TECHNICAL UNIVERSITY OF CRETE

ELECTRICAL AND COMPUTER ENGINEERING

Spectral Photography

Diploma Thesis

by

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Abstract

A common topic which concerns the color industry is the way to optimally reproduce color stimulus identical to the color we are capable of seeing. With spectroscopic technology we can measure surface spectral reflectances of Colorimetric Charts which are the golden standards in color science. Multiple light sources are acquired to form a Spectral Power Distribution Database that could help estimate the spectral signatures of different illumination case scenarios. By exploiting the spectral information features of both the Visible and Near Infrared spectrum each illuminant type has we can match the given illumination and reproduce accurately color from spectral data. Using spectral comparison metrics, illuminant estimation is achieved and color difference measurements across patches on spectrally reconstructed images will lead to the creation of true, according to human vision, computational color with illumination independency.

1 Introduction to Color

1.1 Light

Light is a factor undoubtedly in conjunction with color and can be found in various forms in nature. Whether it is in emission, reflection or transmission form it interacts with objects that surrounds us in our whole lives. This so-called electromagnetic radiation (or EM) includes fluctuations of electric and magnetic fields and color simply without it does not exist[1].

The human visible range is only a small portion of the electromagnetic wave spectrum and is also called visible (from 400 to 750 nm).

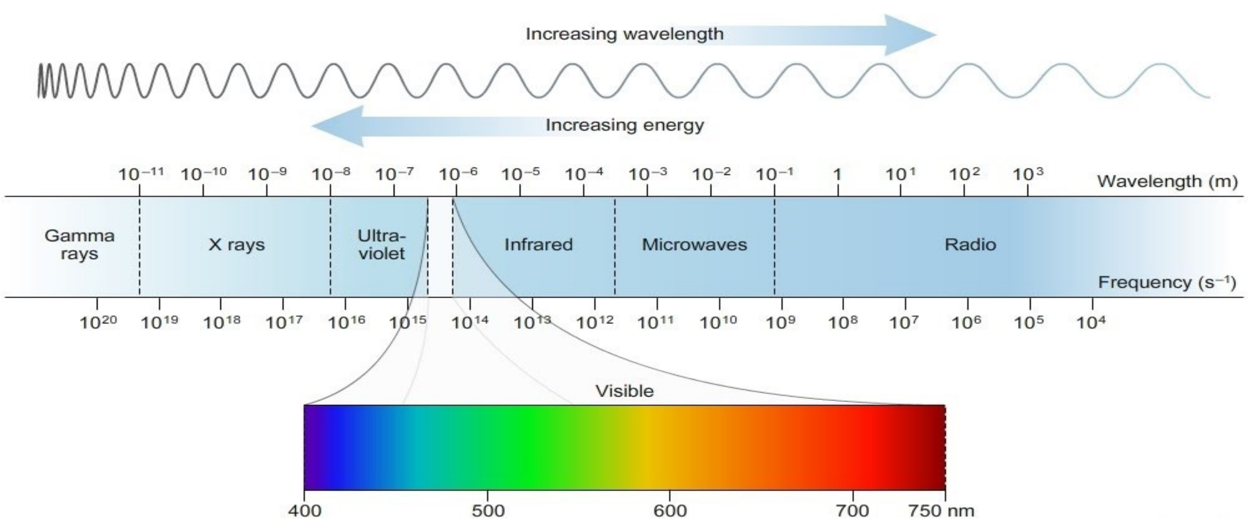


Fig Electromagnetic Spectrum [1]

In the Fig above the visible spectrum is displayed in relation to the rest of the electromagnetic radiation types. The range of this spectrum is clearly defined but the colors being without clear bounds between each other, aren't. So it is a non-finite space whereas different spectral colors are discriminated with their spectral behavior according to wavelength and amplitude.

1.2 Color

As already commented, light can appear in nature and interact in many forms such as emission, reflection and transmission. Objects themselves reflect light in different wavelengths detectable by the human eye and then interpreted by the brain as color. This visual property is nothing but a procedure that occurs at the optic nerves which execute an integration of all external incoming spectral stimuli at the retina.

To be more precise the visual color impression of a non-self-luminous color is due to 3 independent components[2]. These are:

1) Light source (which is related to Spectral Power Distribution known as SPD)
2) Colorants of the color pattern (interactions of light with colorants of the color sample)
3) Observer himself (color perception capability)

The whole color perception concept is affected by the law of additive color mixing. Both the entire colorimetry theory and industrial color physics applications are based on that.

1.3 Color Constancy

Generally a color is considered to be constant if it always produces the same color impression independent of spectrally different illuminations. That is a characteristic that technical visual systems don't apply to. On the contrary, the human visual system has an innate ability to perceive colors under different illumination in a constant manner (referred also as illumination independency feature). That means a white sheet of paper will always be perceived (by humans and not digital cameras) as white despite light changes although the color stimuli itself caused by the sheet is different. It seems that the brain is constructed in such way to interpret colors as if they are always illuminated by white light.

However color stimulus is dependent on the spectral power distribution of the light source. Therefore, color constancy is key parameter to characterize colors, color differences and color appearances by applicable dimensional values rather than to be left entirely to the individual visual perception (a non-objective comparison measure)[3].

1.4 Reflectance

Reflectance is a property of a surface and it is directional. Different kinds of surfaces can give either specular or diffuse reflection. Specular surfaces will have near zero reflectance at all angles besides the appropriate one. Diffuse surfaces have uniform reflectance (called Lambertian). In this project we make the assumption that the ColorChecker we are using is in fact a Lambertian surface and thus has the mentioned attributes[4].

Without the existence of reflected light our eyes would be unable to see the color or texture of objects. That is due to the 3 independent components that constitute non-self-luminous color described in chapter Color. So reflection is the sole reason we can perceive our surroundings as they are. To a human eye reflection of light could be used to identify shapes and patters or estimate distance from an object but to a spectrometer reflection is the portion of light reflected from a surface as function of wavelength.

At this point it must be noted that spectral reflectance can contain similar information to the eye but in a more quantifiable and objective manner. Meaning spectral reflectance allows for comparison of objects of the same color or entirely different textures, Also it can yield information about a sample's material identification based on the theory that because of the nature of a chemical composition light is absorbed and thus cannot be found in scattered or transmitted form.

So in a sense objects really do interact with incident light and that means when a light source with a specific spectral power distribution hits a surface part of that illumination will be absorbed and another one will be reflected. The chemical composition and molecular structure play a big role to an objects reflectance attributes. As a characteristic of an object being a function of wavelength it can be used for material identification with spectral signature or pattern recognition[5]. Examples of spectral signatures across the spectrum are displayed below:

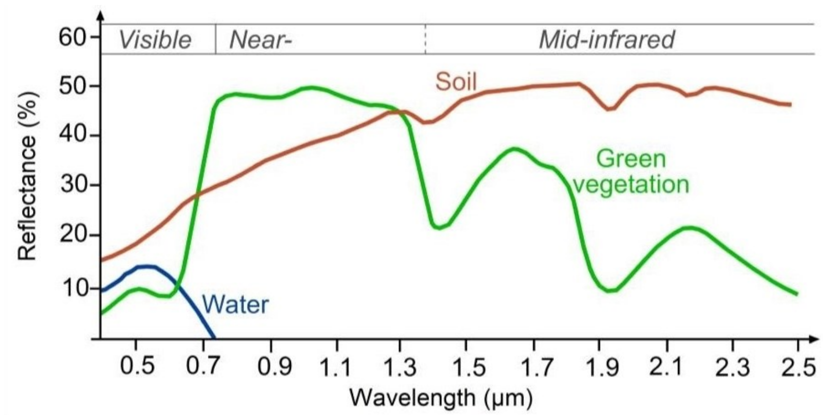


Fig Example of Spectral Signatures [2]

The amount of light that is reflected by an object and how that is reflected scientifically has been proven that depends on the smoothness or surface texture. In the ideal case where surface imperfections are smaller than the wavelength of the incident light (e.g. a mirror-like surface) all light will be reflected equally. But in real world cases most objects will have convoluted surfaces that naturally exhibit diffuse reflections and so light will be reflected in all directions.

To make a simple state reflectance is a property of a surface and it is directional. Different kinds of surfaces can give either specular or diffuse reflection. Specular surfaces will have near zero reflectance at all angles besides the appropriate one. Diffuse surfaces have uniform reflectance and are also known as Lambertian. In the example below these two kinds of surfaces are displayed (mirror reflects all components of white light being reduced to red, green and blue wavelengths and the reddish surface doesn't reflect all wavelengths because it absorbs predominantly blue and less that of green but reflects the red part of the incident light. Note that diffuse light reflected by the surface is reflected to all directions.

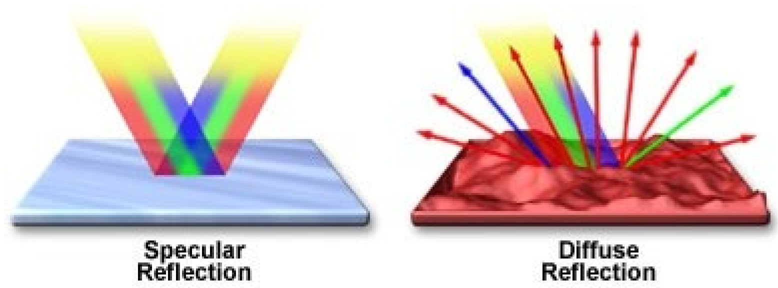


Fig Specular and Diffuse Reflection [2]

Note that in this project we make the assumption that the ColorChecker we are using is in fact a Lambertian surface and thus the mentioned attributes apply to it as well. The reflectance is a physical property of a specimen compared to color which is not.

1.5 Anatomy of the human eye

Before moving on to color reproduction process analysis we must make in depth examination of the human eye anatomy. It is necessary to understand that the perception of the color starts at the retina cells which have different spectral sensitivities known as the cone cells (in fact 3 kinds of those) located in the fovea which is a central part of the retina. This visual sensory organ known as one of the most complex one contains different variations of protein fact that causes differences in the wavelengths absorbed[6].

The three types of cones respond to incoming light with wavelengths peaking at 437 nm , 533 nm and 564 nm and called S, M and L cones respectively (acronyms for Short, Medium and Long Wavelengths)[7]. Light itself can be described in mathematics as a multidimensional space but the human eye, independently of the wavelength composition complexity, performs a convolution rendering all color with 3 color components so humans understand color as a 3 dimensional space after all. For example a blue light that has a wavelength of approximately 450 nm would activate the red cones by a minimum, the green cones by a margin and finally the blue cones predominantly. That relative activation of the three different cones is calculated by the brain which perceives the color as blue[8].

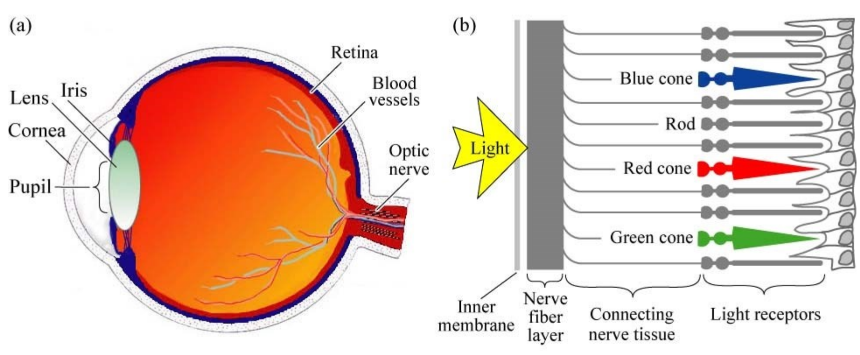


Fig (a) Cross section through a human eye (b) Schematic view of the retina including rod and cone light receptors (adapted from Encyclopedia Britannica, 1994) [3]

From the picture above one can realize that there are two types of photoreceptors involved in sight those are the rods and the cones. Rods actually function at very dim levels of light and are used by the brain for night vision because very few photons can activate a rod. They don't actually help with color vision as they cannot sense the colored light and as cones cannot react to low-intensity light that's the reason why at night everything seems like grayscale e.g. a dark room appears as a shade of gray[9]. Photoreceptor sensitivities are displayed below:

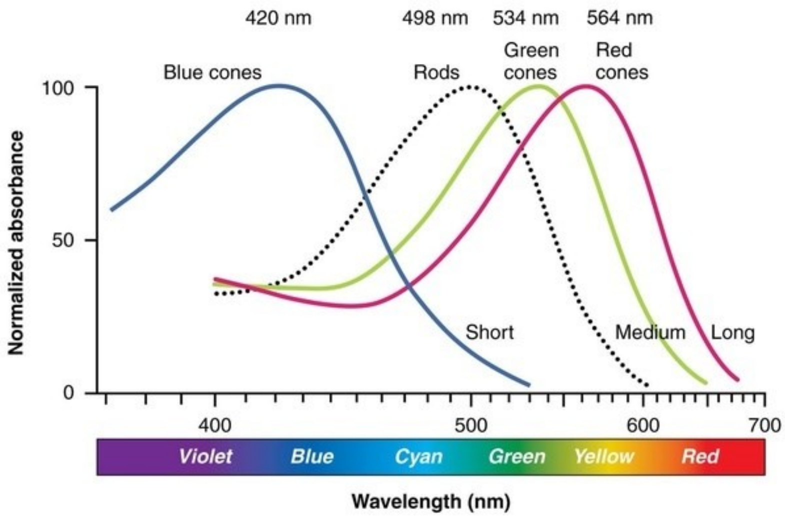


Fig Spectral Sensitivities of the Human eye [4]

The cones as was mentioned were of three types and are labeled by the color they are most sensitive to (blue, green and red by increasing wavelength order). Naturally one can think that other colors are not possible but the fact that cones overlap and the brain integrates the signals emitted by them allows vision filled with millions of colors. Above figure displays the response curve of normalized response spectra of human photoreceptors with their peaks and a color bar to which they correspond to.

2 Color Models and Concepts

2.1 Additive Color Mixing Model

Now that we have some basic idea about human eye anatomy and color basic theory we can move onto the Additive Color Mixing Model. This model is based on the fact that several wavelengths arrive together, e.g. the sunlight, on our visual system and the latter adds them together and decides the resultant color. That means the whole human visual system color perception that occurs in the brain works in additive manner. So adding lights of different colors to create a new color is the essence of the Additive Color Mixing.

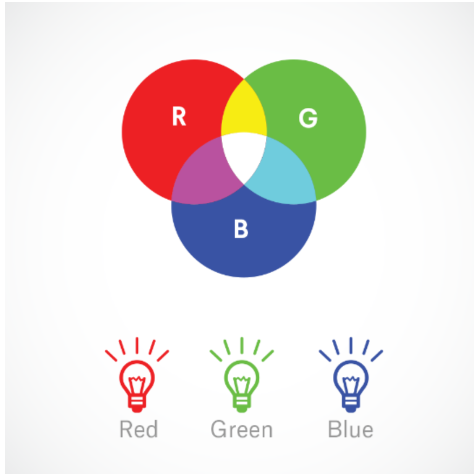


Fig Additive Color Mixing Model [5]

Referring specifically to RGB model we can see that we can have an easy model to understand which allows the mix of any set of 3 color channels (called primaries) to produce other colors. A simple rule of this model is that no combination of 2 primary colors can be used to create the third. The center of all three colors (essentially a combination of all three) is the color white. Finally, we have the complementaries, colors that are opposite each other in the circle and have the special property that if added together they produce white[10].

2.3 Illuminants

As it was mentioned light is highly related to color so the latter cannot exist without the other. In more scientific approach one could say that the entire perception and assessment of non-self luminous colors is based on illumination with a light source. Optical radiation sources may have different spectral power distributions because of the different generation mechanisms of light[11]. With the term Spectral Power Distribution (or SPD) one refers to the normalized spectrum of bands with highest value to the range of 0-1.

Different emission peaks at specific band regions of different illuminants made the colorimetry scientists to define a golden standard common standard to compare illuminants. That means colorimetry experiments couldn't be conducted if we compared illuminant that were different in scale and so a normalization with the highest emission value to nominal range 0-1 was required. Below are displayed some spectrums and their corresponding SPDs on the side for visual explanation (generated by the program):

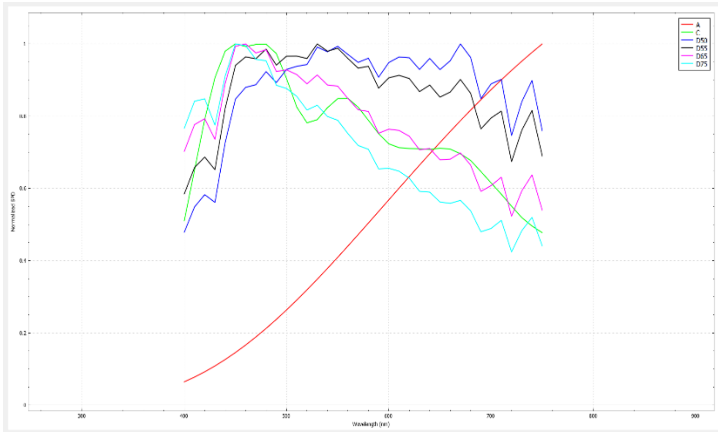


Fig Spectrum & SPDs of CIE Standard illuminants

More on the illuminants themselves we need to elaborate the fact that based on emitted spectrums illuminants can be categorized to 2 groups, the temperature and the luminescence radiators. A table underneath shows these kinds with some examples:

Temperature radiator		Luminescence radiator
Natural	Artificial	Artificial
Sunlight, Scattered light of the Earth atmosphere, stars, galaxies	Blackbody radiator, incandescent lamp, arc lamp	Gas discharge tube, fluorescent lamp, light emitting diode (LED), source of coherent light (laser)

Fig Industrial Color Temperature and Luminescence Radiators [6]

But for coloristical problems of non-self luminous colors we are going to focus on just the technical sources which are used exclusively by the color industry. The real intuition behind this is that there's the need of reproducing the generated spectrum in the same form multiple times[12]. The CIE organization needed to make up a system to globally recognize such kinds of technical illuminants called the illuminants. For example below are some CIE defined illuminants with their properties and the illuminant source they are simulating.

CIE illuminant	CIE abbreviation	Correlated color temperature/K	CIE simulator
CIE standard illuminant A, evening light	A	2,856	Tungsten filament lamp
CIE standard illuminant D65, middle daylight	D65	6,500	UV-filtered xenon lamp
Cold white daylight	FL 2	4,230	Fluorescent lamp CWF, cool white fluorescent
Bluish white daylight	FL 7	6,500	Broadband fluorescent lamp
White daylight	FL 11	4,000	Three-band lamp TL84

Fig Industrial Color Some Standard CIE Illuminants [7]

Let's note that only standardized Illuminants are the illuminant A and illuminant D65 with the first being recommended for simulating evening room light and the second the light during midday.

To be completely accurate CIE specified 7 different illuminants to represent different illuminations which are[13]:

1) Three radiators symbolized as D50, D55, D75 with respective CCTs 5000, 5500 and 7500 K.
2) Twelve fluorescent lamps varying from FL1 – FL 12 with them being FL1-6 of line spectra emission, FL 7-9 broadband and FL 10-12 narrowband spectra.
3) Five High-Pressure lamps symbolized as HP 1-5, 2 of those being sodium vapor lamps and the rest metal halide lamps.

In order to measure all that useful spectral data information we need to use a tool called spectrometer that along with the demanded software can translate light spectrum to digitized data (Spectrum to Computational Color chapter).

2.4 Color Stimulus Equation

After this small introduction to the theory of color vision and visual perception we can define the equation that combines all these concepts together. As discussed objects around us are perceived by their radiance in the visible part of the electromagnetic spectrum and for a specific object, radiance depends on its surface, material properties, shape and scene location. So the color that we are capable of seeing is in fact a quantification of concepts like Illuminant spectrum, Reflectance and spectral sensitivity attributes of the observer (e.g. cones of human eye, a digital sensor etc.).

Given all those parameters and a Lambertian surface we can define a formula for color response as:

$$C_i = \int_{\lambda \in \Omega} I(\lambda)\ R(\lambda)\, S_k(\lambda)$$

Equation of Color Response

whereas $I(\lambda)$ is the illuminant at scene, $R(\lambda)$ spectral reflectance and $S_\kappa(\lambda)$ the cone sensitivity

$k \in \{S,M,L\}$ stands for the tristimulus values of an observer that recognizes 3 values and Ω is the spectrum range (visible spectrum in this case). λ stands for wavelength

But a spectrometer and computational memory cannot interpret wavelengths in a continuous manner like humans do so that's why equations are transformed from integrals (continuous manner) to simple sums (discrete quantifications) in order to describe the nature of this phenomenon (more on this at Spectrum to Computational Color chapter). So the equation of Color Response given at Color Stimuli Equation Chapter can be transformed to their discrete equivalents and so:

$$C_i = \sum_{j=0}^{N-1} I(\lambda)\ R(\lambda)\, S_k(\lambda)$$

Equation of Color Response (digital interpretation)

In this case the wavelengths, reflectance values and spectral sensitivities are discrete values and resultant color c being a tristimulus set can be represented as a vector in 3D space. But spectral sensitivities also need to be matched from visual properties of human vision to quantifiable values which is explained at the start of the next chapter which refers to the defined CIE Color Matching Functions (or CMF) and the CIE Standard Color Spaces.

2.5 CIE 1931 and CIE 1964 Standard Colorimetric Observers

When transforming data from real world unquantifiable data to the digital world scientists of CIE realized that there was a need to match colors of spectrum, always accordingly to human vision, to quantifiable data.

Due to the distribution of cones in the eye tristimulus values depend on the observer's field of view (FOV). In order to eliminate that variable's complexity from the reproduction workflow CIE defined a color-mapping function called the standard (colorimetric) observer to represent an average human's chromatic response within a 2° arc inside the fovea (CIE 1931). A latter more modern approach was the CIE 1964 10° Standard Observer[14].

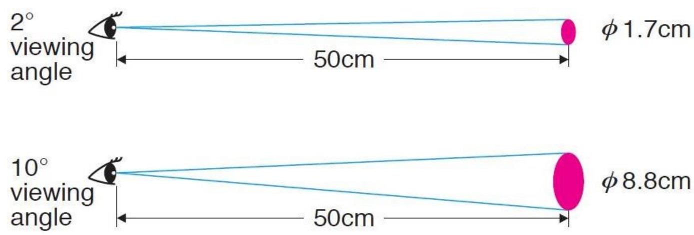


Fig Viewing angles 2° and 10° degrees [8]

2.6 RGB-Color Matching

The graph presented below shows how the colors of the visible part of the spectrum can be matched by using different amounts of the blue, green and red light. With a closer look at the graph below one can observe the negative region that the red curve passes through. This means that not all colors can be matched by the RGB primaries.

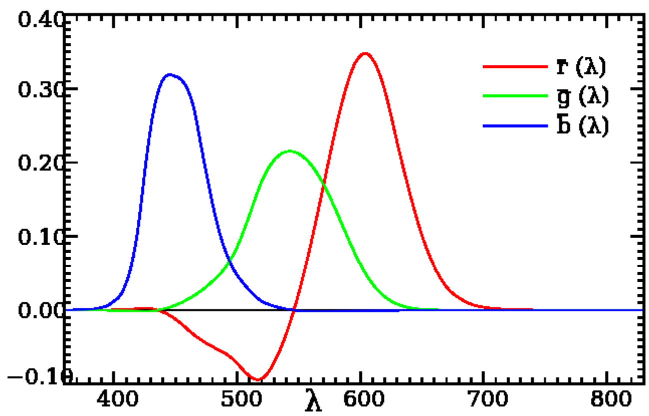


Fig RGB Color Matching [9]

In that manner there's a need to add a red amount of color to the target color before its match with a green and blue mix (CIE Chromaticity Diagram chapter). Another important statement to conclude out of this graph is that pure spectral yellow, a combination of equal amounts of red and green light, compared to a regular yellow is in fact indistinguishable by the eye (Anatomy of the Human Eye).

2.6.1 RGB-Color Matching and Human Color Vision

Before moving on to explain the process that had to be followed in order to resolve the negative region problem let's start the approach of understanding color matching intuitively, given a real like case scenario.

We want to make a color match of a test color (left part of circle at Fig) to match a combination of the three RGB primaries (right part of circle at Fig). The first example is near the middle of the visible spectrum at spectral yellow region (580 nm). For the match to occur the amount of the three primary colors (tristimulus values) projected to the right part of circle may vary until as a whole they match the test color. By definition Additive Color Mixing Model chapter stated that a combination of equal amounts of Red and Green give the color Yellow.

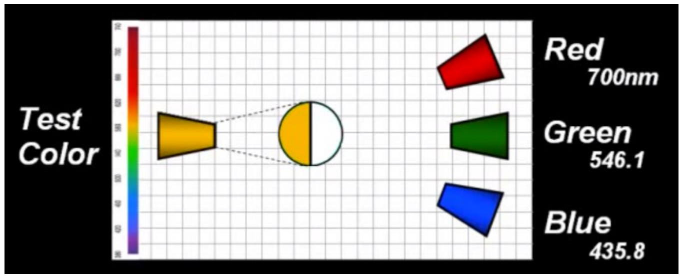
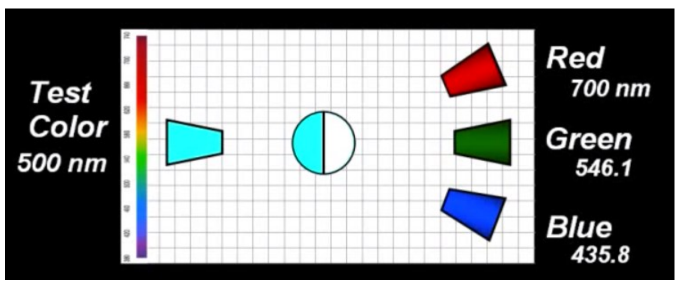


Fig Matching Spectral Yellow Color [10]

Now doing the same with a color of Cyan (500 nm). However, no kind of combination of RGB primaries can be added to create such a color. The setup itself has to be changed for the match to occur and that happens with adding red light to the test color (change the position of the red projector from right to left). That alone changes the test color bringing it to a region where it can be matched by an amount of green and blue. That's why the amount of red that it had to be added to the test color is considered to be in the negative range (remember Color Match RGB)[15].



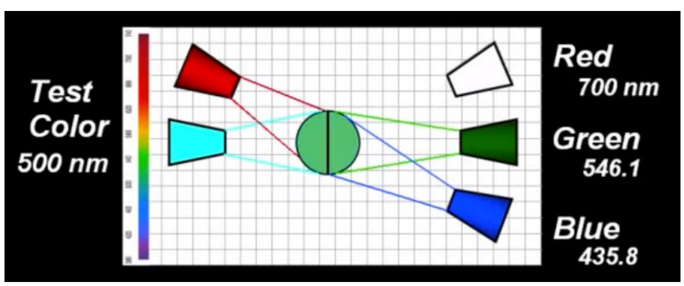


Fig Matching Cyan (Top) & Matching Cyan & Red (Bottom) [10]

Except if color from RGB region is added to the target color the test color simply cannot be matched. That is an important information for one to understand about color matching concept.

2.7 Determination of XYZ Tristimulus Values

The negative region problem had to be solved with the creation of a new Color Space (XYZ or CIEXYZ) with the process that is described below.

2.7.1 RGB space

Let's imagine Red, Green and Blue channels as 3 independent vectors that together form the R-G-B Color Space. So Color Space R-G-B as commented on previous chapters is a 3D space, a cube if one can imagine, that inside it are contained all the colors we are capable of seeing (all possible combinations of RGB). This space may be an easy concept to grasp but it's impractical for applications.

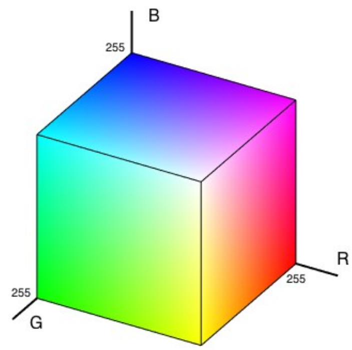


Fig Picture of RGB Cube [11]

2.7.2 RGB Unit Plane

Inside this cube an equilateral triangle (black) can be formed by 1 unit on each of the color axis. Anywhere on this plane the sum of the three values is 1 so it is named Unit Plane.

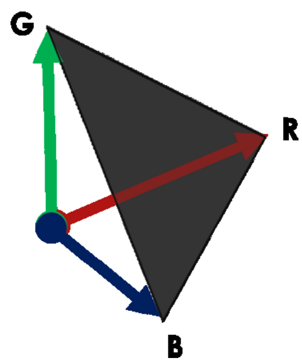


Fig RGB unit plane

2.7.3 XYZ space

Now before finishing the concept of determining XYZ tristimulus values we must recall that the initial tristimulus graph (Fig RGB Color Matching) had a negative region that if it was to be represented in the RGB color space it would fall out of the cube bounds. Scientists of CIE in

1931, created an imaginary set of primaries called X,Y and Z to force a linear transformation of RGB color matching graph to a more convenient fashion, the so-called Color Match XYZ.

