Vectorial Quality Measure for Digital Camera in Opponent FCS

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Abstract

*This paper reconsiders the Luther condition from a spectral and colorimetric point of view. The projection of spectral to colorimetric space is based on matrix **R** theory. The basis of matrix **R** spans a FCS (Fundamental Color Space).*

The spectral colorimetric design for color sensors is discussed based on FCS by clarifying its geometrical structure in relation to the orthogonal color matching function and the FCS basis.

Since opponent-color model is useful for appearance-based color imaging, the paper highlights the opponent FCS with perfect orthogonality and introduces a vectorial quality factor Vq for the spectral-colorimetric evaluation of digital cameras. The spectral response to unit monochromatic stimuli is visualized as a 3-D locus that clearly shows the spectral mismatch with Luther condition. The measured Vqs are compared with Neugebauer's q-factors and also Vora & Trussell's ν-factors.

Introduction

The spectral sensitivities of color input devices such as digital camera or scanner are required to satisfy *Luther condition* in order to capture the correct tri-stimulus values.

The following quality measures for color scanning filters have been conveniently used to estimate the goodness.

[1] Neugebauer's q-factor [1]
[2] Vora&Trussell's ν-factor (generalized q factor) [2]
[3] Tajima's weighted q-factor [3]

Though these factors are helpful for choosing the color filters from a colorimetric point of view, the details in the spectral mismatch are not always clear. From a point of spectral design in RGB camera, Worhtey and Brill analyzed the spectral sensitivity errors using LUM (Locus of Unit Monochromats) in FCS (Fundamental Color Space).

Unfortunately, the LUM error is not numerically measured but mostly discussed in the standard CIE FCS. From a point of color encoding, the FCS based on opponent-color model may be more interesting and attractive.

This paper discusses the spectral LUM responses in an orthogonal FCS with perfect opponent-color basis and measures the LUM error as a mean squared vectorial loci error. A new quality factor, what we call, *Vq* (*Vectorial q-factor*) is not a vector but a single scalar value reflecting the integrated spectral mismatches in the proposed orthogonal opponent-color FCS. The spectral mismatches with Luther condition for high-end digital cameras are introduced in comparison with q-factors or ν-factors.

Fundamental Color Space

FCS is defined as a color space spanned by the orthogonal normalized basis called "*matrix-**F***" derived from the matrix ***R*** theory by J. B. Cohen [4].

In HVSS (Human Visual Sub-Space), n-dimensional color vector ***C*** is decomposed into *fundamental* ***C**** and *metameric black* ***B*** through matrix ***R*** as

$$\boldsymbol{C} = \boldsymbol{C}^* + \boldsymbol{B},\ \boldsymbol{C}^* = \boldsymbol{RC},\ \boldsymbol{B} = (\boldsymbol{I} - \boldsymbol{R})\boldsymbol{C} \tag{1}$$

I denotes unit matrix and ***R*** is the projector onto HVSS (Human Visual Sub-Space) derived from CMF ***A*** as

$$\boldsymbol{R} = \boldsymbol{A}(\boldsymbol{A}^t\boldsymbol{A})^{-1}\boldsymbol{A}^t \tag{2}$$

A is the $n \times 3$ matrix of 1931CIE $\bar{x}(\lambda),\ \bar{y}(\lambda),\ \bar{z}(\lambda)$ CMF.

The marix ***R*** is the $n \times n$ symmetric matrix whose ***i***-th column vector $\boldsymbol{E_i}$ is composed of the *fundamental* for each single spectrum $\boldsymbol{e_i}$ at wavelength λ_i.

$$\begin{aligned} &\boldsymbol{R} = [\boldsymbol{E}_1, \boldsymbol{E}_2, \cdots, \boldsymbol{E}_i, \cdots\cdots, \boldsymbol{E}_n] \\ &\boldsymbol{E}_i = \boldsymbol{Re}_i;\ \boldsymbol{e}_i = [0, 0, \cdots, 1, \cdots\cdots, 0]^t,\ i\text{-}th\ element = 1 \end{aligned} \tag{3}$$

Since the rank of ***R*** is 3, it has only 3 independent vectors and the remaining n-3 are redundant. We can recreate ***R*** by choosing arbitrary triplet from the column (row) vectors. The selected triplet is called "*matrix **E***" and i=*r, g, b* show the spectral primaries at wavelength λ_r, λ_g, λ_b as follows.

$$\boldsymbol{R} = \boldsymbol{E}(\boldsymbol{E}^t\boldsymbol{E})^{-1}\boldsymbol{E},\quad \boldsymbol{E} = [\boldsymbol{E}_r, \boldsymbol{E}_g, \boldsymbol{E}_b]^t \tag{4}$$

Indeed, Fig.1 shows the reconstructed *matrix **R*** from the middle three entries [$\boldsymbol{E}_1$, $\boldsymbol{E}_2$, $\boldsymbol{E}_3$] at λ=540,550, and 560 nm.

