Spectral method of color conversion filter thickness applied to simulation of CIE Illuminants

Paul Butterfield

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SPECTRAL METHOD OF COLOR CONVERSION FILTER THICKNESS DETERMINATION APPLIED TO SIMULATION OF CIE ILLUMINANTS

by

Paul M. Butterfield

A thesis submitted in partial fulfillment of the requirements of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology.

Signature of Author

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Imaging and Photographic Science

Certified by

Franc Grum

Thesis advisor

Name Illegible

Supervisor, Undergraduate Research
Permission Form

Title of Thesis: SPECTRAL METHOD OF COLOR CONVERSION FILTER THICKNESS APPLIED TO SIMULATION OF CIE ILLUMINANTS

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Signature of Author Paul M. Butterfield
Date July 13, 1984
ABSTRACT

A spectral method of determining color conversion filter thickness is described. This method uses spectral data from system parameters to determine thickness. Optimization of the input distribution by varying bulb current is discussed. Using the spectral method of thickness variation, two CIE Illuminants, D55 and D65 were simulated. The simulators were measured for goodness of fit and showed a strong similarity with their respective simulators. Mean square deviations were calculated for each Illuminant and were 11.09 and 11.33 for D55 and D65 respectively.
ACKNOWLEDGEMENTS

The author would like to express his appreciation for the assistance and guidance supplied by thesis advisor, Dr. Franc Grum.

Additionally, thanks are due to Mr. R. Mitchell Miller and Dr. Roy Berns.
DEDICATION

This thesis is dedicated to the author's parents, Mr. and Mrs. Marcius Butterfield.
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I. INTRODUCTION

It is common practice in industry for a high-color temperature source to be created by standardizing a tungsten-halogen source at a low color temperature and elevating the color temperature by use of a color temperature conversion filter. This practice allows the use of lower current and voltage levels creating cooler systems, fewer temperature hazards, and extended bulb life.

Conversion filters are manufactured in a number of different forms. The Eastman Kodak Company manufactures gelatin color conversion filters, specifically Wratten series 78 and 86. These filters convert color temperature only incrementally and are subject to fading. [1]

Davis-Gibson filters are liquid filters which are designed to convert sources approximating CIE Illuminant A to a series of sources of higher color temperatures. The filters are produced by preparing two specified chemical solutions and then combining these two solutions in varying proportions in a glass container to control the amount of color-temperature elevation. The disadvantages of the liquid filters are their lack of convenience and their low stability. [2]

At least two manufacturers, Corning Glass Works, Corning NY, and Jenaer Glaswerkschott & Gen., Mainz West Germany, make uniform blue glass filters designed
specifically for permanent source color temperature conversion. The thickness of the filters may be varied according to the degree of color temperature elevation desired.

The filter thickness required is normally determined by use of a simple formula supplied by the manufacturer. [3]

Equation 1

\[
(1/T_1) - (1/T_2) \times 10^{-6} = K \times t
\]

where:  
- \( T_1 \) is the effective color temperature of the original source.  
- \( T_2 \) is the effective color temperature of the filtered radiation.  
- \( t \) is the thickness of the filter in mm.  
- \( k \) is a constant, characteristic of the filter.

The manufacturer's equation is derived from Wien's equation, a simplified form of the Planckian relation of spectral radiant excitance to absolute temperature. Planck's equation is defined mathematically by Equation 2. [4]
Equation 2

\[ M(\lambda, T) = C_1 \left( \exp\left( \frac{C_2}{\lambda T} \right) - 1 \right)^{-1} \left( \exp\left( \frac{C_2}{\lambda T} \right) - 1 \right)^{-3} \ \text{W m} \]

where:

- \( C_1 \) and \( C_2 \) are radiation constants.

\[
C_1 = 3.74150 \times 10^{-16} \ \text{W m}^{2} \\
C_2 = 0.014388 \ \text{m K}
\]

- \( T \) is the absolute temperature of the blackbody in degrees kelvin.
- \( \lambda \) is the wavelength of the radiation.
- \( M \) is the spectral radiant excitance.

Wien's equation achieves a simplified form by assuming the value of \( \exp\left( \frac{C_2}{\lambda T} \right) \) is large compared with unity, thus the subtraction of unity is omitted. The result takes the form: [5]

Equation 3

\[
M' = C_1 \lambda^{-5} \exp\left( \frac{C_2}{\lambda T} \right) \ \text{W m}^{-3}
\]

The mechanism of the color conversion filter is an induced change in the red-blue ratio of a source. To increase color temperature, the red-blue ratio must be decreased. This is what is accomplished by the application of a blue filter to a low temperature tungsten-halogen source.
The spectral properties of the filter should be such that the chromaticity of the converted source remains near to or on the Planckian locus. As the chromaticities of converted sources move further away from the Planckian locus, as is the case with poor color conversion filters, they become less like Planckian approximates and more like colored sources. This is an important point, if color conversion filters were ideal and had linear spectral densities, a simplified equation would serve adequately to determine thickness. The fact that filtration is not ideal necessitates that spectral distributions be considered.

Important here is the distinction between the terms distribution temperature, color temperature, and correlated color temperature. All of the terms are related, and in varying degrees of strictness, all describe properties of a source with respect to a Planckian radiator at some absolute temperature.

Distribution temperature describes the absolute temperature of a Planckian blackbody whose spectral distribution curve is proportional to, or nearly proportional to the defined source in the visible region. In the case of distribution temperature, the source will necessarily have the same chromaticity as the Planckian radiation, since their distributions are everywhere proportional. Distribution temperature is the most restrictive and specific of the three terms. [6]
Color temperature describes the absolute temperature of the Planckian radiator whose chromaticity is the same as the chromaticity of the source. Since it is possible for sources to have the same chromaticity, but different distributions, the term color temperature is less restrictive than distribution temperature. [7]

Correlated color temperature describes the absolute temperature of the Planckian radiator whose chromaticity lies closest to the chromaticity of the defined source on the uniform chromaticity scale diagram. It may also be thought of as the absolute temperature of the Planckian radiator which most closely approximates it visually. The chromaticities of sources with correlated color temperatures lie off the Planckian locus and their correlated color temperatures are usually found by the use of isotemperature lines in either CIE x,y or CIE U,V space. Correlated color temperature is the least restrictive of the three terms.

Another approximate measure of color temperature is the red/blue ratio. This method uses the measured spectral power at 650 nm and 440 nm to indicate the slope of the spectral distribution and thus allow appropriate conclusions to be drawn about the correlated color temperature, color temperature, and distribution temperature. This method is useful for adjusting incandescent sources because the shape of their distributions is well characterized and thus valid assumptions may be made given only two points from their
spectral distribution. Since the method requires only two simple measurements, it is often used as a relative indicator when changing the current supplied to a source and correspondingly its color temperature.

The CIE Illuminants are numerical definitions of spectral power distributions designed to serve as standards in colorimetry. It is frequently necessary to obtain simulators of the CIE Illuminants, that is, to construct a real, physical light source whose spectral distribution is as close as possible to the numerical specification of spectral power distribution defined by the particular CIE Illuminant. To aid in the approximation of an Illuminant, a measure of goodness of fit must be adopted to provide some method, typically numerical, for evaluating the closeness of the simulated distribution to the defined distribution.

The concepts of least squares error and mean square deviation may be applied to spectral distributions since both concepts are mathematical methods of evaluating the degree similarity of one set of cartesian coordinates to another. Least squares error represents a sum of the differences between two sets of corresponding data after a constant is applied to minimize the sum. Least squares error has been used in previous works to evaluate distribution temperature. [8] It is defined mathematically in Equation 4.
Equation 4

\[ \text{Sum squared error} = \sum_{1}^{2} \left( 1 - \frac{S'(\lambda)}{a S(\lambda)} \right)^2 \]

where:  
1 is starting wavelength.  
2 is ending wavelength.  
\( S'(\lambda) \) is tested distribution.  
\( S(\lambda) \) is defined distribution.  
a is a constant to minimize the sum.

Mean square deviation also allows numerical analysis of similarity between distributions and has been used in the past to evaluate goodness of fit. [9] It is defined below.

Equation 5

\[ D = \left( \frac{1}{n} \right) \sum_{1}^{2} \left( S(\lambda) - F1 S'(\lambda) \right)^2 \]

\[ F1 = \frac{S'(\lambda)}{S(\lambda)} \left( \sum_{1}^{2} \frac{S'(\lambda)^2}{S(\lambda)^2} \right) \]

where:  
\( D \) is mean square deviation.  
\( F1 \) is scaling factor.  
\( n \) is number of data points.
II. EXPERIMENTAL

A. Preparation of Supporting Software

A series of computer programs was developed to allow the manipulation of spectral data necessary to support spectral thickness determination routines. Programming was done on an Apple IIe microcomputer in Applesoft (a proprietary "basic" language). Spectral data was treated in array fashion, such that a spectral distribution of 380 to 700 nm sampled a 5 nm increments would occupy an array of 64 elements.

