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NBS TECHNICAL NOTE 935

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Measurement of Energy Irradiance from Single Pulse Sources

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Measurement of Energy Irradiance from Single Pulse Sources

technical note, no. 935

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Issued February 1977

National Bureau of Standards Technical Note 935
Nat. Bur. Stand. (U.S.), Tech. Note 935, 32 pages (Feb. 1977)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1977

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MEASUREMENT OF ENERGY IRRADIANCE FROM SINGLE PULSE SOURCES

A. R. Schaefer and E. F. Zalewski

A method of measuring the energy irradiance from a single pulsed source, such as a xenon flashtube, is presented. Details of the approach used in this particular measurement are given, along with a discussion of the data analysis. In particular, we consider some of the inherent problems encountered in curve fitting which are also common to other radiometric and photometric measurements.

Key Words: Curve fitting; energy irradiance; flashtube, pulsed source; radiometry.

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1. Introduction

In this paper we describe a method for measuring the amount of energy per unit area, or energy irradiance [1][1], propagating from a pulsed source such as a xenon flashtube at a given distance from the source. The basic measurement procedure is applicable when the energy is either to be measured spectrally (per unit wavelength) or to be integrated over a spectral bandwidth, such as in the case of photopic (luminous) energy. The latter measurement was performed as a special calibration by NBS. While preparing for this calibration, it was realized that little previous documentation existed concerning this type of measurement. Since there is an apparent need for such measurements, this paper is being written to document the procedure we have used at NBS.

We will present a specific method of calibrating the energy per unit area of a pulsed source using a continuous (non-pulsed) standard of either irradiance or illuminance (luminous intensity). The theoretical approach will be outlined, followed by a detailed discussion of the factors contributing to the uncertainty of the measurement. As a specific example, we will describe the particular measurement performed at NBS. Finally, we will conclude with a discussion of the treatment of the data, the curve fitting and its inherent problems.

2. Theory of the Measurement

In measuring the energy irradiance output of a pulsed source, the first problem to arise comes from the fact that the only basic reference standards currently available are constant power sources, such as irradiance or illuminance standards, the latter being derived to measure the radiant power incident on a given area within a known time interval. The integral of power over this time interval is the total energy. That is,

$$W = \int_{t_1}^{t_2} E(t)\, dt \qquad (1)$$

where E(t) is the power irradiance as a function of time and W is the energy per unit area. A continuous source can be chopped by a rotating blade to provide a single pulse within a measurable time interval and the integration can be accomplished electrically. For our measurements, a silicon photodiode and operational amplifier were used. The emitted current, i(t), was proportional to the irradiance incident upon the detector:

$$i(t) = k_1 E(t) \qquad (2a)$$

[1]Figures in brackets indicate the literature references at the end of this paper.

If we write Eq. (2a) in terms of the charge Q, then

$$\frac{dQ}{dt} = k_1 E(t) \quad . \tag{2b}$$

We used an electrometer in its charge measuring mode, in which it behaves essentially like a capacitor. It produces a voltage, V, proportional to the charge, so that,

$$V = \frac{Q}{C} \quad . \tag{3a}$$

Since Q and V change in time we can differentiate and obtain

$$\frac{dV}{dt} = \frac{1}{C}\frac{dQ}{dt} \quad . \tag{3b}$$

Substituting into Eq. (3b) yields

$$C\frac{dV}{dt} = k_1 E(t) \tag{4a}$$

or

$$\frac{dV}{dt} = k E(t) \quad . \tag{4b}$$

Therefore, over a time interval t_1 to t_2:

$$V = k \int_{t_1}^{t_2} E(t)\, dt \quad . \tag{5}$$

Equation (5) is the working relation of the measurement system: a power irradiance pulse is received by the detector, and subsequently a voltage, proportional to the total energy in the pulse, is read on the electrometer capacitor. The calibration is made absolute by the use of a reference standard in the determination of k.

Determination of the system calibration constant, k, can be accomplished by measuring the voltage V_0 that results after applying a pulse of known power irradiance. The energy irradiance integral can be evaluated in the following manner. First, a known constant power irradiance, E_0, is produced at the detector by a suitable standard incandescent lamp. A shutter is placed between the standard lamp and the detector. If one assumes that the shutter instantaneously opens at time t_1 and closes at t_2, then a pulse of known power irradiance is incident on the detector in the specified time interval. From Eq. (5) we can obtain the value of k:

$$k = \frac{V_0}{\int_{t_1}^{t_2} E_0\, dt} = \frac{V_0}{E_0(t_2 - t_1)} \tag{6}$$

3. Detailed Experimental Considerations

We have outlined the essentials of the method whereby energy irradiance calibrations can be made. We shall now go into several more detailed, practical aspects of the measurement which, if not given due attention, could have an adverse effect upon the results.

3.1 The Shutter Mechanism and the Evaluation of the Time Integral

The shutter that provides the time calibration information must have the following characteristics. It must, of course, provide a stable, repeatable, and well-determined open time. In addition, it should expose the entire detector surface to the source in a well defined manner. In this regard, one must be wary of accidentally using the shutter in such a way that the detector will not be illuminated in the same manner by both the shutter and standard lamp combination and the pulsed source to be calibrated. This would be the case, for instance, if one used a shutter opening that was not larger than the detector aperture.

The shutter used for this calibration was a single opening sector disc of 63°, rotating once every half second. The circular detector, area about 1 cm^2, was placed on a radius about 15 cm from the axis of the sector disc. Under these conditions the shutter opening or closing can be approximated by a knife edge shadow moving across the detector in a period about one sixteenth that of the total open time. Let us assume for the purpose of discussion that we have a detector that has the same shape as the opening in the sector disc plus uniform and linear responsivity. The time dependent output of the detector will then be a trapezoid, as outlined in Fig. 1a. Segments t_1 to t_3 and t_4 to t_6 will be straight lines, since the area irradiated is changing linearly with time. In order to apply Eq. (6) one must know the area of this pulse from t_1 to t_6 assuming height E_0. The area of the trapezoid is given by $A = 1/2(t_4 - t_3 + t_6 - t_1) E_0$. Since

$$t_3 - t_2 = t_2 - t_1 = t_6 - t_5 = t_5 - t_4 \qquad (8)$$

then

$$t_4 - t_3 = t_5 - t_2 - 2(t_3 - t_2) \qquad (9)$$

and

$$t_6 - t_1 = t_5 - t_2 + 2(t_2 - t_1) \quad . \qquad (10)$$

Therefore, the area of the trapezoid is simply

$$A = (t_5 - t_2) E_0 \quad . \qquad (11)$$

That is, the area of a trapezoidal pulse is equal to the area of a rectangular pulse drawn through half-power points t_2 and t_5 and of height E_0. This is a useful operational simplification.

In reality, the detector used is generally not rectangular in shape, but circular. Hence the segments t_1 to t_3 and t_4 to t_6 are not straight lines, since the detector area irradiated will not be a linear function of time. They will have a shape similar to that shown in Fig. 1b.

One can calculate from the area of a circular segment, what the area of this pulse shape will be. Let

