Directionally dependent light sources

Stéphane Albin
LISSE
École Nationale Supérieure
des Mines de Saint-Étienne
158, cours Fauriel
42023 Saint-Étienne
France
stephane.albin@emse.fr

Bernard Péroche
LIGIM
Université Claude Bernard Lyon I
Bâtiment Nautibus
8, boulevard Niels Bohr
69622 Villeurbanne Cedex
France
bperoche@bat710.univ-lyon1.fr

ABSTRACT

This paper deals with light sources in computer graphics. Different kinds of light sources and different types of solutions generally used are first described. Then, a new solution for directionally dependent light sources based on Noé and Péroche's model[NP00] is proposed to avoid drawbacks of bilinear interpolation. The use of singular integrals with locally supported functions allows a fast and accurate reconstruction of goniometric diagrams. Application to point light sources is finally compared with some experimental results.

Keywords

Directional luminaires, Light Sources, Photometry, Rendering, Global Illumination.

1 INTRODUCTION

Nowadays, complex light sources are more and more used in computer graphics. This complexity may be spectral (without using three chromatic representations), but also directional. Such light sources can be used to compute more beautiful images, but above all to simulate real scenes. Lighting industry needs to compute images with a good accuracy, in order to guarantee the results of simulations before production. These simulations may be used, for example, for the architectural design of art galleries, offices, museums, gymnasiums, streets and tunnels and for the design of head lights and rear lights.

There are several ways to achieve this accuracy. A first one is the use of measurements of light sources. Thus, since several years, manufacturers of luminaires provide the scientific community with some information on the directional distribution of their products. This allows to model more accurately illuminance in a given scene. A second way is computation methods, and, in some cases, it is even possible to obtain an analytic formula. A third solution is the simulation of the interactions inside the light source device.

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When measurements are used, the notions of *near-field* and *far-field* photometry must be distinguished. With far-field photometry, a light source is regarded as a point. In this case, a *goniometric diagram* is associated with the light source. It is a two-dimensional angular representation of the directional information. On the other side, with near-field photometry, the volume of the light source and more generally its entire geometry acts upon the resulted illuminance. In this case, a goniometric diagram is not sufficient. Far-field photometry is commonly used when radiance is going to be computed at a distance greater than five times the maximum width of the luminaire[Ash93a].

The first goal of this work is to make a survey of different types of light sources, of various representations of the emission of a light source and of known solutions to define and use light sources in computer graphics. Then, a new method to represent a photometric solid from measurements will be presented and applied to point light sources. This method is based on singular integrals with locally supported functions and allows a fast and accurate reconstruction of goniometric diagrams.

The remainder of the paper is organized as follows. A classification of light sources is proposed in Section 2. In Section 3, a review of previous work on light sources in computer graphics is presented. Our representation model is defined in Section 4. In Section 5, some results and a validation method are described. Finally, a conclusion and some further developments are suggested in Section 6.

2 A SURVEY OF LIGHT SOURCES AND THEIR REPRESENTATION

In this section, we will first describe the characteristics of light sources commonly used in computer graphics. Then, several means to represent the emission of a light source will be presented.

2.1 Light Sources Characteristics

In [VG84], Verbeck and Greenberg described light sources as a combination of three parameters: the geometry of the light source, its luminous intensity distribution and its emitted spectral distribution.

2.1.1 Geometry

The shape of a light source may vary widely: let's think to the area of sky seen through a window, a neon or a tungsten lamp, for example. Thus, these geometries are modeled as zero, one or two dimensional objects respectively for point, linear or area light sources. Other marginal light sources do not have any geometry. It may be the case for LEDs, xenon arc lamps, compact fluorescent lamps or strobe lamps[RW97].

2.1.2 Luminous Intensity Distribution

Light sources that have early been used in computer graphics are point light sources which emit uniformly a radiance R given by: $R = \frac{I}{d^2} \cos\theta$, where I is the intensity of the source, θ the incident angle and d the distance between the source and the point where the radiance is computed.

In real world, light sources do not emit uniformly especially for architectural design or car lights. Usually, this distribution is modeled analytically with spot light sources which are zero dimensional light sources where the energy is reduced according to a cone[NDW93]. Another way to take into account this phenomena is to use measurements.

