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TECHNICAL REPORT

Multispectral Image Formats

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Colorimetry

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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
CIE Central Bureau
Babenbergerstrasse 9, A-1010 Vienna, AUSTRIA
Tel: +43(1)714 31 87
e-mail: ciecb@cie.co.at
www.cie.co.at

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This Technical Report has been prepared by CIE Technical Committee 8-07 of Division 8 "Image Technology" and has been approved by the Board of Administration as well as by Division 8 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

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The following members of TC 8-07 "Multispectral imaging" took part in the preparation of this Technical Report. The committee comes under Division 8 "Image Technology".

Authors:

Yamaguchi, M.	Japan	(Chair from 2011)
Hauta-Kasari, M.	Finland	(Chair 2010–2011)
Parkkinen, J.	Malaysia	(Chair 2004–2010)
Herzog, P.	Germany	(Chair 2002–2004)
Derhak, M.	USA	
Hardeberg, J.Y.	Norway	
Helling, S.	Germany	
Hernández-Andrés, J.	Spain	
Hill, B.	Germany	
Hung, P.-C.	Japan	
Imai, F.	USA	
Lenz, R.	Sweden	
Miyake, Y.	Japan	
Morovic, P.	Spain	
Shyu, M.J.	Chinese Taipei	
Vilaseca, M.	Spain	

Advisor:

Simmons, R.	USA
-------------	-----

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MULTISPECTRAL IMAGE FORMATS

Summary

This technical report describes the basic model of multispectral imaging technology followed by the requirements and the examples of multispectral image formats suitable for colour imaging applications. Four example formats are introduced and compared in typical use cases: JPEG 2000, Spectral Binary File Format, Natural Vision, and multispectral image file format AIX. The specifications of those formats except for JPEG 2000 are provided in the Annex.

FORMATS DES IMAGES MULTISPECTRALES

Resume

Ce rapport technique décrit les bases technologiques en imagerie multispectrale puis donne les exigences et des exemples en termes de formats appropriés d'images multispectrales pour des applications en imagerie couleur. Quatre exemples de formats – JPEG 2000, le format de fichier spectral binaire, Vision Naturelle et le format d'image multispectrale AIX - sont introduits et comparés dans des cas typiques d'utilisation. Les spécifications de ces formats, à l'exception de JPEG 2000, sont fournis en annexe.

FORMATE FÜR MULTISPEKTRALE BILDER

Zusammenfassung

Dieser technische Bericht beschreibt das grundlegende Modell der Multispektraltechnik und die daraus resultierenden Anforderungen an multispektrale Bildformate für Anwendungen in der Farbbildtechnik. Es werden vier geeignete Bildformate eingeführt: JPEG 2000, Spectral Binary Format, Natural Vision und das Multispektralformat AIX. Diese vier Formate werden anhand typischer Anwendungsfälle miteinander verglichen. Die Spezifikationen von Spectral Binary Format, Natural Vision und AIX sind im Anhang gegeben.

1 Background

Increasingly, colour imaging is being done with cameras capable of capturing more than three channels or bands. With its focus on promoting colour science, CIE Division 8 "Image Technology" established a technical committee on "Multispectral Image Formats" to address issues related to such imaging.

For the purposes of this discussion, a multispectral image will be considered to be an image with more than three channels or bands of wavelengths. The visible wavelength range is the main concern, but the spectral channels may include bands in the ultraviolet or infrared. The term hyperspectral image is sometimes used, and a hyperspectral image is usually considered as having more channels (for example, more than 50) than a multispectral image. A hyperspectral image is often thought to be one that allows an almost continuous spectrum to be obtained without wavelength interpolation, but a continuous spectrum in each pixel can often be reconstructed from a multispectral image, as described in 3.4. However, the boundary between multispectral and hyperspectral is not accurately defined, so, in this technical report, multispectral and hyperspectral images are not distinguished and the term "multispectral" is used for simplicity. Furthermore, the term "spectral image" refers to a multispectral image, a hyperspectral image, or an image with reconstructed continuous spectra. This document deals with two-dimensional (planar) multispectral images only.

Spectral imaging is found in many applications including medical imaging, document preservation, fashion design, automobile manufacturing, recycling, science, and remote sensing. It is desirable to have a common format that can be used to share spectral images between various users. Candidate formats include those already standardized by other organizations as well as native formats that are currently used by a very select group of individuals or organizations.

The scope of this report includes the study, development, and recommendation of encoding techniques and data formats for the exchange of multispectral images, as well as testing and evaluation.

2 Terms, definitions and abbreviations

For the purposes of this document, the terms, definitions and abbreviated terms given in CIE S 017/E:2011 and the following apply.

