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THE POSSIBILITY OF COMPENSATING ASTRONOMICAL SEEING

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The severe limitations imposed upon nearly all astronomical observations by "seeing"—the effects resulting from passage of light rays through the turbulent atmosphere of the earth—are familiar to every observer. With a small instrument the effect may appear largely as a continual shifting and scintillation of the image of a star, but with a large telescope poor seeing usually manifests itself mainly as an enlargement and blurring of the image. The reason for this difference becomes apparent when one makes a knife-edge test with a large telescope on a bright star. The turbulent elements of the atmosphere appear as shifting dark and bright areas on the image of the objective. In general these turbulent elements or waves have dimensions of the order of a foot or two—small compared to the aperture of a large reflector. Thus the integrated effect of a number of turbulent elements leads to an unsteady enlargement of the image, perhaps with some irregular shifting in position. The seriousness of this is evident when one realizes that ideally the 200-inch Hale telescope is capable of giving diffraction images of stars about 1/40 of a second of arc in diameter, yet the size of the "seeing image" produced is in the range 1/3 second to perhaps 5 or 10 seconds, being about 2 seconds in diameter on the average. Only rarely are images as small as 1/2 second observed, and one may consider himself fortunate to experience one hour out of 1000 of the finest seeing, even at the best locations.

There is no vast difficulty in devising instrumental means for overcoming the random shifting in position of a star image. Guiders have been proposed and tested that work either on the principle of centering a star on a beam-splitting pyramid[1] or on the axis of rotation of a knife-edge.[2] A guider of the latter type has been used at the coudé focus of the 100-inch telescope for some years. Such a guider may function by correcting the aiming of the telescope through the slow motion controls, by moving a plate-holder, or by tilting a gimbal-mounted plane-parallel plate in the optical path. But the far more difficult and more fundamental problem of overcoming the enlargement of a stellar image caused by atmospheric turbulence has generally been regarded as insoluble. In this paper a method is proposed which, although subject to severe limitations, seems to offer in principle a means of compensating or correcting for the effects of atmospheric turbulence.

Consider again the appearance of a large telescope objective when a bright star is observed with a knife-edge at the focus, the eye being a short distance behind. The mirror appears to be covered with a light and dark schlieren pattern, the brighter-than-average areas being those in which the rays are deviated so as to pass the knife-edge. If the shifting patterns due to seeing are averaged out by taking a time exposure, the residual pattern represents deviations from perfection in the figure of the mirror. Excellent illustrations of these effects are given by I. S. Bowen[3] in a paper in which knife-edge photographs of the 200-inch mirror are reproduced, with exposures of 1/20 second to show the effects of seeing, and exposures of 40 seconds to show the figure of the mirror, both before and after final figuring.

If we had a means of continually measuring the deviation of rays from all parts of the mirror, and of amplifying and feeding back this information so as to correct locally the figure of the mirror in response to the schlieren pattern, we could expect to compensate both for seeing and for any inherent imperfections of optical figure. While it is impracticable thus to provide for continuous local corrections to the mirror itself, the equivalent can be accomplished at a conjugate image-plane of the mirror where a relatively small ray-controlling element can be inserted.

Such an element is the Eidophor, a device invented by Professor F. Fischer[4] for the large-screen projection of television. The Eidophor is essentially a thin layer of oil covering a reflecting mirror. A rastered electric charge is deposited on the surface of the oil film by conventional cathode-ray techniques, and through electrostatic forces the oil film is distorted according to the desired pattern. Through refraction this results in a controlled deviation of the light rays reflected by the mirror. The conductivity, viscosity, and surface tension of the oil are so chosen that the induced surface deviations tend to disappear in a time a little longer than the interval between successive applications of the rastered pattern.

The schematic diagram of Figure 1 shows how the Eidophor can in principle be employed as a feed-back element in an electro-optic system for the correction of seeing and mirror figure. The light of a star is brought to a focus at F on the axis of the objective of the telescope. A field lens images the objective on the Eidophor, after which the light is again brought to a focus in the plane of a rotating knife-edge, K. Then the light diverges to form a schlieren image of the objective on the photocathode of a tube such as an image orthicon. Coupled deflection circuits, keystoned for the Eidophor and wedged for the image orthicon, provide similar raster patterns in which the direction of line sweep is perpendicular to the knife-edge. As the schlieren image is scanned by the orthicon, the resulting signal is electronically integrated and used to modulate the intensity of the electron beam of the Eidophor. This completes the feed-back loop of the system by providing corrective deviations to the effective optical figure. By inserting a partially reflecting or dichroic pellicle, P, in front of the knife-edge, a part of the light may be diverted to the focal plane, S, where the star image and a small surrounding field may be observed.

