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Peer reviewed

## Servo-Controlled Infrared Optometer\*

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A device is described that provides an electrical signal proportional to the instantaneous refractive power of the human eye. Infrared light illuminates a target whose optical distance from the subject's eye can be changed rapidly. The position of this target is servo controlled in such a way that it remains conjugate with the retina regardless of changes of the subject's state of accommodation. The position of the target provides a direct measure of refractive power. The device may be used on an undrugged eye and does not interfere with normal visual tasks.

INDEX HEADINGS: Vision; Optical system; Infrared.

During the past century, a large number of different techniques have been developed to measure the state of focus of the human eye.<sup>1</sup> Here, we will describe an optometer that we believe offers substantial improvements over those previously reported. It can be used on an undrugged eye, does not interfere with visual tasks, follows the fastest changes of the refractive state of the eye, has a wide diopter range, and is reliable and relatively easy to align and operate.

### UNDERLYING PRINCIPLE OF OPERATION

Figure 1 is an optical diagram of an eye viewing a point source through a small aperture. (The scale has been deliberately distorted to facilitate exposition.) In Fig. 1(a), the refractive power of the cornea and lens of the eye are such that the point is sharply imaged on the retina. That is, the eye is focused on the point. In this case, if the aperture were moved from position A to position B, the illuminated spot would not move on the retina, although different bundles of rays from the source would strike that spot.

In Fig. 1(b), the refractive power of the eye is less than that required to bring the source into focus on the retina. In this case, a movement of the artificial pupil does change the position of the illuminated spot on the retina. In particular, the retinal spot moves in the same direction as the pupil, e.g., from position A' to B' in response to pupil movement from A to B.

Conversely, in Fig. 1(c), the refractive power of the eye is too great, and the image is formed in front of the retina. Consequently, any movement of the artificial pupil causes a movement of the illuminated retinal spot in the opposite direction.

If you could look into the subject's eye and watch the illuminated spot on the retina while moving the artificial pupil in front of the eye, you could therefore tell whether the source is in focus, or too close to, or too far from the eye. The plane that is conjugate to the retina can readily be found by changing the distance of the source until movement of the artificial pupil produces no movement of the illuminated spot. The resulting distance of the source from the eye is then a direct measure of the refractive power of the eye. (This is closely related to the method called retinoscopy.) The optometer

described below automatically performs these operations, continuously and rapidly.

### IMPLEMENTATION

Figure 2 is a schematic diagram of the complete apparatus. The optical system will be described first.

The subject's head is fixed in position by a dental-impression plate, and he looks through a dichroic mirror DM at whatever visual display is under study. This mirror is coated to transmit visible light but strongly

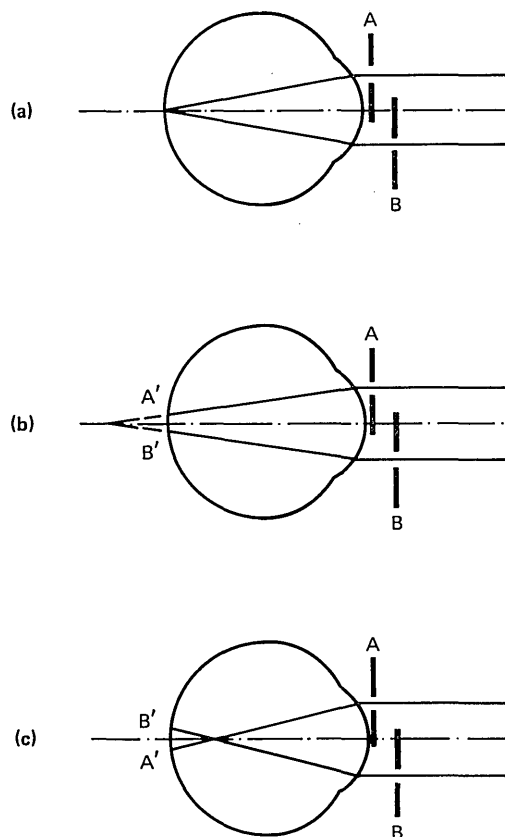


FIG. 1. Imaging a point target at infinity through a small aperture that alternates between two positions, A and B. The intercepted-ray position at the retina will be stationary, or move with the aperture, or opposite to the aperture, respectively, according to whether the eye is focused for infinity (a), beyond infinity (b), or closer than infinity in (c).

reflects the near ir. (Its back surface is antireflection coated for near ir.) Thus, as far as the subject is concerned, he is looking at the display through a piece of ordinary glass. Any visual display whatever may be used so long as its illumination does not contain infrared that is fluctuating rapidly. For example, incandescent-lamp illumination is suitable if the lamp is operated from a source of direct current.