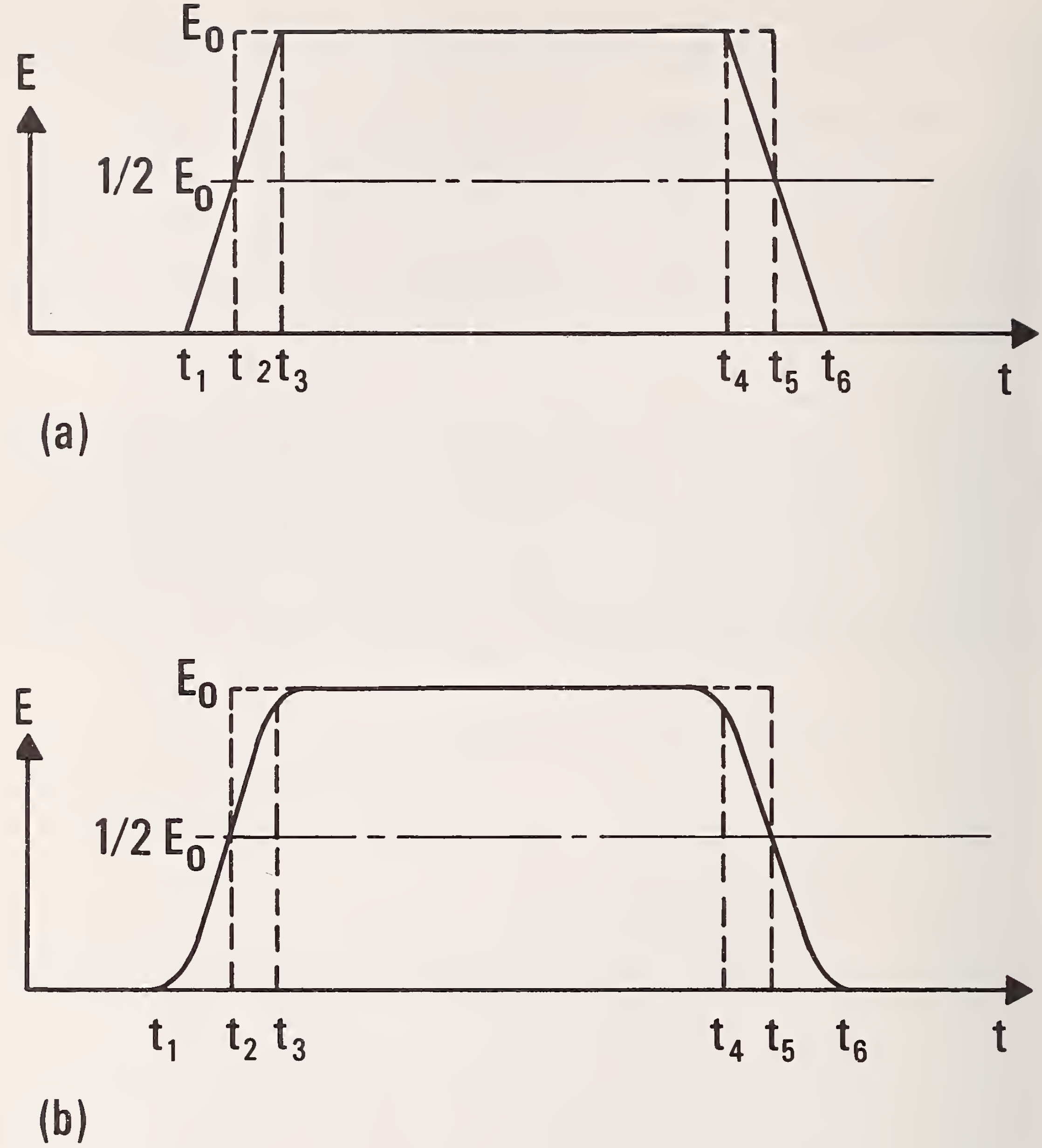

Fig. 1: Shuttered time response of detector illustrating integration of total pulse. A) Detector has same shape as sector disk. B) Circular detector.

$$I_1 = \frac{E_0}{2} - \left[x \sqrt{(E_0/\pi) - x^2} + (E_0/\pi) \sin^{-1}(x \sqrt{\pi/E_0})\right] , \quad (12a)$$

$$I_2 = \frac{E_0}{2} + \left[t \sqrt{(E_0/\pi) - t^2} + (E_0/\pi) \sin^{-1}(t \sqrt{\pi/E_0})\right] , \quad (12b)$$

$$I_3 = \frac{E_0}{2} + \left[x \sqrt{(E_0/\pi) - x^2} + (E_0/\pi) \sin^{-1}(x \sqrt{\pi/E_0})\right] , \quad (12c)$$

$$I_4 = \frac{E_0}{2} - \left[t \sqrt{(E_0/\pi) - t^2} + (E_0/\pi) \sin^{-1}(t \sqrt{\pi/E_0})\right] , \quad (12d)$$

where

$$x = \sqrt{E_0/\pi} - t \quad ; \quad (12e)$$

then the area is

$$A = \int_{t_1}^{t_2} I_1 dt + \int_{t_2}^{t_3} I_2 dt + \int_{t_3}^{t_4} E_0 dt + \int_{t_4}^{t_5} I_3 dt + \int_{t_5}^{t_6} I_4 dt \quad . \quad (13)$$

Working through Eq. (13), and using the fact that, from symmetry, Eqs. 8, 9, and 10 are again true, one gets the result

$$A = E_0(t_5 - t_2) \quad (14)$$

This is the same result obtained for the simpler case treated earlier.

From the foregoing discussion we see that in practice one utilizes Eq. 6 with the following modification: instead of $(t_2 - t_1)$, one uses the time interval between half power points, $(t_5 - t_2)$.

We should emphasize the importance of maintaining a constant measurable shutter motion. Due to mechanical imperfections in the system, one should not assume that an ordinary synchronous motor will drive a rotary shutter wheel at the precisely expected rate. The importance of the accuracy of the time measurement to the overall calibration is obvious.

3.2 Errors Inherent in a Photopic Measurement

There are specific problems that arise from doing this calibration photometrically. In this case, the quantity of interest is the photopic[2] energy irradiance obtained from the time integral of the photopic power irradiance (illuminance) rather than the spectral power irradiance. The measurement is carried out exactly as described above, except that a photopic detector must be used. It must be calibrated with a photometric standard, such as luminous intensity. The uncertainty arises in answer to the question: How well does the detector response actually correspond to the CIE defined $V(\lambda)$ curve?

The photometric standard that was used to calibrate the detector was an incandescent source having a spectral output resembling that of a thermal radiator at 2856 K. This calibrated detector was then used to measure the output of xenon flashtubes which have a very different spectrum. They have a much higher relative energy in the blue than the incandescent standards. These spectral differences coupled with the detector response deviations from the $V(\lambda)$ curve can lead to a sizeable measurement error.

In order to approximate the probable magnitude of this error, hypothetical spectral response curves of several photopic detectors* were used in calculating a theoretical calibration between a blackbody incandescent source at 2856 K and the spectral output of a typical xenon flashlamp. We used the relation:

$$E_{ij} = K_m \int_{380\ \text{nm}}^{760\ \text{nm}} D_i(\lambda)\ E_j(\lambda)\ d\lambda \qquad (15)$$

where E_{ij} represents the illuminance measured by a detector i from a source j, $E_j(\lambda)$ is the spectral irradiance from the j^{th} source, $D_i(\lambda)$ is the spectral responsivity of the i^{th} detector, and K_m is the maximum luminous efficacy. The value of K_m need not be specified since it cancels out in the comparison. For the perfect detector, $D_i(\lambda)$ is the CIE $V(\lambda)$ curve. The integrals were evaluated numerically using Simpson's Rule[3] with 10 nm wavelength intervals.

The hypothetical detector responses usually deviated from the defined $V(\lambda)$ curve by one or two percent, and sometimes more in the extreme red and blue regions. The results of these calculated calibrations differed from those obtained using the perfect photopic detector by as much as 5%. This was in agreement with the results of actual experimental calibrations. The same flashlamp and standard lamp were compared under identical conditions with two different types of photopic detectors (silicon photodiodes from different manufacturers). This experiment yielded results which disagreed by about 4%. The experimental precision of the measurement in each case was about ±0.15%. It is obvious that accurate photometric measurements of this type require precise characterization of the spectral response of the detector being used.

3.3 Electronic Considerations

The following experimental considerations hold true for many types of measurements in addition to the one under discussion. It is important not to overlook them so they will be briefly mentioned at this time.

First, the detector and amplifier should have a response time much faster than the rise times of the pulses being measured. This is to insure that the calibration pulse from the shuttered lamp and the flash pulse are both integrated properly in spite of their different waveforms. This can easily be checked with a variable high speed sector disc and an oscilloscope to monitor the detector-amplifier output as a function of pulse frequency. For this calibration, an FET operational amplifier with low capacitance in the feedback circuit was used. This device proved to have an adequately short rise time. It is the second version of the dc amplifier described in Technical Note 594-2.[4]

Another problem is detector linearity. Although one can attempt to set the energy irradiance from the shuttered source approximately equal to that of the pulse, this is difficult to do exactly. In addition, energy irradiance measurements may have to be made at a number of different distances, and it is impractical to recalibrate the detector for each distance from the flashlamp. Finally, the detector-amplifier obviously must respond to a large variation in signal level during each pulse. It is, therefore, very important to ascertain that the detector and amplifier respond linearly. For the detectors used in these measurements the linearity was checked using the inverse square approximation with a luminous intensity standard lamp. They appeared to be acceptably linear; however, as we will show in Section 5.2, this was not an entirely satisfactory test.

Additional details which must be considered are the accurate measurement of the detector to source distance, the repeatability of the positioning of the lamp and detector, standard lamp accuracy, flashlamp repeatability, noise pickup, and detector-amplifier stability.

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*Information obtained from the specification sheets of several manufacturers.

4. Measurement Procedure

The calibration of a flashlamp (with power supply included) was a two part operation: calibration of the detector-amplifier system for photopic energy using a luminous intensity standard lamp with a timing shutter, and subsequent calibration of the flashlamp using the calibrated detector. It was found experimentally that the system drift during the course of a flashlamp measurement was negligible, hence the calibrations of the detector-amplifier were actually done last, after a given flashlamp measurement. The flashlamp was placed in front of the standard lamp as shown in Fig. 2. In this way, the flashlamp could be removed after measurement without disturbing the detector and standard lamp arrangement.

