第 35 卷第 5 期
2006 年 5 月

光 子 学 报
ACTA PHOTONICA SINICA

Vol. 35 No. 5
May 2006

Practical Methods for Abridging Spectral Reflectance

Wang Ge[1,2], Li Changjun[3], M Ronnier Luo[3]

Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016

2 *Graduate School of Chinese Academy of Science, Beijing* 100039

3 *Department of Color Chemistry, University of Leeds, Leeds LS2 9JT, UK*

Abstract The direct selection, linear, and third order reflectance abridgement methods are discussed and tested. It is found that the third order method is the best when abridging reflectance from 5 nm to 10 nm, 20 nm or 30 nm intervals, while the direct selection method is the best when abridging reflectance from 10 nm to 20 nm or 30 nm. In addition, it's found that abridgment methods are comparative to Vector Subspace Method when the spectral image compression application is considered. The tested and compared results show that the methods can be used in practice when the reflectance abridgement or spectral image compression is required.

Keywords Spectral reflectance; Abridgement; Weighting table; Spectral image; Vector subspace method

CLCN TP391.41 **Document Code** A

0 Introduction

Reflectance function[1] is a figure print of an object and it is essential for many applications such as color reproduction[2], spectral image[3], spectrometer[4,5] and colorant formulation. In some applications, it is required that the known reflectance values at d_0 nm interval must be compressed or abridged into reflectance values at a larger, d_n nm, interval. Here d_n can be divide exactly by d_0.

For example, in some commercial products all colorimetric computations are computed using reflectance at 10 nm (or 20 nm) interval. If we have measured reflectance values at 5 nm (or 10 nm) interval, then the measured reflectance values must be abridged before the commercial product can be used.

Another application example is related to spectral imaging. Spectral imaging has widely gained attention during the past few years. A spectral image contains huge information since each pixel of it is represented by a reflectance vector. Spectral image has the advantage of accurately reproducing the image under any illumination environment over the traditional color image. The image compression[6,7] is an important task since the spectral image data must be small enough to be stored in the image libraries and to be transferred quickly in image data communication.

At first, three methods are given for the reflectance abridgement in the next section, then the performances of the methods are tested in the section after, and finally conclusions are given in the final section.

Tel: 0335-8063946 Email: wangge@ysu.edu.cn

Received date: 2005-01-20

1 Reflectance abridgment methods

Let

$$W_{X,i}^{d_0}, W_{Y,i}^{d_0}, W_{Z,i}^{d_0} \quad (i=0,1,\cdots m) \tag{1}$$

be the weighting table at d_0 (an integer) nm interval in the visible range of wavelength (a,b). Here, $m=(b-a)/d_0$, $a=380$ nm and $b=780$ nm recommended by the International Commission on Illumination (CIE)[8], while for the most industrial applications $a=400$ nm and $b=700$ nm. If the reflectance values of a color object

$$r_i^{d_0} \quad (i=0,1,\cdots,m) \tag{2}$$

are available at wavelength $\lambda_i = a + i d_0$, then the tristimulus values of the color object can be computed by the following summations

$$X=\sum_{i=0}^{m} W_{X,i}^{d_0} r_i^{d_0}; Y=\sum_{i=0}^{m} W_{Y,i}^{d_0} r_i^{d_0}; Z=\sum_{i=0}^{m} W_{Z,i}^{d_0} r_i^{d_0} \tag{3}$$

However, in some applications, it is required that the known reflectance values Eq. (2) at d_0 nm interval have to be compressed or abridged into reflectance values

$$r_k^{d_n} \quad (k=0,1,\cdots,p) \tag{4}$$

at a larger, see d_n nm, interval to calculate the tristimulus vales using the weighting tables

$$W_{X,k}^{d_n}, W_{Y,k}^{d_n}, W_{Z,k}^{d_n} \quad (k=1,2,\cdots p) \tag{5}$$

rather than to use Eq. (3) with d_0 nm interval weighting tables and reflectance values. Here $p=(b-a)/d_n$.

For computing the weighting table at a larger interval, please refer to a recent series of papers by Li, Luo and others[9~11] and references there. Here we mainly concern how to abridge or compress the reflectance values Eq. (2) at d_0 nm interval into reflectance values Eq. (4) at d_n nm interval. It is assumed here that the integer d_n is greater than the integer d_0 and they satisfy

$$d_n = d_0 d \tag{6}$$

Where, d is an integer as well. For example, $d_0=$

$1, d_n = d = 10$, or $d_0 = 10, d_n = 20$, and $d = 2$.

In this section, three methods will be given. They are the direct selection, linear abridgement, and third order abridgement, as will be proposed as the follow.

