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ENHANCEMENT OF NIGHT VISION BY CORRECTION OF OPTICAL ABERRATION OF THE EYE.

WIDE ANGLE MODEL OF THE EYE

FINAL COMPREHENSIVE REPORT

OLEG POMERANTZEFF

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ABSTRACT

A wide angle model of the eye was developed from statistical studies and tested with data from 100 emmetropic volunteers. The data from the volunteers showed that it was necessary to redesign the model to fit several classes of eyes.

Citation of trade names in this report does not constitute an official Department of Army endorsement or approval of the use of such items.

For the protection of human subjects the investigator have adhered to policies of applicable Federal Law 45CFR46.

TECHNICAL REPORT

↙ The purpose of the research done under this grant was to enhance night vision by designing a special contact lens that would correct the off-axis aberrations that occur in eyes with widely dilated pupils. Improving the quality of the off-axis image focused on the retina, when the pupil is dilated to admit more light into the eye, would permit better vision in low-level illumination.

We started by designing a wide angle model of the eye, based on data from statistical studies made elsewhere. (1) The model was designed to represent an average emmetropic eye with parameters similar to those most frequently found in the normal population.

A group of 100 emmetropic volunteers were selected and the parameters to be used in calculating the model were measured on their eyes. (see Appendix) One parameter, the axial length of the eye, could not be measured at that time because the ultrasonic scanner intended for those measurements was at the manufacturer for repairs. The data collected from volunteers showed us that our general model was not applicable to every emmetropic eye. Therefore, we classified the eyes into groups according to their parameters; we planned to develop special modifications of the model for each group.

Before undertaking this redesign, we had to change our approach to the calculation of the basic model itself. The number of layers in the crystalline lens was increased indefinitely, their thicknesses becoming infinitely small. Thus the layers were transformed into isoindicial surfaces. This approach enabled us to condense the computer program and reduce the number of computations.

At this stage the work was interrupted for two reasons: (1) the grant expired and new funds were not available; (2) our Xerox Sigma Three computer system was not adequate for continuation of this project, and we did not have a satisfactory alternative.

The eye model designed under this grant was used to develop the Equator Plus Camera, which is now commercially available and has been extensively used on patients.

The Appendix shows the procedure used for the design of the first wide-angle model of an average emmetropic eye.

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- (1.) Sorsby A, Benjamin B, Davey JB, Sheridan M, Tanner JM: Emmetropia and its aberrations: a study in the correlation of the optical components of the eye. Medical Research Council Special Report Series No. 293. London, Her Majesty's Stationery Office, 1957.

APPENDIX

Measurement of Parameters on a Living Human Eye

The following parameters were used to design a mathematical model of the human eye. To obtain the data necessary for testing the model, these parameters were measured in living eyes.

1. Radius of curvature of the central portion of the front surface of the cornea.
2. Thickness of the cornea.
3. Radius of curvature of the central portion of the back surface of the cornea.
4. Depth of the anterior chamber.
5. Radius of curvature of the central portion of the front surface of the crystalline lens.
6. Thickness of the crystalline lens (unaccommodated).
7. Radius of curvature of the central portion of the back surface of the crystalline lens.

A. The following parameters were measured with various instruments:

1. Radius of curvature of the cornea (front surface).

An ophthalmometer or keratometer provides a direct reading in millimeters or diopters. An ophthalmophakometer has to be calibrated with a sphere (ball bearing) of known diameter. In order to keep the magnification constant, the focusing ring of the camera should be locked after calibration. The focusing will then be done by using the rack and pinion on which the camera body is mounted.

2. Thickness of the cornea

The Haag-Streit phakometer #1, mounted on the slit lamp, provides a direct reading.

Slit-lamp photographs of the cornea can be measured to determine corneal thickness, but this method is less precise than a phakometer.

3. Radius of the back surface of the cornea

This is one of the most imprecise of the measurements that were made, but it is less important because the power of this diopter is small.

The radius can be obtained from a slit-lamp photograph of the cornea. This is done with a Haag-Streit slit lamp and the MIRA photographic attachment. The angle between the viewing system must be known in order to apply the necessary corrections. This angle is not equal to the angle read on the main shaft, because the camera is fitted on one eyepiece tube which makes an angle with the support. Generally, the biomicroscopes are of the Greenough stereomicroscope type with an angle between the two bodies of 10 to 18 degrees.