After aligning the optical bench, detector, and standard lamp with a He-Ne laser to define the optic axis, the flashlamp was installed in the position shown. The flashlamp assembly consisted of a thin vertical discharge tube behind a rectangular aperture and an absorbing glass filter. Using the laser, the flashlamp assembly was centered on the optic axis and aligned by autocollimating the laser reflection from the filter glass. An end gauge was used to measure the separation distances from the detector to the flashlamp aperture. The detector was then placed at the smallest source-detector separation distance to be measured in the experiment. Several flash readings were observed on the oscilloscope to select the proper amplifier and electrometer gains, allowing maximum readings without overload distortion. These settings were unchanged for the remainder of the calibration of that flashlamp and for the subsequent detector calibration using the incandescent lamp. Several flashes were first fired on a "cold" tube to allow its output to stabilize before recording readings. Prior to making a reading, the flashtube power supply was allowed ample time to recharge after a previous flash. A gate switch was then opened to the electrometer, and bucking current from the amplifier was set to null the electrometer output reading at zero. Then the lamp was flashed via a remote trigger switch, and the electrometer gate closed, "locking in" a voltage reading on the electrometer capacitor. Several measurements were made at each distance position.

When these measurements were completed, the detector was left at the maximum distance point and the flashlamp assembly removed as noted earlier. The shutter was installed in front of the detector and the standard lamp turned on and warmed up. The shutter was then started and its time interval determined with an oscilloscope. The oscilloscope time base was calibrated with standard frequency signals. After the lamp warmed up, the detector was momentarily shuttered in order to zero the background current on the detector amplifier. Then a series of readings were made as follows. The pulses were spaced at least 1/2 second apart so they would be easy to isolate with the electrometer gate switch. When the pulses were exactly the proper time width, the gate was momentarily closed, then opened, isolating one pulse. The reading was recorded and the electrometer cleared for the next sample. These readings were then averaged to yield a value for k using Eq. (6). As mentioned earlier, the calibration lamp was a standard of luminous intensity. One must therefore assume that the inverse square approximation is valid. Hence the form of Eq. (6) actually used was

$$k = \frac{V_0(D + \delta)^2}{I_0(t_5 - t_2)} \quad . \tag{16}$$

Here I_0 is the luminous intensity of the standard lamp, D is the measured distance, δ is the correction to the "light center" distance and $(t_5 - t_2)$ is the time interval at the pulse half-height. The value of δ was determined separately by fitting* the measured distances D_i (from about 1.5 to 3 meters) and amplifier readings R_i (assumed proportional to the illuminance) to the following equation

$$R_i\delta^2 + 2R_iD_i\delta + R_iD_i^2 - I_0 = 0 \tag{17}$$

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*Some of the difficulties encountered in curve fitting will be taken up in the next Section.

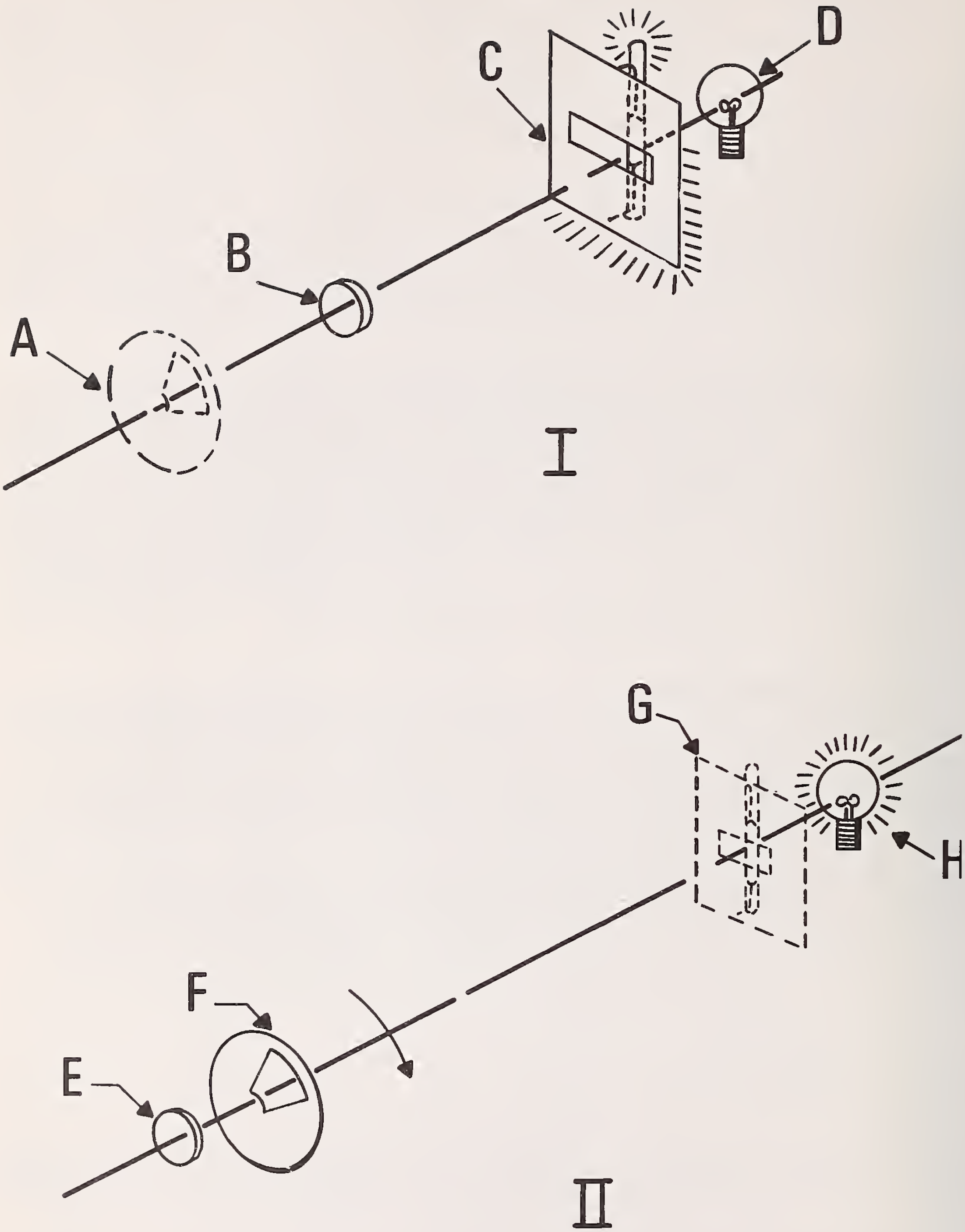

Fig. 2: Experimental setup for measurement. I. Measurement of flashlamp. A) Position of shutter (not used in this part of measurement). B) Detector. C) Flashlamp assembly. D) Lamp standard (in position but not in use in this part of measurement). E) Detector. F) Shutter. G) Position of flashlamp (now removed for this part of measurement). H) Standard lamp.

Finally the flashlamp photopic energy irradiance values, W, were calculated from the measured voltages using the relation.

$$W = V/k \quad . \tag{18}$$

5. Data Analysis

Once the illuminance versus distance data have been obtained, it is often desirable to fit a smooth curve through these points in order to allow interpolation or possibly extrapolation to other desired points. One may be tempted to use some form of the inverse square approximation again, such as

$$I = ED^2 \quad . \tag{19}$$

However, this is not always the best function to describe the variation of illuminance with distance. In fact, by simply assuming there is always a characteristic constant of the source, i.e. the intensity, one can easily be mislead in attempting to interpret the data. Let us first derive the functional form of the relationship that describes the variation of illuminance from the flashlamp as a function of distance.

5.1 A Mathematical Model of the Illuminance from an Apertured Cylindrical Lamp

The xenon flashtubes we measured consisted of a long thin cylinder masked by a rectangular limiting aperture, a fairly common configuration for such sources. In order to make the model of this lamp analytically tractable, we shall assume the following. Consider the narrow cylindrical tube to be a one dimensional, infinitely long vertical linear source of uniform luminance L per unit length. Let us take this to be the x direction. Also consider the source as apertured by an infinitely long horizontal slit of width 2w, in a plane parallel to that of the source and a distance d from it. The axis of the slit is then in the y direction. Finally, consider a rectangular detector, of dimensions 2a in the y' direction and 2b in the x' direction, also in a plane parallel to that of the source and aperture. The detector is at a distance D from the aperture. Figure 3 illustrates this model.

