

Efficient Measurement of Large Light Source Near-field Color and Luminance Distributions for Optical Design and Simulation

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ABSTRACT

The color and luminance distributions of large light sources are difficult to measure because of the size of the source and the physical space required for the measurement. We describe a method for the measurement of large light sources in a limited space that efficiently overcomes the physical limitations of traditional far-field measurement techniques. This method uses a calibrated, high dynamic range imaging colorimeter and a goniometric system to move the light source through an automated measurement sequence in the imaging colorimeter's field-of-view. The measurement is performed from within the near-field of the light source, enabling a compact measurement set-up. This method generates a detailed near-field color and luminance distribution model that can be directly converted to ray sets for optical design and that can be extrapolated to far-field distributions for illumination design. The measurements obtained show excellent correlation to traditional imaging colorimeter and photogoniometer measurement methods. The near-field goniometer approach that we describe is broadly applicable to general lighting systems, can be deployed in a compact laboratory space, and provides full near-field data for optical design and simulation.

Keywords: imaging colorimetry, optical design, illuminance distribution, near-field models, imaging goniometer

1. INTRODUCTION

For optical design and product qualification, the output color and luminance distributions of large light sources are needed to qualify and predict the performance of architectural, automotive, street, security, entertainment and other lighting systems. However, these distributions are difficult to measure because of both the size of the source and the large space required for the measurement. For these lighting systems, measuring in the far-field often requires a substantial distance – 3 meters or more is common – so that setting up the measurements in a controlled laboratory environment can be difficult and expensive.

Traditional measurement methods for obtaining illumination distributions are based on either goniophotometers or imaging colorimeters. In the goniophotometer approach the source is mounted in a two axis goniometer and a stationary photometer is placed in the far-field. The source is rotated in two axes, allowing the entire intensity distribution to be sampled from the point of view of the photometer. The luminous intensity distribution is described by the point measurements, and this distribution can be used to determine an illumination distribution. An alternative configuration of this approach uses a moving mirror goniometer. Photogoniometric measurement can produce very good color and luminance accuracy, but it has two significant limitations for large light sources: (1) the luminous intensity distribution is provided only at the measured distance and (2) to measure from the far-field a large space is required.

To measure an illumination distribution with a stand-alone imaging colorimeter the light from the source is directed onto a screen placed in the source's far-field. The screen must be large enough to capture the entire source output (or at least the portion of it that is of interest) and must be independently calibrated to eliminate screen effects from the measured distribution. The imaging colorimeter is then used to capture the entire illumination pattern in one measurement. This measurement method is very fast and relatively low cost as compared to goniometric methods. For light sources with wide angle output this can require a very large screen to illuminate to obtain a far-field distribution; this may not be physically possible. Also, this method only provides the luminous intensity distribution at the measured distance.

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The space problem is solved for measuring large light sources by looking at them completely differently. Instead of measuring from the far-field, a more space efficient method for measuring the luminance and color output distribution of a large light source is to use a two axis goniometer and a stationary imaging colorimeter positioned within the source's near-field. This method generates a near-field model of the light source that can be extrapolated to generate the illumination distribution at any distance from the light source. This allows measurement in a more compact area than is possible with either the goniophotometer or the stand-alone imaging colorimeter methods. This technique is applicable to large light sources such as down lights, lighting tubes, and automobile headlamps.

2. NEAR-FIELD GONIOMETRIC MEASUREMENT METHODOLOGY

This measurement methodology is based on the concept of combining a series of spatial near-field measurements of a light source into a luminance and color near-field model that can be extrapolated – projected – out to any distance. The measurement set-up consists of a high dynamic range imaging colorimeter for capturing luminance and color data, a two axis goniometric system to tilt and rotate the light source in the imaging colorimeter's field-of-view, and a software system that controls the automated measurement sequence [1]. A typical measurement set-up is shown in Figure 1.

