Designation: F 801 – 96 (Reapproved 2002)

Standard Test Method for Measuring Optical Angular Deviation of Transparent Parts[1]

1. Scope

1.1 This test method covers measuring the angular deviation of a light ray imposed by transparent parts such as aircraft windscreens and canopies. The results are uncontaminated by the effects of lateral displacement, and the procedure may be performed in a relatively short optical path length. This is not intended as a referee standard. It is one convenient method for measuring angular deviations through transparent windows.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *angular deviation*—the departure of a light ray from its original path as it passes through a transparent material. The change in angle of such a light ray. The displacement of an image due to the change in direction of the light ray.

3.1.2 *lateral (or linear) displacement*—the shift or movement of a light ray from its original path as it passes through a transparent material, while maintaining parallelism between the original and final paths. The change in location of an image due to this change in path.

3.1.3 *modulation transfer function (MTF)*—the ratio of output modulation to the input modulation. The modulus of the Fourier transform of the optical spread function.

4. Summary of Test Method

4.1 This test method outlines how measurements can be made by an optoelectronic system employing collimated light, a field lens, and linear diode arrays as the part is held in its installed angle. The positions of two images of a collimated light source are recorded using two linear diode arrays. One array records azimuth or horizontal position while the other records elevation or vertical position. These arrays are at the posterior focal plane of a field lens. The positions are again recorded after the interposition of a transparent part in the optical path. The difference in image position is directly related to the angular deviation imposed by the transparent part. The effects of lateral displacement are removed by the field lens. Sensitivity of measurement may be controlled by choosing appropriate focal length field lenses and spacing of elements on the diode arrays.

5. Significance and Use

5.1 One of the measures of optical quality of a transparent part is its angular deviation. Excessive angular deviation, or variations in angular deviation throughout the part, result in visible distortion of scenes viewed through the part. Angular deviation, its detection, and quantification are of extreme importance in the area of certain aircraft transparency applications, that is, aircraft equipped with Heads-up Displays (HUD). HUDs may require stringent control over the optics of the portion of the transparency (windscreen or canopy) which lies between the HUD combining glass and the external environment. Military aircraft equipped with HUDs or similar devices require precise knowledge of the effects of the windscreen or canopy on image position in order to maintain weapons aiming accuracy.

5.2 Two optical parameters have the effect of changing image position. The first, lateral displacement, is inherent in any transparency which is tilted with respect to the line of sight. The effect of lateral displacement is constant over distance, and seldom exceeds a fraction of an inch. The second parameter, angular deviation, is usually caused by a wedginess or nonparallelism of the transparency surfaces. The effect of angular deviation is related to the tangent of the angle of deviation, thus the magnitude of the image position displacement increases as does the distance between image and transparency. The quantification of angular deviation is then the more critical of the two parameters.

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[1] This test method is under the jurisdiction of ASTM Committee F07 on Aerospace and Aircraft and is the direct responsibility of Subcommittee F07.08 on Transparent Enclosures and Materials.

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[2] *Annual Book of ASTM Standards*, Vol 14.02.

6. Apparatus

6.1 *Transmitter*, capable of projecting collimated light rays from a suitable target. The target may be a transparent cross or an "L" with one arm horizontal and one arm vertical, embedded in an opaque background. The stroke width of the "L" or cross shall be uniform. Choice of an "L" or a cross is optional, since only one half of the cross target is used at any time. The transmitter should be firmly affixed to the floor or other stationary fixture.

6.2 *Receiver*, firmly affixed to the floor or a stable platform, consisting of the following components:

6.2.1 *Displacement Compensation and Imaging Lens*—The sensitivity of the instrument is in part determined by the focal length of the lens. An appropriate focal length may be 10 in. (254 mm).

6.2.2 *Optical Beam Splitter*, to separate the incoming light into two orthogonal elements; one for elevation and the other for azimuth. The type of beam splitter should be chosen to keep both optical path lengths equal.

