Building an optimum computer-designed multispectral system for skylight acquisition

Miguel A. López-Álvarez[1], Javier Hernández-Andrés[2], and Javier Romero[2];
[1]Hewlett-Packard Española (LFP), 08174 Sant Cugat del Vallès, Barcelona, SPAIN.
[2]Color Imaging Lab., Universidad de Granada, 18071 Granada, SPAIN.

Abstract

In previous works [1,2] *authors developed a series of computational simulations in order to study the real behaviour of a multispectral imaging system aimed at skylight spectral recovery. We took into account the effect of several parameters on the spectral shape of the optimum sensors found for recovering skylight spectra. Hence, we studied the influence of different kinds of noise, number and kind of sensors, linear bases, number of representative vectors, size of the training set and the spectral estimation method. In this work we go along these lines by implementing the five optimum sensors found in a realizable case by using a monochrome CCD camera and a Liquid Crystal Tunable Filter (LCTF). We show that the computational simulations resulted in a very realistic study of the behaviour of this practical multispectral system since the spectral recoveries obtained with the real optimum system are quite acceptable for scientific purposes where skylight spectra are used. Hence, we have constructed a real multispectral system for imaging skylight, that could be used later to obtain information about climate parameters like the Angström exponent or the optical depth* [3] *in every pixel of the image.*

Introduction

The advantages of using multispectral imaging systems instead of traditional spectrorradiometers are numerous. For example, one can obtain a radiance spectrum for each pixel of the imaging matrix, typically a Complementary-Metal-Oxide-Semiconductor (CMOS) or a Charge-Coupled device (CCD). Moreover, multispectral systems are cheaper, lighter and more easily portable than clasical spectrorradiometers. These are some of the reasons why this scientific topic has grown considerabily in the last decade, being today an interesting and very productive field [4-9].

Here, we focus our interest on studying an important natural illuminant like skylight [10,11], from the spectral curves of which we can extract information about climate parameters such as the optical depth or the Angstrom exponent [3], that inform us about the size and concentration of aerosol particles. A huge database of multispectral skylight images could be interesting for scientists of many disciplines, since it would provide images of the entire skydome with high spatial and spectral resolution, that could be used in various research topics.

In previous works [1,2] we made a complete theoretical study about a planned optimum multispectral system for spectral imaging of skylight. By developing computational simulations, we obtained results concerning the influence of several parameters on the behaviour of the multispectral system, like the spectral responsitivity of its sensors, the number and type of sensors, the spectral estimation method and linear bases chosen, the number and quality of training spectra and noise. We found that certain values for those parameters could provide very accurate spectral reconstructions. Hence, we now pretend to use these previous results in order to build a prototype of this optimum multispectral system by using a cooled, 12-bit, monochrome CCD camera (model Retiga QImaging SRV1340) and a LCTF (model Varispec from CRi).

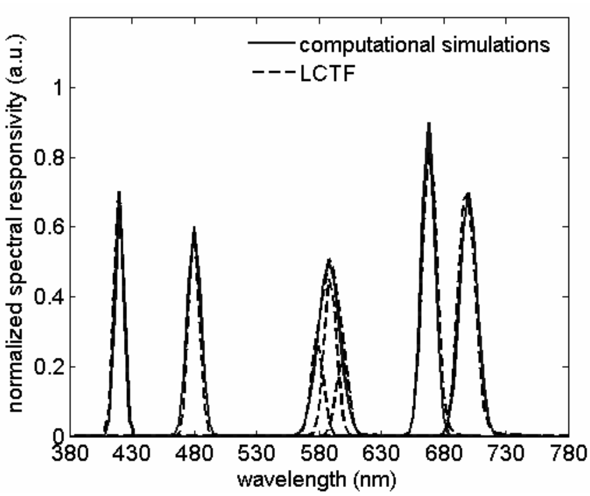


Figure 1. *Optimum sensors found in the simulations and implemented by using the LCTF.*

