Error-Bound Wavelength Selection for Spectral Rendering

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Abstract

This paper proposes two methods aiming at selecting the most significant wavelengths in case of spectral rendering. The first one, called static (which can be seen as a preprocessing), processes in turn the Spectral Power Distributions (SPD) of all the light sources to determine those wavelengths for which these SPD's are approximated with an error kept below a certain bound fixed by the user. The second, called dynamic, continously determine, during the spectral rendering process, the set of significant wavelengths depending on the shapes of the light sources and reflectance spectra. These two methods can be easily incorporated in an existing rendering software.

Keywords

Spectral rendering, global illumination, wavelength selection, radiosity, basis functions.

1 Introduction

Light can be considered as a mixture of electromagnetic waves which propagate at the same velocity called *light velocity*. Each of these waves has a frequency, a period and a wavelength λ. Each wave of a light, called from now on spectral component, has an energy proportional to the square of its amplitude. In addition, each spectral component of light seen in isolation has a characteristic color appearance. Because the wavelength decomposition is fundamental, we can describe any light completely by the amount of power in each of its spectral wavelength components (spectral character). This description consists of a fairly long series of values called *the Spectral Power Distribution* (SPD) of light.

For global illumination computation and more precisely for lighting simulation, the full spectral character of light and surface materials has to be accounted for absolutely. Traditionally, the computer graphics community ignores the spectral nature of light (wavelength dependency) and express all the radiometric quantities for three wavelengths : Red, Green and Blue. Indeed, they use a trichromatic approach which expresses, in the RGB color space, the intensity of the light sources, the objects' color as well as their reflection and refraction properties. As the reflectance and transmittance functions are wavelength dependent, the reflected and transmitted lights also have a spectral character. As will be seen later on, colour information is lost when only three wavelength values are used. This problem is stressed more importantly when the light sources are more complex and characterized by high and spiky frequencies at certain wavelengths. Such light sources are: fluorescent lamps, low pressure sodium lamp (see figures 1 and 2), etc. Furthermore these spiky frequencies may be located at wavelengths different from the three RGB wavelength values. It is very curious that the most famous lighting simulation softwares (like *Radiance* and *Lightscape*) use only a trichromatric approach.

In this paper we argue in favour of the use of the spectral form of light and physical properties of materials. Two main spectral approaches have been attempted. The first one consists in discretizing the visible spectrum by choosing a finite number of wavelengths [1, 2]. The precise number of values necessary to describe the light depends on how finely the wavelength samples are spaced. Typical wavelength spacing ranges between $1\,nm$ and $10\,nm$, depending on the goals of the specification and how rapidly the power may vary with wavelength. The samples may not be evenly spaced. Recall that the human visual system is only sensitive to the wavelengths of light ranging between $380nm$ and $780nm$. As for the second approach, it tries to avoid this sampling process by expressing light and reflectances in a space spanned by a set of orthonormal basis functions [3, 4]. In this way the entire visible spectrum is accounted for in the global illumination computation.

The work described in this paper follows the first approach. It performs a processing aiming at selecting the pertinent and significant wavelength values (those corresponding to the spiky frequencies and others) of either the spectral power distribution of the light sources or the spectral power reflected by each surface within the environment. This selection is guided by an error bound between the actual and sampled spectra. The proposed methods are simple and easy to incorporate in an existing global ilumination software.

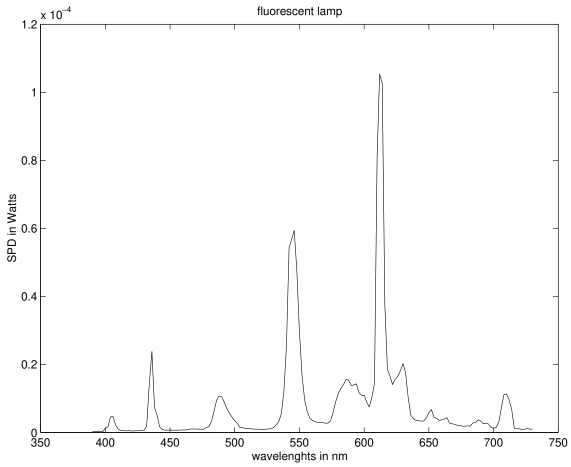

Figure 1: Spectral power distribution of a fluorescent lamp

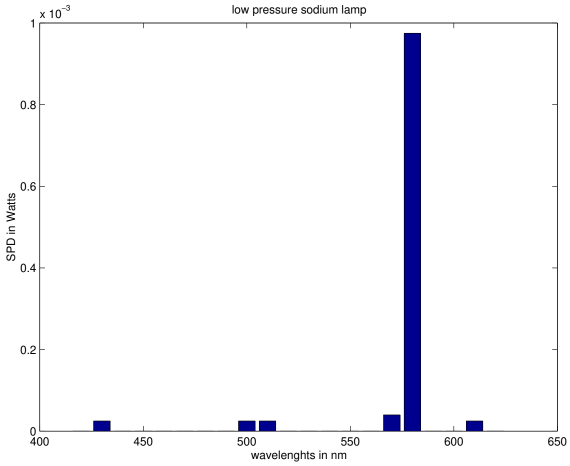

Figure 2: Spectral power distribution of a low pressure sodium lamp

2 Previous Works

2.1 Problem statement

Once global illumination computation is completed, an image of the scene is computed and displayed on a monitor (rendering step). To do this the spectral radiance $L(\lambda)$ of a pixel is projected to a point in a 3D color space such as the XYZ color space defined by the CIE (International Committee for Lighting). This projection is performed by integration. For example the X component is given by

$$X = K \int_{380}^{780} L(\lambda)\bar{x}(\lambda)d\lambda, \tag{1}$$

where K is a constant used to normalize the results, and $\bar{x}(\lambda)$ is one of the matching functions associated with the XYZ space.