2.1

lossless compression

method of data compression that permits reconstruction of the original data exactly, bit-for-bit

[SOURCE: ISO/IEC 15948:2004]

2.2

lossy compression

method of data compression that permits reconstruction of the original data approximately, rather than exactly

[SOURCE: ISO/IEC 15948:2004]

2.3

LUT

look-up table

collection of values used for translating data samples from one value to another, in which the run-time computation of arbitrary transformation is replaced with the table reference of pre-calculated values

2.4

LZW

Lempel–Ziv–Welch

name of a lossless data compression algorithm

2.5

metadata

data associated with a digital image aside from the pixel values that comprise the digital image

[SOURCE: ISO 12231:2012]

Note 1 to entry: In multispectral images, the metadata may include the number of channels, the spectral characteristics of channels, the number of pixels in horizontal and vertical directions, the number of bits in each sample, and the spectral characteristics of channels data.

2.6

Moore–Penrose pseudo-inverse

one of the common types of matrix pseudo-inverse, which is the generalization of the inverse matrix originally defined with respect to a non-singular and square matrix to an arbitrary matrix

2.7

PCA

principal component analysis

mathematical process that transforms correlated variables into uncorrelated ones

2.8

pixel value

discrete value that represents colour, intensity, or other attribute of a pixel

[SOURCE: ISO 12231:2012]

Note 1 to entry: In multispectral images, a pixel consists of multiple channels. The pixel value of each channel may represent the radiance, radiance factor, reflectance factor, or reflectance, sometimes multiplied with a certain scaling factor.

2.9

reconstruction matrix

matrix for the spectral reconstruction from multispectral channel data

2.10

spectral reconstruction

spectral estimation

process to reconstruct continuous (or densely sampled) spectral data from discrete multispectral channel data

Note 1 to entry: Spectral reconstruction is similar to interpolation, but more advanced reconstruction techniques, such as Wiener estimation, are available.

2.11

spectral unmixing

process for the decomposition when mixing multiple spectral components in a pixel

2.12

Wiener estimation

method to estimate the original signal from the observation based on the minimum mean square error criterion, assuming that the original signal and noise are modelled as random processes

Abbreviations

API	Application Program Interface
BSQ	Band Sequential
BIL	Band Interleaved by Line
BIP	Band Interleaved by Pixel
ICC	International Color Consortium

PCS	Profile Connection Space
TIFF	Tagged Image File Format
XML	eXtensible Markup Language
XMP	eXtensible Metadata Platform
ZIP	The name of a file format that supports lossless compression

3 Multispectral image model

3.1 Multispectral image applications

Before considering the general model of multispectral imaging, various multispectral imaging applications are reviewed:

- Spectral or colour measurement (point-based or image-based) (Simpson and Jansen, 1991; Hill and Vorhagen, 1994; Burns and Berns, 1996)
- Object detection, recognition, or pattern classification (Tominaga, 2002; LI et al., 2008; Gomez et al., 2007)
(Spectral signature, spectral texture, matching of reflectance, segmentation)
- Spectral component analysis (Vrhel and Trussell, 1992; Tsumura et. al., 1999; Rabinovich et al., 2004), spectral unmixing (Miao and Qi, 2007)
(PCA, Independent Component Analysis, Nonnegative Matrix Factorization, etc.)
- Narrow band imaging (Gono et al., 2003)
- False colour image display
- Spectral image enhancement (Mitsui et. al., 2005)
- Illuminant estimation (Tominaga and Wandell, 1989; Maloney and Wandell, 1986)
- Colour reproduction (different Illuminant, appearance model, etc.) (Hill, 1998; Yamaguchi et al., 1997; Hardeberg et al., 1998)
- Spectral imaging (spectral printing, imaging simulation, etc.) (Yamaguchi et. al., 2008; Imai et al., 2001; Tzeng et. al, 2000)
- Spectral rendering (artificial spectral image) (Peercy, 1993; Tominaga, 1996)
- Digital archiving (Cotte, 2006; Ribes et al., 2005)

In some of the above applications, the spectral radiance of the object is reconstructed; in others spectral reflectance or spectral transmittance can be the aim of the reconstruction. Spectral reconstruction is explained in 3.4. In other classes of applications, the multichannel data are transformed into a colour image, where the nature of the transformation is determined by the application's requirements.

3.2 Generic model for multispectral imaging systems

Multispectral images can be captured by modifying the spectral sensitivities of the imaging sensors. A simple imaging model (Burns and Berns, 1996; Maloney, 1986; Wandell, 1987) can be described by

$$g_k = a_k \int_{\lambda_{\min}}^{\lambda_{\max}} f_e(\lambda) s_k(\lambda) d\lambda \quad (1)$$

or, specifically for reflective objects,

$$g_k = a_k \int_{\lambda_{\min}}^{\lambda_{\max}} f(\lambda) S(\lambda) s_k(\lambda) d\lambda , \quad (2)$$