The setting of the power supply should be close to the maximum for Kodak Tri-X film and the film should be developed normally. The subject's pupil is dilated and he or she is asked to look straight into the slit. The centering is done so that the reflected image of the slit sends the light back onto the illuminating mirror.

4. Depth of the anterior chamber

The Haag-Streit phakometer #2, mounted on the slit lamp, provides a direct reading.

Slit-lamp photograph measurements, properly corrected, will give the depth. This is less precise than the preceding method. It requires calibration of the magnification of the camera, but may be used as a check on the calculations and the equipment, since it is used anyway to determine Parameter 7, the thickness of the crystalline lens. It is described in section 3 (above).

1.,3.,5.,7. Measurement of the radii of curvature of the cornea and crystalline lens.

These measurements are done with an ophthalmophakometer built in our laboratory.

B. The procedures are as follows:

The values of the indices of refraction of the media are assumed to be:

Cornea	1.376
Aqueous humor	1.336
Crystalline lens (total index)	1.41

The radius of curvature of the anterior surface (Parameter 1) of the cornea is measured with a clinical keratometer or ophthalmometer (Fig. 1).

The thickness of the cornea (Parameter 2) is measured with a Haag-Streit phakometer (attachment #1) (Fig. 2).

The depth of the anterior chamber (Parameter 4) and thickness of the lens are measured with a Haag-Streit phakometer (attachment #2) (Fig. 2).

The radius of curvature of the back surface of the cornea (Parameter 7) is measured from a photograph of a slit lamp section of the cornea.

The radius of curvature of the anterior and posterior surfaces of the crystalline lens (Parameters 5,7) are calculated from the measured size of the Purkinje-Sanson images of those surfaces. The apparatus used is a photo-ophthalmophakometer designed and built in our laboratory (Fig. 3). We will describe only this last procedure because the apparatus is not commercially available and the measurement is not a standard procedure.

Ophthalmophakometry

We photograph the reflections of two light sources from surfaces of the eye; the front surface of the cornea, and front and back surfaces of the the crystalline lens. From the known geometry of the anterior segment of the eye, and the size of the images, the radii of the crystalline lens are computered (See "Calculations").

Figure 3 shows the apparatus. It utilizes the mechanical support and adjustment control from a slit lamp. A single-lens reflex camera is mounted on a rack and pinion mechanism for focusing, in place of the biomicroscope, and the box containing the light source replaces the slit-lamp illumination. A fixation lamp has been added to control the accommodation and the orientation of the eye. This control is done on the eye not under study.

Focusing on the images by moving the entire camera ensures that the magnification is constant. The details of the light source assembly are shown on Figure 4. The tungsten lamp is used during focusing. The pivoting mirrors are motor driven and two microswitches control the motor, the triggering of the camera shutter, and the flash tube. In the normal position, as shown on the figure, the pivoting mirrors reflect the light from the tungsten lamp. By depressing a knob on the control box, the operator initiates the following automatic sequence of events: the motor moves the pivoting mirror away from the flash tube light path; when the mirrors are fully open, a microswitch closes the circuit of a solenoid that actuates the camera shutter. The flash tube is ignited through the synchronization contact of the camera. A second microswitch stops the motor when the mirrors are back in the original position.

Experimental Technique

Fifteen minutes after instillation of two drops of 1% tropicamide for dilation of the pupil and paralysis of accommodation, the subject's head is immobilized on the head rest. The angle between the illumination axis and the camera axis is locked at 40° . The focusing light is switched on and the subject's fixation directed so that the reflected images from the front surface of the cornea and from the posterior surface of the lens appear together in the center of the pupil. These images are focused and photographed. The angle between the light source and the camera is increased to 60° to avoid obscuring the dim reflected images from the anterior lens surface with the very bright corneal images. The camera is focused on the images reflected from the anterior lens surface and a second exposure is made. Figure 5 (left) shows the three sets of Purkinje images when the focusing is done on the more separated images (front surface of the lens). These images are some 6 to 7 mm to the rear of the two other pairs which are approximately in the plane of the pupil. Figure 5 (right) shows the corneal and posterior lens images in focus. The photograph on the right was taken with a nondilated pupil and shows the possibility of studying accommodation of the eye. It is very difficult to observe the anterior lens image in an undilated eye.