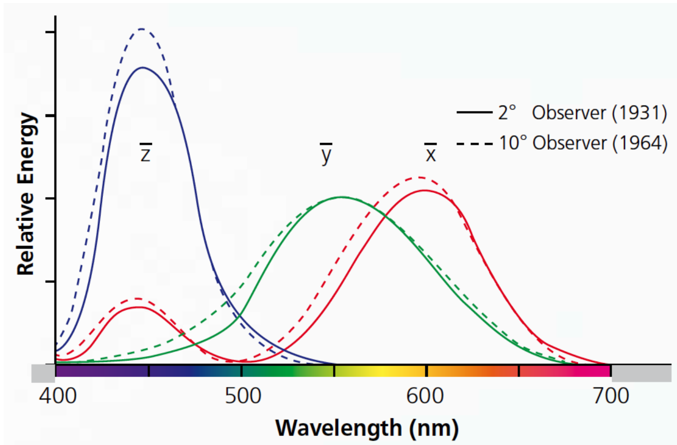


Fig CIE XYZ Color Matching Graphs [12]

The graph above displays the form of the XYZ space and specifically the tristimulus values of the two observers as a function of wavelength. Indeed it looks a lot like RGB Color Matching Graph but the negative region problem is fixed.

2.7.4 XYZ Unit Plane and Mapping to Spectral Locus

Mapping transformed tristimulus XYZ values on new Unit Plane had to be done once again so that all colors would fit to the positive color space. This time it is based on the XYZ values as shown below.

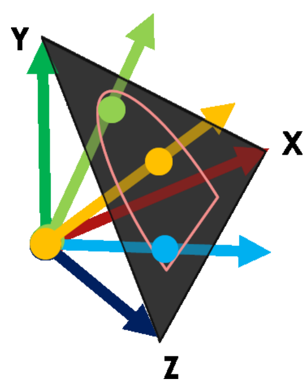


Fig XYZ Tristimulus unit plane and Spectral Locus

Colors towards the X axis will be of red hue, towards to Y will be of green and towards to Z will be of blue. Now tracing all the vectors corresponding to spectral color matches make the construction of a line (pink) called the Spectral Locus (also known as the CIE Chromaticity Diagram). That means colors of the spectrum are mapped to that Color Diagram which is analyzed thoroughly in the chapter called CIE Chromaticity Diagram.

With such a technique we can reduce the 3D space to a 2D space. This 2D space, which in this case is the Unit Plane, contains the tristimulus values and is a useful and intuitive way to represent color. The vector for an intermediate color pierces the unit plane at a specific point. In order to precisely define that point 2 coordinates are required (x,y).

2.8 CIE Chromaticity Diagram

The CIE Chromaticity Diagram also known as Spectral Locus is the result of the transition of the color space that is 3 dimensional space to the unit plane which is a 2 dimensional space. The intuition behind of such a graph is to define a common globally approved color language system. Inside the graph are contained all the color gamut the human eye is capable of seeing. Color position is defined by the 2 spatial coordinated X and Y (luminance) known as chromaticity coordinates.

Around the edges of the graph numbers represent labeled wavelengths that define color starting at blue going through green and stopping at red region. There are no labels at the purple hue area as they are not included in the gamut. According to the Color Mixing Model theory, equal amounts of all colors result to color white (this happens at x=1/3 and y=1/3 known as the equal energy white)[15].

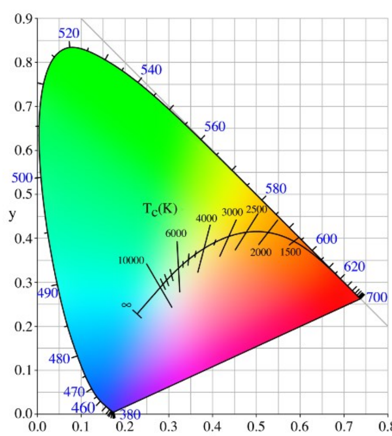


Fig Spectral Locus [13]

One can observe that color White is in fact a whole range of white colors that have different coordinates (defined by CIE standards) and different temperatures.

2.8.1 Reference White

In imaging a reference is essential to be set before the execution of the reproduction process. Plainly a white point is a set of tristimulus values or chromaticity coordinates that serve to define the color “white” in image capture, encoding and reproduction. Based on application different definitions of white points are needed for acceptable results.

For example: a photograph taken indoors may be lit by incandescent light (casting a relative orange light compared to daylight). That means a wrong reference of white let’s say as daylight white point will yield unacceptable results when attempting to color-correct it[15].

To summarize the white point of an Illuminant source is in fact the chromaticity values of a white object under the illumination of that source on the CIE 1931 chromaticity diagram. The SPD graphs that are plotted are Relative SPD Power values and not absolute SPD values because white point is correlated only to color and not to intensity. At this point we need to recognize that illuminant and white points are differently defined concepts. An illuminant has a white point that fully defines it while a white point can match more than one illuminants.

The knowledge of illuminants’ SPD, reflectance spectrum of the specified white object and the definition of CIE observer (CIE 1931 & CIE 1964) allows for a mathematical calculation of the coordinates of the white point in any color space.

$$XYZ_{\ illum} = A^T \ Illum$$

$$sum = X + Y + Z \ and \ xyz = {}^{\mathrm{XYZ}}/_{sum}$$

These equations apply for a given Illuminant and spectral range.

It is substantial to note that white point conversion can be achieved to estimate the color of an object under a different illuminant given the source white point (known illuminant) and the target white point (target illuminant source). This is not a simple White Balancing technique but rather a transformation of known spectra to target spectra called Chromatic Adaptation Transform (most popular being Bradford CAT). Generally a condition for this transformation to work well is that we need to know that the spectral signature of source matches that of the target. For example D75 spectrum is similar to a D65 spectrum but not like so for an illuminant A spectrum.

Spectral data for the destination illuminant don’t need to be available but spectral data for the transforming Illuminant must be. It’s a very dependent method on spectral data (illuminant source data) and less affected on source and target reference white.

So it’s only useful when there’s an indication that spectral data of source and target are comparable however destination spectral data aren’t always available.

2.8.2 Color Temperature

A digital camera in comparison to the average human person’s vision behaves rather differently when photons hit its’ sensor. To be more precise, a camera cannot replicate what we are seeing so the way that it reproduces color digitally, is not constant. Using the same example as before, a camera will produce an image with orange hue under incandescent lighting whereas under daylight a more neutral one. However, we as human beings don't perceive color like so and that's because of the fact of how the brain interprets color which in fact is constant!

In order to differentiate the various use of artificial light sources like LED light, bulbs are labeled with a Correlated Color Temperature (or CCT). Scientifically the SPD of a blackbody radiator can be completely determined by definition or by color temperature in Kelvin (K)[16].

By black body radiator, we refer to a hypothetical object of absorbing all the electromagnetic radiation falling on it. A black body maintained at a constant temperature is a full radiator at the temperature because the radiation reaching and leaving it must be in a state of equilibrium. It is an opaque and non-reflective body and the concept is that it has specific spectrum and intensity depends only on the body's temperature which is assumed for the sake of calculations and theory to be uniform and constant[17]. The fig below displays how much of each wavelength of light is produced by an object (assuming that the object doesn't reflect light and all light is emitted from it).

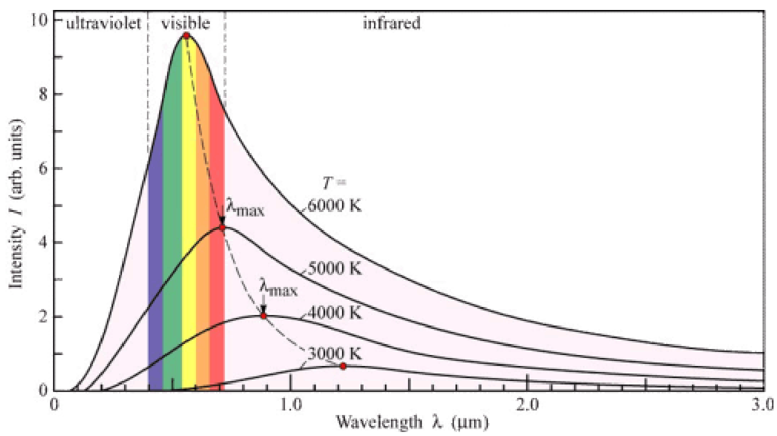


Fig Blackbody Diagram [14]

Note that blackbodies by no means have to look black with stars being a great example (not very reflective) and the shorter the wavelength of the peak wavelength, the higher the average temperature of the star.

The Correlated Color Temperature is a measure of light source color appearance that stands for the proximity of the illuminant source chromaticity coordinates to the blackbody locus. CCT is a single value number that can describe the nature of a black body radiator instead of chromaticity which defines it with 2 values.

CCT as mentioned is measured in degrees Kelvin and this particular rating of temperature represents what kind of tone of white light will be emitted from the light fixture. For example warm white light is referring to a light source with a 2000 to 3000 K rating. The Fig below displays the transition from warm light to cool light.

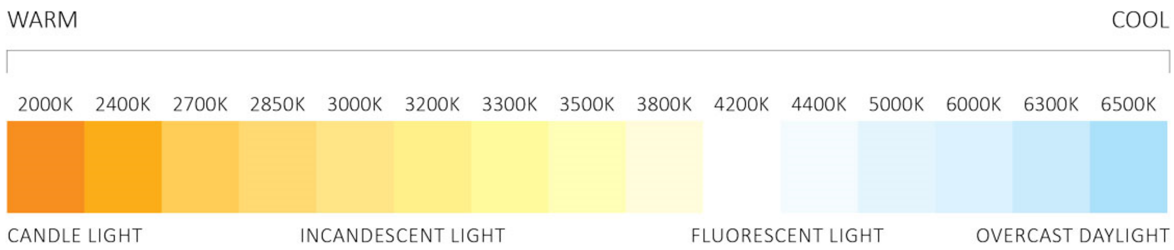


Fig CCT related to Color Perception [15]

At 2000 K region the light will appear very orange-yellow in color and as the temperature increases the color shifts to yellow, yellowish-white, white and then to bluish hue (the Fig below makes up for that definition).

The figure below shows the CCTs for most common Illuminants inside the CIE Chromaticity diagram.

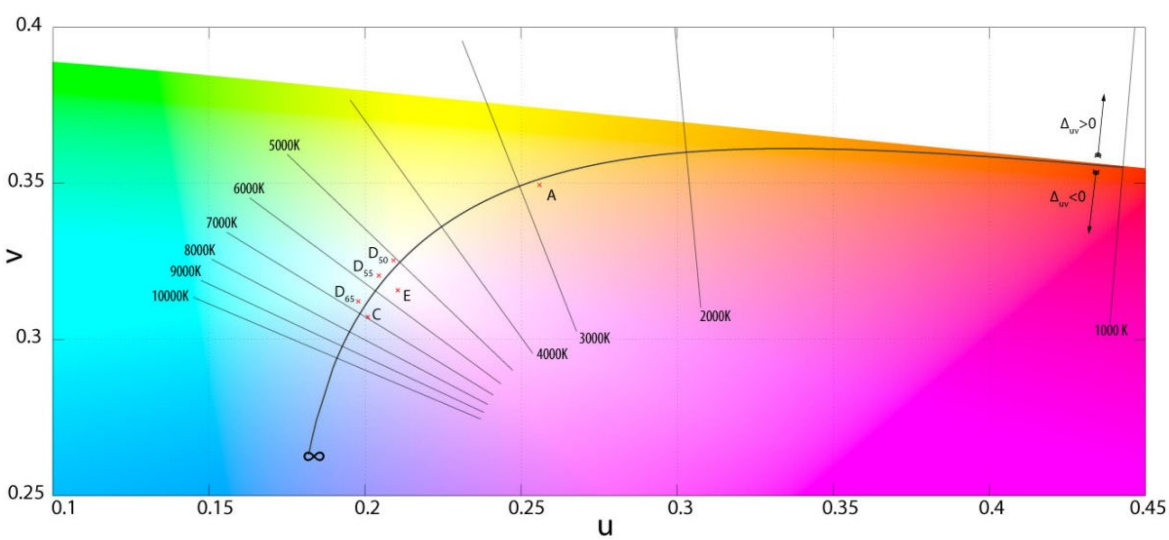


Fig CCTs of the most popular CIE defined Illuminants inside the spectral locus space [16]

2.9 Color Space Definitions

After the explanation of the Color Matching Function (CMF) functionality and the concepts that go along with the CIE Chromaticity Diagram there's a need to define Color Spaces using mathematical equations for the project's purposes.

2.9.1 CIE XYZ

As it was discussed in the chapter Determination of the XYZ Tristimulus values the CIE XYZ Color Space was created as an extrapolation of RGB original values to mathematically avoid the negative region. Specifically, Y stands for luminance, Z is a parameter like the blue component and X is a mixture of cone response curves chosen to be orthogonal to luminance and non-negative. So RGB space is completely different from this one.

Mathematically, tristimulus values can be separated in two equation groups: one for the Emissive case and another for the Reflective and Transmissive Case.

$$X = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda)\, \bar{x}(\lambda)\, d\lambda$$

$$Y = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

$$Z = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda)\, \bar{z}(\lambda)\, d\lambda$$

Fig XYZ equations of Emissive Case

In the first case XYZ tristimulus values are those corresponding to the illumination. So we can calculate any set of XYZ given an illuminant $L_{e,\Omega,\lambda}(\lambda)$ and the CMF whereas λ is the wavelength. Also we need to note that Y is basically the Illumination of our scene (also called the photopic response to illumination).

The reflective/transmissive case equations are displayed below:

$$X = \frac{K}{N}\int_{\lambda} S(\lambda)\, I(\lambda)\, \bar{x}(\lambda)\, d\lambda$$

$$Y = \frac{K}{N}\int_{\lambda} S(\lambda)\, I(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

$$Z = \frac{K}{N}\int_{\lambda} S(\lambda)\, I(\lambda)\, \bar{z}(\lambda)\, d\lambda$$

Fig XYZ Equations of Reflective and Transmissive case

In the second case there's a difference. We no longer have an illuminant but Spectral Reflectance S(λ) multiplied by the Illuminant I(λ) and the CMF and λ is wavelength. The normalization factor N is the photopic response to the Illumination (note that we don't calculate a photopic response to the Reflection at this point) and K is another normalization factor varying from 0-100.

2.9.2 CIE RGB & sRGB

One of many color spaces, is RGB which is distinguished by a particular set of monochromatic (single-wavelength) primaries. In order to solve for the RGB tristimulus values for a color with a known power spectral Distribution S(λ), given the CMF (r(λ),g(λ),b(λ)), one can form the XYZ tristimulus values from the spectrum and afterwards transcend to the RGB Color Space.

The RGB model, specifically the CIE RGB or sRGB, is the most popular model to represent color in imaging and is recognized internationally as a color specific system. While there are many different ways of defining color in really wide gamuts the sRGB stands for the everyday user. The color gamut that can be represented is the one that is produced by the combination of the three RGB primaries.

The original color matches had these wavelengths: Red at 700 nm, Green at 546.1 nm and Blue at 435.8 nm. A triangle can be drawn out of these 3 points that is basically the gamut of colors that RGB can produce. Colors outside of that triangle cannot be represented by that space meaning that a significant part of blue and green colors cannot be matched (see RGB Color Matching).

So naturally the sRGB space is a gamut of chromaticities much smaller than the total RGB gamut so it doesn't include all possible RGB colors (in fact misses a lot of green and orange hues). For visual interpretation the fig with the sRGB gamut along with the popular AdobeRGB gamut is displayed below.

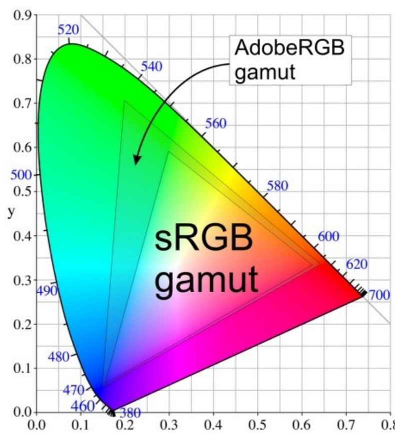


Fig sRGB and AdobeRGB gamut [17]

The sRGB color space has a non linear step γ that is expressed with a gamma value of 2.2. Gamma correction formulas are explained in the Gamma Correction formulas section inside the Appendix. In this project we don't make any kind of gamma correction so we don't use the sRGB form (γ=2.2) but the simple RGB form (γ=1.0). But for the purpose of the standalone sRGB Calculator one can choose whether to apply gamma correction or not.

2.9.3 CIE LAB

This particular Color Space is an immediate derivative of CIE XYZ space and holds critical information when comparing colors (color differences). The first equation represents lightness of a color (L^*=0 yields the color black and L^* =100 indicates white (diffuse white), a^* determines the position between red/magenta and green (negative values indicate green while positive magenta) and b^* show the position between yellow and blue (negative values indicate blue whereas positive yellow).

The CIE LAB Color Space represented in a 3D graph is symbolized like this:

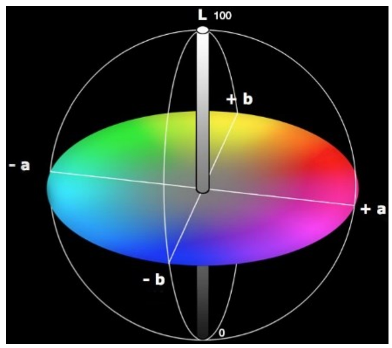


Fig L*a*b* Space [18]

Note that mathematical equations that perform transformations between Color Spaces are explained extensively in the Color Space transformation section created inside the Appendix.

2.10 Metamerism

This property that we are going to comment on is a rather undesirable one in many cases of color technology applications. By definition is related to pairs of color patterns and often rendered unavoidable. Two colors are called metameric to each other (conditional equal) if they match under one illuminant but display a color difference under the change of it[18].This behavior is to be noted as a consequence of additive color mixture of human color sense.

Fig Metameric Pairs [19]

Figure above contains metameric pairs of same dyed wool swatches under 2 different illuminations U30 fluorescent top half and A incandescent bottom half. The samples really do appear to change color and this is of course a matter that troubles manufacturers. By nature metameric matches are quite common in near neutral colors like gray, white and dark. The more the saturation on the colors and the lighter they become the range of possible metameric matches becomes smaller. In order to contain and manage the metamerism factor during color production one needs to know its cause[19].

The reason for the phenomenon to occur is related to the light source and the interaction of the object with light that gives off color perception. In the Fig below there are displayed the spectrums of Illuminant A and D65.

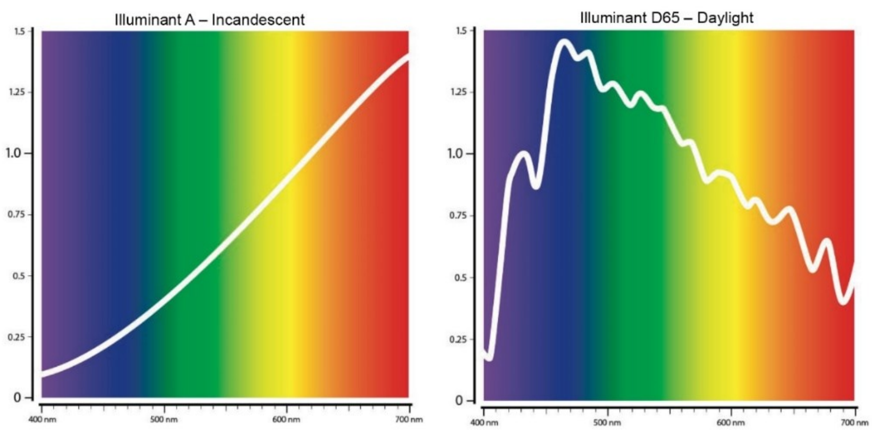


Fig SPD of illuminant A (left) and D65 (right) [19]

The incandescent has high intensity values mainly from the middle to right area in the red region but almost none in blue whereas that doesn't occur for daylight illumination. The increased energy in incandescent red area indicates that objects illuminated by this light source are going to appear redder compared to those under daylight.

The use of a spectrometer can measure the amount of light that is being reflected by an object at each point across the visible spectrum. Data extracted from this process are going to be denoted as the color's 'fingerprint' and can be used for reflectance curve plot.

Metameric pairs are according to the defined shades that appear identical under a single specific lighting condition but in reality really do have different fingerprints. In the figure there are plotted the reflectance curves for two curves.

Both curves display predominant absorption in blue region, moderate in green and strong reflection in red. The curves are twisting over each other which is a factor for metamerism (curves with at least three times intersection are called metameric pair). It is important to note that when objects are considered to be metameric, the metamerism phenomenon is obvious and although under some illuminations appear to be the same color they aren't going to match under all lighting conditions[19].

3 Spectroscopy

Spectroscopy is the science that studies the properties of matter through its interactions with different frequency components of the electromagnetic spectrum. Derives from the Latin word "spectron" (ghost or spirit) and the Greek word "σκοπειν" (to see). It is based on the concept that because of light existence we are not glaring at the molecule itself being matter but its ghost form. There are different types of spectroscopy oriented to different goals but all refer to particular part of the spectrum to achieve that.

So this kind of science deals with the measurements and the interpretation of spectral data produced by the interaction of electromagnetic radiation (EM in short) with matter. Different subjects that apply to this are absorption, emission and scattering of EM radiation by atoms and molecules[20].

3.1 Spectrometer

The Colorimetry Science studies illuminant spectrum with computer aid. So there was a need of the existence of a device that could take in light, quantize it to spectral components, digitize it as a function of wavelength and then display it to the computer via appropriate software.

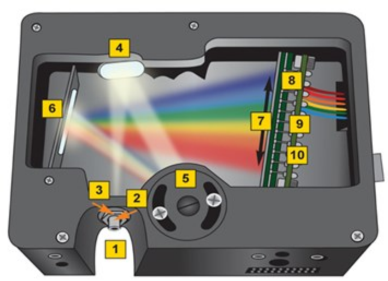


Fig Spectrometer components [20]

The workflow of such a device starts as following:

Light from scene is guided through a fiber optic cable into the spectrometer through a narrow aperture called entrance slit (1) and some filters (2,3). The slit causes a vignette to the incoming light when it enters the spectrometer. Generally the divergent light is then collimated by concave mirror (4) and re-directed onto a diffraction grating (5). The grating then disperses the spatial components of light at slightly varying angles which is then focused by a second concave mirror (6) and after that the separated wavelengths are being focused through some lenses (7) onto the detector module/array (8) simultaneously. Once the light is imaged onto the detector the photons are then converted to electrons which are digitized and right after read out through USB (or serial port) to a computer (9,10). The software is makes an interpolation out of the signal according to the number of pixels in the detector and the linear dispersion of the diffraction grating to create a calibration that enables data to be plotted as function of wavelength over given spectrum range[21]. The final data from the process can be used in multiple applications for different kinds of uses and may be exported at Excel format (Spectra Suite Copy to Clipboard Feature in our model's case).

3.2 Spectral Imaging

Spectral imaging is a combination of spectroscopy and photography in which complete spectrums or spectral information are employed to produce images that can have applications to astronomy, solar physics, Earth remote sensing and more. Based on application parameters that affect the spectral imaging system may vary. To be more precise one parameter is spectral range and states the spectrum where the system operates (visible-NIR-MIR etc). Spectral resolution is another factor that refers to the ability of resolving electromagnetic spectrum features (in short it is the smallest difference $\Delta\lambda$ in wavelengths whereas a wavelength λ can be distinguished). Finally number of bands refers to the total amount of wavelengths that the system actually uses to produce the images[22].

3.3 Spectral Cube

The end result is a digital image with more rich information spectral wise for each pixel compared to an image produced by traditional color cameras that are bound to the visible spectrum only. The data output of this process is known as datacube or spectral cube. The very essence of spectral imaging relies on the concept of the spectral Cube. One can think of the spectral cube like a stack of pictures in which each consequential image is representation for each band or spectral curve for each pixel. A spectral cube representation is displayed below.

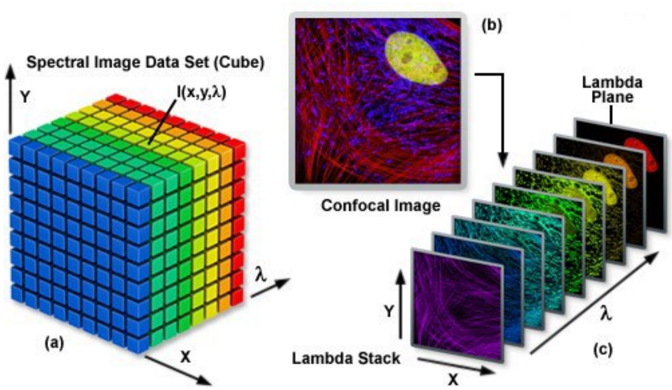


Fig Spectral Cube (Lamda Stack) [21]

Essentially the whole spectral cube construction process is to achieve imaging with spectral information (denser in continuous in hyperspectral imaging) for each pixel of the image. Data stored in a spectral cube is a stack of images of the same object or scene, an image captured for each wavelength independently. Such data demand software to be accessed and used for solving coloristical problems. To perform such kinds of tasks we first must make sure that our spectral cube is flattened thus calibrated with the equal Energy illuminant (flat) across its spectrum range.

Using such a cube which is considered to be uncalibrated with the right software pixel manipulation can be used to perform calibration transformations to given illuminants. Analysis software will be able to recognize features of DB Illuminants (e.g. emission in NIR region or not). Spectral imaging can use the spectral signatures as a power tool for illuminant spectrum discrimination and use the above for quantification of a continuous spectrum. Hyperspectral imaging can capture full resolution spectral signatures whereas multispectral imaging may prove to be inapplicable because it captures data in sparser manner[23].

Human vision extends to about 700 nm but there's a need in scientific research to see well beyond that, into the infrared ranges. Spectral imaging is very useful because unlike the human vision which is interpreted by the brain as 3 primary colors the digital image systems that can recognize many different color channels can employ spectral data and so in N color space. That means spectral imaging can achieve greater and improved color accuracy and differentiation compared to regular color imaging and even access to spectrums like IR which is information invisible to the human eye.

3.4 Multi-Spectral and Hyper-Spectral Imaging

Spectral Imaging systems are divided in 2 main categories Multi-Spectral and Hyper-Spectral Imaging Systems. The basic parameters that characterize them are the spectral range (the spectral region in which they operate) and spectral resolution (wavelength intervals in the lamda direction) but also the number and width of the bands that are being used[24].

Multi-Spectral Imaging (MSI) refers to imaging with discrete number of bands usually between 3 and 10 in number. That means a multi-spectral imaging sensor is a tool that cannot produce the reflectance spectrum of an object and for that reason Spectral Estimation algorithms are employed to figure out the complete spectrum.

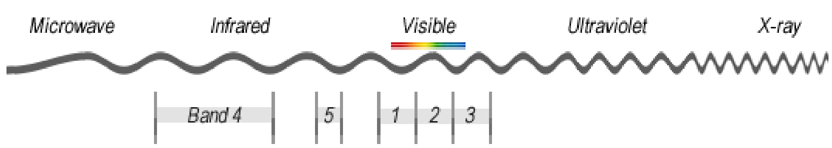


Fig Multispectral Example of 5 wide spectral bands (image not drawn to scale) [22]

Hyper-Spectral Imaging (HSI) deals with the spectrum in a more continuous manner. For example a sensor that covers the spectral range of 500-700 nm with 20 bands of 10 nm interval is considered to be a hyper-spectral one as opposed to a sensor with 20 bands that can cover visible, near infrared, short wave infrared, medium wave infrared and long wave infrared which would be characterized as multispectral (because of range and interval selection). Generally HSI sensors can contain spectral information from 200 continuous bands (or even thousands) thus providing a more complete perspective on a problem.

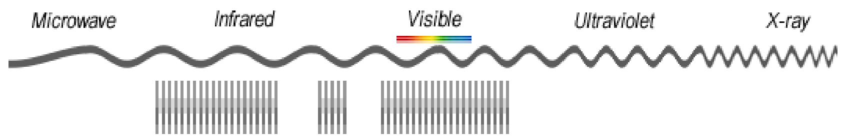


Fig Hyperspectral example of hundreds of narrow bands (image not drawn to scale) [22]

That's why these measurements are more sensitive to the more subtle variations in reflected energy a benefit that multi-spectral measurements don't have.

So hyper-spectral images can contain marginally much more data that are more sensitive to subtle variations in reflected energy compared to multi-spectral images. For example MSI could be used in a forest area mapping task whereas HIS could be used the specific tree species in the same forest area.

To conclude having higher spectral detail in a spectral image produces greater capability to focus in the unseen. HSI requires a certain amount of complexity since for example 200 bands could be employed for an application but it's unknown how many of them display redundancy. Based on application, MSI and HSI can be performed in countless real world applications (Spectral Imaging Applications) enabling scientists to better understand the world.

3.4.1 Spectral Imaging Applications

Spectral images contain lots of useful information that can be used if one knows the relation between the spectrum behavior and the scientific data of the application is about[25].

1 Remote sensing

In such kind of technology it is of outmost importance to differentiate among earth surface features as these features naturally may vary different spectrums will reveal their characteristics. For example multi-spectral satellites like Landsat employ 7-8 bands but a hyper-spectral one can capture earth surface using more than 200 bands which is a huge improvement helping scientists to discriminate objects that were not possible in the past.

2 Seed Viability Studies

A spectral image and most importantly the plot of a reflectance spectrum can produce the viability report for a seed. A viable seed however may appear identical to a non-viable one with simple human vision but these features are revealed by their spectral signature.

3 Biotechnology

Spectral imaging technology can become useful in the biological and medical applications. Being fairly fast and easy to use, it can be used for lab work for wound analysis, fluorescence microscopy and cell biology.

4 Environmental Monitoring

Changes that occur in the environment can be traced with such kind of approach such are C02 emissions, estimate pollution levels and more.

5 Food Vitality

Another important application is the food industry that needs to perform all kinds of inspections like quality control, determine state of decay and sugar estimate distribution. So for example at a production line of apple packaging quality controls can occur that can detect the early bruises of the apples (visible in spectra).

6 Pharmaceutical Products

Spectral data can help with achieving quality control, discrimination between original and fraudulent medicine and estimation of concentrations of substances inside pills.