where the spatial coordinates are omitted for simplicity. In Eqs. (1) and (2), $f_e(\lambda)$ is the spectral power distribution of the captured light from an object. It is usually given by $f_e(\lambda) = a_e L_\lambda$, where L_λ and a_e denote the spectral radiance of the object and a constant which depends on the observation geometry, respectively. $s_k(\lambda)$ is the spectral sensitivity of the k -th channel of the imaging sensor, $S(\lambda)$ is the spectral power distribution of the illuminant, and g_k is the detector output of the corresponding pixel of the captured multispectral image. a_k is the scaling factor that converts the physical quantity in radiometric unit into the range of digital value. $f(\lambda)$ represents the spectral reflection property of the object, e.g., the spectral radiance factor if the solid angle of the emitted light captured by the camera is small enough. When the solid angle is larger, it can be the spectral reflectance factor (Lee, 2005), or for Lambertian surface, $f(\lambda)$ can be considered as the spectral reflectance. The difference among them is often disregarded because it depends on the observation geometry, and thus $f(\lambda)$ is referred to as "spectral reflectance" hereafter. In the case of transmissive object, it represents the transmittance of the object. The index $k = 1 \dots K$, where K is the number of channels. The limits $\lambda_{\min}$ and $\lambda_{\max}$ denote the shortest and longest wavelengths of the considered wavelength range; in the case of visible radiation imaging the lower limit is taken between 360 nm and 400 nm and the upper limit is taken between 760 nm and 830 nm (CIE, 2011). It is also possible to modify the illumination spectrum instead of the spectral sensitivity of the imaging sensor. In this case, in Eq. (2), $S(\lambda)$ is replaced with $S_k(\lambda)$ and $s_k(\lambda)$ is replaced with $s(\lambda)$. The detector output also depends on some other factors, e.g. transmittance of the air and the optics between the source and the sensor, which are omitted in Eqs. (1) and (2) for simplicity. In addition, the photoelectric transfer characteristic, or tone curve, of the imaging sensor is assumed to be linear in Eqs (1) and (2).

If we consider a fluorescent object, the model becomes rather complicated:

$$g_{k,l} = a_{k,l} \int_{\lambda_{\min}}^{\lambda_{\max}} \int_{\mu_{\min}}^{\mu_{\max}} f(\mu, \lambda) S_l(\mu) s_k(\lambda) d\mu d\lambda \quad (3)$$

where the subscript $l = 1 \dots L$ denotes the index for the excitation lights, L is the number of the different excitation lights used in the imaging, $a_{k,l}$ is the scaling factor, and $f(\mu, \lambda)$ represents the fluorescence characteristics; it may be $f(\mu, \lambda) = a_f \beta_\lambda(\mu)$, where $\beta_\lambda(\mu)$ and a_f denote the bispectral radiance factor and a constant that depends on the observation geometry, respectively. The variables μ and λ correspond to the wavelengths of excitation and emission lights with $[\mu_{\min}, \mu_{\max}]$ and $[\lambda_{\min}, \lambda_{\max}]$ being their respective ranges.

3.3 Input of multispectral images

The input process of multispectral images can be mathematically modelled by Eq. (1) in 3.2. However, in real multispectral image capture, some characteristics of the imaging device should be considered. These include camera gain (b_k), dark current (b_{dc}), noise (n_k) and tone curve ($T\{\}$). Then Eq. (1) is rewritten as

$$g_{d,k} = a_k T \left\{ b_k \int_{\lambda_{\min}}^{\lambda_{\max}} f_e(\lambda) S_k(\lambda) d\lambda + b_{dc} + n_k \right\}, \quad (4)$$

where $g_{d,k}$ is the device pixel value of the multispectral image, and a_k is the scaling factor. To derive the spectral radiance, reflectance, or transmittance of the object, it is necessary to characterize the multispectral imaging device. In some cases, the geometrical distortion of an input device should be corrected before the image analysis.

3.4 Spectral reconstruction

If the number of channels is large enough to represent a continuous spectrum in each pixel, and the bandwidth of the spectral sensitivity $s_k(\lambda)$ is narrow, the spectral reflectance $f(\lambda)$ can be simply estimated from $g_{d,k}$ by

$$f_{\text{est}}(\lambda_k) = a_k \frac{g_{d,k}(f) - g_{d,k}(f_{\text{bk}})}{g_{d,k}(f_{\text{w}}) - g_{d,k}(f_{\text{bk}})} \quad (5)$$

where $g_{d,k}(f)$, $g_{d,k}(f_{\text{bk}})$, and $g_{d,k}(f_{\text{w}})$ are the multispectral pixel values of target, black (bk), and white (w) objects, respectively. Again a_k is the scaling factor. The value $g_{d,k}(f_{\text{bk}})$ is obtained with a cap on the camera lens and $g_{d,k}(f_{\text{w}})$ is the multispectral pixel value of a standard white diffuser. When measuring spectral transmittance, $g_{d,k}(f_{\text{w}})$ is captured by the same device without placing any object.

On the other hand, if the number of channels is not enough to directly represent the continuous spectrum, spectral reconstruction is required. Various methods for the reconstruction of spectral reflectance, radiance, or transmittance from the multispectral image data have been developed. It is known that the spectral reflectance of natural objects can be well approximated with a limited number of spectral basis functions (Maloney, 1986; Wandell, 1987; Vrhel et al., 1994). On this basis, the continuous spectral distributions can be reconstructed from the multispectral data of a limited number of channels.