2.1.3 Emitted Spectral Distribution

Light sources can also have a non-uniform spectral distribution. This characteristic is very important for fluorescent lights or LEDs. In this paper, we consider the emission of a light source as the product of a spectral distribution by a luminous intensity distribution.

2.2 Representations

Representing the emission of a light source is a preeminent problem and the computation of illuminance is dependent on this representation. There are two methods to obtain the data necessary to represent a light source: measurements and simulations.

2.2.1 Measurement of a Light Source

Several methods have been suggested to measure a light source. In far-field photometry, the angular distribution of a light source has been first represented by two orthogonal curves $(\theta, \phi = 0)$ and $(\theta = 0, \phi)$ (*cf.* Figure 1) called goniometric diagrams. But, it is not easy to get a good precision with only a few samples.

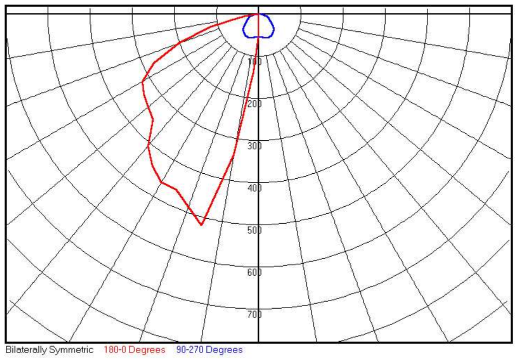


Figure 1: Goniometric diagrams

Nowadays, manufacturers give more and more data corresponding to two-dimensional discretized goniometric diagrams, in matrix form. The most common format is now *IES*[IES95], which is defined by the Illuminating Engineering Society of North America (`http://www.iesna.org`). Figure 2 shows an example of such a goniometric diagram with a large directional variation.

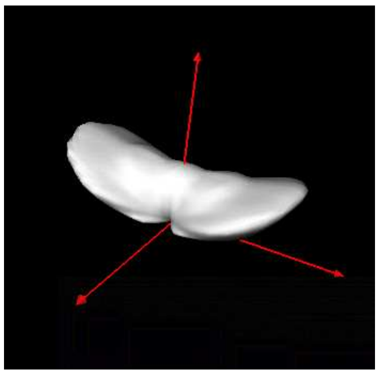


Figure 2: A 2D goniometric diagram

We must also point out the *EULUMDAT* format (`http://www.helios32.com/Eulumdat.htm`), which is a European standard. Even if it is more sophisticated, it is not yet widespread in the lighting community.

Ashdown[Ash93a, Ash93b] showed that the notion of two-dimensional goniometric diagram is not sufficient in a near-field photometry context. He suggested a new way to measure the energy from a light source by using a virtual bounding sphere. A set of photographs is taken by a CCD camera with its lens focused on infinity. In this case, each pixel of an image represents a ray of light.

Thus, the combination of all the images gives a set of rays emitted by the light source. These rays represent a four-dimensional field of light around the luminaire (*cf.* Figure 3).

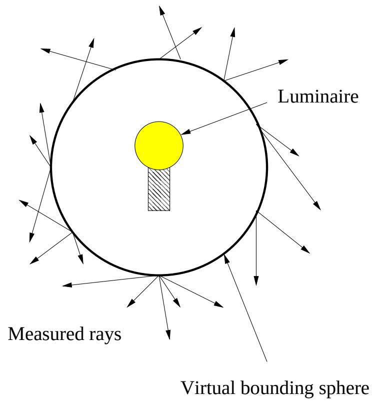


Figure 3: The field of light of a luminaire in near-field photometry

This process has been introduced by Ashdown, but the implementation is due to Radiant Imaging[Ryk94, JM00] (`http://www.radimg.com`). These measurements can be used to compute the illuminance on an object.

Another method has been proposed by Chu and DiLaura in [CD95]. They decompose a complex luminaire as a collection of luminaire pieces, each one associated with a photometric center along the plane lit by the outgoing surface of the luminaire. Then, each luminaire piece is modeled with far-field photometry data computed with a simplex optimization method.

2.2.2 Computed Representations

Energy from a light source may also be represented through a simulation approach. With a right model of a light source device including the luminaire itself (e.g. a filament), some reflectors guiding emission and some disturbing objects like fastenings, the outgoing flow of light can be simulated by casting rays from the emitter. This flow can then be stored in a data structure.