Moreover, lighting engineers are more interested in precisely computing photometric quantities rather than images. These quantities are : luminance, illuminance, exitance, intensity, etc. Note that, for example, the *luminance* quantity L corresponds to the *radiance* radiometric quantity, and is related to its spectral distribution $L(\lambda)$ by :

$$L = K \int_{380}^{780} L(\lambda)V(\lambda)d\lambda, \tag{2}$$

where $V(\lambda)$ is the sensitivity function of the human eye.

For computing the integral 1 or 2:

- Either we select a limited number of wavelengths then we solve the global illumination problem for each wavelength, which yields the spectral radiance for each pixel in a discrete form. The trichromatic components (X, Y, Z in this case) as well as the photometric quantities are computed by applying a numerical integration procedure using these wavelength samples. This approach will be termed, from now on, *sampling-based.*

- Or the full spectral information is handled by projecting all the spectral quantities (spectral power distribution, spectral reflectance and absorption, etc.) into a functional space spanned by a set of orthonormal basis functions depending on wavelength. In this case, for each pixel, global illumination computation results in a spectral radiance expressed with respect to these basis functions. The trichromatic components together with the photometric quantities are computed with an efficient integration procedure like Gaussian quadrature. This approach will be referred to, from now on, as *projection-based method.*

Curiously little attention has been paid to spectral rendering. This is why only a few papers deal with this problem. These papers make use of one of the two above approaches.

2.2 Sampling-based methods

The first sampling-based method is due to Meyer [2]. It uses the Gaussian quadrature technique for computing the trichromatic components (equation 1) in the AC_1C_2 color space. A minimum number of wavelengths are selected by the Gaussian quadrature technique. This method fails when the used light sources are complex and consequently have high spiky frequencies located at certain wavelengths completely different from the ones provided by Gaussian quadrature.

A more recent method [1] tried to solve this problem by partioning the visible spectrum into several pieces: tight pieces surrounding the spiky part of the light sources and wider pieces corresponding to the smooth part of the light sources. For each kind of wavelength piece a different numerical integration (Gaussian quadrature or trapezoidal) is employed using a certain number of wavelength samples. One drawback of this method is that it does not give any means for estimating and bounding the sampling errors as a function of the chosen wavelength samples. We really think the number of selected wavelength samples is too important and can be reduced as will be explained later on in our approach.

2.3 Projection-based methods

The first projection-based method has been devised by Raso et al. [4]. It uses a cubic piecewise polynomial representation of spectra. In fact each spectrum is expressed with two cubic polynomials each one defined on half the visible spectrum. When multiplying the spectral power distribution of a light source by a spectral reflectance the degree of the resulting polynomial becomes greater than 3. This is why the authors propose a degree reduction technique. Dividing the visible spectrum into two spans is not enough for approximating complex light sources. One solution is to increase the number of spans and consequently the number of pieces of the piecewise cubic polynomial approximating the spectra. But this increase would be done at the expense of a more important computation time. This latter could be also augmented by the degree reduction process.

The second more recent approach [3] expresses all the spectra (light sources and reflectance functions) with a set of basis functions. In other words these spectra are projected into the functional space spanned by these basis functions. All the spectra are represented by their projection coefficients. In this way the reflected light is represented by a vector of coefficients resulting from the matrix product between the coefficients of the incoming light and those of the matrix associated with the projection of the reflectance function. A characteristic vector analysis is used to determine the best basis functions. This analysis account for the contributions from the light sources, from one-reflected light and from mutiple-reflected light. This method, although interesting, seems very costly (in terms of computation) and difficult to implement efficiently when physics-based bidirectional reflectance distribution functions are considered. Moreover it fails for light sources with spiky frequencies (as noted by the authors).

2.4 Discussion

None of the sampling-based methods offer an efficient solution to the discretization of the visible spectrum. The former [2] fails for complex light sources while the other [1] does not provide a means for efficiently selecting the wavelength samples. As for the projection-based methods, either they are very difficult to implement or fail for complex light sources.

Our objective is to propose a novel sampling-based method which efficiently reduces the number of wavelength samples while meeting an error-bound criterion. More details are given in the next sections.