We know that the radiant flux, $d\phi_\alpha$, reaching an element $\alpha(x',y')$ of area dx' dy' of the detector surface from an element of source dx is related to the radiance in the following manner,

$$d\phi_\alpha = \frac{L\ dx\ \cos\theta\ dx'\ dy'\ \cos\gamma}{r^2} \quad . \tag{20}$$

Here θ and γ are the angles between the distance r and the normals to the source axis and detector plane, respectively. At this point we shall make another approximation. Let us assume that $\theta=\gamma$, which is equivalent to saying that the detector is slightly curved with a radius of curvature equal to D + d, the center of curvature being coincident with the source axis. We can now calculate the illuminance at the point α on the detector which comes from the entire source:

$$E_\alpha = \frac{d\phi_\alpha}{dx'\ dy'} = L \int_{x_{min}}^{x_{max}} \frac{\cos^2\theta}{r^2}\, dx$$

$$= L(D + d)^2 \int_{x_{min}}^{x_{max}} \frac{dx}{[(D + d)^2 + x'^2 + (x - y')^2]^2} \tag{21}$$

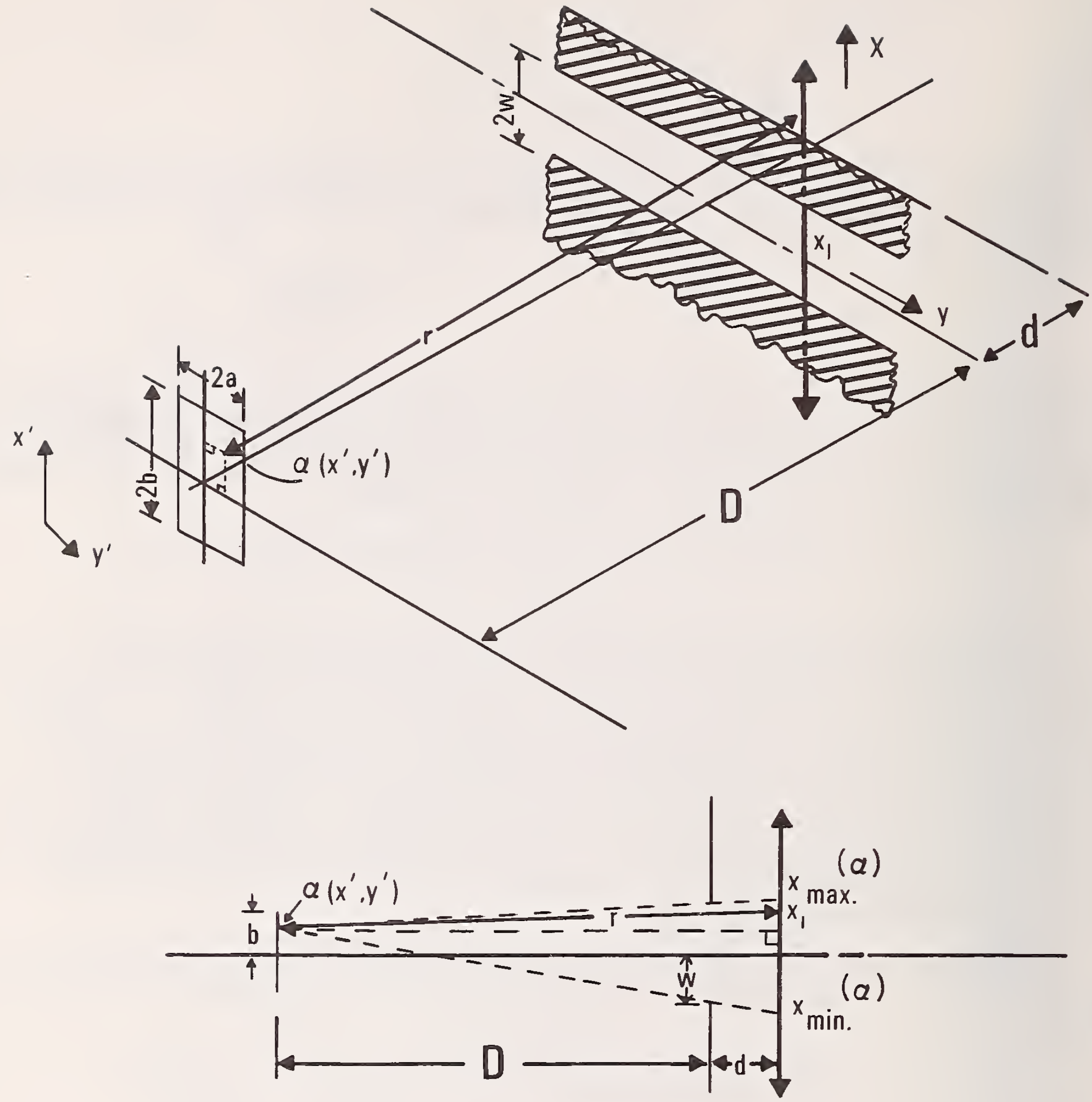

Fig. 3: Illustration of model for analysis of variation of illuminance as a function of detector distance from flashlamp.

The limits of this integral are a function of the slit width and can be determined from the geometry of Fig. 3. They are

$$x_{min} = \frac{-w(D + d)}{D}$$

and

$$x_{max} = \frac{w(D + d)}{D}$$

The result of integrating Eq. 21, is then:

$$\frac{d\phi_\alpha}{dx'\,dy'} = \frac{(D+d)^3\,L}{2[(D+d)^2 + x'^2]}\left\{-\frac{(y'-w)\,D}{[(D+d)^2 + x'^2]\,D^2 + (y'-w)^2\,(D+d)^2}\right.$$
$$+\frac{(y'+w)\,D}{[(D+d)^2 + x'^2]\,D^2 + (y'+w)^2\,(D+d)^2} + \frac{1}{2[(D+d)^2 + x'^2]^{3/2}}$$
$$\left.\times\left[\tan^{-1}\left(\frac{-(y'-w)\,(D+d)}{D[(D+d)^2 + x'^2]^{1/2}}\right) - \tan^{-1}\left(\frac{-(y'+w)\,(D+d)}{D[(D+d)^2 + x'^2]^{1/2}}\right)\right]\right\} \quad (22)$$

To obtain the average illuminance over the entire detector, we must integrate this expression over x' and y' and divide by the detector area. If Eq. (22) is integrated first over y', many terms cancel, leaving

$$\frac{d\phi}{dx'} = \frac{L(D+d)^2}{[(D+d)^2 + x'^2]^{3/2}}\left\{(a-w)\tan^{-1}\left(\frac{-(a-w)\,(D+d)}{D[(D+d)^2 + x'^2]^{1/2}}\right)\right.$$
$$\left.-\,(a+w)\tan^{-1}\left(\frac{-(a+w)\,(D+d)}{D[(D+d)^2 + x'^2]^{1/2}}\right)\right\} . \quad (23)$$

At this point we shall make another approximation to aid in carrying out the analysis. Since D is usually large compared with the detector dimensions,

$$(a \pm w)\,(D + d) << D[(D + d)^2 + x'^2]^{1/2} .$$

Hence we can replace the arctan terms with the first two terms in the series expansion:

$$\tan^{-1} x \cong x - \frac{x^3}{3} .$$

We can now carry out the final integration over x' to give the total flux ϕ intercepted by the detector. After some rather tedious algebra and using the arctan approximation just mentioned, we can write the average illuminance, the flux divided by 4ab, in the following form:

$$\overline{E} = \frac{2Lw}{D(D+d)} \left\{ \frac{1}{2} + \frac{(D+d)^2}{2[(D+d)^2 + b^2]} - \frac{b^2}{6(D+d)^2} - \frac{a^2 + w^2}{4D^2} \right.$$

$$\left. - \frac{(a^2+w^2)\ (D+d)^2}{4D^2[(D+d)^2 + b^2]} - \frac{(a^2+w^2)\ (D+d)^4}{6D^2[(D+d)^2 + b^2]^2} + \frac{(a^2+w^2)\ b^2}{12D^2(D+d)^2} \right\} . \tag{24}$$

We can further simplify Eq. (24) by rewriting it as

$$\overline{E} = \frac{2Lw}{D(D+d)} \left\{ \frac{1}{2} + \frac{1}{2[1 + \frac{b^2}{(D+d)^2}]} - \frac{b^2}{6(D+d)^2} - \frac{a^2+w^2}{4D^2} \right.$$

$$\left. - \frac{a^2+w^2}{4D^2[1 + \frac{b^2}{(D+d)^2}]} - \frac{a^2+w^2}{6D^2[1 + \frac{b^2}{(D+d)^2}]^2} + \frac{(a^2+w^2)\ b^2}{12D^2(D+d)^2} \right\} . \tag{24a}$$

Then, by dropping terms of order greater than

$$\frac{b^2}{(D + d)^2} << 1$$

the average illuminance is approximately given by

$$\overline{E} = \frac{2Lw}{D(D+d)} \left\{ 1 - \frac{2b^2}{3(D+d)^2} - \frac{2(a^2+w^2)}{3D^2} \right\} \tag{25}$$

This equation, rather than the inverse square approximation, is a much better model of the relationship between distance and illuminance of the flashlamp sources we studied.

5.2 Treatment of the Data

In Tables 1 and 2 we have listed, and in Figs. 4 and 5 we have plotted, some measurements made on the same flashlamp using two different detectors. Both detectors were photopically corrected silicon photodiodes operated in the photovoltaic mode (zero reverse bias plus a low input impedance amplifier). The detectors were from two different suppliers and, therefore, would be expected to have different characteristics. Instead of plotting just the illuminance vs. distance for these two sets of measurements, we have plotted the product of illuminance and distance squared versus distance. The distance in these data refers to the measured distance from the aperture of the lamp housing to the detector aperture.

