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Quality Criterion for Digital Still Camera

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ABSTRACT

The main quality requirements for a digital still camera are color capturing accuracy, low noise level, and quantum efficiency. Different consumers assign different priorities to the listed parameters, and camera designers need clearly formulated methods for their evaluation. While there are procedures providing noise level and quantum efficiency estimation, there are no effective means for color capturing accuracy estimation. Introduced in this paper criterion allows to fill this gap.

Luther-Ives condition for correct color reproduction system became known in the beginning of the last century. However, since no detector system satisfies Luther-Ives condition, there are always stimuli that are distinctly different for an observer, but which detectors are unable to distinguish. To estimate conformity of a detector set with Luther-Ives condition and calculate a measure of discrepancy, an angle between detector sensor sensitivity and Cohen's Fundamental Color Space may be used.

In this paper, the divergence angle is calculated for some typical CCD sensors and a demonstration provided on how this angle might be reduced with a corrective filter. In addition, it is shown that with a specific corrective filter Foveon sensors turn into a detector system with a good Luther-Ives condition compliance.

Keywords: Color Capturing Accuracy, Digital Camera, Luther-Ives Condition, Cohen's Fundamental Color Space

1. INTRODUCTION

Sensor spectral sensitivity plays the main role in color capturing accuracy. Luther-Ives condition formulated at the beginning of the last century /1/ determines requirements for camera's spectral sensitivities necessary for correct color capturing. In case of a three-detector camera, this condition may be formulated as follows: a color capturing device with light detectors of three types may be used in correct color reproduction system if and only if a spectral sensitivity of every detector (DSS) in the system may be represented as a linear combination of Cone Fundamentals (CFs). However, a century later, cameras available on the market are still do not satisfy this condition. And an increased number of detectors does not help a camera to become an accurate color-capturing device.

There are many cases of inadequate color capturing caused by DSS and Luther-Ives condition discordance, but most clearly it may be illustrated by the following simple artificial example.

Fig.1 displays DSSs of a typical CCD sensor (solid lines). Minimal difference between a DSS and a linear transformation of human spectral sensitivities is displayed with a dotted line. The difference for red and blue is not small. It is comparable to the corresponding DSS, what leads to unrepairable defects in color capturing. Consider the following two stimuli:

🟧 Stimulus 1 consisting of two monochromatic components: 0.628 W with the wavelength λ=400 nm and 0.848W with the wavelength λ=600 nm, is perceived by a human as a bright orange color. Tristimulus values are (X = 905, Y = 533, Z = 43).

🟩 Stimulus 2 consisting of two monochromatic components: 0.233 W with the wavelength λ=500 nm and 1.000W with the wavelength λ=700 nm, is perceived by a human as a dark green color. Tristimulus values are (X = 2, Y = 79, Z = 63).

However, the sensor with DSSs displayed in Fig.1 perceives these two stimuli as identical. Values produced by detectors are proportional to B = 138, G = 281, and R = 829 respectively and the same for both stimuli, so, the corresponding colors are indistinguishable for the sensor. There is no algorithm that is able to separate the first stimulus from the second using the sensor data. Whatever algorithm is applied, it will produce the same color in both cases. The output color will not necessarily be red or green; it might be yellow, or some other tint, depending on an algorithm used for data processing.