3 Error-Bound wavelength selection

3.1 Motivation

Our objective was to devise sampling-based methods for wavelength selection that fulfill the following requirements:

- Propose a simple and cheap method in terms of computation time and memory storage.
- Carry out a static approach consisting of a preprocessing that selects the significant wavelength values (those corresponding to the spiky frequencies and others) of the spectral power distribution of the light sources only. Indeed, as the reflectance function of any material is generally smooth as seen in figure 3, it seems logical to limit the wavelength selection process to the spectral power distributions of the light sources only. Moreover, given the smoothness of the reflectance functions there is no doubt that the selected wavelengths remain pertinent for the reflected lights.
- Or propose a dynamic approach that selects the most important wavelengths of the spectral reflected light depending, at once, on the reflectance function of the materials and the incident light powers. The number as well as the values of the selected wavelengths may vary with the kind of reflectance properties since the shape of the reflected light powers may vary from surface to surface.
- This selection has to be guided by an error bound between the actual and sampled spectra.
- The sampled spectral power distributions of the light sources and the reflectance and/or transmitance functions must be kept as close as possible to the actual ones.
- The proposed method is simple and easy to incorporate in an existing global illumination software.

3.2 Wavelength suppression

We suppose that the spectral power distribution (SPD) of a light source and spectral reflected light power is given under a finely sampled form, say for a wavelength spacing of $5nm$. The problem now is to find out a method that discards the non pertinent wavelengths while controling the error implied by this wavelength suppression. The method consists in keeping constant (after suppression) the total power associated with the SPD while maintaining the shape of the approximated SPD close to the original one. Recall that the total power E associated with a SPD $E(\lambda)$ is : $E = \int_{380}^{780} E(\lambda)d\lambda$. This suppression method is illustrated by figures 4 and 5. The original SPD is shown in figure 4. After the wavelength λ_0 has been suppressed, the values of the SPD at the two immediate neighboring wavelengths λ_{-1} and λ_1 are modified so that the light power at each side of λ_0 remains unchanged. In other words: $E_1 = E_1' \ and \ E_2 = E_2'$ (see figure 5). In this way the total SPD is kept constant. Note that the shape of the modified SPD remains close to the original one since the change is local, say around the suppressed wavelength. As a result the approximated SPD will no more be

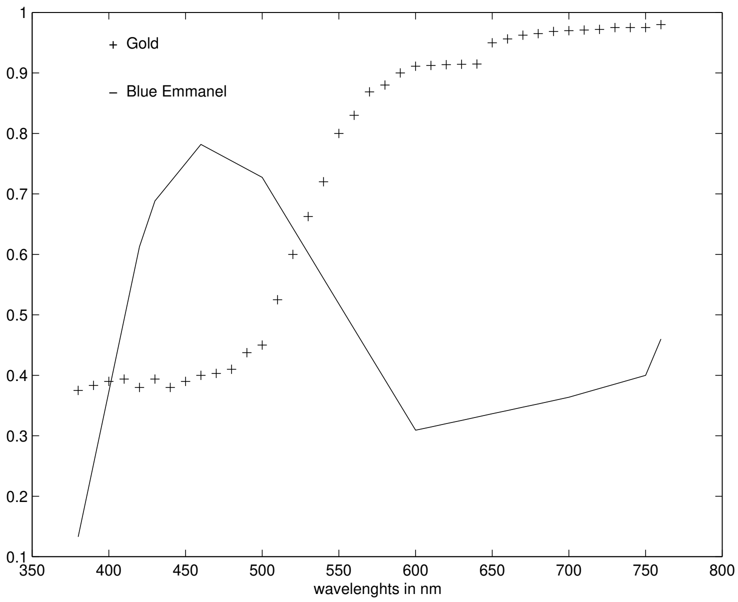

Figure 3: Reflectance functions for Gold and blue Emmanel

sampled at wavelength λ_0 and its values at λ_{-1} and λ_1 are modified and now equal to V'_{-1} and V'_1.

Let us see now how these new values are computed.

From figure 4 we get:

$$\left\{\begin{array}{l} 2E_1 = (V_{-2}+V_{-1})(\lambda_{-1}-\lambda_{-2}) + (V_0+V_{-1})(\lambda_0-\lambda_{-1}) \\ 2E_2 = (V_0+V_1)(\lambda_1-\lambda_0) + (V_2+V_1)(\lambda_2-\lambda_1) \end{array}\right. \tag{3}$$

And from figure 5 we have:

$$\left\{\begin{array}{l} 2E'_1 = (V_{-2}+V'_{-1})(\lambda_{-1}-\lambda_{-2}) + (V'_{-1}+(V'_1+V'_{-1})\frac{(\lambda_0-\lambda_{-1})}{(\lambda_1-\lambda_{-1})}+V'_{-1})(\lambda_0-\lambda_{-1}) \\ 2E'_2 = (V'_{-1}+(V'_1+V'_{-1})\frac{(\lambda_0-\lambda_{-1})}{(\lambda_1-\lambda_{-1})}+V'_1)(\lambda_1-\lambda_0) + (V_2+V'_1)(\lambda_2-\lambda_1) \end{array}\right. \tag{4}$$

To keep the powers unchanged we impose : $E_1 = E'_1$ and $E_2 = E'_2$, which yields, after combining (3) and (4), the following system:

$$\left\{\begin{array}{l} (V'_{-1}-V_{-1})(\lambda_{-1}-\lambda_{-2}) + (2V'_{-1}+(V'_1-V'_{-1})\frac{(\lambda_0-\lambda_{-1})}{(\lambda_1-\lambda_{-1})}-V_0-V_{-1})(\lambda_0-\lambda_{-1}) = 0 \\ (V'_{-1}+(V'_1-V'_{-1})\frac{(\lambda_0-\lambda_{-1})}{(\lambda_1-\lambda_{-1})}+V'_1-V_0-V_1)(\lambda_1-\lambda_0) + (V'_1-V_1)(\lambda_2-\lambda_1) = 0 \end{array}\right.$$