**The Input Path**

The source of light for the optometer itself, labeled S in Fig. 2, is a cluster of four solid-state (gallium arsenide) ir light emitters (Monsanto M120C), mounted adjacent to each other in one header, as shown in the insert to Fig. 2. These sources are switched on and off in pairs, i.e., at one moment the two emitters on the left are on, and then the two on the right are on. The source is thus a pair of spots of infrared light that shift back and forth horizontally. (We use a frequency of 150 Hz, although the frequency is not critical.) The light from these emitters has a peak wavelength of 900 nm and a half-band width of 40 nm, and is completely invisible.

The light-source driver LD has as its input from GN, a sine wave of fixed frequency. At its output, it switches abruptly from one pair of light emitters to the other at each zero crossing of the sine wave.

The source is in the focal plane of lens L<sub>1</sub>, which thus collimates the light. The rays then pass through a rectangular aperture in a stop, ST<sub>1</sub>, through lens L<sub>2</sub>, and are reflected from the dichroic mirror DM to a beam splitter BS. This beam splitter is coated to reflect 50% of the ir and to transmit the remainder; its back surface is antireflection coated for the near ir. The incident light that is reflected from BS is reflected again from the dichroic mirror and into the eye. The light transmitted through BS is removed by a light trap LT. Because the rays from the source are collimated by lens L<sub>1</sub>, an image of the source is formed in the focal plane of L<sub>2</sub>. The eye is placed so that its natural pupil is also in this plane. The focal length of L<sub>1</sub> is chosen so that the largest dimension of the image of the source is 2 mm at the eye. (The focal length of L<sub>2</sub> is determined as explained below.)

If the subject's eye E were correctly focused on the plane of ST<sub>1</sub>, a sharp image of the rectangle would be formed on the retina. Furthermore, because the source is imaged in the plane of the natural pupil, the subject sees the rectangle as though he were looking through a small pair of artificial pupils that are shifting back and forth horizontally across his natural pupil.

When the eye is correctly focused on the plane of ST<sub>1</sub>, the illuminated region of the retina will be stationary as the sources are alternated, but when it is focused nearer or farther than the plane of ST<sub>1</sub>, the illuminated region will move when the source is alternated. The direction of movement, relative to the movement of the source, is an indication of the direction of the focus error, as

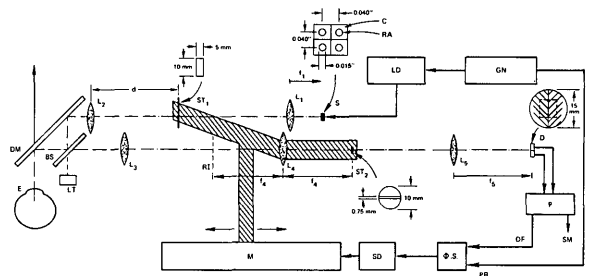


FIG. 2. Schematic diagram of the optometer. Legend: S, gallium arsenide diodes; ST<sub>1</sub>, input stop; DM, dichroic mirror; BS, beam splitter; LT, light trap; RI, plane conjugate to retinal image; ST<sub>2</sub>, corneal stop; D, split-field photocell; P, preamplifier; DF, difference signal; SM, sum signal; PR, phase reference; ΦS, phase sensitive detector; SD, servo driver; M, linear motor; GN, sine-wave generator; LD, light-source driver; C, light-emitter chip; RA, radiating area. ST<sub>1</sub>, L<sub>4</sub>, and ST<sub>2</sub> are mechanically coupled and are driven by M, a linear motor. The eye views any target through the dichroic mirror along the path indicated by the arrow. The inset referring to D illustrates the position of the nominal retinal image on the detector.

indicated in Fig. 1. The remainder of the optical system in Fig. 2 detects the phase of the movement of the retinal image relative to the movement of the source, and automatically and continuously moves the stop ST<sub>1</sub> closer to or farther from the eye, to keep it in that plane where there is no retinal image movement, that is, in the plane conjugate with the retina.

