 (*f* /1.2); (C) 35 mm *T*/1.4 (*f* /1.2); (D) 24 mm *T*/1.6 (*f* /1.4).

The Application of Aspheric Surfaces to Lenses for 35mm Cinematography

With regard to the incorporation of aspheric surfaces into motion-picture and television lenses it can be said that they are in the same class as ordinary photographic lenses with respect to the required aberration correction or the required precision of the aspheric surfaces. In optical systems of this class, not only the reduction of specific aberrations, but also the proper balancing or trade-off among the various aberrations must be considered, and special attention is required to effectively utilize the aspheric surfaces. Research at Canon regarding the utilization of aspheric surfaces for the improved performance of optical systems has been carried out for many years, and the first commercial product containing an aspheric surface was the Canon FD 55 mm *f*/1.2 aspherical lens put on the market in 1971 as a special high speed lens for 35mm single lens reflex cameras. This was an 8-element lens with two cemented pairs.

When a high speed lens composed only of spherical surfaces is used at very wide apertures, image contrast is reduced due to the fact that each image point is surrounded by an aberration fringe of relatively low light intensity. However, when the scene contains very bright highlights such as specular reflections or direct light sources, neon lights, etc., the intensity of the aberration fringe may be sufficiently high to fully expose the film emulsion so that definition and resolution are seriously impaired. These effects are particularly noticeable when photographing in low light conditions or at night (Fig. 4). Although the main function of the aspheric surface in the illustrated lens is the elimination of aberration fringes at maximum lens aperture, it is also necessary to remove aberration at narrower relative apertures. Otherwise, no high resolving power would be achieved and the lens would be inferior to a conventional spherical lens when both are stopped down to narrow apertures. Our ultimate purpose in using an aspheric surface in this lens was to solve the problem of obtaining uniform high quality performance not only at maximum aperture, but also at all intermediate apertures. That this is an exceedingly difficult task will be obvious to any experienced lens designer.

In developing this lens, we attempted to make only one surface aspheric and to attain our ultimate purpose through mutual interaction between the aspheric surface and the other spherical surfaces. Extensive research indicated that it would be most effective to make the third surface aspheric. It was also recognized that the shape of the aspheric surface would be most effective if the curvature became weaker towards the periphery. Figure 4 shows the superiority of the aspheric surface in this lens by comparing enlarged portions of photographs taken with this lens (left) and an ordinary spherical lens (right). It can be seen that the image contrast of the aspheric lens is excellent and that blurring of light is small, even at full aperture.

The technology developed for the design, production, measurement, and image evaluation of aspheric optical systems, accumulated during the creation of this aspheric lens is, of course, applicable to other optical systems, and we have continued our efforts along this line. In motion-picture photography, the obtainment of clear pictures under adverse lighting conditions requires high speed lenses free of aberrations and having high resolution. For this purpose

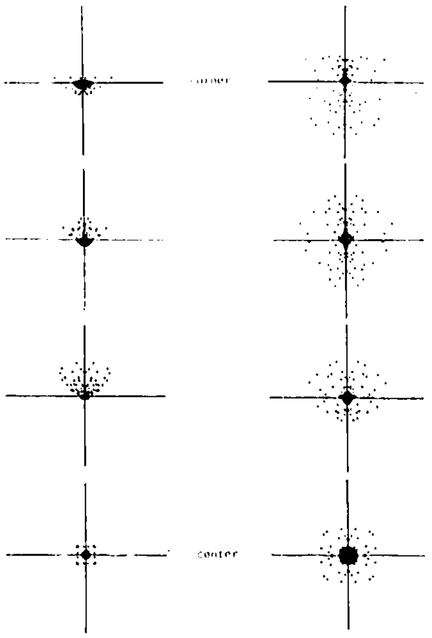

Fig. 6. Spot diagrams showing the spread of point images from the corner to the center of the images area for (left) the aspheric lens 85 mm *T*/1.4 (*f* /1.2) and (right) a conventional spherical lens 85 mm *f*/1.5.

the application of aspheric surfaces is most appropriate. The high speed K35 series of aspheric Canon lenses developed for 35mm motion-picture photography is composed of the following four lenses: 85 mm *T*/1.4 (*f*/1.4), 55 mm *T*/1.4 (*f*/1.2), 35 mm *T*/1.4 (*f*/1.2), and 24 mm *T*/1.6 (*f*/1.4). All are high performance lenses in which aspheric surfaces are advantageously used (Fig. 5).