Derivation of Data for Calculation

We use Kodak Tri-X and process it in D-76. The separation of the pairs of Purkinje images are measured on the negatives with a Joyce Loebel microdensitometer. This instrument provides accurate readings even if the images are badly defined. Figure 6 shows the trace from the microdensitometer for the three pairs of Purkinje images. The calculations are currently made using approximations and paraxial formulae. We are developing a program which will use the ray tracing whenever possible. For the back surface of the crystalline lens this direct approach is impossible because the shell-like structure in front of the back surface is

unknown before completion of the model. In this case the ray tracing is used up to the front surface of the lens and paraxial optics are used in the crystalline lens. The result is used by the computer to make a model with a shell structure. This model is then used to calculate a better value of the radius of the back surface. This iterative method can be repeated, depending upon the convergence of the process.

CALCULATIONS.

List of symbols used in the calculation:

n_1, n_2, n_3, n_4 — indices of refraction of the eye media

t_1 — thickness of cornea

t_2 — depth of anterior chamber

t_3 — thickness of the crystalline lens

r_1 — radius of the front surface of cornea

r_2 — radius of the back surface of cornea

r_3 — radius of the front surface of crystalline lens

r_4 — radius of the back surface of crystalline lens

c_3 — center of curvature of front surface of crystalline lens

c_4 — center of curvature of back surface of crystalline lens

A_1 — vertex of the front surface of cornea

A_2 — vertex of the back surface of cornea

A_3 — vertex of the front surface of crystalline lens

A_4 — vertex of the back surface of crystalline lens

h_1 — height of the Purkinje images from the cornea

h_3 — height of the Purkinje images from the front surface of lens

h_4 — height of the Purkinje images from the back surface of lens

These heights are relative values from the microdensitometric traces.

All distances are given in millimeters.

We know $r_1, h_1, h'_3, h''_4, t_1, t_2, n_1, n_2, n_3$. The value of t_3 is obtained when r is calculated.

For the calculations, the cornea is simplified. It is assumed to be a simple diopter of radius r_1 separating media of index n_0 and n_2 (Figure 7), and all the formulas are paraxial. The power of the simplified cornea in diopters is

$$F_1 = (1000 (n_2 - n_0)) / r_1$$

For the calculation of the radii of the lens we take advantage of the following property of mirrors: the height of an image formed by reflection from a spherical mirror is approximately proportional to the radius of the latter if the object is relatively distant. This principle forms the basis of keratometry. When used with the Purkinje images of the lens, a correction must be applied because these selected images are viewed through the media and refracting surfaces in front of the reflecting surface. What we measure before correction is the radius of the equivalent mirror whose vertex and center of curvature coincide with the images of the vertex and center of curvature of the real mirror formed by the refracting system in front of it. When the radius of the equivalent mirror is known in conjunction with the true vertex position of the mirror, it is a matter of applying the relation of conjugacy to get the true radius of curvature.

From the principle of keratometry we have

$$r'_3 / r_1 = h'_3 / h_1 \quad (I) \quad r''_4 / r_1 = h''_4 / h_1 \quad (II)$$

h''_4 and r''_4 are < 0 . All the other values are < 0 .

Anterior radius of curvature of the lens

$r'_3 = r_1 (h'_3 / h_1)$ This is the radius of the equivalent mirror.

The vertex A'_3 of the equivalent mirror is located in relation to A_1 by the formula

$$(n_2 / T - n_0 / T') = F_1 / 1000 \quad \text{where } T' = \overline{A_1 A'_3} \text{ and } T = \overline{A_1 A_3}$$

The center C'_3 is such that $\overline{A_1 C'_3} = \overline{A_1 A'_3} + r'_3 = T' + r'_3$

The center C_3 is the conjugate of C'_3

$$(n_2/(T + r_3) - n_0/(T' + r'_3)) = F_1/1000$$

Posterior radius of curvature of the lens

We know the true thickness of the lens t_3 .