Method

We found [2] for the Imai-Berns method [12], five optimum Gaussian-like sensors, PCA basis vectors [4] and 12-bit quantization that the optimum sensors are those of figure 1. In this same figure we show how to implement these optimum sensors by using 7 of the 33 available transmittance modes of a VariSpec LCTF by CRi, and adjusting the exposure time of each mode (the spectral sensitivity of the monochrome CCD camera –which was measured by following a calibration method proposed by Ferrero *et al* [13]– is also taken into account). Imai-Berns method computes a so-called matrix G from the sensors' responses of a training spectra, ρ_{ts}, and the coefficients of these spectra, ε_{ts}, in a given linear basis, V, [2] as we show in eq. (1)

$$G = \varepsilon_{ts}\rho_{ts}^{+} \quad (1)$$

where superscript + denotes the Moore-Penrose pseudoinverse [4]. This matrix G is used later to calculate unknown spectra, E_R, from its sensors' responses, ρ, as we can see in equation (2).

$$E_R = VG\rho \quad (2)$$

We trained the system [2] by simulating the camera responses of a set of 1567 skylight spectra measured in Granada [11] (Spain, 37º 11'N, 3º 37'W, altitud 680 m) in 1997. These simulated sensors' responses could be obtained after performing a complete radiometric and noise calibration of the CCD monochrome camera [13]. We then tested [2] the behaviour of the multispectral system by taking real multispectral images, with the CCD camera and the LCTF, corresponding to a set of 125 skylight spectra measured also in Granada in 2007. This measurements were taken simultaneously with a SpectraScan PR650 spectroradiometer in order to compare the results with those obtained with a well-known aparatus.

The quality of the spectral reconstructions is evaluated by using the colorimetric and spectral combined metric [1] (CSCM), which has proved to be an excellent metric to compare spectra from colorimetric and spectral points of view. This metric is calculated as shown in eq. (3), and is made up of the contributions of the spectral metric GFC (goodness-fit-coefficient [11]), colorimetric metric CIELAB ΔE_{ab}^*, and the percentage of the integrated radiance error [10] (IRE(%)) which takes into account differences between the two compared spectra in total energy integrated across the visible spectrum.

$$\mathrm{CSCM} = \mathrm{Ln}(1000(1\text{-}\mathrm{GFC})) + \Delta E_{ab}^* + \mathrm{IRE}(\%) \qquad (3)$$

where Ln stands for natural logarithm, and GFC and IRE(%) are defined as

$$GFC = \frac{\left|\sum_{i=1}^{n} S(\lambda_i) S'(\lambda_i)\right|}{\left|\sum_{i=1}^{n} [S(\lambda_i)]^2\right|^{1/2} \left|\sum_{i=1}^{n} [S'(\lambda_i)]^2\right|^{1/2}} \qquad (4)$$