The *FCS* is a color space spanned by a triplet of basis vectors called "*matrix **F***", which is orthonormalized version of matrix ***E*** using Gram Schmidt method as

$$\begin{aligned} &\boldsymbol{R} = \boldsymbol{FF}^t; \\ &\boldsymbol{F} = [\boldsymbol{F}_1, \boldsymbol{F}_2, \boldsymbol{F}_3] = GramSchmidt[\boldsymbol{E}_1, \boldsymbol{E}_2, \boldsymbol{E}_3] \\ &\boldsymbol{F}^t\boldsymbol{F} = \boldsymbol{I};\ \langle \boldsymbol{F}_j \bullet \boldsymbol{F}_k \rangle = \begin{cases} 1 & for\ \ j = k \\ 0 & for\ \ j \neq k \end{cases} \end{aligned} \tag{5}$$

The symbol $\langle \boldsymbol{u} \bullet \boldsymbol{v} \rangle$ denotes the inner product of ***u*** and ***v***.

The selection of *matrix **E*** is very important to construct orthonormal *FCS* as suggested by Brill, Finlayson, et al [5].

For example, Burns, Cohen, and Kuznetsov [6] created an orthonormal *FCS* called "*R-L-V*" choosing the *matrix **E*** with quasi-orthogonal axes of *Red, Luminosity, and Violet* (λ=770, 563, and 380 nm) as illustrated in ***Fig.1***.

Historically, the orthogonal CMF was firstly proposed by MacAdam [7] and also may be used as a *matrix **E***. Though the classical Guth's opponent CMF was not orthogonal in original, it was recently orthonornalized by Worthey et al [8] and used for evaluating spectral responses for digital camera. Kotera [9] reported that these CMFs span orthonormal *FCS*s close to *R-L-V* but slightly different one another as illustrated in ***Fig.2***.