The surface power of the anterior surface of the lens is

$$F_3 = (1000 (n_4 - n_3))/r_3$$

If $\overline{A_3 A'_4} = t'_4$ (Figure 8), we have

$$n_3/t_4 - n_2/t'_4 = F_2/1000$$

If we put $p' = \overline{A_1 A'_4} = \overline{A_1 A_3} + \overline{A_3 A'_4} = T + t'_4$ and $p'' = \overline{A_1 A''_4}$

we also have

$$n/p' - n/p'' = F_3/1000$$

This gives us the vertex of the equivalent mirror. For the center of the equivalent mirror we apply the same conjugacy but in reverse order because we know the position of the center of the equivalent mirror:

$$\begin{aligned} q^{*''} &= \overline{A_1 C''_4} = \overline{A_1 A''_4} + \overline{A''_4 C''_4} \quad (\text{Figure 9}) \\ &= p'' + r''_4 \quad (r''_4 \text{ is } < 0) \end{aligned}$$

r''_4 being given by equation(II)

$$n_2/q' - n_0/q'' = (n_2 - n_0)/r_1$$

$$q^{*'} = \overline{A_1 C'_4}$$

$$q' = \overline{A_3 C'_4} = \overline{A_3 A_1} + \overline{A_1 C'_4} = -T + q'$$

and by conjugacy through the anterior surface of the lens we get

$$n_3/q - n_2/q' = (n_3 - n_2)/r_3$$

$$\text{with } q = \overline{A_3 C_4}$$

$$\begin{aligned} \text{From } q \text{ and } p = t_3 \text{ we deduce } r_3 &= \overline{A_4 C_4} \\ &= \overline{A_4 A_3} + \overline{A_3 C_4} \\ &= -t_3 + q \end{aligned}$$

FIGURE LEGEND

- Fig. 1 Clinical keratometry (ophthalmometer) is used to measure the radius of curvature of the anterior surface of the cornea.
- Fig. 2 Haag-Streit phakometer mounted on a slit lamp is used to measure (1) the thickness of cornea, (2) depth of the anterior chamber, (3) thickness of the crystalline lens.
- Fig. 3 Overall view of the photoophthalmophatometer, which is the apparatus for measurements of the radii of the curvature of anterior and posterior surfaces of the crystalline lens.
- Fig. 4 Internal structure of the photoophthalmophatometer used to photograph Purkinje images from the anterior and posterior surfaces of a crystalline lens.
- Fig. 5 (left) Photograph of the Purkinje images when camera focused at more separated images (anterior surface of the crystalline lens).
(right) Photograph of the Purkinje images from the cornea and posterior surface of the crystalline lens.
- Fig. 6 The trace from the microdensitometer for the three parts of Purkinje images used for calculation of their separation.
- Fig. 7 Drawing which is used for calculation of the central part of the cornea.
- Fig. 8 Drawing which is used for calculation of the radius of the central curvature of the anterior surface of a crystalline lens.
- Fig. 9 Drawing which is used for calculation of the radius of the posterior surface of the crystalline lens.

