On Near-Field Photometry

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Introduction

The current practice in photometric testing, evaluation and application of luminaires involves the use of far-field photometry—*i.e.*, employing photometric data collected at a distance that is relatively large compared to the size of the luminaire, thus evaluating the luminaire as a point source. There are two major limitations in the application of far-field photometry: a) it is unable to provide data which indicates the actual photometric pattern of luminances on a luminaire; b) in situations where the luminaire is relatively close to the surface it is illuminating, the luminaire is assumed to be photometrically homogenous, which makes it impossible to perform accurate lighting calculations.

In this paper, we will introduce and explain the theory of near-field photometry—*i.e.*, the collection of photometric data which allow us to consider the luminaire not as a point source, but as a combination of individual components, each with unique photometric properties. We will outline the mathematical procedures for obtaining near-field photometric data, and demonstrate how the use of near-field photometry will dramatically improve our ability to accurately represent the luminous intensities of a luminaire, as well as luminance and illuminance patterns on a surface.

The luminance distribution function

Near-field photometry involves the application of a luminance distribution function, which is illustrated in **Figure 1**. This function states that for any luminous body, the luminance at any location p in the direction r can be represented by the function L(p,r).

With the knowledge of L(p,r), all other photometric quantities of the luminous body (or luminaire) itself and its photometric effects on surfaces and environments can be determined. These include luminance distribution of the luminaire, intensity distribution of the luminaire, illuminances on a surface due to the luminaire, and luminances on a surface due to the luminaire.

Luminance distribution of the luminaire

Various aspects of luminaire luminance which can not be derived from far-field photometric data can be

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evaluated using near-field photometric data with the function L(p,r).

First, maximum luminaire luminance can be determined as

$$Lmax = Max \ L(p,r) \tag{1}$$

for all possible p and r. This can be done analytically if the function L(p,r) is well-defined, or computationally if it is arbitrary.

Second, near-field photometric data enables us to consider the luminous distribution of a luminaire within a specific field of view from a given viewpoint. As **Figure 2** illustrates, when a luminaire is viewed at a relatively close distance, it is not viewed from a single viewing angle but within a field of view which is comprised of many viewing angles. In practice, L(p,r) enables us to view a luminaire luminance realistically. That is, we can discern the luminance pattern and identify all the bright and dark areas of the luminaire from a given viewpoint.

Such an accurate representation of luminaire luminance distribution is not possible to obtain using far-field photometry because the luminaire is treated as a point source. Far-field photometry allows us to calculate only average luminaire luminance at a specific viewing angle, as follows:

$$L(r) = \frac{1}{Ap} \int L(p,r)dAp \tag{2}$$

Here, L(r) is independent of the position variable p. Thus, far-field data offers us little hint as to how the luminaire actually appears.

The accurate representation of luminaire luminance distribution made possible by near-field photometry is especially useful in computer graphics, where the numerical function L(p,r) can be translated to a graphic image which produces a realistic picture of the luminaire.

Intensity distribution of the luminaire

It is sometimes convenient, in photometric calculations, to deal with intensity rather than luminances. Using the luminous distribution function L(p,r), the intensity distribution function can be determined by

$$dI_{dA}(p,r) = L(p,r) \cdot dAp \qquad (3)$$

where dA is the differential area that yields the intensity distribution, and dAp is the projected differential area in the direction r. In practice, one can consider a luminaire to be comprised of a large number of luminaire pieces, with each of the pieces having a different intensity distribution. dI_{dA} (p,r) is a function describing those discrete intensity distributions. Similarly, when the distance is large compared to the size of the luminaire, far-field photometry computes the resultant intensity as follows:

$$I(r) = \int dI_{dA}(p,r) \qquad (4)$$

That is, the resultant intensity at a given direction is simply the integration of the individual intensities at that direction. Again, the far-field method offers us no indication of the actual distribution of intensities on the luminaire itself.