The output of the instrument is a voltage proportional to the axial position of ST<sub>1</sub>, which is convenient because the refractive power of the eye in diopters is linearly related to the axial position of ST<sub>1</sub>, according to the relation<sup>2</sup>

$$D_e = -\frac{1}{f_2} \left( 1 - \frac{d}{f_2} \right), \tag{1}$$

where D<sub>e</sub> is the refractive power of the eye,<sup>3</sup> f<sub>2</sub> is the focal length of lens L<sub>2</sub> in meters, and d is the distance of ST<sub>1</sub> from L<sub>2</sub> in meters. Thus, we see that the greatest positive power that the optometer can measure (when ST<sub>1</sub> is against L<sub>2</sub>, i.e., d=0) is the reciprocal of the focal length of L<sub>2</sub>. The greatest negative power (where d > f<sub>2</sub>) is set by the otherwise arbitrary position of lens L<sub>1</sub>.

**Detection Path**

Some of the light reflected from the retina emerges from the eye and is reflected from the dichroic mirror DM. Half of this light passes through the beam splitter BS (the other half is lost), and then through lens L<sub>3</sub>, which is at its focal distance from the natural pupil, and whose focal length is identical with L<sub>2</sub>. Thus, lens L<sub>3</sub> collimates the light diverging from the plane of the pupil of the eye, and it also forms an image of the retina in a plane labeled RI (retinal image). When the stop ST<sub>1</sub> is conjugate with the retina, the distance between L<sub>3</sub> and RI is equal to d (i.e., the distance between L<sub>2</sub> and ST<sub>1</sub>), regardless of the position of ST<sub>1</sub>. This is so be-

cause when  $ST_1$  is in focus on the retina, the retina, by reciprocity, is simultaneously in focus in the plane of  $ST_1$ . Thus  $ST_1$  and RI are optically equivalent planes equally distant from identical lenses  $L_2$  and  $L_3$ , respectively.

Lens  $L_4$  is rigidly attached to the movable carriage that holds  $ST_1$ , and in such a position that RI is in its focal plane when  $ST_1$  is in its correct axial position, i.e., conjugate to the retina. Thus,  $L_4$  collimates the light from the retinal image. It also forms an image of the natural pupil in its second focal plane. Input light reflected from the cornea forms an image (generally referred to as a corneal image) of the aperture in  $ST_1$ . This is a virtual image that falls almost exactly in the natural pupil plane. Thus, an image of the corneal image also appears in the second focal plane of  $L_4$ . This corneal reflection is quite strong in comparison with the light reflected from the retina; furthermore, the amount of corneally reflected light passing through  $L_3$  will change strongly as the position of the source changes. Therefore, it can introduce strong artifact signals unless it is eliminated. This is accomplished by stop  $ST_2$ , which is also rigidly attached to the carriage that holds  $ST_1$  and  $L_4$ , and is located in the second focal plane of  $L_4$ . The stop contains a round aperture, larger than the image of the natural pupil, with an opaque bar running horizontally across it. The bar is positioned so that the corneal image falls entirely on it, while most of the light reflected from the retina passes on to lens  $L_5$ . The corneal stop must be made larger than the actual corneal image in order to minimize the need for critical subject alignment (discussed below) and also to provide tolerance for eye movements. The horizontal bar permits great freedom of horizontal eye movement.

Because  $L_4$  collimates the light from the retinal image in plane RI, another image of the retina is formed in the focal plane of  $L_5$ , where a photodetector D is placed. This detector is a large-area, split-field, silicon planar photocell, placed so that the dividing line between the two halves runs vertically down the middle of the image of  $ST_1$ , as indicated in the inset to Fig. 2.<sup>4</sup> Whenever the retinal image of  $ST_1$  moves from side to side (i.e., whenever  $ST_1$  is not conjugate with the retina), the relative amounts of light falling on the two halves of the detector change, and a signal is generated that is used to drive  $ST_1$  (and  $L_4$  and  $ST_2$ ) toward the plane of best focus.