The reconstruction methods can be categorized into linear and nonlinear techniques. Examples of linear technique are Moore–Penrose pseudo-inverse (Pratt and Mancill, 1976), Wiener estimation (Pratt and Mancill, 1976) and PCA (Vrhel and Trussell, 1992). In linear reconstruction, the spectral reflectance of the object is estimated by an equation of the form

$$f_{\text{est}} = M g \quad (6)$$

where $f_{\text{est}} = (f_{\text{est}}(\lambda_1) f_{\text{est}}(\lambda_2) f_{\text{est}}(\lambda_3) \dots f_{\text{est}}(\lambda_N))^t$ is the vector representation of estimated spectral reflectance and $g = (g_1 g_2 g_3 \dots g_K)^t$ is the multispectral image data obtained using Eq. (1) or $g_k = T^{-1} \{g_{d,k} / a_k\} - b_{\text{dc}}$ from Eq. (4). M is an $N \times K$ matrix for the spectral reconstruction. When applying Wiener estimation, M is often derived from the spectral sensitivity of the input device, illuminant spectrum, and the correlation matrices of object and noise.

Nonlinear estimation methods have more variations, but some of them can be considered as combinations of linear estimations. Some of the reconstruction methods require an iterative process, such as the one based on compressive sensing theory (Gehm et al., 2007).

3.5 Output or display of multispectral image

When the output or display of a multispectral imaging system is in the form of an image, the multispectral image is normally converted to a colour or monochromatic image, depending on the application. The colour image under a certain illuminant (called the rendering illuminant) can be obtained from the estimated reflectance by using the CIE colour-matching functions as

$$\{X, Y, Z\} = \int_{\lambda_{\min}}^{\lambda_{\max}} f_{\text{est}}(\lambda) s_r(\lambda) \{\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)\} d\lambda \quad (7)$$

where the spatial coordinates are omitted, (X, Y, Z) are the XYZ tristimulus values, $s_r(\lambda)$ is the spectral power distribution of the rendering illuminant, and $(\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda))$ are the CIE colour-matching functions. The tristimulus values can then be transferred to output or display devices for colorimetric reproduction.

The spectral radiance $f_{\text{est}}(\lambda) s_r(\lambda)$ can be used to derive device signals for spectral displays, such as multi-primary colour displays (Murakami et al., 2004), and the spectral reflectance can be directly employed as the data for spectral printing (Tzeng et al., 2000).

In some applications, output images are not rendered in natural colour, but false or enhanced colour. False colour representation is often adopted for the results of image analysis, such as PCA or image segmentation. An easy method of colour representation for a multispectral

image is assigning certain bands to R, G, B channels of a display, for example, { band1 = R, band4 = G, band5 = B } (Gono et al., 2003).

Multispectral imaging is also employed for pigment analysis of art paintings (Cotte, 2006; Ribes et al., 2005), biological samples, and stained histological microscopic images. Also the decomposition of fluorescent dye is an important application of multispectral imaging in fields such as biomedical imaging. Those processes are sometimes called colour unmixing (Rabinovich et al., 2004), which can be achieved very effectively by multispectral imaging. In such cases, the colourization is based on the unmixed component images.

3.6 Workflow model

From the above considerations, the workflow model of multispectral imaging can be schematically illustrated as in Figure 1 (Yamaguchi et al., 2008).

Once a multispectral image is captured by an input device, raw image data are obtained. The pixel value of each multispectral channel depends on the characteristics of input device, such as the spectral sensitivity, dark current level, noise deviation and tone curve as in equations (1) and (3). It also depends on the illuminant spectrum of the input environment, which is also required for reflectance estimation. The characteristics of the input device may be partly corrected after the image is captured, as indicated in "post-processing (device correction)" box of Figure 1. In such cases, some of the input device characteristics, such as the dark current and tone curve, can be disregarded.

To make use of the stored multispectral data afterward, it is important to know such information about the input device. For this purpose, the profile data of the spectral input device should be attached to the image data. By applying spectral reconstruction techniques, the matrix to estimate the spectral reflectance, transmittance, or radiance can be derived. Instead of storing the reconstructed spectra, which would require much more capacity, it is convenient to store the original multispectral image data with such estimation matrices (see Eq. (6)).

Artificial spectral images can also be considered. In these cases, the image can be accompanied by the characteristics of the virtual input device or spectral reconstruction matrix. For convenience, it is also possible to include the matrix needed to estimate the tristimulus values under a certain illuminant.

When a multispectral image is processed, as in enhancement, pattern analysis and false colour assignment, the pixel values of the multispectral image may be modified. For false colour assignment, for example, the specification of each band of the multispectral image is required. The result of image processing may be a colour image or a single channel image when the processing aims at visualization or quantification. In some cases the output may be multispectral. It is sometimes possible to define the visualization method in metadata with preserving the original or modified multispectral image.

In image display or printing, the tristimulus values can be derived using the reconstructed spectra under an arbitrary illuminant. To make use of conventional colour management systems, a standard illuminant (such as CIE D65 or D50) can be specified for output to conventional colour display or printing devices.