Deville and Paul[DP95] proposed such a method. They defined a set of virtual surfaces around the light source. The outgoing flow is stored according to these surfaces which are later used during the rendering phase. Heidrich *et al.*[HKSS98] suggested more or less the same approach but stored the light field in a lumigraph.

As these methods are very specific, they are difficult to be really applied. To obtain a good accuracy, the internal geometry of the light source and the *BRDF* of the reflectors must be known, which may become difficult with the increasing complexity of current devices. Finally, the internal light source itself can have a complex directionally dependent distribution.

3 PREVIOUS WORK

There are mainly two methods to compute illuminance from a light source: with an analytic formula or by discretization. In fact, there is also a third solution which consists in using data from simulation.

3.1 Analytic Solutions

The most common model is diffuse point light source already presented in Section 2.1.2.

Nishita *et al.*[NON85] introduced a model taking into account linear light sources with penumbra and shadow detection. Although this model is defined in near-field photometry, it only solves the directionally dependent case with an uniform emission along the line. Several papers[PA90, OF01] have been published since then for linear light sources.

Arvo[Arv94] developed a solution to take planar non-diffuse light sources into account. This work has been extended to planar linearly-varying light sources in [CA00] and to planar non-diffuse linearly-varying light sources in [CA01]. Though very attractive, these models have a directional variation reduced to Phong-like phenomena. These formula are unusable with a specific directional variation given by an *IES* file. In [TT91] and [TT97], Tanaka and Takahashi presented two methods for area light sources. DiLaura proposed in [DiL95] a solution for non-diffuse planar area light sources by using contour integral along the emitting surface.

3.2 Discretization Solutions

A second possible solution is to use discretization methods. Many papers have been presented in this way.

Ouellette and Fiume[OF99] introduced a method for diffuse linear light sources. Illuminance is computed by detecting discontinuities that are caused by occluding objects. Each part of the line contributing to the result is evaluated by low-degree numerical quadratures. Picott[Pic92] and Heidrich *et al.*[HBS00] also presented some solutions for linear light sources.

Directionally dependent light sources in far-field photometry context have been studied by Languénou and Tellier[LT92]. They introduced an interpolation method to get a value for any direction (θ, ϕ) from goniometric diagrams (*cf.* Section 2.2.1).

For near-field photometry, a first attempt was made by Houle and Fiume[HF93] for planar light sources. After sampling the surface, a 2D goniometric diagram is linked to each sample point. The resulting contribution is computed by interpolating values between points. Therefore, it is not easy to establish a correlation between the location and the variation of the luminous intensity distribution.

In [SWZ96], Shirley *et al.* proposed a method with stochastic sampling. In 1999, Zaninetti *et al.*[ZBP99] introduced a model based on an adaptive subdivision of a planar rectangular surface. This model works for planar diffuse light sources, and is easily extended to non-uniform surfaces, as all sub-sources are independent, and to any planar light source thanks to a mask.

In Brotman and Badler's paper[BB84], light sources are modeled with polygons to get polyhedra. Thus, any geometry may be achieved. Radiance is computed by a random sampling of polygons.

4 RECONSTRUCTION OF DIRECTIONALLY DEPENDENT LIGHT SOURCES IN A FAR-FIELD PHOTOMETRY CONTEXT

A simple solution for reconstructing a goniometric diagram is bilinear interpolation. But this method has some drawbacks which are difficult to eliminate like the need of regular measurements. Similarly, this method cannot be used if measurements are noisy. We will introduce a new method to reduce those problems.

4.1 Our Method

In a far-field photometry context, light sources can be considered as simple points. Their luminous intensity distribution can be represented by a two-dimensional goniometric diagram (*cf.* Figure 2). The goal of this section is to introduce a new $\mathcal{C}^1$ representation of a goniometric diagram from measurements.

4.2 Main Idea

To reconstruct such a diagram whatever the incident direction, we use Noé and Péroche's model[NP00], which was previously introduced for *BRDFs*' measurements. We will apply it to two-dimensional goniometric diagrams reconstitution.