6.2.3 *Two Linear Charge Coupled Devices* (*CCD or diode*) *Arrays*, each located at the focal plane of the displacement compensating lens. One array is oriented horizontally (for the measurement of azimuthal changes), and the other oriented vertically (for the measurement of elevation changes). An appropriate element spacing of the arrays is 0.001 in. (0.0254 mm). Using this element spacing, and the 10-in. (254-mm) lens, each diode will represent the equivalent of 0.1 milliradian (mrad) angular deviation.

6.2.4 *Electronic System* that will determine the center diode of the band of illuminated diodes on each CCD array.

6.2.5 *Electronics System* that will convert the number to be displayed on a digital readout.

6.3 *Transmitter and Receiver Lenses* should be of achromatic construction to reduce the effect of aberrations on the measurement.

6.4 *Dioptometer*, to verify attainment of collimated light.

6.5 For further information on the rationale and development of the design see the appendixes. (Appendix X1-Appendix X4.)

7. Test Specimen

7.1 The part to be tested should be positioned in such a manner as to approximate its installed configuration. No special conditioning other than cleaning is required.

8. Calibration and Standardization

8.1 Position the transmitter and receiver so that the optical axes of both are parallel and approximately colinear. The light from the transmitter shall pass through the test specimen to fall on the receiver lens. Depending on the configuration of the test specimen, locate the transmitter and receiver approximately 4 ft (305 mm or less) apart.

8.2 Adjust the transmitter lens or target position to provide collimated light. A dioptometer is sufficient for this adjustment.

8.3 Adjust the receiver field lens and positions of the CCD arrays so each array is at the focal plane of the lens. Perform rough adjustment by using the receiver lens to sharply focus the target from the previously adjusted transmitter. Check by interposing a thick optical flat (plane parallel-sided transparent plate) in the optical path, and tilting the flat with respect to the optical axis. When correctly adjusted, there will be no movement of the transmitter image at the plane of the CCD array. If the image moves (the readout varies by more than 0.1 mrad), adjust the position of the appropriate CCD array to eliminate this movement.

8.4 An accuracy test may be made by interposing a standard or highly accurate optical wedge in the light path between transmitter and receiver. The display should accurately indicate the angular deviation imposed by the optical wedge in both the vertical or horizontal meridians. An alternative method would be to tilt the transmitter or receiver on an accurate tilt table. The tilt, converted to milliradians, should equal that shown on the display. The latter method is usually preferable since it yields a continuous accuracy check over the entire range of measurement.

8.5 A check to ensure operation of all diodes may be performed by illuminating the entire CCD array and noting the default reading on the display. (This default reading is also dependent on the specific circuitry used, but should be a constant).

NOTE 1—The area of transparency being measured at any one time is related to the smallest diameter lens being used at the transmitter or receiver. The system will average angular deviations throughout a subset of this area. Use of lenses of significantly larger or smaller diameters will affect repeatability of measurement from one instrument to another. Use of lenses with small diameters will improve performance on transparencies with rapidly changing angular deviations, but will reduce available light energy at the CCD array, possibly below its threshold. Lens size is further discussed in the annex.

8.6 Certain variations may be as a result of the following sources of error:

8.6.1 Transmitter or receiver lens malfocus. Noncollimated light from the transmitter will cause the receiver to measure some lateral displacement as well as angular deviation.

8.6.2 Poor transparency optics (MTF losses) will cause a blurred image on CCD arrays. If this blur is asymmetric, some error will be introduced. If the MTF loss is great enough, the light energy will fall below the threshold of the CCD array, and a no-reading condition will result.

9. Procedure

9.1 Mount the transparent part on a fixture that allows accurate determination of the elevation and azimuth position of the part.

9.2 Locate and firmly mount the transmitter at an appropriate position corresponding to the observational point of interest (pilot's eye designed position), or along a line connecting this point with the receiver lens.

9.3 Locate and firmly mount the receiver external to the transparent part and at a distance of 4.9 ft (1.5 m) from the transmitter.

9.4 Establish a baseline or zero determination without a transparency in the optical path. Record the number as displayed on the digital readout under this condition.

9.5 Locate the transparency between the transmitter and receiver. Take readings at points specified by the using activity by rotating the canopy about a critical point such as the pilot's eye position or other position of interest specified by the using activity. The difference between these readings and the baseline figures solely represent the angular deviation in milliradians through each point.