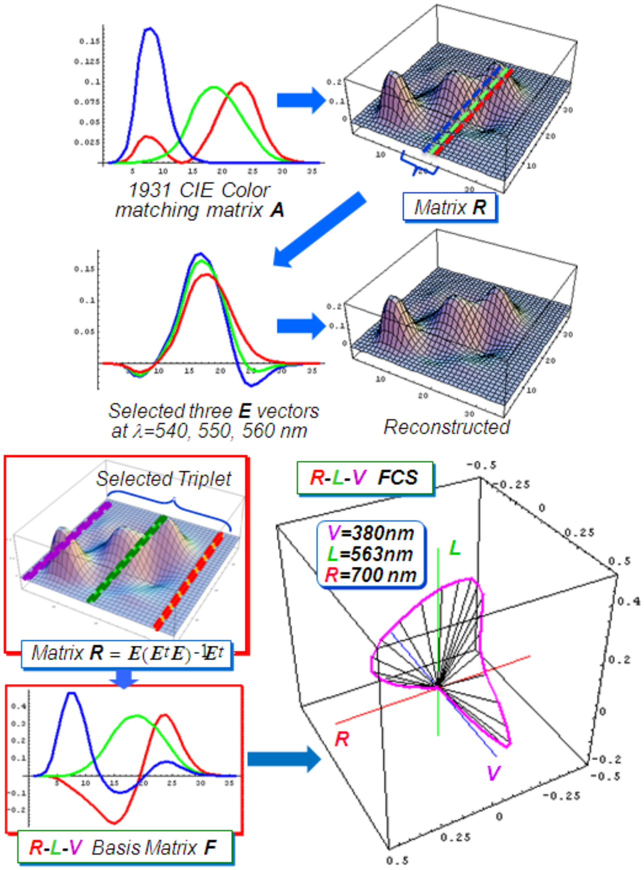

***Figure 1** Construction of FCS*

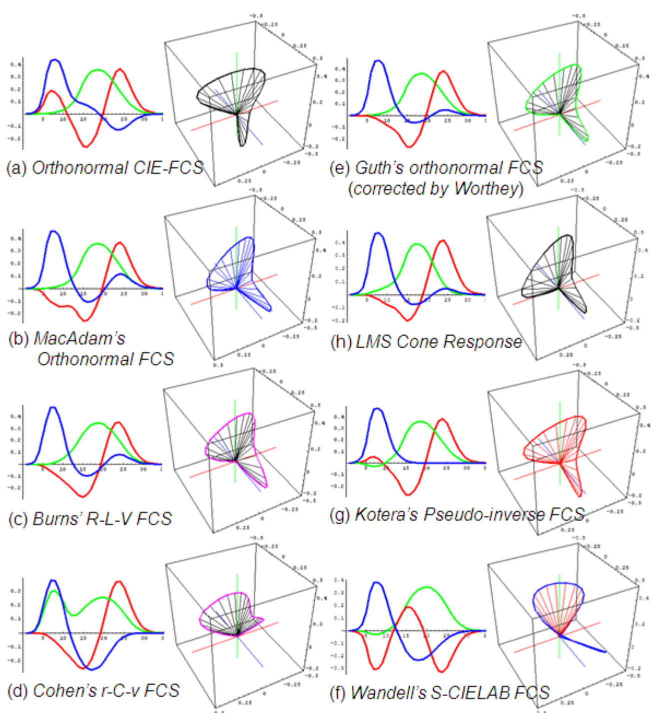

***Figure 2** Typical basis matrix F and its FCS*

Orthonormal Opponent FCS

Spectral Decomposition of Fundamentals

Setting the basis $\boldsymbol{F}_2$ to an *achromatic fundamental* and ($\boldsymbol{F}_1$, $\boldsymbol{F}_3$) to arbitrary orthogonal *chromatic fundamentals* in *matrix* $\boldsymbol{F}$, the *matrix* $\boldsymbol{R}$ is decomposed [4] as

$$\begin{aligned} &\boldsymbol{R} = \boldsymbol{F}\boldsymbol{F}^t = \boldsymbol{R}_A + \boldsymbol{R}_C \\ &\boldsymbol{R}_A = \boldsymbol{F}_2\boldsymbol{F}_2^{\,t},\ \ \boldsymbol{R}_C = \boldsymbol{R} - \boldsymbol{R}_A \end{aligned} \tag{6}$$

$\boldsymbol{R}_A$ and $\boldsymbol{R}_C$ are the orthogonal projectors to decompose the basic *fundamental metamer* $\boldsymbol{C}^*$ into the *achromatic* and the *chromatic fundamentals* $\boldsymbol{C}_A^*$ and $\boldsymbol{C}_C^*$ as

$$\begin{aligned} &\boldsymbol{C}^* = \boldsymbol{C}_A^* + \boldsymbol{C}_C^* \\ &\boldsymbol{C}_A^* = \boldsymbol{R}_A\boldsymbol{C} = \boldsymbol{R}_A\boldsymbol{C}^* \\ &\boldsymbol{C}_C^* = \boldsymbol{R}_C\boldsymbol{C} = \boldsymbol{R}_C\boldsymbol{C}^* \end{aligned} \tag{7}$$

When the chromatic projector $\boldsymbol{R}_C$ is orthogonal to the achromatic projector $\boldsymbol{R}_A$, the inner product between them should be zero as

$$\langle \boldsymbol{R}_A \bullet \boldsymbol{R}_C \rangle = 0 \tag{8}$$

Indeed, the *matrix* $\boldsymbol{F}$ in "*R-L-V*" *FCS* is composed of orthonormal basis functions with achromatic luminousity axis and satisfies the condition of Eq. (8). As well, *FCS*s derived from CMF by MacAdam or Guth also satisfy the same condition.

Orthonormal Opponent FCS

As well known, Luminance/Chrominance color models with opponent-color axes assigned to "*Red-Green* (*R-G*)" and "*Yellow-Blue* (*Y-B*)" have been widely used for color imaging, analysis, and picture coding. *YIQ* used in NTSC Television is a opponent-color system by a simple linear transformation from *XYZ*. CIELAB is a most popular uniform color space mapped on the *R-G* and *Y-B* Cartesian opponent-color coordinates. Hence, a foundation of *FCS* with orthogonal and opponent-color structure is a lot of fun in practical use.