Programs were written to perform mathematical operations on two spectral distributions, and to allow distributions to be operated upon with a constant. A plotting program was written to allow up to seven distributions to be plotted on a single axis. A program to calculate chromaticities for either the 2-degree or 10-degree observer with any illuminant was written. Programming was written to generate Planckian blackbody distributions for the range of useful absolute temperatures. In addition, programs were written to correct disparate distribution scaling, match wavelength increments, and normalize distributions. To determine the goodness of fit, a program was written to calculate the mean square deviation
between two sets of spectral data. These programs were integrated into a menu-type format to allow them to be used as a single package. (see Appendix A for listings of the computer programs.)

B. Spectral Thickness Determination Software

A computer program to determine the required filter thickness for specific color temperature conversion was written. The program was designed to determine the required filter thickness on the basis of spectral data of system components. The following four parameters were input to the computer program:
1. The initial distribution of a low-color temperature source.
2. The spectral transmittance of the nominal color conversion filter thickness.
3. The nominal color conversion filter thickness.
4. The desired high-color temperature spectral power distribution.

The mechanism of thickness determination was based upon a least squares fit of distributions.

Routines within the program were written to calculate the spectral transmittance per unit thickness of the color conversion filter. Programming was effected to allow the spectral transmittance per specified thickness to be
calculated internally each time the routine was executed in order to minimize calculation and rounding error. The surface reflection of each air-glass interface was mathematically subtracted before determining a fractional thickness, then mathematically replaced to avoid the introduction of error.

Filter thickness was determined by changing filter thickness such that the least squares error between the initial distribution filtered by a given filter thickness and the desired distribution were minimized. Program flow followed these steps:

1. Determine the product of the initial spectral power distribution and the nominal filter thickness to obtain the distribution of a filtered source.

2. Calculate the least squares error between the filtered source and the desired spectral power distribution.

3. Mathematically increment the thickness of the filter and determine the product of the new thickness and the initial spectral power distribution to obtain a new filtered source.

4. Calculate the least squares error between the new filtered source and the desired spectral power distribution.
5. Repeatedly increment filter thickness, determine a new filtered source, and calculate least squares error, changing the thickness to move toward minimum least squares error.

6. When thickness has been determined within the precision of measurement, then record the thickness specified and grind filter. (see Appendix B for a listing of the computer program.)

C. Construction and Measurement of Apparatus

To determine the practical application of the algorithm, a lamp assembly was constructed to hold a standardized source and filter. A quartz tungsten-halogen source rated at 1000 watts was clamped into a mounting support. The assembly was fitted for optical bench mounting to facilitate later measurements. A 0-120-Volt variable transformer was used to supply current to the source. The voltage supplied to the bulb was regulated by a 3.5 digit-precision digital volt meter which measured the voltage drop across a precision 1.00 amp resistor to determine the current drawn by the source. The source was characterized by measurement with the Munsell Laboratory's spectroradiometer. (see Appendix C)

A range of voltages was selected to yield color temperatures from 2700K to 3200K by use of the red/blue
ratio at 650 nm and 440 nm. Measurements were made at 5 nm increments from 380 to 700 nm over the range of voltages. These data were transferred to the Munsell Color Laboratory computer which converted the data to absolute units and allows extensive manipulation of the data. Using this software, a series of plots and tables were generated which display the change in distribution with voltage. These spectral power distributions served as the low color temperature source for conversion to the daylight illuminants.

A color conversion filter of unit thickness was obtained and measured for both spectral transmittance and physical thickness. Spectral transmittance was measured with the Diano Hardy spectrophotometer in the Munsell Color Laboratory. The unit uses a double-beam, dual-monochromometer system and has a constant bandpass of 1 nm. Data was sampled using a computer at 5 nm increments. Physical thickness was measured on each of the filter's four corners with a Starret constant-tension-ratchet micrometer. Thickness was specified in fractions of an inch coincident with the micrometer. Conversion to metric units was made later. The precision of the micrometer was 0.00025 cm. The measured spectral transmittance and the physical thickness of the filter were used as input to the spectral thickness determination program.
D. Determination of Filter Thicknesses for D55 and D65

Under ordinary circumstances, the measured spectral power distributions of the lamp would be used as the input to the spectral thickness routine as the low-color temperature distribution. Planckian radiators were substituted in this research since they correlate highly with low temperature tungsten sources and are easier to manipulate. Also input to the program were the spectral transmittance of the color conversion filter of unit thickness, the filter’s measured unit thickness, and the desired output distribution. Both D55 and D65 were used as desired output distributions.

To further improve the fit of the distributions, the temperature of the input low temperature blackbody was varied and the thickness for each temperature was calculated. A combination of resultant least squares error values, chromaticity coordinates, and visual goodness of fit was used to select the best low temperature input. The thicknesses specified were shipped to an optics firm for grinding and polishing.

E. Test of Method

Ground filters were placed on the lamp housing with the lamp operating at the correct low color temperature. Measurements were made of the filtered spectral power
distribution and compared to the corresponding daylight illuminants. Comparisons were made with respect to closeness of chromaticities as well as closeness of distributions. Supplemental correction filters were applied in an attempt to better the degree of Illuminant simulation. In addition, the goodness of fit of the modeled filtration using the computer was checked to determine its validity in application to the problem.
III. RESULTS

A. Spectral Thickness Determination

A method of spectral thickness determination was developed to allow selection of optimum filter thickness to achieve a specific resultant spectral distribution. The following table illustrates the thicknesses chosen to optimize goodness of fit for the two illuminants simulated.

Table 1

Filter thickness shown in relation to input and desired output.

<table>
<thead>
<tr>
<th>Distribution of input source</th>
<th>Calculated Temperature of input source</th>
<th>CIE Illuminant</th>
<th>Filter thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>2700 K</td>
<td>I I Illuminant D55</td>
<td>I</td>
<td>.5740 cm</td>
</tr>
<tr>
<td>2950 K</td>
<td>I I Illuminant D65</td>
<td>I</td>
<td>.5692 cm</td>
</tr>
</tbody>
</table>
B. Simulation of CIE Illuminants D55 and D65

Upon calculation of filter thickness, the spectral distribution of the input source attenuated by the given thickness was mathematically predicted. The filters were then ground, and the physical results were measured. The following six tables represent the spectral distribution of each of the two simulated illuminants, their computer predicted simulators, and the physically realized simulators. Following the tables are two graphs which present the same results graphically.
**TABLE 2**

Spectral Distribution of CIE Illuminant D55

<table>
<thead>
<tr>
<th>CIE Illuminant D55</th>
<th>535 nm --&gt; 103.16</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 nm --&gt; 32.58</td>
<td>540 nm --&gt; 102.1</td>
</tr>
<tr>
<td>385 nm --&gt; 35.34</td>
<td>545 nm --&gt; 102.53</td>
</tr>
<tr>
<td>390 nm --&gt; 38.09</td>
<td>550 nm --&gt; 102.97</td>
</tr>
<tr>
<td>395 nm --&gt; 49.52</td>
<td>555 nm --&gt; 101.48</td>
</tr>
<tr>
<td>400 nm --&gt; 60.95</td>
<td>560 nm --&gt; 180.68</td>
</tr>
<tr>
<td>405 nm --&gt; 64.75</td>
<td>565 nm --&gt; 98.61</td>
</tr>
<tr>
<td>410 nm --&gt; 68.55</td>
<td>570 nm --&gt; 97.22</td>
</tr>
<tr>
<td>415 nm --&gt; 70.07</td>
<td>575 nm --&gt; 97.48</td>
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<tr>
<td>420 nm --&gt; 71.58</td>
<td>580 nm --&gt; 97.75</td>
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<tr>
<td>425 nm --&gt; 69.75</td>
<td>585 nm --&gt; 94.59</td>
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<tr>
<td>430 nm --&gt; 67.91</td>
<td>590 nm --&gt; 91.43</td>
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<tr>
<td>435 nm --&gt; 76.76</td>
<td>595 nm --&gt; 92.93</td>
</tr>
<tr>
<td>440 nm --&gt; 85.61</td>
<td>600 nm --&gt; 94.42</td>
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<tr>
<td>445 nm --&gt; 91</td>
<td>605 nm --&gt; 94.78</td>
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<tr>
<td>450 nm --&gt; 97.99</td>
<td>610 nm --&gt; 95.14</td>
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<tr>
<td>455 nm --&gt; 99.23</td>
<td>615 nm --&gt; 94.68</td>
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<td>460 nm --&gt; 100.46</td>
<td>620 nm --&gt; 94.22</td>
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<td>465 nm --&gt; 100.19</td>
<td>625 nm --&gt; 92.33</td>
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<tr>
<td>470 nm --&gt; 99.91</td>
<td>630 nm --&gt; 90.45</td>
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<tr>
<td>475 nm --&gt; 101.33</td>
<td>635 nm --&gt; 91.39</td>
</tr>
<tr>
<td>480 nm --&gt; 102.74</td>
<td>640 nm --&gt; 92.33</td>
</tr>
<tr>
<td>485 nm --&gt; 100.41</td>
<td>645 nm --&gt; 90.59</td>
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<td>490 nm --&gt; 98.08</td>
<td>650 nm --&gt; 88.85</td>
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<td>655 nm --&gt; 89.59</td>
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<td>680 nm --&gt; 89.96</td>
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<td>525 nm --&gt; 102.1</td>
<td>685 nm --&gt; 84.82</td>
</tr>
<tr>
<td>530 nm --&gt; 104.21</td>
<td>690 nm --&gt; 79.68</td>
</tr>
</tbody>
</table>
**TABLE 3**