10. Calculation

10.1 With appropriate selection of receiver lens focal length and CCD array diode separation, the display readout will be in 0.1-mrad increments. The sensitivity of the instrument may be varied by altering either of these parameters. Assuming a 0.001 in. (0.025 mm) diode spacing as standard, increasing the focal length will improve the sensitivity as follows:

$$a = \arctan(0.001/f)$$

where:

a = sensitivity (minimum measurable angle), mrad and
f = focal length of receiver lens, in.

10.2 Although the separation distance between the projector and receiver is not critical and does not affect the measurement accuracy, it does have an effect on both the light energy at the image plane and the maximum amounts of angular deviation that can be measured. The largest distance from the optical axis at the image plane that does not produce vignetting may be calculated as follows:

$$H = f_2 \times (d_2 - d_1)/2S$$

where:

H = maximum unvignetted ray height at image plane,
d_2 = diameter of receiver lens,
d_1 = diameter of transmitter lens,
S = separation between transmitter and receiver, and
f_2 = focal length of receiver lens

10.3 A typical linear CCD array containing 512 elements, each with a 0.001 in. (0.025 mm) spacing, has an active surface 12.5 mm long. The maximum angular deviation that can be detected by such an array may be calculated as follows.

$$M = 2 \times \arctan(12.5/f_2)$$

where:

M = maximum angular deviation from one end of array to the other and
f_2 = focal length of receiver lens

11. Report

11.1 Draft a graph or chart, derived from the digital data, showing the angular deviation found at each point of interest.

12. Precision and Bias

12.1 *Precision*—The data used to develop this section was obtained as the result of a round-robin test reported at the September 1990 F7.08 subcommittee meeting. The written report was entitled "Angular Deviation Revisited: Results of a Round Robin Test" and is available from ASTM International headquarters.[3] It should also be noted that there are only a few organizations capable of making these types of measurements on aircraft transparencies. At the time of the inter-laboratory test program there were only 5 measurement devices available at 3 facilities. Although this is a lower number than that recommended by Practice E 691, the results provide a reasonable indication of the expected repeatability and reproducibility of the procedure. If more measurement systems become available in the future, the interlaboratory test may be repeated to obtain an updated estimate of precision and bias.

12.1.1 There are two primary sources of error with this procedure: (*1*) those dealing with the measurement device itself, and (*2*) those dealing with the positioning of the part to be measured. Since this procedure only addresses the measurement device and not positioning equipment this section will be confined to data relating to the precision of the measurement device itself.

12.1.2 Measurements of azimuth and elevation angular deviation of two windscreens by two organizations using precise positioning equipment resulted in a total of 880 data points. These 880 points were measured twice to determine repeatability. 832 of the 880 points, or 94 %, were within ±0.1 milliradian from the first measurement to the second measurement. Thus the 95 % confidence interval for repeatability for this test method is ±0.1 (it should be noted that the least count of the device described in this test method is 0.1 milliradian so the confidence interval value has been rounded off to the nearest 0.1 milliradian even though the statistically calculated confidence interval would be slightly more than 0.1 milliradians). The third organization that participated in these tests had a less precise manual positioning device that was not capable of repositioning the windscreens as accurately as the automated systems. Since the objective of the interlaboratory test was to assess the measurement device and not the positioning equipment these data were not included in the determination of repeatability.

12.1.3 A calibrated optical wedge with an angular deviation of 5.07 milliradians was used to determine overall precision and bias of this test procedure. A total of 5 devices located in 3 laboratories were used in this evaluation. The wedge was positioned in each of 4 orientations (up, down, right, left) and two locations (in front of the receiver and in front of the transmitter) for a total of 8 readings per device. The standard deviation between the average readings of the 5 devices was 0.095 milliradians indicating a 95 % confidence interval for reproducibility between devices of ±0.2 milliradians (rounded to the nearest 0.1 milliradians) or about ±4 %. The overall standard deviation for all 40 data points (5 devices times 8 readings each) was 0.15 milliradians indicating an overall 95 % confidence interval of ±0.3 milliradians or about ±6 %.