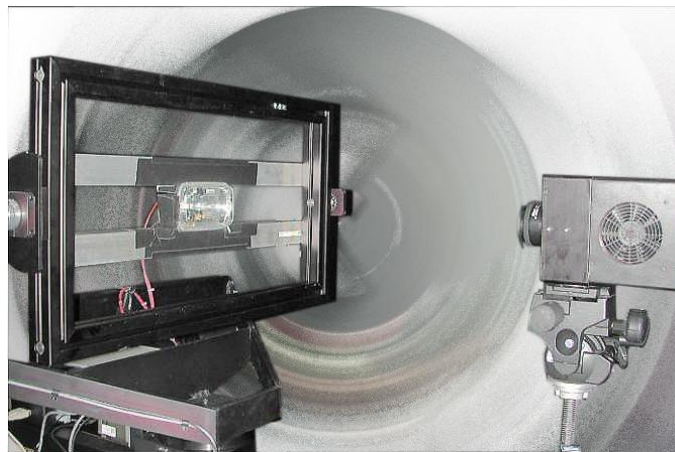


Fig. 1. A two-axis goniometer set up for direct measurement of a light source using an imaging colorimeter

2.1 Two-axis Goniometer

The two-axis goniometer is designed to support motion through a tilt range of $\pm 90^\circ$ (from facing straight down and to facing straight up) and rotation $\pm 90^\circ$ from left to right for each tilt angle. The rotational accuracy of the goniometer is 0.25° in each rotational axis. The particular mechanical design used for the goniometer in the measurements described here uses a rectangular frame that roughly describes the measurement plane and provides mechanical attachment points for mounting the light source securely. Properly balanced light sources of up to 25kg in weight can be supported. It is possible for light sources to extend beyond the boundaries of the frame as shown in Figure 2; here the light tubes are about 1.2m in length. The frame is sufficiently robust that the light source's power supply can be attached to the frame, if needed. It is also relatively straightforward to route power cables so that they do not interfere with the movement of the goniometer during measurement. This system is a Radiant Imaging NFMS-800.

2.2 Imaging Colorimeter

The imaging colorimeter selected should have sufficient spatial resolution and dynamic range to measure the fine scale features of the light source. The system used for the measurements described herein is a Radiant Imaging PM-1423F-1 imaging colorimeter with a 1536×1024 pixel resolution and a 14-bit ($>16K$ gray levels) dynamic range. Because the light source is viewed directly, ND (neutral density) filters may be required. The focal length of the lens is selected to allow

the imaging colorimeter to capture the full detail of the light source, at a working distance that is reasonably close to the goniometer. The imaging colorimeter can be used to make colorimetric, photopic, or radiometric measurements. [2]



Fig. 2. The two-axis goniometer used allows the measurement of light sources that extend outside of the boundaries of the frame so that light tubes and panels can also be measured directly.

2.3 Measurement Control and Analysis Software

The measurement sequence is automated by the use of control software to direct the positioning of the goniometer – and so the light source – relative to the imaging colorimeter. The control software synchronizes the measurements made by the imaging colorimeter with the steps and pauses in the goniometer’s motion. In addition, the control and analysis software allows review of the individual images acquired, as well as integrating the measurement results into a complete near-field model of the light source. Figure 3 shows a screen capture of the control and analysis software used (Radiant Imaging PM-NFMS software).

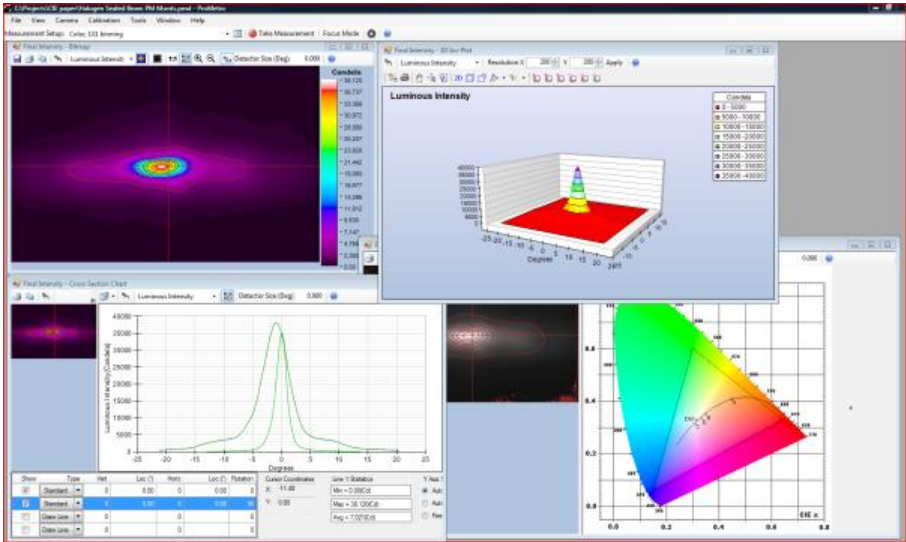


Fig. 3. The control and analysis software performs three principal functions: (1) measurement set-up, (2) automated measurement control, and (3) measurement analysis. For the later function, the figure shows some analysis functions applied to one of the captured colorimetric images of a sample light source.