This system can be rewritten as:

$$\left\{\begin{array}{l} V'_{-1}A + V'_1B + C = 0 \\ V'_{-1}D + V'_1E + F = 0 \end{array}\right.$$

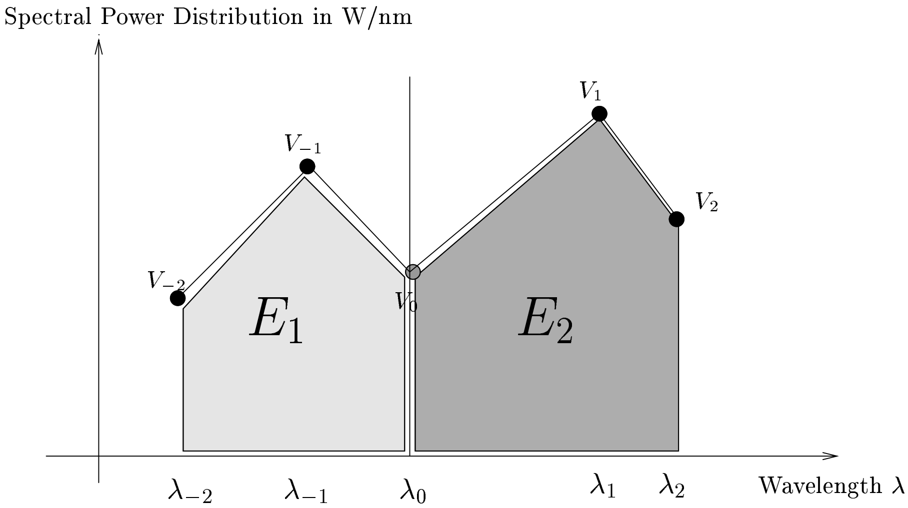

Figure 4: Initial SPD : λ_0 is the wavelength to be suppressed

With :

$$\begin{cases} A = 2\lambda_0 - \lambda_{-1} - \lambda_{-2} - \frac{(\lambda_0 - \lambda_{-1})^2}{(\lambda_1 - \lambda_{-1})} \\ B = \frac{(\lambda_0 - \lambda_{-1})^2}{(\lambda_1 - \lambda_{-1})} \\ C = -V_{-1}(\lambda_0 - \lambda_{-2}) - V_0(\lambda_0 - \lambda_{-1}) \\ D = \lambda_1 - \lambda_0 - \frac{(\lambda_1 - \lambda_0)(\lambda_0 - \lambda_{-1})}{(\lambda_1 - \lambda_{-1})} \\ E = (\lambda_1 - \lambda_0)(1 + \frac{(\lambda_0 - \lambda_{-1})}{(\lambda_1 - \lambda_{-1})}) + (\lambda_2 - \lambda_1) \\ F = V_0(\lambda_0 - \lambda_1) - V_1(\lambda_0 - \lambda_2) \end{cases}$$

We finally obtain :

$$\boxed{\begin{cases} V_1' = \frac{A \times F - D \times C}{D \times B - A \times E} \\ V_{-1}' = \frac{C \times E - B \times F}{D \times B - A \times E} \end{cases}} \tag{5}$$

3.3 Error calculation

Since we keep unchanged the powers at each side of the suppressed wavelength (see figure 6) we have:

$$\mathcal{A}rea(V_0IB) = \mathcal{A}rea(BV_1V_2V_1')$$

and

$$\mathcal{A}rea(V_0IA) = \mathcal{A}rea(AV_{-1}V_{-2}V_{-1}'),$$

where $\mathcal{A}rea()$ is the area of the polygon defined by the mentioned vertices.

The error due to the suppression of the wavelength λ_0 is expressed in $Watt/nm$ and given by:

$$Error_{\lambda_0} = \int_{\lambda_{-2}}^{\lambda_2} |E(\lambda) - E'(\lambda)| d\lambda = 2 \times \mathcal{A}rea(V_0AB) \;\; Watt/nm.$$