### Electronics

The two halves of the photodetector drive a dual preamplifier P that has as available outputs the (amplified) signal from the sum of the two halves of the detector as well as the difference between the two halves. The sum output is used for aligning the instrument.<sup>5</sup> The difference signal is fed into an amplifier that is sharply tuned to the frequency of the sine-wave generator. The amplified and filtered signal is then fed to a phase-sensitive demodulator. The demodulator com-

pares the phase of the difference signal with that of the sine-wave generator, and delivers an output whose dc level is proportional to the difference signal. For example, if the difference signal is large and in phase with the reference sine wave, the output of the demodulator will be a large, positive voltage; if the difference signal is small and out of phase with the reference, the output will be a small, negative voltage.

The output of the demodulator drives the circuits that control the servo motor, which, in turn, mechanically shifts the carriage containing  $ST_1$ ,  $ST_2$ , and  $L_4$ , to complete the servo loop. (We are using a slightly modified Esterline Angus speed servo kit, which is a fast linear servo motor.) When the optometer is in operation, the carriage continuously maintains an axial position such that  $ST_1$  is conjugate with the retina. Because the correct axial position is linear with the refractive power of the eye, in diopters, any measure of the position of the carriage can be used as a readout for the optometer. We use a retransmit potentiometer (available with the servo motor), which is simply a slide wire mounted on the servo motor, with a wiper attached to the carriage, to provide a voltage that is linear with carriage position.

## ALIGNMENT

### Possible Calibration Artifacts

Let us examine now some of the potential sources of error in this instrument. We will consider first how changes of the size of the subject's pupil affect the instrument. Because the natural pupil almost never constricts to smaller than 2 mm in diameter under natural viewing conditions, and because the largest dimension of the image of the source in the plane of the pupil is just 2 mm, the natural pupil has no effect upon the input light (as long as the image is reasonably well centered on the natural pupil). However, the amount of light falling on the photodetector does depend linearly upon the area of the natural pupil because the circular aperture in  $ST_2$  is larger than the image of the pupil. Thus, when stop  $ST_1$  is not conjugate with the retina, the difference signal that drives the servo will change with pupil size. But this changes only the tightness and speed with which the servo seeks its null. In other words, changes of pupil size cause only second-order changes of response.

A more important problem arises if the two pairs of light sources do not deliver exactly equal amounts of light to the eye. In this case, even if stop  $ST_1$  were precisely conjugate with the retina, there would still be a difference signal, an artifact, generated in the detector (at either  $0^\circ$  or  $180^\circ$ ) if the retinal image were not exactly centered on the photodetector, or if the two halves of the detector have differing sensitivities. This artifact signal would cause the carriage to move until a real difference signal just compensated for the artifact. If everything else were perfectly constant, the result would simply be a fixed error of the optometer reading. However, any change of instrument sensitivity, such as the

increase of sensitivity that would accompany an increase of the size of the natural pupil, would cause a change of the error. Therefore, it is important to insure that when the source alternates from left to right, there is no correlated change of the total amount of light falling on the detector. This is readily accomplished by adjusting the relative intensities at the two source positions until the ac component of the sum signal (from the two halves of the detector) is zero. In contrast to the difference signal, the sum signal is very insensitive to the position of the slider, so that it is unnecessary to position the slider accurately for this adjustment.<sup>6</sup> It is easy to show that this adjustment also overcomes any potential source of artifact from different sensitivities of the two halves of the split-field cell.

Once this electronic adjustment has been made, the tolerances for mechanical alignment of the device can be greatly relaxed. For example, the axial position of  $ST_1$  that yields a null will not then be affected if the image of  $ST_1$  is not centered on the dividing line between the two halves of the detector. Thus, the calibration of the instrument is unaffected even if the average position of the image of  $ST_1$  should shift across the detector when the carriage is moved (if, for example, the two paths are not precisely parallel or if  $L_4$  is not centered correctly).

### Subject Alignment

The only really critical alignment necessary to avoid artifacts is the alignment of the eye to prevent any light reflected by the cornea from reaching the detector. It would be possible to eliminate the corneal reflection merely by moving the eye sideways or up or down until the corneal light entirely missed lens  $L_3$ . Although this is quite easy to do, two results must be considered. First, if the eye is too far from the optic axis of the instrument, the natural pupil can intercept a portion of the input light, which would cause a serious artifact. (Even if the natural pupil seems large enough to avoid this problem, it must be remembered that the pupil constricts when the subject increases his accommodation and that some tolerance is needed to permit a certain amount of eye movement.)