12.2 *Bias*—The average reading for the 5 devices was 5.17 milliradians indicating an average positive bias of 0.1 milliradians or about 2 percent. However, the standard deviation for this average measurement was 0.15 milliradians indicating this average was not statistically different from the value of the calibrated wedge. Since there is nothing inherent in the procedure that should produce a bias, and since the average measured value was not statistically different than the optical wedge value, it is concluded that there is no bias in this procedure.

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[3] Request Research Report F07-1002.

13. Keywords

13.1 aiming accuracy; aiming error; angular deviation; deviation; refraction

APPENDIXES

(Nonmandatory Information)

X1. DIRECT MEASUREMENT OF ANGULAR DEVIATION[4]

X1.1 This procedure bypasses the problems inherent in various grid line slope measures by directly measuring the angular deviation of a light ray passing through the transparency. Distortion has often been defined as the rate of change of deviation. Deviation is defined as the angular change of direction of a light ray as it passes through the transparency. If we could find a sufficiently sensitive and accurate method of measuring angular deviation and employ this method with sufficient measurement density, we should be able to determine the distortion in any transparency.

X1.2 Whenever a ray of light passes through a transparency at an angle other than the normal (a "normal" is a line drawn perpendicular to the transparency surface), several events occur (see Fig. X1.1). One of these events results in the lateral displacement of the ray by a relatively small and constant amount. This lateral displacement is usually operationally insignificant beyond a few meters, but contaminates angular deviation measures made with short "throw distances."

X1.3 A second event causes the light ray to undergo an angular directional change. This angular error can be quite significant when considering its effect on apparent target position as seen by the pilot. For each milliradian of error, the target's true position will be displaced from its apparent position by 1 ft (0.3 m) for each 1000 ft (300 m) of range. In other words, a transparency inducing a mere 10 mrad error can move the apparent position of a target located 3000 ft (900 m) away a distance of 30 ft (9 m), more than enough to miss the target.

X1.4 Angular deviation is caused by both relatively local areas of nonparallelism, as well as overall nonparallelism of the surfaces of the transparency. The angle of installation, pilot's line of sight, and other factors contribute to modifying the severity of this problem. The end result of this problem is to produce a nonlinear mapping of external objects. In other words, the actual position of the target does not correspond with its apparent position as seen from the cockpit.

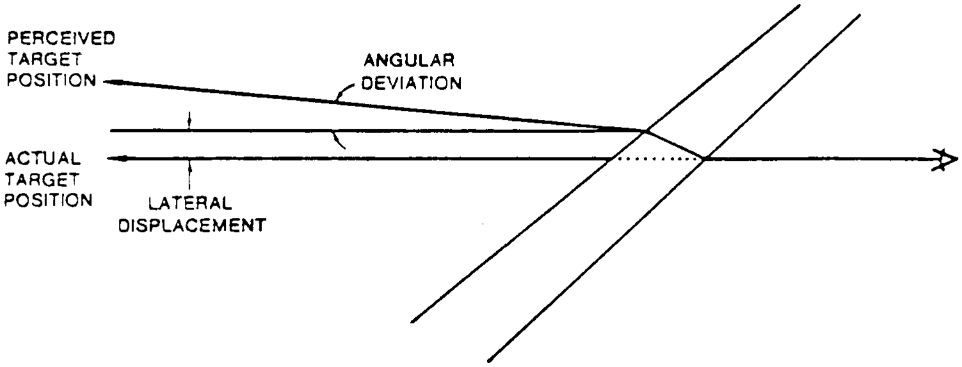

FIG. X1.1 Lateral Displacement and Angular Deviation Effects of Aircraft Transparencies