1) Method 1: Direct selection

Note that, $r_i^{d_0} \approx R(\lambda_{a+id_0})$, thus, for a given integer d and for any integer i between 0 and m it can be represented by the following

$$i = kd + j \quad (k = 0, 1, \cdots, p; j = 0, 1, \cdots, d-1) \tag{7}$$

Thus $r_i^{d_0}$ can be denoted by $r_{k,j}^{d_0}$ if $i = kd + j$. Since

$$r_{k,0}^{d_0} = r_{kd+0}^{d_0} \approx R(\lambda_{a+kdd_0}) = R(\lambda_{a+kd_n}) \approx r_k^{d_n} \tag{8}$$

therefore, method 1 shows

$$r_k^{d_n} = r_{k,0}^{d_0} = r_{kd+0}^{d_0} \quad (k = 0, 1, \cdots, p) \tag{9}$$

2) Method 2: Linear abridgement

Normally it is known how to obtain more missing values between the known values by interpolation, but it's not know how to get rid of the extra values. However, one rule that ought to follow is the tristimulus values computed using the abridged reflectance values at d_n nm intervals must equal or close to the tristimulus values computed using the original reflectance values at d_0 nm intervals. In order to solve the problem, the following steps are followed:

• Interpolate weights $W_{X,k}^{d_n}, k = 0, 1, \cdots, p$ into $W_{X,i}^{d_0}, i = 0, 1, \cdots, m$, using linear interpolation.

• Do the summations using interpolated weights $W_{X,i}^{d_0}$ and measured reflectance values $r_i^{d_0}$ to obtain tristimulus value X.

• Reordering the summations in step 2 in terms of $W_{X,k}^{d_n}$ since $W_{X,i}^{d_0}$ are functions of $W_{X,k}^{d_n}$. The coefficients $W_{X,k}^{d_n}$ are the reflectance values wanted at d_n nm intervals.

3) Step 1: Linear interpolation

As did above, for any i between 0 and m it can be represented using Eq. (7). Thus, $W_{X,i}^{d_0}$ can be denoted by $W_{X,k,j}^{d_0}$ for convenience. As the interpolation

$$W_{X,k,0}^{d_0} = W_{X,k}^{d_n} \quad (k = 0, 1, \cdots, p) \tag{10}$$

and $W_{X,k,j}^{d_0}, j = 1, \cdots, d-1$ are linear combination of $W_{X,k}^{d_n}$, and $W_{X,k+1}^{d_n}$, i. e.

$$W_{X,k,j}^{d_0} = c_{1,j} W_{X,k}^{d_n} + c_{2,j} W_{X,k+1}^{d_n} \tag{11}$$

where

$$c_{1,j} = 1 - \frac{jd_0}{d_n} = 1 - \frac{j}{d}, c_{2,j} = \frac{jd_0}{d_n} = \frac{j}{d} \tag{12}$$

Note that, if the interpolated values $W_{X,i}^{d_0} = W_{X,k,j}^{d_0}$ $(i = kd + j)$ are qualified weights at d_0 nm interval for computing tristimulus value X, they should satisfy

$$\sum_{i=0}^{m} W_{X,i}^{d_0} = \sum_{k=0}^{p} W_{X,k}^{d_n} \tag{13}$$

However, there oue

$$\sum_{i=0}^{m} W_{X,i}^{d_0} = \sum_{k=0}^{p} W_{X,k,0}^{d_0} + \sum_{k=0}^{p-1}\sum_{j=1}^{d-1} W_{X,k,j}^{d_0} = \sum_{k=0}^{p} W_{X,k}^{d_n} + \sum_{k=0}^{p-1}\sum_{j=1}^{d-1}(c_{1,j} W_{X,k}^{d_n} + c_{2,j} W_{X,k+1}^{d_n}) = \sum_{k=0}^{p} W_{X,k}^{d_n} + (\sum_{j=1}^{d-1} c_{1,j}) \cdot \sum_{k=0}^{p-1} W_{X,k}^{d_n} + (\sum_{j=1}^{d-1} c_{2,j}) \sum_{k=0}^{p-1} W_{X,k+1}^{d_n} = (1 + \sum_{j=1}^{d-1} c_{1,j}) W_{X,0}^{d_n} \cdot W_{X,0}^{d_n} + (1 + \sum_{j=1}^{d-1} c_{1,j} + \sum_{j=1}^{d-1} c_{2,j}) \sum_{k=1}^{p-1} W_{X,k}^{d_n} + (1 + \sum_{j=1}^{d-1} c_{2,j}) \cdot W_{X,p}^{d_n} = \frac{d+1}{2} W_{X,0}^{d_n} + d\sum_{k=1}^{p-1} W_{X,k}^{d_n} + \frac{d+1}{2} W_{X,p}^{d_n} \tag{14}$$

Thus, in order to let the basic Eq. (13) be satisfied, it ought to use the scaled values $\overline{W}_{X,k}^{d_n}$ rather than $W_{X,k}^{d_n}$ to do the interpolation at step 1, where

$$\overline{W}_{X,0}^{d_n} = \frac{2}{d+1} W_{X,0}^{d_n}; \overline{W}_{X,p}^{d_n} = \frac{2}{d+1} W_{X,p}^{d_n}$$

$$\overline{W}_{X,k}^{d_n} = \frac{1}{d} W_{X,k}^{d_n} \quad (k = 1, 2, \cdots, p-1) \tag{15}$$

Thus, Eq. (10) and Eq. (11) should be replaced by

$$W_{X,k,0}^{d_0} = \overline{W}_{X,k}^{d_n} \quad (k = 0, 1, \cdots, p) \tag{16}$$

and

$$W_{X,k,j}^{d_0} = c_{1,j} \overline{W}_{X,k}^{d_n} + c_{2,j} \overline{W}_{X,k+1}^{d_n}$$
$$(k = 0, 1, \cdots, p-1; j = 1, 2, \cdots, d-1) \tag{17}$$

