An experimental apparatus for measuring the relative illumination of finite conjugate lenses

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SENIOR RESEARCH PROJECT

AN EXPERIMENTAL APPARATUS FOR MEASURING THE RELATIVE ILLUMINATION OF FINITE CONJUGATE LENSES

by

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ABSTRACT

The apparatus described is designed to measure relative illumination of finite conjugate lenses with comparable accuracy and reliability than existing methods and provides a graphical output with less time expended for data acquisition.

An opto-mechanical scanning system is utilized for transmitting light pulses from known image field positions to a photomultiplier tube. The light pulses are transmitted to the phototube via an optical system consisting of an array of lucite rods (light pipes) positioned in the image plane of the lens under test. The rods terminate at a cylindrical housing which contains a rotating lens prism assembly which scans the end of each lucite rod in sequence and relays the illumination values to the photomultiplier. The output current of the tube is displayed on a cathode ray tube oscilloscope and photographed.

Data obtained with this apparatus were compared to data obtained using photographic photometry. Results indicate that the apparatus is very repeatable and that data acquisition time is significantly reduced.
INTRODUCTION:

A number of photographic systems produce excellent qualitative results. By suitable calibration of the various components of the system, the information gathering capability of the system can be greatly increased. One of the calibrations frequently encountered in the field of photographic instrumentation involves the measurement of relative illumination or the amount of illumination "fall off" in the image plane of a photographic objective. This decrease in illuminance at the off axis positions may be due to such causes as barrel vignetting, absorption and cosine variations. Relative illumination is defined as the ratio of the illuminance at the focal plane, for off-axis field positions, to the illuminance for the center of the field. This assumes that the luminance of the object field, as observed from the lens, is the same throughout the field, or that the field is a Lambert's law surface. Relative illumination is specified as the per cent of axial illuminance for image points at given angular distances. Two methods of measurement exist.

Extended Source Method

This method is based on filling the lens with light from an extended uniform source of adequate size, placed in the object plane of the lens. The extended source should be uniformly bright over the useful area to within ±3%. A photodetector is displaced laterally to the position corresponding to the required angular positions and the corresponding percentage of axial illumination is determined from a calibration curve of the photocell. Curves
are plotted of per cent illuminance vs field angle or distance from the axis.

**Densitometric Method:**

In this method, the photoelectric detector is replaced by a photographic emulsion. Exposures are made and the films processed with control strips which were exposed in a sensitometer. The negatives are densitometered at the positions corresponding to the required angular positions. The illuminance is determined from a calibration curve derived from the sensitometric data. A curve of per cent illuminance versus distance from axis is plotted.¹

Both of these methods are time consuming and the accuracy of results doubtful when equipment is adapted to obtain data. Recording of data and plotting of curves becomes tedious when a great number of lenses are evaluated. The proposed apparatus is designed to minimize these problems.
OBJECTIVES:

To design, construct and evaluate a system for measuring the relative illumination of finite conjugate lenses. This apparatus will measure relative illumination with equal or better accuracy than existing methods with a considerable reduction in data acquisition time.

DESCRIPTION OF APPARATUS:

The apparatus is comprised of five main components:

1. Light Source
2. Optical Bench
3. Scanning System
4. Multiplier Photometer
5. Readout Equipment

Light Source:

The requirement for a maximum of ±3% variation in luminance across the object format was achieved by using three high intensity projection lamps in a plane parallel to a diffusing screen comprised of flashed opal and groundglass. The source is enclosed to prevent stray light from reaching the scanning system, and air cooled by two fans. This arrangement resulted in a source uniformly bright to within ±2% over a six inch diagonal. (See Figure 1)
Optical Bench:

The optical bench consists of a lens holder and light source holder which slide along two parallel six foot long steel ways. The scanning system and image plane are mounted permanently on one end of the bench, so that changes in magnification are facilitated by moving the light source and lens relative to the scanning system. (Refer to Fig. 2)

Scanning System:

The scanning system consists of an array of nineteen .125" diameter lucite rods mounted .345" apart in the image plane of the lens under test. The image diagonal is 6.25" long. The light pipes serve to transmit the light from the image plane to the inner wall of a cylindrical aluminum housing. The aluminum housing contains a rotating lens-prism assembly which transmits the light from the end of each light pipe in sequence, to a photomultiplier tube. The scanner is driven by a synchronous, 6 RPM motor, resulting in a scan rate across the image plane of 4 seconds, with one complete scan every 10 seconds. It is mounted in a ball bearing race for rigidity and smooth operation. (Refer to Fig. 3)

