CIE Tristimulus filter matching to CCD cameras.

Important considerations for the special case when CCD-type instruments are used for colorimetric-photometric or radiometric applications:

1) CCD camera responsivity is known, (averaged over all pixels)
2) The filters are uniform across the surface

Requirement 1.) is very difficult to achieve precisely. It would basically require measurement of each pixel’s spectral sensitivity, and evaluate an average across the camera surface. Hopefully the deviation from the average of each pixel is not too much, and therefore one average spectral sensitivity function can be used as basis for the filter matching.

More significant problem arises from the fact that some CCD cameras have different average spectral responsivitiees even if they are the same type and obtained from the same manufacturers. The reason for the variation is due mainly to the surface Oxide layers, which could result in several peaks and valleys across the visible spectral region; the exact location of those depending on the layer thickness.

The presence of the peaks and valleys causes other problems as well: for filter matching it is necessary to average those parts of the sensitivity function to obtain a smoothly changing curve.

Back-lit cameras do not have these type of problems; they show much better reproducibility from camera to camera from the spectral sensitivity function point of view.
This is an example of spectral response variations on 4 cameras of same types and from the same manufacturers.

In order to achieve requirement 2.) full-glass filtering is needed. A good quality glass supplier has to be found unless it is possible to produce glass layers in house.

After the glass-manufacturer has been found, many different available color-glass samples have to be bought and prepared as test-pieces for transmissivity vs. wavelength measurements. It is important to prepare the glass-samples with the same care what will be necessary for the preparation of the final filters. They need to be polished to a thickness less then 1 mm, in many cases as thin as 100 microns. Each sample has to be measured, and their thicknesses carefully recorded.

When several dozen samples have been tested and their results tabulated, a mathematical program can calculate the best fit to a target function, considering several glass layer transmissivities multiplied by the detector sensitivity.

At this stage a very good match can be seen, but in many cases it would require too many layers of colored glasses and many different thicknesses for each, some too thin or too thick for practical considerations.

Compromise has to be made at this point, considering that the minimum thickness of a layer has to be more the 25 microns for uniformity and breakage, and the maximum thickness cannot be more than a certain value before the transmitted light level would be too low for detection.
More restrictions have to be considered from the point of view of economy; too many layers with extreme thicknesses would make the fabrication prohibitively expensive.

After the limits have been included into the mathematics, the program finally comes up with the best possible solution for the target. In many cases more then one solution exists, (here the optimum has been already excluded, different levels of compromise has been considered only)

In some cases to obtain the most useful combination the type of light source spectral power distribution or reflected light distributions are considered which will be tested with the instrument; making the fit to the target the best in those spectral regions where the light power has relatively highest value and loosen it in those regions where the light output is negligible.

In the case of tristimulus colorimeters, the target curves are the CIE Xbar, Ybar and Zbar functions. Ybar is the same as the \( V(\lambda) \) photopic sensitivity function.

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**The Goodness of the Fit**

In order to determine how good a filter-detector combination would work to measure photometric quantities the CIE organization developed a measure, the so-called \( f_1' \) number, which is expressed in percentage; it’s definition is:

\[
f_1' = \frac{\int |s^*(\lambda)_{rel} - s_T(\lambda)_{rel}| d\lambda}{\int s_T(\lambda)_{rel} d\lambda}
\]

where

- \( s^*(\lambda)_{rel} \) is the target spectral responsivity
- \( s_T(\lambda)_{rel} \) is the spectral distribution of Standard Illuminant A
- \( d\lambda \) is the relative spectral responsivity of the detector

This \( f_1' \) number was originally used only for Ybar or \( V(\lambda) \) detectors; and since most measurements were carried out for light sources similar to the incandescent light, a weighing function was introduced, the spectral power distribution of the CIE A source, (2856 K° lamp).
The best matched detector-filter combinations are resulting \( f_1' < 1.5\% \) for \( V(\lambda) \) types. These type of detectors are very expensive and very difficult to make but would measure photometric quantities with high precision otherwise possible to obtain only by spectroradiometric measurements. Most commonly available detectors have \( f_1' < 5\% \); those detectors with \( f_1' < 3\% \) are considered very good and are widely used in many applications.

It became common to use the \( f_1' \) number definition to express goodness of the fit for Xbar and Zbar detectors as well, however it has not been generally accepted yet. The CIE is working on this question within a technical committee right now, and it may modify the definition somewhat for the specific cases.

For more general use, it is customary to replace the \( S(\lambda)A \) function with the Equi-energy function (1) where the colorimeter is intended to be used on many different types of light sources.

It is possible to use other measures for determining the goodness of the fit; in certain applications for example it is important to define maximum deviations allowed from the target function throughout the spectral region.

Filters can be matched to detectors (CCD type as well) to achieve uniform response through a wide spectral region. These types of detectors can be used for radiometric measurements where the light power expressed in Watts are needed.

Filters can be matched to light sources as well, to transform it’s color temperature to higher or lower values.