4) Step 2: Do summations

$$X = \sum_{i=0}^{m} W_{X,i}^{d_0} r_i^{d_0} = \sum_{k=0}^{p} W_{X,k,0}^{d_0} r_{k,0}^{d_0} + \sum_{k=0}^{p-1}\sum_{j=1}^{d-1} W_{X,k,j}^{d_0} r_{r,j}^{d_0} \tag{18}$$

5) Step 3: Reordering the summations in terms of $W_{X,k}^{d_n}$

$$X = \sum_{i=0}^{m} W_{X,i}^{d_0} r_i^{d_0} = \sum_{k=0}^{p} W_{X,k,0}^{d_0} r_{k,0}^{d_0} + \sum_{k=0}^{p-1}\sum_{j=1}^{d-1} W_{X,k,j}^{d_0} r_{k,j}^{d_0} = \sum_{k=0}^{p} \overline{W}_{X,k}^{d_n} r_{k,0}^{d_0} + \sum_{k=0}^{p-1}\sum_{j=1}^{d-1} (c_{1,j} \overline{W}_{X,k}^{d_n} + c_{2,j} \overline{W}_{X,k+1}^{d_n}) r_{k,j}^{d_0} = \sum_{k=0}^{p} \overline{W}_{X,k}^{d_n} r_{k,0}^{d_0} + \sum_{k=0}^{p-1} [\sum_{j=1}^{d-1} (c_{1,j} r_{k,j}^{d_0}] \overline{W}_{X,k}^{d_n} + \sum_{k=0}^{p-1} [\sum_{j=1}^{d-1} c_{2,j} r_{k,j}^{d_0}] \cdot \overline{W}_{X,k+1}^{d_n} = \frac{2}{d+1} W_{X,0}^{d_n} (r_{0,0}^{d_0} + \sum_{j=1}^{d-1} c_{1,j} r_{0,j}^{d_0}) + \frac{1}{d} \sum_{k=1}^{p-1} W_{X,k}^{d_n} \cdot (r_{k,0}^{d_0} + \sum_{j=1}^{d-1} c_{2,j} r_{k-1,j}^{d_0} + \sum_{j=1}^{d-1} c_{1,j} r_{k,j}^{d_0}) + \frac{2}{d+1} W_{X,p}^{d_n} (r_{p,0}^{d_0} + \sum_{j=1}^{d-1} c_{2,j} r_{p-1,j}^{d_0}) \tag{19}$$

Considering using Eq. (3) for computing the tristimulus values with information at d_n nm interval gives the following computation formula for $r_k^{d_n}$

$$r_0^{d_n} = \frac{2}{d+1} (r_{0,0}^{d_0} + \sum_{j=1}^{d-1} c_{1,j} r_{0,j}^{d_0});$$

$$r_p^{d_n} = \frac{2}{d+1} (r_{p,0}^{d_0} + \sum_{j=1}^{d-1} c_{2,j} r_{p-1,j}^{d_0})$$

$$r_k^{d_n} = \frac{1}{d} (r_{k,0}^{d_0} + \sum_{j=1}^{d-1} c_{2,j} r_{k-1,j}^{d_0} + \sum_{j=1}^{d-1} c_{1,j} r_{k,j}^{d_0})$$
$$(k = 1, 2, \cdots, p-1) \tag{20}$$

6) Method 3: Third order abridgement

Like the above deriving the linear abridgement method, the three basic steps are still used.

7) Step 1: The third order interpolation

As did above, for any i between 0 and m it can be represented using Eq. (7). Thus, $W_{X,i}^{d_0}$ can be denoted by $W_{X,k,j}^{d_0}$ for convenience. Like in the linear interpolation, there still are

$$W_{X,k,0}^{d_0} = W_{X,k}^{d_n} \quad (k = 0, 1, \cdots, p) \tag{21}$$

However, the third order interpolation for the middle points $W^{d_0}_{X,k,j}$ is much complicated than the linear interpolation. It can be considered in three cases: predicting the points $W^{d_0}_{X,0,j}$ using leftist three known values $W^{d_n}_{X,0}$, $W^{d_n}_{X,1}$, and $W^{d_n}_{X,2}$, the middle points $W^{d_0}_{X,k,j}$ using four known values $W^{d_n}_{X,k-1}, W^{d_n}_{X,k}, W^{d_n}_{X,k+1}$, and $W^{d_n}_{X,k+2}$, and the points $W^{d_0}_{X,p-1,j}$ using the three rightist known values $W^{d_n}_{X,p-2}, W^{d_n}_{X,p-1}, W^{d_n}_{X,p}$. In the first and last cases, the second order interpolation formula is used.

