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Error Analysis and Corrections to Pupil Diameter Measurements with Langley Research Center's Oculometer

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ERROR ANALYSIS AND CORRECTIONS TO PUPIL DIAMETER MEASUREMENTS WITH LANGLEY RESEARCH CENTER'S OCULOMETER

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SUMMARY

Factors that can affect oculometer measurements of pupil diameter are: horizontal (azimuth) and vertical (elevation) viewing angle of the pilot; refraction of the eye and cornea; changes in distance of eye to camera; illumination intensity of light on the eye; counting sensitivity of scan lines used to measure diameter, and output voltage.

To estimate the accuracy of the measurements, an artificial eye was designed and a series of runs performed with the oculometer system. When refraction effects are included, results show that pupil diameter is a parabolic function of the azimuth angle similar to the cosine function predicted by theory: this error can be accounted for by using a correction equation, reducing the error from 6% to 1.5% of the actual diameter. Elevation angle and illumination intensity effects were found to be negligible. The effects of counting sensitivity and output voltage can be calculated directly from system documentation. The error for counting sensitivity is ±.085mm and could be reduced by increasing the speed of the system's internal clock. The error for voltage output is ±.025mm and could be lowered by reducing the sensitivity of the digital to analog converter. The overall accuracy of the unmodified system is about 6%. After correcting for the azimuth angle errors, the overall accuracy is approximately 2%.

INTRODUCTION

Langley Research Center has been involved in measuring pilot scan patterns for several years. Langley's original effort was devoted to the modification of commercial oculometer equipment for use in the limited space of simulation and flight cockpits with more recent emphasis on the application of the oculometer to data collection and analysis. One parameter measured by the oculometer is pupil diameter, and to date little effort has been devoted to its analysis. However, recent studies (ref. 1) have shown the pilot's pupil diameter to increase during a simulated landing as touchdown approaches. Pupil diameter is influenced by several factors such as ambient illumination intensity, but it also has been shown to be influenced by stress and cognitive workload (ref. 2 and 3). It was recognized (ref. 4) that the pupil diameter as measured by Langley's oculometer was inaccurate when the eye was looking away from the oculometer. This causes a foreshortening effect. If meaningful results of attempts to relate pupil diameter to pilot cognitive activity are going to be obtained, a better estimate of pupil diameter will be needed.
Therefore, in an effort to understand and evaluate the errors associated with the current pupil diameter measurements made with Langley's oculometer, tests and analysis were initiated. Several factors, in addition to the foreshortening

effect due to not looking directly into the oculometer, were investigated, such as the accuracy of estimating the start and end of the pupil on the television raster lines, output voltage accuracy, and refraction due to the cornea of the eye. These errors were analyzed and methods are recommended for correcting some of these errors in order to obtain a good measurement of pupil diameter.

SYMBOLS

F1	focal length of positive lens, mm
F2	focal length of negative lens, mm
L1	vidicon to positive lens distance, mm
L2	vidicon to negative lens distance, mm
P	distance from eye to camera lens, mm
PDa	actual pupil diameter, mm
PDm	measured pupil diameter, mm
Ψ	azimuth angle, angle in the horizontal direction between the line of sight and the electro-optic head of the oculometer, deg
θ	elevation angle, angle in the vertical direction between the line of sight and the electro-optic head of the oculometer, deg

EQUIPMENT AND TESTS

In order to evaluate separately the error effects of the oculometer interface and computer system and the refractive characteristics of a human eye, a simulated eye without refractive properties was made by placing on a light box a piece of cardboard over translucent paper. The cardboard had a large hole representing the pupil and the paper had a small hole which simulated the cornea reflection. The intensity of the light bulb could be varied to simulate any level of reflected light from the pupil. The light box was mounted vertically such that it could rotate about vertical axis to change the azimuth angle (fig. 1).

The oculometer used in the experiment is described in reference 5, Appendix A. The electro-optic head of the oculometer system was replaced with a camera mounted in a tripod 1.7 meters away from the eye, level with the center of the eye at the beginning of the experiment. The camera had a horizontal resolution almost as good as the one in the electro-optic head. A zoom lens was used to adjust the simulated pupil size to correspond to that normally encountered in oculometer operations. The pupil diameter output voltage was read from a digital voltimeter.

Eight different cases were run. Three had varied light intensities of the light box; the lowest intensity at which the oculometer could detect a pupil, the highest intensity at which the oculometer could detect a pupil, and a middle intensity level. Two runs were made changing the distance from the camera, one at 1.5 meters and one at 1.8 meters, keeping the illumination at middle intensity. Two runs were made changing the elevation angle of the camera to 10° and 20° by raising the tripod and pointing the camera down to keep the eye in the video frame. The distance from the eye to the camera was constant (1.7 meters). Finally, a run was made combining all three variables; distance was set at 1.5 meters, elevation angle was 10° and illumination intensity was high. For each case, the camera was positioned according to that case's specifications, the light box was rotated from -60° to 60°, adjusting the intensity for each angle to maintain constant video voltage level of the pupil.

RESULTS AND DISCUSSION

The first three factors, azimuth angle, elevation angle, and video illumination level, were analyzed by performing experiments. The effects of refraction were taken from reference 6. Finally, the effect of system characteristics were estimated from system documentation.