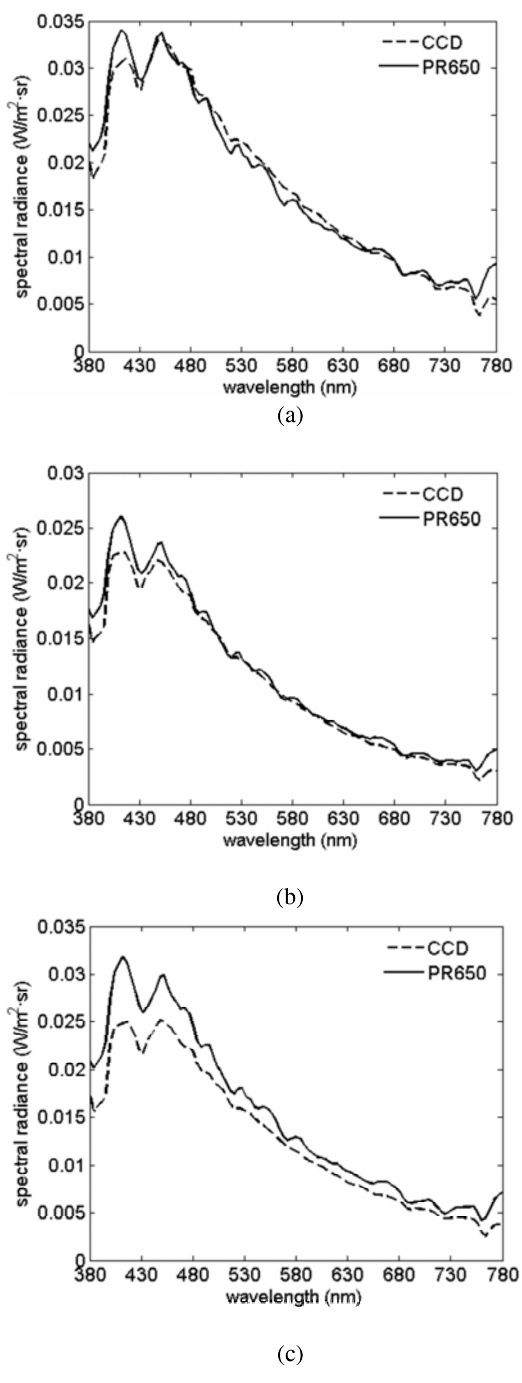
$$IRE(\%) = 100 \frac{\left|\sum_{i=1}^{n} S(\lambda_i) - S'(\lambda_i)\right|}{\sum_{i=1}^{n} S(\lambda_i)} \qquad (5)$$

with *S* and *S*' being the sampled spectra (at *n* wavelengths) that we are comparing. Several characteristics of these metrics should be pointed out. First, GFC tends to the unity for perfect matches, hence we calculate its complement as 1-GFC. Second, we give the same weight to the three terms in the left-hand side of equation (3), assuring that the three points of view taken into account have the same relative importance [9].

Results

In figure 2 a, b and c we show respectively the 10th, 50th and 90th percentiles of the CSCM metric when reconstructing the 125 skylight spectral curves belonging to the test set. We can see that the estimated curves (in dashed line in figure 2) are really accurate when compared to the original curves measured with the spectroradiometer (solid line), hence demonstrating the capability of this multispectral system to obtain very precise spectral estimations of this kind of natural illuminant.

In table 1 we show the mean and standard deviations of the values of various metrics (CSCM and the three metrics that compose it) when recovering the spectral set of 125 skylight measurements used for test. The values obtained are very accurate, though a little worse than those obtained in the computational simulations [2] for the same noise situation (we could estimate that the total signal to noise ratio level in our practical system is about 30dB). This might be due to the effect of some experimental errors that could not be taken into account in the previous theoretical study



(a)

(b)

(c)

Figure 2. *(a) 10th percentile (CSCM = 3.12), (b) 50th percentile (CSCM = 7.48), (c) 90th percentile (CSCM = 16.76) over the test set of 125 spectral measurements taken in Granada in 2007 when using the Imai-Berns method with five optimum sensors and five PCA vectors.*

We also studied the accuracy obtained with the multispectral system built from the monochrome CCD camera

©2008 Society for Imaging Science and Technology

and the LCTF, when the 33 available channels –or transmittance modes– of the LCTF were used. In this case we also used the Imai-Berns method for spectral estimation, and we studied various cases with different numbers of basis vectors in order to obtain the optimum number of them to be used when recovering skylight with this 33-channel multispectral system. We found that using 6 PCA vectors gave the best results, according to previous results [1,2,5,8,12] where the optimum number of PCA vectors was found to be lesser than the number of sensors if this number was above a certain threshold, which depended on the specific multispectral system.