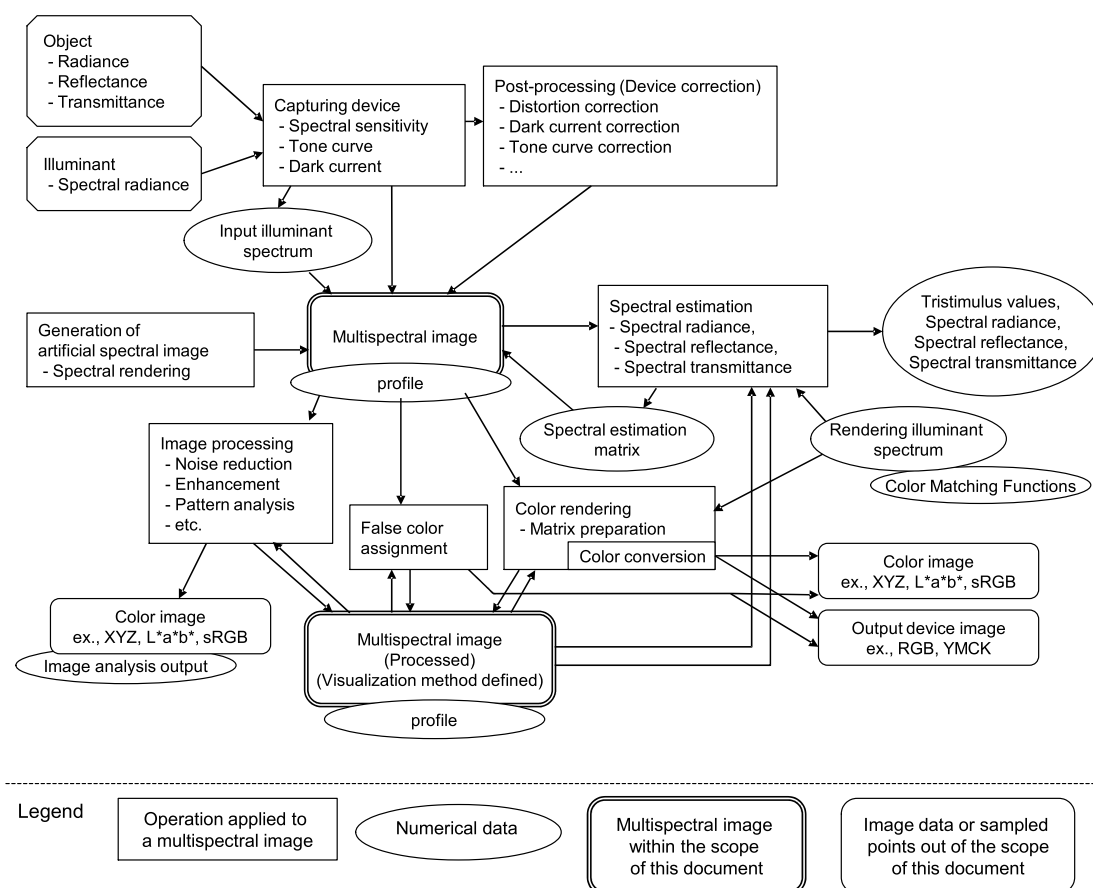


Figure 1 – Workflow model of multispectral imaging systems

4 Encoding of multispectral images

In the encoding of multispectral images, some issues that are different from those encountered for monochromatic or colour image encoding must be addressed.

(a) *Metadata are essential in the workflow of multispectral imaging systems.*

In contrast to traditional grey-scale or colour images, the number of channels varies in multispectral images. The meaning of each channel also depends on the imaging devices. Such information is required in applications of multispectral imaging, and should be stored as metadata. In the encoding of multispectral images, both the image data stream and metadata should be addressed, as shown in Figure 2.

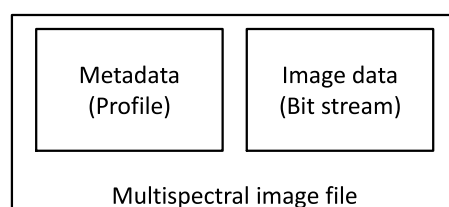


Figure 2 – Structure of multispectral image file

(b) *More than three channels in a single pixel*

In the image data stream there are several different schemes to store pixel data with more than three channels used in conventional multispectral formats. The order of binary data in the image can be as follows (where x_i and y_j are coordinates of pixel (i, j) within each frame):

Band sequential, "BSQ":

$g(x_1, y_1, \lambda_1), g(x_2, y_1, \lambda_1), \dots, g(x_P, y_1, \lambda_1),$ $g(x_1, y_2, \lambda_1), g(x_2, y_2, \lambda_1), \dots, g(x_P, y_2, \lambda_1),$ $\vdots$ $g(x_1, y_Q, \lambda_1), g(x_2, y_Q, \lambda_1), \dots, g(x_P, y_Q, \lambda_1),$	λ_1 Frame
$g(x_1, y_1, \lambda_2), g(x_2, y_1, \lambda_2), \dots, g(x_P, y_1, \lambda_2),$ $g(x_1, y_2, \lambda_2), g(x_2, y_2, \lambda_2), \dots, g(x_P, y_2, \lambda_2),$ $\vdots$ $g(x_1, y_Q, \lambda_2), g(x_2, y_Q, \lambda_2), \dots, g(x_P, y_Q, \lambda_2),$	λ_2 Frame
$\vdots$	$\vdots$
$g(x_1, y_1, \lambda_K), g(x_2, y_1, \lambda_K), \dots, g(x_P, y_1, \lambda_K),$ $g(x_1, y_2, \lambda_K), g(x_2, y_2, \lambda_K), \dots, g(x_P, y_2, \lambda_K),$ $\vdots$ $g(x_1, y_Q, \lambda_K), g(x_2, y_Q, \lambda_K), \dots, g(x_P, y_Q, \lambda_K)$	λ_K Frame