Azimuth Angle

The oculometer allows the pilot to move his head within a cubic foot and rotate his eyes to 30° horizontally (azimuth angles) and -10° to 30° vertically (elevation angles). Azimuth angle causes the most noticeable effect on the measured pupil diameter: as much as 18% decrease in the measured pupil diameter at 30°. Theoretically, if the pupil is an exact circle and no refraction takes place, the measured pupil diameter is proportional to the cosine of the azimuth angle and independent of the elevation angle. The exact equation is:

$$PD_m = PD_a \cos \Psi \left[\frac{1}{1 - \left(\frac{PD_a \sin \Psi}{2p} \right)^2} \right]$$

where p is the distance from the eye to the camera lens (See figure 2 for a schematic illustration and derivation of this equation). However, the term $\frac{PD_a \sin \Psi}{2p}$ is so close to zero that the equation can be simplified to

$$PD_m = PD_a \cos \Psi$$

The results shown in figure 3 agree with theoretical predictions. This correction factor reduces the error to about 4% of the actual diameter between azimuth angles of -30° and 30°. Data corrected in this manner is also shown in Figure 3.

Since no refraction occurred in this experiment, pupil diameter data from reference 6 were used to determine the effects of refraction for various azimuth angles. As seen in figure 4, refraction causes the pupil diameter to be larger than the theoretical measurements by about 10% at an azimuth angle of 30°. To correct the raw measurements, a correction equation can be used:

$$PD_a = \frac{PD_m}{(1 + .000569|\Psi| - .0001025\Psi^2)}$$

This equation was found by curve fitting and nondimensionalizing data from reference 6, and gives a maximum error of about 2.5% of the actual diameter within the azimuth angle range of 30°. Most of this error seems to be caused by noisy data at negative azimuth angles. If these points are ignored, the maximum error is less than 1.5%.

Elevation Angle

For this experiment, the elevation angle had virtually no effect on the pupil diameter measurements (fig. 5). For azimuth angles between -30° and 30°, the maximum difference between measured value and actual pupil diameter was about 6%. The measurements at 0° appear to have been shifted about 5° to the right--this is attributed to misalignment of the camera. Refraction effects on horizontal pupil diameters due to elevation angles can be estimated by looking at the vertical pupil diameters of reference 6 as a function of azimuth angle (fig. 6). The relationship between elevation angle and pupil diameter is very small and for small angles, less than 30° as is the general case of data using Langley's oculometer, the error is negligible.

Illumination Intensity

The effects of illumination intensity were essentially negligible (fig. 7). At high and middle intensity, the maximum difference was about 1%. Between low and high, the maximum was about 4%. This error is caused by the fact that the hardware defines the edge of the pupil as the location along the raster line at which the video level crosses a certain amplitude. Because of the camera response characteristics, the pupil edge is not precisely a square wave, but is a continuous curve. Therefore, as the pupil intensity is increased, this amplitude criteria is achieved at a more distal location resulting in a slightly larger pupil. The hardware tries to compensate for this by adjusting the amplitude criteria to a certain percentage of the peak pupil level, but this still results in the aforementioned 4% error. This error can be minimized by keeping the intensity level constant and in medium to high range, which will keep this error below 1%.

Distance

The effect of distance was also as expected--the pupil diameter is proportional to the distance to the camera (fig. 8). This is accounted for in actual oculometer runs by a remote focusing servo. The accuracy of the focusing servo can be calculated by considering the correction factor built into the system, PD_a - MAG x PD_m, where MAG is a constant used to convert vidicon values of pupil diameter into absolute dimensions. MAG is inversely proportional to K1, a constant: $K1 - L2^2 + L2(L1 - F1) + F2(L1 - F1)$, assuming L2 has an accuracy of the input analog to digital converter (1 in 1024) and using typical values for F1, F2, and L1, the pupil diameter measurements are accurate to .007%, which is negligible.

However, since the oculometer has a depth of field of approximately 25mm, it would be possible for the value of MAG to be incorrect. This would result in an error proportional to the depth of field divided by the distance from the eye to the positive lens. For most typical installations, this error would be approximately 1%.

Output Voltage

The pupil diameter output voltage comes from a 0 - 10 volt digital to analog converter. At a sensitivity of 2.54 mm per volt and assuming the system is accurate to 1 count out of 1024 for maximum output, the pupil diameter voltage is accurate to .025 mm. This error could be cut in half by reducing the output sensitivity to 1.27 mm per volt. This sensitivity is about the lowest that can be used and not cause the output voltage to exceed the maximum allowable.

Scan Line Clock Pulse Rate

The effects of counting sensitivity of the scan lines that measure the pupil diameter can be calculated given the following system characteristics: the system internal clock operates at 10 Megahertz, there are 525 scan lines per camera frame, operating at 30 frames per second, and each raster line length is equivalent to 39.1 mm at the typical eye location. This results in a counting sensitivity of 16.7 clock cycles per mm. Assuming that the system is accurate to two cycles, one at the beginning of the diameter and one at the end, the accuracy of the pupil diameter measurements is then $\sqrt{2(.06)^2} = .085$ mm. To improve this accuracy, the speed of the systems internal clock would have to be increased. However, this may not be possible with the current system.