7 Medical Diagnose

Detection of disease at the early stages (possibly disease prevention method) without the need for biopsy and further contamination of regions of the body. Examples given are detection of cancer types (even at early stages) and retinal diseases.

8 Forensics

Spectral information can be proved to be a useful tool for the Police as it can be employed for tampered document analysis, arson investigations, bloodstains display, comparison among fibers, gunpowder residue identification and fingerprint enhancement. All these could be of great interest to crime scene investigators.

9 Oil and Gas

Detection of onshore oil seeps is also viable with spectral data.

Spectrum to Computational Color

Most modern age cameras employ the RGB Color Space to produce color but in that manner such types of cameras don't actually capture the entire span of radiant energy that created the human visual response.

That's why imaging engineers employ spectral data to reproduce color one of the reasons why is because of the higher color depth that can be achieved (n bands are essentially n combinations of colors whereas RGB is the combination of just 3). A high quality colored image is the image that is considered to be a faithful representation of the outside world represented in a way that the observer sees as true to life. Scientists have developed ways to achieve fidelity with the use of the Standard Observer and the golden standard of CIE gamut and it is the essence of this project to find out ways to represent such true-like color and resolve metameric problems.

A metameric pair could appear as such in the human eye but not in the computational color produced by the camera and vice versa.

3.4.2 Spectral to Color and Gamma

Computational color in order to be true to the non-linear nature of human eye interpreted color must involve the complexity of an important variant called gamma. Without it, shades in a scene captured by a digital camera are not displayed on a standard monitor as they would with human vision. To be more precise this variable defines the relation between a pixel's intensity value and it's actual luminance. Similar terminology used for gamma is gamma correction, gamma encoding or gamma compression.

Important aspects of Gamma

As already commented, human eyes don't perceive light, therefore color, as the cameras would do. A digital camera is operating in a linear fashion, twice the number of photons hitting the sensor results leads to twice the signal as a result. But our eyes don't actually work that way. Twice the light is perceived as being a fraction brighter and increasingly so for higher intensities (hence a non-linear relationship).

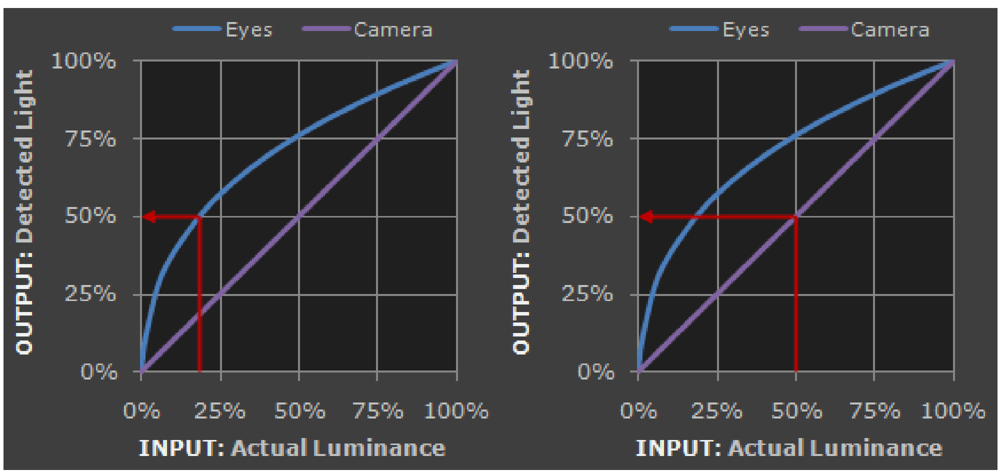


Fig Perceived by our eyes (Left) and displayed by the camera (Right) as twice as bright [23]

Gamma encoding aids to efficient tone storage. Since as explained gamma encoding redistributes tonal levels closely to the way that are interpreted by our eyes fewer bits are required to define a given tonal range. Without it many bits would be assigned to brighter tones (because a camera is more sensitive in that region) and few would remain to be distributed for darker tones (less sensitive region for a camera).

Fig Original Gradient

Fig Linearly Encoded Gradient (5 bits)

Fig Gamma Encoded Gradient

Indeed in the example above, the Linearly encoded gradient is using an insufficient amount of levels for dark tones description and an excess of levels for bright tones (5 bits → 2^5 levels). The Gamma Encoded gradient however performs decently at distributing the tones evenly at the entire image which is considered to be perceptually uniform.

Display Gamma

This is the type of gamma that we are referring to when performing monitor calibration and adjusting contrast settings. For example an image to be properly displayed through graphics card and CRT electronics which apply display gamma so that the human eye can perceive it as if he saw the original scene. The purpose of display gamma is to be applied as a compensation for a file's encoded gamma to ensure that the image is not brightened (in an unrealistic fashion) when displayed on screen.

The imaging industry has agreed upon a standard display gamma of 2.2 so there would be no misunderstandings about the gamma standards. Now if someone would like to perform gamma correction to display RGB values in sRGB Color Space the sRGB transfer function must be used (located at the Appendix under section Gamma Companding functions).

3.5 Spectra and Illuminant Estimation

Manufactured devices don't render color as they should according to the illumination of a scene and that leads to the creation of misleading colors. All this imply that achieving color constancy is an ill-posed problem. Searching for an accurate illuminant estimation is hard due to the ambiguities of unknown reflections and local patch appearances. So the issue is how to make an electronic device that captures images to become color constant (a process that is also known as white-balancing), to be able to simplify incident color signal to its components which in this case are the illuminant and the reflectance on the scene.

Currently, digital imaging is based on the fact that systems "see" only in the visible part of the spectrum using the RGB model which states that color constancy can only be achieved by information from that region or assumptions about the illuminated scene. Most popular algorithms that make such assumptions divided in two categories statistical-based and learning-based. Some statistical-based examples are[26]:

Gray World

This algorithm states that in a balanced photograph the average of all the colors is a neutral grey illuminant cast. So the illuminant of the scene can be found with a simple comparison of the averaged color and grey.

Simplest Color Balance

In a balanced photo brightest color is considered white and the darkest black. A removal of color cast with histogram scaling of RGB (0-255 values) can occur and outliers can be dealt with (%) saturation. This automated method is used in Adobe Photoshop creative program developed for image editing.

Robust Auto White Balance

In this case slightly off-gray candidates based on YUV coordinates will reveal the illuminant. A parameter is set to represent the off-gray threshold and based on that algorithm performance is changed. More functional in video cameras whereas gain can be changed easily in an automated way within just a few frames.

But using the near infrared information much more can be achieved. Data captured by spectral cameras at the visible and infrared spectrum can be the key to color constancy. That's because that the infrared spectrum allows for a bigger spectrum to be thoroughly examined together with visible. With a glance at the Spectral Power Distribution of some of the most common illuminants (fig displayed below generated by program).

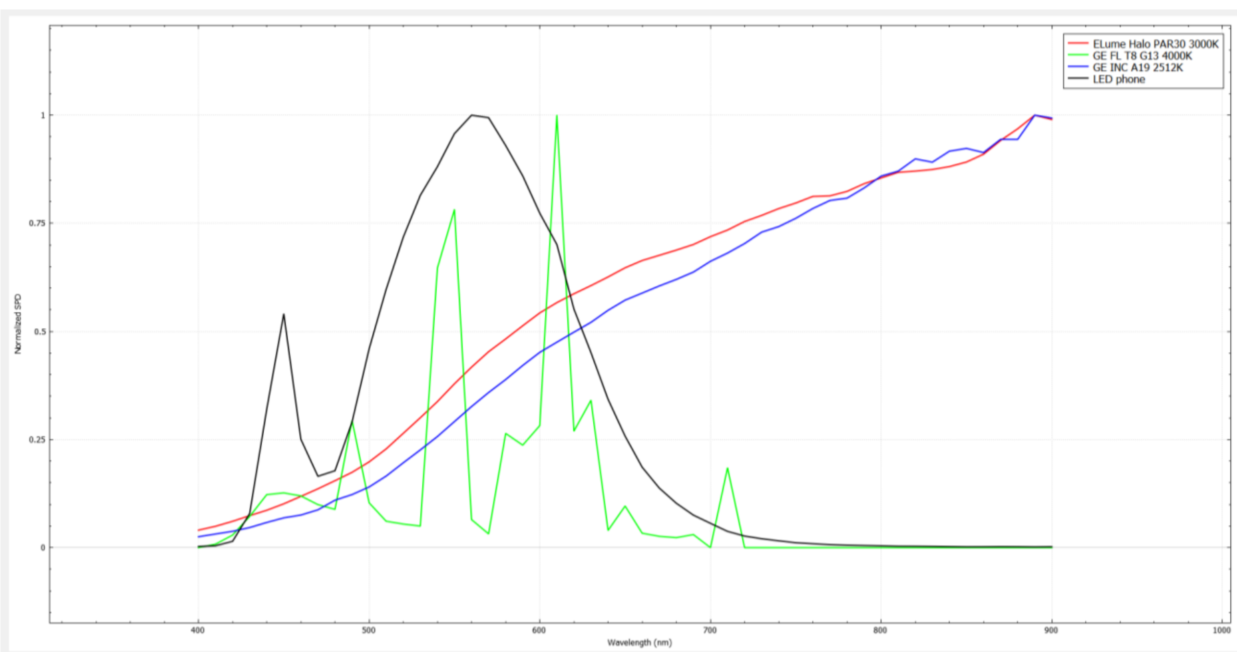


Fig SPDs of common Illuminants

We can see that both Led and Fluorescent Lamps virtually have no emission in NIR (feature that can be exploited for illuminant classification) and also Incandescent Lamp is an order of magnitude higher in NIR compared to visible. These spectral characteristics are of outmost importance for the purposes of illuminant estimation.

4 Technical Part

4.1 Project Approach

Generally, illuminant estimation can be applied to calibrated Spectral Cubes (where the Cube is calibrated to the sensitivity of the camera's sensor) and to un-calibrated Spectral Cubes (where the Cube is not calibrated at all and the reflectance data is indistinguishable from the spectral data). As a problem this has 2 unknown parameters in un-calibrated case: the illuminant I(λ) and the reflectance R(λ) at a given wavelength if the sensitivity of the camera is known. However, when calibration is applied the reflectance parameter can be found so the only unknown parameter will be that of the Illuminant.

Before choosing an approach there's been a search on the most recent illuminant estimation approaches in the scientific world and we concluded to 2 different approaches:

1) Multispectral Imaging with statistical algorithms[27]

In this approach popular statistical algorithms (Gray-World,Max-RGB,Gray-edge) are extended to use multispectral data (N dimensions) to acquire the estimate of the illuminant in the sensor domain.

2) Illuminant estimation using NIR ratios[28]

Following the paper's teaching in this project's approach the difference is that we create un-calibrated spectral data using a calibrated cube multiplied with Illuminants (data simulation). The initial Illuminant (scene illumination) is given by user as input, while the rest are contained in the database (described in Dataset section) used for spectra comparison.

The paper elaborates extensively on the significance of the NIR in Illuminant Estimation problem and the fact that the doubling the estimation range makes the process easier. As for the Illuminant estimation itself, the NIR Imaging paper states that ratios of VISIBLE band data over a selected NIR band data will give off the information that will reveal features of the input spectral signature and could be compared to those of the database (these data are included in the formed un-calibrated cube). Below there's an example of the ratios at specific wavelengths of an incandescent lamp (red line) and its' spectrum[28] (blue line).

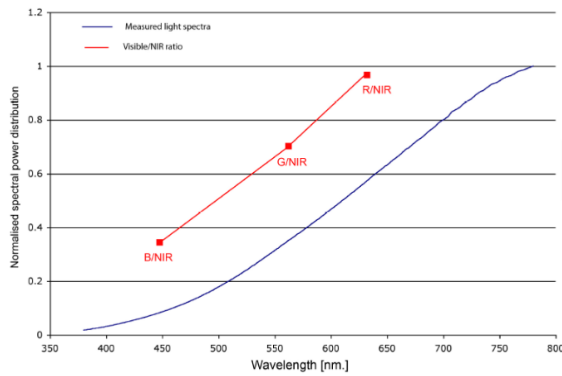


Fig Full INC Spectrum and Ratios of RGB over NIR channel [24]

Scaling the problem not to 3 but to n bands we have n-1 ratios n are the bands (VISIBLE+NIR) that are selected for the estimation range (given the fact that the ratios are reduced by 1 because of the division). However, there's the problem of division with 0 (not all illuminants have emission in NIR so the denominator could be zero in cases of Led or Fluorescent Lamps). That means in cases of no NIR emission a different approach should be followed and that would be of simple mean of band data, instead of ratio, for all the wavelengths selected with the last being excluded as it would always be 0. Ratio and mean values will be denoted as metric values from now on.

Also, it was found that ratios alone are not good enough of an approach to search for closest observed illuminant (COI) spectrum in the database. So for the ratio case the mean of NIR band data was added separately and accounted for the search too. However, the algorithm needs to decide whether to apply one method or another during execution time and for that reason NIR emission must be evaluated. In order for this approach to be more realistic Gaussian noise is added to simulate the noise of the system and this is going to affect the COI extraction results so it's this project's task to find an acceptable threshold for that matter. Also thermal noise is to be considered set to be at 4/255, a threshold that is defined according to spectral camera experiments. Subsequently, the metric value at 900 nm (a limitation explained in Description of Experimental Setup Section) is compared to that of the thermal noise (validity check) to decide whether NIR emission occurs. Of course, that means NIR emission implies search in the Database for NIR emissive illuminants only and same logic applies to non-emissive illuminants (exclusion approach). Results are attached to the Results and Elaboration section of this thesis.

After COI extraction one must evaluate the results not only from the similarity of the spectral signatures but from the chromatic differences derived from the spectrally reconstructed images after these have been gamma corrected (Appendix: Gamma Correction Formulas). So for that reason a colored image is to be produced from the spectral data of the input illuminant and another one from the 1st COI as well. Spectrally reconstructed colored images are images that are constructed from the un-calibrated cube and afterwards gamma corrected according to sRGB Color Space standards (Gamma Correction Formulas). Images created from this task should contain the true-like color that's not overly saturated or dark and when comparisons between original and COI occur they must not have high deviations at DE values. From now on by DE we will denote the CIE 76 Delta E color difference metric (Appendix: Color Difference Metrics)

Light and device independency can be achieved through this pre-processing. Note that this procedure is implemented using spectral data and aims to the creation of colored images, produced from an equalized based on white, un-calibrated cube. That alone differs from the traditional White Balancing algorithms which are considered to be post-processing procedures so the results yielded are going to be different and not comparable by nature.

4.2 Materials and Experimental Equipment

Simple Description

During this project there was the immediate need of a golden standard in coloristical problems and that was the Xrite Color Checker SG 140. From this chart we formed a spectral cube using the MUSES9-HS and measure the spectrum of different Illuminants with the use of USB 4000 VIS-NIR (Ocean Optics spectrometer). Color fidelity needs to be achieved in concordance with spectral and color difference metrics and that is where the Qt developed program will perform the necessary calculations to match and compare spectrums at both.

4.2.1 Colorimetric Chart Xrite Color Checker SG 140

The Digital ColorCheker SG target is a tool that is specifically designed to apply for the needs of digital imaging. It includes 140 patches that were chosen for their location in the color space so that they can expand the color gamut while being of reference to highest quality available.

It is a target that contains the colors of Standard ColorChecker target with colors which represent natural objects, human skin tones, foliage and blue sky. The additional skin tone reference colors exist to aid for greater accuracy and consistency over a wide variety of skin tones and gray scale steps provide accurate white balancing control for neutral tone regardless of lighting condition[29].

Important note is that while 24 patches of the chart have colors similar to the original ColorChecker and are laid like so there are also 44 patches on the periphery of the target are in fact pattern of 3 neutral patches (white, gray and black). A total of 14 patches were selected to simulate the appearance of various skin shades (beyond the 2 of the original ColorCheker) and many saturated were added for color gamut extension in order to better match the sensors of digital cameras.

However, the chart has a Semi-Gloss finish (thus the acronym SG in name) so the chart colors are not the same as in the other ColorCheckers[30]. So any related future work related to the classic ColorChecker or data derived from it is not to be associated with results and data derived from this chart.

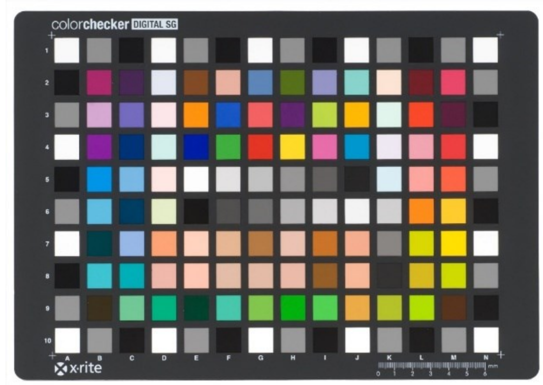


Fig Color Checker Digital SG [25]

Physical Details

Array of 140 colors with 24 patches originated from regular 24 ColorChecker, 17-step gray scale and 14 unique skin tone colors. Totally there are 14 columns and 10 rows of patches of semi-gloss surface.

Every colored square is constructed so that it can reflect light in the same manner as its' real life equivalent color in the whole visible range independently of illumination and color reproduction process.

4.2.2 Hardware

4.2.2.1 MUSES9-HS

For the project needs a camera was demanded that had spectral capabilities. The camera that has been used was MUSES9-HS, which is a handheld hyperspectral camera system for field use that has various modes, can acquire and display data at both invisible and invisible bands. While it is operating at the 360-1000 nm range (ultraviolet-visible-infrared spectral regions), the system collects a stack of images which constitute a spectral cube and each image corresponds to a spectral band. The whole spectrum can later be calculated for every image pixel (a vector rendered in multidimensional spectral space).

Tunable filter	
Wavelength tuning range	360-1000 nm (extendable)
Bandwidth (FWHM)	7-18 nm
Light throughput (efficiency)	75-95% (unpolarised)
Tuning speed	Few seconds even snap-shot/realtime
Control	Computer control
Operation modes	Color and Spectral Imaging
Camera's sensor	
Sensor-type	CMOS
Sensor dimensions	1/1.8"
Thread	C-mount or F-mount

Resolution	6.4 Mega Pixels (3096 x 2080)
Sensor Size	7.4 mm x 5 mm
Diagonal	8.92 mm
Exposure Range	32 µs – 1000 s
Focus Distance to Sensor	12.5 mm
Interface / Data Acquisition Protocol	USB 3.0
Dimension	ϕ62 mm x 36 mm
Working Temperature	- 5°C – 45°C
Data Transfer Speed	Higher than 1Gbps (USB 3 or GbEth)
Sensor's cooling	Not necessary due to high light throughput
Supported Resolution	10bit ADC/14 bit ADC,3096x2080 60fps / 30fps, 2560x2048 62fps/ 31 fps, 2048x1080 116fps/ 58fps, 1280x980 130fps/ 65 fps, 800x600 204.7fps / 102.3fps, 640x480 253.1 fps/ 126.5 fps, 320x240 479.7 fps/ 239.8 fps and user defined
Lens	
MUSES9-HS system is equipped with a 16 mm C-Mount lens, with an aperture range from f/1.4 to f/16, focusing range from 300mm to Infinity and the Field of View @ Min Working Distance is 125 mm. Nearly all types of lenses can be used with the proper adapters (not provided in the package).	

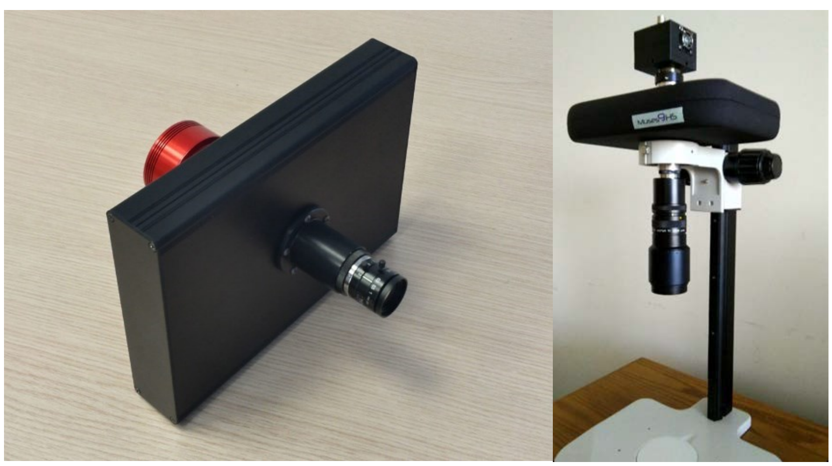


Fig MUSES9HS standalone & mounted on stand [26]

The camera system itself is accompanied with user friendly interactive software for easy data acquisition and extended system control over light with calibration functions (light source selection flexibility). It is compatible to stationary and mobile computer platforms (laptops, tablets). Equipped with high-resolution CMOS sensor produces images of very high quality details and along with a C-Mount focus system offers high flexibility over lenses selection (may be extended with adapters). Also simultaneous spectral imaging can achieved across UV-VIS-NIR spectrums. This particular camera is used for calibrated Spectral Cube capturing purposes.

Calibrated spectra cube as a term means that the spectral data contained are affected only by the camera sensitivity itself and the calibrations in it and those parameters are unaffected by the Illumination in a scene. The un-calibrated spectral cube implies that Illumination complexity is added to the calibrated spectral information[31].

4.2.2.2 Spectrometer: Ocean Optics USB 4000 VIS-NIR

The tool we are using to make the spectral reflectance measurements of a surface is the USB4000-VIS-NIR. A small in size spectrometer that is configured to measure in both the visible and the near infrared spectrum. With an effective wavelength range of 350 to 1000 nm this high-performance device provides high flexibility and more applications can be made with it. This device using the necessary sampling equipment can produce valuable information about the illumination in the scene. Besides the modular nature of the product and its' fast integration time it's highly portable so one can bring it directly to the sample source. It implements triggering functions and it can be compatible to other devices without the use of external power[32].

Fig USB4000-VIS-NIR [20]

Product Specifications

Physical details	
Dimensions	89.1 mm x 63.3 mm x 34.4 mm
Weight	190 g
Detector details	
Detector	Toshiba TCD1304AP (3648-element linear silicon CCD array)
Range	200-1100 nm
Pixels	3648
Pixel Size	8 µm x 200 µm
Pixel well depth	100.000 electrons
Spectroscopic	
Optical Resolution	~ 0.1 – 10 nm FWHM (config. Dependent)
Signal-to-noise ratio	300:1 (full signal)
A/D resolution	16 bit
Dark Noise	50 RMS counts
Dynamic range	3.4 x 10^6 (system); 1300 single acquisition
Integration time	3.8 ms – 10 s

Stray light	< 0.05% at 600 nm; < 0.10% at 435 nm
Corrected linearity	> 99%
Electronics	
Power Consumption	250 mA @ 5 VDC
Inputs/Outputs	8 onboard digital user programmable GPIOS
Connector	22-pin connector

This colorimetric tool can be used to operate in multiple kinds of experiments like Absorbance, Color Measurement, Irradiance, Reflective & Transmittance scenarios. In the project approach, it is mainly handled as a Reflectance measuring device.

4.2.3 Software

During the development of this project different kinds of programs were used. These are:

Spectra Suite: Official interface of Ocean Optics that comes along the USB-4000 hardware for the spectroscopic measurements. This program allows for measuring the spectral reflectances of colorimetric chart patches under the light sources on lab's possession. For more precise results the program can perform averaging of frames to reduce noise and with built in function can plot the hyperspectral camera patch measurement on CIE Chromaticity Diagram.

Qt Framework: This project is developed on the Qt framework because of its potential of a non-deprecated programming language like that of MATLAB but C++ with extensions including signals and slots logic. Particularly its ease of use makes construction of a friendly User Interface relatively easy. Also a lot of optimization can be done for long and demanding tasks in order to reduce the CPU load. Finally, the Qt-based application will have cross-platform attributes meaning that can be run on various software and hardware platforms.

ImageJ: As an open source image processing program designed for scientific applications of modern imaging proved to be useful as it is easy to use for fast feature observation. Imaging tasks like image stacking, division of images to the primary channels image histograms and calculations of image differences etc. are already implemented and ready to be used.

4.2.3.1 UI application structure

The application that is created is a window that changes based on user actions. Totally it has 3 pages the main one, the imageStackDialog one whereas the user can give a spectral cube as input and choose an Illuminant and the ShowStacked that takes the colored image that is made out of the Spectral to Color process from imageStackDialog ui and displays it.

The Qt implementation uses 3 already implemented classes:

CustomView Class: (developed by the Technical University of Crete photonics Lab) for image manipulation (zoom in, zoom out) and intuitive interaction handling (drag plot).

QCustomPlot Class: (found in the internet with Default license GPL given for free use) implements the functionality of drawing various Plots and handle events that happen inside the ui. (http://www.qcustomplot.com/)

QtXlsx Class: free for use for generating, extracting data and editing existing .xlsx files. Also, it doesn't require Microsoft Excel to be installed to operate correctly. (http://qtxlsx.debao.me/)

Main

It is the first ui that user comes upon and has the functionality of giving the user access to other ui that are available. A press open Image Stack button under File Tab will display to the user the ImageStackDialog ui while a button press on Illuminant estimation will diplay the Illuminant Detector ui. Main functionality of this ui is to be able to browse file explorer for a png image of 24 big and split it in its primary R,G,B channels (grayscale).

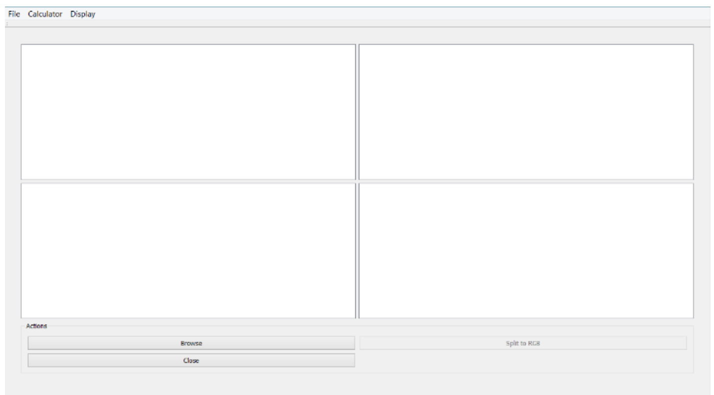


Fig Mainwindow ui

ColorSpaceConverter

This ui will provide Color Space transformations between 3 Color Spaces necessary for the program functionality at other ui. It implements the linear Algebra equations that represent transformations between sRGB, CIE XYZ and CIELAB Color Space. The user has to define if gamma correction is applied or not (default value 1), if there's going to be a chromatic adaptation and choose the illuminant itself. Afterwards with a press of the corresponding button the 3 tupples of each RGB, XYZ, LAB Spaces will be filled and the produced RGB color will be rendered near the transformed values.

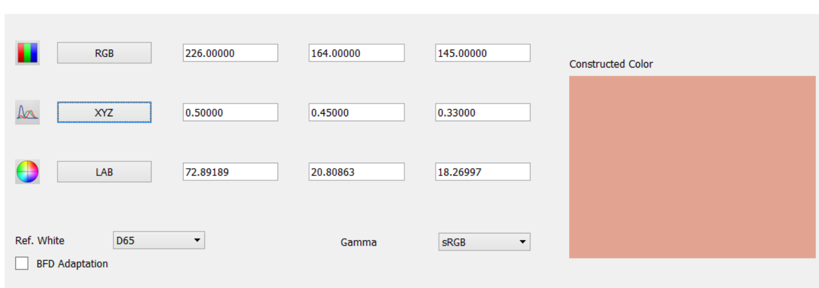


Fig ColorSpaceConverter ui

GraphPlotter ui

The GraphPlotter ui (ui derived from QCustomPlot) is used to draw plots also supports plot selection and display features. In the Standalone version (under the Display Tab) the user is prompted to select multiple excel files of illuminants to be plotted. On left click events upon a drawn SPD, the interpolated line and the plot name become highlighted in blue and while the user hovers the mouse back and forth wavelength and relative power values are displayed above the data points. On legend plot name click events the corresponding SPD will be hidden and on double right click event all hidden SPDs will be revealed again. Also, there's the functionality of right events that pops a menu prompting the user with options like selecting his own custom SPD to be plotted, delete a certain SPD (enabled when SPD is already selected) and delete all the SPDs plotted inside the graph (that functionality is enabled at imageStackDialog ui). The initial QCustomPlot functionality is supported and has not been changed.

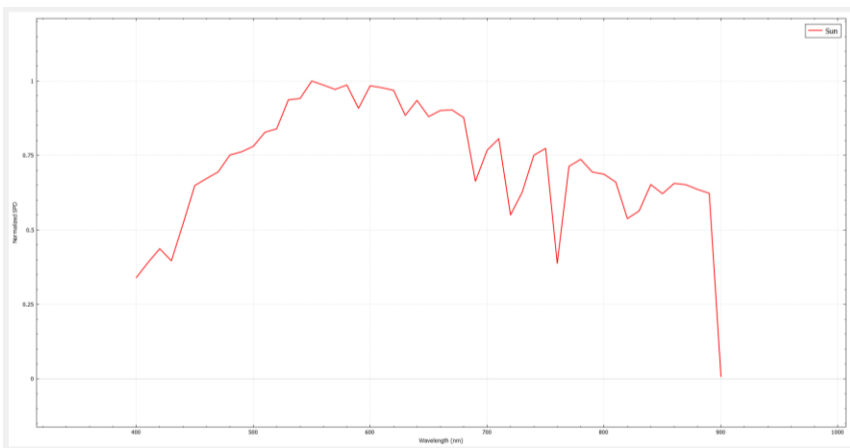


Fig GraphPlotter ui

imageStackDialog

At this ui the user can define the spectral bands that can be used as input (they must be at visible spectrum). Then optionally selects to plot the SPD of the Illuminant (via GraphPlotter ui) that he chooses from the combo box or select a custom illuminant of his own (GraphPlotter menu here doesn't let the user add custom graphs on plot). If the Custom Illuminant intensity values do not match the bands that the user gave as input, the illuminant will be declined and an error will pop up. To proceed to the next ui which handles color differences calculations the user simply needs to follow these steps and press the ok button or simply press cancel to return to the main page.

