

# Virtual Spectrophotometric Measurements for Biologically and Physically-Based Rendering (Extended Abstract)

Gladimir V. G. Baranoski  
Department of Computer Science  
University of Utah, USA  
gbaranos@cpsc.ucalgary.ca

Jon G. Rokne  
Department of Computer Science  
The University of Calgary, Canada  
rokne@cpsc.ucalgary.ca

Guangwu Xu  
Diversinet Corp.  
Toronto, Canada  
gxu@dvnet.com

The group of measurements necessary to characterize both the color and surface finish of an object is called the *measurement of appearance* of an object [4]. This group of measurements involves the spectral energy distribution of propagated light, measured in terms of reflectance and transmittance, and the spatial distribution of that light, measured in terms of the bidirectional reflectance distribution function (BRDF) and the bidirectional transmittance distribution function (BTDF). The variations in the spectral energy distribution affect appearance characteristics such as hue, lightness and saturation, while the changes in the spatial distribution affect appearance characteristics such as gloss, reflection haze, transmission haze, luster and translucency as noted by Hunter and Harold [4]. Measuring these appearance characteristics is crucial for realistic rendering.

Spectrophotometry is defined as the quantitative measurement of reflection and transmission properties as a function of wavelength. In the real world the measurement of the spectral distribution of reflected and transmitted radiant power is made with a spectrophotometer. In order to evaluate reflectance and transmittance models one needs to resort to a computer simulation of this device, called a virtual spectrophotometer. This is normally implemented using ray casting algorithms combined with stochastic techniques applied to particle transport simulations [2, 3]. The purpose of these devices is to determine the numerical value of an estimand, or expected value, to which the readings of reflectance, or transmittance, of a model converge. This estimand will correspond to a reflectance, or transmittance, value for a given wavelength and illuminating geometry.

In the full paper [1] the main aspects of virtual spectrophotometry are discussed in detail. An introduction to the area of measuring spectral characteristics of various materials is first provided. Some background from physics is then introduced as required for spectrophotometry. The general characteristics of actual spectrophotometers are also discussed.

The main topic of the paper is virtual spectrophotometers, virtual spectrophotometry and strategies for reducing the number of samples required to obtain asymptotically convergent measurements.

At this point a brief section on applications of virtual spectrophotometry presented. This is followed by a careful formulation of virtual spectrophotometers. A virtual spectrophotometer, being a virtual device, is only described by its geometry. This geometry is sketched in Figure 1, where the spherical coordinate system is described by the coordinates  $\phi_i$  and  $\theta_i$ ,  $D$  is the distance between emitter and specimen and  $r_1$  and  $r_2$  are the radii of the emitter and the specimen.

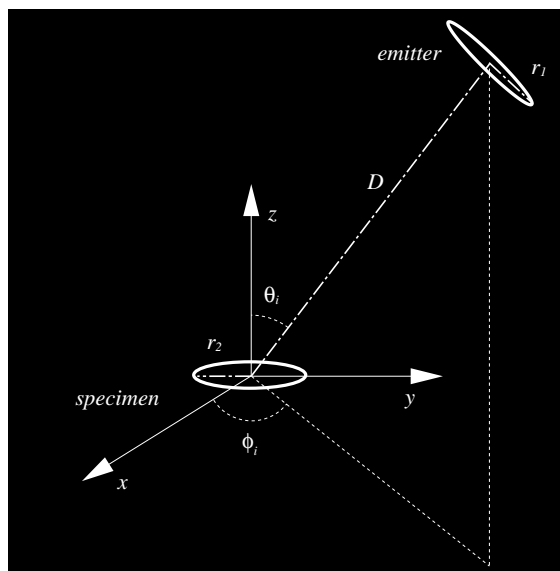


Figure 1. Sketch of a virtual spectrophotometer.

The virtual spectrophotometer is employed to make mea-

measurements of radiation coming from a specimen with rays being emitted to the specimen from an emitter. This means that both the origin of a ray on the emitter and the point of impact on a sample are random quantities suggesting a Monte Carlo approach.

Actual measurements of reflectance and transmittance are performed using spectrophotometers equipped with an integrating sphere which is usually used to measure the hemispherical reflectance factor, *i.e.*, a reflectance factor for a hemispherical reflected solid angle.

Similarly, virtual spectrophotometers are used to measure the hemispherical reflectance factor for a computer generated model. This enables control over the spectral data generation from computer models and allows us to perform experiments at different sampling resolutions, which are essential requirements for rendering applications.