One would expect from the inverse square approximation that at large distances the quantity ED^2 would approach a constant value. On this basis we would be inclined to reject the data from detector 2 (Fig. 5). However, let us see how well each of these data sets will fit the equation we have derived in the previous section. For the flashlamp we measured, d was about 4 cm and w was about 0.5 cm. Both detectors were of the same size with $a = b \approx 0.5$ cm. The only unknown in Eq. (25) is the luminance, L, which can be obtained by using the value of the illuminance measured at one distance. If we arbitrarily choose the points at 1.52 m, the average value of the illuminance measured by detector 1 is 0.281 lux and from detector 2 it is 0.286 lux. The luminance can now be computed and in turn we can compute a theoretical ED^2 based on these single measurements of illuminance. These calculated curves are drawn in Figs. 6 and 7 along with the experimental points. It is obvious that the theoretical curve fits the data from detector 2 (Fig. 7) very well while the curve obtained from the data of detector 1 (Fig. 6) does not. Here is a case where

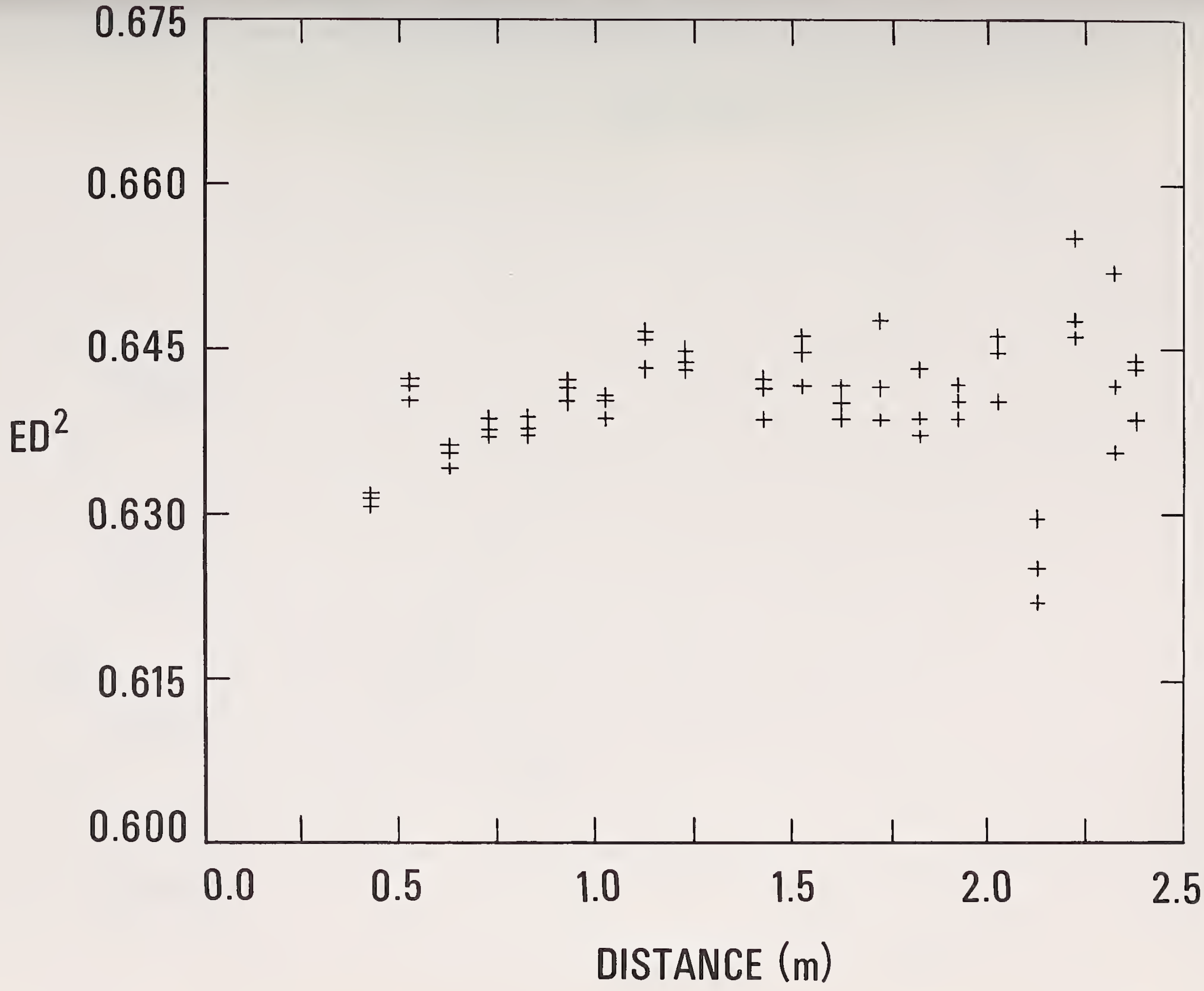

Fig. 4: Plot of illuminance-distance squared product versus distance of a given flashlamp with detector 1.

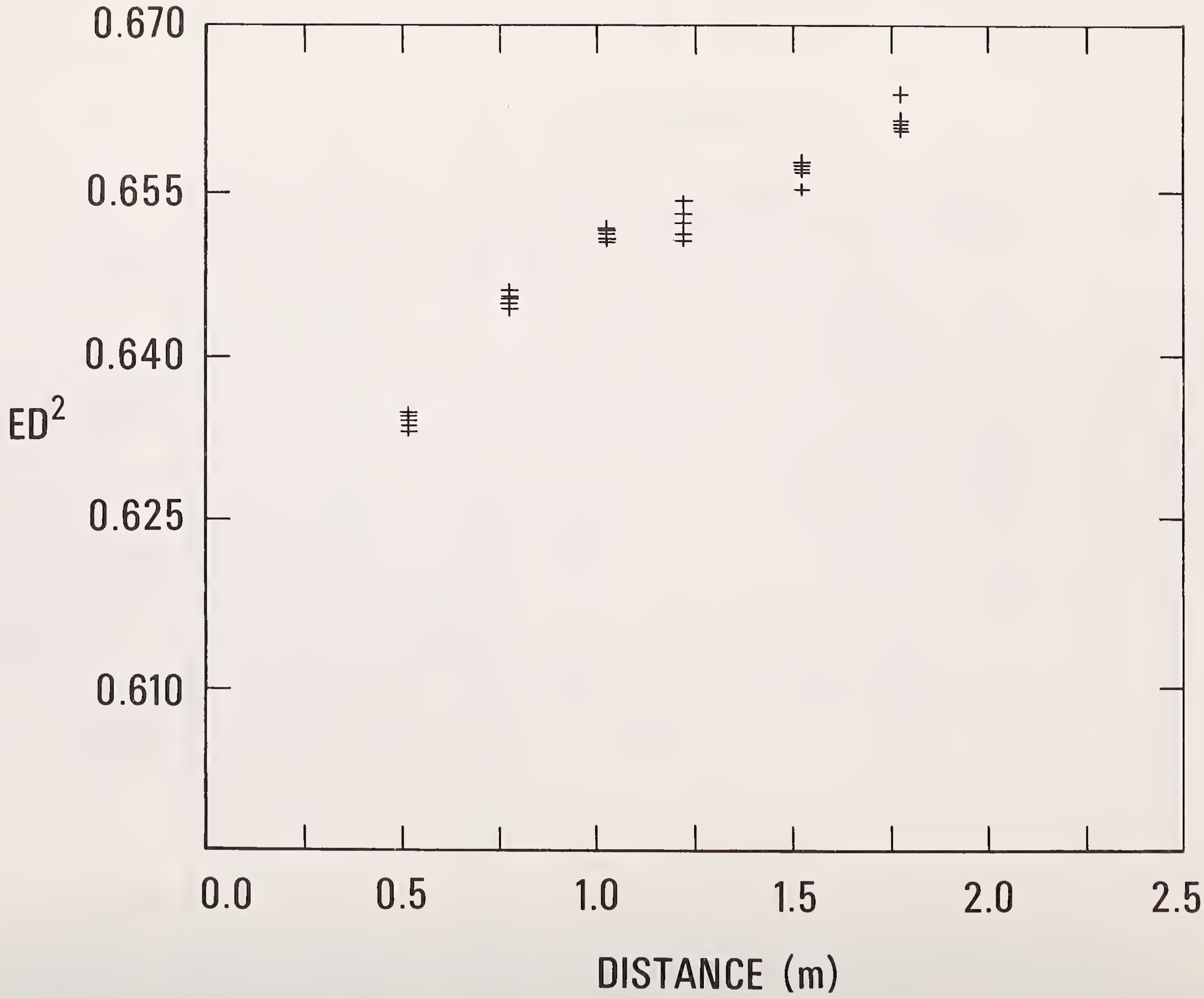

Fig. 5: Plot of illuminance-distance squared product versus distance of a given flashlamp with detector 2.