Lens #1 (6 mm, f:1.2) forms an image of the light pipe exit face at the entrance pupil of lens #2. Lens #2 (50 mm, f:2) produces an enlarged image of the exit pupil of lens #1 at the photocathode of the photomultiplier tube, ensuring that the entire surface of the photocathode is uniformly illuminated. A folded optical path is used to keep the apparatus as compact as possible. 

(in principle)

* A similar scanning system was used by J. Hughes, RIT '64 in his Research Project, "A Kinetic Densitometer".
OPTICAL BENCH

Fig. 2a- Overall view of system

Fig. 2b- Scanner and Photomultiplier Assembly
A groundglass is located in the image plane, just below the light pipe array to facilitate focussing and measurement of magnification. A reticle of known dimensions mounted at the light source is used in this operation. (Refer to Fig. 3)

**Photomultiplier Photometer:**

A photomultiplier photometer was constructed for maximum sensitivity and for the ability to substitute phototubes of different spectral sensitivities. The direct current supply voltages for the photomultiplier are provided by a full wave rectified power supply. (For circuit, refer to Fig. 4)

Voltages for each dynode and for the anode are provided by equally spaced taps on a voltage divider network across the rectified power supply. The photomultiplier tube (RCA 931-A) features a combination of high photosensitivity, high secondary emission and small D.C. dark current. The spectral response covers the range from approximately 3000 to 6200 angstroms, with a peak at 4000 angstroms. The output current of the 931A is a linear function of the exciting illumination under normal operating conditions. ² (Refer to Fig. 4a)

**Readout Equipment:**

The output of the photomultiplier was displayed on a cathode ray tube oscilloscope. A chart recorder may also be used, if a 1/2 RPM motor is substituted for the 6 RPM motor. The output is displayed as voltage vs horizontal sweep time, which can be interpreted as per cent illuminance vs. distance in the image plane of the lens. (Refer to Fig. 4b)
Fig. 3  SCANNING SYSTEM
Fig. 4  ELECTRICAL SCHEMATIC-PHOTOMULTIPLIER PHOTOMETER

- Filament Transformer UTC No. FT-6
- Voltage Divider 10-20000 nA, 1 watt resistors
- Output
- PMT RCA-931-A
- Voltage Divider: 10-20000 nA, 1 watt resistors
- 240 volts
- 1000 volts
- 240 volts
- 120 volts
- 5 volts
- High Voltage Transformer UTC No. S-45
- Rectifier 5R4-GX
- Choke UTC No. B-17
- Interlock NE-51 Lamp
- 115v. AC on-off switch
Fig. 4a- Photomultiplier Tube Housing

Fig. 4b- Power Supply and Oscilloscope
Calibration of Equipment:

Considerable variation was encountered in the illuminance emerging from the light pipes due to such causes as unequal (rod) length, losses due to surface imperfections, variation in polish at the light pipe ends, and losses at the radii where the pipes enter the cylindrical housing. This variation was minimized by utilizing sections of continuous neutral density wedges mounted over the image plane end of the light rod array. With the light source mounted close to the image plane, the continuous wedges were moved across each of the light pipes, one at a time, while observing the output signal on the oscilloscope. Density values ranged from .10 to .56. Using this method, the illumination exiting from each of the pipes was matched to ±½%.

The linearity of the phototube output was checked by adjusting the output of the tube so that a value of 100% was observed on the oscilloscope graticule and then introducing known neutral density values into the optical path. The resulting transmission values were compared to calculated values and indicated that there was no measurable departure from linearity.