The model can be described as follows: to each measurement over the sphere, a locally supported spreading function is associated. This function is used to get some energy even not exactly on a measurement (*cf.* Figure 4). Furthermore, the local support allows a fast computation since the function is null outside its domain of definition and do not have to be evaluated.

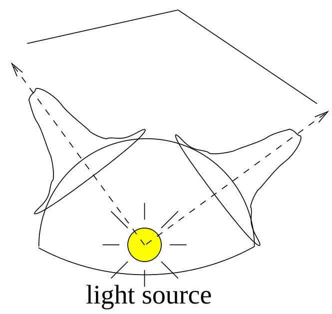


Figure 4: A kernel is associated to each measurement

Let us denote f the function to be reconstructed. The singular integral of f is defined by [Ach56]:

$$I(f)(\vec{X}) = \int_{\Omega} f(\vec{x}) K(\vec{x} \cdot \vec{X}) d\omega(\vec{x}) \qquad (1)$$

where:

- $\vec{X}$ is the incident direction;
- Ω is the unit sphere;
- $K()$ is a spreading kernel with support ρ;
- $\vec{x} \cdot \vec{X}$ is the dot product between $\vec{x}$ and $\vec{X}$.

If the kernel checks the following properties

$$\int_{-1}^{1} K(t)dt = \frac{1}{2\pi} \quad \text{and} \quad \lim_{\rho \to 1} \int_{-1}^{1} K(t)tdt = \frac{1}{2\pi} \qquad (2)$$

then [Ach56]

$$\int_{\Omega} I(f)d\omega = \int_{\Omega} f d\omega \quad \text{and} \quad \lim_{\rho \to 1} I(f) = f \qquad (3)$$

4.3 An Example of Kernel

Let $\cos\theta = \frac{\vec{x} \cdot \vec{X}}{||\vec{x}|| \times ||\vec{X}||}$. Like Noé and Péroche, we chose:

$$K(\cos\theta) = \begin{cases} 0 & \text{if } \cos\theta \in [-1; \rho] \\ \frac{k+1}{2\pi(1-\rho)} \left(\frac{\cos\theta - \rho}{1-\rho}\right)^k & \text{if } \cos\theta \in [\rho; 1] \end{cases} \qquad (4)$$

where ρ and k are parameters for K.
k is linked to the shape of the kernel K and ρ to the size of its support. Figure 5 shows some kernels with $\rho = 0.5$ (the support is thus $[\frac{-\pi}{3}; \frac{\pi}{3}]$).

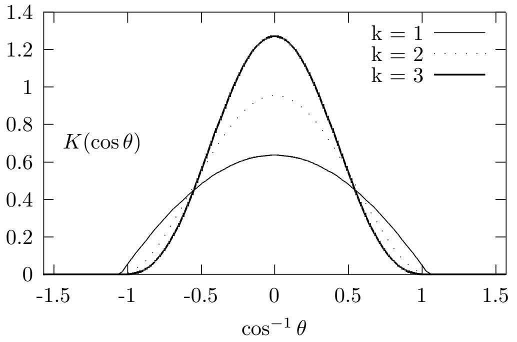


Figure 5: Kernels with different degrees (from [NP00])

4.4 Discretization

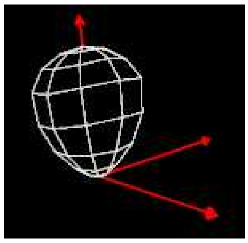
A goniometric diagram is a collection of couples $(\vec{X}_i, F_i)$, where $\vec{X}_i$ is an incident direction and F_i the associated measurement. We may define a continuous function F representing the goniometric diagram by discretizing the singular integral of f:

$$F(\vec{X}) = \sum_{i=1}^{n} F_i K(\vec{X} \cdot \vec{X}_i) \Delta\omega_i^2 \qquad (5)$$

$\Delta\omega_i^2$ is computed in such a way to minimize the error between the reconstructed and the original function. Noé and Péroche showed that $\Delta\omega_i^2$ is a constant equal to $\frac{\sum_{i=1}^{n} f(\vec{X}_i) F_i}{\sum_{i=1}^{n} f(\vec{X}_i)^2}$.
By putting kernels according to measurements, we can get a good approximation of function f. Furthermore, this approximation may be computed very quickly because all supports are restricted to the evaluation area. Finally, we must point out that this method is not an interpolation but an approximation. So, some information (measurements) is needed to compute values.