2.4 Measurement Set-up and Execution

In setting up the measurement, the imaging colorimeter needs to be carefully positioned relative to the zero point of the goniometer. We positioned the imaging colorimeter so that the image axis of the camera (i.e., the central line of sight of the imaging colorimeter lens) is directed through the center point of rotation for the goniometer when the goniometer is centered (i.e., positioned at the center point of rotation along each axis of rotation) – so the face of the imaging colorimeter is parallel to the frame of the two-axis goniometer. Initial positioning is done by manual positioning, with final alignment done using a laser alignment system with fine tuning by software centering of the goniometer.

During a measurement run, the source is typically tilted through a $\pm 90^\circ$ range (from facing straight down to facing straight up) and rotated $\pm 90^\circ$ horizontally for each tilt angle (but in an efficient series of motions to increase measurement speed). The measurement steps can be as small as 0.1° , though for practical applications very good results can be obtained with steps as large as 2.5° to 5° . It is also possible to have a different step sizes through different portions of the measurement – smaller when viewing the source near normal and larger when viewing from more extreme angles. Testing time typically ranges from $\frac{1}{2}$ hour up to 2 hours depending on the source and the measurement resolution desired. Typically over 1000 individual images are collected to describe the performance of a light source.

Each individual imaging colorimeter measurement captures both a brightness (luminance) and color profile of the source from a particular angle. The goniometric system moves the light source through a series of inclination angles relative to the fixed position of the imaging colorimeter – tilting and rotating the source until a complete set of measurements are taken. The multiple images capture the spatial distribution of the light output of the source (which is modeled as an extended, rather than a point, source) from multiple points of view.

2.5 Near-field Models and Ray Set Generation

Once the complete set of measurements is obtained, they are combined in software into a complete near-field model of the light source which describes the luminance and color output of light source. The data acquired is output light intensity as function of location on the source (x,y,z) and direction (Θ,ϕ) : $I(x,y,z,\Theta,\phi)$. This intensity function can also include color coordinates if color measurements are made. The near-field model can be used to generate ray sets for optical design and to extrapolate far-field distributions for illumination design and performance characterization.

For optical modeling, the intensity function is used to generate a ray set for import into optical modeling software. The ray set is generated by randomly selecting the direction the ray will travel in (Θ',ϕ') and an origination pixel (x',y',z') on the light source. This random selection is either done via Monte Carlo methods, or by weighting the direction and origin based on the measured luminance distribution. This second approach, known as importance sampling, results in improved modeling accuracy with fewer rays in the ray set; this also reduces processing time when running optical design software. To generate the ray, the measured intensity function is “morphed” to extrapolate an intensity value with that origin and direction, and the origination point of the ray is the point along that ray where it intersects a user defined optical surface. Usually hundreds of thousands to tens of millions of rays are generated to form a ray set.

2.6 Extrapolation to Far-field Luminous Intensity Distributions

To generate a far field distribution the same methodology is followed, except that the intensity distribution is simplified to $I(\Theta,\phi)$ by setting $(x,y,z) = (0,0,0)$ for all the measured data. This has the effect of treating the light source as a point source and so yields the far-field luminous intensity distribution.

3. EXAMPLE OF MEASUREMENT RESULTS

The near-field goniometer measurement method can be applied to a broad range of large light sources, such as architectural lighting, spot lights, and automobile headlamps. In each of these cases, the illumination plane of interest can be many meters from the source, and so requiring a large space to measure using far-field measurement methods. For example, traditionally the output of an automobile headlamp is measured at about 100ft (~ 30m) from the source. This requires a specialized (and expensive) testing facility. While such a facility may indeed be specified for certification testing, it is generally too expensive to use for testing intermediate designs, for evaluating and qualifying sources from different manufacturers, or for quality tracking. With the near-field measurement method described above the source can be measured in the space of just a few meters, and so in a normal sized laboratory.