The chromatic projector $\boldsymbol{R}_C$ is further decomposed into two opponent-color components $\boldsymbol{R}_R$ and $\boldsymbol{R}_B$ by choosing an appropriate pair of ($\boldsymbol{F}_1$, $\boldsymbol{F}_3$). Thus, the *chromatic fundamental* $\boldsymbol{C}_C^*$ is decomposed into two opponent-color *fundamentals* $\boldsymbol{C}_R^*$ and $\boldsymbol{C}_B^*$ corresponding to *R-G* and *Y-B* hue axes as follows.

$$\begin{aligned} &\boldsymbol{R}_C = \boldsymbol{R}_R + \boldsymbol{R}_B \\ &\boldsymbol{R}_R = \boldsymbol{F}_1\boldsymbol{F}_1^{\,t},\ \ \boldsymbol{R}_B = \boldsymbol{F}_3\boldsymbol{F}_3^{\,t} \end{aligned} \tag{9}$$

$$\begin{aligned} &\boldsymbol{C}_C^* = \boldsymbol{C}_R^* + \boldsymbol{C}_B^* \\ &\boldsymbol{C}_R^* = \boldsymbol{R}_R\boldsymbol{C}_C^*,\ \ \boldsymbol{C}_B^* = \boldsymbol{R}_B\boldsymbol{C}_C^* \end{aligned} \tag{10}$$

To be perfectly opponent for $\boldsymbol{C}_R^*$ and $\boldsymbol{C}_B^*$, it is desirable that the projectors $\boldsymbol{R}_R$ and $\boldsymbol{R}_B$ satisfy the following zero-sum conditions. That means the gray input with flat spectrum should be achromatic without any red-green or yellow-blue components.

$$\begin{aligned} &Sum[\boldsymbol{R}_R] = \sum_{j=1}^{n}\sum_{k=1}^{n} R_R(j,k) = 0\ ;\ R_R(j,k)\ \textit{is jk element} \\ &Sum[\boldsymbol{R}_B] = \sum_{j=1}^{n}\sum_{k=1}^{n} R_B(j,k) = 0\ ;\ R_B(j,k)\ \textit{is jk element} \end{aligned} \tag{11}$$

Although the *matrix* $\boldsymbol{F}$ in "*R-L-V*" *FCS* surely satisfies the orthonormal condition in Eq. (5) and the orthogonality between achromatic and chromatic components in Eq. (8), the zero-sum condition in Eq. (11) didn't hold good, and MacAdam's or Guth's *FCS*s as well.

In the "*R-L-V*" *FCS*, the fundamental of λ_g =563 nm single spectrum is selected as the vector $\boldsymbol{E}_2$ to reflect the *Luminosity*, but $\boldsymbol{E}_2$ doesn't exactly mean the *luminance* which is defined as a linear mixture of *R, G, B* components.

Since the entry of *matrix* $\boldsymbol{E}$ may be any linear combination of arbitrary column vectors $\{\boldsymbol{E}_i\}$; i=1~n, for instance, the second vector $\boldsymbol{E}_2$ may be given by the weighted sum of $\{\boldsymbol{E}_i\}$ by illuminant ***D65*** that means the fundamental of ***D65*** itself.

$$\boldsymbol{E}_2 = \sum_{i=1}^{n} D_{65}(\lambda_i)\boldsymbol{E}_i = \boldsymbol{RD}_{65}\,;\ \boldsymbol{D}_{65} = SPD\ \ of\ illuminant$$
$$\boldsymbol{D}_{65} = [D_{65}(\lambda_1), D_{65}(\lambda_2), \cdots, D_{65}(\lambda_n)]^t \qquad (12)$$

The zero sum condition can be obtained by replacing the vector $\boldsymbol{E}_2$ with the fundamental of white illuminant such as *EE* (*Equal-Energy*) or *D65*. Since *EE* is not popular in practice, *D65* is recommended as most widely used. Thus "*R-D65-V*" *FCS* is created by introducing the fundamental of *D65* into vector $\boldsymbol{E}_2$ in Eq. (12) and a getting the *matrix* $\boldsymbol{F}$ by GramSchmidt. Now "*R-D65-V*" becomes a perfect opponent-color *FCS* with zero sum condition [10].