Figure 2 shows how the modulating signal for the Eidophor is derived. We assume for the moment that the ray deviations due to atmospheric turbulence can be represented as deviations in the optical figure of the objective mirror of the telescope. One trace of the raster pattern across the mirror is represented where

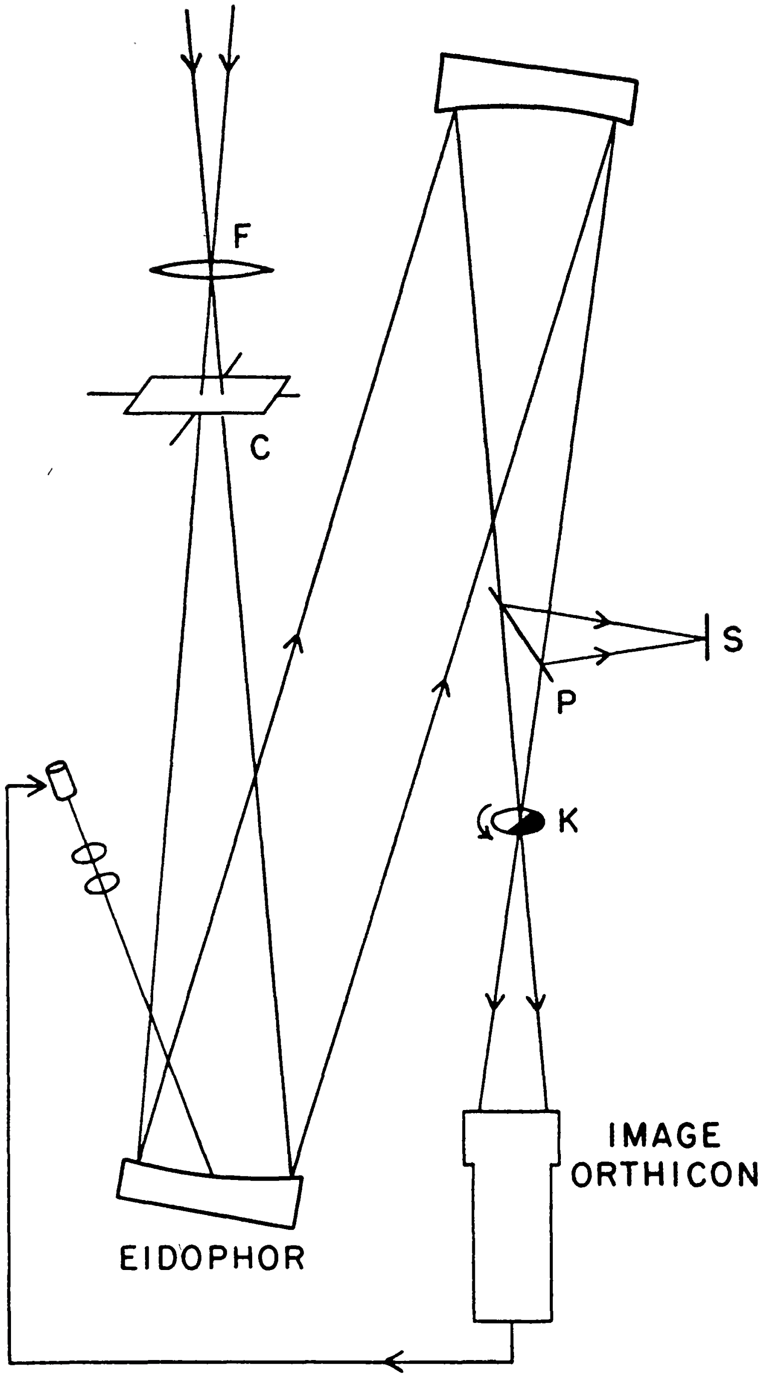

FIG. 1.—Schematic diagram of seeing compensator. A schlieren image of the telescope objective, formed on the image orthicon, is transferred electronically in the form of a modulated electric charge to the surface of the oil film covering the Eidophor mirror. This feed-back process results in the correction of ray deviations due either to atmospheric turbulence or to optical imperfections. *F* is a field lens and *C* is a fast guider for centering the control star on the knife-edge, *K*. The two mirrors are off-axis paraboloids.