When using far-field photometry in applications where the receiving surface is close to the luminaire, the luminaire is again divided up into many pieces, and the intensity distribution is computed as follows:

$$I_{dA}(r) = I(r)\left(\frac{dA}{A}\right) \qquad (5)$$

With this method, the intensity distribution of the luminaire at any location with area dA is proportional to the entire luminaire distribution (area A), and that proportionality is equal to dA/A. The validation of this equation demands photometric homogeneity of the luminaire; i.e., since $I_{dA}(r)$ is independent of location, it is assumed that every discrete portion of the luminaire behaves, photometrically, exactly the same as the entire luminaire. Homogeneity is a necessary assumption that enables us to use far-field photometry in near-field applications, but it does not account for the luminaire's variety of luminous intensities.

It should be noted here that far-field photometric measurement does not require photometric homogeneity of the actual luminaire, only sufficient distance from the luminaire.

Note that **Equation 4** is derived from the near-field function $dI_{dA}(p,r)$. Far-field photometrics can be derived from near-field photometrics. However, near-field photometrics cannot be obtained from far-field photometrics. Hence, far-field photometry can be viewed as a specific case of the more general theory of near-field photometry.

Lighting Calculations

Because near-field photometry acknowledges the diversity of luminance and intensity distributions on the surface of the luminaire, it enables us to calculate luminance and illuminance calculations as well as task contrasts and other visual quantities with greater accuracy. If the luminaire were perfectly homogeneous, then the photometric data obtained by far-field means would be identical to its near-field data, and the lighting calculations, such as illuminances and luminances on a surface, would be exact. In a real luminaire, however, perfect homogeneity is seldom achieved.

For normal indoor lighting calculations, the exactness of the calculations depends on the degree to which the luminaire deviates from perfect homogeneity, and on the distance between the luminaire and the location on the surface at which the calculations are performed. This distance factor is important because the smaller the distance, the more influence a localized portion of the luminaire will exert on the outcome of the calculations. As the distance increases, the localized portion begins to lose its dominance, because more and more of the entire luminaire comes into play. This is especially important in calculations for task-oriented lighting systems, wall-wash lighting systems, and indirect lighting systems, where illuminances and luminances must be calculated on a surface that is very close to the luminaire.

Surface illuminance calculations

For calculating illuminances on a surface due to a luminaire, we can employ the principle of near-field photometry that the luminaire may be divided up into many pieces, each with the luminous distribution function L(p,r).

At a given point s on a surface (**Figure 3**), the differential illuminance dE is determined as follows:

$$dE = \frac{L(p,r) \cdot \cos\Phi \cdot dAp}{d^2} \qquad (6)$$

where L(p,r) is the luminous distribution function of the luminaire at point p, direction r, and projected area dAp; d is the distance between points p and s; and Φ is the angle made between r and the direction from which the illuminance is to be determined.

Since dI_{dA} (p,r) = L(p,r) dAp, the above equation can be written as

$$dE = \frac{dI_{dA}(p,r)\cos\Phi}{d^2} \qquad (7)$$

The total illuminance E at point s due to the entire luminaire can be determined as

$$E = \int dE$$
$$= \int \frac{L(p,r)\cos\Phi dAp}{d^2} \qquad (8)$$
$$= \int \frac{\cos\Phi dI_{dA}(p,r)}{d^2}$$

This equation shows that the overall illuminance at a given point is the result of all the individual luminous areas dA, each with a different intensity distribution.

Surface luminance calculations

Using **Equation 6** set forth above, it is then possible to determine luminance values on a perfectly diffuse reflecting surface and/or a non-diffuse surface from any given viewpoint.