Band interleaved by line, "BIL":

$g(x_1, y_1, \lambda_1), g(x_2, y_1, \lambda_1), \dots, g(x_P, y_1, \lambda_1),$ $g(x_1, y_1, \lambda_2), g(x_2, y_1, \lambda_2), \dots, g(x_P, y_1, \lambda_2),$ $\vdots$ $g(x_1, y_1, \lambda_K), g(x_2, y_1, \lambda_K), \dots, g(x_P, y_1, \lambda_K),$	y_1 line
$g(x_1, y_2, \lambda_1), g(x_2, y_2, \lambda_1), \dots, g(x_P, y_2, \lambda_1),$ $g(x_1, y_2, \lambda_2), g(x_2, y_2, \lambda_2), \dots, g(x_P, y_2, \lambda_2),$ $\vdots$ $g(x_1, y_2, \lambda_K), g(x_2, y_2, \lambda_K), \dots, g(x_P, y_2, \lambda_K)$	y_2 line
$\vdots$	$\vdots$
$g(x_1, y_Q, \lambda_1), g(x_2, y_Q, \lambda_1), \dots, g(x_P, y_Q, \lambda_1),$ $g(x_1, y_Q, \lambda_2), g(x_2, y_Q, \lambda_2), \dots, g(x_P, y_Q, \lambda_2),$ $\vdots$ $g(x_1, y_Q, \lambda_K), g(x_2, y_Q, \lambda_K), \dots, g(x_P, y_Q, \lambda_K)$	y_Q line

Band interleaved by pixel, "BIP":

$g(x_1, y_1, \lambda_1), g(x_1, y_1, \lambda_2), \dots, g(x_1, y_1, \lambda_K)$	(x_1, y_1) pixel
$g(x_2, y_1, \lambda_1), g(x_2, y_1, \lambda_2), \dots, g(x_2, y_1, \lambda_K)$	(x_2, y_1) pixel
$\vdots$	$\vdots$
$g(x_P, y_1, \lambda_1), g(x_P, y_1, \lambda_2), \dots, g(x_P, y_1, \lambda_K)$	(x_P, y_1) pixel
$g(x_1, y_2, \lambda_1), g(x_1, y_2, \lambda_2), \dots, g(x_1, y_2, \lambda_K)$	(x_1, y_2) pixel
$g(x_2, y_2, \lambda_1), g(x_2, y_2, \lambda_2), \dots, g(x_2, y_2, \lambda_K)$	(x_2, y_2) pixel
$\vdots$	$\vdots$
$g(x_P, y_Q, \lambda_1), g(x_P, y_Q, \lambda_2), \dots, g(x_P, y_Q, \lambda_K)$	(x_P, y_Q) pixel

Here P and Q denote the numbers of pixels in the x and y directions, respectively.

The scheme for storing pixel data is sometimes selected depending on the imaging apparatus: for example, BSQ is suitable for cameras with a filter-wheel, whereas BIL often matches imaging devices with gratings or prism spectrometers. On the other hand, BIP is usually convenient for spectral processing.

As another way to store pixel data, an encoding method compatible with RGB-based imaging systems has been proposed (Keusen and Praefcke, 1995). In this method, the first three channels are standard RGB, while the remaining channels represent the spectral data that are orthogonal to the RGB components.

(c) Compression methods for multispectral images

Compression is another important aspect of multispectral image encoding and there are several different approaches:

- Lossless compression

Basically the same techniques that are used in grey scale image compression, such as PNG (Portable Network Graphics) and LZW (Lempel–Ziv–Welch), can be applied to each channel of a multispectral image.

- Lossy, spatial compression only

Each channel is compressed independently. Techniques for grey scale images are applicable, such as JPEG compression.

- Spectral transform and spatial compression

A spectral transform, such as PCA, prior to spatial compression effectively reduces the redundancy in spectral data. As the spectral reflectance of natural objects has high spectral correlation, this approach achieves a higher compression ratio than methods using spatial compression only (Markas and Reif, 1993; Saghri et al., 1995). When considering colour reproduction applications, several methods suitable for preserving colour accuracy as well as accurate spectral reconstruction have been proposed (Keusen and Praefcke, 1995; Yu et. al., 2006).

- Spectral and spatial (3D) compression

Greater efficacy may be realized by applying 3-D compression, considering spectral and spatial correlations of the 3-D data cube of a spectral image. One method for this is known as 3-D SPIHT (Set Partitioning In Hierarchical Tree) (Dragotti et al., 2000), which utilizes 3-D wavelet transforms.