Second, it has been reported,<sup>7</sup> and we have verified, that the spherical aberration of the eye changes with changes of refractive power (Fig. 6). Therefore, for any given change of refractive power, the optometer would read a different change if the image of the source is centered on the pupil than if it is near one edge. (The optometer reads only the refractive power of that portion of the entrance pupil of the eye that is actually illuminated by the image of the source.)

With the eye centered on the optic axis of the optometer, which is the practice we have adopted, light from the corneal reflection enters  $L_3$ , but is removed by the corneal stop  $ST_2$ . As noted earlier, because the stop is a horizontal bar, the eye need only be aligned accurately in the vertical direction (or horizontally if you prefer

to make the bar across  $ST_2$  vertical). It is also important to align the eye axially, so that the image of the corneal reflection is sharply focused in the plane of  $ST_2$ . The easiest way to accomplish this alignment is to place a mirror at  $45^\circ$  just behind  $ST_2$ , and to examine the image in the plane of  $ST_2$  with an ir viewer. This is actually a very rapid alignment procedure.

### Selection and Calibration of Range

On the basis of Eq. (1), the instrument could be calibrated directly, in, say, diopters per millimeter on the carriage track, or diopters per volt of the electrical read-out. However, the basis for such a calibration must be carefully examined.

First, the focal length of  $L_2$  that is used in the equation must be the focal length at a wavelength of 900 nm. If the lens is an achromat, this will be negligibly different from its focal length in the visible. Next, the chromatic aberration of the eye must be considered. The optometer actually measures the refractive power of the eye at 900 nm, which, extrapolating from published chromatic-aberration data, is between  $\frac{3}{4}$  and 1 diopter weaker than at 550 nm.<sup>1</sup>

In addition, another factor must be considered. When the carriage is in the position that nulls the difference voltage, the stop  $ST_1$  is nominally conjugate with the retina. But that is inexact because the retina is thick enough that the difference between its front and back surfaces can be as great as 0.5 mm, which corresponds to almost 2 diopters. If the plane that acts as the principal reflector for 900-nm light is not the same as the plane of the visual sensitivity, then the optometer will read a different refractive power than the power determined by finding the plane that yields optimal visual acuity.

As yet, there is no clear evidence to indicate what plane of the retina is the effective reflector for radiation at 900 nm. However, it is likely that it is reflected not from a single plane, but from one or more regions of the retina, possibly including the inner limiting membrane, because Weale has shown that an appreciable percentage of the visible light reflected from the retina is specular.<sup>8</sup> In general, the reading of the optometer will be a measure of the refractive power of the eye referred to some plane that is the equivalent of the sum of all sources of reflection.

Our optometer consistently gives a reading about 1.5 diopters different from the plane of best visual focus. That is, when a fine target is presented to the subject at optical infinity and he indicates, by his high acuity, that the target is conjugate with his visual receptor cells, the carriage drives stop  $ST_1$  to about 1.5 diopters beyond the focal plane of  $L_2$ . Chromatic aberration probably accounts for between  $\frac{3}{4}$  and 1 diopter of this discrepancy, as noted above. We tentatively explain the remaining  $\frac{1}{2}$  to  $\frac{3}{4}$  diopter by postulating that the capillary bed of the retina, which is about 0.3 mm, or 1

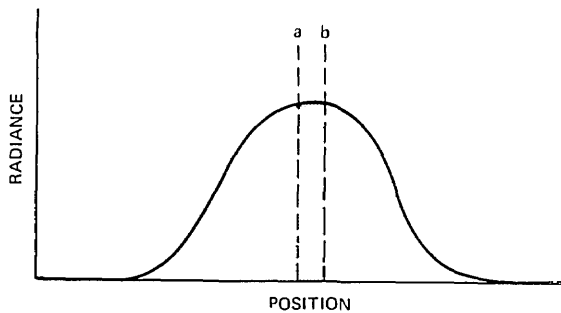


FIG. 3. Detecting retinal image movement. The smooth curve represents the spatial distribution of irradiance on the photodetector, and the two dashed lines represent two positions of the dividing line between the halves of the photodetector. (For ease of illustration, assume that the photocell moves, rather than the image.) The magnitude of the signal from each half of the photocell is directly proportional to the shaded area, i.e., to the product of the peak irradiance of the image and the movement distance  $ab$ .

dioppter, closer to the cornea than the receptor endings, contributes a large component of reflected light at 900 nm.