For a perfectly diffuse surface, luminance of that surface is defined as follows: $L = \varrho \times E$ where L is luminance, ϱ is reflectance, and E is illuminance. Hence, luminances may be calculated using the luminance distribution function as in **Equation 6** above:

$$
\begin{aligned}
L &= \varrho \int dE \\
&= \varrho \int \frac{L(p,r)\cos\Phi daP}{d^2} \\
&= \varrho \int \frac{\cos\Phi dI_{dA}(p,r)}{d^2}
\end{aligned}
\tag{9}
$$

For a non-diffuse surface (*i.e.*, a surface which has directional reflectance characteristics), the reflectance of that surface can be defined by a reflectance distribution function. There are three sets of variables for this function: the direction of incidence (ri), the direction of reflection (rr), and the location on the surface of the point (ps) at which the reflectance is being determined. We can represent the reflectance distribution function of a surface by β (ps, ri, rr).

Again using **Equation 6**, luminance is calculated at point ps as follows:

$$
\begin{aligned}
L(ps,ri,rr) &= \int \beta(ps,ri,rr)dE \\
&= \int \frac{b(ps,ri,rr)\cdot L(p,r)\cos\Phi dAp}{d^2} \\
&= \int \frac{b(ps,ri,rr)\cdot \cos\Phi dI_{dA}(p,r)}{d^2}
\end{aligned}
\tag{10}
$$

Having established the luminance distribution function and reflectance distribution function, it is then possible to determine the luminance pattern on the reflecting surface from any specific viewpoint (**Figure 4**). This can be done by considering all the L(ps,ri,rr) on the reflecting surface produced by L(p,r) of the luminaire. It is convenient, though not always valid, to assume that the surface is homogeneous; that is, the reflectance of any point on the surface is independent of its location. In that case, the reflectance distribution function becomes β(ri,rr).

Another quantity, the bi-directional reflectance distribution function (BRDF) is a special form of β(ri,rr)

in which the vertical angle component of the reflecting direction is fixed and rotationally symmetrical (*i.e.*, is independent of the horizontal angle). In order to evaluate the luminance pattern of a reflecting surface within a given field of view, one needs to have many BRDF's of various vertical angles for reflecting direction. This is, of course, equivalent to obtaining the reflectance distribution function, with the assumption that the reflectance is rotationally symmetrical.

Determination of near-field photometry

In this portion of the paper we will outline the procedure for determination of the luminance distribution function, L(p,r), set forth above. To determine this function, we will first empirically determine the intensity distribution function, $dI_{dA}(p,r)$, and then from that determine L(p,r).

To determine $dI_{dA}(p,r)$, we can use the equation

$$
E_s = \int \frac{\cos\Phi dI_{dA}(p,r)}{d^2}
\tag{11}
$$

If a large number of measurements of E's from various locations near and around the luminaire are obtained, the equation can then be solved for $dI_{dA}(p,r)$.

As mentioned at the outset of this paper, $dI_{dA}(p,r)$ represents two sets of variables: the position variables (x,y,z) and the directional variables (ψ,θ) where ψ is the horizontal angle and θ is the vertical angle. Hence, $dI_{dA}(p,r)$ becomes $dI_{dA}(x,y,z,\psi,\theta)$.

In approaching this equation, one has to decide, first of all, whether to use $dI_{dA}(x,y,z,\psi,\theta)$ as it is, a function of five variables; or whether to treat it as two separate sets of variables as follows:

$$
\Delta I_{dA}(x,y,z)(\psi,\theta)
\tag{12}
$$

In the latter case, each location (x,y,z) is regarded as a separate luminaire piece, each with an intensity distribution $\Delta I_{dA}(x,y,z)(\psi,\theta)$. We believe that this approach is the better one, for the following two reasons:

1. Approaching the problem as a function of five variables (x,y,z,ψ,θ) involves finding an approximate function of those variables, which has an averaging effect that in essence gives equal importance to each location (x,y,z) regardless of its photometric significance. The separation of the variables $((x,y,z)(\psi,\theta))$, on the other hand, allows us to decide which locations are more or less important photometrically. For example, we may decide to put more computational emphasis on the locations where radical distributions are expected, and less emphasis where the distributions are well-behaved.