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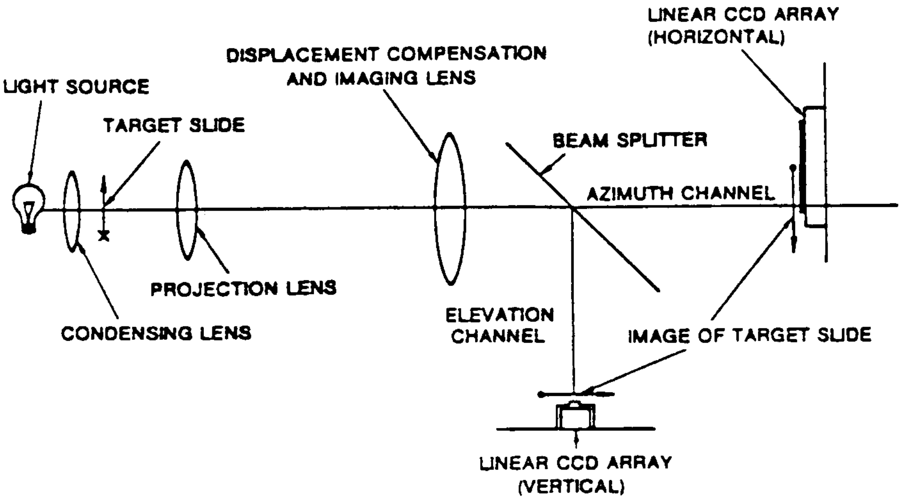
[4] Genco, L. V., and Task, H. L., *Aircraft Transparency Optical Quality: New Methods of Measurement*, AFAMRL-TR-81-21, February 1981, Air Force Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, OH 45433.

X2. DESCRIPTION OF DEVICE[4]

X2.1 Fig. X2.1 shows a pictorial top view of the optical system. From left to right, light from an incandescent lamp is collected by a condensing lens to illuminate the target slide. The projection lens is located 1 focal length from the target slide such that it collimates the image of the target slide. This portion of the system is positioned such that the projection lens is approximately at the design eye position or observer position for the transparency under test. The remainder of the system (the receiver) is located on the other side of the transparency.

X2.2 The receiving lens compensates for lateral displacement (thus eliminating that error source) and images the target slide one focal length away. A beam splitter divides the light into two approximately equal intensities: one channel to measure azimuth (horizontal) deviation and one to measure elevation (vertical) deviation. Except for a 90° rotation about the optical axis, both channels are identical. In each channel a segment of the target slide image intersects a charge coupled device (CCD) linear array and its associated electronics. The positional change of this intersection between windscreen and no windscreen conditions is mathematically related to the angular deviation of the windscreen at the point measured.



NOTE 1—The windscreen to be measured is positioned between the projection lens and the displacement compensation lens.

FIG. X2.1 Pictorial Layout of Windscreen Angular Deviation Measurement Device

X3. THEORY OF OPERATION[4]

X3.1 The target slide is shown in Fig. X3.1. The dimensions and location of the "L" are not critical; however, the stroke width of the "L" must be uniform to reduce error. The image of the "L" is produced at the plane of the CCD array. The array is offset from the optical axis so that only one leg of the "L" intersects the array as shown in Fig. X3.2.

X3.2 As the individual CCDs are sampled, the electronic output signal appears as shown in Fig. X3.3. Typically, several CCD elements are activated as shown by the series of spikes between *A* and *B* in Fig. X3.3. To ascertain the location of the center position of the "L" segment, a counter counts CCD clock pulses until the output of the array exceeds a detection threshold level. The first counter stops counting at this point (*A*) and a second counter starts counting. The second counter counts every second pulse until the output of the array falls below the threshold (*B*). The counts from both counters are added. This resulting count corresponds to the center of the "L" leg segment. This position is shown as (*C*) in Fig. X3.3. Eq X3.1 shows this relationship.

$$C = A + \frac{B - A}{2} \tag{X3.1}$$

where:
C = center position CCD element number,
A = front edge of "L" element number, and
B = back edge of" L" element number.