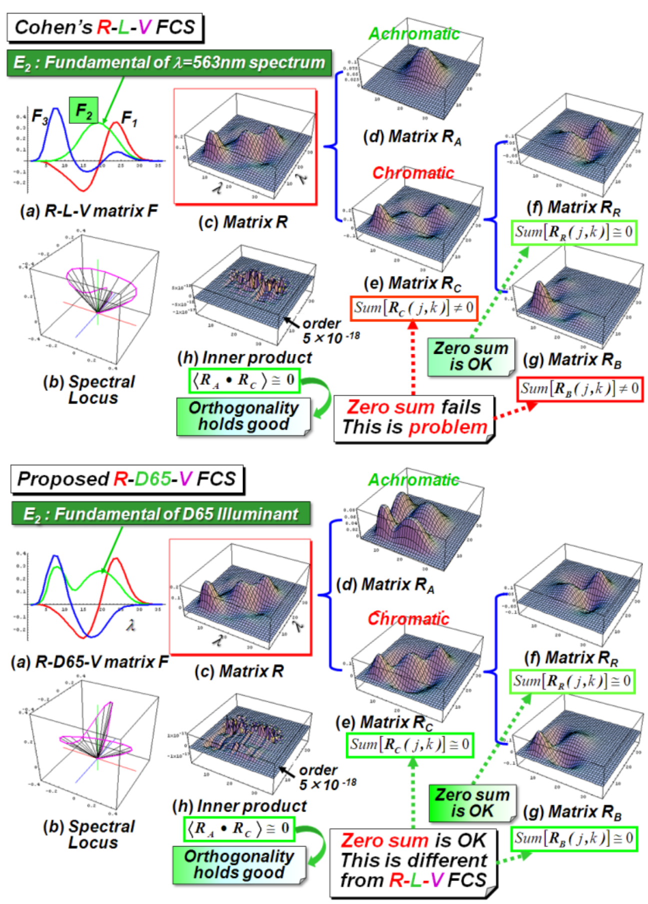

Figure 3 *Opponency tests for FCS by decomposition of matrx* ***R***

Fig.3 summarizes how the *matrix R* is decomposed into the achromatic $\boldsymbol{R}_A$ and chromatic $\boldsymbol{R}_c$ components and further into the *opponent-color matrices* $\boldsymbol{R}_R$ and $\boldsymbol{R}_B$. The upper half is the decomposition for "*R-L-V*" and the lower half is for the "*R-D65-V*" *FCS*. Although $\boldsymbol{R}_A$ and $\boldsymbol{R}_c$ are orthogonal each other in both models, the zero-sum conditions in the matrix $\boldsymbol{R}_B$, hence $\boldsymbol{R}_c$ don't hold good for "*R-L-V*", while they are almost maintained in the "*R-D65-V*" with the negligible small errors. The zero-sum condition in *Yellow-Blue fundamental matrix* $\boldsymbol{R}_B$ is the definitive difference between them. That is, "*R-L-V*" is imperfect but "*R-D65-V*" is one of the perfect orthogonal opponent-color FCS.

Quality Measure of Color Scanning Filter

q-factor

Neugebauer's q-factor has been easily used for estimating the goodness of RGB color scanning filters. It's convenient for measuring the RGB channel errors independently.

Letting the spectral sensitivity in *R, G, and B* channel be $\boldsymbol{S}_{Cam}$=[$S_R(\lambda)$, $S_G(\lambda)$, $S_B(\lambda)$], the q-factor is given by

$$q_j = \sum_{k=1}^{3} \left\langle \boldsymbol{S}_j \bullet \boldsymbol{A}^{ort}{}_k \right\rangle^2 \Big/ \left\| \boldsymbol{S}_j \right\|^2 ;\ \ j = R, G, B$$
$$\boldsymbol{A}^{ort} = \left[\boldsymbol{A}^{ort}{}_1, \boldsymbol{A}^{ort}{}_2, \boldsymbol{A}^{ort}{}_3\right] = GramSchmidt[\boldsymbol{A}] \qquad (13)$$

Where, $\boldsymbol{A}^{Ort}$ denotes an orthogonal CIE CMF and q_j simply means the power of cosine between the j=*R, G, B* spectral sensitivity vector and the corresponding CMF, taking the value of $0 \le q_j \le 1$. If the $\boldsymbol{S}_j(\lambda)$ is a linear transform of CMF, the Luther condition is perfectly satisfied with q_j=1.

Though Neugebauer used MacAdam's orthogonal CMF as $\boldsymbol{A}^{ort}$, this paper applied the orthonormalized standard CIE1931CMF by GramSchmidt.