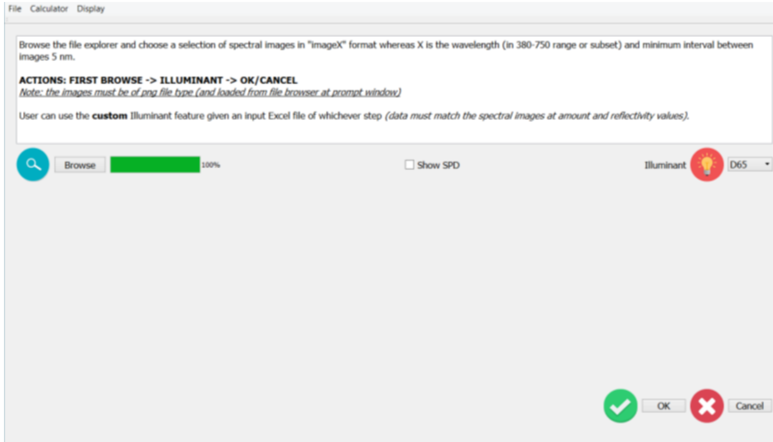


Fig ImageStackDialog ui

ShowStacked

This ui will take the image that is produced by the spectra to color process and display it on the first window. At this point the user is given the functionality of changing the cube he previously selected by pressing Insert Cube button and that sends him back to ImageStackDialog ui to use the previous ui. However he can simply press Change illuminant combo button to change the illuminant he used or set a custom one and then a new image is created accordingly (spectral bands remain unchanged). To point out the whole functionality of this ui one must understand that in order to find the minimum bands needed to achieve color fidelity we must make comparisons between the images we make. That is the reason we have 2 windows that can display images created from spectral data. So after a second image has been initialized and it is under the same illuminant as the first one (colorimetry rule stated on DE difference) we can start the DE comparisons. It is to be noted that this particular ui can also be used as a standalone ui for colored images to be compared but user must be alert since no different illumination check occurs (DE colorimetry rule).

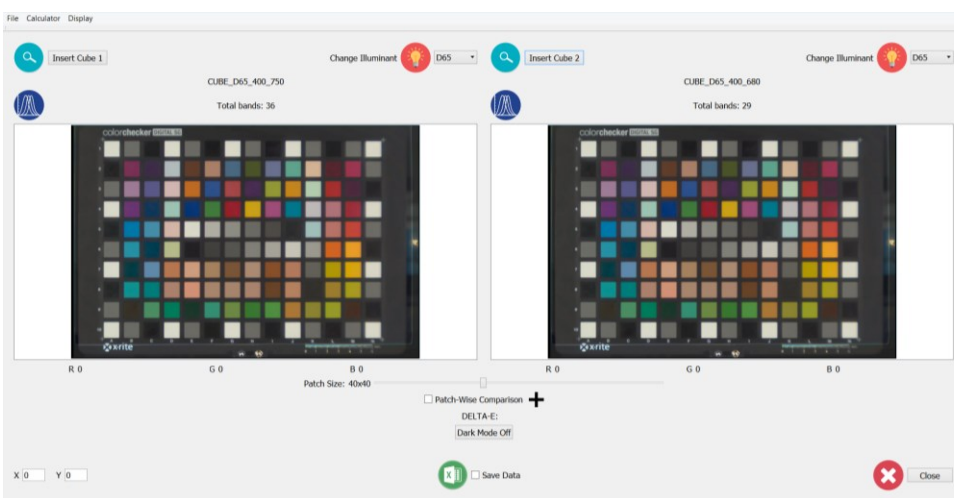


Fig ShowStacked ui

On click events on whichever part of the image (except from outside its bounds) cause a change on the R G B text boxes under the image showing the values of the channels at the exact click point. Also when user has both images initialized he can perform DE comparisons with click events. By default a DE comparison is a point-wise comparison of the point where the user has clicked. The user can also use the patch-wise comparison which generally represents better what the difference is that we are seeing by calculating differences inside a patch with the center being the click point and then averaging them out (for ease of use the user also can change the size of the patch to match his needs by clicking the checkbox of Cross/Square). The DE result is displayed under the image with color (red, gold, green correspondingly if DE belongs to cases DE >2.3, 1 <= DE <= 2.3, 0 <= DE < 1 and gray if second image is not initialized). In order to aid the user to distinguish color differences the Dark mode is available (all functionality is disabled so comparison parameters must be set before enabling it) and the ui is turned black at the push of Dark Mode button

Besides this functionality user can export the results of the DE comparisons on .xlsx format (with Save Data option). Inside the generated .xlsx the first row will show RGB data of both images, second row will show LAB data and third will show if click or patch wise comparison was executed and the result (at patch wise comparison the RGB, LAB values are those of the center).

IlluminantDetector

The Illuminant Estimation approach lies with this ui and with it the functionality of recognizing a pattern of spectral signature inside an Illuminant Database. The user can browse for spectral data of a cube and set an Illuminant or automatically change current one (this will be the known since this is the trained approach version). User must set the Gaussian noise parameter of standard deviation before selecting the illuminant input (mean value is 0).The program will figure out the Illuminant SPD for the selected wavelengths and display in the first window the SPD values and in the second the corresponding Metric values (ratio values or mean values) via GraphPlotter ui. Note that in the Illuminant Detector ui the menu that pops on right click events has been disabled.

Then with the extraction of COI list option the program searches in the given database to find the COIs and display (SPD and Metric values) of 4 of nearest (first is the known illuminant itself since it also exists in DB and the rest are the immediate COI after that comply to the criteria) and displays near the loading bar how many Illuminants had actually useful information, thus of compare value in the entire database. Elapsed time information is displayed too when the COI extraction process is completed successfully.

Finally, the user has the option to plot the full Spectrum of those Illuminants across the 400-900 nm range with Plot Full COI Spectrums and Export to Excel the extracted COI list (4 illuminants) along with their SAM values.

Spectral 2 Color option will make a colored image out of spectra for the input illuminant and then will make colored images for the 1st COI that has been found and save them. The user optionally can display them too after a windows prompt has popped.

The Clear all option is to reset all parameters even the history of extracted COI lists.

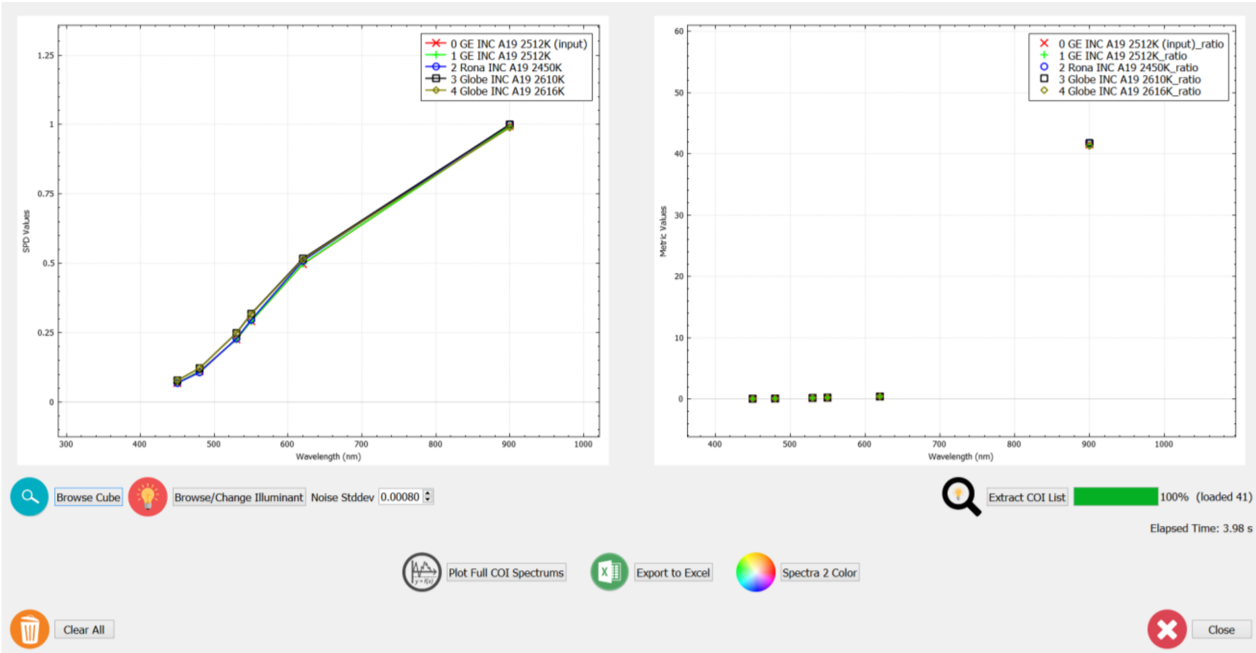


Fig Illuminant Detector ui with search results in LSPD of GE INC A19 2512K Lamp

Note: the Plot Full COI Spectrums button will display the noised version of input illuminant but the Spectral 2 Color uses the original input Illuminant (without the noise that is intrinsic to the system) to generate the spectrally reconstructed image.

4.2.4 Dataset

For the experiments conducted in this project 2 datasets where used:

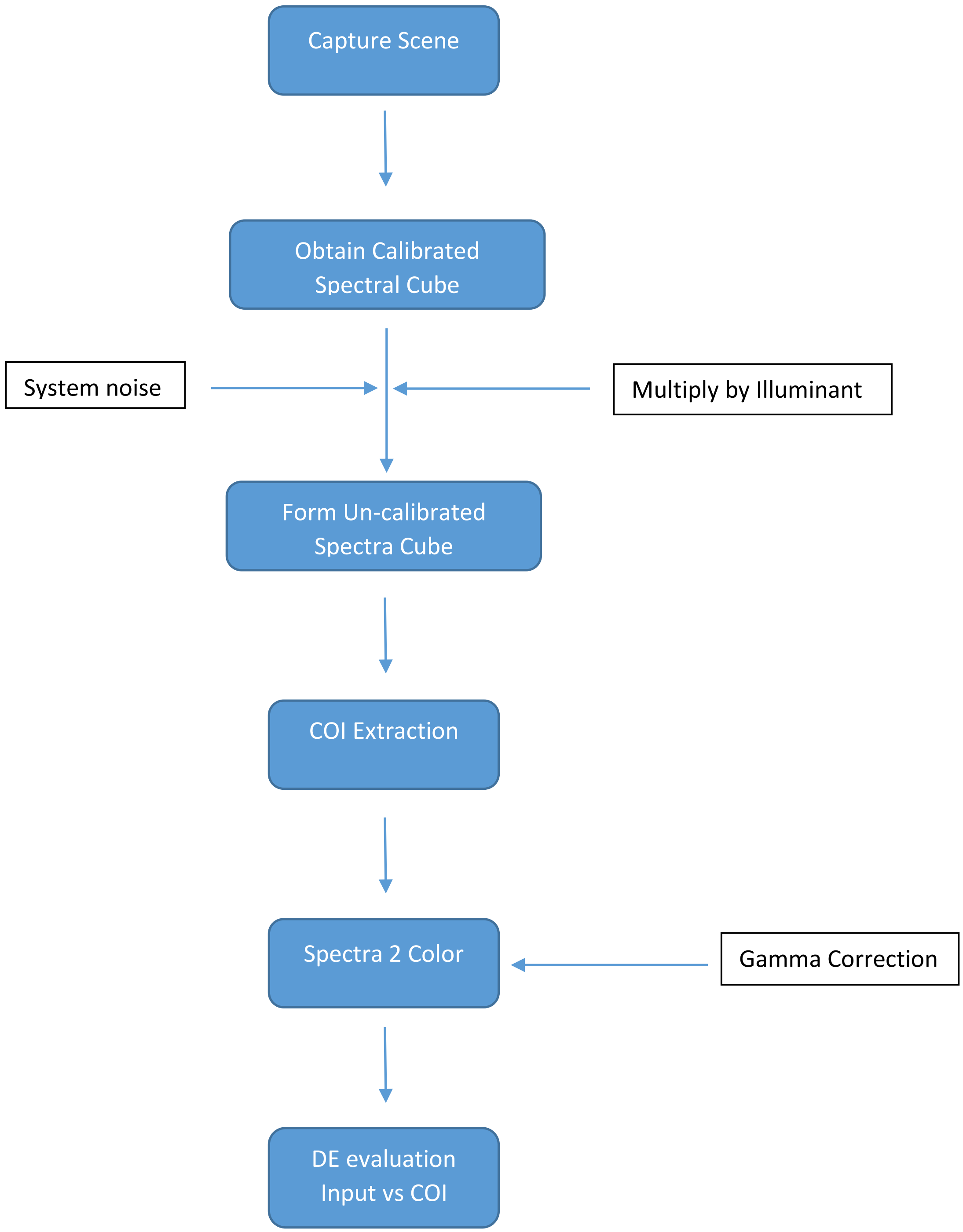
CIE Standard Illuminants

The CIE Standard Illuminants used are A,C,D50,D55,D65,D75.

LSPD DB

The LSPDD (Lamp Spectral Power Distribution Database) distributed online (www.lspdd.com) for public use from which 170 illuminants (6 different types) spectral data where taken and then were normalized to SPDs.

4.2.5 Color Formation Flowchart



4.3 Description of the experimental Setup

For the experiment it was discovered that using the ColorChecker spectra with subtle changes of NIR paper[28], namely using additionally the mean of the NIR image, results acquired could be more optimized COI approximations.

To be more specific using the second Setup (450,480,530,550,620 & 900) without the extra NIR information (5 data) and with the NIR (6 data) produced the following results using the SAM metric. Note that results below refer only to the illuminants of the Dataset that are emissive at 900 nm.

5 data points vs 6 data points

HALO

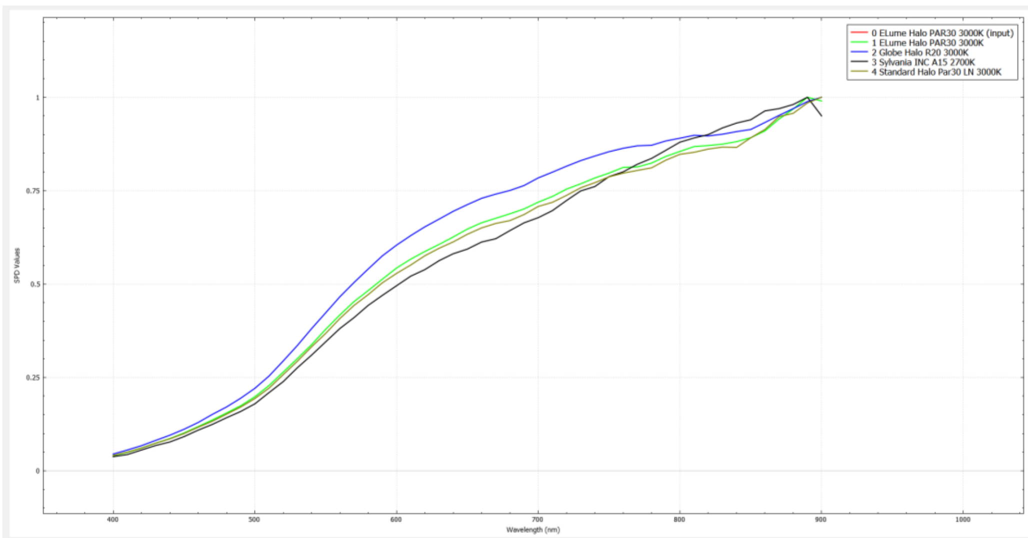


Fig HALO 5 data setup

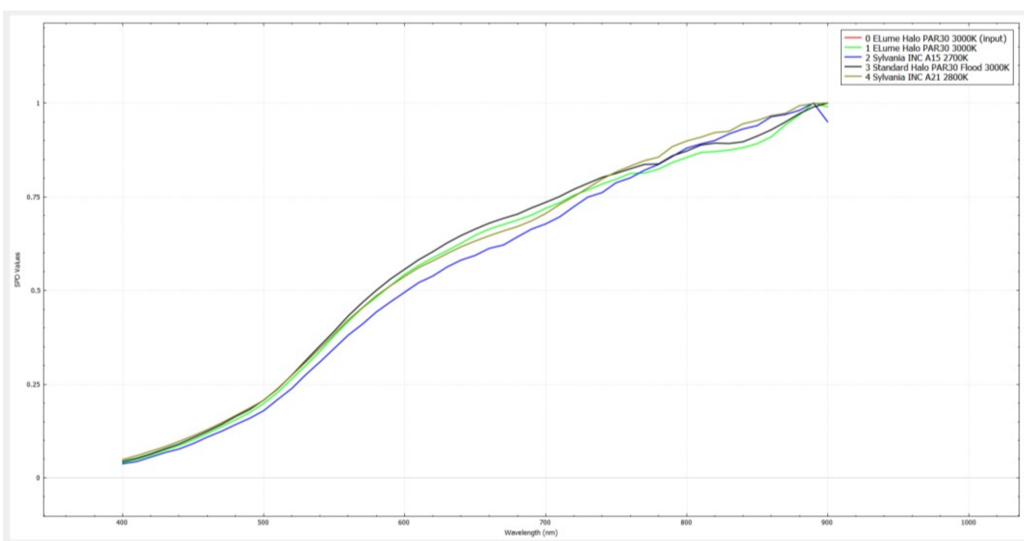


Fig HALO 6 data setup

INC

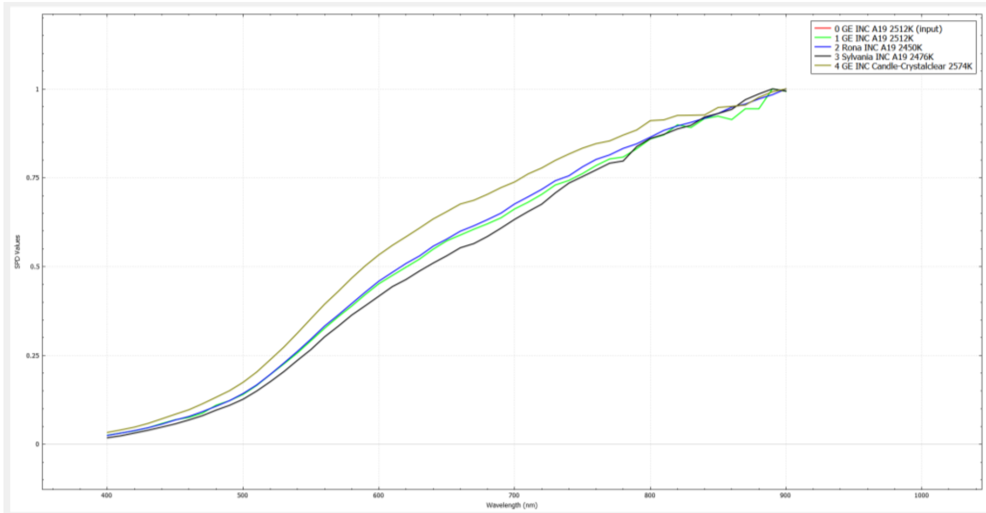


Fig INC 5 data setup

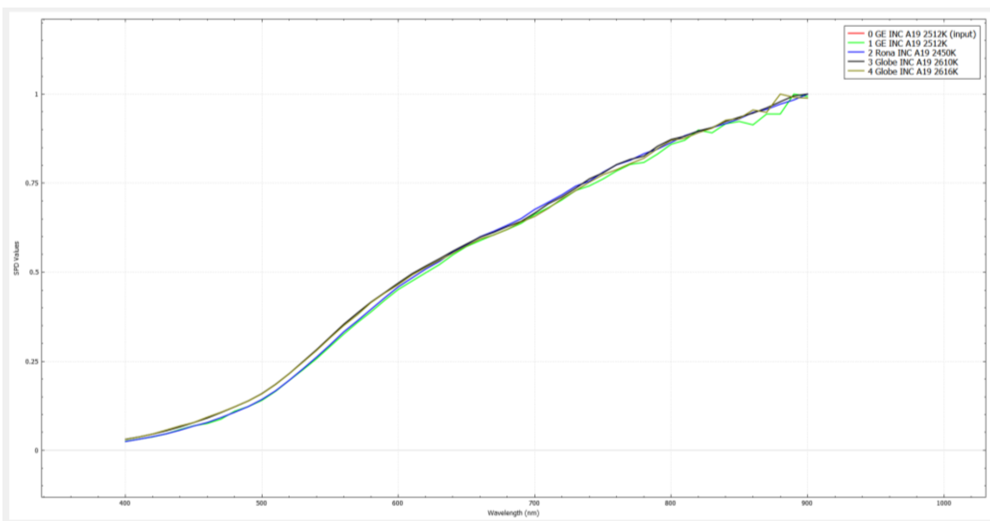


Fig INC 6 data setup

From the results one can conclude that in cases of incandescent and halogen lamps the extra (mean) NIR information yields better COI List results compared to results without it so the implementation that utilizes both visible and nir data is used.

Naturally this implementation lacks of spectral band selection flexibility but it is a limitation of the lab equipment and that's the reason of the band selection for the 2 experimental Setups. This innate flaw of this approach must be reminded at results review since sometimes it could jeopardize the results of the COI extraction. For example, the band intensity information at 900 nm that is used for NIR emission detection cannot be sufficient when the NIR emission occurs at 850 nm.

4.4 Results and Elaboration

In this results section we are going to elaborate on the scientific results of the spectral to color process and we are going to evaluate them based on spectral and chromatic difference metrics measured on the Color Checker chart.

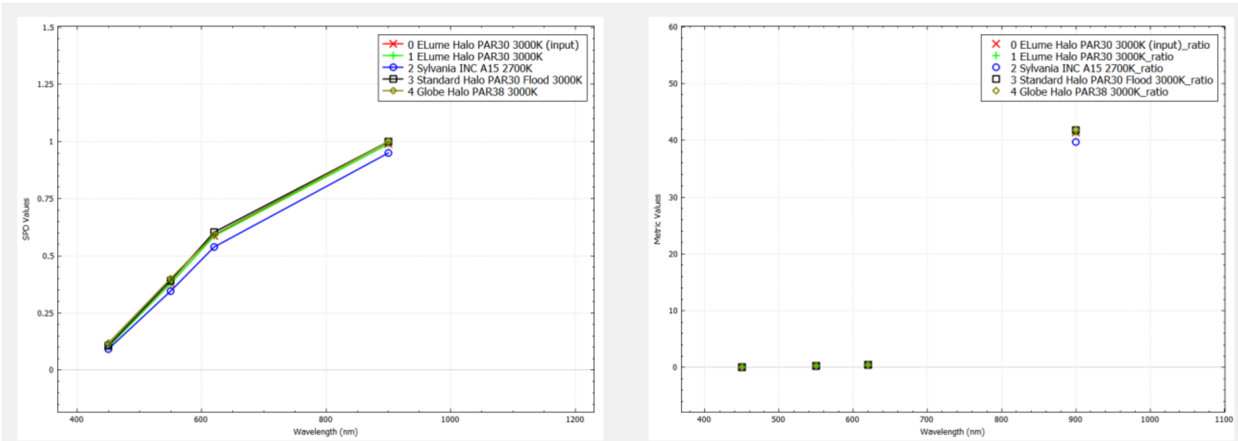
Multiple types of illuminants have been tested in order to prove this method applies to all kinds of illumination scenarios that include Incandescent, Fluorescent, Compact Fluorescent, Metal Halide, High Pressure Sodium (dataset LSPD DB), phone LED and Arcon lamp (last two measured in lab). Note that randomly we selected one illuminant for each type and searched for it in the DB (DB contains the illuminant that is searched) and that the input illuminant spectrum is kept for comparison reasons only not to yield results (illuminant spectrum cannot be extracted from the un-calibrated spectral cube).

4.4.1 Single Illuminant Estimation

For the Single Illuminant Estimation the approach starts under the assumption that the illumination is same at the whole scene, hence single illuminant estimation. The approach is executed as described in the chapter Project approach on Illuminant Estimation with the use of SAM metric. Results of COI extraction and Metric values are displayed in the following pages:

1st SETUP (450,550,620 & 900)

HALO



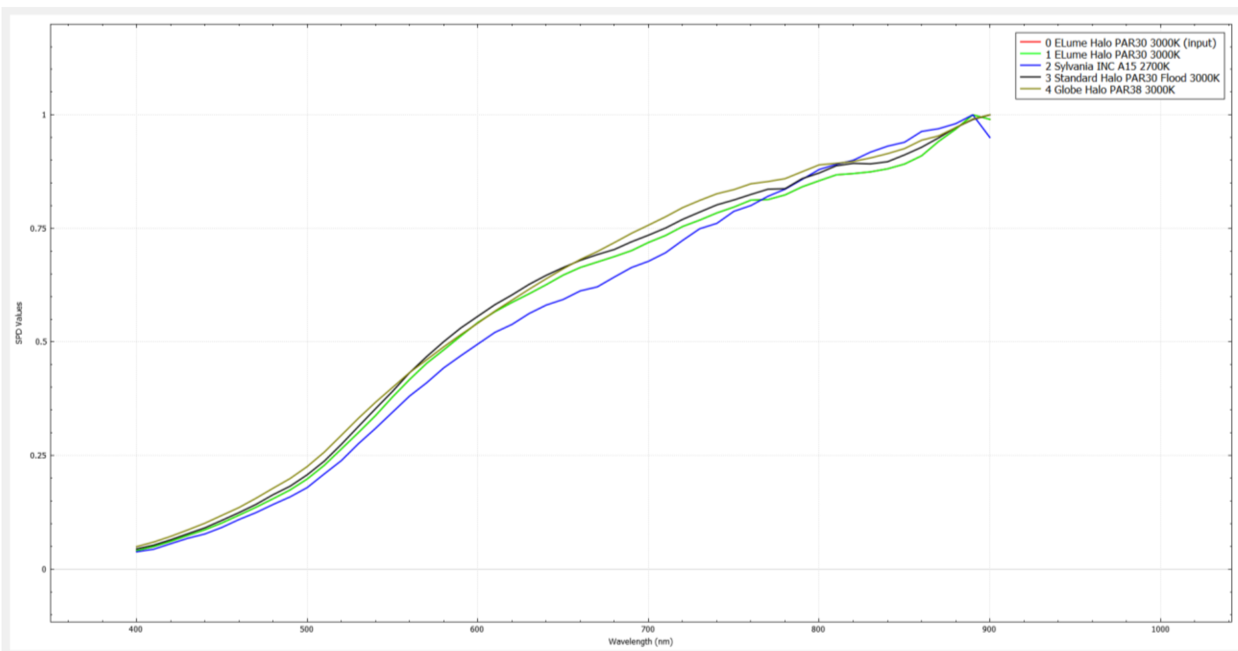


Fig Halo COI extraction (Top) and Full Spectrum (Bottom) at 1st Setup

COI	Metric Value
ELume Halo PAR30 3000K	0
Sylvania INC A15 2700K	8.66404E-05
Standard Halo PAR30 Flood 3000K	0.000131001
Globe Halo PAR38 3000K	0.000342872

INC

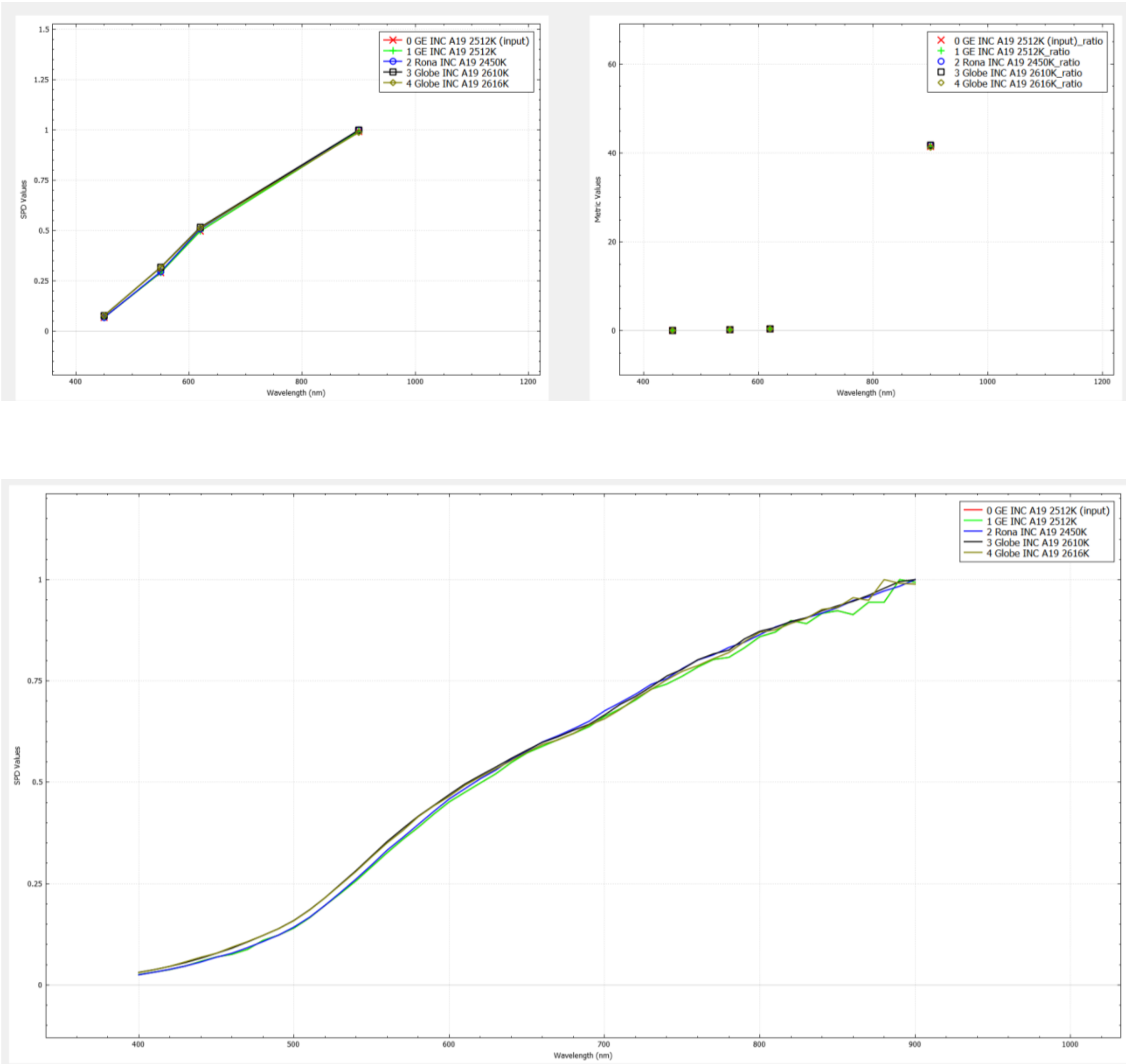


Fig INC COI extraction (Top) and Full Spectrum (Bottom) at 1st Setup

COI	Metric Value
GE INC A19 2512K	0
Rona INC A19 2450K	7.65957E-05
Globe INC A19 2610K	0.000471875
Globe INC A19 2616K	0.000637602