The formula for $W^{d_0}_{X,0,j}$ is given as following

$$W^{d_0}_{X,0,j}=c_{L,1,j}W^{d_n}_{X,0}+c_{L,2,j}W^{d_n}_{X,1}+c_{L,3,j}W^{d_n}_{X,2} \quad (j=1,2,\cdots,d-1) \tag{22}$$

where the coefficients are given by

$$\begin{aligned} c_{L,1,j}&=(\frac{j}{d}-1)(\frac{j}{d}-2)/2 \\ c_{L,2,j}&=\frac{j}{d}(2-\frac{j}{d}) \quad (j=1,2,\cdots,d-1) \\ c_{L,3,j}&=\frac{j}{d}(\frac{j}{d}-1)/2 \end{aligned} \tag{23}$$

While for predicting $W^{d_0}_{X,p-1,j}$, there is

$$W^{d_0}_{X,p-1,j}=c_{R,1,j}W^{d_n}_{X,p-2}+c_{R,2,j}W^{d_n}_{X,p-1}+c_{R,3,j}W^{d_n}_{X,p} \quad (j=1,2,\cdots,d-1) \tag{24}$$

where

$$\begin{aligned} c_{R,1,j}&=\frac{j}{d}(\frac{j}{d}-1)/2 \\ c_{R,2,j}&=(1+\frac{j}{d})(1-\frac{j}{d}) \quad (j=1,2,\cdots,d-1) \\ c_{R,3,j}&=\frac{j}{d}(1+\frac{j}{d})/2 \end{aligned} \tag{25}$$

Finally, for the middle $W^{d_0}_{X,k,j}$ the third order formula is used

$$W^{d_0}_{X,k,j}=c_{1,j}W^{d_n}_{X,k-1}+c_{2,j}W^{d_n}_{X,k}+c_{3,j}W^{d_n}_{X,k+1}+c_{4,j}W^{d_n}_{X,k+2} \quad (k=1,2,\cdots,p;j=1,2,\cdots,d-1) \tag{26}$$

where the coefficients are given by

$$\begin{aligned} c_{1,j}&=-\frac{j}{d}(1-\frac{j}{d})(2-\frac{j}{d})/6 \\ c_{2,j}&=(\frac{j}{d}-1)(\frac{j}{d}+1)(\frac{j}{d}-2)/2 \\ c_{3,j}&=\frac{j}{d}(\frac{j}{d}+1)(2-\frac{j}{d})/2 \qquad (j=1,2,\cdots,d-1) \\ c_{4,j}&=\frac{j}{d}(\frac{j}{d}-1)(\frac{j}{d}+1)/6 \end{aligned} \tag{27}$$

Note that all the above interpolation coefficients satisfy

$$\left.\begin{aligned} &c_{1,j}+c_{2,j}+c_{3,j}+c_{4,j}=1 \\ &c_{1,j}=c_{4,d-j};c_{2,j}=c_{3,d-j}, \\ &c_{L,1,j}=c_{R,3,d-j};c_{L,2,j}=c_{R,2,d-j} \\ &c_{L,3,j}=c_{R,1,d-j} \end{aligned}\right\} (j=1,2,\cdots,d-1) \tag{28}$$

Note also that if the interpolated values $W^{d_0}_{X,k,j}$ ($i=kd+j$) are qualified weights at d_0 nm interval for computing tristimulus value X, they should satisfy

$$\sum_{i=0}^{m}W^{d_0}_{X,i}=\sum_{k=0}^{p}W^{d_n}_{X,k} \tag{29}$$

On the other hand, it can be shown that

$$\sum_{i=0}^{m}W^{d_0}_{X,i}=\sum_{k=0}^{p}W^{d_0}_{X,k,0}+\sum_{j=1}^{d-1}W^{d_0}_{X,0,j}+\sum_{k=1}^{p-2}\sum_{j=1}^{d-1}W^{d_0}_{X,k,j}+\sum_{j=1}^{d-1}W^{d_0}_{X,p-1,j}=aW^{d_n}_{X,0}+bW^{d_n}_{X,1}+cW^{d_n}_{X,2}+d\sum_{k=3}^{p-3}W^{d_n}_{X,k}+cW^{d_n}_{X,p-2}+bW^{d_n}_{X,p-1}+aW^{d_n}_{X,p} \tag{30}$$

Here

$$\begin{aligned} a&=[1+\sum_{j=1}^{d-1}(c_{L,1,j}+c_{1,j})] \\ b&=[1+\sum_{j=1}^{d-1}(c_{L,2,j}+c_{1,j}+c_{2,j})] \\ c&=[1+\sum_{j=1}^{d-1}(c_{L,3,j}+c_{1,j}+c_{2,j}+c_{3,j})] \end{aligned} \tag{31}$$

Thus, in order to let the basic Eq. (29) be satisfied, it ought to use the scaled values $\overline{W}^{d_n}_{X,k}$ rather than $W^{d_n}_{X,k}$ to do the interpolation at step 1, where

$$\begin{aligned} &\overline{W}^{d_n}_{X,0}=\frac{1}{a}W^{d_n}_{X,0}, \overline{W}^{d_n}_{X,1}=\frac{1}{b}W^{d_n}_{X,1}, \overline{W}^{d_n}_{X,2}=\frac{1}{c}W^{d_n}_{X,2} \\ &\overline{W}^{d_n}_{X,k}=\frac{1}{d}W^{d_n}_{X,k} \quad (k=3,\cdots,p-3 \\ &\overline{W}^{d_n}_{X,p-2}=\frac{1}{c}W^{d_n}_{X,p-2}, \overline{W}^{d_n}_{X,p-1}=\frac{1}{b}W^{d_n}_{X,p-1}, \\ &\overline{W}^{d_n}_{X,p}=\frac{1}{a}W^{d_n}_{X,p} \end{aligned} \tag{32}$$