Overall Accuracy

The overall accuracy of the system, as it is now, can be calculated based on the sum of squares estimate of each individual error (table I). This gives an accuracy of 0.20 mm for small pupils (~3 mm) and .50 mm for larger pupils (~8 mm). Assuming that the parabolic correction factor eliminates this error, the accuracy of small and larger pupils are, respectively, ±.09 mm and ±.12 mm (table I). Thus, for Langley's oculometer, the limiting accuracy of pupil diameter is the system clock pulse rate.

CONCLUSIONS

The results of this study indicate that corrections can be applied to the pupil diameter data in the form of a second order equation involving only azimuth angle and the measured pupil diameter, which essentially eliminates errors due to the geometry of the measurements and retraction of the eye. The other errors caused by the oculometer system are essentially fixed and very little can be done to eliminate them. Some operational methods such as keeping the intensity in the mid to high range, and keeping close track of image focus can help reduce these errors. One system modification which may or may not be practical, is to increase the internal clock rate. And finally, one software change, rescaling of the pupil diameter output voltage, could reduce its effect by half. In total, these corrections result in an overall error of about ±.09 to ±.12 mm depending on the pupil diameter.

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TABLE I - OVERALL OCULOMETER ACCURACY

ERROR SOURCE	uncorrected accuracy mm		corrected accuracy mm	
	small (~3mm)	large (~8mm)	small (~3mm)	large (~8mm)
azimuth angle and refraction	±.18	±.49	0	0
distance	±.03	±.08	±.03	±.08
scan lines	±.085	±.085	±.085	±.085
output voltage	±.025	±.025	±.012	±.012
total accuracy	±.20	±.50	±.09	±.12

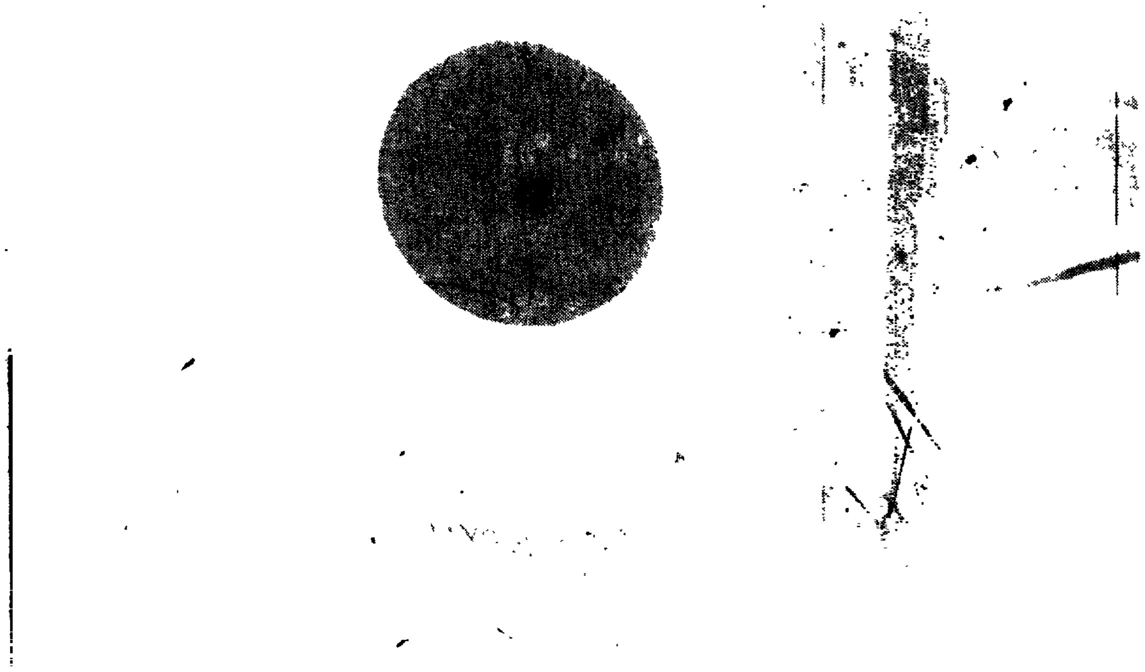
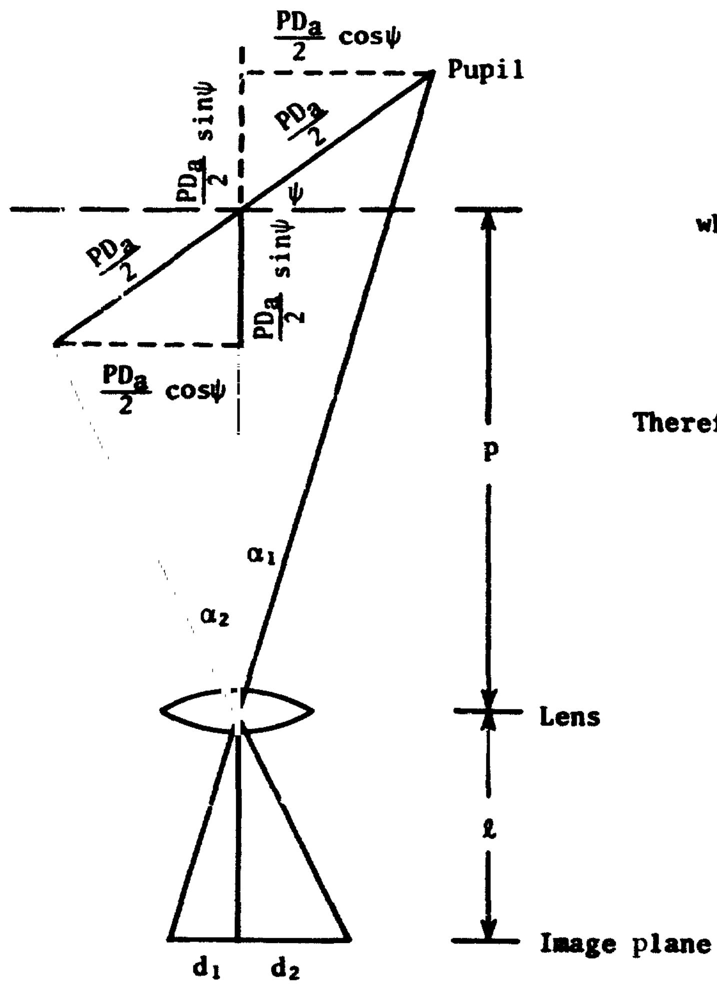