2. In addition, the separation of variables into two groups allows us to take advantage of the symmetry that usually exists in most real luminaires. By grouping together similar parts of a symmetrical whole, we

can reduce the number of different intensity distributions to a minimum, thereby reducing the number of data points to be gathered, and hence reducing the computational complexity.

Using this method of separating the variables, and dividing the luminaire into a number of smaller luminaire pieces each with a different intensity distribution, we can determine Es as follows:

$$E_s = \sum_{i=1}^{n} \frac{\Delta I_{dA}(x_i, y_i, z_i)(\psi,\theta) \times \cos\phi_i \times A_i}{d_i^2} \qquad (13)$$

where n is the total number of luminaire pieces, and Ai is the area of the ith luminaire piece. It should be noted that one is not limited as to how the luminaire is to be divided, and this division can be totally arbitrary.

By taking illuminance measurements at many points near and around the luminaire, the above equation can be expanded to a system of equations:

$$E_{s1} = \sum_{i=1}^{n} \frac{\Delta I_{dA}(x_1, y_1, z_1)(\psi,\theta) \cos\phi_{i1}}{d_{i1}^2}$$

$$|$$
$$|$$
$$|$$
$$E_{sj} = \sum_{i=1}^{n} \frac{\Delta I_{dA}(x_{ij}, y_{ij}, z_{ij})(\psi,\theta) \times \cos\phi_{ij}}{d_{ij}^2}$$

$$(14)$$

where E_{si} is the first illuminance measurement and E_{sj} is the jth illuminance measurement.

In matrix form,

$$\begin{bmatrix} E_s \end{bmatrix} = \begin{bmatrix} \frac{\cos\Phi}{d^2} \end{bmatrix} \begin{bmatrix} I \end{bmatrix} \qquad (15)$$

Or,

$$\begin{bmatrix} I \end{bmatrix} = \begin{bmatrix} \frac{\cos\Phi}{d^2} \end{bmatrix}^{-1} \begin{bmatrix} E_s \end{bmatrix} \qquad (16)$$

The above equation directly evaluates $I(x,y,z)(\psi,\theta)$, which involves a set of discrete number pairs of (ψ,θ) for each luminaire piece. In choosing (ψ,θ) pairs, we should take into consideration the fact that, due to the nature of spherical coordinates, for equal increments of ψ and θ the data points are not equally spaced; they are farther away from each other near the equator and crowded together near the poles, until they become the same point (when $\theta = 0$ or 180 regardless of ψ).

One way to account for this fact is to choose (ψ,θ) pairs in such a way that points on the unit sphere are equal distance from one another. In other words, all sets of three points on the sphere form equilateral spherical triangles of equal areas.

In a case where the luminaire distribution varies drastically, we may wish to choose smaller spacing on particular luminaire pieces. For any one piece, we can decide how many points of (ψ_i,θ_i) we need and how they should be distributed. This, of course, is the beauty of dividing the luminaire into discrete sections— $\Delta I_{dA}(x,y,z)$ (ψ,θ) instead of using one all-encompassing function $I(x,y,z,\psi,\theta)$.

The one potential drawback to employing this kind of direct evaluation is the error introduced when a value falls in between two measured values; for example, when θ_{ii+1}. In this instance, we must compromise by choosing a value for either θ_i or θ_{i+1}.

Or, if we want to be more exact, we can employ an interpolating function which allows us to use a set of coefficients for describing $\Delta I_{dA}(x,y,z)(\psi,\theta)$, rather than evaluating $\Delta I_{dA}(x,y,z)(\psi,\theta)$ directly. If we select a good function, we can not only reduce the number of unknowns to be solved, but we can also avoid the possibility of error due to discrete values of (ψ_i,θ_i). One such function is the spherical harmonic function:

$$Y_{1,k}(\psi,\theta) = Ke^{-ik\psi}P_1^k(\cos\theta) \qquad (17)$$

where

$$P_1^k(\cos\theta) = \sum_{s=-\frac{1}{2}}^{\frac{1}{2}} \frac{i^{\frac{1}{2}} + s + k(1+k)!\cos^{\frac{1}{2}-s}\theta \sin^{\frac{1}{2}+s}\theta}{2^{\frac{1}{2}+s}(\frac{1}{2}-s)!k!(\frac{1}{2}-s-k)!} \qquad (18)$$