The combined stability of the photomultiplier, power supply, oscilloscope, and light source showed a drift (in percent illuminance value) of not more than 1 1/2% over a period of ten minutes when all components were operated from a constant voltage transformer.
EVALUATION PROCEDURE:

Method of Data Collection:

Electronic Method (scanning apparatus):

The lens to be tested was placed in the lens holder, set at the required magnification (1:1) and focussed. The light source, photometer, and oscilloscope were turned on for a warm-up period of ten minutes. The scanner drive motor was turned on and the output signal of the photomultiplier displayed on the oscilloscope. By varying either the input voltage to the photomultiplier or the scale attenuators on the oscilloscope, the maximum deflection was adjusted to 100%. (The output current which is being displayed is directly proportional to the illumination level.) The oscilloscope trace was photographed on Polaroid material and processed according to the manufacturer's instructions. (Refer to sample data, Fig. 5)

Densitometric Method:

The lens was placed in a view camera and set at the required magnification (1:1) and focus setting. The uniform source was photographed on Panatomic-X sheet film. The exposures chosen resulted in densities that fell on the straight line portion of the characteristic curve. The film was stored for a period of twelve hours prior to processing, allowing the latent image to stabilize. The six replicates for each lens and a control strip were processed together to minimize processing variability. The film was developed for 4½ minutes in Kodak DK-50 developer at 68°F using A.S.A. agitation, dried and densitometered. Data from the control strip was plotted versus
SAMPLE DATA for ELECTRONIC METHOD

Fig. 5a- Oscilloscope Trace - No lens in system

Fig. 5b- Relative Illumination for 6" f:4.5 lens

Fig. 5c- Relative Illumination for 3" f:1.9
illuminance at the sensitometer step wedge. (Refer to appendix I) Densities at the required image field positions were converted to illuminance values and tabulated.

Replicated data from both methods was averaged and plotted. (Refer to Fig. 6a, 6b) The resulting curves were compared statistically, using the densitometric method as a standard. Variance was calculated to determine the repeatability of the two methods. (Refer to Appendix II, III)\(^3,4\)

**RESULTS:**

1) The relative illumination as determined by the densitometric method and by the electronic method is as follows:

<table>
<thead>
<tr>
<th>Distance from axis in inches</th>
<th>Relative Illumination</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>(\frac{1}{2})</td>
<td>92</td>
</tr>
<tr>
<td>1</td>
<td>80</td>
</tr>
<tr>
<td>(1\frac{1}{2})</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>39</td>
</tr>
<tr>
<td>(2\frac{1}{2})</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3&quot; f:1.9 Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Densitometric</td>
</tr>
<tr>
<td>Electronic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distance from axis in inches</th>
<th>Relative Illumination</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>(\frac{1}{2})</td>
<td>99</td>
</tr>
<tr>
<td>1</td>
<td>98</td>
</tr>
<tr>
<td>(1\frac{1}{2})</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
<td>93</td>
</tr>
<tr>
<td>(2\frac{1}{2})</td>
<td>89</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6&quot; f:4.5 Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Densitometric</td>
</tr>
<tr>
<td>Electronic</td>
</tr>
</tbody>
</table>

2) The variance of each of the two methods is as follows:

<table>
<thead>
<tr>
<th>3&quot; f:1.9 Lens</th>
<th>6&quot; f:4.5 Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Densitometric: (s^2 = 169)</td>
<td>Densitometric: (s^2 = 58.4)</td>
</tr>
<tr>
<td>Electronic : (s^2 = 0.60)</td>
<td>Electronic : (s^2 = 0.35)</td>
</tr>
</tbody>
</table>

3) The data acquisition and evaluation time for both methods are as follows:

<table>
<thead>
<tr>
<th></th>
<th>min.</th>
<th>max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Densitometric</td>
<td>55'</td>
<td>120'</td>
</tr>
<tr>
<td>Electronic</td>
<td>5'</td>
<td>20'</td>
</tr>
</tbody>
</table>
Figure 6a
Relative Illumination of 6" f:4.5 lens
Figure 6b
Relative Illumination for 3" f:1.9 lens
CONCLUSIONS:

1.) Data acquired using the scanning apparatus is comparable to data obtained by the densitometric method.

2.) The apparatus exhibits a higher degree of repeatability than the densitometric method.

3.) Data acquisition time is reduced by a factor of six to ten times.