Figure 1.- Simulated pupil mounted on rotatable light box.



$$PD_m = \frac{p}{\ell}(d_1 + d_2)$$

where: $d_1 = \ell \tan\alpha_1$, $d_2 = \ell \tan\alpha_2$,

$$\tan\alpha_1 = \frac{PD_a}{2}\cos\psi \Big/ \left(p + \frac{PD_a}{2}\sin\psi\right), \text{ and}$$

$$\tan\alpha_2 = \frac{PD_a}{2}\cos\psi \Big/ \left(p - \frac{PD_a}{2}\sin\psi\right)$$

Therefore,

$$PD_m = \frac{p}{\ell}\left[\ell \frac{PD_a}{2}\cos\psi \Big/ \left(p + \frac{PD_a}{2}\sin\psi\right) + \ell \frac{PD_a}{2}\cos\psi \Big/ \left(p - \frac{PD_a}{2}\sin\psi\right)\right]$$

$$PD_m = \frac{PD_a}{2}\cos\psi\left(\frac{1}{1 + \frac{PD_a}{2p}\sin\psi} + \frac{1}{1 - \frac{PD_a}{2p}\sin\psi}\right)$$

$$PD_m = \frac{PD_a}{2}\cos\psi\left[\frac{2}{1 - \left(\frac{PD_a}{2p}\sin\psi\right)^2}\right]$$

$$PD_m = PD_a\left[\frac{1}{1 - \left(\frac{PD_a}{2p}\sin\psi\right)^2}\right]$$

Fig. 2 - Schematic and mathematical description of pupil foreshortening.