Camera FCS by Matrix $\boldsymbol{R}_{Cam}$

The device FCS such as digital camera is structured from the camera *matrix* $\boldsymbol{R}_{Cam}$ corresponding to *matrix* $\boldsymbol{R}$ by just replacing the CMF A with camera sensitivity S_{Cam} as

$$\boldsymbol{R}_{Cam} = \boldsymbol{S}_{Cam}(\boldsymbol{S}_{Cam}{}^t\boldsymbol{S}_{Cam})^{-1}\boldsymbol{S}_{Cam}{}^t \qquad (14)$$

Now the deviation from the Luther condition is measured by the difference between matrices $\boldsymbol{R}_{Cam}$ and matrix $\boldsymbol{R}$.

Since a linear transformation of CMF also belongs to the family of CMFs, a linear matrix operation for camera sensitivity $\boldsymbol{S}_{Cam}$ may be allowed without affecting the Luther condition. Hence the basis matrix $\boldsymbol{F}_{Cam}$ of camera FCS is derived from the following two steps.

[Step1] Get best fit camera sensitivity to CIE CMF

Least Squares' method

The linear transformation matrix $\boldsymbol{M}_{Fit}$ for getting the camera sensitivity $\boldsymbol{S}_{Fit}$ closest to CIE.CMF $\boldsymbol{A}$ is obtained by the method of least squares as

$$[\boldsymbol{S}_{Fit}]^t = \boldsymbol{M}_{Fit}\boldsymbol{S}_{Cam}{}^t \quad for\ \boldsymbol{min}\left[E\left\{\left\|\boldsymbol{S}_{Fit} - \boldsymbol{A}\right\|^2\right\}\right]$$
$$\boldsymbol{M}_{Fit} = \left[\boldsymbol{A}^t\boldsymbol{S}_{Cam}\right]\left[\boldsymbol{S}_{Cam}{}^t\boldsymbol{S}_{Cam}\right]^{-1} \qquad (15)$$

Fit First method

According to *"Fit First"* method [13] by Worthey and Brill, the same $\boldsymbol{S}_{Fit}$ is obtained by operating the camera matrix $\boldsymbol{R}_{Cam}$ directly on $\boldsymbol{A}$ like as

$$\boldsymbol{S}_{Fit} = \boldsymbol{R}_{Cam}\boldsymbol{A} = \left[\boldsymbol{S}_{Cam}(\boldsymbol{S}_{Cam}{}^{t}\boldsymbol{S}_{Cam})^{-1}\boldsymbol{S}_{Cam}{}^{t}\right]\boldsymbol{A} \quad (16)$$

It's easy to prove that Eq. (15) equals Eq. (16).

[*Step2*] *Get basis Matrix F for camera FCS*

Next, we get the camera basis matrix $\boldsymbol{F}_{Cam}$ by orthonormaliz -ing $\boldsymbol{S}_{Fit}$ with Gram Schmidt process as

$$\boldsymbol{F}_{Cam} = GramSchmidt\left[\boldsymbol{S}_{Fit}\right] \quad (17)$$

Now the camera FCS is spanned by the triplet basis of $\boldsymbol{F}_{Cam}$.

ν-factor in relation to Camera FCS

Neugebauer's *q*-factor is surely useful for judging the goodness of individual color filter independently but not for estimating a set of *RGB* in total. Hence *ν*-factor is proposed as a generalized *q*-factor extended to measure the total goodness for a set of multi-channels more than three.

The *ν*-factor is simply described as a deviation between the matrices $\boldsymbol{R}$ and $\boldsymbol{R}_{Cam}$, in the sense of squared error of directional cosine between the projection matrices as

$$\nu(\boldsymbol{R},\boldsymbol{S}) = Trace[\boldsymbol{RS}] / \alpha \quad (18)$$

Assuming the spectral inputs are independent random variables, it's simply reduced to the average of *q*-factors as

$$\nu = (1/\alpha)\sum_{i=1}^{\beta} q_i \quad (19)$$

Where α denotes the rank of matrix $\boldsymbol{R}_{Cam}$ (=3) and β means the number of color channels (=3 for normal *RGB* camera).

Vectorial q-factor

In the past papers [11] [12], the colorimetric error for color scanner is evaluated as a spectral loci error using a virtual spectral target composed of Sine SPDs.

Recently, Worthey and Brill [13] advanced the same concept in the elegant manner by visualizing the LUM error in FCS. This clarified the defect in the spectral sensitivity design but missed to give the numerical measure unfortunately.