Spectral Distribution of Computer Predicted D55 Simulator

<table>
<thead>
<tr>
<th>Computer Predicted D55 Simulator</th>
<th>535 nm --&gt; 84.5286867</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 nm --&gt; 37.3844798</td>
<td>540 nm --&gt; 84.4125092</td>
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<td>385 nm --&gt; 40.662757</td>
<td>545 nm --&gt; 85.4821269</td>
</tr>
<tr>
<td>390 nm --&gt; 40.1116284</td>
<td>550 nm --&gt; 88.4854757</td>
</tr>
<tr>
<td>395 nm --&gt; 51.5199345</td>
<td>555 nm --&gt; 94.0658664</td>
</tr>
<tr>
<td>400 nm --&gt; 55.6201258</td>
<td>560 nm --&gt; 100</td>
</tr>
<tr>
<td>405 nm --&gt; 61.5316755</td>
<td>565 nm --&gt; 105.245819</td>
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<tr>
<td>410 nm --&gt; 67.1196163</td>
<td>570 nm --&gt; 106.49592</td>
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<td>415 nm --&gt; 70.326896</td>
<td>575 nm --&gt; 105.948642</td>
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<td>420 nm --&gt; 73.614617</td>
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Spectral Distribution of Realized D55 Simulator

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### Table 7

**Spectral Distribution of Realized D65 Simulator**

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Relative spectral characteristics of CIE Illuminant D55 and a computer predicted and realized simulator.

Figure 1. Relative spectral power

- Blue: CIE Illuminant D55
- Green: Predicted simulator
- Red: Realized simulator

wavelength (nm)
Figure 2.

Relative spectral characteristics of CIE Illuminant D65 and a computer predicted and realized simulator.
CIE 1960 u,v chromaticity diagram

---

Dotted line is daylight locus.
Solid line is blackbody locus.

Figure 3

UCS Chromaticities of CIE Illuminants and Predicted and Realized Simulators
The first order test of the goodness of a simulator is a plot of the chromaticities of the simulator with those of the Illuminant. Figure 3 is a plot of the two illuminants simulated, CIE Illuminants D55 and D65 in Uniform Color Space (UCS). Plotted next to each illuminant are the predicted simulators and the realized simulators. A square around each of the Illuminants represents the first order limit for chromaticities of each simulator. The allowable range for both the $u$ and $v$ coordinates is $\pm 0.0225$. [11] Table 9 contains the tabularized chromaticities which compose the plot.

Table 8

UCS Chromaticities of CIE Illuminants and Computer Predicted and Realized Simulators

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</tr>
<tr>
<td>Computer Predicted D65 Simulator</td>
<td>0.2339</td>
<td>0.3075</td>
</tr>
<tr>
<td>Realized D65 Simulator</td>
<td>0.2350</td>
<td>0.3095</td>
</tr>
<tr>
<td>Realized D65 Simulator with CC05G</td>
<td>0.2324</td>
<td>0.4695</td>
</tr>
</tbody>
</table>
The degree of similarity between the spectral results achieved was calculated using mean square deviation. Comparisons were made between each CIE Illuminant and its predicted and realized simulator. Comparisons were also made between the predicted simulators and the realized simulators, to assess the validity of the prediction.

Table 9

Mean Square Deviation between Spectral Distributions for CIE Illuminant D55.

<table>
<thead>
<tr>
<th>Mean Square Deviation between:</th>
<th>Value:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illuminant D55 and Computer Predicted Simulator</td>
<td>12.57</td>
</tr>
<tr>
<td>Illuminant D55 and Realized Simulator</td>
<td>11.09</td>
</tr>
<tr>
<td>Computer Predicted Simulator and Realized Simulator</td>
<td>4.76</td>
</tr>
</tbody>
</table>
Table 10

Mean Square Deviation between Spectral Distributions for CIE Illuminant D65.

<table>
<thead>
<tr>
<th>Mean Square Deviation between:</th>
<th>Value:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illuminant D65 and Computer Predicted Simulator</td>
<td>10.71</td>
</tr>
<tr>
<td>Illuminant D65 and Realized Simulator</td>
<td>11.33</td>
</tr>
<tr>
<td>Computer Predicted Simulator and Realized Simulator</td>
<td>3.59</td>
</tr>
</tbody>
</table>
IV. DISCUSSION

The initial selection of the source for the low-color temperature input was a 10-Watt tungsten-halogen bulb. Although this source fitted the spectral profile desired for the system, its power output was not adequate. The response of the Munsell Color Laboratory spectroradiometer was not constant with a change in the decade scale of the spectroradiometer's ammeter. To solve the problem, a General Electric 1000-Watt tungsten-halogen bulb was used. The spectral power distribution was still of the correct profile, and the increased power resultant allowed for excellent spectroradiometer constancy. No perceptable fluctuations appeared as a result of ammeter decade changes.

Planck's equation was used to generate low-color temperature distributions to be input to thickness determination routines. This method was chosen instead of making a series of measurements of the tungsten-halogen source supplied with incremented current values. This was not only more convenient than successive measurements but preserved the tungsten filament and allowed a spectral input free of measurement irregularities. If measured spectral data were used as input, any irregularities in measurement would be reflected as irregularities in the thickness of filter chosen.
The use of Planck’s Equation was followed by a characterization of the tungsten-halogen source. By varying the current supplied to the source, the shape of the tungsten-halogen source could be changed to fit the shape of the Planckian distribution. This method worked extremely well for the low color temperatures needed for input.

Within the spectral thickness determination routine is the subtraction of surface reflection. Since the filter when ground to any thickness still has two surfaces, each with some surface reflection, some non-linearity could exist in the system. The problem is seemingly complicated by the fact that the surface reflection from the second air-glass interface is also a function of the spectral transmittance of the filter. After determining the amount of change induced by the spectral transmittance of the filter, it was determined that the surface reflection could be subtracted out by removing 8% of the transmittance before applying a factor to the filter thickness, and later replacing the 8% to predict the resultant filtered distribution. The error induced by this small assumption was unmeasurable and had no effect on either thickness specification nor prediction of output distribution.

The spectral method for determining the color conversion filter thickness was applied to simulation of CIE Daylight Illuminants D55 and D65. The CIE (Commission Internationale de l’Eclairage) defines several Illuminants,
but the Illuminants D55 and D65 were used for this work since they are within the useful working range of the color conversion filter and are commonly used Illuminants in the laboratory. The same methods used in this thesis could be applied to any CIE Illuminant with appropriate filtration and light source.

Additional filtration was added to the final simulators D55 and D65 in an attempt to improve the degree of goodness of fit. Since the simulators lie on the blackbody locus they require a light green filter to cause their chromaticity to shift slightly and lie on the daylight locus. This may be seen clearly in Figure 3. A color correction filter, Eastman Kodak designation CC05G was applied to each simulator and the resulting chromaticities calculated. The values are given in Table 3. The amount of conversion resulting from the application of the filter was much too great and resulted in a shift across the daylight locus to result in a poorer simulator. In order to realize better simulators, a lighter green filter must be selected. The spectral transmittances of the ideal filters may be computed using spectral division of the Illuminant by the simulator if the additional filtration is deemed necessary.
V. CONCLUSIONS

The devised method of spectral determination of color conversion filter thickness is effective. It requires the following three input parameters:
1. The spectral distribution of a low-color temperature source.
2. The spectral transmittance of the filter at unit thickness.
3. The spectral power distribution of the desired illuminant.

Using only these parameters, the spectral method will allow specification of the correct filter thickness. It will also predict the distribution which will result from applying that thickness to the low-temperature tungsten source.

The precision of the prediction of the spectral distribution is as good as the precision of the input information. No assumptions are made regarding the linearity of the filter's spectral transmittance as is done with the simplified equations currently recommended for color conversion filter thickness determination.

The method may be used to allow simulation of any desired distribution. The same three input parameters are required in all cases. The ability of an input distribution and a single filter to approximate some output is dependent
upon the shapes of each input distribution. The simulators created to model the CIE Illuminants D55 and D65 for this thesis showed acceptable goodness of fit for Illuminant simulators. This is due to the fact that each simulator was the result of only one input distribution and one filter of some given thickness.