Thus, Eq. (22), Eq. (24) and Eq. (26) should be respectively replaced by

$$\begin{aligned} &W^{d_0}_{X,0,j}=c_{L,1,j}\overline{W}^{d_n}_{X,0}+c_{L,2,j}\overline{W}^{d_n}_{X,1}+c_{L,3,j}\overline{W}^{d_n}_{X,2} \\ &W^{d_0}_{X,k,j}=c_{1,j}\overline{W}^{d_n}_{X,k-1}+c_{2,j}\overline{W}^{d_n}_{X,k}+c_{3,j}\overline{W}^{d_n}_{X,k+1}+c_{4,j}\overline{W}^{d_n}_{X,k+2} \quad (k=1,2,\cdots,p-2) \\ &W^{d_0}_{X,p-1,j}=c_{R,1,j}\overline{W}^{d_n}_{X,p-2}+c_{R,2,j}\overline{W}^{d_n}_{X,p-1}+c_{R,3,j}\overline{W}^{d_n}_{X,p} \end{aligned} \tag{33}$$

8) Step 2: Do summations

$$X=\sum_{i=0}^{m}W^{d_0}_{X,i}r^{d_0}_{i}=\sum_{k=0}^{p}W^{d_0}_{X,k,0}r^{d_0}_{k,0}+\sum_{j=0}^{d-1}W^{d_0}_{X,0,j}r^{d_0}_{0,j}+\sum_{k=1}^{p-2}\sum_{j=1}^{d-1}W^{d_0}_{X,k,j}r^{d_0}_{k,j}+\sum_{j=1}^{d-1}W^{d_0}_{X,p-1,j}r^{d_0}_{p-1,j} \tag{34}$$

9) Step 3: Reordering the summations in terms of $W^{d_n}_{X,k}$

$$\begin{aligned} X&=\sum_{i=0}^{m}W^{d_0}_{X,i}r^{d_0}_{i}=\sum_{k=0}^{p}W^{d_0}_{X,k,0}r^{d_0}_{k,0}+\sum_{j=1}^{d-1}W^{d_0}_{X,0,j}r^{d_0}_{0,j}+\sum_{k=1}^{p-2}\sum_{j=1}^{d-1}W^{d_0}_{X,k,j}r^{d_0}_{k,j}+\sum_{j=1}^{d-1}W^{d_0}_{X,p-1,j}r^{d_0}_{p-1,j}=\sum_{k=0}^{p}\overline{W}^{d_n}_{X,k}r^{d_0}_{k,0}+ \\ &\sum_{j=1}^{d-1}(c_{L,1,j}\overline{W}^{d_n}_{X,0}+c_{L,2,j}\overline{W}^{d_n}_{X,1}+c_{L,3,j}\overline{W}^{d_n}_{X,2})r^{d_0}_{0,j}+\sum_{k=1}^{p-2}\sum_{j=1}^{d-1}\cdot \\ &(c_{1,j}\overline{W}^{d_n}_{X,k-1}+c_{2,j}\overline{W}^{d_n}_{X,k}+c_{3,j}\overline{W}^{d_n}_{X,k+1}+c_{4,j}\overline{W}^{d_n}_{X,k+2})\cdot \\ &r^{d_n}_{k,j}+\sum_{j=1}^{d-1}(c_{R,1,j}\overline{W}^{d_n}_{X,p-2}+c_{R,2,j}\overline{W}^{d_n}_{X,p-1}+c_{R,3,j}\overline{W}^{d_n}_{X,p})\cdot \\ &r^{d_0}_{p-1,j}=\sum_{k=0}^{p}W^{d_n}_{X,k}r^{d_n}_{k} \end{aligned} \tag{35}$$

Here, the third order abridgement formulae for $r^{d_n}_k$ are the followings

$$\begin{aligned} r^{d_n}_0&=\frac{1}{a}[r^{d_0}_{0,0}+\sum_{j=1}^{d-1}(c_{L,1,j}r^{d_0}_{0,j}+c_{1,j}r^{d_0}_{1,j})] \\ r^{d_n}_1&=\frac{1}{b}[r^{d_0}_{1,0}+\sum_{j=1}^{d-1}(c_{L,2,j}r^{d_0}_{0,j}+c_{1,j}r^{d_0}_{2,j}+c_{2,j}r^{d_0}_{1,j})] \\ r^{d_n}_2&=\frac{1}{c}[r^{d_0}_{2,0}+\sum_{j=1}^{d-1}(c_{L,3,j}r^{d_0}_{0,j}+c_{1,j}r^{d_0}_{3,j}+c_{2,j}r^{d_0}_{2,j}+ \\ &c_{3,j}r^{d_0}_{1,j})] \\ r^{d_n}_k&=\frac{1}{d}[r^{d_0}_{k,0}+\sum_{j=1}^{d-1}(c_{1,j}r^{d_0}_{k+1,j}+c_{2,j}r^{d_0}_{k,j}+c_{3,j}r^{d_0}_{k-1,j}+ \\ &c_{4,j}r^{d_0}_{k-2,j})] \quad k=3,4,\cdots,p-3 \end{aligned}$$