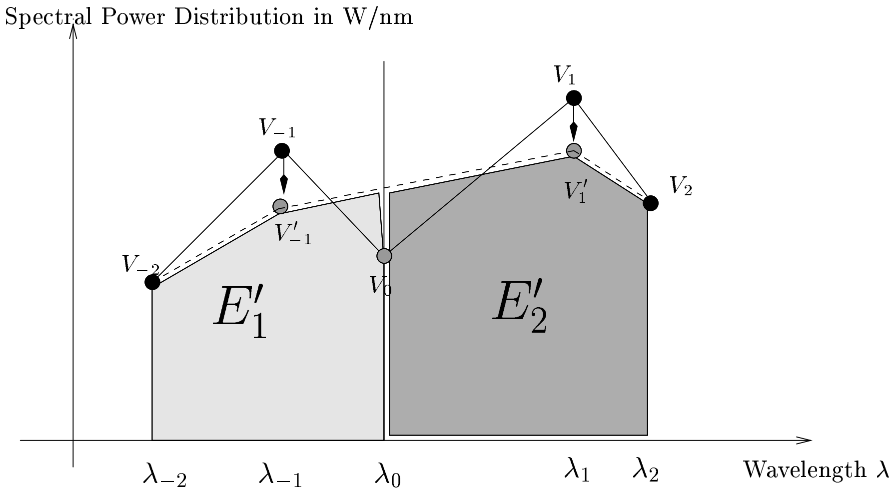

Figure 5: Modified SPD after suppression of λ_0

With

$$\mathcal{A}rea(V_0AB) = \frac{1}{2}|det(\vec{AV_0}, \vec{AB})|$$

where $E(\lambda)$ qnd $E'(\lambda)$ are the original and the modified SPD, $det(\vec{AV_0}, \vec{AB})$ is the determinant of the vectors $\vec{AV_0}$ and $\vec{AB}$.

We obtain then:

$$Error_{\lambda_0} = |det(\vec{AV_0}, \vec{AB})| \tag{6}$$

The point A (resp. B) results from the intersection of the lines $(V'_{-1}V'_1)$ and $(V_{-1}V_0)$ (resp. (V_1V_0)).

By setting:

$$\begin{cases} a_1 = \frac{(V_0 - V_{-1})}{(\lambda_0 - \lambda_{-1})} \\ b_1 = V_{-1} - a_1\lambda_{-1} \\ a_2 = \frac{(V'_1 - V'_{-1})}{(\lambda_0 - \lambda_{-1})} \\ b_2 = V'_{-1} - a_2\lambda_{-1} \\ a_3 = \frac{(V_1 - V_0)}{(\lambda_1 - \lambda_0)} \\ b_3 = V_0 - a_3\lambda_0 \end{cases}$$

We obtain the coordinates of A and B as follows:

$$\text{A} \left(\begin{array}{l} \alpha_1 = \frac{(b_1 - b_2)}{(a_2 - a_1)} \\ \alpha_2 = a_1\alpha_1 + b_1 \end{array} \right) \text{ and B } \left(\begin{array}{l} \beta_1 = \frac{(b_2 - b_3)}{(a_3 - a_2)} \\ \beta_2 = a_3\beta_1 + b_3 \end{array} \right) \tag{7}$$

The suppression of each wavelength λ_{0_i} entails an error $Error_{\lambda_{0_i}}$. After suppressing a certain number of wavelengths the total error is given by :

$$Error(E, E') = \int_{380}^{780} |E(\lambda) - E'(\lambda)| d\lambda.$$

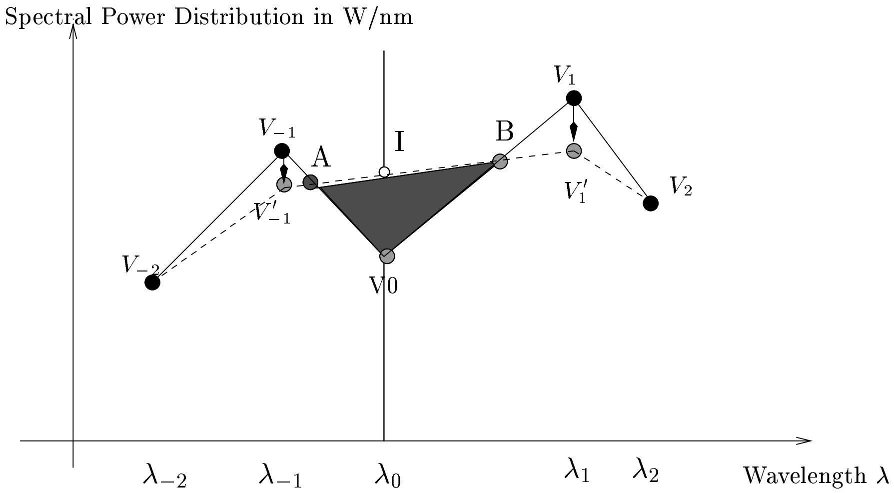

Figure 6: Error

We can bound the total error as: $Error(E, E') \leq \sum_{\lambda_{0_i}} Error_{\lambda_{0_i}}$. Rather than computing $Error(E, E')$ after each suppression of a wavelength it is easier to compute an upper bound which is equal to the cumulative sum of the errors $Error_{\lambda_{0_i}}$.

3.4 Static Wavelength Selection

The wavelength selection method described hereafter consists in determining the wavelengths which are significant for the light source SPD's only. It may be seen as a preprocessing step.

3.4.1 Wavelength suppression for a single source

The algorithm of figure 7 shows how the useless wavelengths are left out for a light source i defined by its SPD E_i. Recall that each E_i is a finely discretized spectrum (wavelength spacing of $5nm$). Let Λ be the total set of wavelengths :

$$\Lambda = \{\lambda_i \ / \ \lambda_i \in [380nm, 780nm], \ \ \Delta\lambda = (\lambda_{i+1} - \lambda_i) = 5nm\} \tag{8}$$

This algorithm is a function which returns the reduced set of wavelengths $set\_of\_\lambda = \Lambda - \{\lambda_{0_i}\}$, the λ_{0_i}'s being the suppressed wavelengths. It also provides the SPD S_i approximating E_i.