The spectral method has limitations because it allows optimization of only one system parameter, thickness, while all other parameters must remain constant. This limitation leaves room for further work. Programming could be written which would allow simultaneous optimization of several parameters to simulate a distribution. This would allow simulation of a distribution using multiple filters and variation of the electrical current supplied to the source.
VI. REFERENCES


VII. APPENDIX A

Listings of Supporting Software

Menu program and file display and correction program

100 HIMEM: 38400
110 DIM VIEW(100); DIM A(100): DIM B(100)
120 D$ = CHR$(4): O$ = D$ + "OPEN": R$ = D$ + "READ": W$ = D$ + "WRITE": C$ = D$ + "CLOSE": V$ = D$ + "VERIFY"
130 PRINT D$; "PRH3"
140 TEXT: HOME
150 ANS$ = ""
160 PRINT "INPUT DESIRED FUNCTION"
170 PRINT : PRINT "E DATA ENTRY"
180 PRINT "V VIEW AND CORRECT DATA"
190 PRINT "P PLOT CURVES"
195 PRINT "Z PLOT TO PRESENT"
200 PRINT "M MATHEMATICAL CURVES OPERATIONS"
210 PRINT "K CONSTANT OPERATIONS ON CURVES"
220 PRINT "S SPECTRAL THICKNESS DETERMINATION"
225 PRINT "A AUTOMATIC SPECTRAL THICKNESS DETERMINATION"
226 PRINT "D DEVIATION, MEAN-SQUARE"
230 PRINT "T DISTRIBUTION TEMPERATURE"
240 PRINT "B PLANCKIAN BLACKBODY CURVES"
245 PRINT "C CALCULATE CHROMATICITY"
250 PRINT "N NORMALIZE SPECTRAL DISTRIBUTION"
260 PRINT "F SMOOTH DATA"
270 PRINT "G CONVERT: TRANS & DENSITY"
280 PRINT "W CORRECT WAVELENGTH SCALING"
290 PRINT "Q LOG SPECTRAL POWER DISTRIBUTION"
300 PRINT "? CATALOG"
310 PRINT "L LIST"
320 PRINT "Q QUIT"
330 GET ANS$...
340 PRINT
410 T = HW: INPUT HW: IF T < > HW THEN END
420 T = WI: INPUT WI: IF T < > WI THEN END
430 FOR ARG = 1 TO PTS
440 INPUT CRT(ARG)
450 NEXT ARG
460 PRINT C$;CRT$
470 VTAB 6: PRINT "CORNING FILE: ";CRT$;" HAS BEEN INPUT."
480 STHICK = .2294
490 VTAB 8: PRINT "INPUT FILNAME FOR CIE DISTRIBUTION COMPARATOR"
500 INPUT "[Q TO QUIT, C TO CATALOG]: ";CIE$
510 IF CIE$ = "Q" THEN PRINT D$;"RUN SPECTRAL"
520 IF CIE$ = "C" THEN GOSUB 890: GOTO 310
530 PRINT V$;CIE$
540 PRINT O$;CIE$
550 PRINT R$;CIE$
560 T = PTS: INPUT PTS: IF T < > PTS THEN END
570 T = LW: INPUT LW: IF T < > LW THEN END
580 T = HW: INPUT HW: IF T < > HW THEN END
590 T = WI: INPUT WI: IF T < > WI THEN END
600 FOR ARG = 1 TO PTS
610 INPUT CIE(ARG)
620 NEXT ARG
630 PRINT C$;CIE$
640 VTAB 9: PRINT "CIE FILE: ";CIE$;" HAS BEEN INPUT."
650 THICK = STHICK: INC = -.05
660 GOSUB 940
670 GOSUB 900
680 GOSUB 950
690 GOSUB 960
700 PRINT "THICKNESS= ";THICK;" IN.": POKE 36,30: PRINT "LEAST SQUARES ERROR= ";LSE
710 GOSUB 1000: REM AUTO THICKNESS ROUTINE
720 OLD = LSE
730 GOTO 730
740 END : REM

****** SUBROUTINES ******
890 PRINT D$;"CATALOG": PRINT "HIT ANY KEY TO CONTINUE"; GET A$: RETURN
900 REM NORMALIZATION OF FSOURCE AND CIE TO 100 AT 560
910 W560 = (560 - LW) / WI
920 T1 = FSOURCE(W560): T2 = CIE(W560)
930 FOR ARG = 1 TO PTS: FSOURCE(ARG) = FSOURCE(ARG) * 100 / T1
940 FOR ARG = 1 TO PTS: SOURCE(ARG) = SOURCE(ARG) * 10 ^ (.4 * 34294 * LOG (CRT(ARG) * .01)) * (THICK / STHICK))
950 NEXT : RETURN
350 IF ANS$ = "M" THEN PRINT D$;"RUN OPERATE"
360 IF ANS$ = "K" THEN PRINT D$;"RUN CONSTANT"
370 IF ANS$ = "Q" THEN END
380 IF ANS$ = "V" THEN 950
389 IF ANS$ = "P" THEN PRINT D$;"RUN PLOTTER"
390 IF ANS$ = "Z" THEN PRINT D$;"RUN PLOT2PRESENT"
395 IF ANS$ = "D" THEN PRINT D$;"RUN MEAN"
400 IF ANS$ = "L" THEN LIST : END
410 IF ANS$ = "?" THEN PRINT D$;"CATALOG": PRINT "CONTINUE [C]": GET A$: PRINT : IF A$ = "C" THEN PRINT D$;"RUN SPECTRAL"
420 IF ANS$ = "B" THEN PRINT D$;"RUN BBODY"
430 IF ANS$ = "S" THEN PRINT D$;"RUN THICK"
435 IF ANS$ = "A" THEN PRINT D$;"RUN AUTO THICK"
440 IF ANS$ = "N" THEN PRINT D$;"RUN NORM"
450 IF ANS$ = "F" THEN PRINT D$;"RUN SMOOTH"
460 IF ANS$ = "H" THEN PRINT D$;"RUN SCALE"
465 IF ANS$ = "C" THEN PRINT D$;"RUN CHROMA"
470 IF ANS$ = "G" THEN PRINT D$;"RUN DENS"I"
480 IF ANS$ = "O" THEN PRINT D$;"RUN LOG"
490 IF ANS$ = "E" THEN 520
500 IF ANS$ = "H" THEN HOME : GET G$
510 GOTO 120
520 REM DATA ENTRY
530 HOME
540 PRINT "IS A WAVELENGTH RANGE FROM 380 TO 780 NM ACCEPTABLE?"
550 LOWAV = 380:HIWAV = 780
560 GET ANS$
570 IF ANS$ < > "N" THEN 600
580 INPUT "LOW WAVELENGTH: ";LOWAV
590 INPUT "HIGH WAVELENGTH: ";HIWAV
600 PRINT "IS A WAVELENGTH INCREMENT OF 5 NM ACCEPTABLE?"
610 WAVI = 5
620 GET ANS$
630 IF ANS$ < > "N" THEN 650
640 INPUT "WAVELENGTH INCREMENT: ";WAVI
650 PTS = (HIWAV - LOWAV) / WAVI + 1
660 IF PTS = INT (PTS) THEN 700
670 HOME
680 PRINT "PLEASE PICK WAVELENGTHS AND INCREMENTS WHICH "
690 PRINT "ARE EVENLY DIVISIBLE": GOTO 540
700 PRINT "COMMENCE DATA ENTRY": PRINT
710 FOR ARG = 1 TO PTS
720 W = LOWAV + (WAVI * (ARG - 1))
PRINT "WAVELENGTH = ";W;
INPUT "     RAD. EXCIT. = ";A(ARG)
NEXT ARG
HOME
PRINT "DATA ENTRY IS COMPLETE."
PRINT : PRINT
INPUT "INPUT DATA FILE NAME [Q TO QUIT]: ";FILNAM$
IF FILNAM$ = "Q" THEN 140
PRINT D$;FILNAM$
PRINT W$;FILNAM$
PRINT PTS
PRINT LOWAV
PRINT HIWAV
PRINT WAVI
FOR ARG = 1 TO PTS
PRINT A(ARG)
NEXT ARG
PRINT C$;FILNAM$
HOME : PRINT "DATA HAS NOW BEEN SAVED"
PRINT "UNDER FILENAME: ";FILNAM$
FOR T = 1 TO 800: NEXT T
GOTO 140
REM VIEW DATA
HOME : PRINT "PLEASE INPUT THE NAME OF THE DATA FILE"
PRINT "THAT YOU WISH TO VIEW"
PRINT "[C TO CATALOG]"
INPUT "[Q TO QUIT]";FILNAM$
IF FILNAM$ = "C" THEN PRINT D$;"CATALOG": PRINT "HIT AN Y KEY": GET A$: GOTO 960
IF FILNAM$ = "Q" THEN 140
PRINT V$;FILNAM$
PRINT O$;FILNAM$
PRINT R$;FILNAM$
INPUT PTS
INPUT LOWAV
INPUT HIWAV
INPUT WAVI
FOR ARG = 1 TO PTS
INPUT VIEW(ARG)
NEXT ARG
PRINT C$;FILNAM$
HOME
PRINT "FILENAME: ";FILNAM$: PRINT
PRINT "THE FILE CONTAINS ";PTS;" DATA POINTS."
PRINT "THE WAVELENGTH RANGE IS:" 
PRINT LOWAV;" TO ";HIWAV;" NM," 
PRINT "IN INCREMENTS OF ";WAVI;" NM."
FOR ER = 1 TO 2000: NEXT ER
FOR ARG = 1 TO PTS
W = LOWAV + (WAVI * (ARG - 1))
1210 PRINT "WAVELENGTH=";W;"nm"
1220 PRINT "OUTPUT=";VIEW(ARG)
1230 NEXT ARG
1240 IF ANS$ = "P" THEN PR# 0
1250 PRINT : PRINT "WANT TO SEE THAT AGAIN??"
1260 PRINT "[Y FOR SCREEN] [P FOR PRINTER]"
1270 PRINT "CONTROL-S TO STOP AND START"
1280 GET ANS$
1290 IF ANS$ = "Y" THEN 1120
1300 IF ANS$ = "P" THEN PR# 1: PRINT CHR$ (9); "80N": GOTO 1
1310 PRINT "DO YOU WISH TO CORRECT ANY OF"
1320 PRINT "THESE DATA??"
1330 GET ANS$
1340 IF ANS$ = "N" THEN 140
1350 REM CORRECT DATA LISTING
1360 HOME
1370 PRINT "DATA CORRECTION"
1380 PRINT "YOU MAY CHANGE THE VALUE OF RADIANT"
1390 PRINT "EXCITANCE FOR ANY WAVELENGTH VALUE"
1400 INPUT "PLEASE INPUT THE WAVELENGTH: ";W
1410 IF W < LOWAV OR W > HIWAV THEN 1400
1420 ARG = ((W - LOWAV) / WAVI) + 1
1430 PRINT "WAVELENGTH = ";W;
1440 INPUT " RAD. EXCIT. = ";VIEW(ARG)
1450 PRINT "ANOTHER CORRECTION??"
1460 GET ANS$
1470 IF ANS$ = "Y" THEN 1400
1480 HOME
1490 PRINT "PLEASE INPUT THE FILE NAME"
1500 INPUT "[ Q TO QUIT ] ";FILNAM$
1510 IF FILNAM$ = "Q" THEN 140
1520 PRINT C$;FILNAM$
1530 PRINT W$;FILNAM$
1540 PRINT PTS
1550 PRINT LOWAV
1560 PRINT HIWAV
1570 PRINT WAVI
1580 FOR ARG = 1 TO PTS
1590 PRINT VIEW(ARG)
1600 NEXT ARG
1610 PRINT C$;FILNAM$
1620 GOTO 140
Plotting program with hardcopy graphics dump