The error in camera LUM from HVSS is easily measured by the average spectral deviation, what we call, *vectorial q-factor* as

$$Vq = 1 - MSE\left\{\left\|\boldsymbol{A}^{Ort} - \boldsymbol{F}^{Cam}\right\|\right\} = 1 - \left[\sum_{j=1}^{3}\sum_{k=1}^{n}\left\{\boldsymbol{A}_j^{Ort}(\lambda_k) - \boldsymbol{F}_j^{Cam}(\lambda_k)\right\}^2\right] \Big/ \left\|\boldsymbol{A}^{Ort}\right\|^2 \quad (20)$$

Estimation Results in Digital Camera

In practice, the spectral goodness is estimated for four commercial high-end digital cameras.

Evaluation in orthonormal standard CIE FCS

First the LUM errors between camera and human vision are estimated using the standard orthonormal CIE FCS as summarized in ***Fig.4***. The numerical *Vq* values are listed in Table.1 in comparison with ***q***-factors and ***ν***-factors. The camera LUMs are obtained starting from the measured spectral sensitivity $\boldsymbol{S}_{Cam}$, calculating the best fit sensitivity $\boldsymbol{S}_{Fit}$,, and converting to the basis matrix $\boldsymbol{F}_{Cam}$.

Evaluation in orthonormal opponent-color FCS

As well, the same estimation is performed using *R-D65-V* orthonormal *opponent-color* FCS as shown in ***Fig.5.*** The results are little different from ***Fig.4***.

The *Vq values* in opponent-color FCS show the severe assessment rather than in the orthonormal CIE FCS as listed in the last row in **Table.1**.

All of ***q***, ***ν*** factors and *Vq* tell that camera ***C*** is the best and camera ***M*** is the worst. However the camera ***N****-1 and* ***N****-2* (same maker) marked somewhat different scores in *Vq* from the conventional ***q*** or ***ν*** factors. The more detailed analysis is necessary but left behind as a future work.

Conclusions

The paper reconsidered the Luther condition from a spectral and colorimetric point of view. Recently a new concept of *spectral colorimetry* has been oriented to design the better multi-band camera incompatible with colorimetric and spectral reproduction.

The key point of proposed approach lies in the use of opponent-color FCS with zero-sum conditions, that means

[1]*Colorimetrically*: Luther condition corresponds to the *fundamental* based on the matrix ***R*** theory of human vision

[2]*Spectrally*: the opponent-color FCS is based on the spectral decomposition of *chromatic fundamental* with the perfect opponent-color axes that reflect the LUM error spectrally important to color appearance in relation to the camera design.

Furthermore, it's desirable to discuss the *device metamerism* from a point of spectral imaging. The FCS based approach to this problem is also left behind as a future work.

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Author Biography

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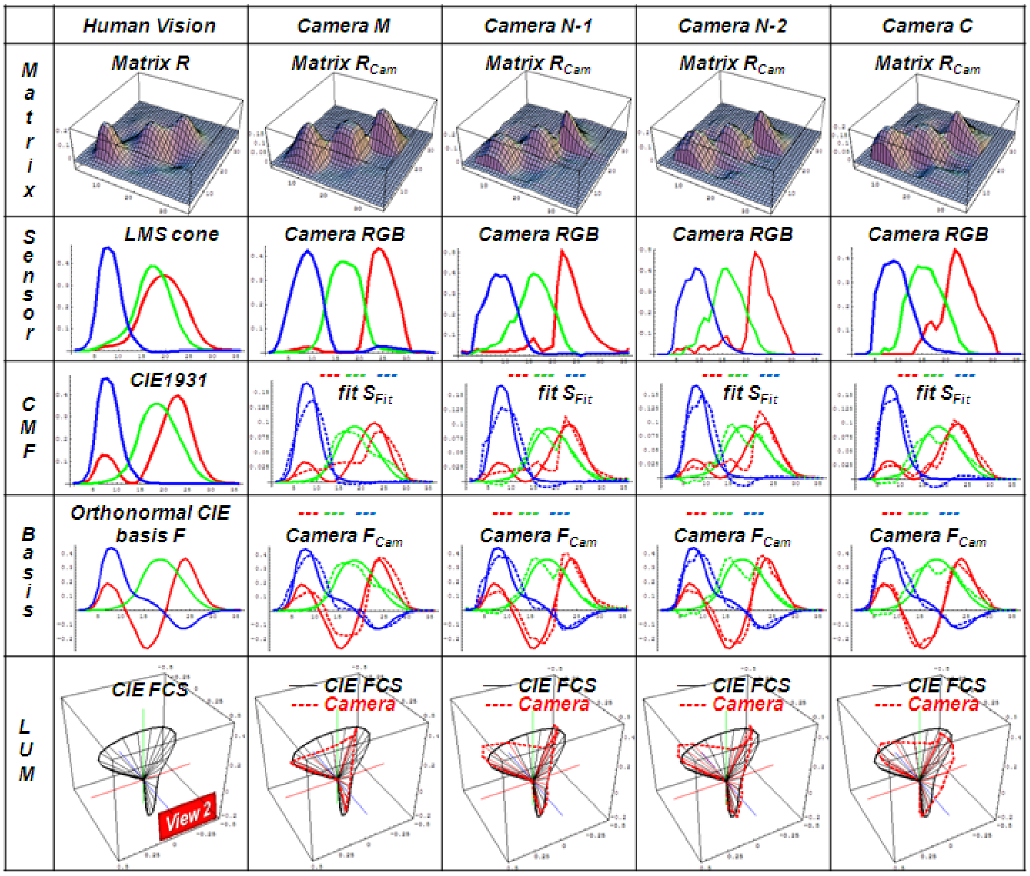