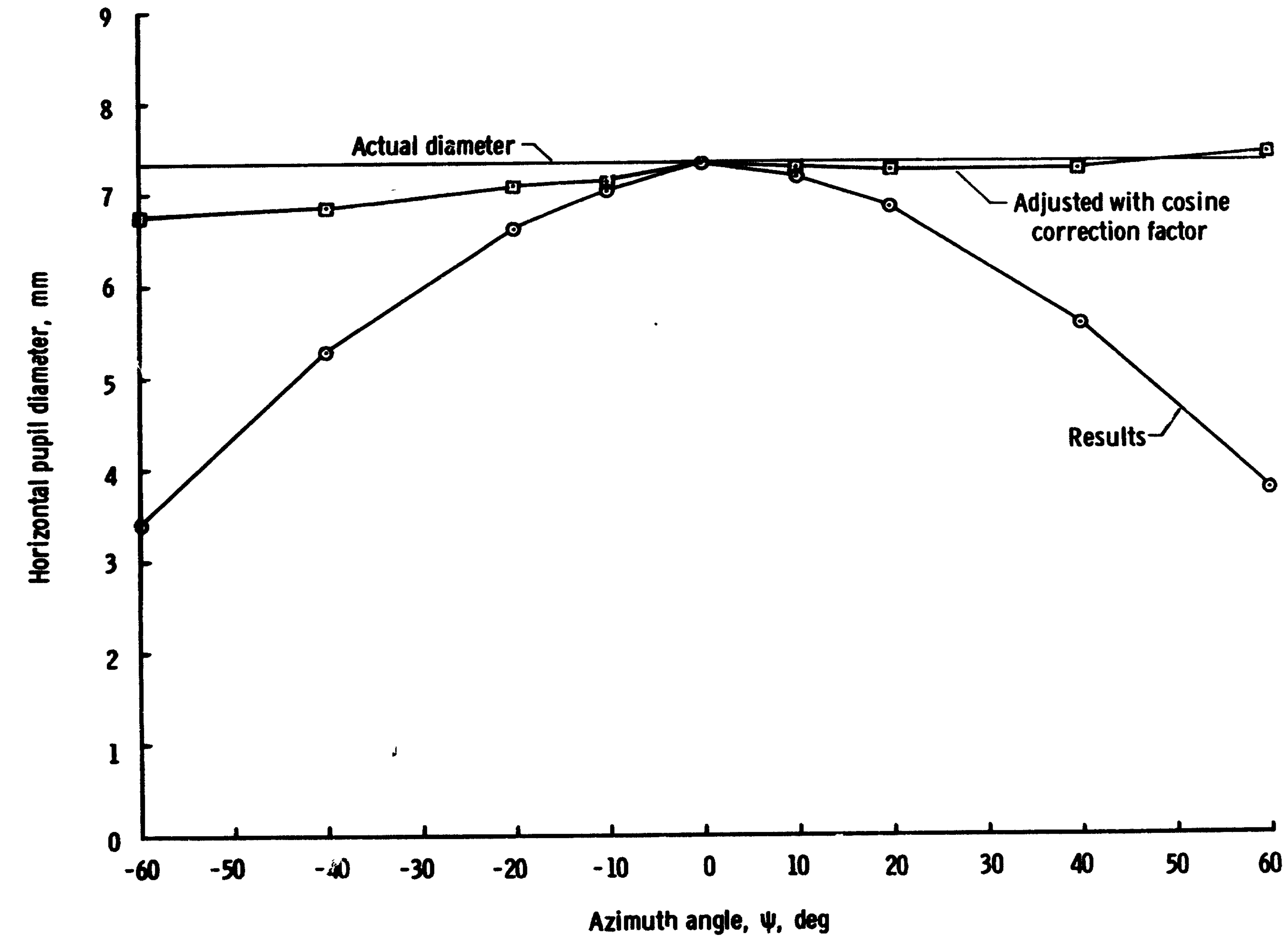


Figure 3.- Apparent and adjusted diameter of simulated pupil at various azimuth angles.

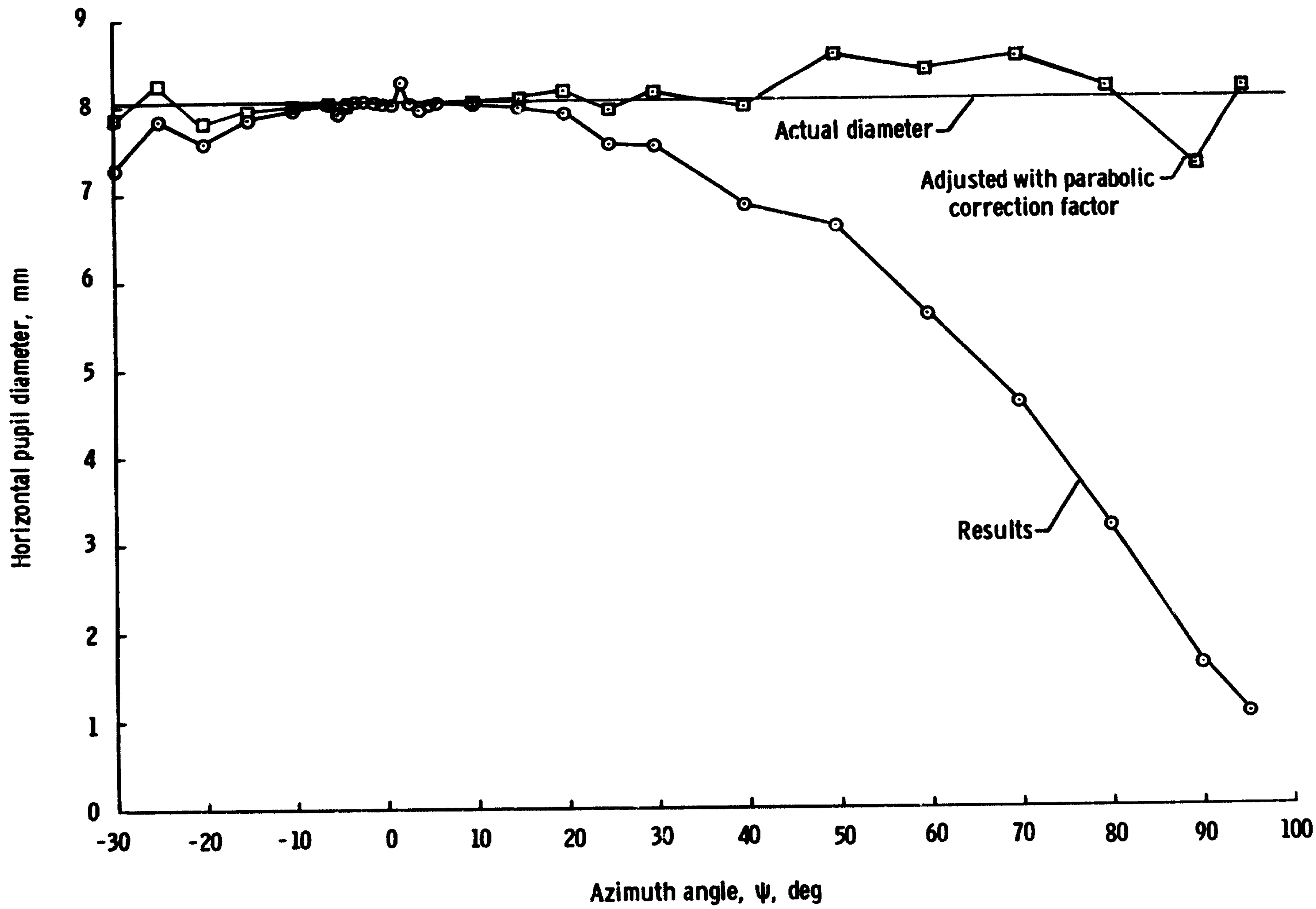


Figure 4. - Pupil diameter (ref. 6) of large drugged eye at various azimuth angles.