3.1 Measurement Results for an Automobile Headlamp

We measured a sealed beam automobile headlamp (Philips Halogen H4701 high beam) using the near-field imaging goniometer method and have compared it to both imaging colorimeter and photogoniometer measurements. The measurement set-up has already been shown in Figure 1. Here the distance from the imaging colorimeter to the face of the light source mounted on the two axis goniometer was 680mm. The other two measurements were performed at 3.4m. Figure 4 shows the direct images taken of the headlamp at various inclinations relative to the imaging colorimeter.

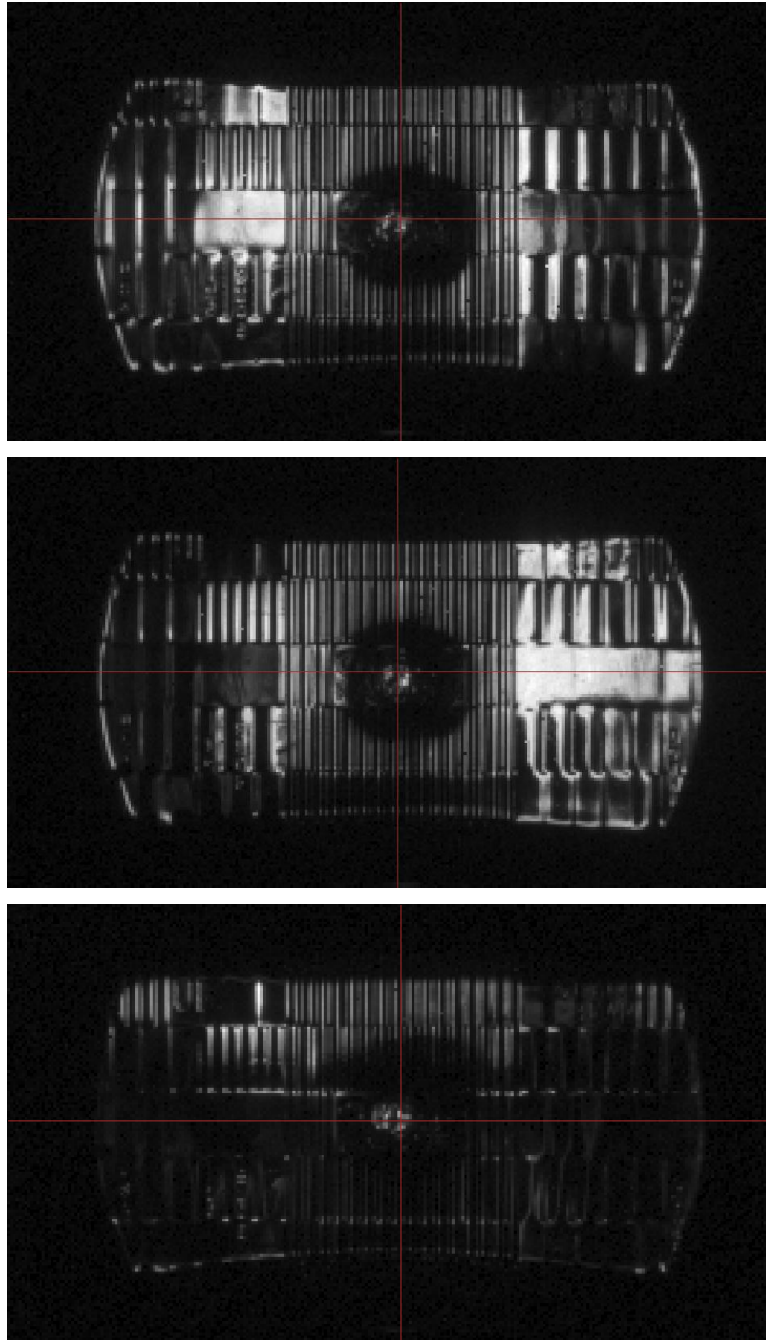


Fig. 4. Captured images of an automobile headlamp taken at various rotational positions relative to the imaging goniometer. As the headlamp's position changes the distribution of light on the observed face of the light source also changes.