We have not yet studied enough subjects to draw firm conclusions about the consistency of this dioppter shift in the population. Until that is done, and even afterwards if there is a wide variation in the population, the dc calibration of the instrument with respect to the visual process itself must be performed on each individual subject. However, the relative calibration, that is, the number of diopters per unit of carriage travel, can be correctly determined from Eq. (1) because it is reasonable to assume that the configuration of the reflection pattern does not change during accommodation.

The problem of absolute calibration is basic to any ir optometer and is a question that warrants considerable further study, in view of the potential usefulness of ir optometry. Of course, this instrument could readily be operated with visible light, by using different light sources.

### Near-Infrared Line-Spread Function

Before arriving at the optometer design shown in Fig. 2, we tested several much simpler and more elegant designs. All of them worked superbly on model eyes, but with real eyes they failed completely. Those attempts left us with the impression that ir images may be badly blurred on the retina. This was further suggested by the fact that whenever we tried to examine a subject's retina in near-ir light, using an ophthalmoscope and ir viewer, the detail seemed very badly blurred.

We therefore made some preliminary measurements of the line-spread function, on the retina, for 900-nm radiation. Although the results of these measurements are not yet firm enough to justify reporting them in quantitative form, they do confirm that the spread function for 900-nm illumination is very much broader than

for visible light, i.e., at least  $1^\circ$  of arc as compared with a few minutes in the visible.

The breadth of the line-spread function in the near ir has important implications for the design of ir optometers. For example, changes of the definition of the retinal image of a fine grating illuminated by ir light cannot be used because the definition will be very poor regardless of the state of focus of the eye.

The optometer described here is insensitive to the breadth of the line-spread function, however, because as illustrated in Fig. 3, the difference signal is proportional only to the height of the shaded area, regardless of the shape of the irradiance profile at its edges (as long as the detector is large enough to catch most of the light).

The broad line-spread function is important in determining the width of the rectangular aperture in  $ST_1$ . If the line-spread function were very narrow, then the aperture in  $ST_1$  need be only wide enough that its image is wider than the (very narrow) insensitive strip between the two halves of the photocell. If the aperture were made wider than that, the response of the instrument would, at first, improve somewhat, until the aperture became as wide as the largest side-to-side movement of the image. Any further increase of width would not increase the difference-signal strength, though it would increase the quantum noise in the signal, which increases

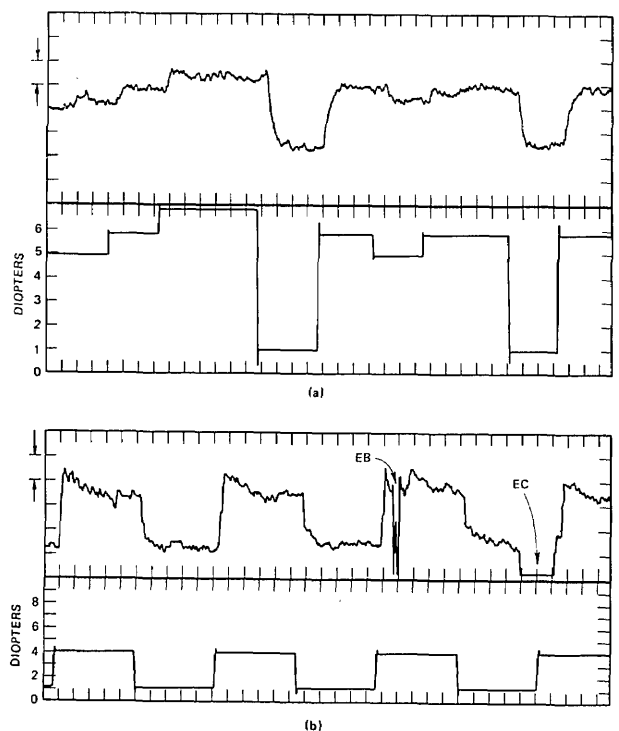


FIG. 4. Typical optometer records. The lower trace in each record is the stimulus distance as a function of time. The calibration marks represent 1-diopter shifts. The time markers indicate 1-sec intervals. Note the automatic recovery from an eye blink (EB) and from closing the eye (EC).

as the total amount of light falling on the detector increases.