$$r^{d}_{p^n-2}=\frac{1}{c}\Big[r^{d_0}_{p^0-2,0}+\sum_{j=1}^{d-1}(c_{R,1,j}r^{d_0}_{p^0-1,j}+c_{2,j}r^{d_0}_{p^0-2,j}+$$
$$c_{3,j}r^{d_0}_{p^0-3,j}+c_{4,j}r^{d_0}_{p^0-4,j})\Big]$$
$$r^{d}_{p^n-1}=\frac{1}{b}\Big[r^{d_0}_{p^0-1,0}+\sum_{j=1}^{d-1}(c_{R,2,j}r^{d_0}_{p^0-1,j}+c_{3,j}r^{d_0}_{p^0-2,j}+$$
$$c_{4,j}r^{d_0}_{p^0-3,j})\Big]$$
$$r^{d}_{p^n}=\frac{1}{a}\Big[r^{d_0}_{p^0,0}+\sum_{j=1}^{d-1}(c_{R,1,j}r^{d_0}_{p^0-1,j}+c_{4,j}r^{d_0}_{p^0-2,j})\Big] \quad (36)$$

2 Performance of the methods considered

In this section it will test the methods proposed in the last section using two sets of data. Both sets were measured from Munsell color book between 400 nm and 700 nm at 5 nm[12] and 10 nm intervals respectively. The 10 nm interval data were measured at University of Derby. Firstly, for each reflectance measured, the tristimulus values can be obtained under a particular illuminant and a CIE standard observer, which is called the standard tristimulus values. Secondly, the reflectance can be abridged into a lager interval (from 5 nm to either 10 nm or 20 nm) using each of the above methods. Thirdly, the (batch) tristimulus values can also be computed from the abridged reflectance under the same illuminant and CIE standard observer. Finally, the performance of a particular method can be measured using the color difference between the standard and the batch tristimulus values. The smaller the color difference is, the better the method is. Here the CIELab color difference[13] is used. Six Illuminats (D65, A, F11, F02, F07 and D50) and CIE 1931 standard observer are used in the tests.

1) Test 1: Abridge 5 nm interval data to 10 nm, 20 nm, and 30 nm intervals

For the calorimetric applications it is normally required abridging reflectance from a smaller interval to 10 nm or 20 nm intervals. While for the image compression, the reflectance can be abridged to 30 nm interval or larger.

Firstly, the results from 5 nm to 10 nm and from 5 nm to 20 nm are listed in Table. 1 and Table. 2 respectively, where the average (Ave) and maximum (Max) color differences are reported. RAMI refers to the direct selection method, RAMII the linear abridgement method, and RAMIII the third order abridgement method. From the tables it can be seen that the RAMIII is the best either in terms of average or maximum error. Direct selection and the linear abridgement methods have roughly the same performances. They are simple, but result in big errors. For the third order abridgement method, it is very accurate when compressing from 5 nm interval to 10 nm intervals. The errors increase with the increasing of the destination wavelength interval. Besides, the errors are bigger under the fluorescent illuminants compared with those under the continuous illuminants.

Table. 1 Compress reflectance at 5 nm interval to reflectance at 10 nm interval

	RAMI	RAMII	RAMIII
ILLs	Ave/Max	Ave/Max	Ave/Max
D65	0.28/1.20	0.09/0.36	0.03/0.19
A	0.22/0.89	0.08/0.31	0.02/0.16
F11	0.49/2.21	0.27/1.25	0.24/1.06
F02	0.44/2.16	0.23/1.13	0.20/1.01
F07	0.40/1.83	0.19/0.88	0.16/0.74
D50	0.25/1.07	0.09/0.34	0.02/0.17

Table. 2 Compress reflectance at 5 nm interval to reflectance at 20 nm interval

	RAMI	RAMII	RAMIII
ILLs	Ave/Max	Ave/Max	Ave/Max
D65	0.59/2.26	0.46/1.88	0.09/0.44
A	0.48/2.24	0.39/1.55	0.09/0.80
F11	0.87/4.39	0.58/2.77	0.51/2.45
F02	0.73/4.27	0.50/2.28	0.32/1.81
F07	0.70/3.52	0.49/2.23	0.25/1.40
D50	0.54/1.97	0.44/1.73	0.10/0.54

In the spectral compression, the less components the compressed reflectance vector has, the better it is. If compressed the reflectance at 5 nm interval into reflectance at 30 nm interval, then the original reflectance vector has 61 values, the compressed reflectance has only 11 components. The vector subspace method (VSS)[14] is a well-know method for the spectral compression. The method has three steps. First, them basis vectors must be computed using principle component analysis or singular value decomposition method. Here m is the number of the components of the original reflectance vector. Then the original reflectance vector is compressed into its first p optimum coefficients under this set of basis vectors. Finally, the vector must be reconstructed based on the compressed p coefficients. The comparisons between the vector subspace method and our methods have been done and results are

Table. 3 Compress reflectance at 5 nm interval to reflectance at 30 nm interval

	RAMI	RAMII	RAMIII	VSM
ILLs	Ave/Max	Ave/Max	Ave/Max	Ave/Max
D65	0.93/3.80	1.11/4.62	0.50/2.25	0.12/2.41
A	0.80/2.92	0.94/3.65	0.37/2.62	0.10/1.91
F11	1.36/7.54	1.23/7.10	0.91/4.71	0.76/6.73
F02	1.12/5.17	1.13/4.75	0.70/3.09	0.44/4.20
F07	1.08/4.90	1.14/4.84	0.63/2.83	0.32/3.02
D50	0.89/3.42	1.07/4.26	0.44/1.96	0.12/2.46
RD	0.01/0.03	0.01/0.03	0.01/0.03	0.00/0.02

listed in Table. 3. For a fare comparison, we choose p=11 for vector subspace method.