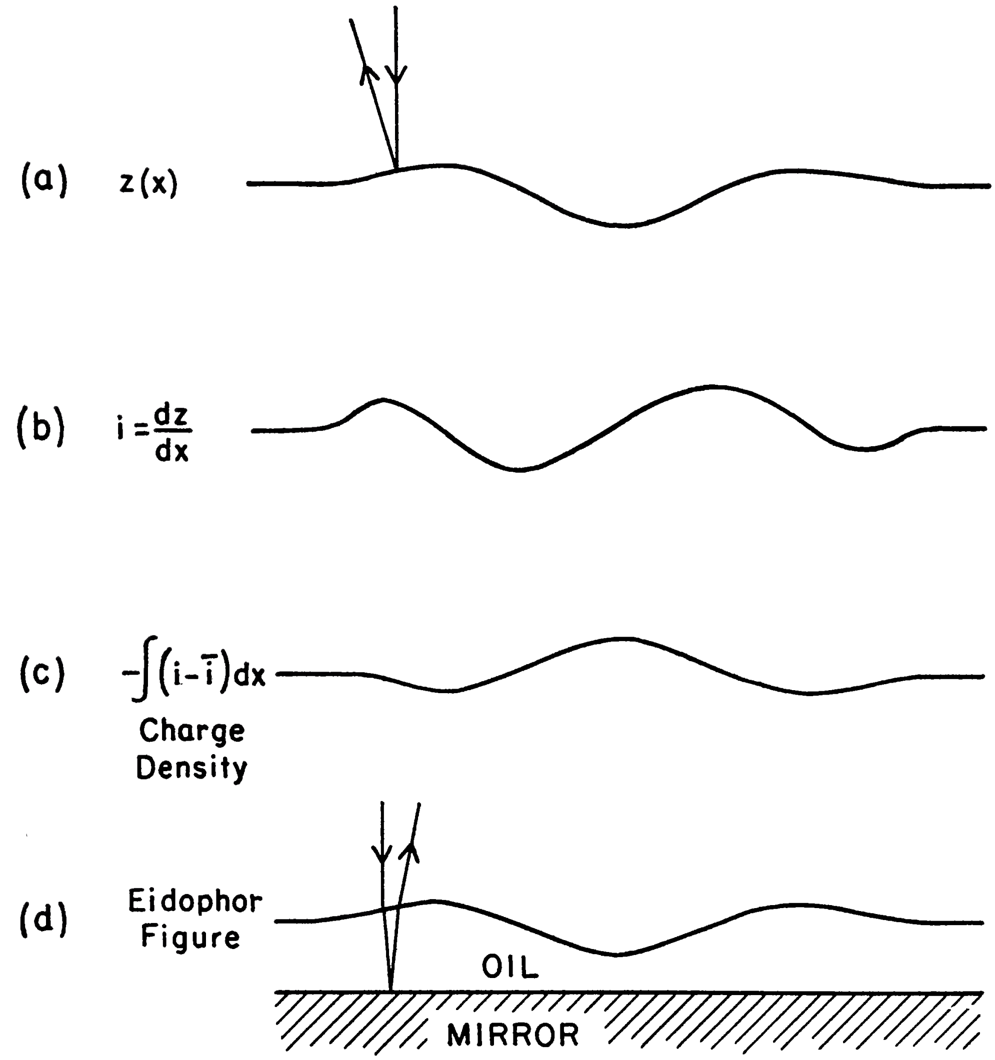

FIG. 2.—(*a*) Cross section of corrugations in effective figure of telescope objective. (*b*) Corresponding intensity pattern observed in knife-edge image. (*c*) Integrated photoelectric current along trace of raster. (*d*) Resulting deformation of Eidophor figure, showing correction of deviated ray.

x is the linear distance along the surface and $z(x)$ represents vertical deviations from perfect figure (2*a*). The intensity (2*b*) at any point of the schlieren image, and therefore the instantaneous signal current, i, of the image orthicon, is proportional to dz/dx. To convert from i to the optical figure it is then necessary to form the integral $-\int(i - \bar{i})dx$ and to modulate the intensity of the scanning beam of the Eidophor accordingly; a corresponding deformation of the Eidophor surface will result (*2d*). The areas of greatest specific electric charge become depressed in a time of a few milliseconds, and the oil film assumes temporarily the same figure as the mirror; but since it functions by refraction instead of reflection, the induced ray deviations are in the opposite sense so as to correct the initial deviations. The integration of the signal current of the image orthicon is quite simply accomplished by means of a resistor and a capacitor.