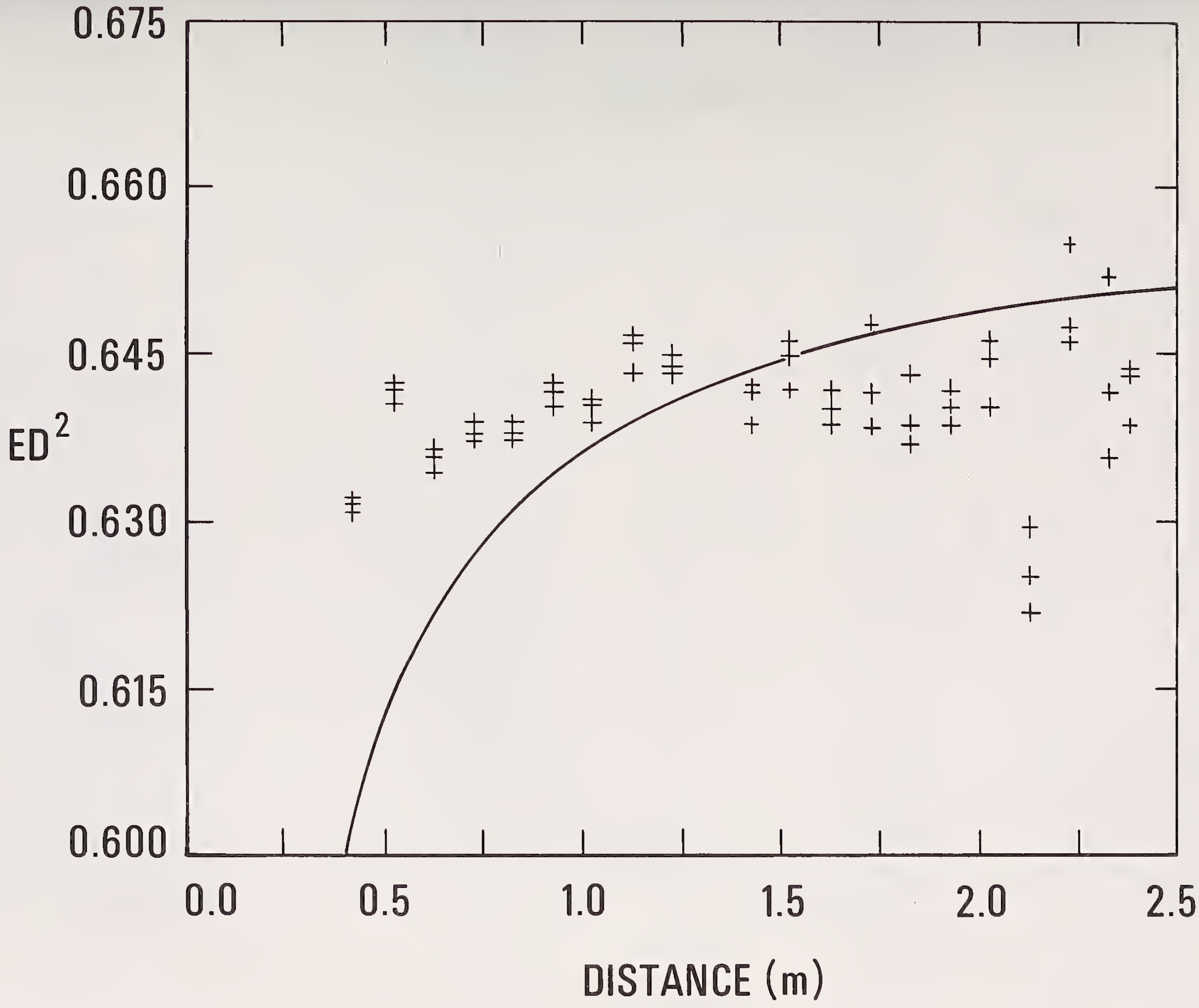

Fig. 6: Data of Fig. 4 with theoretical curve derived from Eq. 25.

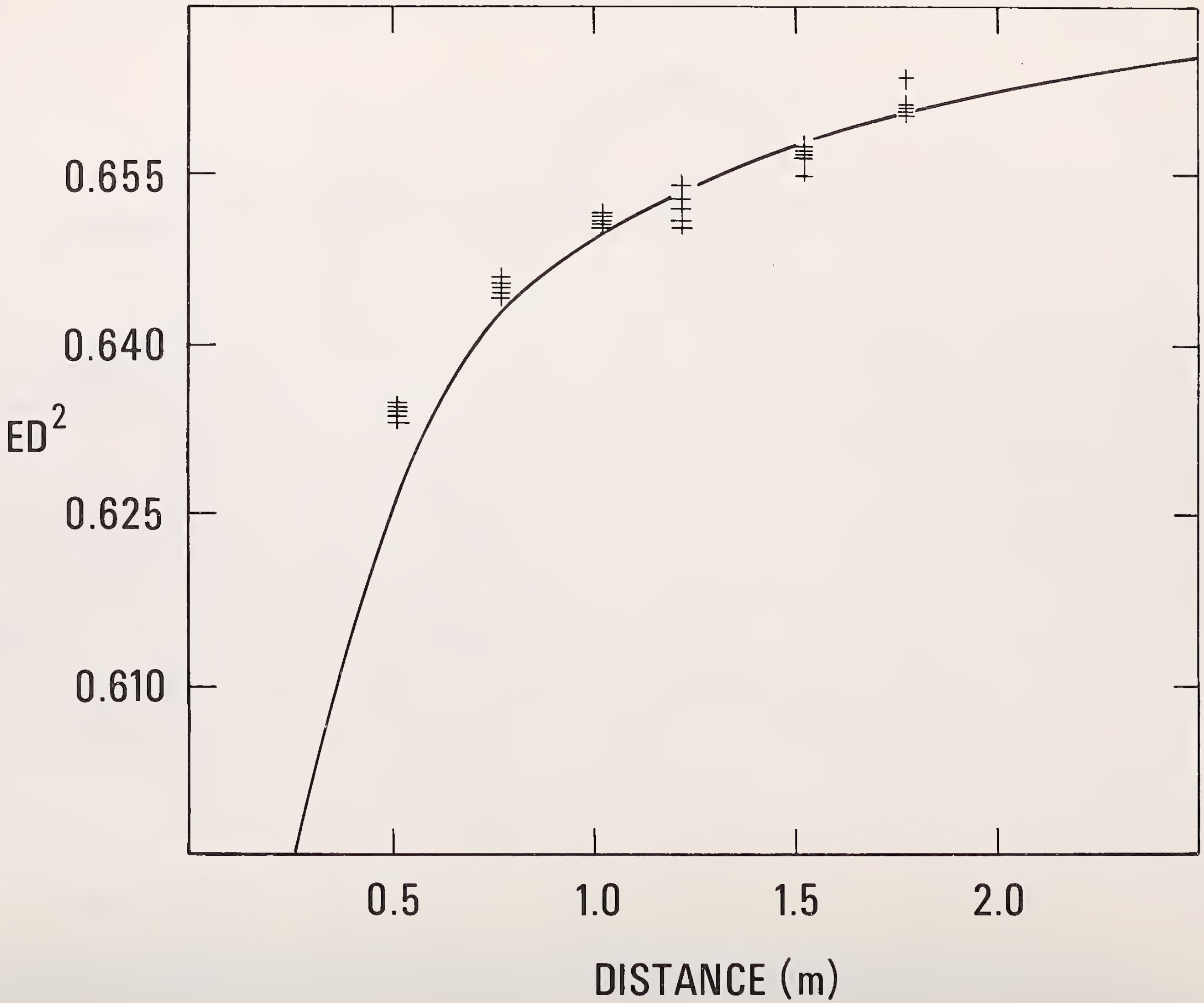

Fig. 7: Data of Fig. 5 with theoretical curve derived from Eq. 25.

intuition based on the inverse square approximation may lead to an incorrect interpretation of the experimental results.

One might ask how well the inverse square approximation with a term to correct the distance as in Eq. (17) would fit these two sets of data. The answer is given in Figs. 8 and 9. Here we have plotted the curves obtained by fitting all the data to a function of the form given in Eq. (17). The fit appears to be reasonably good for detector 1 and fair for detector 2. On the other hand, the distance correction term δ computed from the data of detector 1 is 0.23 cm and from detector 2 it is 2.18 cm--a difference of a factor of ten for two sets of data obtained using the same lamp. The inverse square approximation itself gives no indication of which detector is more linear. In fact, even after fitting all the data to an equation with a correction for distance one may still be misled into believing that detector 1 is better than detector 2. One must know in some detail how the illuminance from a source varies with distance before beginning the data analysis.

6. Curve-Fitting

If one were to interpolate or possibly to extrapolate to large distances in order to determine the so-called "constant of the source", that is the intensity, one must fit the experimental data to a smooth curve. Using Eq. (25) we may fit our data to several different approximations of the same function. We may take as the best approximation an equation of the form:

$$1 = \frac{A_1}{ED(D+d)} + \frac{A_2}{ED(D+d)^3} + \frac{A_3}{ED^3(D+d)} \tag{26}$$

or we may assume that A_2 and A_3 will be very small and just fit to an equation of the form

$$1 = \frac{B_1}{ED(D+d)} \tag{27}$$

In both Eqs. (26) and (27) we would have to use the approximate values of d. Since the lamp is placed behind a filter of unknown index of refraction and since it was difficult to measure the exact separation between the lamp and the aperture, it may be well to include d in the unknown coefficients to be determined from the fitting. Equation (27) can be rewritten as

$$ED^2 + dED = B_1 \tag{28a}$$

or

$$1 = C_1ED^2 + C_2ED$$

Taking the data obtained from detector 2 we used a least square method to fit them to each of the above three equations. These curves are plotted in Fig. 10 along with the original data. All three equations provide a reasonable fit to the data with Eqs. (26) and (28) having a better fit. The difference between interpolated values of $\bar{E}$ at 0.6 m are: from Eq. (26), 1.774 lux; from Eq. (27), 1.764 lux; and Eq. (28), 1.774 lux. The extrapolated values at 0.4 m are: from Eq. (26), 3.920 lux; from Eq. (27), 3.849 lux; and from Eq. (28), 3.900 lux. The "intensity" computed from each of these equations, that is, the value of ED^2 at 10 m is: from Eq. (26), 0.671 cd; from Eq. (27), 0.675 cd; and from Eq. (28), 0.668 cd. The difference between the interpolations obtained using Eqs. (26) and (28) are negligible, however, the differences between both extrapolations are about 0.5%.