The field angles of the 85 mm *T*/1.4 and 55 mm *T*/1.4 lenses in this series are rather narrow, and the aspheric surfaces are used mainly to remove aberration fringes. As an example, Fig. 6 shows the effect of the aspheric surface in the 85 mm *T*/1.4 lens. In this figure, the image quality of the lens at full aperture is presented by "spot diagrams" for several image portions computed and plotted by computer. The aspheric lens (left) is compared with a conventional spherical lens (right). The spherical lens is of somewhat older design, but has a maximum aperture of *f*/1.5. It was used because we did not have a spherical lens more closely resembling the specifications of the new lens. The spot diagrams in Fig. 6 correspond to four different image portions from the center (bottom) to the corner (top) of the image area. The diagrams on the left relate to the new aspheric lens. It can be seen that its point images are much more sharply confined. This demonstrates the advantages derived from the use of an aspheric surface, obtained as a result of recent advances in automated lens design technology.

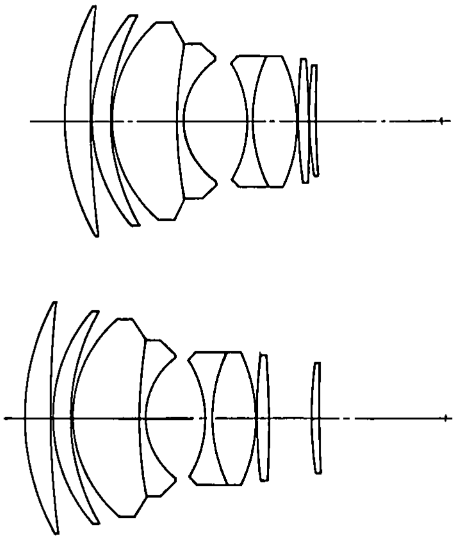

Fig. 7. Floating mechanism in the Canon 85 mm *T*/1.4 lens. Top: lens focused for long distance; bottom: lens focused for macrophotography.

To retain the outstanding image quality of aspheric lenses when they are used at short object distances or for macrophotography, a "floating mechanism" is used for the focusing of these new lenses (Fig. 7). It can be seen that there is a change in the internal spacing between the front and rear elements of the lens. This, in effect, maintains optimum aberration correction, which otherwise would vary significantly with large changes in object distance.

For the 35 mm *T*/1.4 (Fig. 8) and 24 mm *T*/1.6 lenses, the field angles are rather wide, and back focal distances must be made rather long, relative to their focal lengths. Hence, the inverted telephoto lens configuration was adopted. In this design, barrel-type distortion, typical for inverted telephoto lenses, causes problems, in addition to the off-axis aberration fringes characteristic of high speed lenses. Here, the elimination of both these aberrations was the primary purpose for using an aspheric surface in these lenses.

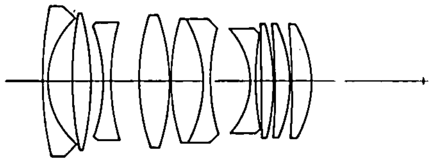

Fig. 8. Cross section of the Canon K35 35 mm *T*/1.4 lens which is of the inverted telephoto lens type.

Again we had to investigate which of the various surfaces should be made aspheric and what precise form the aspheric surface should have. This was necessary because these lenses differ from the lenses with the longer focal lengths with regard to lens type and have different requirements for correction of aberrations. The two lenses which resulted from this investigation provide sharp images even at full aperture, as is generally characteristic of aspheric lenses. It is not possible to show meaningful comparison graphs with spherical lenses because no spherical lenses of comparable specification are available. This may be taken as confirming in an indirect way that it is difficult to produce quality lenses like these without the use of aspheric surfaces.

Acknowledgments

This paper has been written with the cooperation of Mr. G. H. Cook. The authors wish to express their thanks for his useful advice and suggestions.

Editor's Note: An important consequence of the work described in this paper must be called to the attention of the reader if the record is to be complete. Mr. Hiroshi Suzukawa of Canon and Mr. Wilton R. Holm of the AMPTP Motion Picture and Television Research Center (which collaborated with Canon) were honored on 31 December 1976 by the Academy of Motion Picture Arts and Sciences with a Class III Scientific or Technical Award for the "Series of Canon Super Speed Lenses."