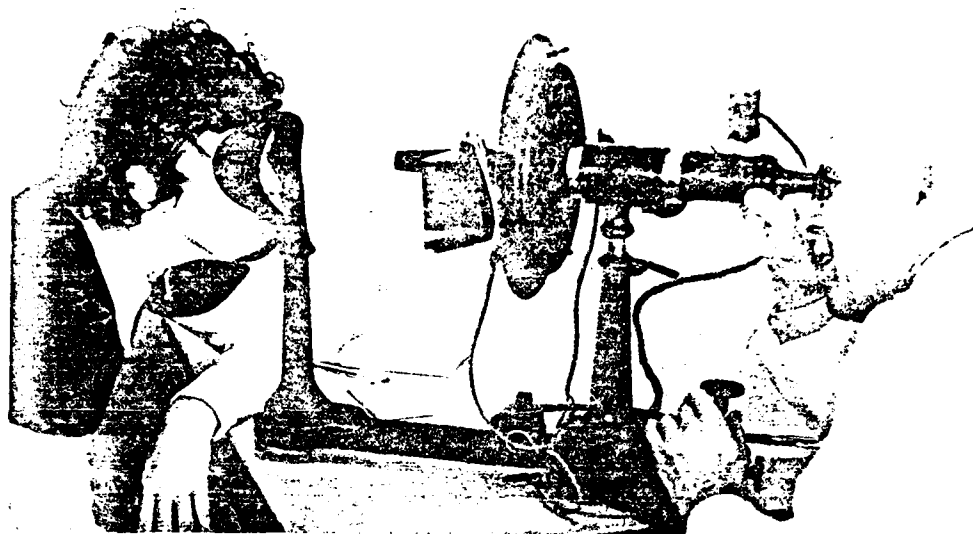


Figure 1

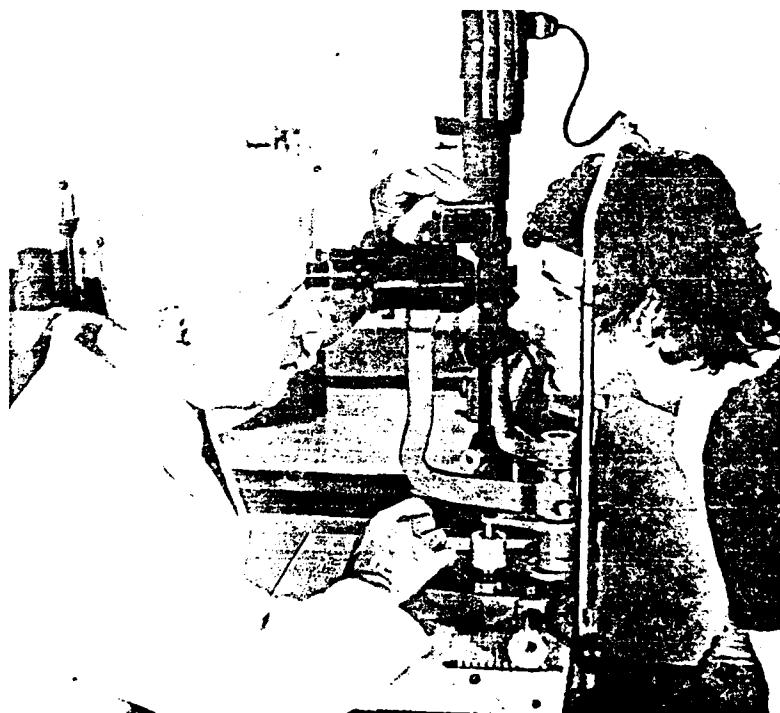


Figure 2