In the last row of Table. 3, the errors (RD) in terms of reflectance differences between the original and reconstructed reflectance vectors are also reported. The reflectance difference used is the following[10]

$$RD=\frac{1}{m}\sum_{i=1}^{m}|r_i^{d_0}-\bar{r}_i^{d_0}| \qquad (39)$$

where $r_i^{d_0}$ are the original reflectance values and $\bar{r}_i^{d_0}$ are the reconstructed reflectance values. As mentioned before, the reflectance abridgement methods do not need the reconstruction, but for reflectance accuracy comparison the abridged reflectance values at d_n nm interval are interpolated into d_0 nm using the third order interpolation method.

Once again, the direct selection and the linear abridgement methods are not as good as the other two methods in terms of colorimetric accuracy. The vector subspace method is better than the third order abridgement method in terms of average color difference and reflectance accuracy, but the third order abridgement method is better than the vector subspace method in terms of maximum color differences. Besides, the third order abridgement method is a decompression-free method.

Besides, one example can be given in a Fig. 1 where it can draw the curves of one reflectance measured at 5 nm interval and three sets of abridged data. The abridged data are at 10 nm, 20 nm and 30 nm interval respectively. The third order abridgment method was used to obtain the three sets of abridged data.

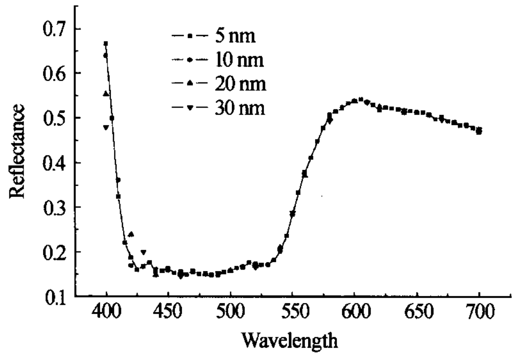

Fig. 1 Reflectance curves of the original (measured at 5 nm interval) and three sets of abridged data (10 nm, 20 nm, 30 nm)

From Fig. 1 it can see that all the three sets of the abridged data are surrounding the original reflectance curve tightly.

2) Test 2: Abridge 10 nm interval data to 20 nm and 30 nm interval

Similar to test 1, the results from 10 nm to 20 nm and from 10 nm to 30 nm intervals are listed in Tables. 4 and 5 respectively. However, it can be seen from Tables. 4 and 5 that RAMI and RAMIII roughly have the same performance and RAMII is the worst. While for the spectral image compression application (Table. 5), the vector subspace method (VSM) is the best.

Table. 4 Compress reflectance at 10 nm interval to reflectance at 20 nm interval

	RAMI	RAMII	RAMIII
ILLs	Ave/Max	Ave/Max	Ave/Max
D65	0.09/0.39	0.48/2.01	0.09/0.47
A	0.09/0.62	0.42/1.59	0.08/0.84
F11	0.35/2.05	0.65/3.30	0.43/2.56
F02	0.13/0.37	0.45/1.75	0.13/0.49
F07	0.13/0.45	0.47/1.77	0.12/0.57
D50	0.09/0.37	0.47/1.90	0.09/0.55

Table. 5 Compress reflectance at 10 nm interval to reflectance at 30 nm interval

	RAMI	RAMII	RAMIII	VSM
ILLs	Ave/Max	Ave/Max	Ave/Max	Ave/Max
D65	0.36/1.59	1.33/5.70	0.47/2.15	0.08/1.52
A	0.32/2.05	1.16/4.49	0.41/2.86	0.06/1.01
F11	0.60/4.28	1.58/8.29	0.90/4.84	0.22/3.13
F02	0.39/2.01	1.27/4.84	0.48/2.18	0.10/1.23
F07	0.36/1.76	1.34/5.05	0.46/2.04	0.09/1.30
D50	0.35/1.67	1.30/5.38	0.46/2.25	0.08/1.48
RD	0.00.0.01	0.01/0.01	0.00/0.01	0.00/0.01

It can also give another example in a Fig. 2 where it can draw the curve of one reflectance measured at 10 nm interval and two sets of abridged data. The abridged data are at 20 nm and 30 nm interval respectively. The third order abridgment method was used also to obtain the two sets of abridged data.