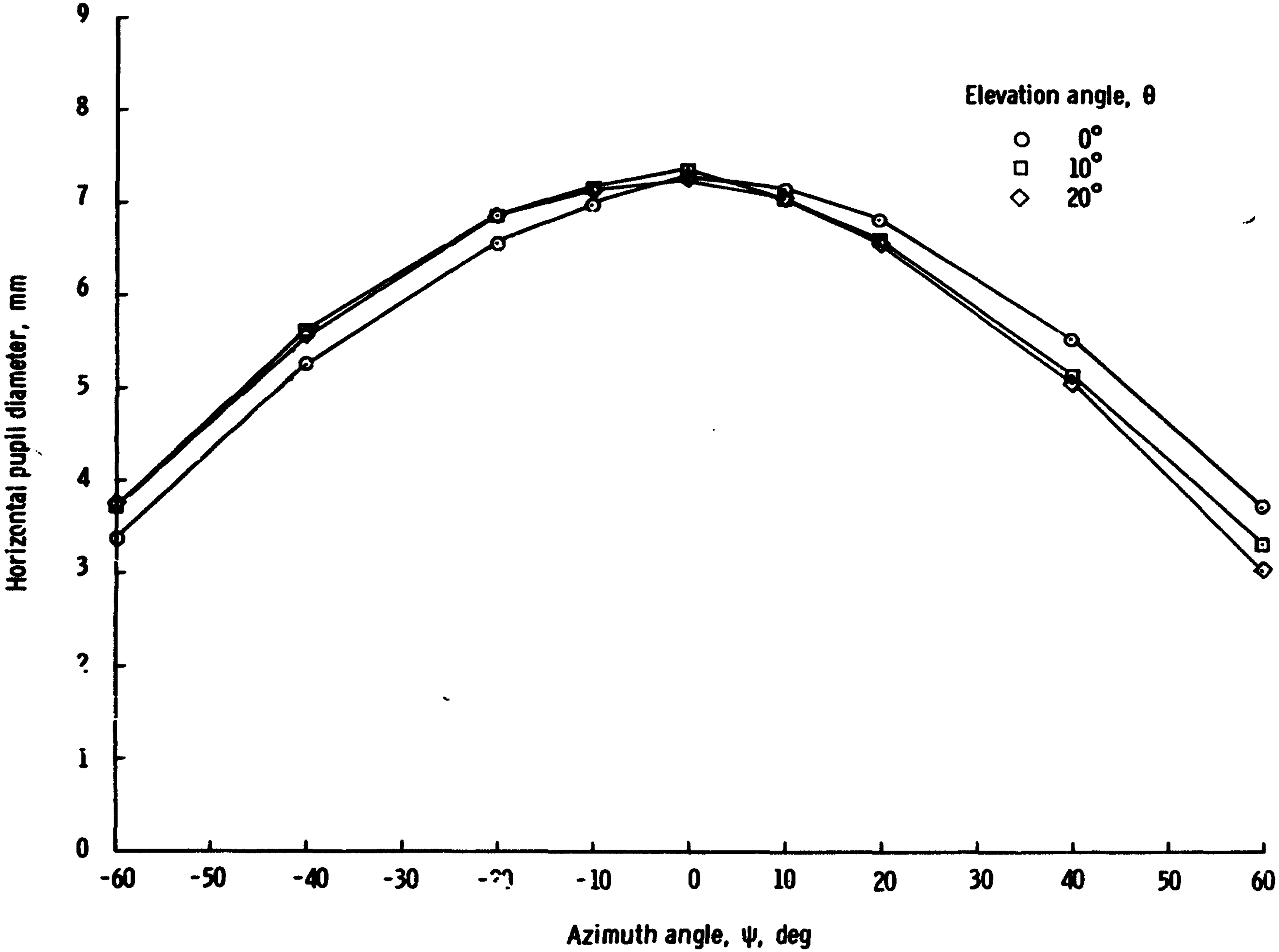


Figure 5. - Apparent pupil diameter of simulated pupil as affected by elevation angles and azimuth angles.