MH

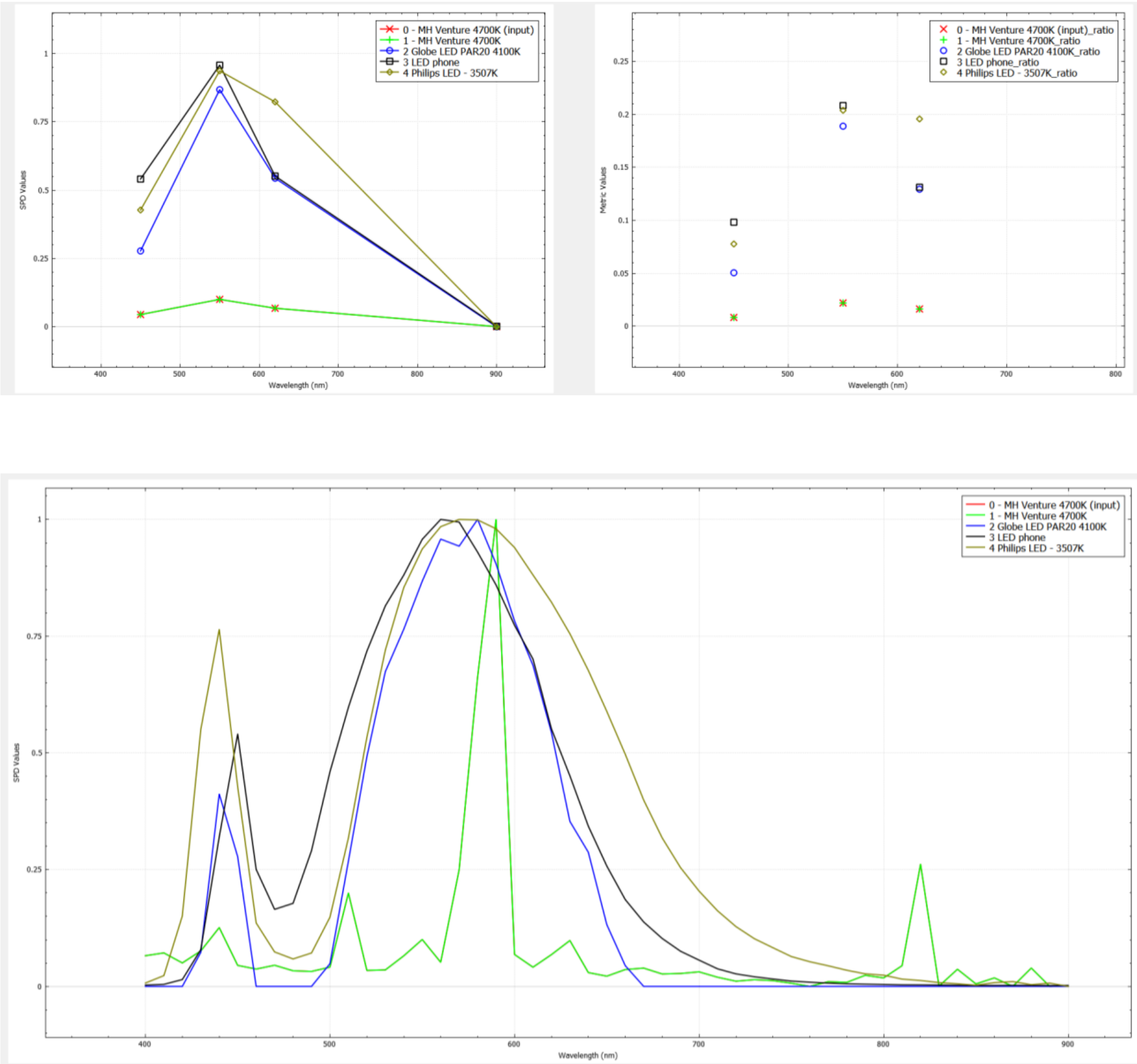
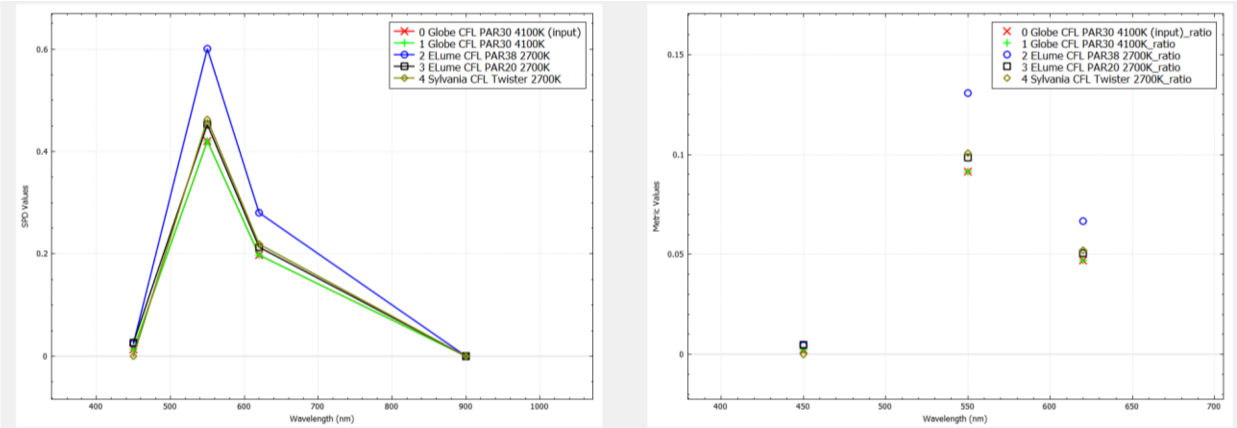


Fig MH COI extraction (Top) and Full Spectrum (Bottom) at 1^{st} Setup

COI	**Metric Value**
- MH Venture 4700K	0
Globe LED PAR20 4100K	0.083077256
LED phone	0.112843361
Philips LED - 3507K	0.124933958

CFL



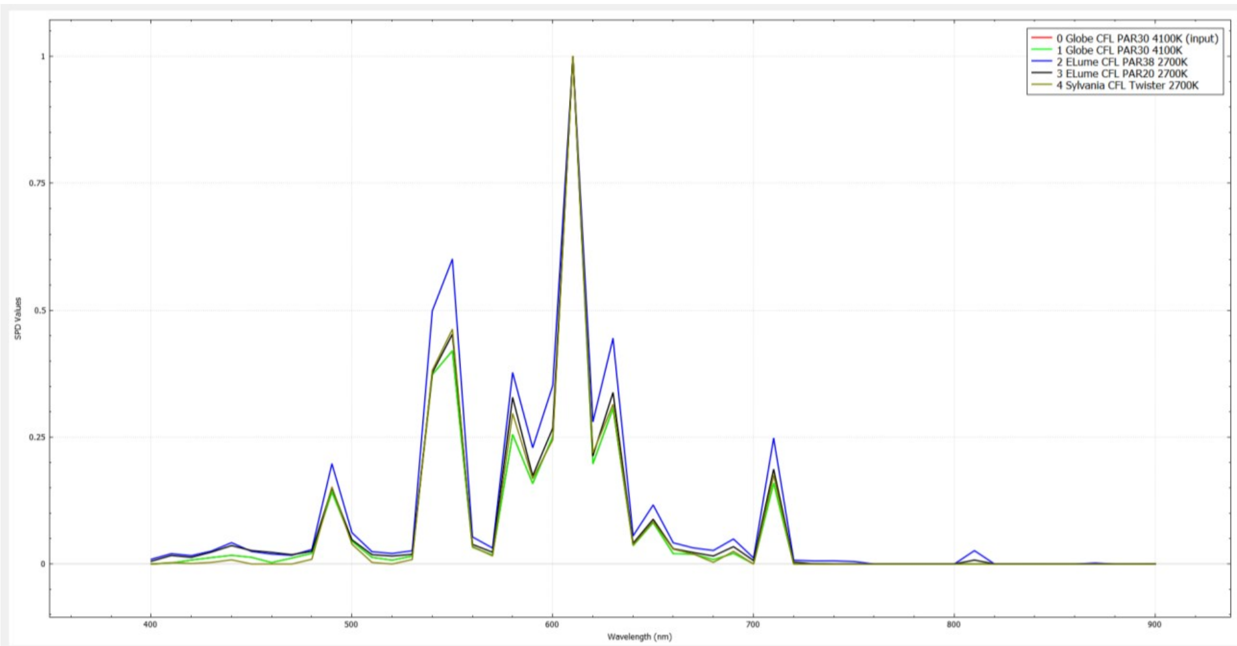


Fig CFL COI extraction (Top) and Full Spectrum (Bottom) at 1st Setup

COI	Metric Value
Globe CFL PAR30 4100K	0
ELume CFL PAR38 2700K	0.008100554
ELume CFL PAR20 2700K	0.020243971
Sylvania CFL Twister 2700K	0.023336432

FL

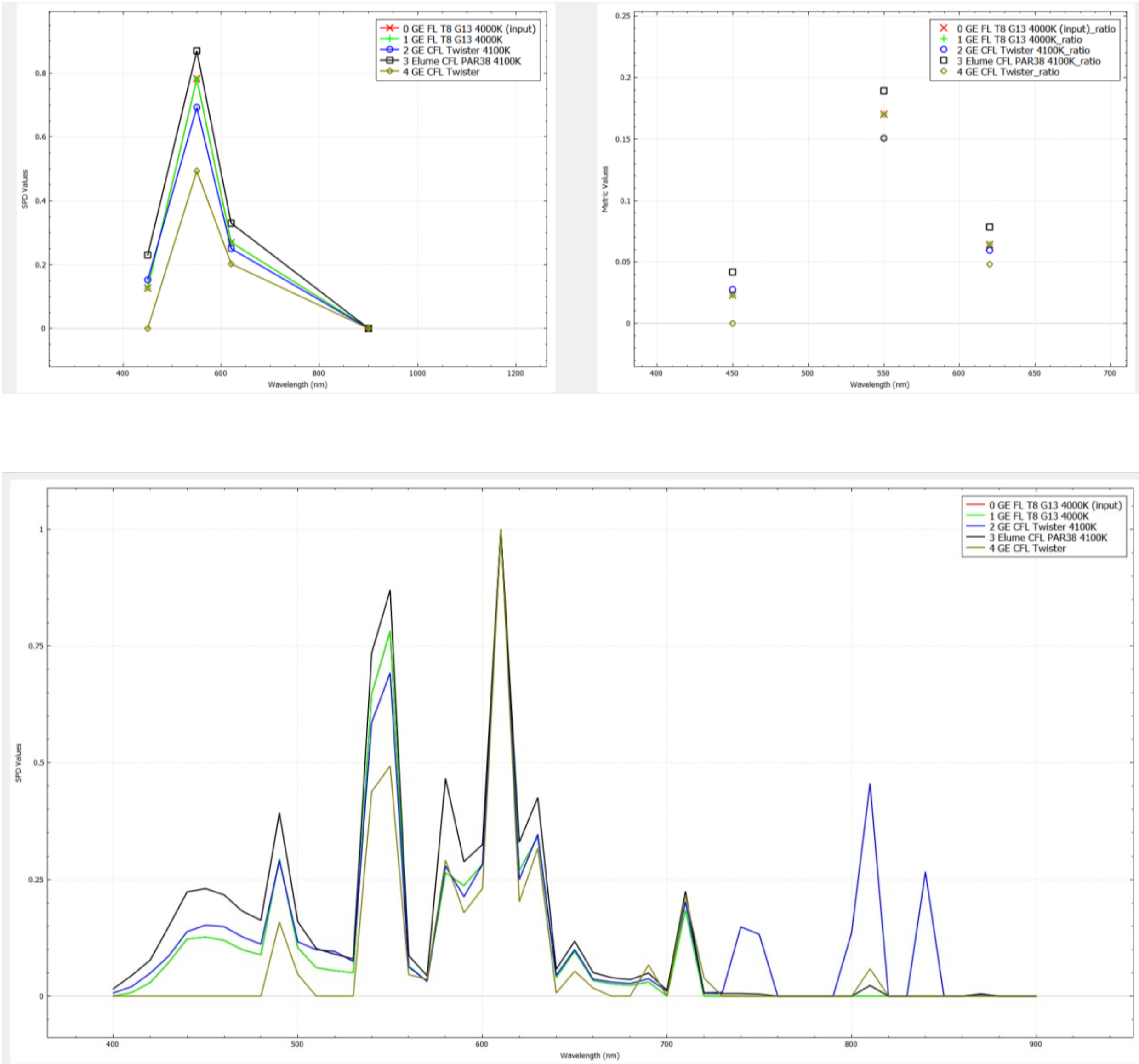


Fig FL COI extraction (Top) and Full Spectrum (Bottom) at 1st Setup

COI	**Metric Value**
GE FL T8 G13 4000K	0
GE CFL Twister 4100K	0.045802661
Elume CFL PAR38 4100K	0.082111376
GE CFL Twister	0.139768735

LED

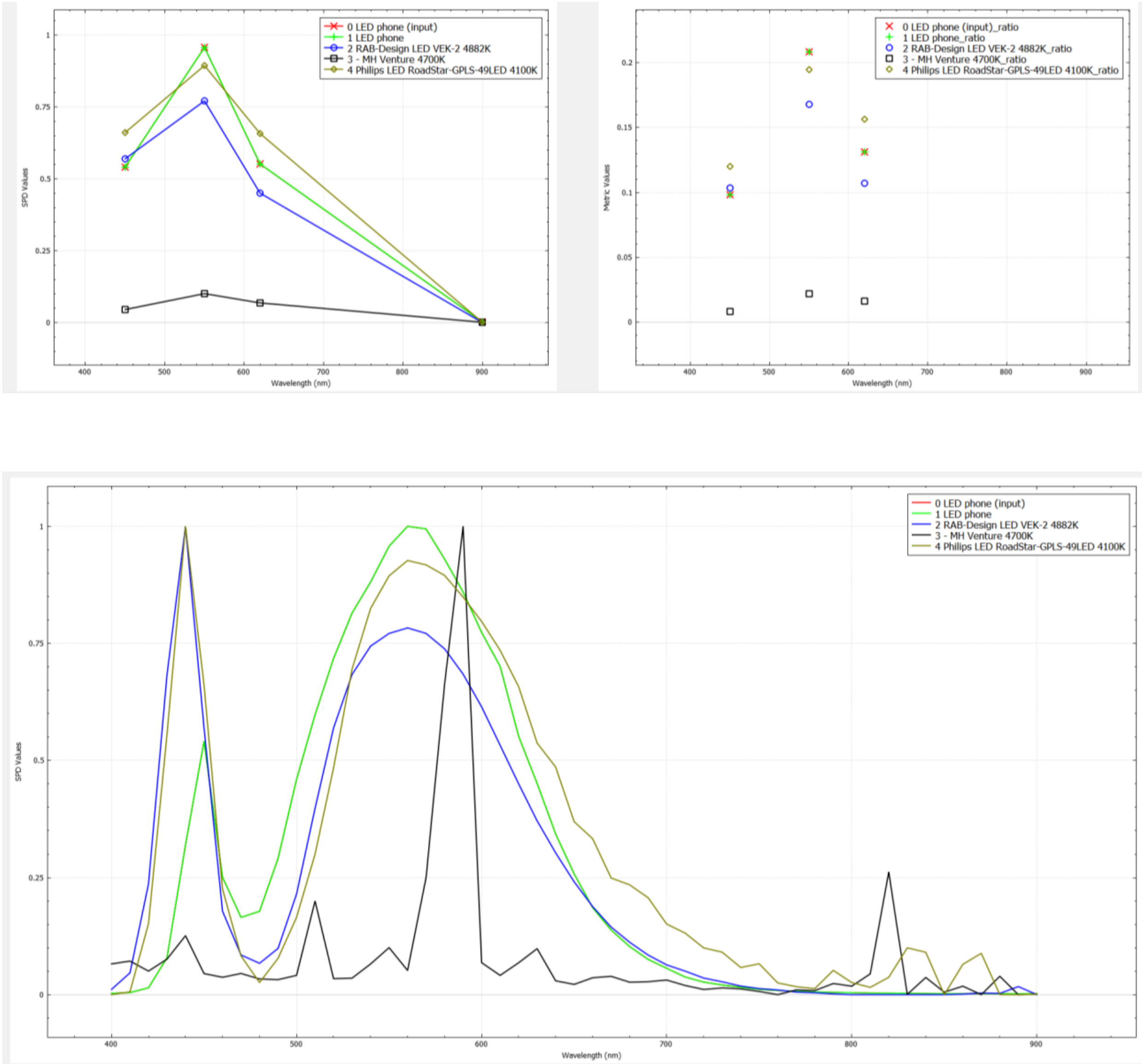


Fig LED COI extraction (Top) and Full Spectrum (Bottom) at 1st Setup

COI	**Metric Value**
LED phone	0
RAB-Design LED VEK-2 4882K	0.099824037
- MH Venture 4700K	0.112843361
Philips LED RoadStar-GPLS-49LED 4100K	0.125686768

ARCON

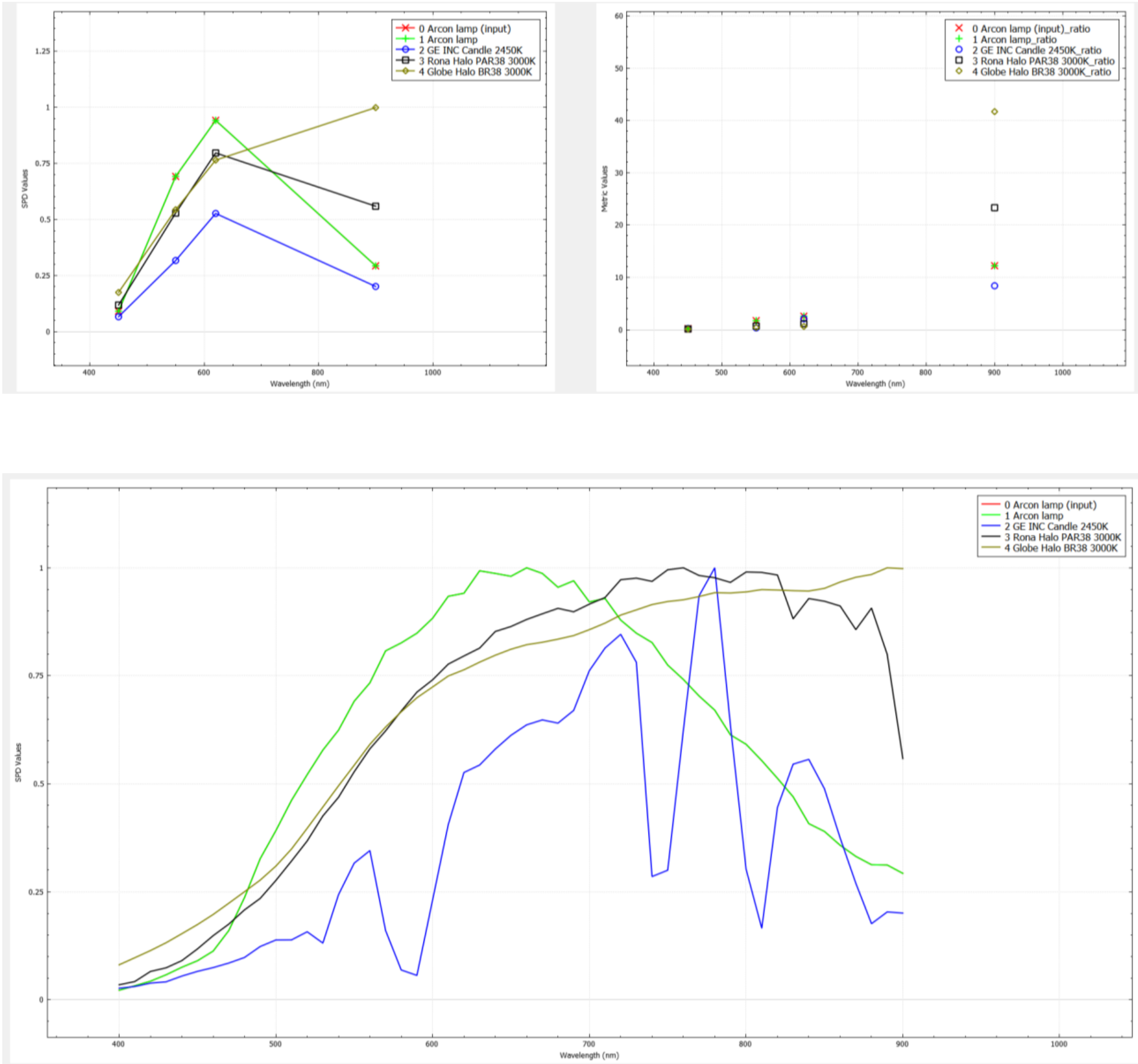


Fig ARCON COI extraction (Top) and Full Spectrum (Bottom) at 1st Setup

COI	Metric Value
Arcon lamp	0
GE INC Candle 2450K	0.038403394
Rona Halo PAR38 3000K	0.190807884
Globe Halo BR38 3000K	0.230292833

HPS

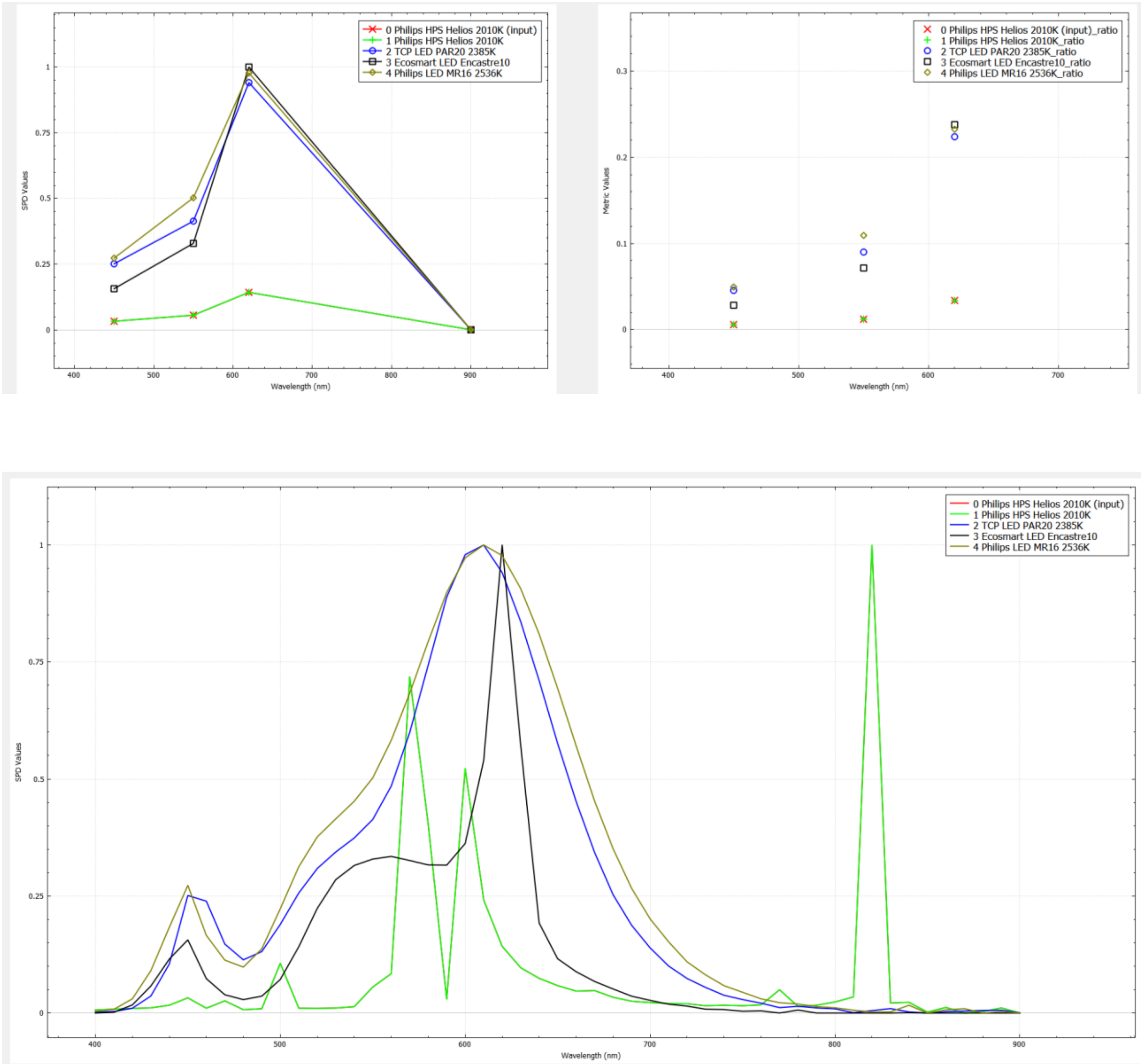
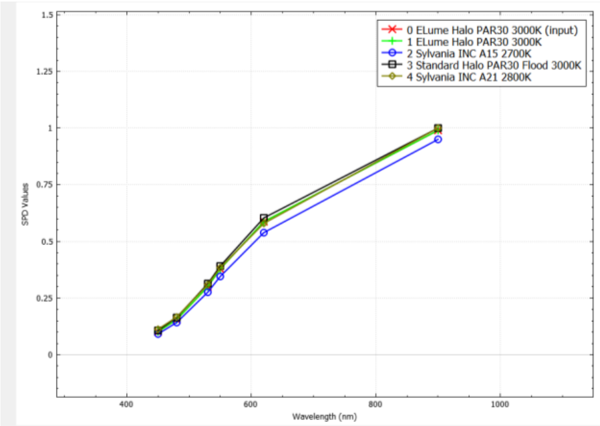


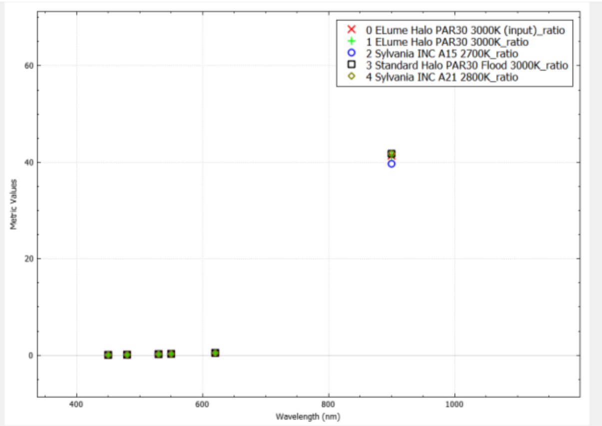
Fig HPS COI extraction (Top) and Full Spectrum (Bottom) at 1st Setup

COI	Metric Value
Philips HPS Helios 2010K	0
TCP LED PAR20 2385K	0.045805164
Ecosmart LED Encastre10	0.06982026
Philips LED MR16 2536K	0.099183825

2nd SETUP (450,480,530,550,620 & 900)