On the other hand, when the line-spread function is broad, there is a definite advantage of further widening the rectangular aperture in  $ST_1$ . In this case, until the aperture width is comparable to the line-spread function itself, increased width primarily increases the flux density rather than the width of the image on the detector, and this, in turn, increases the magnitude of the difference signal. The optimal aperture has a width roughly equal to the half-width of the line-spread function. Thus, when we increased the width of the aperture in  $ST_1$  from 1 to 5 mm, (i.e., from an angular subtense of  $40'$  to  $3^{\circ}20'$  on the retina), a large improvement of the signal/noise ratio resulted.

**SOME REPRESENTATIVE RESULTS**

Figure 4(a) shows typical responses of a young subject under the following conditions. The visual target was a coarse, vertical grating with a small fixation mark near its center, presented monocularly. Its optical distance from the subject [indicated by the lower line in Fig. 4(a)] was changed without any accompanying change of size or brightness.<sup>9</sup> These responses show a typical latency of about 0.4 sec.

Figure 4(b) is a record taken by Robert Randle of NASA Ames Research Center, using an optometer essentially the same as that described in this paper. The record shows a subject with very high response velocities (about 20 diopters per second). It is interesting, in contrast, that extremely low response velocities to monocular step displacements of targets are also common, even among the under-30-year-old population (e.g., 6 sec to complete a 2-diopter response), although the 0.4-sec latency (to the beginning of the response) seems to be quite constant in all responses that we have thus far recorded.

Figure 5 shows a response to a sine-wave target displacement while the frequency of the sine wave gradu-

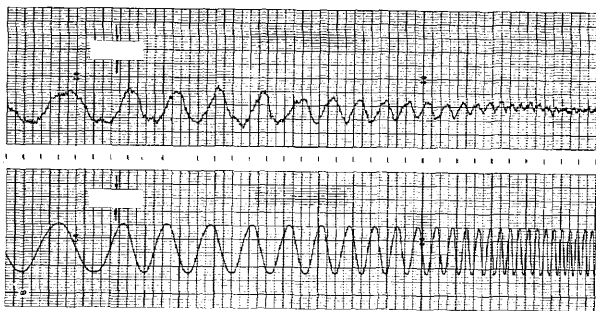


FIG. 5. Response to a 3.5-diopter peak-to-peak sinusoidal target displacement of increasing frequency. The lower trace is the stimulus distance as a function of time. The upper trace is the optometer record. The arrow pairs indicate 1-diopter calibration marks. The time markers indicate 1-sec intervals. The response is  $180^{\circ}$  out of phase and is down to  $\frac{1}{2}$  amplitude at approximately 1 Hz.

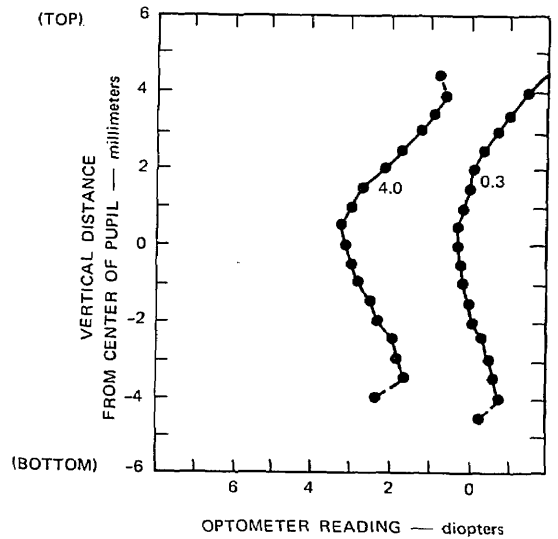


FIG. 6. Spherical aberration of the human eye for two different fixation distances, corresponding to 0.3- and 4.0-diopter refractive powers. These curves represent the refractive power measured along a vertical line down the center of the pupil. At both fixation distances, the center of the entrance pupil manifests greater refractive power than the edges. That is, the eye exhibits overcorrected spherical aberration over the entire normal viewing range of this particular subject, at least in the vertical meridian. (This particular subject's aberration is quite symmetric, but many eyes show strong asymmetries.)

ally increases. Note that the response amplitude is down to one half and lags by  $180^{\circ}$  at about 1 Hz.