The measured near-field images can be used to review the performance of the light source directly, or can be extrapolated to generate a luminous intensity distribution at any distance from the source. Figure 5 compares a direct view of the source with the luminous intensity distribution at 680mm from the source – i.e., the location of the imaging colorimeter – and 3.4m.

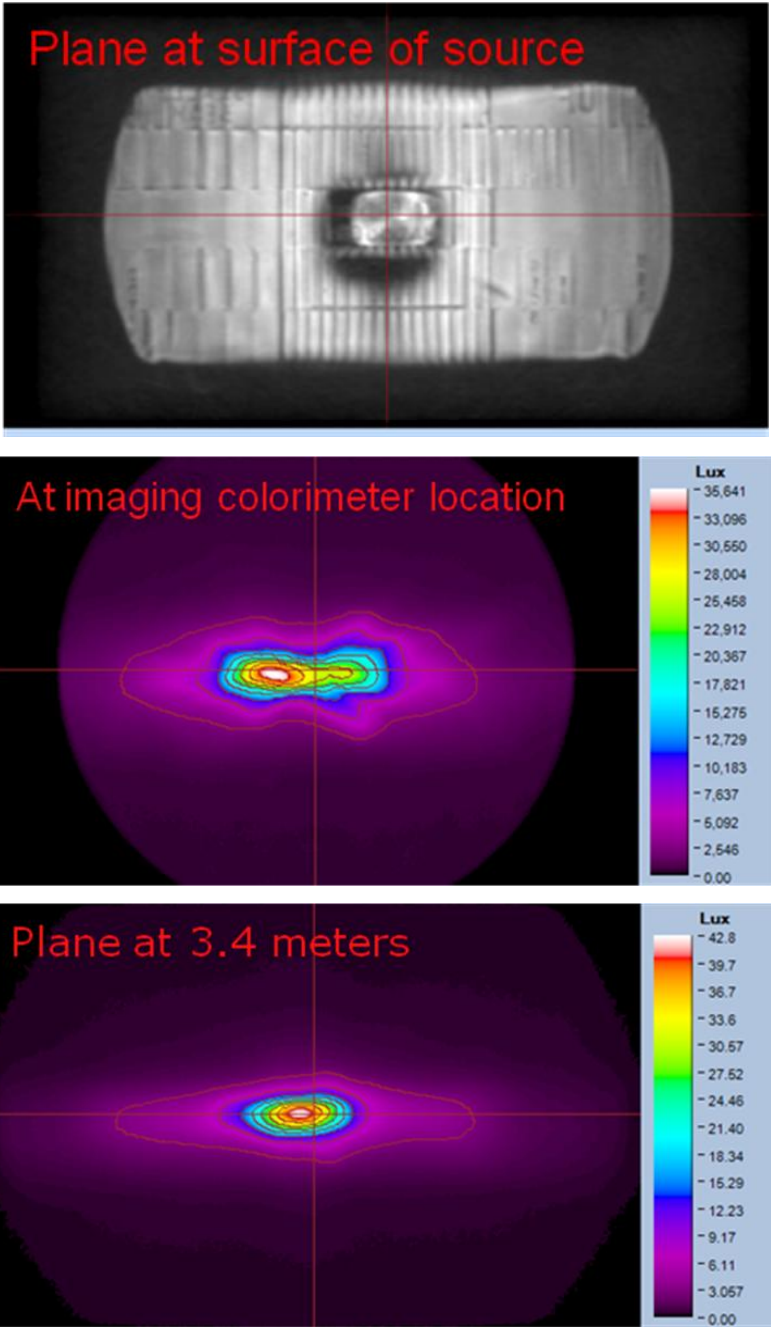


Fig. 5. A comparison of the output of an automobile headlamp at the lamp, at 680mm (which is still in the near-field of the source), at 3.4m which is in the far-field. The change in the structure of the luminous intensity distribution between the near-field and far-field is evident.