The last extrapolation to very large distances shows that the exact form of the equation to which one chooses to fit the data affects the determination of the "intensity". We have

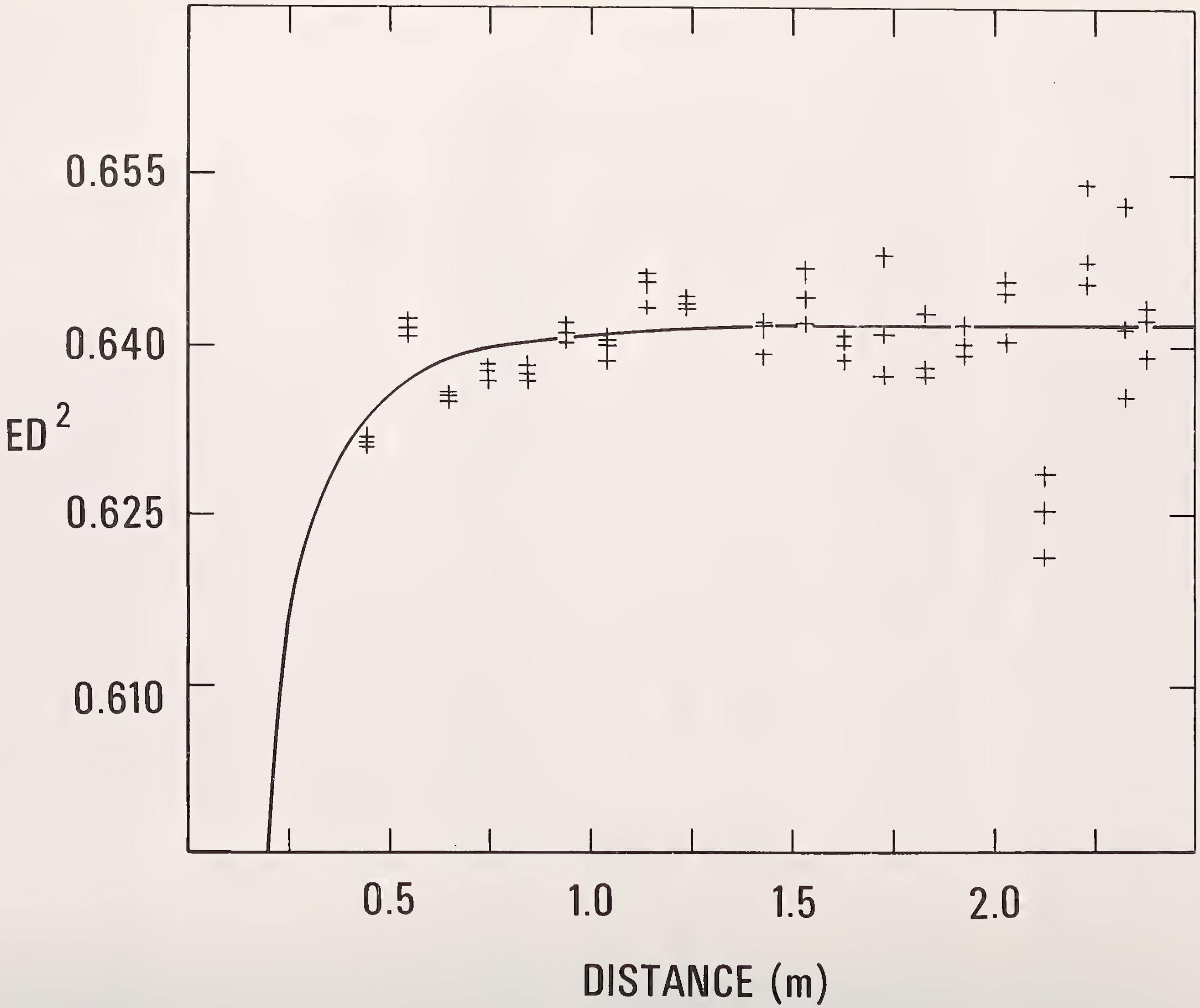

Fig. 8: Data of Fig. 4 with curve fitting of Eq. 17.

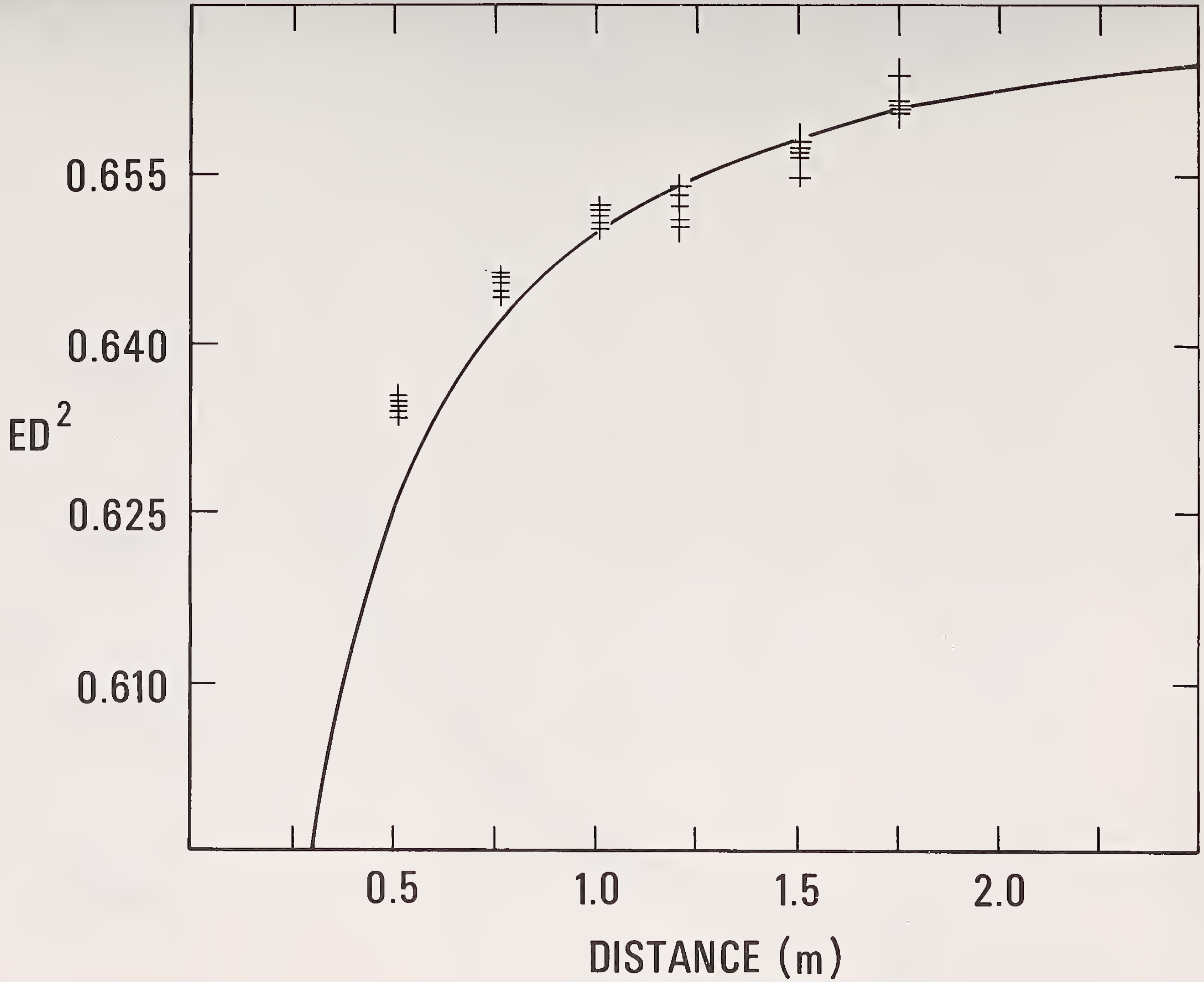

Fig. 9: Data of Fig. 5 with curve fitting of Eq. 17.