It is a form of trigonometrical polynomials which is bounded and well-behaved. This function allows arbitrary step size—i.e., the distances between data points need not be equal. This function is also orthogonal with the base of the spherical coordinates: $\sin\theta \, d\theta \, d\psi$. The advantage of this feature is that if a reasonable number of coefficients is used, say, n terms, then the first m terms are always the same regardless of the exact value of n, provided that $n > m$. Hence we can increase the precision of the interpolation within a limited computing capacity, since we can compute the first m coefficients in one step, and then later compute the remaining coefficients in a second step.

From the above equation,

$$\Delta I_{dA}(x,y,z)(\psi,\theta) = Y_{0,0}(\psi,\theta) + Y_{1,0}(\psi,\theta) + Y_{1,\pm1}(\psi,\theta)$$
$$+ Y_{2,0}(\psi,\theta) + Y_{2,\pm1}(\psi,\theta) + Y_{2,\pm2}(\psi,\theta) + \dots$$
$$= C_0 H_0(\psi,\theta) + C_1 H_1(\psi,\theta) + C_2 H_2(\psi,\theta) + \dots$$

where $C_0 \dots C_n$ are the coefficients to be found. Thus,

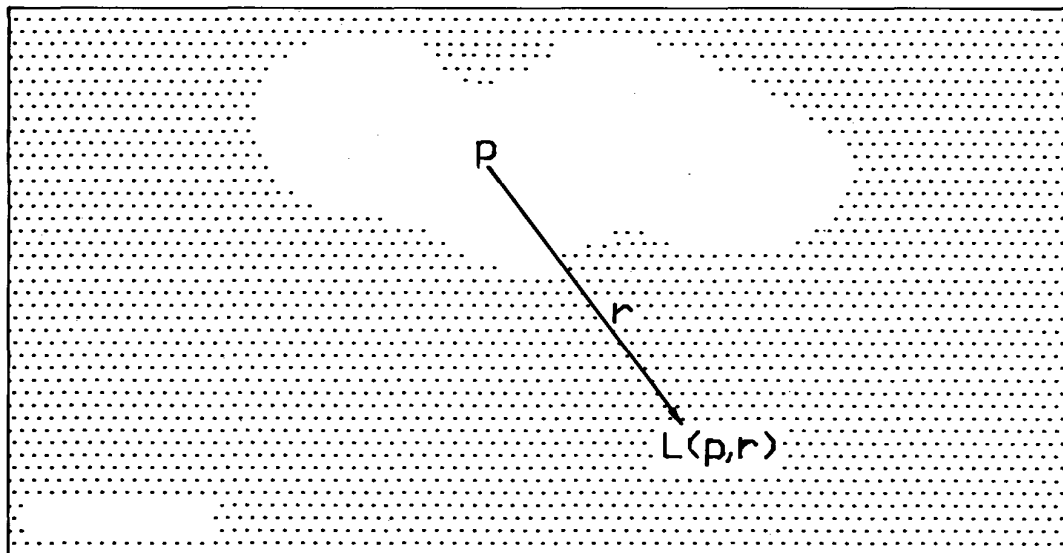$$\Delta I_{dA}(x,y,z)(\psi,\theta) = \sum_{k=0}^{m} C_k H_k(\psi,\theta) \qquad (20)$$