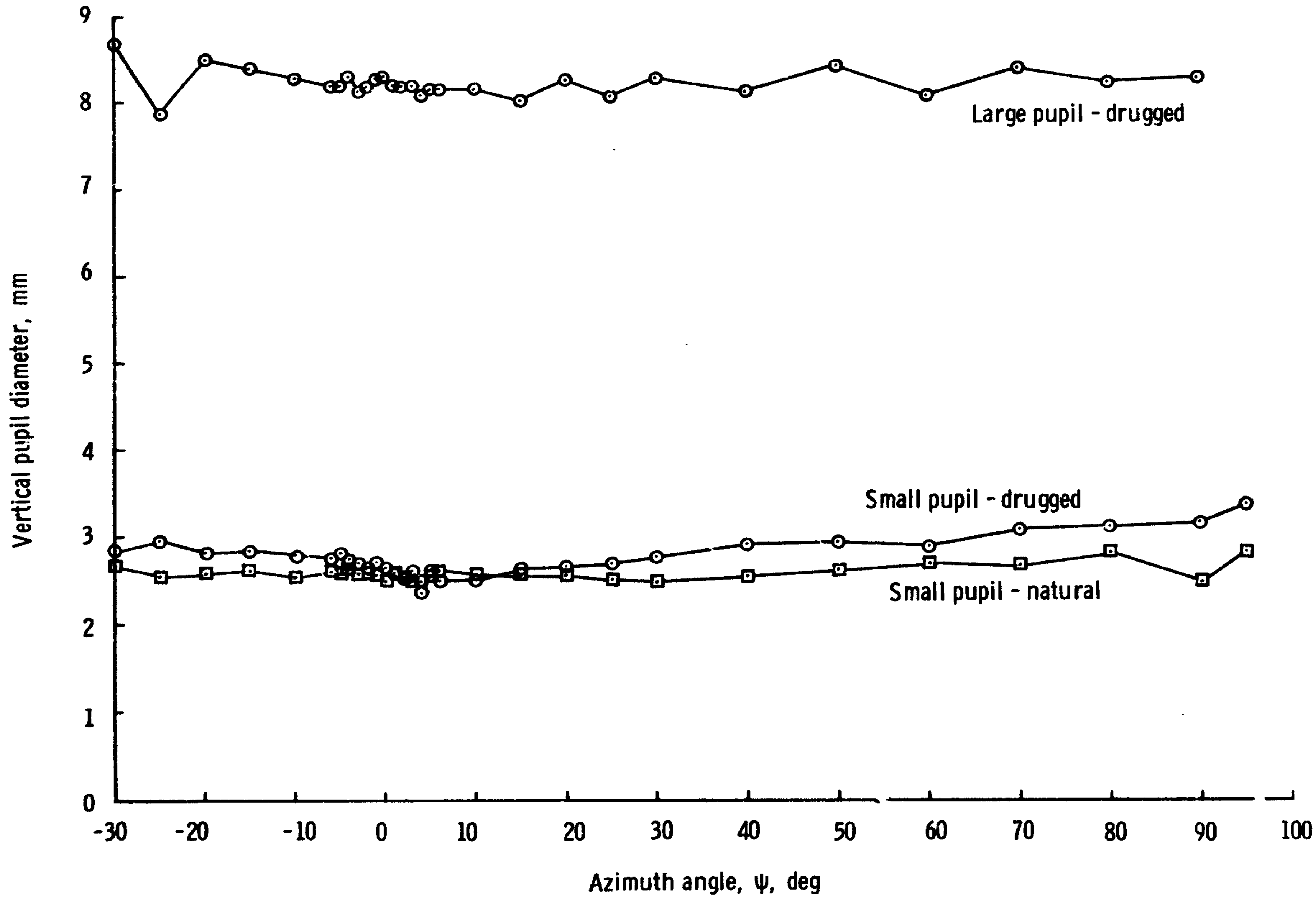


Figure 6. - Pupil diameter (ref. 6) measured at various elevation angles.