- Spectral video compression

There are not many reports of the compressions of multispectral video. An example approach is to apply a spectral transform and a video compression standard sequentially (Takamura and Yashima, 2004).

5 Requirements for multispectral image formats

One of the first actions of TC 8-07 was to establish a list of desired criteria for a multispectral image format. The requirements are categorized into four groups, "basic", "highly desirable", "nice to have", and "optional", depending upon the importance of each item. Table 1 summarizes those criteria. Although the requirements depend on the application, the requirements shown in Table 1 assume generic applications, particularly scientific use or R&D purposes, rather than industrial, specific-purpose systems.

It is necessary that the multispectral image data should be usable in various types of operating systems (platform independent) and royalty free to allow the exchange of data for not only commercial applications but also experimental or scientific purposes.

In most multispectral applications, high accuracy is required, so images with many channels, many pixels, many bits, and large size must be stored.

Image compression is therefore essential for multispectral image applications, as the sizes of data files will be much larger than those of conventional grey scale and colour images. Since the technologies of multispectral image compression are still under development, both lossless and lossy compression methods which act independently for each channel are categorized as being of the highest importance. As the important applications include spectral measurement, it is also highly desirable to have the capability to store uncompressed data. Other advanced compression technologies are categorized as being of lower importance or not included.

In scientific applications, multispectral images are sometimes captured by uncalibrated devices and the calibration is done using the white and black images. In such cases, it is necessary to store raw data, such as naked camera output, dark current bias values and camera gain. It is also convenient to store geometric registration information including a pin cushion model along with a grid of registration control points. In some measurement applications, absolute radiometric values are required, and the units of measurement need to be included in the data format after calibration. However the units of data are not always necessary, for example, when a target image is captured along with reference image data, such as $g_{d,k}(f_{bk})$ and $g_{d,k}(f_w)$ in Eq. (5), and all datasets are stored for later calibration processing. In airborne and satellite imaging applications geolocation information is also necessary.

In many cases, it is necessary to reconstruct a continuous spectrum from multispectral pixel data. If linear reconstruction is employed, as in Eq. (6), the reconstruction matrix is required along with the multispectral data of each pixel. Then the continuous spectrum can be easily reconstructed by just multiplying the channels by the matrix M . For this purpose, the reconstruction matrix should be stored in the metadata of the multispectral image file. This is a convenient method for industrial applications. Another relevant consideration is compatibility with conventional RGB-based systems, so that the first three channels in the image file can be directly employed in conventional systems, while a multispectral image can be reconstructed by reading all the data (Hill, 1998). Such functionality can be straightforwardly implemented in BSQ mode, which utilizes a planar packing of image data.

It is better if the multispectral image file contains information about the spectral characteristics of filters or sensors, as such information is useful for understanding the meaning of the image data or designing spectral reconstruction methods.

Functions that are convenient for some applications but not mandatory are categorized as "optional" in Table 1. These functions include encoding image data in terms of colorimetric values under an arbitrary illuminant or output device signals for spectral display or spectral printers.

Table 1 – Requirements for a spectral image format

<i>Basic</i> - Platform independent - Lossless compression (ZIP, LZW, etc.) - Lossy compression (JPEG, Wavelets, etc.), independent for each channel - Geolocation information (e.g. latitude and longitude of the corner pixels) - High Accuracy: many channels, many pixels, many bits - Ability to store raw data such as naked camera outputs, dark current bias values, camera gain - Unevenly-sampled spectral interval - Royalty free - File size limitation - Archiving Application (details)
<i>Highly desirable</i> - Ability to store uncompressed data - Geometric registration information including pin cushion model along with a grid of registration control points - Possibility to store company specific information (native tags) - Storage compatible with L*a*b*, RGB possible (e. g., L*, a*, b*, ch4, ch5, ch6, ...) - Reconstruction matrix stored as part of the file format - Simple usage, easy spectral reconstruction (e.g. just multiply the channels by a matrix in order to yield the spectra) - All information in one file - Units of the data (e.g. reflectance (per cent or one) or radiance (watts per square metre, etc.)) - Planar packing available - Industrial Application (simple reconstruction)
<i>Nice to have</i> - Spectral characteristics of filters, sensors, etc. - Different ways of channel storage - Ability to store output device data
<i>Optional</i> - Image data can be represented in terms of encoded colorimetric values under arbitrary illuminant - Image data can be represented in terms of display device signal - The tone curve of each channel can be either linear or not (with the curve included) - Nonlinear bit encoding available - Spatial subsampling (independent for each channel) - dark noise in each channel (and the manner in which it was determined) - API library available - Storage of arbitrary colour management function

6 Candidate formats

Candidate algorithms that were initially brought forward for consideration were TIFF, GeoTIFF, MUSE/AIX, NITF (National Imagery Transmission Format) 2.0, Natural Vision Format, HDF5 (Hierarchical Data Format 5), JPEG, JPEG 2000, SPB (SPectral Binary) and ENVI (ENvironment for Visualizing Images). A matrix was constructed using these formats and the format criteria. As time progressed, many formats were eliminated from future consideration.