HALO





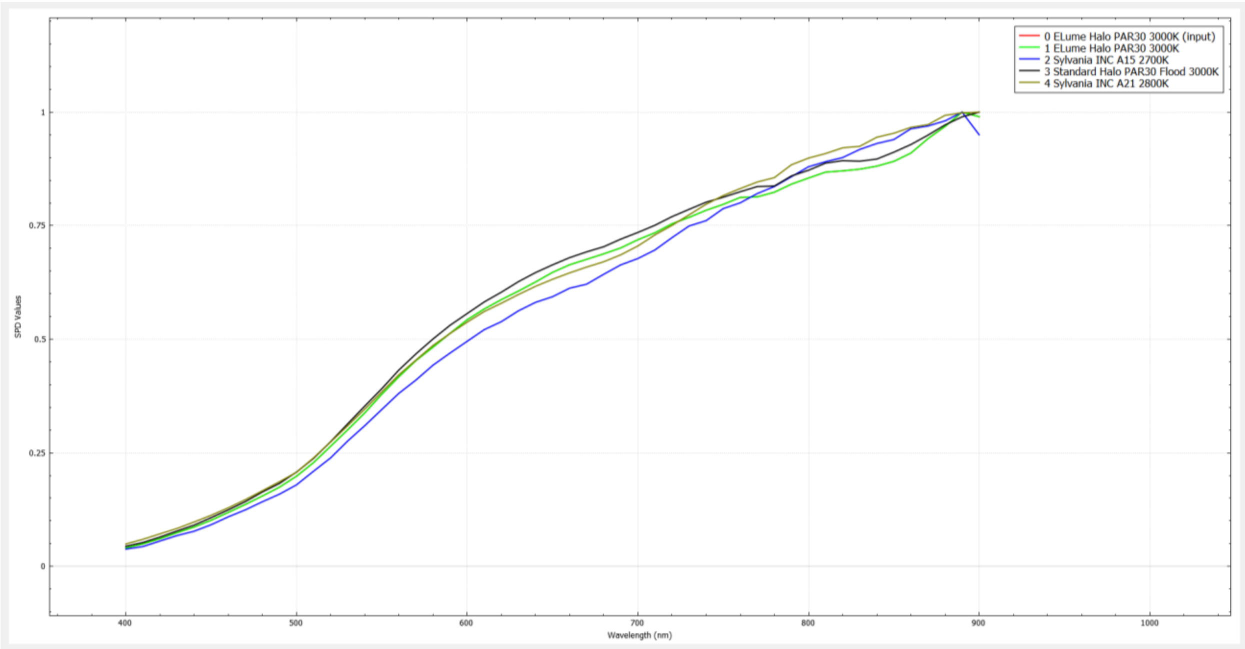


Fig HALO COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	Metric Value
ELume Halo PAR30 3000K	0
Sylvania INC A15 2700K	8.82175E-05
Standard Halo PAR30 Flood 3000K	0.00020007
Sylvania INC A21 2800K	0.000425779

INC

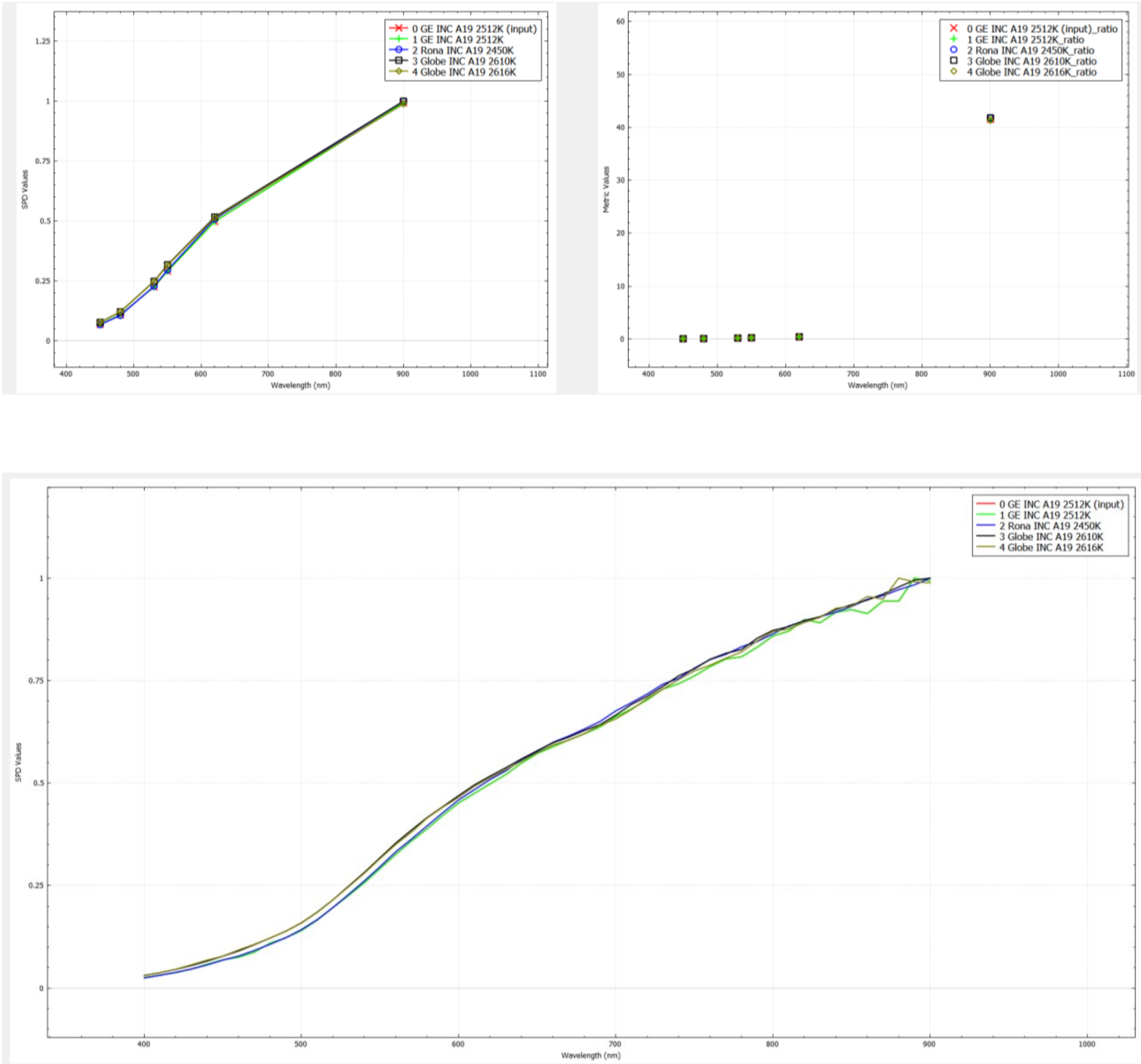


Fig INC COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	Metric Value
GE INC A19 2512K	0
Rona INC A19 2450K	0.000103363
Globe INC A19 2610K	0.000601299
Globe INC A19 2616K	0.000785955

MH

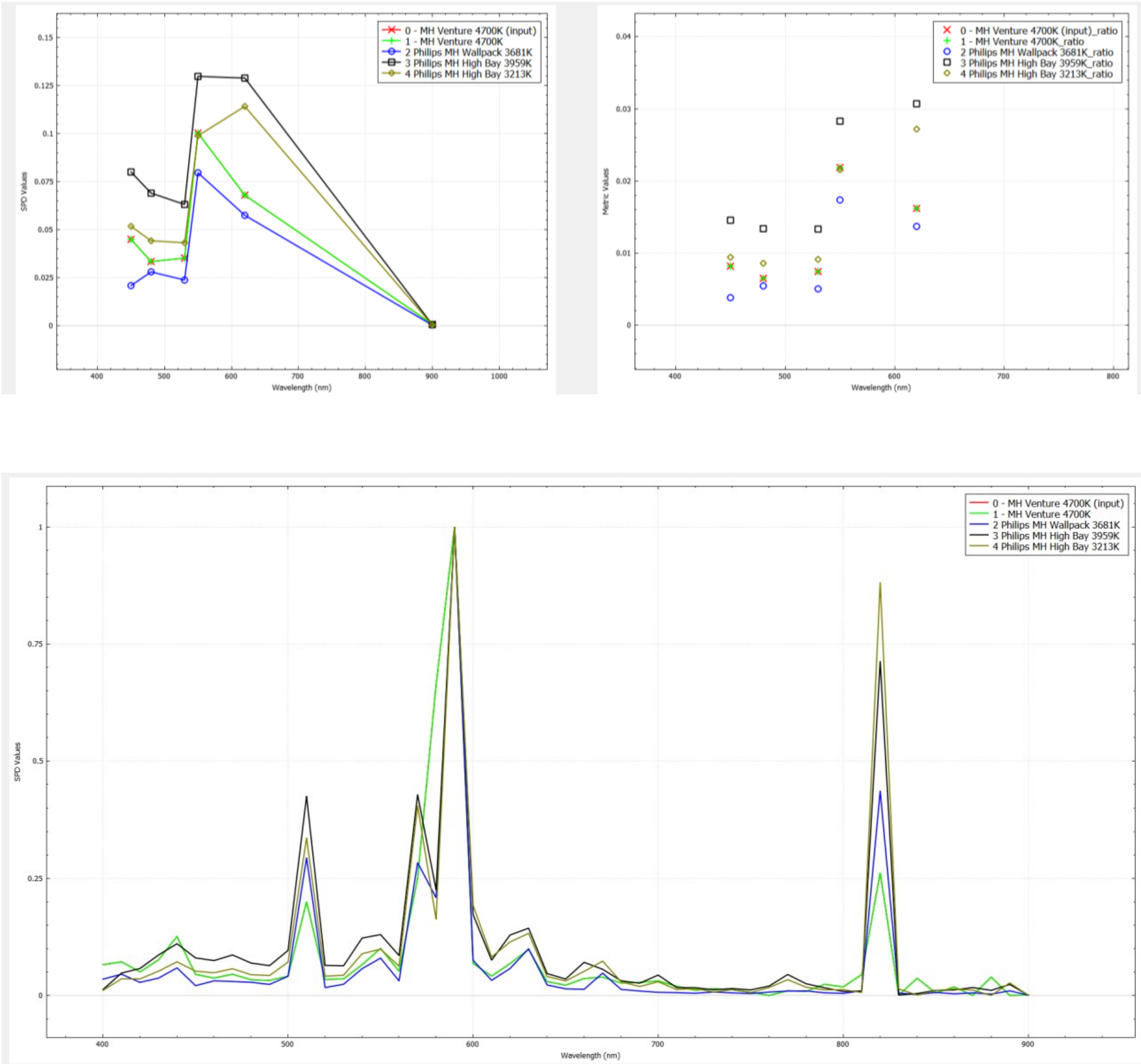


Fig MH COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	Metric Value
- MH Venture 4700K	0
Philips MH Wallpack 3681K	0.124314925
Philips MH High Bay 3959K	0.18752913
Philips MH High Bay 3213K	0.240461864

CFL

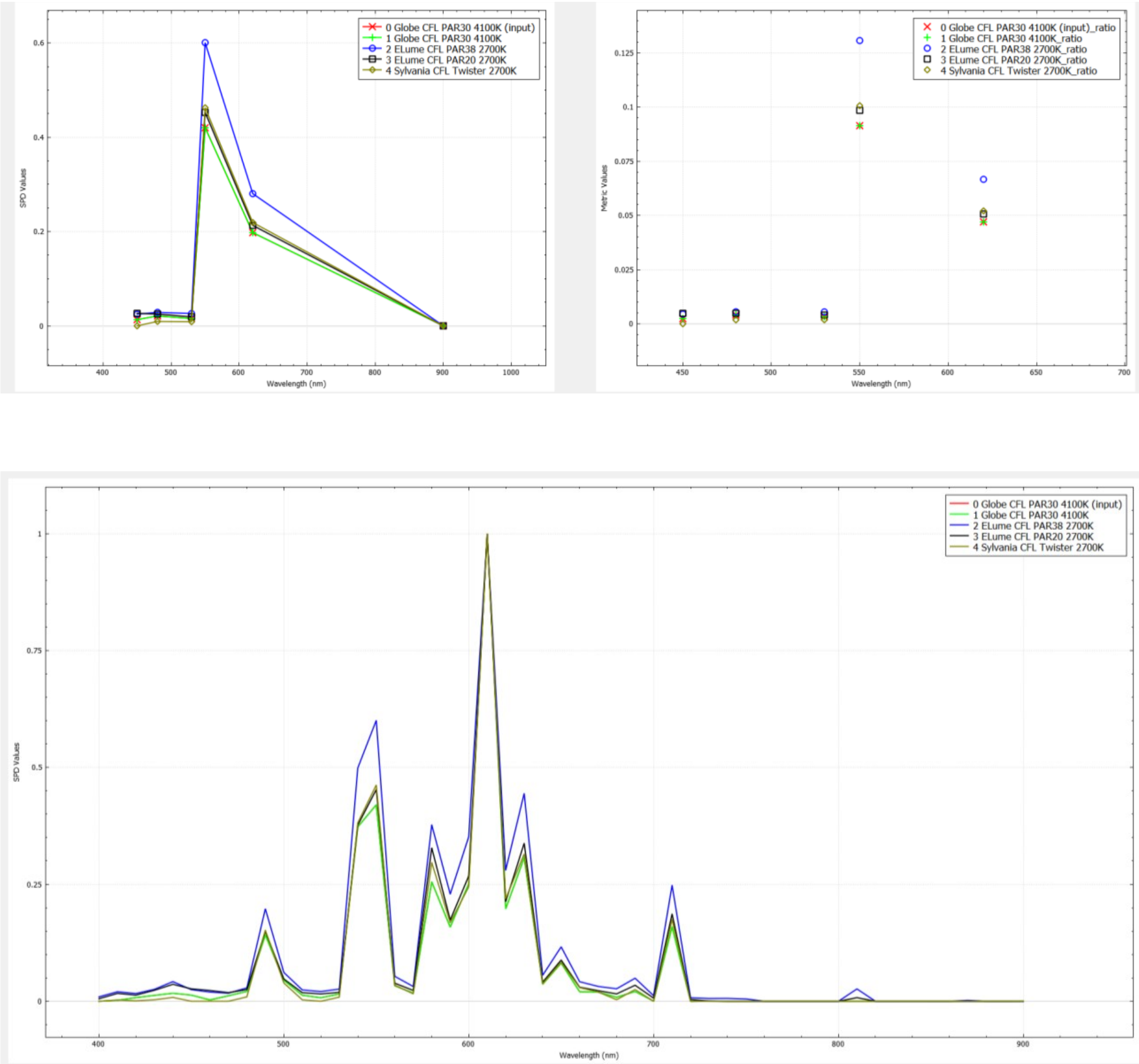


Fig CFL COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	Metric Value
Globe CFL PAR30 4100K	0
ELume CFL PAR38 2700K	0.010120247
ELume CFL PAR20 2700K	0.021094041
Sylvania CFL Twister 2700K	0.036499634

FL

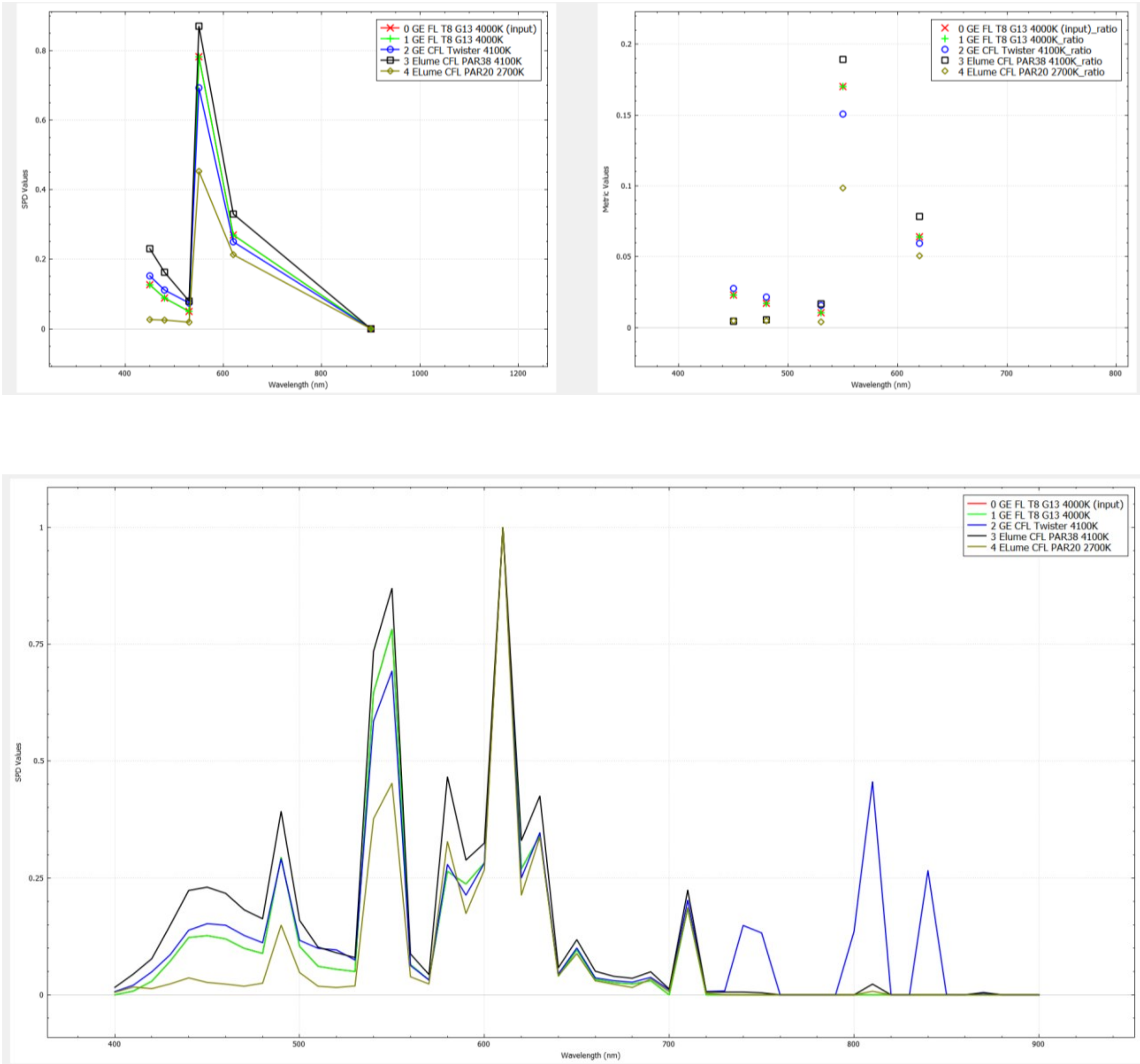
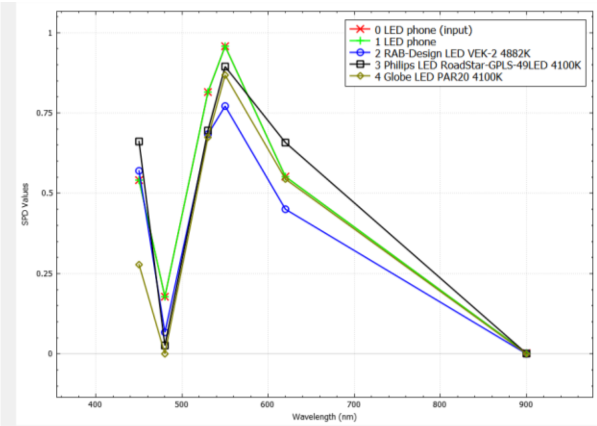
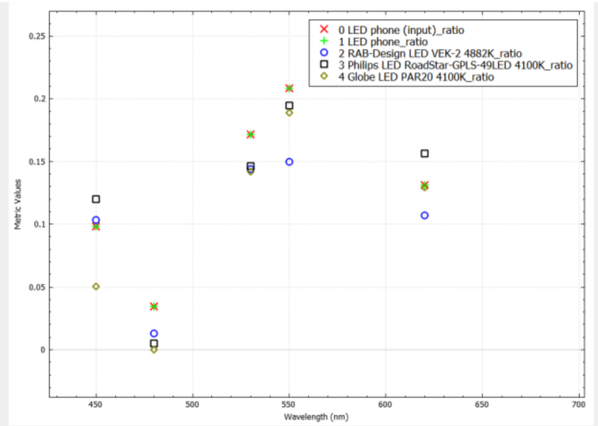


Fig FL COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	Metric Value
GE FL T8 G13 4000K	0
GE CFL Twister 4100K	0.069402048
Elume CFL PAR38 4100K	0.101188299
ELume CFL PAR20 2700K	0.150320814

LED





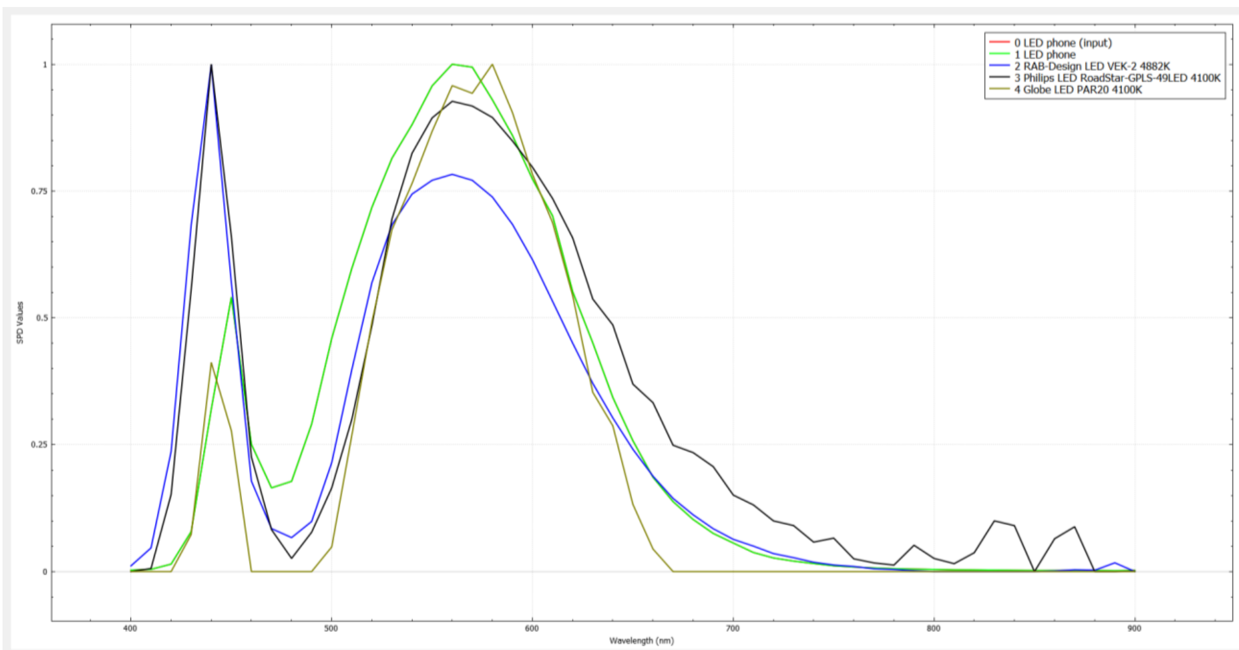


Fig LED COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	**Metric Value**
LED phone	0
RAB-Design LED VEK-2 4882K	0.103023134
Philips LED RoadStar-GPLS-49LED 4100K	0.167400821
Globe LED PAR20 4100K	0.180401321

ARCON

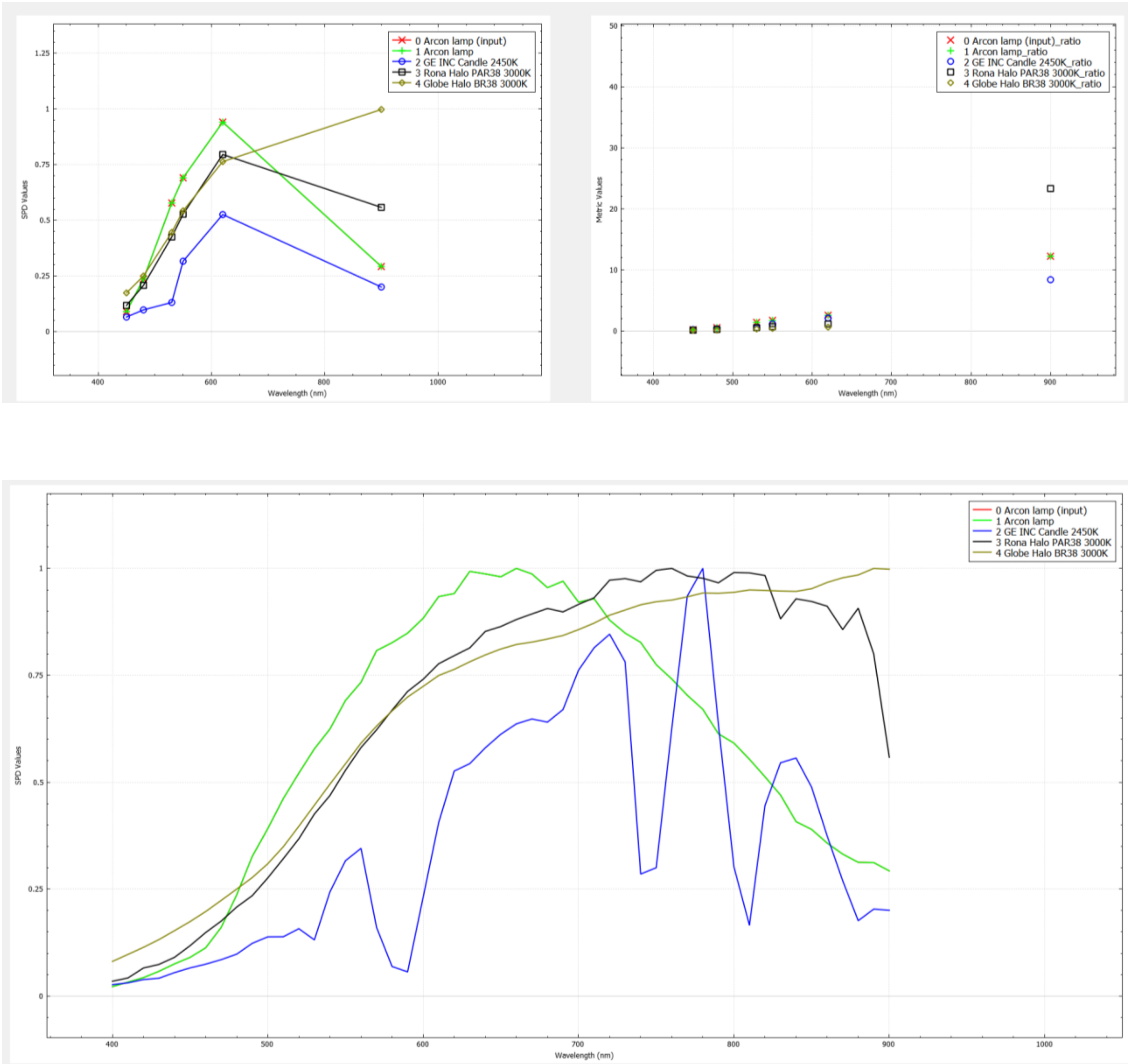


Fig ARCON COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	Metric Value
Arcon lamp	0
GE INC Candle 2450K	0.06892691
Rona Halo PAR38 3000K	0.211484002
Globe Halo BR38 3000K	0.254298958

HPS

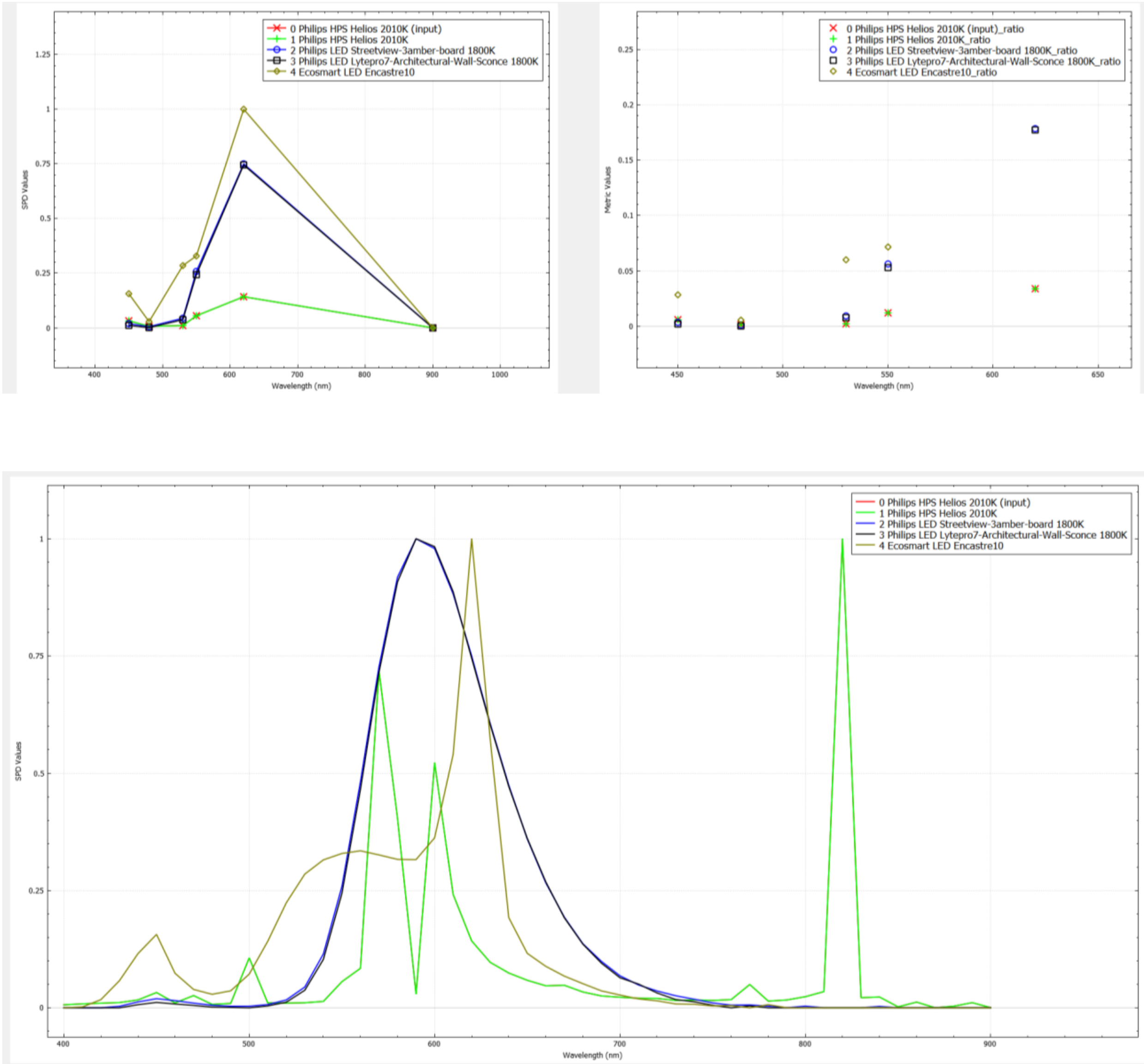


Fig HPS COI extraction (Top) and Full Spectrum (Bottom) at 2nd Setup

COI	Metric Value
Philips HPS Helios 2010K	0
Philips LED Streetview-3amber-board 1800K	0.15218486
Philips LED Lytepro7-Architectural-Wall-Sconce 1800K	0.164972157
Ecosmart LED Encastre10	0.187794739

In cases of HALO, CFL and FL both Setups display very similar performance. In INC and ARCON cases results are exactly the same. For MH input the results are proven to be better for the 2nd Setup (LED is included in the COI list on the 1st Setup which belongs to different illuminant family). Same stands for the LED as COI list of 2nd Setup (MH is included in the 1st Setup COI list). Finally, for HPS the COI list of 2nd Setup manages to handle slightly better an unfamiliar illuminant compared to 1st Setup. Overall, the 2nd Setup seems to be the more versatile option to approach this problem and will be used for the following trials.