Wavelength_implying_smallest_error($E_i, S_i,\ \Lambda_{search},\ Error$) is a function (see figure 8) which provides the wavelength λ_0 the suppression of which entails the smallest error $Error$ for the light source i. This wavelength must belong to the set Λ_{search}. $\Lambda_{already}$ is a set of wavelengths which is empty when only one kind of source is used but varies in case of different kinds of light source with different SPD's (see figure 9). The procedure modify_SPD(E_i, S_i, λ_0) modifies the values of the SPD E_i at the two wavelengths λ_{-1} and λ_1 around λ_0 (see figure 5) to give the approximated SPD S_i associated with E_i.

```
Wavelength_suppression_single_source(Λ, Λ_already, E_i, S_i) {
    /*E_i : initial SPD's;   S_i: approximated SPD's after wavelength suppression */
    total_error = 0;
    Λ_search = Λ − Λ_already;
    set_of_λ = Λ;
    while (total_error ≤ Error_bound) and (Λ_search ≠ ∅) {
        λ_0 = Wavelength_implying_smallest_error(E_i, S_i, Λ_search, Error_λ0);
        set_of_λ = set_of_λ − {λ_0};
        Λ_search = Λ_search − {λ_0};
        total_error += Error_λ0;
    }
    return (set_of_λ);
}
```

Figure 7: Wavelength suppression for a single source

3.4.2 Wavelength suppression for several sources

Let $E = (E_1, ..., E_n)$ be a set of different SPD's E_i associated with the light sources. The objective is to find out the smallest set of pertinent wavelengths keeping the total error $total\_error_i$ due to each light source i below the threshold $Error_{bound}$.

Let $\mathcal{P}$ be the set of all the permutations P_i of the E's elements. We can write $P_i = \{E_{i_1}, E_{i_2}, ...E_{i_n}\}$, where $i_j \in [1, n]$.

The algorithm handling several kinds of light sources is given by figure 9.

For each permutation i_j, each SPD E_{i_j} is processed so that the useless wavelengths are suppressed from the set $\{\Lambda - \Lambda^{previous}_{already}\}$. Once all the SPD's E_{i_j} in the same permutation have been processed the selected wavelengths are contained in the set Λ_{final}. $\Lambda^{previous}_{already}$ is no more than the set $\Lambda_{already}$ corresponding to the SPD $E_{i_{(j-1)}}$ processed just before E_{i_j}.

After having processed all the SPD's in a permutation, the total set of non-suppresed wavelengths is saved in $\Lambda_{already}$. Let P_i and P_{i+1} be two permutations processed successively and Λ_i, Λ_{i+1} the associated $\Lambda_{already}$ sets respectively. If the number of elements of Λ_{i+1} is larger than that of Λ_i then Λ_{i+1} is discarded else it becomes the new set $\Lambda_{already}$ and the modified SPD's are saved in S_{i_k} (procedure Save_SPD()). Once all the permutations have been accounted for, the algorithm returns the final set of wavelengths Λ_{final} and the final approximated SPD's are saved in $S^{final}_{i_k}$.

3.5 Dynamic Wavelength Selection

The problem now is to select the significant wavelengths for either the radiosity emitted by any surface or the reflected/refracted radiance at each of its points. The number as well as the values of the selected wavelengths vary from surface to surface. It may also vary for the same surface during the illumination computation.

```
Wavelength_implying_smallest_error(E_i, S_i, Λ_search, Error) {
    Error = HUGE ;
    λ_0 = 0 ;
    foreach λ ∈ Λ_search {
        Error_λ = compute-error(λ );
        if (Error_λ < Error ){
            Error = Error_λ;
            λ_0 = λ ;
        }
    }
    modify_SPD(E_i, S_i, λ_0);
    return (λ_0 )
}
```

Figure 8: Determining the wavelength implying the smallest error

Let us explain the principle of the method in case the radiosity method is used for illumination computation with shooting as resolution scheme. Suppose that the spectral light power $E_j(\lambda)$ (irradiance) impinging on surface i and coming from surface j has already been approximated for a certain number of selected wavelengths within a set Λ_j by means of the procedure *Wavelength_suppression_single_source( )* (figure 7). Suppose also that the reflectance function $\rho(\lambda)$ of the receiving surface i is given under a finely discretized form (for example with a wavelength spacing of 5 nm). To select the significant wavelengths for the outgoing radiosity $B_i(\lambda) = \rho(\lambda)\ E_j(\lambda)$ we operate as follows. First we reconstruct the signal $E_j(\lambda)$ by means of a linear interpolation for the wavelengths in the set $\{\Lambda - \Lambda_j\}$ (see equation 8 for the definition of Λ). We obtain then a finely discretized spectrum $E_j^f(\lambda)$ defined for each λ in Λ. Next we compute the finely discretized radiosity $B_i^f(\lambda) = \rho(\lambda) E_j^f(\lambda)$. Afterwards we select the significant wavelengths of $B_i^f(\lambda)$ by invoking again the procedure *Wavelength_suppression_single_source( )* (figure 7) which approximates $B_i^f(\lambda)$ with $S_i(\lambda)$. After a while, if surface i is chosen for shooting its energy to a surface k, then the spectral light power impinging on surface k will be: $E_i(\lambda) = F_{ik}\ S_i(\lambda)\ \frac{A_k}{A_i}$, where F_{ik}, A_i, A_i are respectively the form factor between surfaces i and k, the area of surfaces i and j. The process is then repeated with $E_i(\lambda)$ as new incoming spectral light power.