For proper performance of the system it is essential that the star image be kept accurately centered on the axis of rotation of the knife-edge. This may be accomplished by combining with the Eidophor system an image-centering device of the kind already described. The output of the image orthicon at the relatively low frequency of rotation of the knife-edge is selectively amplified, rectified according to phase, and applied to a two-co-ordinate image-centering element such as a plane-parallel plate (*C*, Fig. 1).

The technical problems encountered by those engaged in the development of the Eidophor system for its original purpose—the high-intensity projection of television—have been formidable, yet it has been successfully demonstrated. It is possible that in some respects the requirements placed on the device as suggested here are less severe. For example, since velocity modulation of the Eidophore scanning beam is not used, the focus of the beam is not so critical. From the standpoint of communications theory, it is evident that the rate at which information is to be supplied by the scanning of the schlieren image of the objective must approach the rate of transmission of intelligence in the average television picture, and this would appear to be not entirely hopeless.

There are two severe limitations of the system—the very small angular field in which one may hope to compensate atmospheric turbulence, and the dependence upon magnitude of the control star. The angular field depends directly upon the height in the atmosphere at which the turbulence occurs and upon the size of the turbulent elements. For example, if the turbulent layer is at a height of about 3000 feet, an element a foot in diameter subtends an angle of about a minute of arc. Therefore, compensation of the seeing could be expected only within a few seconds of arc of the control star. But on some occasions the layers responsible for poor seeing are at a very low level indeed, even in and about the dome; under such conditions the field restrictions would be much alleviated.

The other severe limitation lies in the rate at which information becomes available for the functioning of the system. Schlieren observations with the 200-inch mirror suggest that under average conditions a picture of 1200 elements and a picture repetition rate of 60 per second would be adequate. With this telescope in $1/60$ second, a star of magnitude 14 should produce some 600 electrons at the cathode of a phototube, sufficient for a significant measure. But with 1200 picture elements—a factor corresponding to 7.7 magnitudes—a control star brighter than magnitude 6.3 would be required for the functioning of the Eidophore correcting system. With allowance for various losses and the fact that part of the light must be subtracted for useful observations, the effective limit might well be closer to the fourth or fifth magnitude. It is worth noting that this limit does not vary with the aperture of the telescope used. The limiting magnitude is, however, quite dependent upon the quality of the seeing that one is attempting to compensate.

Because of the extremely limited angular field and the requirement of a bright control star it would appear that possible uses of this system of seeing compensation would be restricted largely to high-dispersion spectroscopy of the control stars themselves and to the investigation of the brighter stars for close companions. A double star would produce a kind of pseudo-astigmatic effect on the Eidophor, and this should be recognizable on a monitoring oscilloscope. On rare occasions the near-occultation of a bright star by one of the planets of the solar system might permit the observation of the planet with the aid of the seeing compensator. The Galilean satellites of Jupiter may be sufficiently bright to serve as control objects for the study of this planet, but their diameters (about 1 second) are large for the purpose.

If, because of flexure, the difficulties in mounting a very large telescope mirror precluded the attainment of the usual standards in the optical figure, the Eidophor might be used primarily as a figure corrector, in which case the field limitation encountered in the compensation of seeing would not apply.

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[2] H. W. Babcock, *Ap. J.*, **107,** 107, 1948.

[3] *Pub. A.S.P.*, **62,** 91, 1950.

[4] Fischer and Thiemann, *Schweiz. Arch. Angew. Wiss. Tech.*, **7,** 1941, Nos. 1, 2, 11, 12; **8,** 1942, Nos. 5, 6, 7, 10. E. Labin, *J. Soc. Motion Picture and Television Eng.*, **54,** 393, 1950. E. Baumann, *J. British Institution of Radio Engineers*, **12** (New Series), No. 2, 69, 1952.