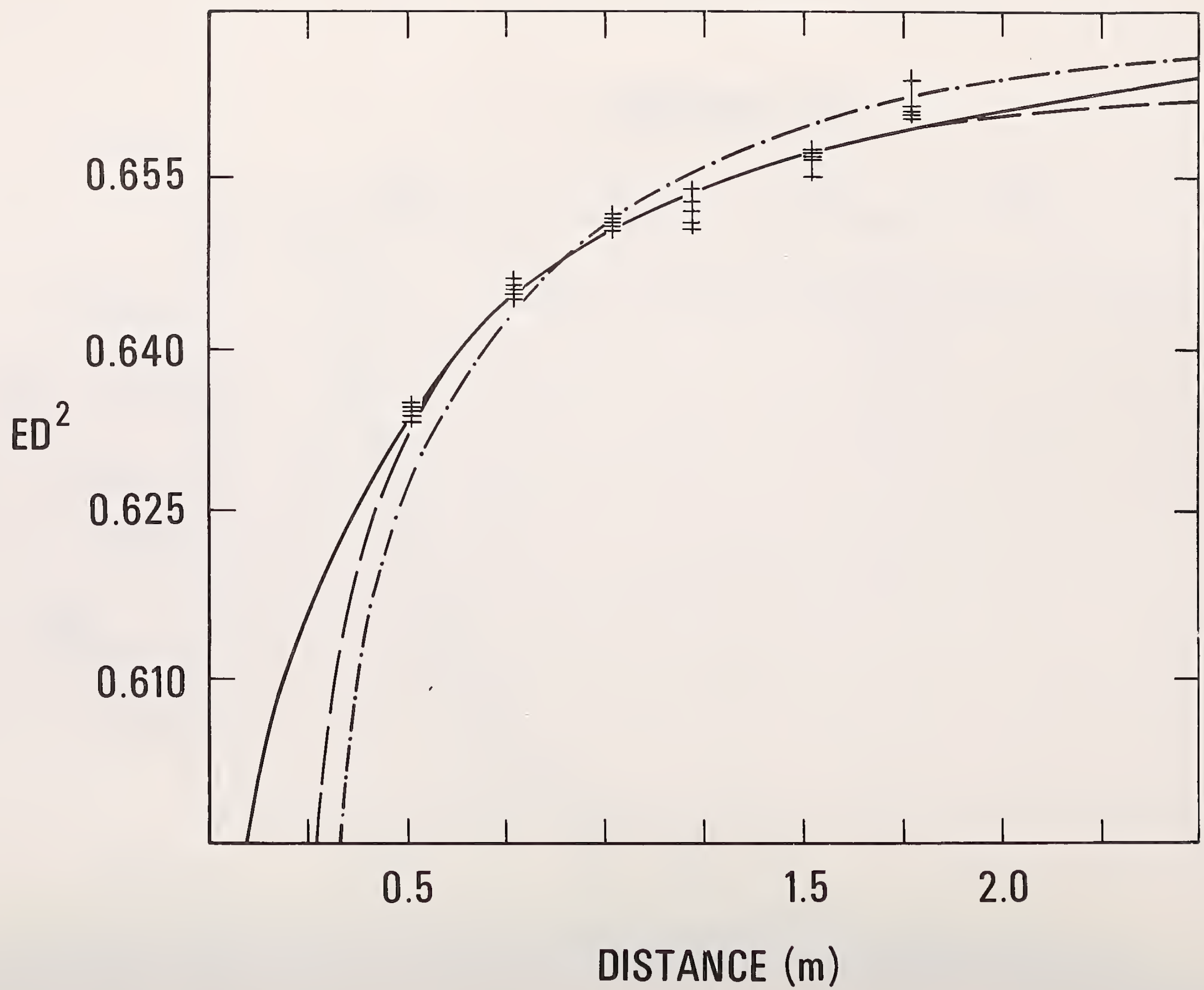

Fig. 10: Data of Fig. 5 with three curve fitting equations. __.__. is Eq. 27. __ __ __ is Eq. 28. ________ is Eq. 26.

not attempted to weigh any of our data. Had we done so, to account for the increase in noise at large distances for example, this would have affected our determination of the "intensity" even more.

This exercise in data analysis and curve fitting alludes to a serious problem in photometry: having intensity as the base unit and fundamental quantity. This is unfortunate because, as demonstrated in this work, the accurate determination of the intensity of a source is subject to unquantifiable errors which are of necessity introduced by curve-fitting.

7. Summary

We have presented a method which is useful in determining the energy irradiance or illuminance output of single flashes from a pulsed source. We have described a general approach, discussed a specific technique employed, and presented in detail a general model which can be used to describe the illuminance (and irradiance) as a function of distance from an aperture-lamp configuration typical of flash sources. We have examined a number of experimental details and the effects they have upon the results of these measurements. Finally, we have indicated some of the difficulties encountered in curve fitting, and how they could yield erroneous results. Although several of the techniques employed in this measurement could obviously be refined and improved if desired, the basic approach should be satisfactory to many needs.

****

The authors gratefully acknowledge the contributions and stimulating discussions with J. Geist, particularly concerning the models for data analysis.

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TABLE 1

Illuminance of a Given Flashlamp as a Function of Distance as Measured by Detector 1.

D Distance (m)	E Illuminance (lux)	ED^2
.4141	3.6841	.63174
	3.6828	.63152
	3.6815	.63130
.5141	2.4277	.64164
	2.4316	.64167
	2.4251	.64095
.6141	1.6843	.63518
	1.6856	.63567
	1.6856	.63567
.7141	1.2519	.63839
	1.2489	.63686
	1.2508	.63783
.8141	.96126	.63708
	.96218	.63769
	.96336	.63847
.9141	.76875	.64235
	.76757	.64136
	.76678	.64070
1.0141	.62282	.64051
	.62296	.64065
	.62125	.63889
1.1141	.52048	.64603
	.51891	.64408
	.52101	.64669
1.2141	.43672	.64374
	.43685	.64393
	.43738	.64471
1.4141	.32103	.64196
	.32129	.64248
	.31985	.63960
1.5141	.28125	.64476
	.28229	.64715
	.28007	.64206
1.6141	.24526	.63898
	.24617	.64135
	.24591	.64067
1.7141	.22065	.64830
	.21830	.64139
	.21725	.63831
1.8141	.19552	.64345
	.19382	.63785
	.19395	.63828
1.9141	.17537	.64252
	.17458	.63962
	.17485	.64061

Table 1 (continued)

D Distance (m)	E Illuminance (lux)	ED^2
2.0141	.15796	.64078
	.15914	.64557
	.15940	.64662
2.1141	.13912	.62178
	.14082	.62938
	.14003	.62585
2.2141	.13218	.64798
	.13179	.64607
	.13362	.65504
2.3141	.12197	.65316
	.11988	.64196
	.11883	.63634
2.3641	.11504	.64295
	.11517	.64368
	.11438	.63927

TABLE 2

Illuminance of a Given Flashlamp as a Function of Distance as Measured by Detector 2.

D Distance (m)	E Illuminance (lux)	ED^2
.5152	2.3896	.63427
	2.3861	.63334
	2.3922	.63496
	2.3913	.63472
	2.3887	.63403
.7652	1.1017	.64508
	1.1035	.64613
	1.1026	.64561
	1.1009	.64461
	1.1026	.64561
1.0152	.63157	.65091
	.63243	.65180
	.63243	.65180
	.63139	.65073
	.63209	.65145
1.2152	.44104	.65129
	.44174	.65232
	.44070	.65079
	.44209	.65284
	.44287	.65400
1.5152	.28609	.65681
	.28626	.65720
	.28635	.65741
	.28617	.65700
1.7652	.21235	.66167
	.21313	.66410
	.21217	.66111
	.21226	.66139
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	6. Performing Organization Code
7. AUTHOR(S) A. R. Schaefer and E. F. Zalewski	8. Performing Organ. Report No.
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A method of measuring the energy irradiance from a single pulsed source, such as a xenon flashtube, is presented. Details of the approach used in this particular measurement are given, along with a discussion of the data analysis. In particular, we consider some of the inherent problems encountered in curve fitting which are also common to other radiometric and photometric measurements.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*) Curve fitting; energy irradiance; flashtube; pulsed source; radiometry.

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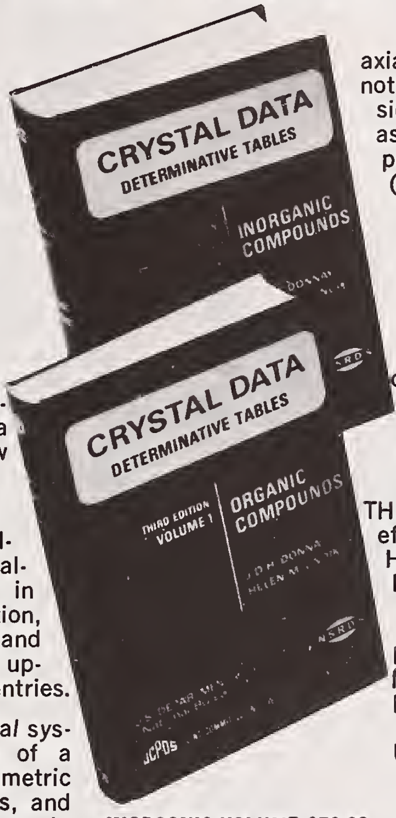

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