The remaining candidates are JPEG 2000 (an international standard), Spectral Binary file format (a simple format from Finland), Natural Vision format (a native format from Japan), and the multispectral Image file format AIX (a native format from Germany) (Jetsu et al., 2005). The specification of JPEG 2000 is available from (ISO/IEC/ITU 2004a; ISO/IEC/ITU 2004b). The complete documentation for the Spectral Binary, Natural Vision, and AIX formats are attached as annexes to this report. The details of these formats are described in the following subclauses.

6.1 JPEG 2000

General Description of JPEG 2000

JPEG 2000 (ISO/IEC/ITU 2004a; ISO/IEC/ITU 2004b) is an advanced standardized image format with a coding system developed to serve applications "into the next millennium." It was developed by the Joint Photographic Experts Group and was approved as an ISO standard in Dec. 2000. JPEG 2000 addresses areas where earlier standards failed to produce the best quality or performance such as in high-compression ratios or image scalability. It also provides capabilities to markets that previously had not used compression (e.g. medical imaging). JPEG 2000 provides an open system approach to the storage and transmission of imagery. Image data are stored as wavelets and metadata are stored in XML.

Old compression paradigms put all the choices on the encoder end of the imaging process. The JPEG 2000 standard allows choices on the decoding end, including image resolution, signal-to-noise fidelity, visual fidelity, target file size, lossless/lossy, region-of-interest, and tiles. In fact, the JPEG 2000 standard only specifies a decoder and bit-stream syntax. Since the standard is issued in several parts, the user should be aware that any particular implementation may not comply with all parts.

JPEG 2000 features and benefits include the following:

- 1) Improved compression efficiency (estimated 5 %–30 % better than conventional JPEG compression depending on the image size and bit rate)
- 2) From lossy to lossless compression (providing a selectable quality level based on requirements)
- 3) Multiple resolution (provides end-user selectable quality)
- 4) Embedded bit-stream (provides progressive decoding)
- 5) Region of interest coding (reduces the amount of data that must be decompressed when only a small area of the image is of interest)
- 6) Error resilience (helps ensure no loss of data)
- 7) Bit stream syntax (gives quick access to any region or component of the image)
- 8) High fidelity based on options for large numbers of spectral components, high bit depth, and lossless compression
- 9) Discrete wavelet transform which provides the following benefits:
 - Multiple resolution representation (provides end-user selectable quality)
 - Lossless representation with integer filters (for high fidelity)
 - Better decorrelation than Discrete Cosine Transform (DCT), resulting in higher compression efficiency (increases compression ratio at a given quality level)
 - Frequency band decomposition where each subband can be quantized according to its visual importance (optimizes compression for human visual system)

Since its introduction, JPEG 2000 has slowly been gaining acceptance in various imagery user communities. Of particular note are the digital cinema, medical, and remote sensing communities, which have all embraced the new technology. JPEG 2000 is also being used in document and cultural preservation, e.g. the United States' and Japanese national archives are being digitized and converted to JPEG 2000 format. JPEG 2000 also extends to video and 3-D compression (being used by the medical industry to get greater compression ratio). The higher complexity of JPEG 2000 has been a drawback to its acceptance for commercial digital

camera applications, where JPEG DCT is perfectly adequate. Communities that have embraced JPEG 2000 technology typically deal with more complex imagery (e.g. multispectral) where the advantages of JPEG 2000 outweigh the added complexity.

JPEG 2000 vs. CIE Established Requirements

The following describes how JPEG 2000 performs relative to each of the format requirements established by the CIE committee.

Basic

- Platform independent: Works across all computer platforms.
- Lossless compression: Yes.
- Lossy compression: Yes, no compression limit.
- Geolocation information: Yes.
- High accuracy: channel limit (16 384 channels); pixel limit $((2^{32} - 1) * (2^{32} - 1))$; bit limit (38 bits/pixel).
- Ability to store raw data: Yes.
- Unevenly-sampled spectral interval: Yes.
- Royalty free: Yes.
- File size limitation: 2^{64} bytes.
- Archiving application: Intended for archiving as well as transmission.

Highly Desirable

- Geometric registration information: Reference grid + grid for each band.
- Possibility to store company-specific information (native tags): Native tags can be created in XML format.
- Storage compatible with L*a*b*, RGB: Any spectral representation of the data is possible.
- Reconstruction matrix: Can be stored in metadata.
- Simple usage, easy spectral reconstruction: Yes.
- All information in one file: Yes.
- Units of the data: Can be stored in metadata.
- Planar packing available: Can be packaged band-by-band or any other way.
- Industrial application (simple reconstruction): Free Java viewers can read and reconstruct.

Nice to Have

- Spectral characteristics of filters, sensors, etc.: Can be stored in metadata.
- Channel storage: Components.
- Ability to store output device data: Can be stored in the metadata.

Optional

- Image data can be represented in terms of encoded colorimetric values under arbitrary illumination: With use of ICC profiles, this can be accomplished without modifying the original data.
- Image data can be represented in terms of display device signal: With use of ICC profiles, this can be accomplished without modifying the original data.