Figure 1
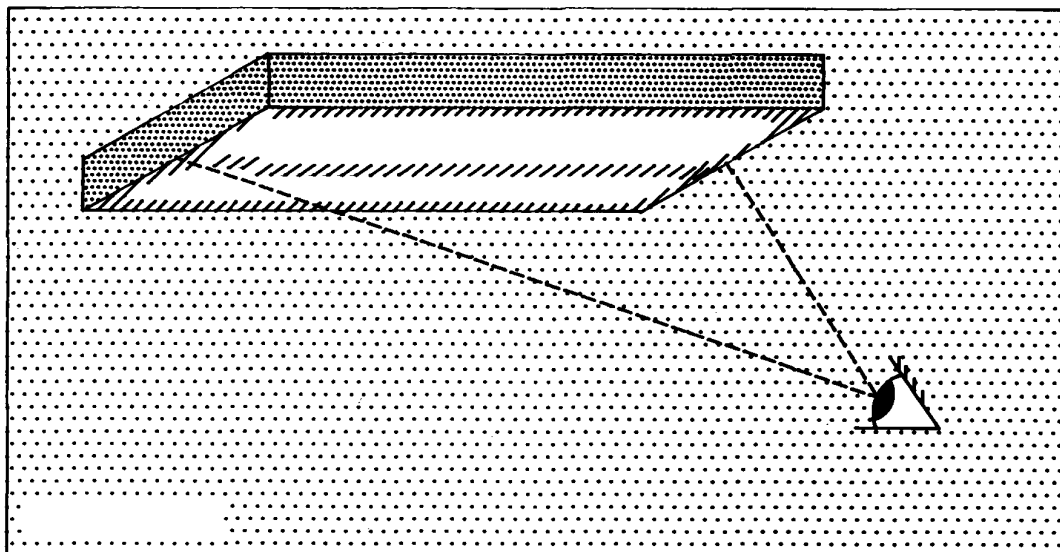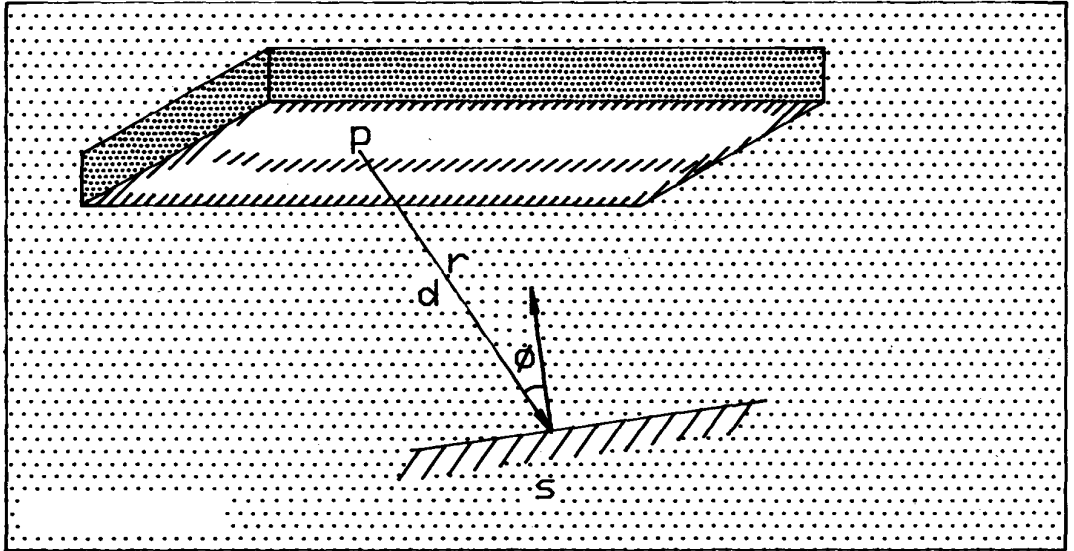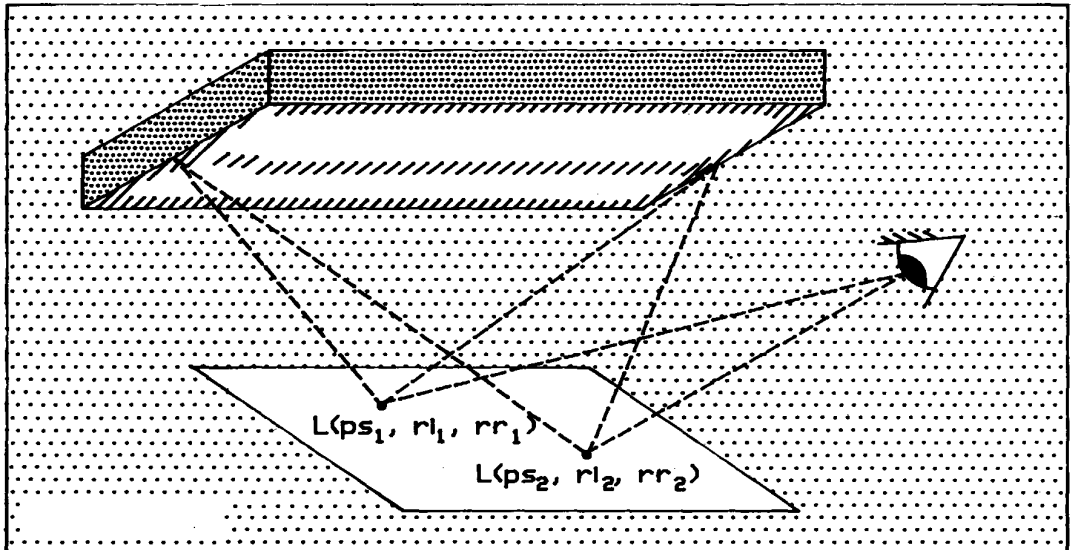