2 HIMEM: 8192: CLEAR :D$ = CHR$ (4)
4 DIM A(7,95): DIM PTS(7): DIM LOWAV(7): DIM HIWAV(7): DIM WAVI(7): DIM FL$(7)
6 HOME : PRINT "NUMBER OF FILES TO BE PLOTTED:" : PRINT "INPUT 8 FOR CATALOG"
8 PRINT "INPUT 0 TO QUIT " : GET T : PRINT
10 IF T > 7 THEN PRINT D$:"CATALOG": PRINT "HIT ANY KEY": GET A$ : GOTO 6
12 IF T = 0 THEN PRINT D$:"RUN SPECTRAL"
14 HOME : PRINT "ENTER NAMES OF THE ";T; "FILES TO BE PLOTTED"
16 FOR I = 1 TO T
18 PRINT "FILE # ";I; : INPUT " = " ;FL$(I)
20 NEXT I
22 FOR I = 1 TO T
23 PRINT D$:"VERIFY" ;FL$(I)
24 PRINT D$:"OPEN" ;FL$(I)
26 PRINT D$:"READ" ;FL$(I)
28 INPUT PTS(I); INPUT LOWAV(I); INPUT HIWAV(I); INPUT WAVI(I)
30 FOR ARG = 1 TO PTS(I)
32 INPUT A(I,ARG)
34 IF MAX < A(I,ARG) THEN MAX = A(I,ARG)
36 NEXT ARG
38 PRINT D$:"CLOSE" ;FL$(I)
40 NEXT I
42 IF T = 1 THEN 64
44 FOR I = 2 TO T
46 IF PTS(I - 1) = PTS(I) AND LOWAV(I - 1) = LOWAV(I) AND HIWAV(I - 1) = HIWAV(I) THEN 60
48 NG = 1
50 PRINT "FILES ";I - I; " AND ";I; " HAVE:"
52 IF PTS(I - 1) < > PTS(I) THEN PRINT "UNEQUAL # OF POINTS"
54 IF LOWAV(I - 1) < > LOWAV(I) THEN PRINT "UNEQUAL LOW WAVELENGTHS"
56 IF HIWAV(I - 1) < > HIWAV(I) THEN PRINT "UNEQUAL HIGH WAVELENGTHS"
58 IF WAVI(I - 1) < > WAVI(I) THEN PRINT "UNEQUAL WAVELENGTH INCS."
60 PRINT : NEXT I
62 IF NG = 1 THEN PRINT "RETURNING TO MENU" : PRINT D$;"RUN SPECTRAL"
64 PRINT : PRINT "SCALE GRAPH TO WHAT 'Y' VALUE?"
66 PRINT "MAXIMUM Y VALUE IS ";MAX : PRINT "IS THIS OK?": GET A$
41

IF A$ < > "N" THEN 72
70 INPUT "NEW VALUE: "; MAX
72 HGR
74 HPLT 0,5 TO 0,159: HPLT 0,159 TO 279,159
76 FOR I = 1 TO T
78 FOR ARG = 1 TO PTS(1)
80 HPLT INT ((279 / PTS(1)) * ARG), INT (159 - (A(I, ARG) * 159 / MAX))
82 NEXT ARG
84 NEXT I
86 UTAB (22): PRINT "HARDCOPY OUTPUT? [Y/N]"; GET ANS$: IF A$ < > "N" THEN 90
88 PRINT : PRINT D$; "RUN SPECTRAL"
90 HIMEM: 38400: PR# 1: PRINT CHR$ (27); CHR$ (102): FOR S = 1 TO 5: PRINT CHR$ (10): NEXT S
92 PRINT CHR$ (9); "GD"
94 PRINT CHR$ (27); CHR$ (114): FOR S = 1 TO 3: PRINT CHR$ (10): NEXT S: PRINT CHR$ (27); CHR$ (102)
96 PRINT " 0"
98 PRINT " ;LOWAV(1); PRINT "; Wave
length in nm"; POKE 36,72: PRINT HIWAV(1)
100 PRINT CHR$ (27); CHR$ (114): FOR S = 1 TO 14: PRINT CHR$ (10): NEXT S: PRINT CHR$ (27); CHR$ (102)
102 PRINT " MAX"
104 FOR S = 1 TO 14: PRINT CHR$ (10): NEXT S
106 FOR I = 1 TO T
108 POKE 36,20: PRINT "FILE "; I; = " ;FL$(I)
110 NEXT I
112 POKE 36,20: PRINT "WAVELENGTH RANGE: "; LOWAV(1); TO "; HI
WAV(1); "; nm"
114 POKE 36,20: PRINT "WAVELENGTH INCREMENT: "; WAU(1); " nm"
116 FOR S = 1 TO 11: PRINT CHR$ (10): NEXT S: PR# 0
118 PR# 6
Mathematical file operation program