Figure 4 Results in spectral errors for digital cameras estimated in orthonormal standard CIE FCS

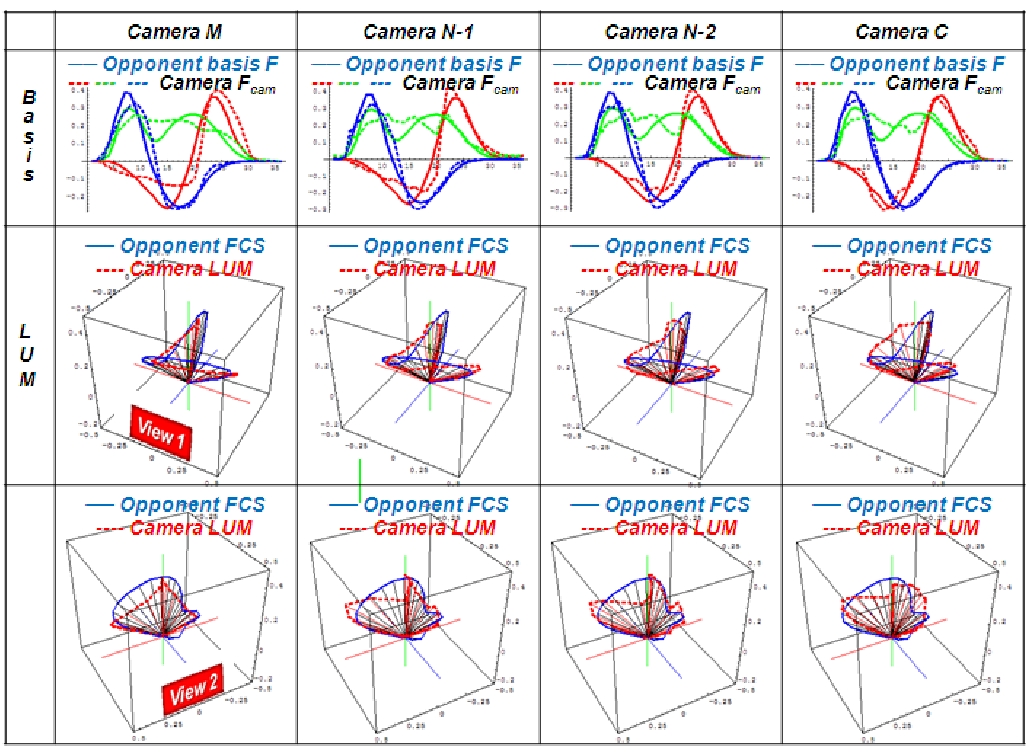

Figure 5 Results in spectral errors for digital cameras estimated in R-D65-V opponent-color FCS

Table 1 Measured quatity factors for digital cameras

measures \ Cameras		M	N-1	N-2	C
q-factor	q-Red	0.839	0.868	0.867	0.955
	q-Green	0.953	0.953	0.927	0.932
	q-Blue	0.920	0.900	0.914	0.944
-factor		0.904	0.907	0.902	0.944
Vectrial Vq	Orthonormal CIE FCS	0.909	0.929	0.920	0.940
	Opponent-color R-D65-V FCS	0.869	0.890	0.888	0.927