The data in Fig. 6 are measures of the spherical aberration of a subject's eye, obtained with the optometer in the following way. One member of each vertical pair of ir light emitters was disconnected, so the light entered the pupil through a 1-mm spot that moved horizontally back and forth over a distance of 1 mm. The pupil was dilated with two drops of 10% neosynephrin. (Though dilation is not required in using the optometer, it was used here to permit measurement of a larger portion of the entrance pupil of the eye.) While the subject held his focus on a target, the image of the ir source was made to trace out a vertical track down the middle of the pupil.

The two curves in Fig. 6 are plots of the readings of the optometer as a function of vertical position at the eye, for two different distances between the target and the eye, namely, 3 m (0.33 diopters) and 25 cm (4 diopters). For this subject, the refractive power at the edges of his entrance pupil is less than at the middle (i.e., his eye manifests overcorrected spherical aberration), and the amount of aberration is greater when he is looking at the nearer target.

**ACKNOWLEDGMENTS**

We gratefully acknowledge the invaluable assistance of G. Eilers in the design of the servo-control circuits, and R. Randle, Ames Research Center, NASA, for furnishing the records in Fig. 4(b).

## REFERENCES

\* Work was supported by Contract No. NAS2-5097 between NASA, Ames Research Center, and Stanford Research Institute.

<sup>1</sup> See Y. Le Grand, *Form and Space Vision*, rev. ed. (Indiana University Press, Bloomington, Ind., 1967), for an interesting review of early techniques. Recently, optometers have been described by M. J. Allen and J. H. Carter, *Am. J. Optom.* 37, 403 (1960); F. W. Campbell and J. G. Robson, *J. Opt. Soc. Am.* 49, 268 (1959); J. G. Carter, *Arch. Soc. Am. Ophthal. Opt.* 4, 137 (1962); N. Roth, *Rev. Sci. Instr.* 36, 1936 (1965); J. Warshawsky, *J. Opt. Soc. Am.* 54, 375 (1964). All of these instruments operate on the same underlying principle. The one described here most closely resembles Campbell and Robson's optometer.

<sup>2</sup> This is a consequence of the fact that the eye is in the focal plane of  $L_2$ . The relationship is derived, e.g., in G. Westheimer, *Vision Res.* 6, 669 (1966).

<sup>3</sup> We will use the convention, here, of stating the refractive power of the eye relative to its power when accommodated for infinity. That is, 0.0 diopters of refractive power means that the retina is conjugate with infinity; at 2.0 diopters, the retina is conjugate

with a plane 1/2.0 m away, etc. The absolute refractive power of a normal eye accommodated for infinity is about 60 diopters (i.e., its equivalent focal length is about 17 mm).

<sup>4</sup> We are using a quadrant cell, Electro Nuclear Labs (Menlo Park, Calif.) model 640A, in which the two members of each vertical pair are connected in parallel.

<sup>5</sup> The dc component of the sum is directly proportional to the area of the subject's natural pupil, and may be monitored if pupil size is of interest.

<sup>6</sup> If there were inhomogeneities of transmittance across the entrance pupil of the eye, the relative amounts of light transmitted to the retina from the two source positions might vary with eye movements. The resulting artifact could be avoided if the sum signal were used continuously and automatically to control the relative intensities of the sources.

<sup>7</sup> A. Ivanoff, *Les aberrations de l'oeil* (Editions de la Revue d'optique, Paris, 1953).

<sup>8</sup> R. A. Weale, *J. Physiol.* (London) 186, 175 (1966).

<sup>9</sup> The optical display system used in these experiments is described in Crane and Cornsweet, *J. Opt. Soc. Am.* 60, 577 (1970).



R. F. Hoban (l.), Sandoz Chemicals, and F. T. Simon, Clemson University, at meeting of Inter-Society Color Council Problem Committee on Colorimetry of Fluorescent Materials, 29 September 1969.