X3.3 The accuracy capability of the optical system is determined by the lens quality of the projection lens (L_1) and the receiver lens (L_2), the spacing of the CCD array elements and the focal length of L_2. The minimum detectable angular deviation is calculated as shown in Eq X3.2.

$$a = \arctan \frac{h}{f_2} \tag{X3.2}$$

where:
a = minimum measurable angle,
h = spacing of CCD array elements, and
f_2 = focal length of L_2

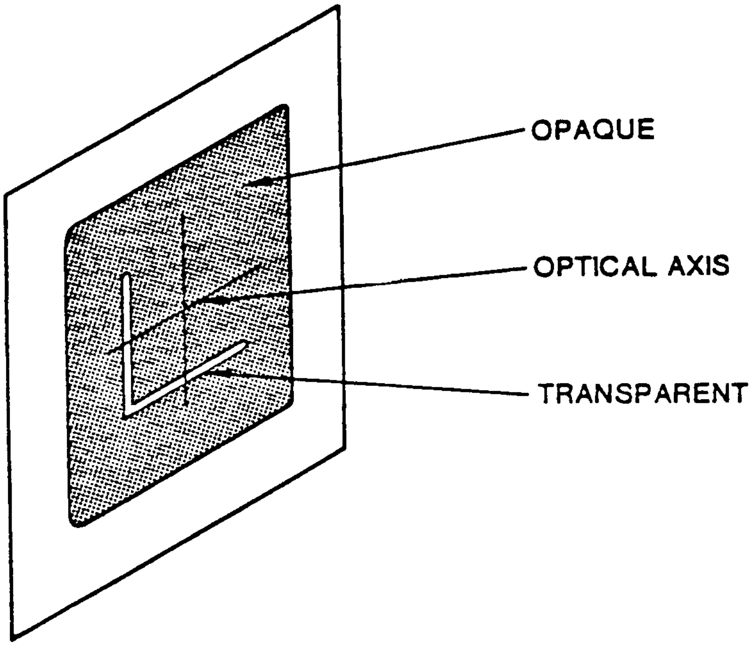


FIG. X3.1 Target Pattern for the Projector Half of the Angular Deviation Measurement Device

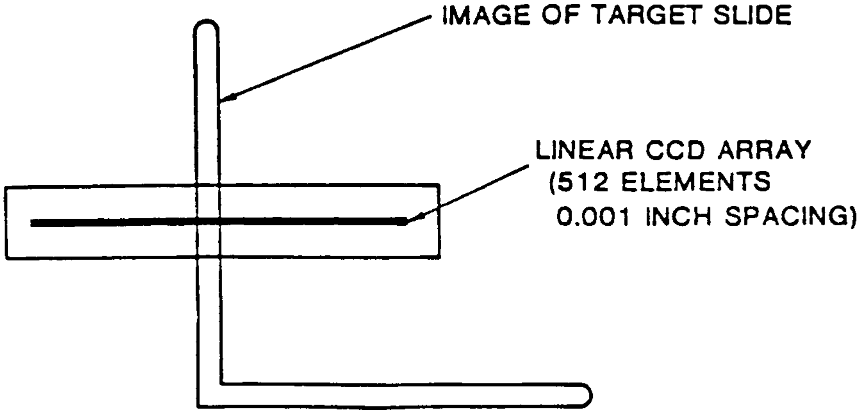


FIG. X3.2 Intersection of the Image of the Target Pattern with the Vertical Channel CCD Array

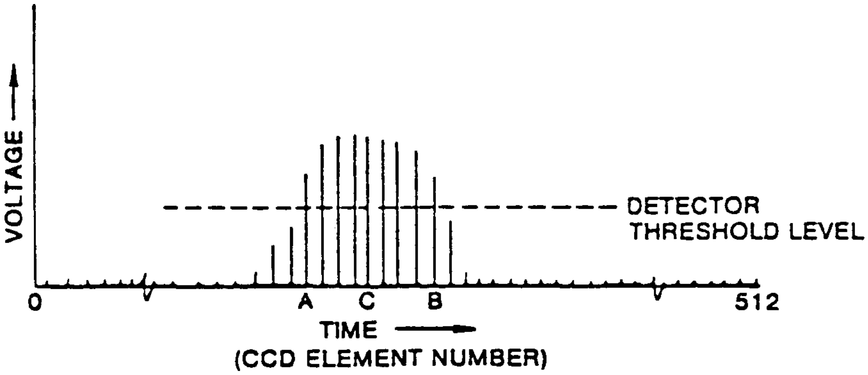


FIG. X3.3 Signal Output from the CCD Array Electronics Showing the Pulses Resulting from the Intersection of the Target Pattern Leg Segment and the CCD Array (A—B)