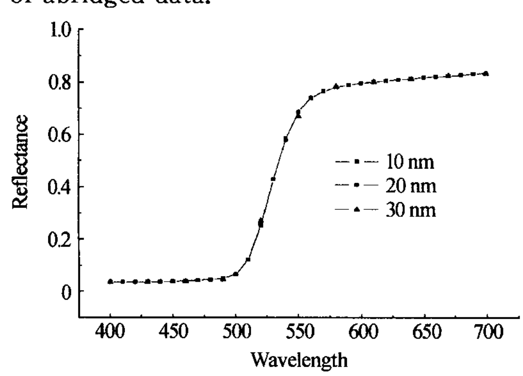

Fig. 2 Reflectance curves of the original (measured at 10 nm interval) and two sets of abridged data (20 nm, 30 nm)

From Fig. 2 it can see that all the two sets of the abridged data are surrounding the original reflectance curve tightly too.

3 Conclusions

Three reflectance abridgement methods have been given and tested in this paper. For the colorimetric computation applications from 5 nm to 10 nm or from 5 nm to 20 nm reflectance abridgement, the third order method is the best, while for the abridgement from 10 nm to 20 nm, the direct section is simper and slightly better in accuracy than the third order method. For the image compression application, when the original reflectance is at 5 nm interval, the third order method is an alternative choice to the vector subspace method and has the advantage of decompression free compared with the vector subspace method. However, when the original reflectance is at 10 nm interval, the vector subspace method is still the only choice according to the accuracy.

References

1 Hawkyard C J. Synthetic reflectance curves by additive mixing. *JSDC*, 1993, **109**(10): 323～329

2 Li C J, Luo M R. The estimation of spectral reflectances using smoothness constraint condition. The Proceedings of TS&T/SID Colour Imaging Conference' 2001. Arizona, USA, 2001: 62～67

3 Pakkinen J, Jaaskelainen T. Spectral Imaging. Proc. Of International Congress of Imaging Science, 2002, 383～384

4 Yang X X, Zhou S Z, Xiang L B. Studies of error limited of high speed rotary specetrometer. *Acta Photonica Sinica*, 2004, **33**(3): 338～341

5 Zhao Z L, Ma Z, Li Y C. The application of conjugated gradient method in scopetomography imaging specetrometry. *Acta Photonica Sinica*, 2004, **33**(6): 685～688

6 Kaarna A, Parkkinen J. Transform based lossy compression of multispectral images. *Pattern Analysis & Applications*, 2001, **4**(1): 39～50

7 Lü Q B, Xiang L B. Interference spectral image compress based on classification algorithm. *Acta Photonica Sinica*, 2004, **33**(6): 681～684

8 CIE TC1-38 Report. Compatibility of Tabular Spectral Data for Computational Purpose. CIE TC1-38/84, New Publication, From D, April 2002

9 Li C J, Luo M R, Rigg B. A Novel Method for Computing Optimum weights for calculating CIE tristimulus values. The first European Conference on Color in Graphics, Image and Vision, University of Poitiers, France, 2002, 216～220

10 Li C J, Cui G H, Zhao D Z *et al*. A simple method for computing optimum weighting tables for tristimulus integration. *Acta Optica Sinica*, 2003, **11**: 1346～1353

11 Li C J, Luo M R, Rigg B. A new method for computing optimum weights for calculating CIE tristimulus values. *Color Research and Application*, 2004, **29**(2): 91～103

12 http://www. lut. fi/ltkk/tite/research/color/lutcs-database. html

13 CIE Publication. No. 15. 2, Colorimetry, 2nd ed., Central Bureau of CIE, Vienna, 1986

14 Jaaskelainnen T, Parkkinen J, Toyooka S. Vector subspace model for color representation. *J Opt Sco Am*, 1990, **A7**: 725～730

光谱反射比的实际删节方法研究

王 葛[1,2] 李长军[3] M Ronnier Luo[3]

1 中科院沈阳自动化研究所，沈阳 110016

2 中国科学院研究生院，北京 100039

3 Department of Color Chemistry, University of Leeds, Leeds LS2 9JT, UK

收稿日期：2005-03-04

摘 要 为了将测量间隔较小的光谱反射比数据删节或者压缩成间隔较大的数据，给出了三种方法，即：直接选取法、线性删节法和三阶删节法，并对其特性进行了仿真验证．从仿真的结果可以看出：若将测量间隔为 5 nm 的数据压缩成间隔为 10 nm、20 nm 或 30 nm 的数据，则采用三阶删节方法误差最小；若将测量间隔为 10 nm 的数据压缩成间隔为 20 nm 或 30 nm 的数据，则直接选取法似乎结果更好一些．另外，还给出了三阶删节方法与“向量子空间法”在光谱图像压缩方面的特性比较，比较的结果发现，三阶删节方法要比“向量子空间法”更好一些．可以看出，删节方法无论是对光谱反射比的删节还是对光谱图像的压缩，其结果都能很好的满足工业需求．

关键词 光谱反射比；删节与压缩；加权表；光谱图像；向量子空间法

Wang Ge is a Ph. D student in Graduate School of the Chinese Academy of Sciences. He studies at Shenyang Institute of Automation of the Chinese Academy of Science. He received his B. Sc. (1999), M. Sc. (2002) in Hebei University of Science & Technology and Yanshan University respectively. He is interested in computing weighting tables for calculating CIE tristimulus values and rebuilding reflectauce.