Since virtual spectrophotometry is conducted using Monte Carlo evaluation, the number of samples required for convergence to within a region with a given error tolerance and confidence is of importance.

A ray density analysis is therefore performed to determine the least number of sample rays required to obtain estimates within the region of asymptotic convergence of the estimand with high confidence. This analysis is based on Bernoulli's theorem and Chebyshev's inequality resulting in an equation for the least number of sampling experiments required to obtain estimates with an error tolerance  $\epsilon$  and a confidence  $\delta$  as given by:

$$k_c = \left\lceil \frac{1}{4\epsilon^2\delta} \right\rceil \quad (1)$$

A second analysis is performed using the *exponential* Chebyshev inequality. Based on this inequality it is shown that the least number of sampling experiments need to obtain estimates with an error tolerance  $\epsilon$  and a confidence  $\delta$  is given by:

$$k_e = \left\lceil \frac{\ln(\frac{2}{\delta})}{2\epsilon^2} \right\rceil \quad (2)$$

It is shown that (2) gives better results than (1).

The bound on the number of sample rays derived from the *exponential* Chebyshev inequality can be written as:

$$N = \left\lceil \frac{\ln(\frac{2}{\delta})}{2\mu^2} \right\rceil \quad (3)$$

where  $\mu$  is the uncertainty of the virtual spectrophotometer modeling the uncertainty of a real spectrophotometer.

For spectrophotometric measurements aimed at rendering applications an accuracy of 1% is satisfactory, *i.e.*,  $\delta = 0.01$ . Also, according to data provided in the spectrophotometry literature [5, 6, 8], the absolute precision of actual spectrophotometers is around 0.995, which allows us to set  $\mu = 0.005$ . Applying the proposed bound, the

number of sample rays required under these conditions is

$$\boxed{N = 10^{5.02}} \text{ (or } \log N = 5.02\text{)}.$$

The paper now consider reflectance models with different levels of complexity to illustrate the use of the proposed bound (3) under different measurement conditions. The first model is a simulation of reflectance for dielectrics similar to a model by Shirley [7]. The second model is a wavelength dependent reflectance model simulating light propagation in foliar tissues. Two different sampling strategies, namely random and stratified sampling [7], are used for both the emitter and the specimen to increase the scope of observations.

Two sets of experiments were performed. In the first set the applicability of the model to evaluate reflectance models was tested. In the second experiment the suitability of the bound for data generation from previously validated models. An experimental procedure was set up.

The results of the experiments are presented in two sets.

In the first set the conical-hemispherical reflectance for the incident direction  $\phi_i = 0^\circ$  and  $\theta_i = 70^\circ$  in the spherical coordinate system. Graphs are provided showing that estimates stabilize when  $\log N \geq 5$ .

In the second set the directional-hemispherical reflectance is sampled in intervals of  $1^\circ$ . Graphs are provided showing that for directional-hemispherical reflectance curves obtained using the ray density given by the proposed bound (Equation (3)) present a high reliability/cost ratio.

In conclusion the paper states that the aim was to provide a better theoretical foundation for research required for biologically and physically based rendering applications.

## References

- [1] G. Baranoski, J. Rokne, and G. Xu. Virtual spectrophotometric measurements for biologically and physically-based rendering. *submitted for publication*, 2000.
- [2] E. Cashwell and C. Everett. *A Practical Manual on the Monte Carlo Method for Random Walk Problems*. Pergamont Press, New York, 1959.
- [3] A. Glassner. *Principles of Digital Image Synthesis*, volume 2. Morgan Kaufmann, San Francisco, 1995.
- [4] R. Hunter and R. Harold. *The Measurement of Appearance*. John Wiley & Sons, New York, second edition, 1987.
- [5] D. Judd and G. Wyszecki. *Color in Business, Science and Industry*. John Wiley & Sons, New York, third edition, 1975.
- [6] D. MacAdam. *Color Measurements Theme and Variations*. Springer Verlag, Berlin, 1981.
- [7] P. Shirley. *Physically based lighting for computer graphics*. PhD thesis, Dept. of Computer Science, University of Illinois, November 1990.
- [8] G. Zerlout and T. Anderson. Multiple-integrating sphere spectrophotometer for measuring absolute spectral reflectance and transmittance. *Applied Optics*, 20(21):3797–3804, November 1981.