X4. DESIGN CONSIDERATIONS[4]

X4.1 Although the separation distance (S) between the projector and the receiver is not critical and does not affect the measurement accuracy, it does have an effect on the light energy at the image plane. As shown in Fig. X4.1 the diameter of L_2 is greater than the diameter of L_1. This increases the angular coverage at the image plane that is not vignetted. The largest distance from the optical axis at the image plane that does not incur vignetting is also shown in Fig. X4.1 and is calculated as shown in Eq X4.1.

$$H_1 = \frac{d_2 - d_1}{2S} f_2 \tag{X4.1}$$

where:

H_1 = maximum unvignetted ray height at image plane,
d_2 = diameter of lens L_2,
d_1 = diameter of lens L_1,
f_2 = focal length of lens L_2, and
S = separation between projector and receiver

X4.2 From Eq X4.1 it is apparent that it is desirable to keep Ssmall and d_2 much larger than d_1 to achieve a large value of H_1. The focal length f_2 can also be increased (which increases accuracy as well) except that the image irradiance changes as a function of $1/(f_1 + f_2)^2$. Thus, the irradiance drops as the square of the focal length as accuracy and vignetting effects improve linearly with f_2.

X4.3 Fig. X4.2 shows the optical ray trace for 50 % vignetting.

X4.4 The 50 % vignetting ray height at the image plane is calculated as shown in Eq X4.2.

$$H_2 = \frac{d_2}{2S} f_2 \tag{X4.2}$$

where:

H_2 = image ray height for 50 % vignetting,
d_2 = diameter of lens L_2,
S = separation distance between projector and receiver, and
f_2 = focal length of L_2.

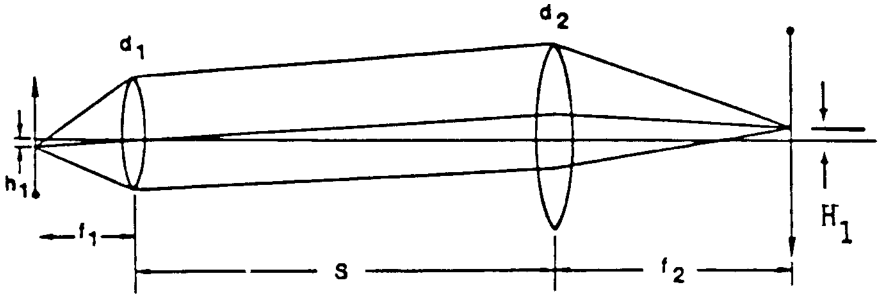


FIG. X4.1 Projector-Receiver Ray Trace Showing Maximum Distance h_1 Possible Without Incurring Vignetting at Lens L_2 Due to Diameter d_2

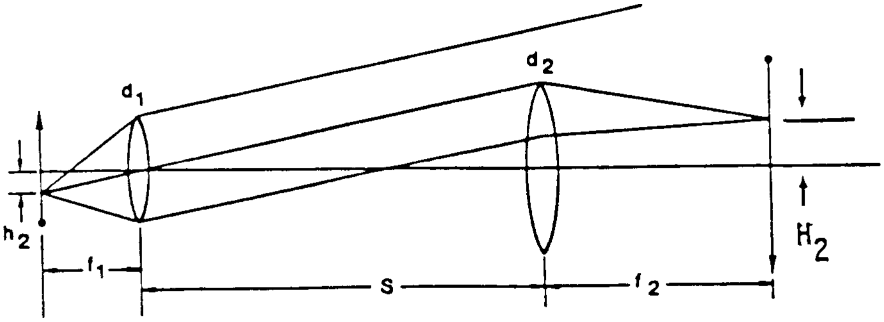


FIG. X4.2 Projector-Receiver Ray Trace for 50 % Vignetting Due to Lens L_2 Diameter d_2

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