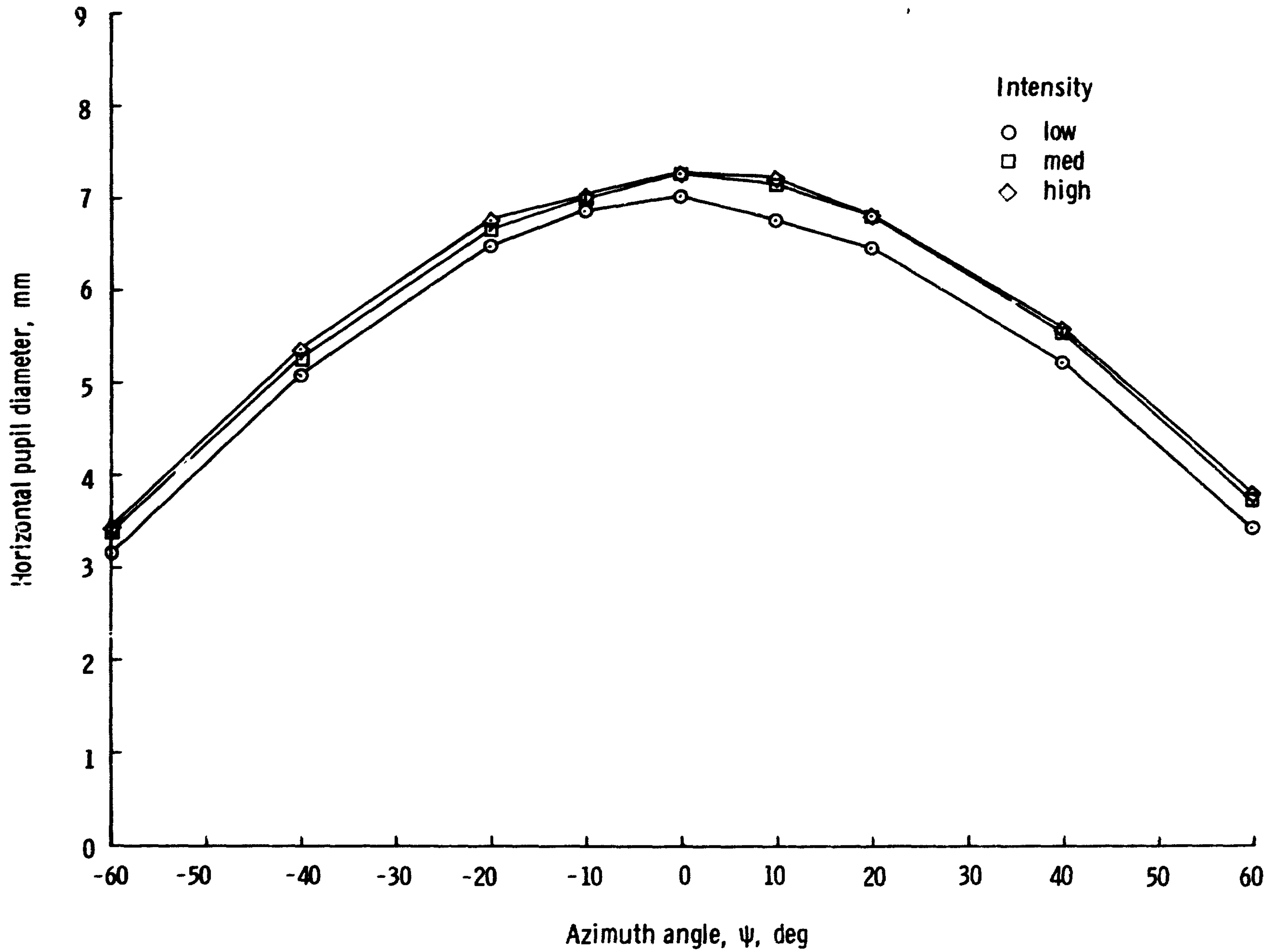


Figure 7. - Effects of illumination level of apparent pupil diameter at various azimuth angles.

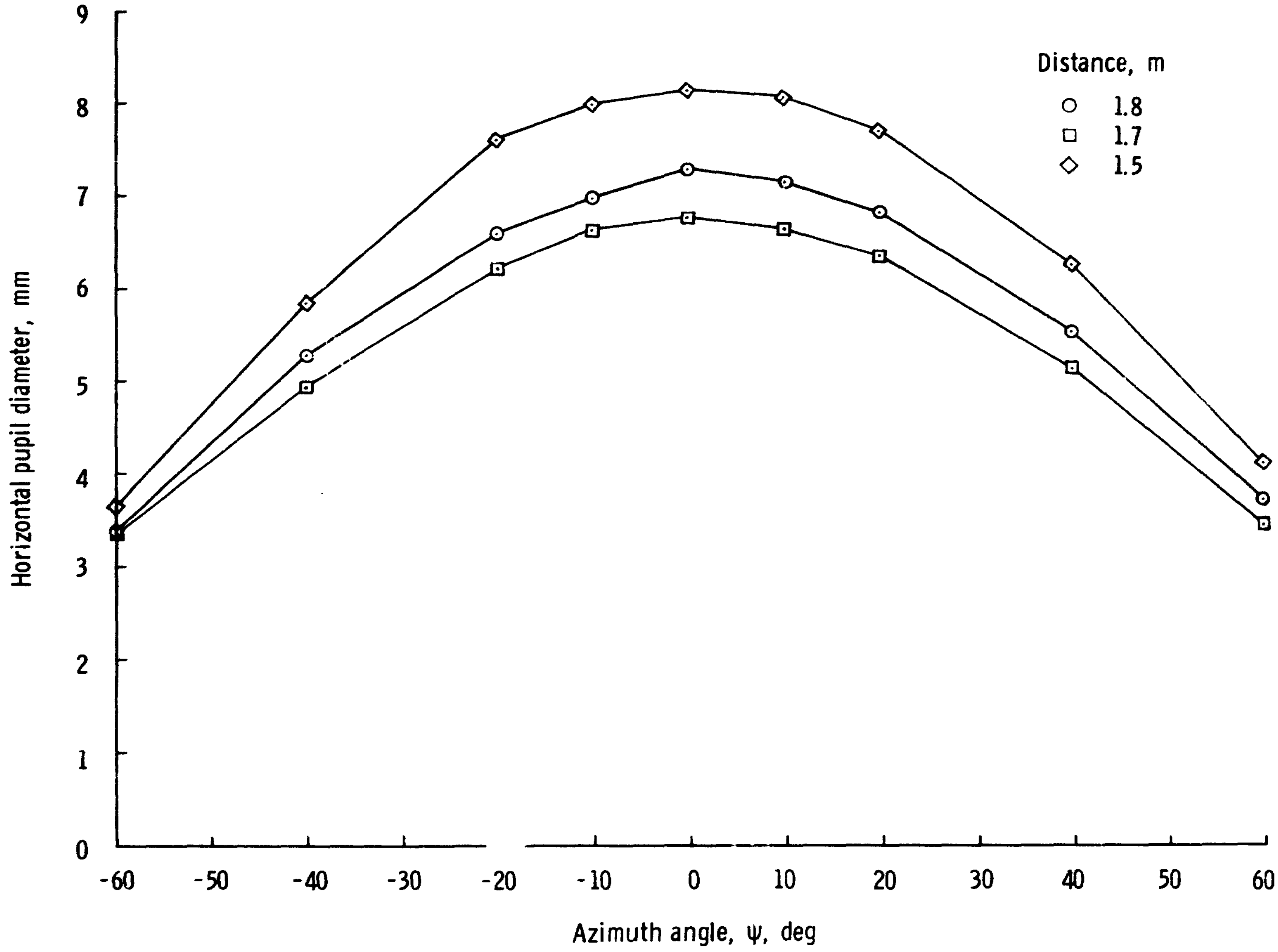


Figure 8. - Effects of eye distance from camera on apparent pupil diameter for various azimuth angles.