Figure 2

Figure 3

Figure 4

Combining **Equations 13 and 20,**

$$E_s = \sum_{i=1}^{n} \left[\frac{(\sum_{k=0}^{m} C_{ik}H_{ik}(\psi,\theta)) \cos\phi_i}{d_i^2} \right] \qquad (21)$$

Therefore, as before,

$$E_{sl} = \sum_{i=1}^{n} \left[\frac{(\sum_{k=0}^{m} C_{ikl}H_{ikl}(\psi,\theta)) \cos\phi_{il}}{d^2_{il}} \right] \qquad (22)$$

$$E_{sj} = \sum_{i=1}^{n} \left[\frac{(\sum_{k=0}^{m} C_{ikj}H_{ikj}(\psi,\theta)) \cos\phi_{ij}}{d^2_{ij}} \right]$$

In matrix form,

$$\left[E_s \right] = \left[\frac{H(\psi,\theta)A}{d^2\cos\phi} \right] \left[C \right] \qquad (23)$$

Or

$$\left[C \right] = \left[\frac{H(\psi,\theta)A}{d^2\cos\Phi} \right]^{-1} \left[E_s \right] \qquad (24)$$

In the above matrix, C is an array of coefficients of the interpolating functions that describe the luminaire pieces from 1 to n. Once the intensity distribution function is known, the luminance distribution can be determined:

$$L(p,r) = \frac{dI_{dA}(p,r)}{dAp} \qquad (25)$$

Conclusion

Far-field photometry, which is actually a derivation of near-field photometry, is not applicable in all lighting situations due to its assumptions regarding test distance and photometric homogeneity. Near-field photometry, on the other hand, recognizes the fact that real luminaires are not photometrically homogeneous, but can be divided into individual, localized portions, each with a unique photometric distribution. These distributions can be found, as discussed above, either by direct evaluation or by employing an interpolation function. Thus, with near-field photometry, we can evaluate a luminaire with more precision, and achieve greater accuracy in lighting calculations.

Discussion

I do not believe that anyone familiar with photometry and its applications has ever disputed the inadequacy of far-field photometry where used for prediction of near-field applications. Lautzenheiser, Weller and Stannard (REF 1) attacked the exact same inadequacy several years ago in their paper describing a near-field photometry procedure.