Table 1. Mean ± standard deviation values of various metrics over the test set of 125 spectral measurements taken at Granada in 2007 when using the five optimum sensors of the Imai-Berns method with five PCA vectors

GFC	0.998±0.001
CIELAB ΔE*ab	0.87±0.21
IRE (%)	7.05±5.85
CSCM	8.97±6.00

Table 2. Mean ± standard deviation values of various metrics over the test set of 125 spectral measurements taken at Granada in 2007 when using the Imai-Berns method with 33 channels and different numbers ,n, of PCA basis vectors. The best case for the CSCM metric was obtained for n = 6.

n = 5	GFC	0.998±0.001
	CIELAB ΔE*ab	0.70±0.23
	IRE (%)	6.31±5.44
	CSCM	8.24±5.62
n = 6	GFC	0.998±0.001
	CIELAB ΔE*ab	0.70±0.23
	IRE (%)	6.31±5.43
	CSCM	8.23±5.58
n = 7	GFC	0.998±0.001
	CIELAB ΔE*ab	0.71±0.23
	IRE (%)	6.30±5.42
	CSCM	8.26±5.57
n = 33	GFC	0.997±0.001
	CIELAB ΔE*ab	0.85±0.21
	IRE (%)	6.30±5.43
	CSCM	8.49±5.57

In figure 3 we show the measured spectral transmittances of these modes of our LCTF. One would expect that using a major number (33 instead of 7) of filters in the multispectral system leads to an improved accuracy in the spectral reconstructions. Some authors [1,2,5,7,8] have proven that this is not the case in real systems where noise is a key point influencing the behaviour of the camera. We show in table 2 that the results obtained by using the 33 modes are very similar to those obtained when using only the 7 modes of the LCTF that leads to the implementation of the 5 optimum sensors found in the theoreticall study [2]. The difference in the time comsumed by both approaches is significative, since using only 7 modes instead of 33 reduces the total exposure time of each multispectral image from 60 seconds to 14. Hence, here we have proved that using a small number of optimum sensors leads to almost the same results obtained when using all the available modes, but at an interesting reduction of total exposure time.

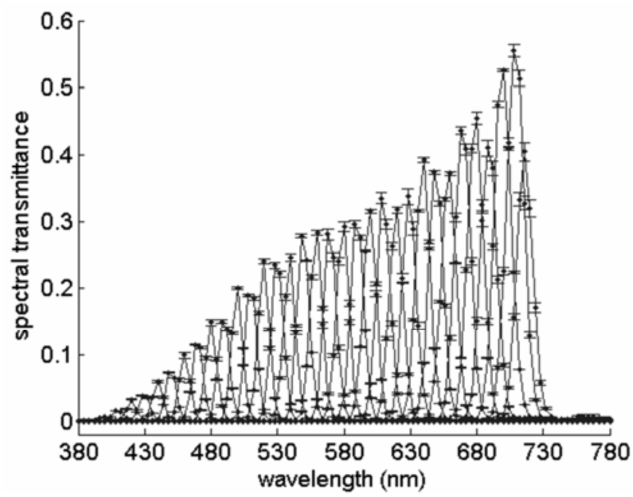


Figure 3. *Spectral transmittance of the 33 modes of the Varispec liquid-cristal-tunable filter measured in our laboratory three times (error bars show the standard deviation obtained at each sampled wavelength).*

Conclusions

We have proved that accurate multispectral estimations of skylight can be obtained by using a monochrome CCD camera attached to a liquid-crystal-tunable-filter. The spectral curves of skylight obtained with such a system are really similar to the ones measured with a spectrorradiometer simultaneously, with several advantages in price, weight, spatial resolution and portability.

We implemented the five optimum sensors found in a previous computational study [2] for the Imai-Berns method, and we showed that these five optimum sensors can be implemented by using just seven transmittance modes of the LCTF and adjusting their exposure times. We demonstrated that using a small number of optimum sensors provides almost the same spectral results as using all the available channels of the system, with a significant improve in time. Hence we can recommend developing an optimization procedure prior to building a multispectral system.

References

[1] M. A. López-Álvarez, J. Hernández-Andrés, J. Romero, R. L. Lee Jr., "Designing a practical system for spectral imaging of skylight", Appl. Opt. 44, 5688-5695, (2005).