3.2 Comparison with Other Measurement Methods

We repeated the measurement of the automobile headlamp with an imaging colorimeter (by measuring the illumination pattern on a screen) and with a goniophotometer. Both of these measurements were made at 3.4m and were compared to the extrapolated distribution obtained from the near-field goniometer measurement. The luminous intensity distributions obtained for all three methods at 3.4m is shown in Figure 6. A comparison of the horizontal cross-section through each of the distributions is shown in Figure 7.

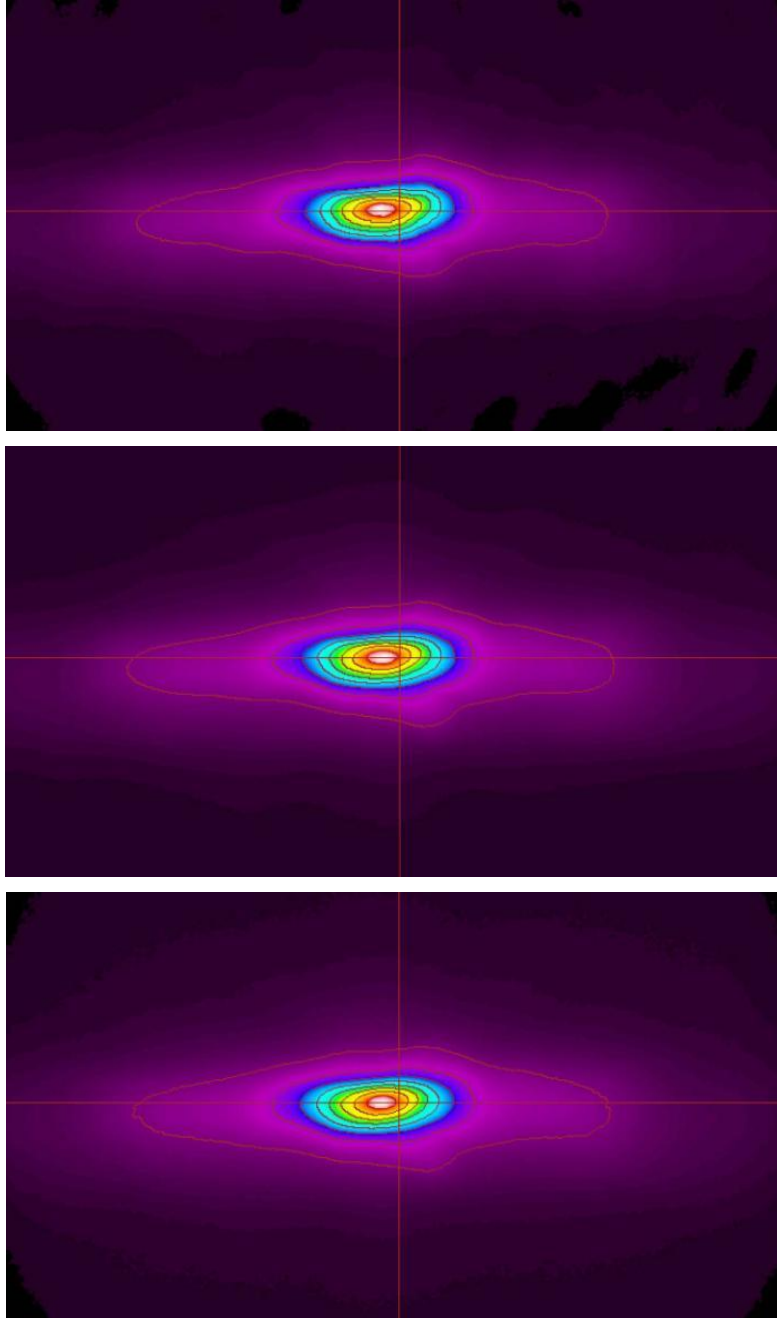


Fig. 6. A comparison of the luminous intensity distribution of an automobile headlamp at 3.4m as measured by a spot goniophotometer, an imaging colorimeter, and via extrapolation from the near-field model measured using the .