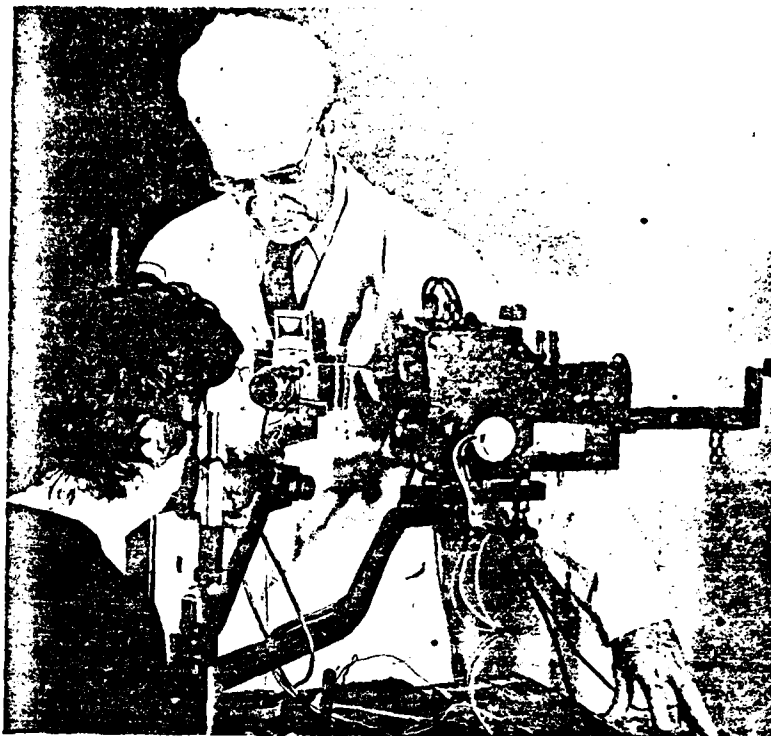


Figure 3

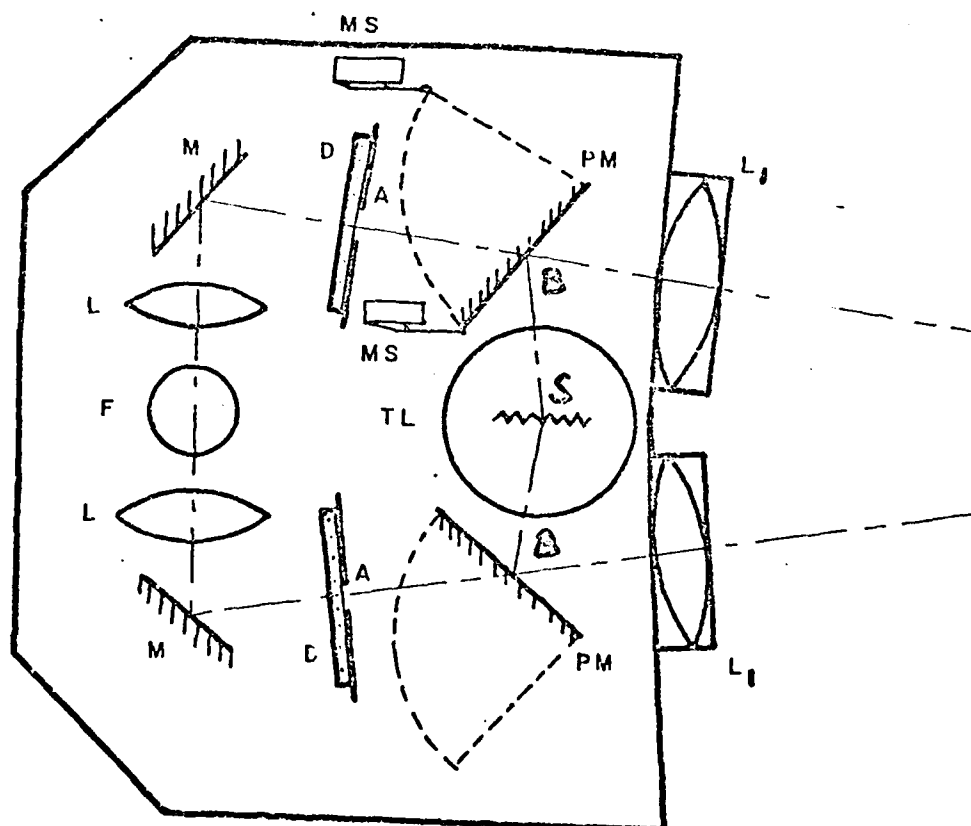
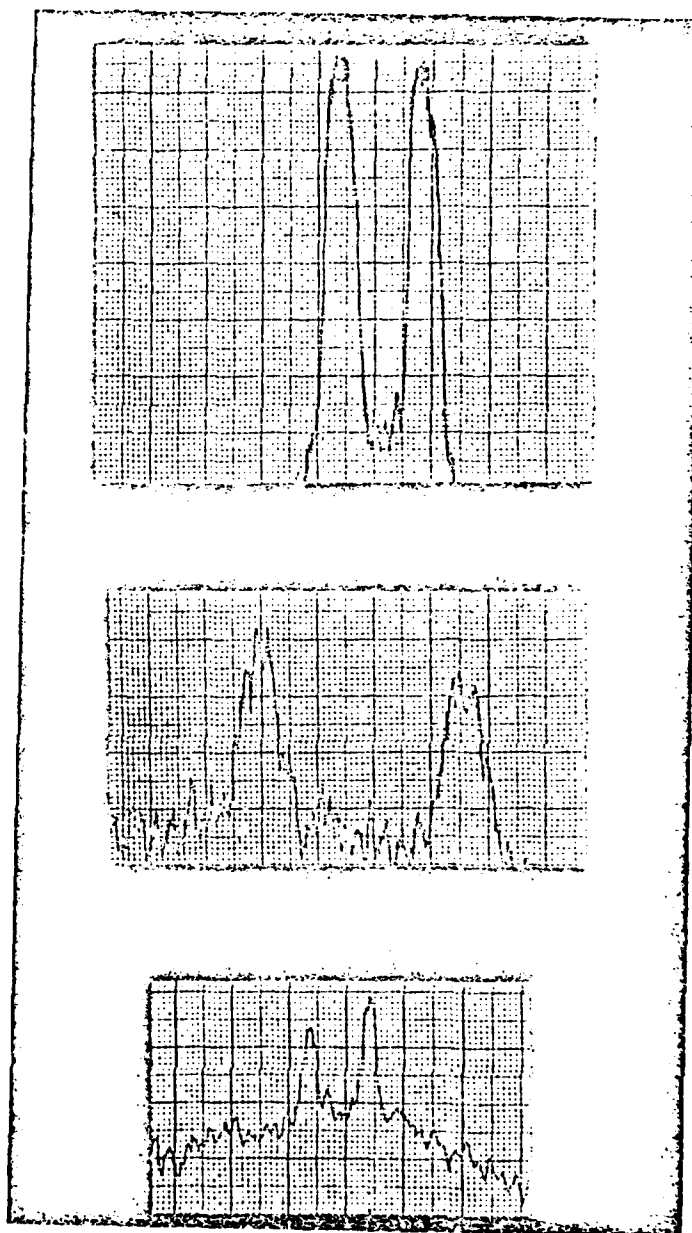