The consequence of this method is that the number as well as the values of the selected wavelengths change from surface to surface because it adapts at once to the shape of the incoming light power and that of the surface reflectance. This adaptation changes dynamically during the shooting process. Note that the same principle can be applied to other illumination computation methods using radiance instead of light power (such as ray tracing, two-pass and multi-pass methods, Monte-Carlo...). In this case irradiance will be replaced with incoming radiance, radiosity with reflected radiance and reflectance with bidirectional reflectance distribution function (BRDF).

4 Results

4.1 Approximated Spectral Power Distribution

Figure 11 shows the original spectrum of a lamp which is similar to the spectrum of a *blue sky*. It also shows the corresponding approximated spectrum defined for 6 selected wavelengths. This results has been obtained with an error bound of 0.0003 and accounts for the existence in the scene of two other kinds of light source: *sun* and *D6500*. In fact the 6 selected wavelengths are used for representing at once the 3 spectra: *blue sky*, *sun* and *D6500*. As it can be seen in this figure only 4 wavelengths are sufficient for representing the *blue sky* spectrum alone. Note that these 3 spectra are smooth, which explains the small number of wavelengths. Conversely, figure 10 gives the non-smooth original spectrum of a fluorescent lamp together with its approximation for 11 and 6 selected wavelengths corresponding to an error bound of 0.00084 and 0.0026 respectively.

4.2 Images of scenes containing different kinds of light source

This section shows images generated with our wavelet radiosity program using either the static or dynamic wavelength selection method. In order to assess the correctness of the results provided by our methods we compare the images generated with both wavelength selection methods with a reference image. The reference image of a scene is calculated using the static wavelength selection method with a low error bound, which amounts to use finely discretized light source spectra. Comparison is performed in the $L^*u^*v^*$ color space. In this space we evaluate the distance between a reference image and another obtained for less wavelengths by averaging the distances between the corresponding pixels on both images. It is well known that a distance greater than 1 is perceptible by the human eye. The value 1 is then the perceptual difference threshold which will be called V_{thres}.

Tests have been performed on a scene whose reference image (see figure 12) has been calculated with an error bound $Error_{bound}$ equal to 0.0001, which amounts to use 26 wavelengths. This scene contains 4 kinds of light source: *fluorescent lamp, D6500, BlueSky* and *Sun*. The SPD's associated with these sources are smooth while the fluorescent lamp has a spectrum containing peaks. The fluorecent light source is hung on the ceiling and illuminates the scene mainly in the red and green colors but very weakly in the blue color.

4.2.1 Static wavelength selection method

Table 1 gives the number of selected wavelengths for different error bounds $Error_{bound}$. For each case the mean $L^*u^*v^*$ distance between the reference image and the calculated images (with the static wavelength selection technique) is computed. All the wavelength values are given in nanometers. As seen in figure 14 and table 1, 12 wavelengths $(470, 490, 530, 540, 550, 560, 600, 610, 620, 640, 700, 710)$ seem sufficient for accurately representing the 4 different SPD's of the light sources. Indeed, the mean distance is close to 1 which corresponds to V_{thres}. Of course, the distance for 18 wavelengths is smaller $(390, 450, 480, 490, 500, 530, 540, 550, 560, 580, 600, 610, 620, 630640, 700, 710, 720)$. For 6 wavelengths $(530, 550, 560, 600, 610, 620)$, even though the distance is larger, the difference with 12 wavelengths is hardly visible. On the other hand, for 4 wavelengths $(530, 600, 610, 620)$ the error is larger and the resulting image looks too red (see figure 16). This is due to the fact that the 3 wavelengths 600, 610 and 620 correspond to the position of the most important peak of the fluorescent light source which gives a red color, while for the wavelength 530 the spectrum value is negligible with respect to this peak. As for the 4 wavelengths ($456.4, 490.9, 557.7, 631.4$) obtained with Meyer's method, they provide an image (see figure 17) that looks too green. This result is foreseeable since these 4 wavelengths do not correspond the actual peaks of the fluorescent lamp except the peak located at $\lambda = 490.9$ representing the green color. Indeed, for the other wavelengths $456.4, 557.7$ and 631.4 the original spectrum is nearly equal to 0 (see figure 1). Moreover table 1 proves the inefficiency of choosing Meyer's wavelengths. Note that our method provides 4 different wavelengths implying a smaller error.

Image	$Error_{bound}$	Number of Wavelengths	Mean $L^*u^*v^*$ Distance	Visual Difference
figure 13	0.0003	18	0.12	NO
figure 14	0.0008	12	1.5	NO
figure 15	0.002	6	3.1	NO
figure 16	0.0033	4	4.1	YES (too blue)
figure 17		4 (Meyer)	5.7	YES (too green)

Table 1: Results: Static method

4.2.2 Dynamic wavelength selection method

The dynamic wavelength selection method has been applied to the same scene (figure 12) with different numbers of wavelengths fixed by the user. The difference between the obtained reference image and the one obtained with the static method is hardly visible. Table 2 summarizes the obtained results and shows that the obtained results are slightly better than those provided by the static method since the distances are smaller.