DISCUSSION OF RESULTS:

Inspection of the relative illumination curves reveals that in one case, (6" f:4.5 lens) the apparatus produces data that are somewhat higher than the densitometric method indicates, while in the case of the 3" f:1.9. lens, the reverse is true. Statistical tests, however, failed to detect any significant difference between the two methods. A possible explanation for this is that most of the electronic data falls well within the two sigma limits marked on the densitometrically derived curves. (Refer to Fig. 6a, 6b)

The variability of the densitometric data is very high when compared to the electronic data. This can, in part, be explained by the nature of photographic photometry. When measuring relative illumination, only a small portion of the D-log E curve is utilized, and relatively small density differences must be detected. There are a great number of steps in the photometric process, each step introducing a certain amount of variability. Since a small density difference results in a rather large change in transmission, one would expect that errors are magnified.
The scanning apparatus is simple to operate and serves to minimize the number of steps involved in the acquisition of data. The chances for error (especially human error) are minimized and considerable savings in time are realized.

---FOOTNOTES---

2. Radio Corporation of America, "Data Sheet- 931-A Multiplier Phototube" (1958)
ACKNOWLEDGEMENTS

The authors are indebted to professors B. Carroll, A. Rickmers, W. Shoemaker, and H. Todd for their cooperation and guidance in the execution of this project.

Furthermore, we wish to thank Elgeet Optical Co. for the loan of the oscilloscope and light source. The help, advice and encouragement received from Robert Volk and Ken Hood of the R.I.T. Mechanical Department, Richard Neumann, Lenore Fedele, Alfonso Nazzaro, Robert Nobilini and James Savage was gratefully appreciated.
CALIBRATION CURVE-DENSITOMETRIC DETERMINATION OF RELATIVE ILLUMINATION

Panatomic X, Developed 4½ min., 68°F, ASA Agitation
DK-50 Developer
Incident Illumination at Sensitometer Wedge = 1970 mc
Exposure Time = .20 sec.

\[ \gamma = \frac{D}{\log E} \]

\[ \gamma = \frac{1.38 - 0.68}{3.094 - 1.694} = 0.36 \]
APPENDIX II

STATISTICAL ANALYSIS

$\chi^2$ Test for Goodness of Fit - 3" f:1.9 lens

$H_0: \bar{X}_e = \bar{X}_p \quad H_1: \bar{X}_e \neq \bar{X}_p$

<table>
<thead>
<tr>
<th></th>
<th>$\bar{X}_e$</th>
<th>$\bar{X}_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>93</td>
<td>91</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>79</td>
</tr>
<tr>
<td>4</td>
<td>62</td>
<td>63</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

\[ \overline{X}_e = \text{Averages of Electronic Data} \]
\[ \overline{X}_p = \text{Averages of Densitometric Data} \]

Using the general formula

\[ \chi^2 = \sum_{i=1}^{n} \frac{(X_e - X_p)^2}{X_p} \]

we obtain:

\[ \chi^2_3 = \frac{(100-100)^2}{100} + \frac{(93-91)^2}{91} + \frac{(80-80)^2}{80} + \frac{(62-63)^2}{63} + \frac{(32-39)^2}{39} + \frac{(8-12)^2}{12} \]

\[ \chi^2_3 = 2.39 \]

\[ \chi^2_{0.05} = 11.07 \text{ (book value)} \]

On the basis of the above evidence, we state with 95% confidence that there is no difference between the two methods.

A similar test on the 6" f:4.5 data yielded the following results:

\[ \chi^2_3 = 0.645 \]

\[ \chi^2_{0.05} = 11.07 \text{ (book value)} \]

Calculation of Standard Deviation

General formula:

\[ s = \sqrt{\frac{\sum (x-x)^2}{n-1}} \]

Calculated Values for 3" f:1.9

Densitometric Method: $s = 13$
Electronic Method: $s = 0.775$

Calculated Values for 6" f:4.5

Densitometric Method: $s = 7.6$
Electronic Method: $s = 0.59$
APPENDIX III

F Test:

General Formula: \( F = \frac{s^2}{s^2_p} \)

The following values were calculated:

3" f:1.9 lens

\[
F_{\text{calc}} = \frac{(13)^2}{(0.775)^2} = 281
\]

6" f:4.5 lens

\[
F_{\text{calc}} = \frac{(7.6)^2}{(0.590)^2} = 168
\]

\[
F_{\text{book}} = 5.05
\]

On the basis of the above evidence, we can state with 95% confidence, that there is a significant difference between the variances of the two methods. The variance of the photographic method is significantly higher than the variance of the apparatus.