100 DIM A(100): DIM B(100): DIM P(100)
110 D$ = CHR$ (4)
120 HOME : PRINT : PRINT "PLEASE INPUT FILENAMES OF FILES"
130 PRINT " TO BE OPERATED ON [Q TO QUIT]: "; INPUT "FILE 1: "; WUN$
140 IF WUN$ = "Q" THEN PRINT D$; "RUN SPECTRAL"
150 INPUT "FILE 2: "; TWO$
160 PRINT "PLEASE INPUT OPERATION [M,D,A,S]: ";
170 GET OPERA$
180 IF OPERA$ = "M" THEN PRINT : PRINT "MULTIPLICATION": GOTO 240
190 IF OPERA$ = "D" THEN PRINT : PRINT "DIVISION": GOTO 240
200 IF OPERA$ = "A" THEN PRINT : PRINT "ADDITION": GOTO 240
210 IF OPERA$ = "S" THEN PRINT : PRINT "SUBTRACTION": GOTO 240
220 IF OPERA$ = CHR$ (3) THEN END
230 VTAB 8: GOTO 170
240 PRINT D$ "OPEN"; WUN$
250 PRINT D$ "READ"; WUN$
260 INPUT PW
270 INPUT LW
280 INPUT HW
290 INPUT WW
300 FOR ARG = 1 TO PW
310 INPUT A(ARG)
320 NEXT ARG
330 PRINT D$ "CLOSE"; WUN$
340 PRINT D$ "OPEN"; TWO$
350 PRINT D$ "READ"; TWO$
360 INPUT PT
370 INPUT LT
380 INPUT HT
390 INPUT WT
400 FOR ARG = 1 TO PW
410 INPUT B(ARG)
420 NEXT ARG
430 PRINT D$"CLOSE";TWO$
440 IF PT = PW AND LT = LW AND HT = HW AND WT = WW THEN 500
450 IF PT < > PW THEN PRINT "NUMBER OF POINTS NOT EQUAL"
460 IF LT < > LW THEN PRINT "LOW WAVELENGTHS NOT EQUAL"
470 IF HT < > HW THEN PRINT "HIGH WAVELENGTHS NOT EQUAL"
480 IF WT < > WW THEN PRINT "WAVELENGTH INCs. NOT EQUAL"
490 FOR T = 1 TO 900: NEXT T; GOTO 110
500 PRINT "INPUT FILE NAME FOR THE RESULTING"
510 INPUT "DATA: ";THR$
520 PRINT D$"OPEN";THR$
530 PRINT D$"WRITE";THR$
540 PRINT PW
550 PRINT LW
560 PRINT HW
570 PRINT WW
580 FOR ARG = 1 TO PW
590 IF OPERA$ = "M" THEN PRINT A(ARG) * B(ARG)
600 IF OPERA$ = "D" THEN PRINT A(ARG) / B(ARG)
610 IF OPERA$ = "A" THEN PRINT A(ARG) + B(ARG)
620 IF OPERA$ = "S" THEN PRINT A(ARG) - B(ARG)
630 NEXT ARG
640 PRINT D$"CLOSE";THR$
650 HOME : PRINT "THE DATA HAVE BEEN SAVED"
660 PRINT "UNDER FILENAME: ";THR$
670 FOR T = 1 TO 1000: NEXT T
680 PRINT D$;"RUN SPECTRAL"
100 DIM M(100)
110 HOME : D$ = CHR$ (4)
120 PRINT : PRINT "--- OPERATIONS WITH A CONSTANT ---"
130 INPUT "INPUT CONSTANT: "; CNST
140 PRINT "INPUT OPERATION [M,D,A,S]: "; OPERA$
150 PRINT : PRINT "INPUT DATA FILE NAME"
160 INPUT "[ Q TO QUIT ]: "; FILNAM$
170 IF FILNAM$ = "Q" THEN PRINT : PRINT D$; "RUN SPECTRAL"
180 PRINT ; PRINT "INPUT NEW FILENAME FOR THE MODIFIED"
190 INPUT "DATA: "; FLNAM$
200 PRINT D$"OPEN"; FILNAM$
210 PRINT D$"READ"; FILNAM$
220 INPUT PTS
230 INPUT LW
240 INPUT HW
250 INPUT WI
260 FOR ARG = 1 TO PTS
270 INPUT M(ARG)
280 NEXT ARG
290 PRINT D$"CLOSE"; FILNAM$
300 PRINT D$"OPEN"; FILNAM$
310 PRINT D$"WRITE"; FILNAM$
320 PRINT PTS
330 PRINT LW
340 PRINT HW
350 PRINT WI
360 FOR ARG = 1 TO PTS
370 IF OPERA$ = "M" THEN PRINT M(ARG) * CNST
380 IF OPERA$ = "D" THEN PRINT M(ARG) / CNST
390 IF OPERA$ = "A" THEN PRINT M(ARG) + CNST
400 IF OPERA$ = "S" THEN PRINT M(ARG) - CNST
410 NEXT ARG
420 HOME : PRINT "DATA HAS NOW BEEN SAVED"
430 PRINT "UNDER FILENAME: "; FLNAM$
440 FOR T = 1 TO 1000; NEXT T
450 PRINT : PRINT D$; "RUN SPECTRAL"
Mean Square Deviation program

100 DIM A(100): DIM B(100)
110 D$ = CHR$(4)
120 HOME : PRINT : PRINT "PLEASE INPUT FILENAMES OF FILES"
130 PRINT " TO BE OPERATED ON [Q TO QUIT]: ": INPUT "ILLUMINA
NT DISTRIBUTION: ";WUN$
140 IF WUN$ = "Q" THEN PRINT D$;"RUN SPECTRAL"
150 INPUT "SIMULATING DISTRIBUTION: ";TWO$
155 PRINT "OUTPUT TO PRINTER?? [Y/N]: ";: GET P$
160 GOSUB 200
170 GOSUB 490
190 END
200 REM DISK READING SUBROUTINE
205 PRINT
210 PRINT D$;"VERIFY";WUN$
220 PRINT D$;"OPEN";WUN$
230 PRINT D$;"READ";WUN$
240 INPUT PW
250 INPUT LW
260 INPUT HW
270 INPUT WW
280 FOR ARG = 1 TO PW
290 INPUT A(ARG)
300 NEXT ARG
310 PRINT D$;"CLOSE";WUN$
320 PRINT D$;"VERIFY";WUN$
330 PRINT D$;"OPEN";TWO$
340 PRINT D$;"READ";TWO$
350 INPUT PT
360 INPUT LT
370 INPUT HT
380 INPUT WT
390 FOR ARG = 1 TO PT
400 INPUT B(ARG)
410 NEXT ARG
420 PRINT D$"CLOSE";TWO$
430 IF PT = PW AND LT = LW AND HT = HW AND WT = WW THEN RETURN
440 IF PT < > PW THEN PRINT "NUMBER OF POINTS NOT EQUAL"
450 IF LT < > LW THEN PRINT "LOW WAVELENGTHS NOT EQUAL"
460 IF HT < > HW THEN PRINT "HIGH WAVELENGTHS NOT EQUAL"
470 IF WT < > WW THEN PRINT "WAVELENGTH INCS. NOT EQUAL"
480 FOR T = 1 TO 980: NEXT T: GOTO 110
490 REM MEAN-SQUARE ROUTINE
494 HOME
495 IF P$ = "Y" THEN PRINT D$;"PR#1"; PRINT CHR$ (9);"30N"
500 PRINT : PRINT "MEAN-SQUARE DEVIATION "
510 F = .:NU = .:DE = .: REM INIT TO ZERO
520 FOR ARG = 1 TO PT
530 NU = NU + B(ARG) * A(ARG): DE = DE + B(ARG) ^ 2
540 NEXT
550 F = NU / DE
555 PRINT : PRINT "ILLUMINANT FILE: ";WUN$
556 PRINT "SIMULATOR FILE: ";TWO$
557 PRINT
560 D = .: REM INIT D TO ZERO
570 FOR ARG = 1 TO PT
580 D = D + ((A(ARG) - (B(ARG) * F)) ^ 2)
590 NEXT
600 D = SQR (D / PT)
610 PRINT "FACTOR F = ";F
620 PRINT "MEAN-SQUARE DEVIATION = ";D
621 IF P$ = "Y" THEN PRINT D$;"PR#0"; PRINT D$;"PR#3"
630 RETURN
Planckian Blackbody program

100 DIM M(900)
110 C1 = 3.741 x 10^ - 16; C2 = 1.4388 x 10^ - 2: D$ = CHR$(4)
120 HOME: PRINT "PLANCKIAN BLACKBODY SPECTRA"; PRINT
130 PRINT "IS A WAVELENGTH RANGE FROM 380 TO 780 NM ACCEPTABLE?"
140 PRINT: PRINT "[Q TO QUIT]"
150 LW = 380: HW = 780
160 GET ANS$
170 PRINT: IF ANS$ = "Q" THEN PRINT D$; "RUN SPECTRAL"
180 IF ANS$ < > "N" THEN 210
190 INPUT "LOW WAVELENGTH: "; LW
200 INPUT "HIGH WAVELENGTH: "; HW
210 PRINT "IS A WAVELENGTH INCREMENT OF 5 NM ACCEPTABLE?"
220 WI = 5
230 GET ANS$
240 IF ANS$ < > "N" THEN 260
250 INPUT "WAVELENGTH INCREMENT: "; WI
260 INPUT "ABSOLUTE TEMPERATURE: "; T
270 PTS = (HW - LW) / WI + 1
280 IF PTS = INT(PTS) THEN 320
290 HOME
300 PRINT "PLEASE PICK WAVELENGTHS AND INCREMENTS WHICH "
310 PRINT "ARE EVENLY DIVISIBLE"; GOTO 130
320 PRINT: PRINT: FLASH: PRINT "WORKING"; NORMAL
330 FOR ARG = 1 TO PTS: W = LW + (WI x (ARG - 1)): M(ARG) = C1 / ((W x 1E - 9)^5) / (EXP(C2 / ((W x 1E - 9) x T) - 1)): NEXT
340 HOME: PRINT "LOW WAVELENGTH: "; LW
350 PRINT "HIGH WAVELENGTH: "; HW
360 PRINT "WAVELENGTH INC.: "; WI
370 PRINT "ABS. TEMPERATURE: "; T; "K": PRINT
380 PRINT "INPUT DATA FILE NAME"
390 PRINT "[R TO RESTART]"
400 INPUT "[Q TO QUIT]: "; FILNAM$
410 IF FILNAM$ = "R" THEN 110
420 IF FILNAM$ = "Q" THEN PRINT: PRINT D$; "RUN SPECTRAL"
430 PRINT D$"OPEN"; FILNAM$
440 PRINT D$"WRITE"; FILNAM$
450 PRINT PTS
460 PRINT LW
470 PRINT HW
480 PRINT WI
490 FOR ARG = 1 TO PTS
500 PRINT M(ARG)
510 NEXT ARG
520 PRINT D$"CLOSE"; FILNAM$
530 PRINT: PRINT "DATA HAS NOW BEEN SAVED"; PRINT "UNDER FILE NAME: "; FILNAM$: PRINT D$; "RUN SPECTRAL"
Chromaticity coordinate program