Fixed Number of Wavelengths	Mean $L^*u^*v^*$ Distance	Visual Difference
18	0.1	NO
12	1.38	NO
6	3.08	NO

Table 2: Results: Dynamic method

5 Conclusion

We have presented two methods for sampling the spectral power distributions of light and the reflectance/transmittance spectra of materials. These methods have been implemented in a wavelet radiosity program. The first one is static and can be seen as a preprocessing while the second is dynamic since it may evolve during the rendering process depending on the spectral shape of the incoming light and the surface properties. The static method results in a reduced set of wavelengths at which all the spectra (SPD's of light sources, reflectance/transmittance functions, irradiance, radiosity, radiance...) will be sampled once for all. The sampling method is guided by an error bound fixed by the user and keeps the shape as well as the power associated with the approximated SPD's close to the orignal one. As for the dynamic method, which relies on the same wavelength selection method, it continuously samples the reflected/refracted light powers during the rendering process. This sampling is performed whenever a light is reflected/refracted by a surface. As a result, the number together with the values of the selected wavelengths may differ when moving from a surface to another. Both methods may be easily incorporated in an existing software with a very slight modification. Note that the dynamic sampling method gives better results since it also accounts for the surface properties.

References

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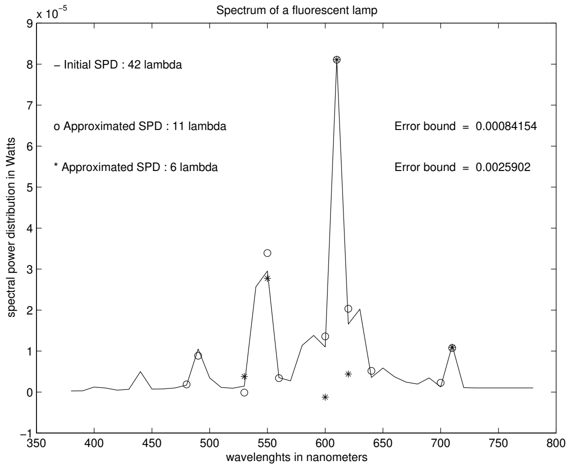
```
Wavelength_supression_all_sources(Λ,{E_i },{ S_i }) {
    Λ_already = ∅ ;
    previous_size = HUGE;
    Λ^previous_already = ∅;
    for (i = 1; i ∈ [1, Number_of_permutations]; i ++) { /* for each permutation P_i*/
      for (j = 1; j ∈ [1, n]; j ++) { /* for each SPD E_ij in the permutation P_i*/
        Λ_already = Wavelength_suppression_single_source(Λ, Λ^previous_already, E_ij, S_ij );
         /*Determine the new selected wavelengths */
        set_of_new_λ = Λ_already − Λ^previous_already ;
        if ((set_of_new_λ ≠ ∅) and (j > 1)) {
         /*Evaluate the previously processed SPD's at */
         /* the new selected wavelengths and store them in S_ik */
           for (k = j − 1;k ≥ 1; k −−) { Evaluate_SPD(E_ik, S_ik,set_of_new_λ) } ;
        }
        Λ^previous_already = Λ_already;
      }
      if (size(Λ_already) < previous_size) {
      /* Results provided by the current permutation are better */
      /* than those obtained at the previous permutations */
        previous_size = size(Λ_already) ;
        Λ_final = Λ_already;
         /* Save the approximated SPD's */
        for (j = 1; j ∈ [1, n]; j ++) {Save_SPD( S_ij, S^final_ij ) } ;
      };
    } ;
    return (Λ_final); /* return the final set of selected wavelengths */
}
```

Figure 9: Wavelength suppression for several kinds of light source



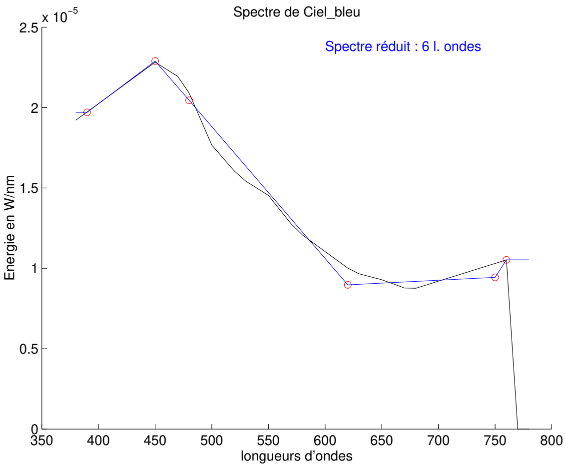


Figure 10: Approximated spectrum of fluorescent light source

Figure 11: : Approximated Blue Sky spectrum: $Error_{bound} = 0.0003$

Figure 12: Image reference with 4 different light sources: *Fluorescent*, *D*6500, *BlueSky* et *Sun*

Figure 13: Image obtained with 18 λ's

Figure 14: Image obtained with 12 λ's

Figure 15: Image obtained with 6 λ's

Figure 16: Image obtained with 4 λ's

Figure 17: Image obtained with 4 λ's determined by Meyer's method