The problem reduced to two parts is: 1. The test procedure and technique required. 2. The suitability of the mathematics used to apply the information.

The procedure described by Lautzenheiser and Fawcett works well. Its disadvantages are the time to perform the procedure and, translating the time into dollars, the subsequent high cost.

The suitability of the mathematics is another problem. All polynomial functions have, by their very nature, a degree of oscillation associated with their use between data points. This oscillation becomes apparent in the applications the author mentioned, such as indirect and wall washers. The more pathologically non-uniform the distribution, the greater chance for oscillations that seriously affect the end results, illumination on the work plane.

The author has stated the real problem throughout his paper. We are living in a near-field, with no adequate way of describing what happens in that near-field. Pure mathematics can begin to describe what happens, but empiricism lets us see it. We must make a monumental effort to test the mathematics against the empirical data so that we can really predict what is going to happen in an installation.

I think the software developers call that procedure Beta testing.

This discussion is not intended as an adverse criticism to this paper; as a matter of fact, it is just the opposite. I only feel that the author stopped before he was finished and hope that he will publish further papers covering not only rigorous mathematics, but rigorous testing and confirmation procedures as well.

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References

Lautzenheiser, T., Weller, G., and Stannard, S. 1984. Photometry For Near-Field Applications. *JIES* 13(No. 2).

The author has provided us with an in-depth analysis of a photometric procedure which is receiving increasing interest. I am in full agreement that traditional photometry is inadequate in many applications.

At first review, the author's technique for actually performing the near-field measurements would seem to involve a very large task. Illuminance readings at many positions is necessary, and must be performed for each desired luminaire piece. Perhaps several

thousand photocell readings will be necessary to characterize a luminaire. However, with modern technology this need not be a problem. Using a dedicated microcomputer connected through multiplexer electronics to multiple silicon photocells, such data can be collected rapidly and accurately. A rate of 16 readings per second should be attainable.

A different method of data collection is also possible. Near-field photometry can be performed using a standard rotating mirror photometer, such as is employed now by almost all photometric laboratories. An attachment is placed on the arm which holds the mirror, holding the photocell close to and aimed at the test luminaire. In this case, the mirror is not used, but as it rotates, the photocell itself rotates around the luminaire at close distance. Only the luminaire piece of interest is exposed. A complete photometric test thus is performed on each luminaire piece. As all normal electronics, software and photometer automation is used, each test is completed in a few minutes, making this a practical data collection technique. This method has the advantage of performing more complete photometry, as a full intensity distribution is taken on each luminaire piece, including data at vertical angles close to 90 degrees, which are highly influential in glare calculation. Existing mathematics and lighting design software then can be used with this photometric data.

Upon examination, however, the two techniques essentially are equivalent. Each consists of multiple illuminance readings treated mathematically to develop the quantities of interest. The difference is in the mechanical and electronic systems used to collect the data.

Many questions must be answered: How many luminaire pieces? What test distance(s)? How many data points? How do we block light from the remainder of the luminaire without overheating the lamps and disturbing the readings?

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Author's Rebuttal
To T.L. Ballman and I. Lewin

In response to Mr. Ballman's comment, the subject of near-field photometry needs to be dealt with in three different phases. The first phase is its foundation—the theoretical understanding of its concepts and of the mathematics needed for obtaining near-field data. The second phase is a data gathering technique that enables us to obtain a large number of data in a convenient and practical manner. Lautzenheiser, Weller and Stannard proposed an approach. The third phase is to engineer suitable mathematics for the purpose of reconstructing the luminance distribution function.

Only after the above three phases are resolved can

we proceed on to the practical applications of near-field photometry. "On Near-field Photometry" is intended to address the first of the three phases.

In response to Dr. Lewin's comments, the beauty of the proposed technique in data gathering is that no part of the luminaire needs to be blocked. The only requirement is that readings be taken at many different locations. The attachment on an existing photometer that Dr. Lewin mentioned is exactly what the author has installed in his laboratory for near-field data collection.