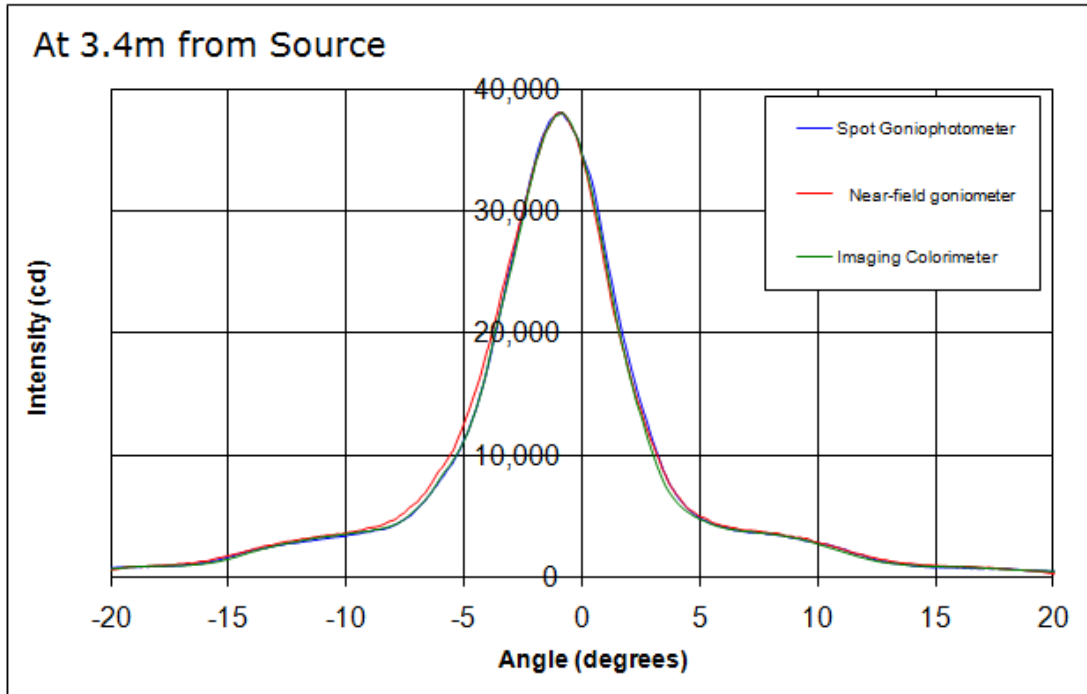


Fig. 7. A comparison of horizontal cross-section through the luminous intensity distribution of the output of an automobile headlamp at 3.4m as measured by three different methods shows excellent agreements between the methods. In particular, the extrapolated distribution obtained from the near-field measurement of the light source is a very good match to the data obtained by the two direct measurement techniques.

A number of observations should be made relative to the measurement methods. First, the extrapolated luminous intensity distribution generated based on the near-field goniometer measurements shows an excellent match to the distributions obtained by the direct measurement methods using an imaging colorimeter and a photogoniometer. Second, the near-field goniometer generated model uniquely enables the extrapolation of the luminous intensity distribution to arbitrary distances from the light sources, allowing it to be used for more general optical design applications.

4. CONCLUSIONS

The near-field goniometer light source measurement method provides full near-field data for optical design and simulation, color distribution by angle, and capture detailed images of the lighting system in multiple configurations. This data is very useful for lighting system development and design assessment. This approach is broadly applicable to general lighting systems including measurement of architectural lighting and other large luminaires.

The choice of measurement method will depend on a number of factors including the intended use of the data, the time required to make the measurement, space constraints, and cost. These trade-offs are summarized in Table 1. An important distinction is that the near-field goniometer measurement method generates a near-field model which contains significantly more information about the light source performance than is represented in the luminous intensity distributions obtained from the other two methods. This detailed data can be used for general optical design applications, such as simulating the effects of the light source in a complex optical environment.

Table. 1. Comparison of measurement attributes for methods for measuring luminance distribution for large (extended) light sources. The measurement method chosen will depend on measurement objectives, logistics (space and time), and cost.

	Instrument Type		
	Imaging Colorimeter	Imaging colorimeter + goniometer	Spot Goniophotometer
Near Field Measurements		•	
Far Field Measurements	•	•	•
Angular Resolution	High	High	High
Luminance/Color Accuracy	Good	Good	Excellent
Space Requirement	Large	Medium	Large
Cost	Low	Medium	Low/High
Speed	Fast	Slow	Slow
Comments	Good compromise between speed and comprehensive data	Provides the most comprehensive data, smallest space	High accuracy but requires large space for extended sources

REFERENCES

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