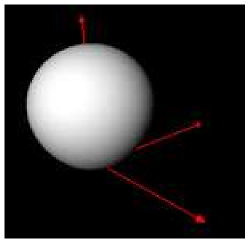
4.5 The Choice of ρ

With a *BRDF*, measurements are not stored uniformly: there are often more samples in the specular direction. Thus, the size of the support, which depends on ρ, cannot be constant. With goniometric diagrams, each measurement is done according to a regular grid. Thus, ρ can just depend on the discretization step called ds. Figure 6 shows a measured goniometric diagram and some reconstructions with different values of ρ. If a small value is chosen (b), the reconstruction will be too smooth to take particular emissions into account. On the other hand, with bigger values (d), the support of the kernels will be restricted, and holes can appear.

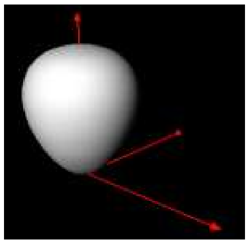


Measurements

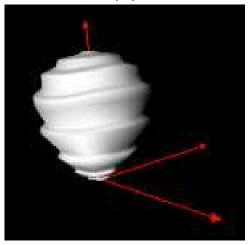
(a)



$\rho = 0.26$
$\Rightarrow \theta = 75$ degrees
(b)



$\rho = 0.951$
$\Rightarrow \theta = 18$ degrees
(c)



$\rho = 0.9925$
$\Rightarrow \theta = 7$ degrees
(d)

Figure 6: Influence of ρ on the reconstruction of the diagram

After many experiments, we chose $\rho = \cos^{-1}(0.6 \times ds)$ which seems to be a good compromise between smoothing and holes. On our example, the discretization step was 30 degrees. So, we took $\rho = \cos^{-1}(0.6 \times 30) = 0.951$.

4.6 A Fast Evaluation

Kernels' storage has been achieved during a preprocessing step. In the rendering pass, any value must be computed very quickly. For that, we use the propriety of locality. We chose a locally supported function (only defined for $[\rho; 1]$). So, we just need a data structure over the sphere to store our kernels. Like Noé and Péroche, we used an igloo structure. As shown in Figure 7, each cell contains a list of kernels that are not nil. In this figure, only the kernel centers are represented by points. Of course, as a kernel may be large, it may overlap more than one igloo cell. Thus, to evaluate the function for an incident direction, only the kernels overlapping the right cell must be computed.

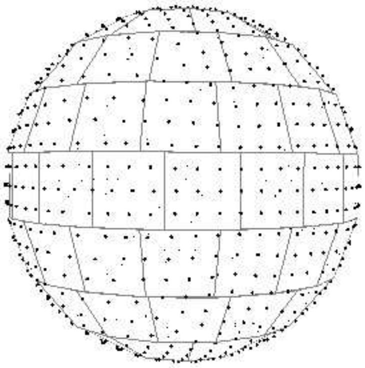


Figure 7: An igloo with kernels

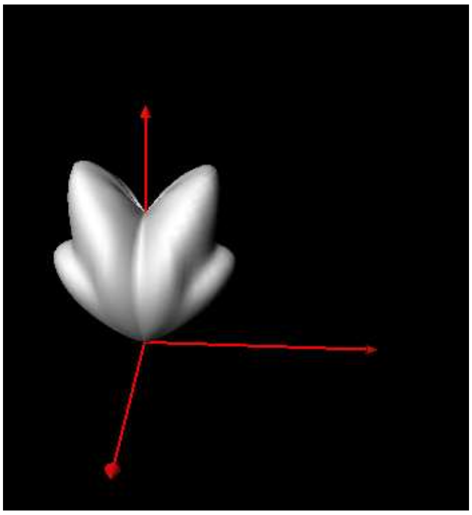


Figure 9: The goniometric diagram of the light source used for the office

Figure 8: An office with a typical directionally dependent light source

5 RESULTS AND VALIDATION

Figure 8 shows an office lit with a directionally dependent light source described in Figure 9 in order to get an efficient illuminance on the desk runner. This image is computed with a global illumination method [SP01].