Figure 4



Figure 5

Figure 6



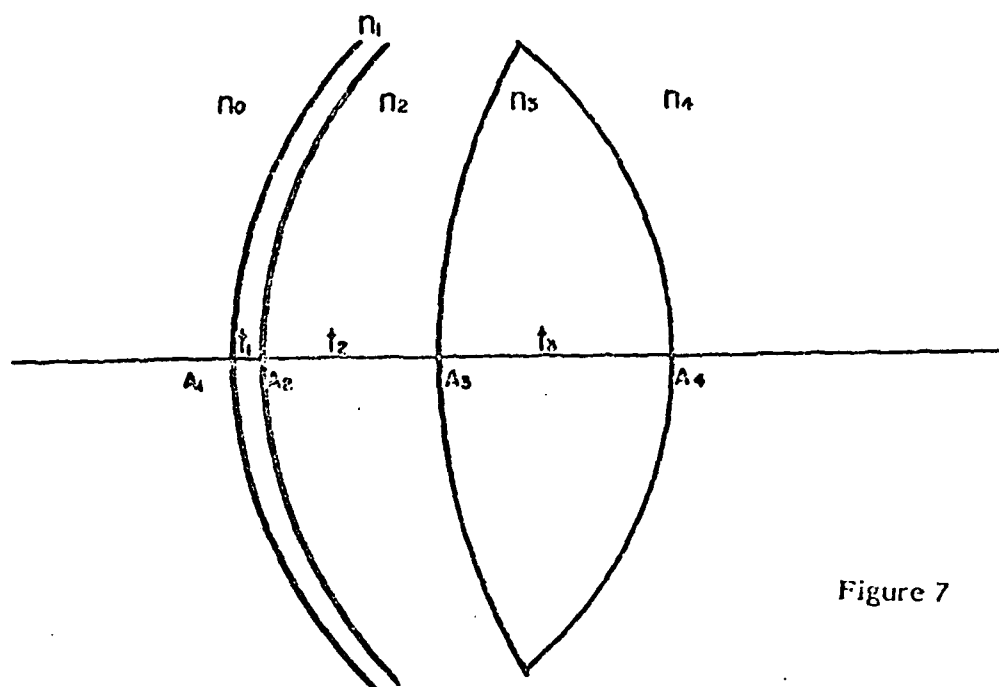


Figure 7

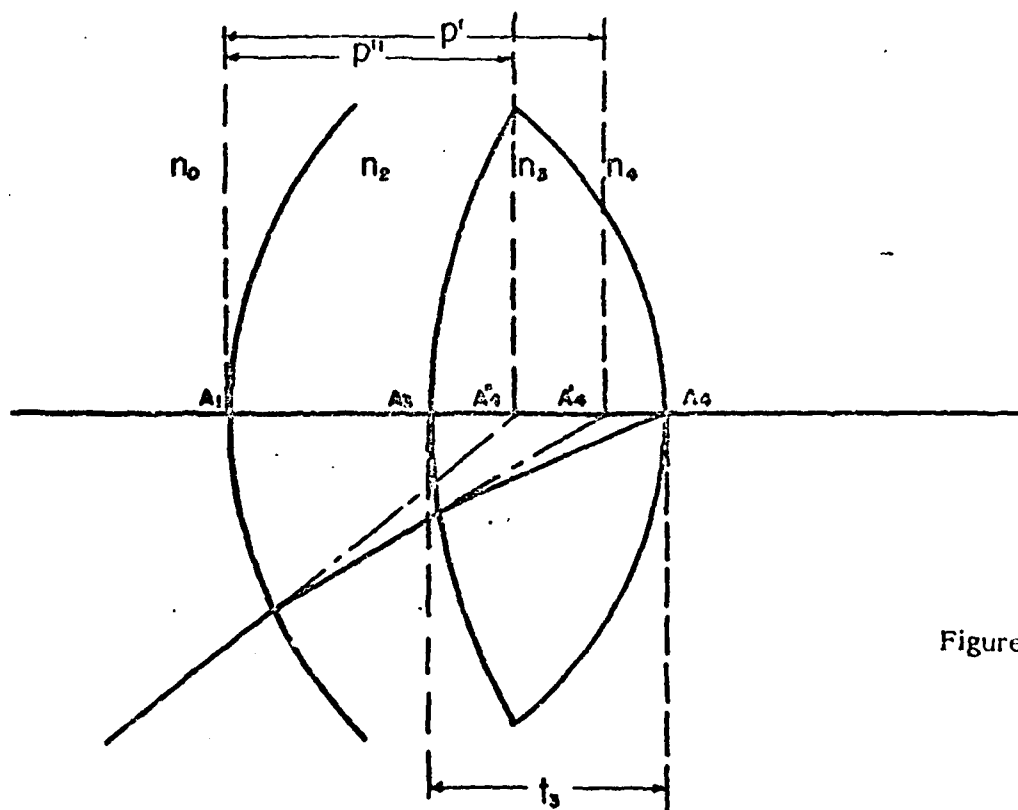