Note that ARCON & HPS illuminants are indicatively presented cases since they have no direct equivalents inside the Database except for the illuminants themselves. In conclusion, no COI List could be of significant matching value to correspond to their spectrum so these 2 illuminants will not be used to deduct any conclusions.

4.4.2 Spectra to Color from Illuminant Estimation Results

Results in this section are the spectrally reconstructed images (400-750 with 10nm step) along with their gamma corrected equivalents using the 2nd Setup results first COI. No DE differences are presented here because in this case the first COI always is found to be the input illuminant.

HALO

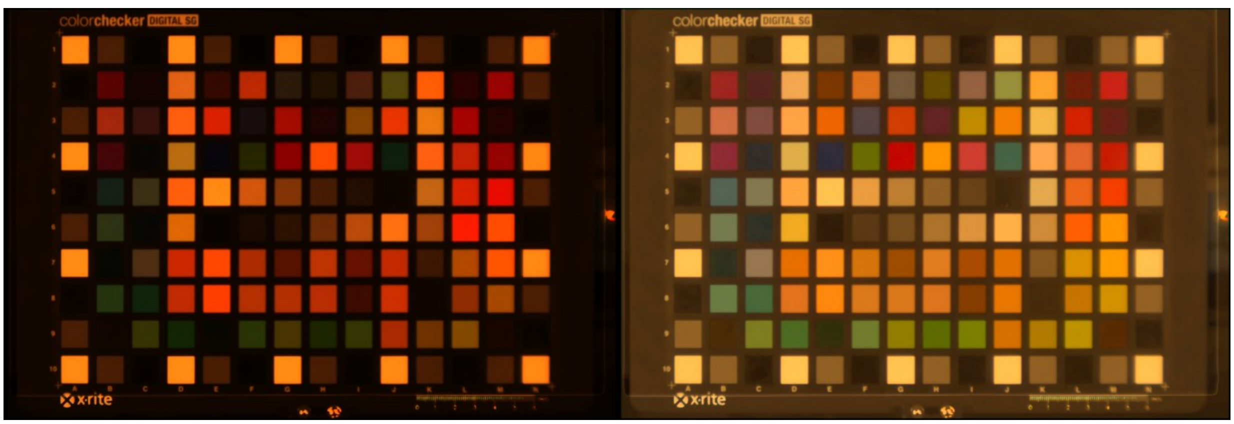


Fig HALO spectrally reconstructed image and gamma corrected equivalent

INC

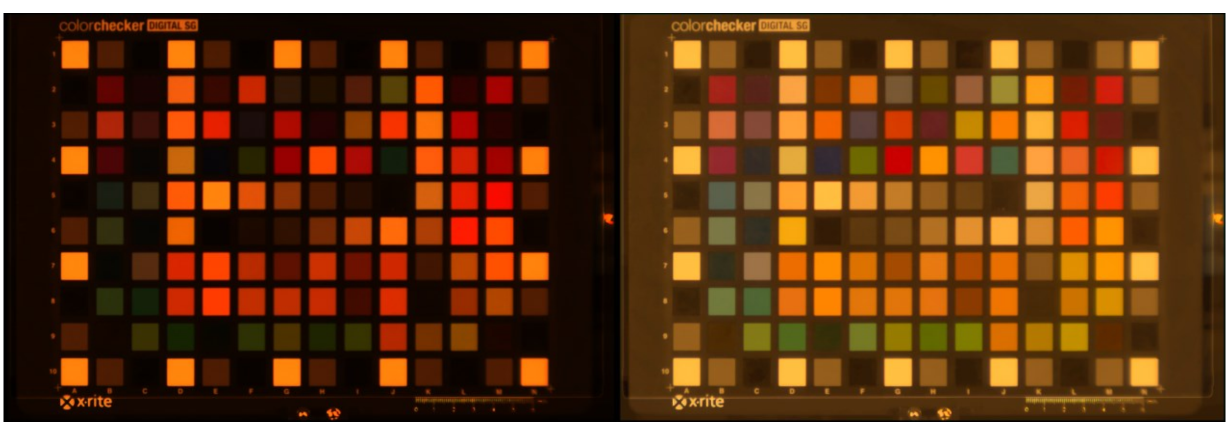


Fig INC spectrally reconstructed image and gamma corrected equivalent

MH

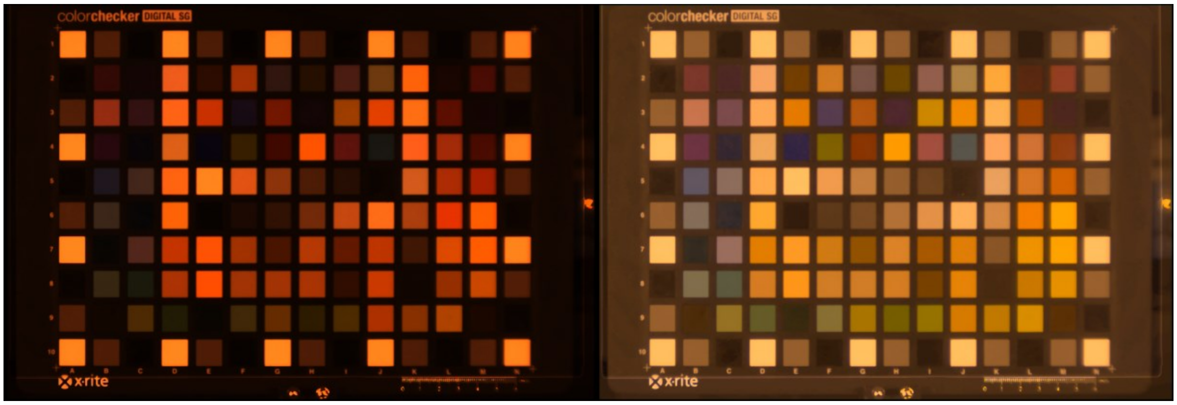


Fig MH spectrally reconstructed image and gamma corrected equivalent

CFL

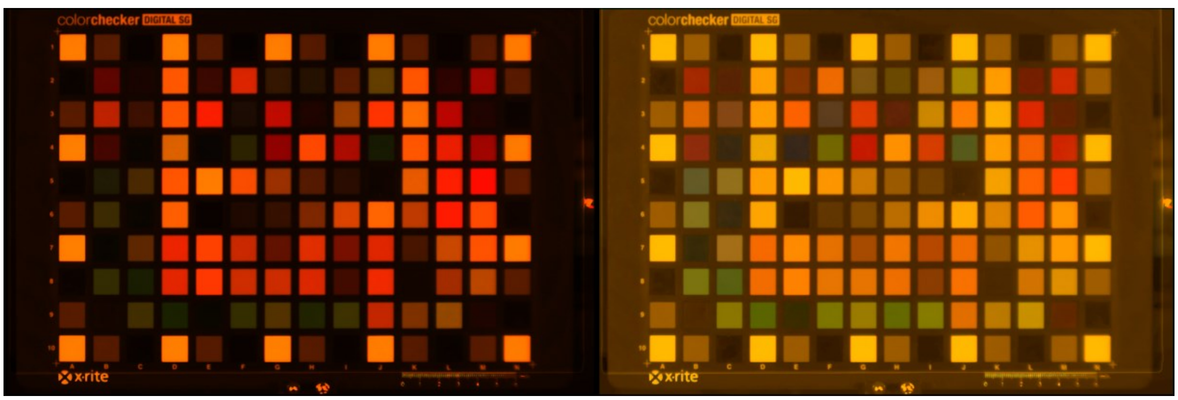


Fig CFL spectrally reconstructed image and gamma corrected equivalent

FL

Fig FL spectrally reconstructed image and gamma corrected equivalent

LED

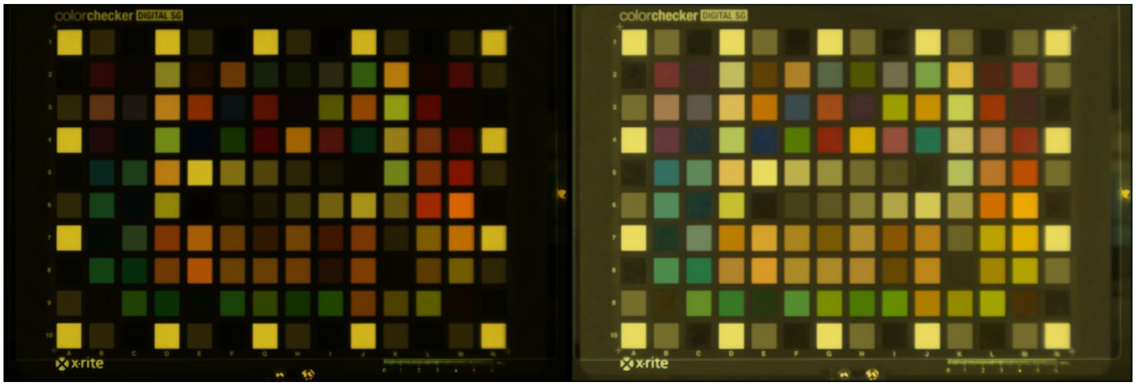


Fig LED spectrally reconstructed image and gamma corrected equivalent

D65 Spectra 2 Color

The D65 is an indicatively presented case because it is not included in Illuminant Database but is an example Illuminant with cool CCT to better display sRGB gamma correction since all Illuminants that have been tested are on the warm side of CCT.

Fig D65 spectrally reconstructed image and gamma corrected equivalent

4.4.3 Single Illuminant Estimation with noise

Since this is a design of a system there's a need to approach the problem realistically by simulating the noise it contains and the results' tolerance to the system's noise. The additive noise that is applied to the system follows the Gaussian distribution with mean = 0 and stddev = 0.008. Other noise setups with mean = 0 have been used for Illuminant Estimation but yielded worse results that the proposed. DE differences are calculated upon 8 patches on ColorChecker (E4-H4,E5-H5) with the DE patch comparator that standalone ShowStacked ui offers (using DE patch pixels are 60x60).

These DE values will determine the success of the COI extraction since the spectrally reproduced color must be identical to what a human being interprets as color under the given illuminants (Appendix section Color Difference Metrics). It is vital to note that for a successful Illuminant match delta e difference must be of low value. That means illuminants from similar families could be a potential match but also illuminants from the same family could yield different DE results.

Note that input illuminant is affected by the system's noise but for latter delta e differences the original input illuminant is used and that the results yielded are a worst case scenario.

HALO

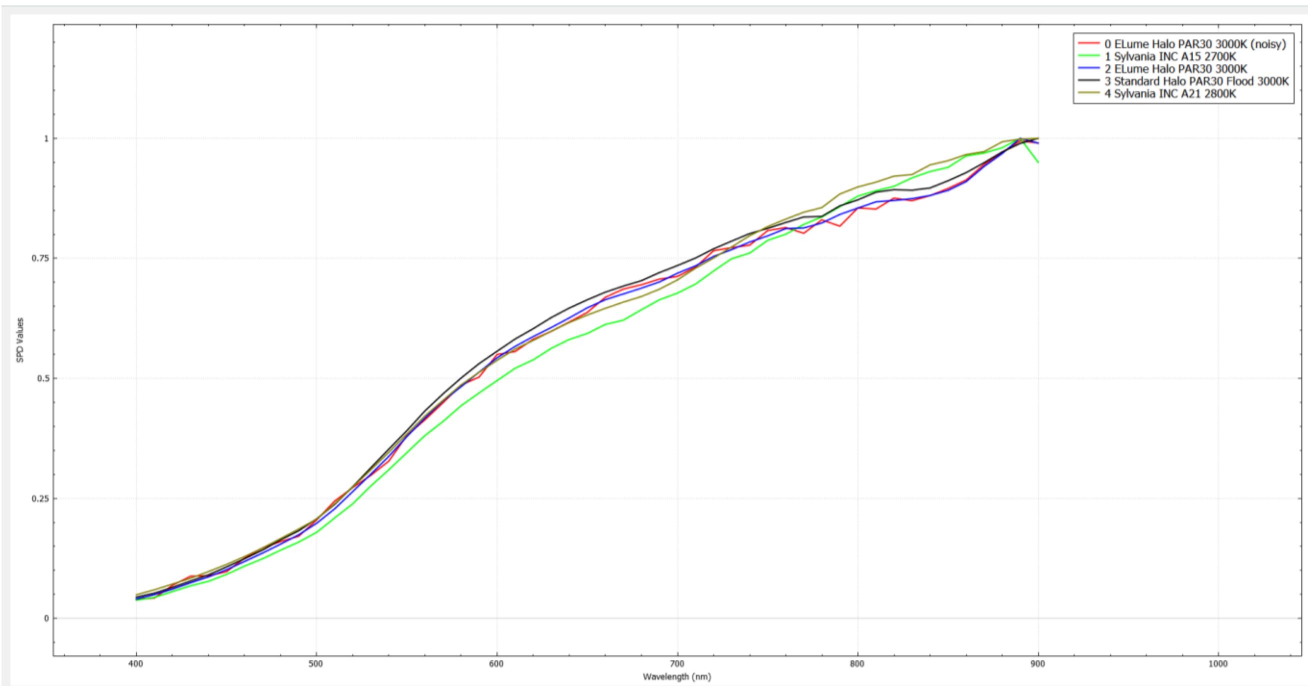


Fig Noised Halo COI extraction

INC

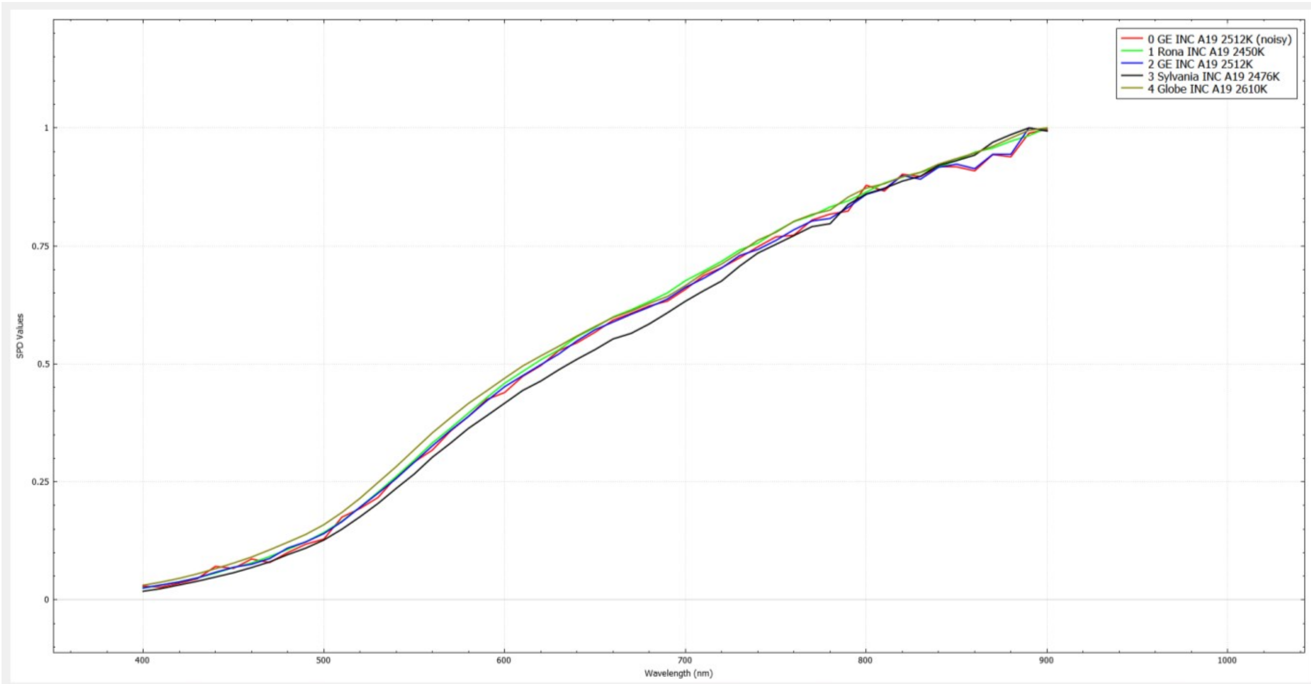


Fig Noised INC COI extraction

MH

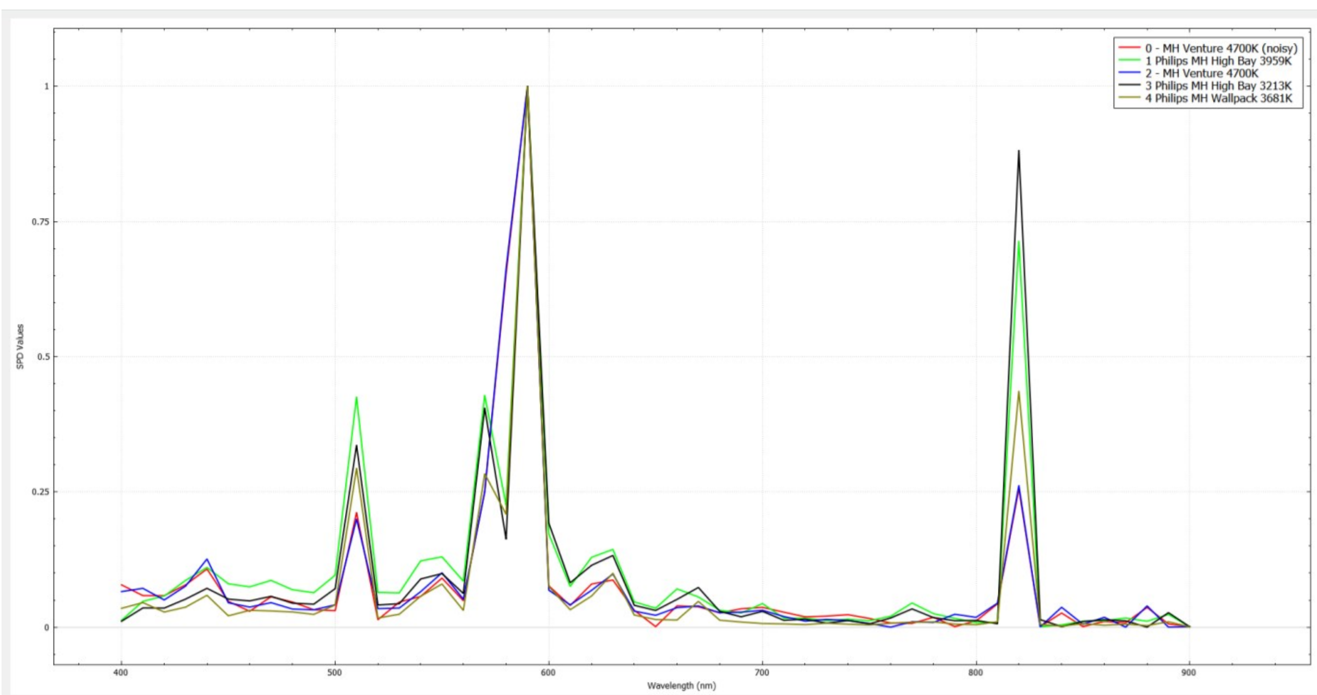


Fig Noised MH COI extraction

CFL

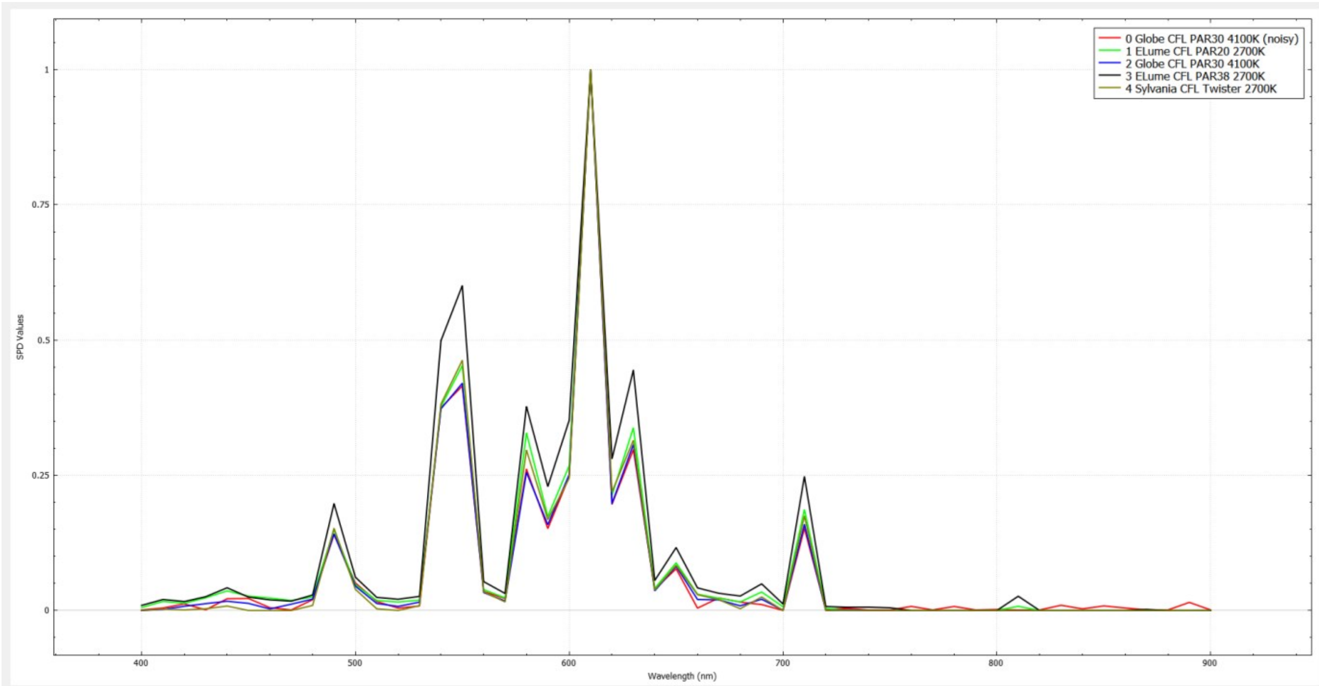


Fig Noised CFL COI extraction

FL

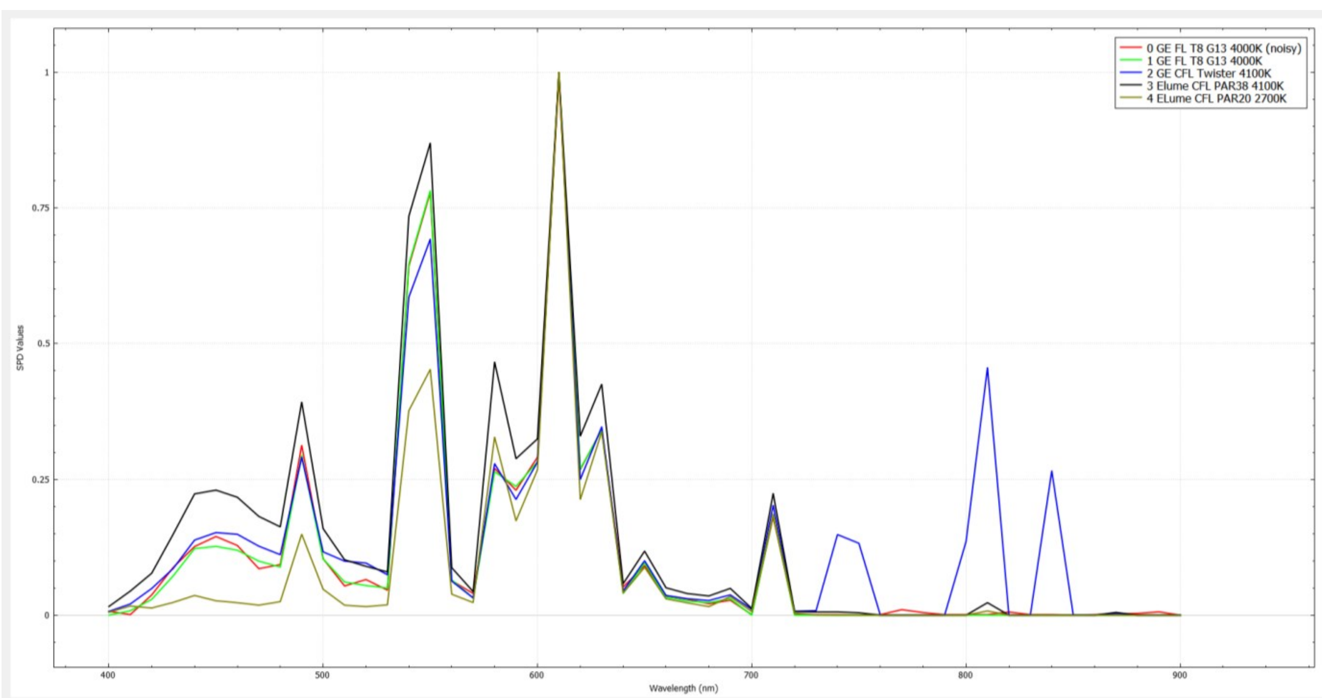


Fig Noised FL COI extraction

LED

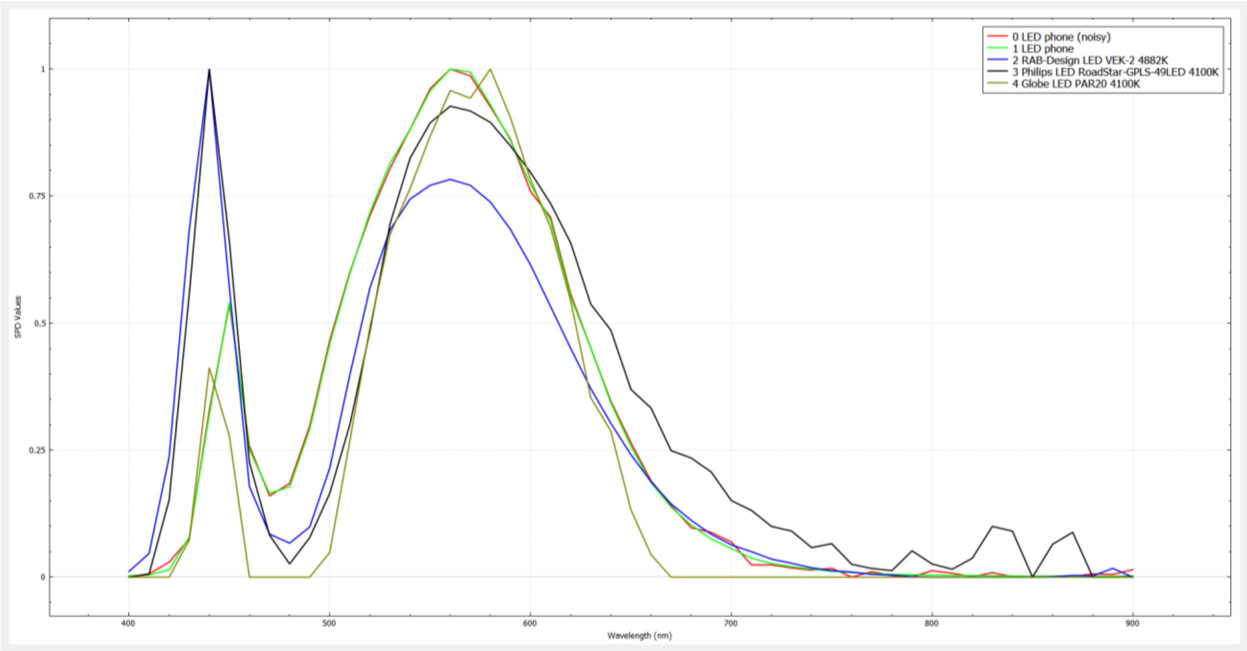
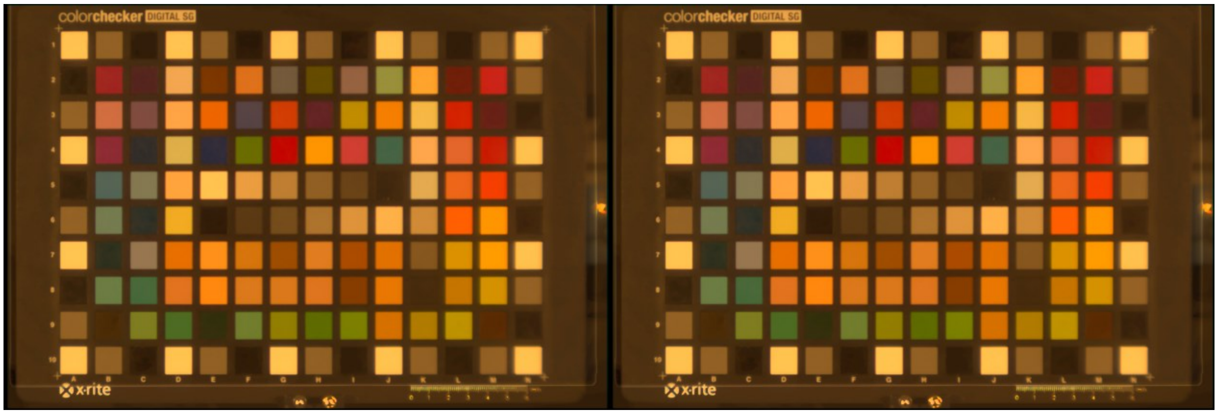


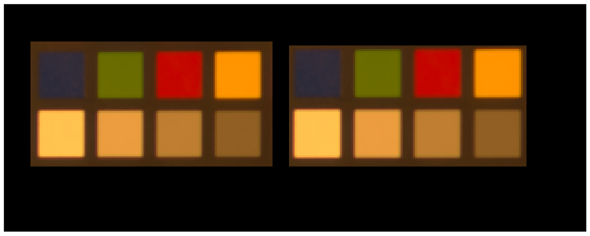
Fig Noised LED COI extraction

4.4.4 Spectra to Color from Illuminant Estimation with noise

Images below derived from original and 1st COI Illuminants derived from the graphs above. These spectrally reconstructed images are gamma corrected first before performing the DE comparisons.