5.1 Validation

In this section, we will describe the method used to evaluate our model. It is based on a comparison between our simulation and real measurements. Slater[Sla89] did such an experiment. Nine point luminaires with a known goniometric diagram (Figure 10) were set on the ceiling of an empty room. The reflectivity of the walls, of the floor and of the ceiling were respectively 0.3, 0.2 and 0.7. 169 photocells were set at 0.75m above the floor to measure the radiance in the room. Figure 11 shows the measurements from photocells achieved by Slater.

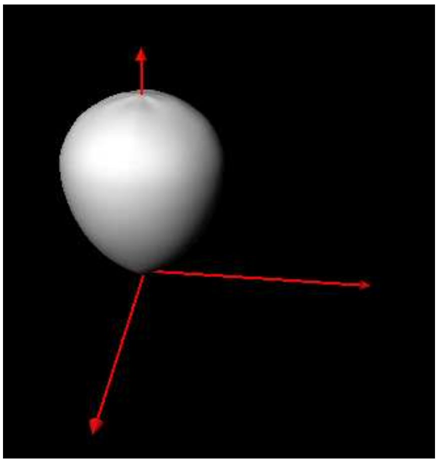


Figure 10: The goniometric diagram used by Slater

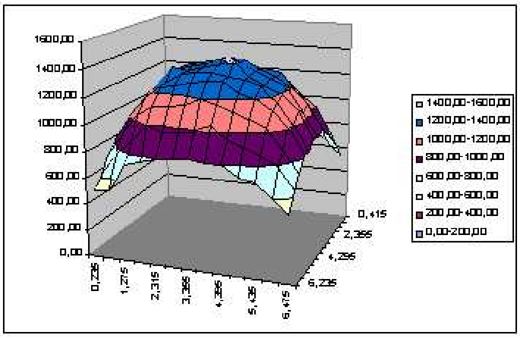


Figure 11: Measurements from Slater's experiment

Figure 12 shows a comparison between measurements from Slater and point directionally dependent light sources (with the goniometric diagram shown in Figure 10). The average distance is about 4.10%, with a minimum of 0.03% and a maximum of 17.02%. In the lighting community, an error around 15% is often judged acceptable. So, with an average error in the region of 5%, we may say that our model is consistent with the needs in this domain.

For this image, radiance is computed by ray-tracing whitout global illumination. Large errors occur on the edges of the virtual ground located at 0.75m above the floor because indirect reflections on walls are not taken into account. When computing global illumination, the mean error is reduced to 2.72% instead of 4.10% before.

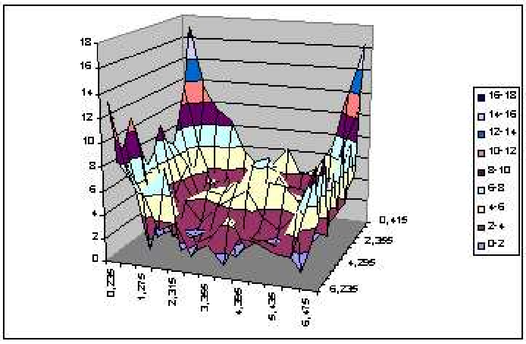


Figure 12: Comparison between Slater's measurements and a directional point light source

If a planar luminaire is designed in such a way that the emission is spatially uniform over the surface, only one goniometric diagram can be used to reconstruct the emission function for any point on the plane. This case is solved by using our method and the adaptive subdivision method from [ZBP99].

6 CONCLUSION AND FURTHER DEVELOPMENTS

We have introduced a new model to reconstruct a goniometric diagram for light sources in a far-field photometry context. This model has two advantages: first, a good precision with singular integrals; second, locally supported functions allow a fast evaluation since only kernels that are in the neighborhood of the direction to be evaluated are computed. This method has few drawbacks, except the need of a sufficient number of measurements.

For future work, we would like to be able to compute simple scenes at interactive rates, in order to allow interactive simulations of complex light sources for inside architectural design for example. This could be achieved by pre-computing and tabulating the reconstructed function. For non uniform planar luminaires, a knowledge of the goniometric diagrams distribution should be given in order to be able to apply our method. Finally, a major improvement would be to take near-field photometry into account.

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