[2] M. A. López-Álvarez, J. Hernández-Andrés, E. M. Valero, J. Romero, "Selecting algorithms, sensors and linear bases for optimum spectral recovery of skylight", J. Opt. Soc. Am. A, 24, pp. 942-956, (2007).

[3] R. M. Goody and Y. L. Yung, Atmospheric Radiation, Theoretical Basis, 2nd edition, (Oxford University Press, London, 1995). Chap. 5.

[4] J. Y. Hardeberg, Acquisition and Reproduction of Color Images: Colorimetric and Multispectral Approaches, (Dissertation.com, Parkland, Fla., 2001), pp. 121-174.

[5] D. Connah, S. Westland, and M. G. A. Thomson, Optimization of a Multispectral Imaging System, Proc. 1st CGIV (2002), pp. 619-622.

[6] H. Haneishi, T. Hasegawa, A. Hosoi, Y. Yokoyama, N. Tsumura, and Y. Miyake, "System design for accurately estimating spectral reflectance of art paintings", Appl. Opt. 39, 6621-6632 (2000).

[7] N. Shimano, K. Terai, and M. Hironaga, "Recovery of spectral reflectances of objects being imaged by multispectral cameras", J. Opt. Soc. Am. A, 24, 3211-3219 (2007).

[8] J. L. Nieves, E. M. Valero, S.M.C. Nascimento, J. Hernández-Andrés, and J. Romero, "Multispectral synthesis of daylight using a commercial digital CCD camera", Appl. Opt. 44, 5696-5703 (2005).

[9] M. A. López-Álvarez, J. Hernández-Andrés, E. M. Valero, and J. L. Nieves, Colorimetric and Spectral Combined Metric for the Optimization of Multispectral Systems, Proc. 10th Congress of the International Colour Association (AIC'05), (Granada, Spain, 2005), pp. 1685-1688.

[10] J. J. Michalsky, "Estimation of Continuous Solar Spectral Distributions from Discrete Filter Measurements: II. A Demonstration of Practicability," Sol. Energy 34, 439-445 (1985).

[11] J. Hernández-Andrés, J. Romero, and R. L. Lee, Jr., "Colorimetric and spectroradiometric characteristics of narrow-field-of-view clear skylight in Granada, Spain," J. Opt. Soc. Am. A 18, 412-420 (2001).

[12] F. H. Imai and R. S. Berns, Spectral Estimation Using Trichromatic Digital Cameras", Proc. of the International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives (Chiba, Japan, 1999), pp. 42-48.

[13] A. Ferrero, J. Campos y A. Pons, "Low-uncertainty absolute radiometric calibration of a CCD", Metrología 43, S17-S21 (2006).

Authors Biography

Miguel A. López-Alvarez received his B.Sc. in physics in 2003, and his B.Sc. in electronics engineering in 2007 from the University of Granada (SPAIN). This year he also received his Ph.D. -from the same university- in color science, with his thesis concerning multispectral systems for studying natural illuminants. Since February 2008 he is working as a color engineer in Hewlett-Packard in Barcelona, developing large format inkjet color printers.

Javier Hernández-Andrés is Associate Professor in the Optics Department at the University of Granada (SPAIN). Since 2007 he is Topical Editor in Computational&Machine Vision for the Journal of the Optical Society of America A. He was program co-chair of the 10th Congress of the International Colour Association AIC Colour 05. He also is academic coordinator at the University of Granada of the International Master Erasmus Mundus CIMET "Color in Informatics and Media Technology".

Javier Romero obtained his M.S. in Physics in 1979 and his Ph.D. in Optics in 1984, both from the University of Granada, where he is Professor. His research has been focused on colorimetry, color vision, optical properties of the atmosphere and multispectral color imaging. He has occupied several research positions such as: president of the Spanish Color Committee (1991-1994), Member of the Executive Committee of the AIC (1997-2001) and Secretary-Treasurer of the AIC (2007-2010).

©2008 Society for Imaging Science and Technology