Colorimetric and Spectral Combined Metric for the Optimization of Multispectral Systems

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ABSTRACT

We present here a new combined metric which takes into account spectral, colorimetric and integrated irradiance similarity between two spectra to be compared. This approach does not avoid 'mononumerosis', as would be desirable, but does seek to find a balance between three different, and important points of view in spectral match quality. This permits us to work with a single but meaningful cost function in minimization problems using, for instance, simulated annealing algorithms. The annealing algorithm requires us to minimize a single cost function and thus we propose a solution that calculates both the spectral and colorimetric similarity of any pair of skylight spectra. We also compare it with some other widely used metrics in an experiment to recover skylight spectra.

1. INTRODUCTION

The importance of the metric selected for evaluating a spectral match has been studied by several authors[1,2]. However, no consensus exists about what metric should be used in order to measure the quality of a spectral reconstruction. Essentially there are two kinds of metric: colorimetric and spectral[1].

Colorimetric metrics such as those proposed by the CIE (CIELUV, CIELAB, CIE94, or CIEDE2000) approximate color differences observed by the human eye. To calculate such metrics, we need only to know the tristimulus values of a given color signal, and consequently we cannot distinguish between metamers.

Spectral metrics are those which measure the distance between two spectral curves, such as RMSE or GFC[3] (a widely accepted[1,2] index of similarity between two spectra, which uses Schwartz's inequality). These metrics distinguish between metamers but do not consider human vision.

Some new metrics have been proposed for comparing spectra that take into account properties of the human visual system, such as weighted RMSE (WRMSE) with the diagonal of matrix R proposed by Cohen[1,2]. Viggiano proposed a spectral comparison index (SCI)[4], the properties of which have also been studied by other authors[1,2]. Another metric widely used in solar radiation measurements is the percentage of the integrated irradiance error[5] (IIE(%)) across the visible spectrum.

Some authors[6] have searched for optimum sensors using only one of the metrics described above. Because their results depend on the metric used, they are not particularly useful in selecting sensors for our planned multispectral system. Imai *et al.* suggest that "mononumerosis" should be avoided when evaluating the quality of spectral matches[1]. By this term they mean that *several* metrics should be used to assess color reconstruction from both colorimetric and spectral standpoints. Day[7] used thresholds for RMSE and CIEDE2000 metrics when searching for optimum sensors; Hernández-Andrés *et al.*[8] used GFC, CIELUV, and IIE(%) in a similar way.

2. METHOD

As mentioned above, we must use a single cost function when developing a simulated annealing algorithm. This approach may seem to contradict the recommendations of Imai *et al.*[1] Yet it does not, because we actually construct a simple single-cost function or metric that combines several metrics at once. We use GFC as a spectral metric, CIELAB as a colorimetric cost function, and IIE(%) as a metric for comparing the spectral curves of natural illuminants. In principle, our new metric should approach zero for near-perfect matches (in contrast to GFC, which tends to unity for perfect matches) and give approximately the same weight to the GFC, CIELAB, and IIE(%) metrics. So, our combined CSCM metric is calculated by

$$CSCM = Ln(1 + 1000(1 - GFC)) + \Delta E_{ab} + IIE(\%) \tag{1}$$

Equation (1) is a combined metric that is zero for perfect matches and thus is a good candidate for developing an annealing search algorithm. Its chief advantage is that it quantifies spectral mismatches among metamers, perceptual differences in color matches and differences in such integrated radiometric quantities as irradiance or radiance. Though this metric may not avoid "mononumerosis," it clearly combines the properties of various metrics relevant to skylight spectra.

3. RESULTS

In a previous work[9], we developed an exhaustive search of the set of three sensors which give the best spectral reconstruction of skylight in the presence of noise (measured via the signal to noise ratio, SNR) using a pseudoinverse algorithm and linear reconstructions with the eigenvectors obtained by a principal components analysis (PCA) from a set of 1567 measurements taken in Granada. Table 1 shows the means and standard deviations (SD) for this same set of 1567 skylight spectra when recovered using the optimum sensors found[9] and the first 3 eigenvectors at various noise levels. Note that the GFC, CIELAB, and IIE(%) terms are roughly equal in each row of Table 1, thus justifying our weights for them in Eq. (1).

Table 1. Means and standard deviations (SD) for 1567 skylight spectra measured in Granada, Spain, using 3 eigenvectors in linear-recovering spectra at different signal-to-noise ratios (SNR).

SNR	GFC±SD	CIELAB ΔE_{ab}±SD	IIE(%)±SD	LN(1+1000(1-GFC))±SD	CSCM±SD
40dB	0.9993±0.0012	0.7±0.5	1.3±0.7	0.4±0.3	2.4±1.1
30dB	0.9987±0.0016	0.9±0.5	3.2±1.9	0.7±0.4	4.8±2.2
26dB	0.9981±0.0023	1.3±0.7	5.0±3.5	0.9±0.5	7.3±4.1

Once we have proposed the CSCM metric, we developed a simulated annealing search algorithm using just one of the three metrics which compose CSCM. As Table 2 shows, using only a single metric produces results that work well according to that metric but that perform poorly according to the other metrics. In particular, CIELAB alone should not be used as a cost function because its small ΔE_{ab} errors come at the price of large GFC and IIE(%) errors. Thus we use the CSCM, which strikes a balance between the three different metrics when recovering skylight spectra. This balance is more apreciable with a lower SNR.