100 DIM ILLUM(68), XBAR(68), YBAR(68), ZBAR(68), T(68), SX(68), SY(68), SZ(68)
110 D$ = CHR$(4)
120 O$ = D$ + "OPEN"; R$ = D$ + "READ"; W$ = D$ + "WRITE"; C$ = D$ + "CLOSE"; V$ = D$ + "VERIFY"
130 HOME
135 PRINT "CHROMATICITY CALCULATION PROGRAM"
136 PRINT "LOADING 2-DEGREE OBSERVER"
140 PRINT O$; "XBAR"
150 PRINT R$; "YBAR"
160 INPUT PTS
170 INPUT LW
180 INPUT HW
190 INPUT WI
200 FOR ARG = 1 TO PTS: INPUT XBAR(ARG): NEXT
210 PRINT C$; "XBAR"
220 PRINT O$; "YBAR"
230 PRINT R$; "YBAR"
240 INPUT PTS
250 INPUT LW
260 INPUT HW
270 INPUT WI
280 FOR ARG = 1 TO PTS: INPUT YBAR(ARG): NEXT
290 PRINT C$; "YBAR"
300 PRINT O$; "ZBAR"
310 PRINT R$; "ZBAR"
320 INPUT PTS
330 INPUT LW
340 INPUT HW
350 INPUT WI
360 FOR ARG = 1 TO PTS: INPUT ZBAR(ARG): NEXT
370 PRINT C$; "ZBAR"
380 READ ILLUM$
381 PRINT
382 PRINT ILLUM$
390 PRINT V$; ILLUM$
400 PRINT O$; ILLUM$
410 PRINT R$; ILLUM$
420 INPUT PTS
430 INPUT LW
440 INPUT HW
450 INPUT WI
460 FOR ARG = 1 TO PTS: INPUT ILLUM(ARG): NEXT
470 PRINT C$; ILLUM$
560 FOR ARG = 1 TO PTS: T(ARG) = 1: NEXT
575 CX = .: CY = .: CZ = .: REM SET TRISTIM VALUES TO ZERO
580 FOR ARG = 1 TO PTS: CX = CX + (ILLUM(ARG) * XBAR(ARG) * T(ARG)): CY = CY + (ILLUM(ARG) * YBAR(ARG) * T(ARG)): CZ = CZ + (ILLUM(ARG) * ZBAR(ARG) * T(ARG)): NEXT
590 SUM = CX + CY + CZ
600 X = CX / SUM: Y = CY / SUM
605 U = 4 * CX / (CX + 12 * CY + 3 * CZ)
606 V = 6 * CY / (CX + 15 * CY + 3 * CZ)
610 PRINT "x=": X
620 PRINT "y=": Y
622 PRINT "u'=": U
624 PRINT "v'=": V
625 GOTO 380
630 PRINT "ANOTHER FILE (Y/N): "; GET A$
640 IF A$ = "Y" THEN 380
999 PRINT: PRINT D$"RUN SPECTRAL"
File normalization program

100 DIM M(180)
110 HOME : D$ = CHR$(4)
120 PRINT "-- Normalization Program --": PRINT
130 PRINT "This program normalizes a spectral"
140 PRINT "distribution to a specified value"
150 PRINT "at a specified wavelength": PRINT
160 PRINT "INPUT DATA FILE NAME"
170 INPUT "[Q TO QUIT]: " ; FILNAM$
180 IF FILNAM$ = "Q" THEN PRINT : PRINT D$; "RUN SPECTRAL"
190 PRINT : INPUT "INPUT NORMALIZATION VALUE: "; NRM
200 PRINT : INPUT "INPUT NORMALIZATION WAVELENGTH: "; WAVL
210 PRINT : INPUT "INPUT FILENAME FOR NORMALIZED DATA: "; FLNA
220 PRINT D$; "VERIFY" ; FILNAM$
230 PRINT D$"OPEN" ; FILNAM$
240 PRINT D$"READ" ; FILNAM$
250 INPUT PTS
260 INPUT LW
270 INPUT HW
280 INPUT WI
290 FOR ARG = 1 TO PTS
300 INPUT M(ARG)
310 NEXT ARG
320 PRINT D$"CLOSE" ; FILNAM$
330 FCTR = M((WAVL - LW) / WI) + 1)
340 PRINT D$"OPEN" ; FILNAM$
350 PRINT D$"WRITE" ; FILNAM$
360 PRINT PTS
370 PRINT LW
380 PRINT HW
390 PRINT WI
400 FOR ARG = 1 TO PTS
410 PRINT M(ARG) / FCTR * NRM
420 NEXT ARG
430 HOME : PRINT "DATA HAS NOW BEEN SAVED"
440 PRINT "UNDER FILENAME: "; FILNAM$
450 PRINT : PRINT D$; "RUN SPECTRAL"
Density/Transmittance conversion program

100 D$ = CHR$(4):O$ = D$ + "OPEN":R$ = D$ + "READ":W$ = D$ + "WRITE":C$ = D$ + "CLOSE"
110 DIM M(100)
120 HOME
130 PRINT "-- Density/Transmittance conversion program --"
140 PRINT "Transmittance data in percent form."
150 PRINT "CONVERT TO DENSITY [D] OR TRANSMITTANCE [T]? ": GET A$
160 IF A$ = "D" THEN PRINT "CONVERT FROM %TRANS. TO DENSITY"
170 IF A$ = "T" THEN PRINT "CONVERT FROM DENSITY TO %TRANS."
180 GOTO 200
190 GOTO 150
200 PRINT "INPUT DATA FILE NAME"
210 INPUT "[ Q TO QUIT ]: ";FILNAM$
220 IF FILNAM$ = "Q" THEN PRINT : PRINT D$;"RUN SPECTRAL"
230 PRINT : INPUT "INPUT FILENAME NEW DATA: ";FLNAM$
240 PRINT O$;FLNAM$
250 PRINT R$;FLNAM$
260 INPUT PTS
270 INPUT LW
280 INPUT HW
290 INPUT WI
300 FOR ARG = 1 TO PTS
310 INPUT M(ARG)
320 NEXT ARG
330 PRINT C$;FLNAM$
340 PRINT O$;FLNAM$
350 PRINT W$;FLNAM$
360 PRINT PTS
370 PRINT LW
380 PRINT HW
390 PRINT WI
400 FOR ARG = 1 TO PTS
410 IF A$ = "D" THEN PRINT -.4342945 * LOG (M(ARG) / 100)
420 IF A$ = "T" THEN PRINT 10 ^ (2 - (M(ARG) / .4342945))
430 NEXT ARG
440 PRINT C$;FLNAM$
450 HOME : PRINT "DATA HAS NOW BEEN SAVED"
460 PRINT "UNDER FILENAME: ";FLNAM$
470 PRINT : PRINT D$;"RUN SPECTRAL"
Wavelength scale correction program

100 DIM M(1000): DIM N(1000)
110 D$ = CHR$(4): D$ = D$ + "OPEN": R$ = D$ + "READ": W$ = D$ + "WRITE": C$ = D$ + "CLOSE": V$ = D$ + "VERIFY"
120 HOME: PRINT "--- Scale correction program ---"
130 PRINT: PRINT "This program corrects"
140 PRINT "disparities between the wavelength"
150 PRINT "ranges and increments of two data files."
160 PRINT: PRINT "INPUT TWO FILES TO BE CORRECTED"
170 PRINT "[Q TO QUIT]"
180 INPUT "FILE NAME 1: "; F1$ = "Q" THEN PRINT: PRINT D$; "RUN SPECTRAL"
190 INPUT "FILE NAME 2: "; F2$
200 PRINT V$; F1$
210 PRINT D$; F1$
220 PRINT R$; F1$
230 INPUT MPTS
240 INPUT MLW
250 INPUT MHW
260 INPUT MWI
270 FOR ARG = MLW TO MHW STEP MWI
280 INPUT M(ARG)
290 NEXT ARG
300 PRINT C$; F1$
305 PRINT V$; F2$
310 PRINT D$; F2$
320 PRINT R$; F2$
330 INPUT NPTS
340 INPUT NLW
350 INPUT NHW
360 INPUT NWI
370 FOR ARG = NLW TO NHW STEP NWI
380 INPUT N(ARG)
390 NEXT ARG
400 PRINT C$; F2$
410 HW = MHW
420 IF MHW > NHW THEN HW = NHW
430 LW = NLW
440 IF MLW > NLW THEN LW = MLW
450 WI = 5
460 IF NWI = 10 OR MWI = 10 THEN WI = 10
470 PTS = (HW - LW) / WI + 1
480 PRINT : PRINT "SCALED FILES WILL CONTAIN"
490 PRINT " PTS:" ;PTS;" DATA POINTS"
500 PRINT : PRINT "WAVELENGTH RANGE: ";LW;" TO ";HW;" nm"
510 PRINT : PRINT "WAVELENGTH INCREMENT: ";WI;" nm"
520 PRINT : INPUT "NEW FILE NAME 1: ";N1$
530 INPUT "NEW FILE NAME 2: ";N2$
540 PRINT O$;N1$
550 PRINT W$;N1$
560 PRINT PTS; PRINT LW; PRINT HW; PRINT WI
570 FOR ARG = LW TO HW STEP WI
580 PRINT N(ARG)
590 NEXT ARG
600 PRINT C$;N1$
610 PRINT O$;N2$
620 PRINT W$;N2$
630 PRINT PTS; PRINT LW; PRINT HW; PRINT WI
640 FOR ARG = LW TO HW STEP WI
650 PRINT M(ARG)
660 NEXT ARG
670 PRINT C$;N2$
680 PRINT : PRINT " - finished! -": PRINT D$;"RUN SPECTRAL"
Log spectral power distribution program