HALO

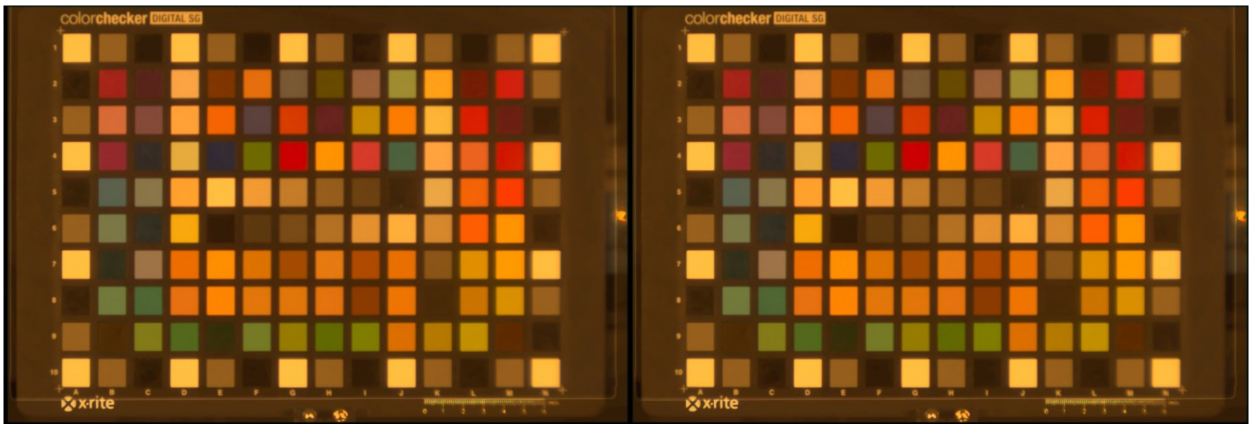


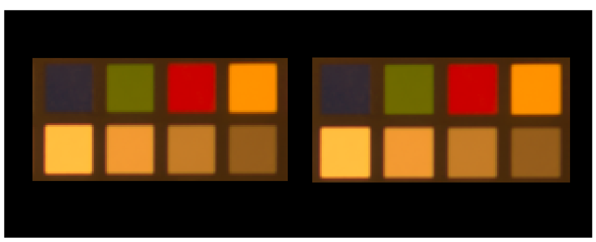


Patch	E4	F4	G4	H4	E5	F5	G5	H5
DE	0.2297	0.1614	1.08	0.057	0.196	0.206	0.257	0.29

Fig Noised HALO spectrally reconstructed images of Original & 1st COI and DE

INC

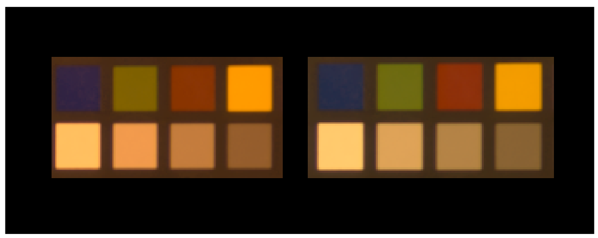




Patch	E4	F4	G4	H4	E5	F5	G5	H5
DE	0.331	0.132	0.046	0.028	0.377	0.468	0.459	0.48

Fig Noised INC spectrally reconstructed images of Original & 1st COI and DE

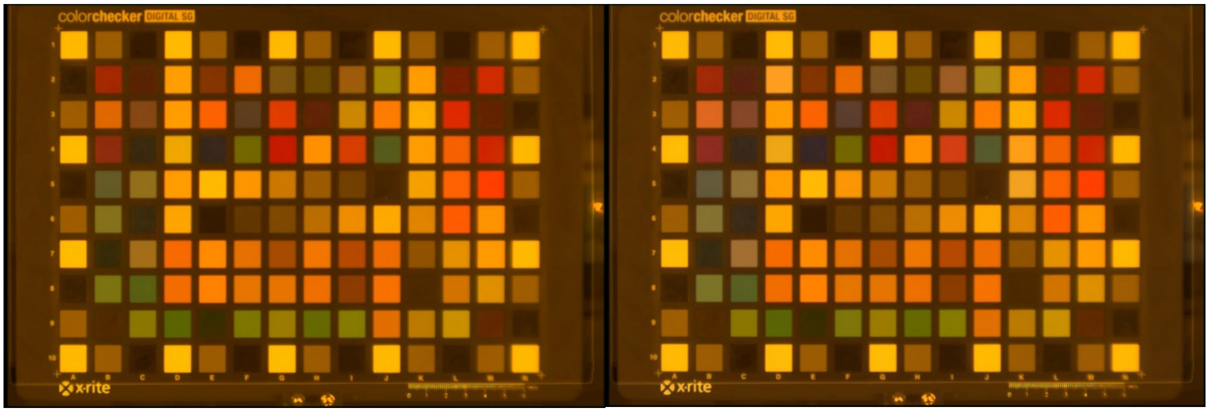
MH

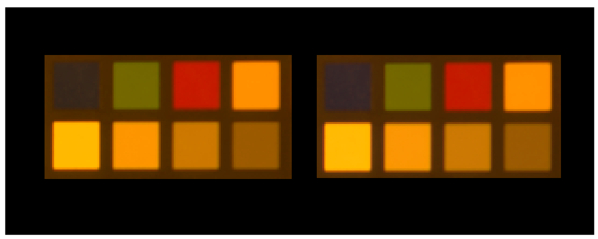


Patch	E4	F4	G4	H4	E5	F5	G5	H5
DE	10.23	19.78	14.01	2.54	3.66	6.48	6.134	5.712

Fig Noised MH spectrally reconstructed images of Original & 1st COI and DE

CFL

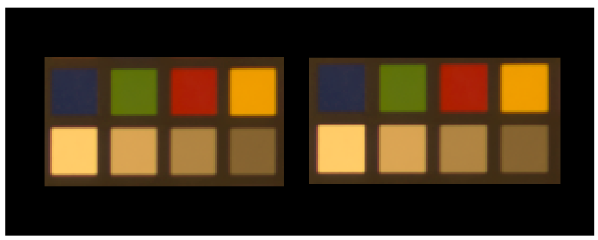




Patch	E4	F4	G4	H4	E5	F5	G5	H5
DE	11.07	0.055	1.163	0.328	5.382	5.22	4.782	3.42

Fig Noised CFL spectrally reconstructed images of Original & 1^{st} COI and DE

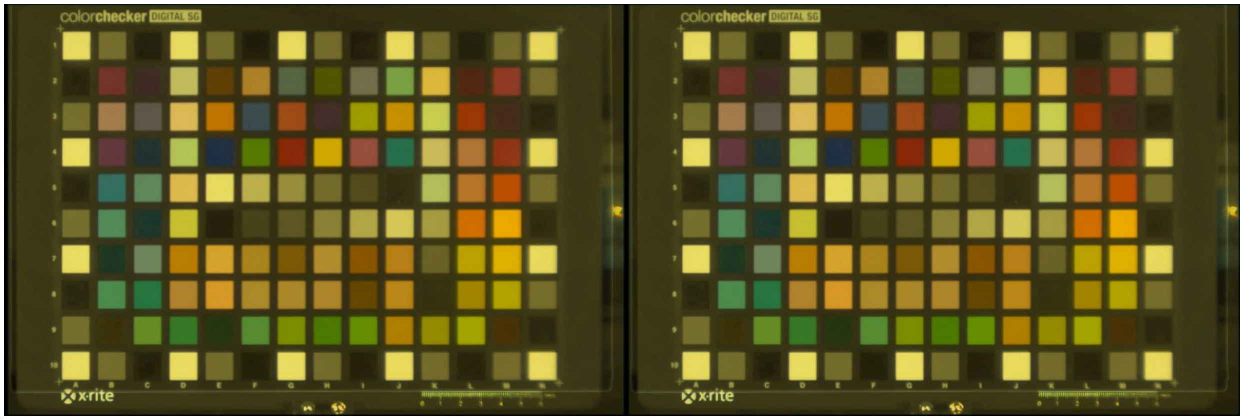
FL

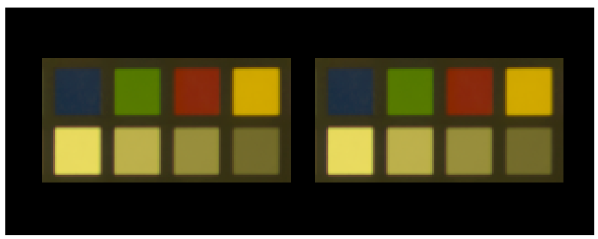


Patch	E4	F4	G4	H4	E5	F5	G5	H5
DE	0	0	0	0	0	0	0	0

Fig Noised FL spectrally reconstructed images of Original & 1st COI and DE

LED





Patch	E4	F4	G4	H4	E5	F5	G5	H5
DE	0	0	0	0	0	0	0	0

Fig Noised MH spectrally reconstructed images of Original & 1st COI and DE

4.5 Conclusion

This approach while it is not perfect, since it cannot match the difficult cases of CFL and MH illuminants, proves to be versatile in recognizing all other types. The single illuminant estimation begins with extracting illuminant information out of spectral reflectances of the given illuminant that successfully reveals matching spectral signatures included in the LSPD database. With spectra 2 color process true like color is reconstructed out of the closest COI spectrum and then it is gamma corrected.

At this point a firm base of a spectra to color program tool has been created that can offer the user the program functionality to match spectral data of virtually any single illumination scene (given the fact they have an equivalent in the used database) and present it at a computer screen with color fidelity along with the complementary tools to evaluate to aid for the evaluation of the success of the algorithm.

4.6 Future Work

Future tasks based on this project could be the matching of a spectral signatures derived out of complex scene that contain multiple illuminants, research for the minimum spectral band sampling rate that could guarantee color fidelity, true like spectral to color real-time application for mobile photography/videography or even a full scale machine learning algorithm that could exploit results yielded from this project.

5 Appendix

Conversions between Color Spaces Section

For the purposes of the project conversions among Color Spaces are demanded. These transformations are fully defined by CIE. In order to transcend from RGB to XYZ space we need to define a Matrix M with Reference White (also known Color Working Space Matrix or CWM) and gamma if correction is applied. As for XYZ to LAB conversion we need to have Reference White information. We need to explain beforehand that Reference White is the one that corresponds to the illuminant whereas when we have a Custom Illuminant we can calculate the Reference White with the XYZ tristimulus values from the equation and afterwards divide by the photopic response to the illumination.

The transitions that were used are displayed below[33]:

The RGB to XYZ transition Matrix:

In order to make the conversion from RGB to XYZ (vice versa applies too) a transition matrix is needed. This particular matrix called Color Working Space Matrix is made out of the chromaticity coordinated of a RGB system (x_r,y_r), (x_g,y_g) and (x_b,z_b) and a reference white point (X_w,Y_w,Z_w). This transformation only refers to the linear part of the equation and doesn't bother with gamma correction which is an extra step.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = [M] \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

whereas

$$[\mathrm{M}] = \begin{bmatrix} SrXr & SgXg & SbXb \\ SrYr & SgYg & SbYb \\ SrZr & SgZg & SbZb \end{bmatrix}$$

With $X_r = \frac{Xr}{Yr}$, $Y_r = 1$, $Z_r = \frac{(1-Xr-Yr)}{Yr}$

And the corresponding ones for (Xg, Yg, Zg) and (Xb, Yb, Zb)

$$\begin{bmatrix} Sr \\ Sg \\ Sb \end{bmatrix} = \begin{bmatrix} Xr & Xg & Xb \\ Yr & Yg & Yb \\ Zr & Zg & Zb \end{bmatrix}^{-1} \begin{bmatrix} Xr \\ Yg \\ Zb \end{bmatrix}$$

That means the XYZ to RGB transition demands the inversion of the M matrix like so:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = [M]^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The XYZ to L*a*b* transition formulas:

Before moving on to showing the transition equations it must be noted that LAB Color Space is the CIELAB or L*a*b* not to be mistaken with HunterLAB also often denoted as L*a*b*. In order to convert from XYZ to L*a*b* Color Space the following formulas were used:

$$L^* = 116\, f_y - 16$$

$$a^* = 500\ (f_x - f_y)$$

$$b^* = 200\,(f_y - f_z)$$

Where

$$f_x = \begin{cases} \sqrt[3]{x_r}, & x_r > \varepsilon \\ \dfrac{(\kappa x_r + 16)}{116}, & x_r \le \varepsilon \end{cases}$$

$$f_y = \begin{cases} \sqrt[3]{y_r}, & y_r > \varepsilon \\ \dfrac{(\kappa y_r + 16)}{116}, & y_r \le \varepsilon \end{cases}$$

$$f_z = \begin{cases} \sqrt[3]{z_r}, & z_r > \varepsilon \\ \dfrac{(\kappa z_r + 16)}{116}, & z_r \le \varepsilon \end{cases}$$

Fig L*a*b* equations

$$x_r = \frac{X}{X_r},\ y_r = \frac{Y}{Y_r}\ and\ z_r = \frac{Z}{Z_r}$$

With predefined constants $\varepsilon = {}^{216}/_{24389}$ (≈ 0.08856) and $\kappa = {}^{24389}/_{27}$ (≈ 903.3) and X_r, Y_r, Z_r the reference white tristimulus values.

Note that transformation from RGB to L*a*b* isn't directly defined so there must be first a transformation to XYZ Color Space and afterwards to L*a*b*.

The L*a*b* to XYZ transition formulas:

The inverse transformation from L*a*b* to XYZ Color Space can also be applied displayed below given X_r, Y_r, Z_r which are the reference white tristimulus values:

$$X = x_r X_r$$

$$Y = y_r Y_r$$

$$Z = z_r Z_r$$

Where

$$x_r = \begin{cases} {f_x}^3, & {f_x}^3 > \varepsilon \\ (116\, f_x - 16)/\kappa\ , & otherwise \end{cases}$$

$$y_r = \begin{cases} ((L+16)/116)^3, & L > \kappa\varepsilon \\ L/\kappa\ , & otherwise \end{cases}$$

$$z_r = \begin{cases} {f_z}^3, & {f_z}^3 > \varepsilon \\ (116\, f_z - 16)/\kappa, & otherwise \end{cases}$$

$$f_x = \frac{\alpha}{500} + f_y$$

$$f_z = f_y - \frac{b}{200}$$

$$f_y = (L + 16)/116$$

$$\varepsilon = \begin{cases} 0.008856 & Actual\ CIE\ standard \\ {}^{216}/_{24389} & Intent\ of\ the\ CIE\ standard \end{cases}$$

$$\kappa = \begin{cases} 903.3 & Actual\ CIE\ standard \\ {}^{24389}/_{27} & Intent\ of\ the\ CIE\ standard \end{cases}$$

Gamma Correction formulas

Correction is applied in cases of standardized color spaces like sRGB which has a gamma value of $\gamma = 2.2$ (for fast computing implementation) for gamma companding formula or the complex sRGB companding formula and has an exponent of 0.45 (for reference look for Companding and Inverse Companding formulas at this section). That means when we want to make a transformation of XYZ to RGB or RGB to XYZ we must use that specific gamma value for correction (LAB to RGB cannot occur directly). Values that are gamma corrected are also denoted as companded values.

The RGB to XYZ with gamma correction transformation:

1. **Inverse Companding**

The companded RGB channels noted as (R,G,B) or simply V are made linear noted as (r,g,b) or simply v.

Inverse Gamma Companding

$$v = V^{\gamma}$$

Inverse sRGB Companding

$$A = \begin{cases} V/12.92 & V \leq 0.04045 \\ \left((V + 0.055)/1.055\right)^{2.4} & otherwise \end{cases}$$

Inverse L* Companding

$$v = \begin{cases} 100v/\kappa & V \leq 0.08 \\ \left((V + 0.16)/1.16\right)^{3} & otherwise \end{cases}$$

$$\kappa = \begin{cases} 903.3 & Actual\ CIE\ standard \\ 24389/27 & Intent\ of\ the\ CIE\ standard \end{cases}$$

2. **Linear RGB to XYZ**

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = [M] \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

The XYZ to RGB with gamma correction transformation:

1. XYZ to Linear RGB

$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = [M]^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The above gives the linear RGB values denoted as r,g,b.

2. Companding

The linear RGB channels denoted as (r,g,b) or simply v are made non-linear denoted as (R,G,B) or simply V.

Gamma Companding

$$V = v^{1/\gamma}$$

sRGB Companding

$$A = \begin{cases} 12.92v & v \le 0.0031308 \\ 1.055v^{1/2.4} - 0.055 & otherwise \end{cases}$$

L* Companding

$$V = \begin{cases} v/100 & v \le \varepsilon \\ 1.16\sqrt[3]{v} - 0.16 & otherwise \end{cases}$$

$$\varepsilon = \begin{cases} 0.008856 & Actual\ CIE\ standard \\ 216/24389 & Intent\ of\ the\ CIE\ standard \end{cases}$$

$$\kappa = \begin{cases} 903.3 & Actual\ CIE\ standard \\ 24389/27 & Intent\ of\ the\ CIE\ standard \end{cases}$$

Color Difference Metrics

How can one science quantify perceived difference in color? A question that is really not easily answered as one may think. Developing color difference metrics that correspond to what the human eye is capable of seeing is the foundation of setting up the basics for a system that makes high quality color reproduction. So a colorimetrical system that matches perceived color differences as closely as possible made color-differences formulas, a reality.

First we need to denote that ΔE (or Delta E, dE) is a measure of change in visual perception of two given colors hence a chromatic difference.

In this section we are going to take a look at three Delta E algorithms that are used today: DE76 (or simply Delta E), DE94 and DE00. For simplicity and computation efficiency DE76 is employed.

Typically Delta E is as we have already commented plainly a metric to understand human eye color difference perception (with delta derived from mathematics as a change in a variable). On a scale the Delta E value can range from 0 up to 100 (may be even more).

Delta E 76

The most commonly used color difference metric is DE76 and that's because of its simplicity and low computation cost. Given the CIE constructed LAB Color Space and 2 colors we can calculate the DE76 metric as shown below:

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}$$

Fig DE76 Equation

That formula does indeed look something like a Euclidean Distance formula and in fact it is. That all makes sense if one imagines CIELAB color space in 3D form. So a direct distance measure should give off correct results. However, the LAB color space is not uniform perceptually and displays differences in saturation. So when are comparing two points in LAB color space and in fact for hues at the same lightness level it works well but things start to fall apart when we have two saturated colors of different hues.

Below a matrix displays to what visual perception these numbers correspond to:

Delta E	**Perception**
0	Exactly the same
<= 1.0	Not perceptible through human vision
1 – 2	Perceptible through close observation
2 – 10	Perceptible at a glance
11 – 49	Colors are more similar than opposite
100	Colors are exact opposite

Note that this table is to be taken as a general guide and not as de facto rule. There's a possibility to have a Delta E value below 1.0 for two colors that do appear different.

Spectral Data Difference Quantification Metrics

In order to be able to tell spectral reflectances (essentially data) from one another we need quantify metrics that can compare two spectra and display how close they are associated, hence spectral difference metrics.

The statistical method that is chosen for spectral data comparison will mainly depend on the purpose of the comparison. Methods and software that can be applied to spectral data but before there must be defined the precision, heterogeneity, accuracy and generally the main objective of the comparison in order for appropriate tool selection and error rate minimization.

In this project in order to evaluate spectral differences between reference spectra and observed spectra derived from an Illuminant Database a metric is needed. That particular metric will help define a measure of proximity between those Spectral Power Distributions. Some popular metrics that are used in the project are:

Root mean Square Error (RMSE)

The most commonly known metric is the root mean square error and is defined as the average of the squares of the errors meaning the average squared difference between estimated values (known spectra) and what is estimated (observed spectra) under square root. The RMSE formula is displayed below with with regular Y_i denoting known value and Y_i capped denoting the observed value.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)}$$

Fig RMSE formula

Spectral Angle Mapper Metric (SAM)

Spectral Angle Mapper (also known as SAM) is employed. Being a physically-based spectral classification algorithm working in n-Dimensional space it can match reference spectra with a value. More precisely, this metric measures the spectral similarity of two spectra in degree form meaning that it treats spectral data as vectors of n dimensions while n is the spectral bands. The lower the SAM value the closer the observed illuminant spectrum will be to that of the reference. However two spectra might match one another at a specific band region while being completely different at another so band range must be carefully selected when searching for possible close spectrums on different illuminant cases. When SAM metric is equal to zero the two spectra are identical and when the degree is higher than 1 it means that the spectrums are obviously different. In the graph below there are displayed two vectors representing spectral data and the equation to find the SAM value:

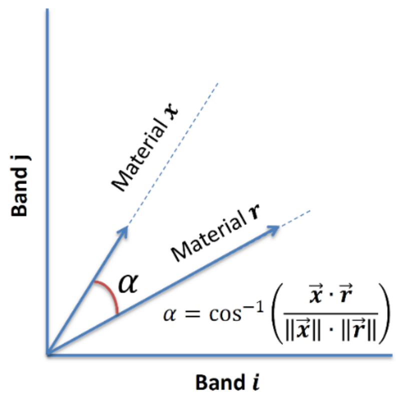


Fig SAM metric display and formula

Weighted Integrated Factor (WiFac)

Another metric that has been used is that of Weighted Integrated factor which is another type of mean square over the curve data samples. The formula is displayed below:

$$Score_{WiFac} = 1 - \sqrt{\frac{\sum max(f[n]^2, g[n]^2) \cdot \left(1 - \frac{\max(0, f[n] * g[n])}{\max(\delta, f[n]^2 * g[n]^2)}\right)^2}{\max(\delta, \Sigma max(f[n]^2, g[n]^2))}}$$

$$\delta = 1.0\text{E-}06$$

Where f, g the 2 curves under comparison.

6 Bibliography

Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010

Edoardo Provenzi, Computational Color Science Variational Retinex-like Methods, ISTE Ltd and John Wiley & Sons, Inc, Great Britain and United States, 2017

Steven Shevel, The Science of Color Second Edition, Elsevier Science, 2003

6.1 References

1. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 11
2. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 37

3. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 166
4. Shevel S., The Science of Color 2nd Edition, Elsevier Science, Amsterdam, Boston, United States, 2003, pp 89
5. http://olympus.magnet.fsu.edu Specular and Diffuse Reflection
6. OpenStax, J. Gordon Betts , Peter Desaix, Eddie Johnson, Jody E. Johnson, Oksana Korol, Dean Kruse, Brandon Poe, James A. Wise, Mark Womble, Kelly A. Young, Anatomy & Physiology, OpenStax College ,2013, pp 585
7. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 111
8. OpenStax, J. Gordon Betts , Peter Desaix, Eddie Johnson, Jody E. Johnson, Oksana Korol, Dean Kruse, Brandon Poe, James A. Wise, Mark Womble, Kelly A. Young, Anatomy & Physiology, OpenStax College ,2013, pp 588
9. OpenStax, J. Gordon Betts , Peter Desaix, Eddie Johnson, Jody E. Johnson, Oksana Korol, Dean Kruse, Brandon Poe, James A. Wise, Mark Womble, Kelly A. Young, Anatomy & Physiology, OpenStax College ,2013, pp 589
10. Youtube video Color Vision 1: Color Basics, Craig Blackwell, 2013
11. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 14
12. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 18
13. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 23
14. Shevel S., The Science of Color 2nd Edition, Elsevier Science, Amsterdam, Boston, United States, 2003, pp 302
15. Youtube video Color Vision 2: Color Matching, Craig Blackwell, 2013
16. Youtube video, What is CCT? Color Correlated Temperature Explained. CCT Applications., BSE, 2015
17. Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 15
18. Shevel S., The Science of Color 2nd Edition, Elsevier Science, Amsterdam, Boston, United States, 2003, pp 104
19. https://www.xrite.com What is metamerism?
20. https://www.news-medical.net What is Spectroscopy?
21. http://bwtek.com How does a Spectrometer Work?
22. https://resonon.com What is Spectral Imaging and why should I use it?
23. Marcus Borengasser, William S. Hungate and Russel Watkins,Hyper Spectral Remote Sensing Principles and Applications, CRC Press, 2007, pp 48
24. https://gisgeography.com Multispectral vs Hyperspectral Imagery Explained
25. http://grindgis.com/remote-sensing 10 Important Applications of Hyperspectral Image
26. https://web.stanford.edu Color Balancing Algorithms
27. Paper Haris Ahmad Khan, Jean-Baptiste Thomas, Jon Yngve Hardeberg and Olivier Laligant, Illuminant estimation in multispectral imaging, 2017, 34, 1085

28. Paper Clément Fredembach and Sabine Süsstrunk Illuminant estimation and detection using near-infrared, 2009
29. https://www.xrite.com Digital SG ColorChecker
30. http://www.babelcolor.com The ColorChecker (Pages 1/3)
31. http://www.spectricon.com and MUSES Manual by Spectricon
32. https://oceanoptics.com USB4000-VIS-NIR
33. http://brucelindbloom.com Useful Color Equations

6.2 Sources

[1] https://sites.google.com/site/chempendix/em-spectrum

[2] http://olympus.magnet.fsu.edu/primer/java/reflection/specular/index.html

[3] https://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap16/chap16.htm

[4] https://commons.wikimedia.org/wiki/File:1416_Color_Sensitivity.jpg

[5] http://hyperphysics.phy-astr.gsu.edu/hbase/vision/addcol.html

[6] Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 14

[7] Georg. A. Klein, Springer Series in Optical Sciences 154, Industrial Color Physics, Springer, Germany, 2010, pp 21

[8] https://sensing.konicaminolta.us/blog/understanding-standard-observers-in-color-measurement/

[9] https://physics.stackexchange.com/questions/240374/scaling-of-the-cie-rgb-color-matching-functions/264363

[10] Color Vision 2: Color Matching YOUTUBE link https://www.youtube.com/watch?v=82ItpxqPP4I

[11] https://stackoverflow.com/questions/29953652/drawing-3-d-rgb-cube-model-with-matlab

[12] https://measurewhatyousee.com/2017/08/17/color-measurement-of-solid-colors/

[13] https://tex.stackexchange.com/questions/177079/tikz-chromaticity-diagram

[14] http://www.khadley.com/courses/Astronomy/ph_207/topics/radiation207/blackbody-radiation.html

[15] https://www.elementalled.com/correlated-color-temperature/

[16] https://www.cinema5d.com/what-is-color-temperature/

[17] https://www.avsforum.com/forum/139-display-calibration/1932473-two-mostly-unrelated-questions-one-about-adobergb-another-about-image-resolution.html

[18] https://docs.esko.com/docs/en-us/colorpilot/16.1/userguide/home.html?q=en-us/common/cop/concept/co_cop_QuantifyingColors.html

[19] https://www.xrite.com/blog/what-is-metamerism

[20] https://oceanoptics.com/

[21] https://books.google.gr/books?id=p_VMYNR0elEC&pg=PA48&lpg=PA48&dq=capturing+a+spectral+cube&source=bl&ots=2zYvTtSbIt&sig=uOiRoZ1uvbmvXJfFogHFbUshSEI&hl=el&sa=X&ved=0ahUKEwjF9P2yrOTbAhXK_qQKHXIEDuMQ6AEIZjAN#v=onepage&q=capturing%20a%20spectral%20cube&f=false

[22] https://gisgeography.com/multispectral-vs-hyperspectral-imagery-explained/

[23] https://www.cambridgeincolour.com

[24] https://infoscience.epfl.ch/record/133341/files/IR_ill_est.pdf

[25] https://imagescience.com.au/products/x-rite-colorchecker-digital-sg

[26] http://www.spectricon.com/products/muses-9-hs/ and MUSES-9-HS manual