Figure 8

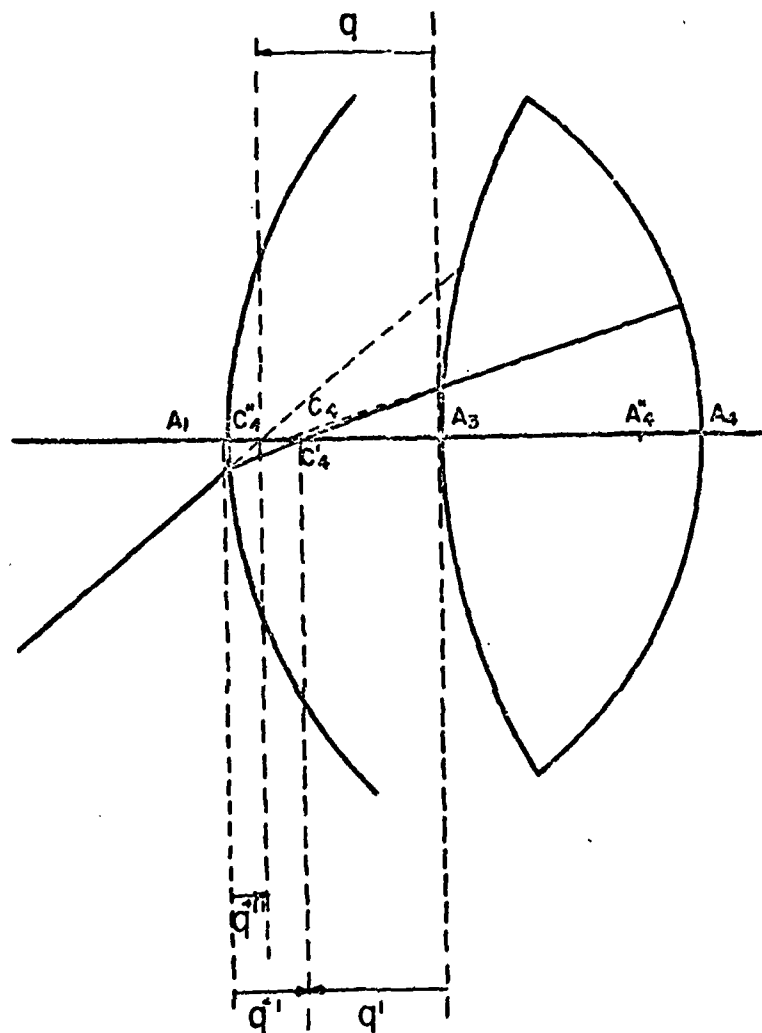


Figure 9

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