Table 2. Comparison of mean and standard deviation values found using annealing searches with various metrics and SNR, reconstructions with 3 eigenvectors, and the 1567 Granada skylight spectra. The best result for each metric appears in bold type when it alone was the annealing algorithm's cost function

Cost function	SNR	GFC±SD	ΔE_{ab}±SD	IIE(%)±SD	CSCM±SD
GFC	40dB	**0.9994±0.0012**	0.8±0.6	1.3±0.7	2.5±1.1
CIELAB		0.9923±0.0131	**0.3±0.2**	2.3±1.6	4.3±2.3
IIE(%)		0.9972±0.0040	1.3±0.8	**0.7±0.5**	3.2±1.4
CSCM		0.9993±0.0012	0.7±0.5	1.3±0.7	**2.4±1.1**
GFC	30dB	**0.9993±0.0013**	1.0±0.5	3.9±2.0	5.4±2.4
CIELAB		0.9926±0.0102	**0.8±0.3**	3.9±2.4	6.2±2.8
IIE(%)		0.9795±0.0262	2.6±1.8	**1.6±1.3**	6.6±2.8
CSCM		0.9987±0.0016	0.9±0.5	3.2±2.0	**3.3±4.9**

Finally we compare CSCM metric with other widely used metrics[1,2] (spectral RMSE, Viggiano's spectral comparison index SCI, and weighted RMSE with Cohen Matrix *R* diagonal) in three type of case with different skylight spectra: a pair of identical skylight spectra shifted 2% and 5% in magnitude relative to the maximum of the curve with highest randiance, a pair formed by a skylight spectrum and its linear reconstruction with first three eigenvectors obtained with PCA from our 1567 measurements -as explained above- but without simulated noise, and a pair of a skylight spectrum with one metamer constructed via an equation used by Viggiano[2], which tries to exaggerate the defficient behaviour of colorimetric metrics when metamerism is present. The mean and standard deviation (SD) values of these matches for our set of 1567 skylight spectra are shown in Table 3 and some particular spectra are represented in figure 1. Note that the SD values for the shifted spectra are zero because all the samples have the same RMSE with no deviation since the shift is the same.

Table 3. Means and standard deviations for the metrics used in different skylight spectral matches.

Match	GFC	CIELAB ΔE_{ab}	IIE(%)	CSCM	SCI	RMSE	wRMSE
	±SD	±SD	±SD	±SD	±SD	±SD	±SD
2% shift.	0.99993	0.46	3.99	4.55	0.238	0.036	0.007
	±0.00004	±0.04	±0.14	±0.21	±0.002	±0	±0
5% shift.	0.99941	1.12	9.97	11.57	0.595	0.09	0.017
	±0.00021	±0.09	±0.36	±0.58	±0.006	±0	±0
3 eigenvct.	0.99952	0.76	0.24	1.35	0.158	0.028	0.006
	±0.00105	±0.55	±0.22	±1.05	±0.092	±0.017	±0.003
metamers	0.85044	0	33.79	38.79	1.866	0.525	0.053
	±0.02181	±0	±2.09	±2.20	±0.092	±0.031	±0.003

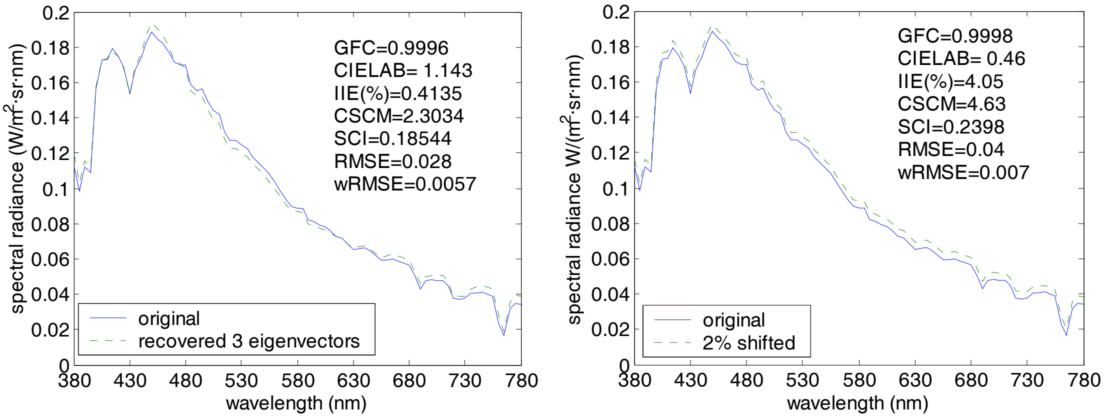

Figure 1. Samples of skylight spectral matches and their values for the metrics studied.

We can see how GFC alone does not reflect well the spectral differences caused by a constant shift in the curves, which can be important if the total energy estimation received by the system is relevant. CIELAB fails to measure the lack of quality in the spectral match of metamers (this fact has been exagerated in this experiment). WRMSE, Viggiano's SCI and CSCM seem to take into account all these factors, but CSCM units seem more intuitive and manageable, rendering this metric a good candidate for minimization algorithms that require a single cost function.

4. CONCLUSIONS

We propose a new combined metric which takes into account three different points of view when measuring the quality of spectral matches. It tries to find an equilibrium between the three metrics, one spectral, one colorimetric and one that calculates the error in the total integrated radiance. This single metric could be useful when developing a minimization algorithm that needs to evaluate a single cost function, as occurs in simulated annealing algorithms. The metric proposed here achieves the aims we set out in the introduction: it detects the lack of quality in the spectral match of metamers, also considers human vision and tends to zero for perfect matches. The units of the CSCM metric seem more intuitive than other metrics compared here.

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