100 DIM M(100)
110 HOME : D$ = CHR$ (4)
120 PRINT : PRINT "-- Log Spec. Power --"
130 PRINT "INPUT DATA FILE NAME"
140 INPUT "[ Q TO QUIT ]: " ; FILNAM$
150 IF FILNAM$ = "Q" THEN PRINT : PRINT D$ ; "RUN SPECTRAL"
160 PRINT : INPUT "INPUT FILENAME NEW DENSITY DATA: " ; FILNAM$
170 PRINT D$ "VERIFY" ; FILNAM$
180 PRINT D$ "OPEN" ; FILNAM$
190 PRINT D$ "READ" ; FILNAM$
200 INPUT PTS
210 INPUT LW
220 INPUT HW
230 INPUT WI
240 FOR ARG = 1 TO PTS
250 INPUT M(ARG)
260 NEXT ARG
270 PRINT D$ "CLOSE" ; FILNAM$
280 PRINT D$ "OPEN" ; FILNAM$
290 PRINT D$ "WRITE" ; FILNAM$
300 PRINT PTS
310 PRINT LW
320 PRINT HW
330 PRINT WI
340 FOR ARG = 1 TO PTS
350 PRINT .4343 * LOG (M(ARG) / 100)
360 NEXT ARG
365 PRINT D$ "CLOSE" ; FILNAM$
370 HOME : PRINT "DATA HAS NOW BEEN SAVED"
380 PRINT "UNDER FILENAME: " ; FILNAM$
390 FOR T = 1 TO 1000 : NEXT T
400 PRINT : PRINT D$ ; "RUN SPECTRAL"
Listing of Spectral Thickness Determination Program

Spectral thickness determination program

100 DIM SOURCE(100): DIM CRT(100): DIM CIE(100): DIM FSOURCE(100)
110 D$ = CHR$ (4)
120 D$ = D$ + "OPEN"; R$ = D$ + "READ"; W$ = D$ + "WRITE"; C$ = D$ + "CLOSE"; V$ = D$ + "VERIFY"
130 HOME
140 PRINT D$; "PR#3": PRINT "-SPECTRAL THICKNESS DETERMINATION PROGRAM-": PRINT
150 PRINT "INPUT FILENAME FOR INITIAL SOURCE."
160 INPUT ": [Q TO QUIT, C TO CATALOG] ": ;SOURCE$
170 IF SOURCE$ = "Q" THEN PRINT : PRINT D$; "RUN SPECTRAL"
180 IF SOURCE$ = "C" THEN GOSUB 890: GOTO 130
190 PRINT V$; SOURCE$
200 PRINT D$; SOURCE$
210 PRINT R$; SOURCE$
220 INPUT PTS
230 INPUT LW
240 INPUT HW
250 INPUT WI
260 FOR ARG = 1 TO PTS
270 INPUT SOURCE(ARG)
280 NEXT ARG
290 PRINT C$; SOURCE$
300 VTAB 4: PRINT "SOURCE FILE: "; SOURCE$; " HAS BEEN INPUT."
310 CRT$ = "CORNING % TRANSMITTANCE"
320 PRINT V$; CRT$
330 PRINT D$; CRT$
340 PRINT R$; CRT$
350 T = PTS: INPUT PTS: IF T < > PTS THEN END
360 T = LW: INPUT LW: IF T < > LW THEN END
T = HW: INPUT HW: IF T < > HW THEN END
T = WI: INPUT WI: IF T < > WI THEN END
FOR ARG = 1 TO PTS
INPUT CRT(ARG)
NEXT ARG
PRINT C$;CRT$
VTAB 6: PRINT "CORNING FILE: ";CRT$;" HAS BEEN INPUT."
STHICK = .2294
VTAB 8: PRINT "INPUT FILENAME FOR CIE DISTRIBUTION COMPARATOR"
INPUT "[Q TO QUIT, C TO CATALOG]: ";CIE$
IF CIE$ = "Q" THEN PRINT D$;"RUN SPECTRAL"
IF CIE$ = "C" THEN GOSUB 890: GOTO 310
PRINT V$;CIE$
PRINT O$;CIE$
PRINT R$;CIE$
PRINT [Q TO QUIT, C TO CATALOG]: ";CIE$
T = PTS: INPUT PTS: IF T < > PTS THEN END
T = LW: INPUT LW: IF T < > LW THEN END
T = HW: INPUT HW: IF T < > HW THEN END
T = WI: INPUT WI: IF T < > WI THEN END
FOR ARG = 1 TO PTS
INPUT CIE(ARG)
NEXT ARG
PRINT C$;CIE$
VTAB 9: PRINT "CIE FILE: ";CIE$;" HAS BEEN INPUT."
THICK = STHICK: INC = -.05
GOSUB 940
GOSUB 900
GOSUB 950
PRINT "THICKNESS= ";THICK;IN."; POKE 36,30: PRINT "LEAST SQUARES ERROR= ";LSE
GOSUB 1000: REM AUTO THICKNESS ROUTINE
OLD = LSE
GOTO 730
END : REM
**** SUBROUTINES ****
PRINT D$;"CATALOG": PRINT "HIT ANY KEY TO CONTINUE"; GET A$: RETURN
REM NORMALIZATION OF FSOURCE AND CIE TO 100 AT 560
W560 = (560 - LW) / WI
T1 = FSOURCE(W560):T2 = CIE(W560)
FOR ARG = 1 TO PTS:FSOURCE(ARG) = FSOURCE(ARG) * 100 / T1
CIE(ARG) = CIE(ARG) * 100 / T2: NEXT : RETURN
FOR ARG = 1 TO PTS:FSOURCE(ARG) = SOURCE(ARG) * 10 ^ (.4
34294 * LOG (CRT(ARG) * .01)) * (THICK / STHICK)): NEXT : RETURN
REM CALCULATION OF LEAST SQUARES ERROR BETWEEN FSOURCE AND CIE

B = .:C = .: FOR ARG = 1 TO PTS:D = (FSOURCE(ARG) / CIE(ARG)); C = C + D:B = B + (D * D); NEXT :A = B / C

LSE = .: FOR ARG = 1 TO PTS:LSE = LSE + ((1 - (FSOURCE(ARG) / (A * CIE(ARG)))) ^ 2); NEXT :RETURN

REM ******** AUTO THICKNESS ROUTINE ********

1010 IF THICK = STHICK THEN THICK = THICK + INC: RETURN
1020 IF LSE < OLD THEN THICK = THICK + INC: RETURN
1030 IF LSE > OLD THEN INC = INC * -.4:THICK = THICK + INC: RETURN
Figure 4

Photograph of Apparatus
Figure 4 depicts the 1000-Watt source on the left of the optical bench. The dark object further to the right is an adjustable aperture used to reduce flare. The filter was mounted here when it was included in measurement. The unit to the right of the aperture is the monochromometer portion of the spectroradiometer. It is fitted with a stepper motor which is visible on the front of the unit. The photomultiplier is attached on the right of the monochromometer. On the floor below the monochromometer is the variable transformer used to control the voltage supplied to the source. To the right of the monochromometer is the ammeter which measures the output of the photomultiplier and sends it to the computer on the far right. The multimeter between the monochromometer and the computer measures the voltage drop across a precision 1.00-ohm resistor (not visible) to determine the current drawn by the source.
VII. VITA

Paul M. Butterfield was raised in New Hampshire, and attended Oyster River High School in Durham. During his high school career, he worked as a darkroom technician for the Transcript Newspaper in Dover, NH. Upon graduation in 1980 with a National Merit Scholar Commendation, he was accepted to the Rochester Institute of Technology.

In January of 1982, Mr. Butterfield began working as a technician in the research labs of the Eastman Kodak Company. Currently he is completing his Bachelor of Science degree requirements with the submission of this thesis, Spectral Determination of Color Conversion Filter Thickness Applied to Simulation of CIE Illuminants.