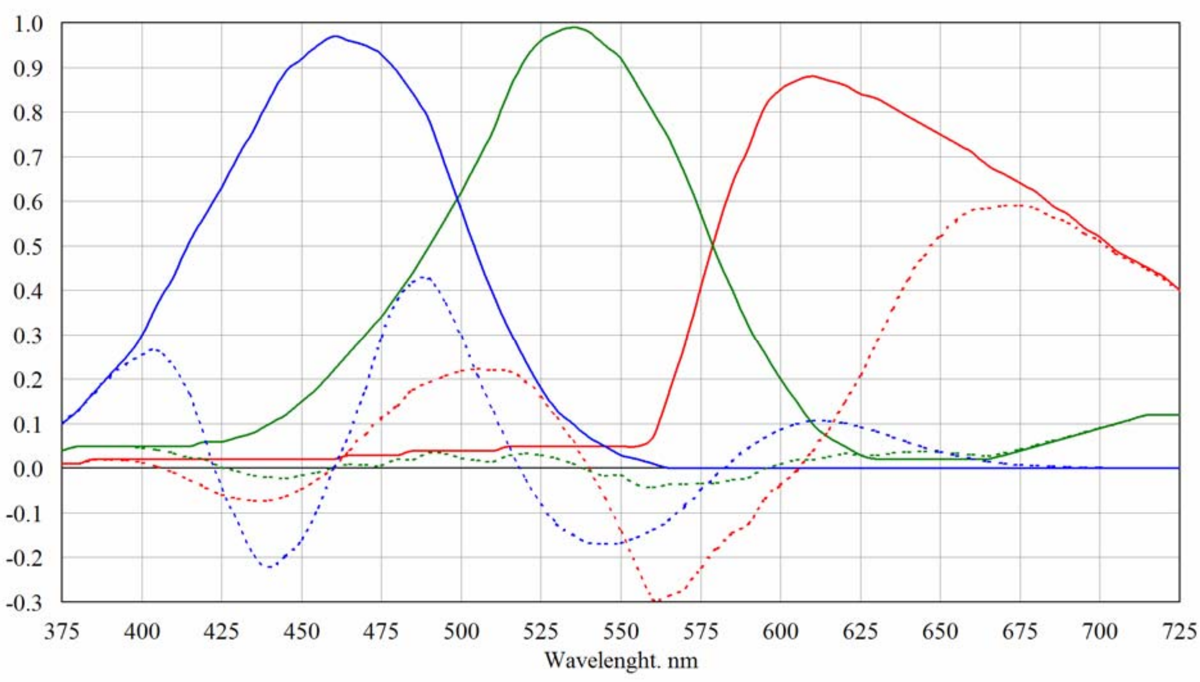

Fig. 1. DSSs of a typical CCD sensor are displayed with bold solid lines. Residual DSS components are displayed with dotted lines.

Such a big difference between human perception and the sensor results is due to the fact, that man's perceptibility drops 100 times in 600 nm to 700nm range, while sensitivity of the red detector drops less than twice. The considered example is very artificial, but natural scene images also have color problems due to similar reasons. Currently, there is no consumer digital camera on the market able to provide accurate colors. Brightness of a red stimulus heavily depends on its spectral distribution. For example, consider two light-emitting diodes. The first one is 650 nm and the second, three times more powerful, is 700 nm. The second diode looks less bright for a human, but more bright for the sensor.

The difference in human and sensor red sensitivity affects not only red colors, but also those, which have red as a part of mixture, for example, yellow. Two yellow stimuli, one is narrow band and other is wide band, may look identically yellow for a human, while the sensor records the first one as yellow and the second as orange due to sensor's oversensitivity to red in the range 625 –725nm. Mostly clear it becomes apparent in scenes with wide range of yellow tints.

Shifted to the right peak of blue DSS results in a problem with green and blue colors. An excess sensitivity for blue and green around 480 nm and deficit in 435-440nm range, where peaks human sensitivity for blue, causes inadequate record of a green-and-blue stimulus, making it dependent on the stimulus spectral distribution.

Besides technological difficulties in detector manufacturing, one of the reasons hampering the progress in accurate color capturing is deficiency of an effective method to estimate a rate of conformity of any given three-detector set to Luther-Ives condition. Suggested in this paper use of an angle between detector sensor sensitivity and Cohen's Fundamental Color Space as measure of discrepancy may help to solve this problem.

2. FUNDAMENTAL COLOR SPACE (FCS)

In his 1953 doctoral thesis Wyszecki suggested to represent a stimulus spectral distribution as a sum of two functions:

$$s(\lambda) = s_f(\lambda) + s_r(\lambda) \tag{1}$$

where $s_f(\lambda)$ is a fundamental component. It is the same for all stimuli that have an identical influence upon a human. Tristimulus values of $s_f(\lambda)$ are equal to Tristimulus values of $s(\lambda)$.

$s_r(\lambda)$ is a residual component. It has no influence upon a human and its Tristimulus values are equal to zero.

The choice of the fundamental component involves some arbitrariness. The arbitrariness may be significantly reduced if $s_f(\lambda)$ is defined as an orthogonal projection of $s(\lambda)$ onto a subspace spanned by Cone Fundamentals (CFs), so-called a Fundamental Color Space (FCS) introduced by Jozef Cohen in 1982. Then the residual component $s_r(\lambda)$ is orthogonal to FCS .

Evolving Wyszecki and Cohen ideas, formula (1) may be applied not only to a stimulus, but also to a detector. In this case, $s(\lambda)$ is DSS, and $s_f(\lambda)$ is an orthogonal projection of the DSS onto FCS. An angle between $s(\lambda)$ and $s_f(\lambda)$ is an angle between DSS and FCS. Three-detector set satisfies Luther-Ives condition when this angle is equal zero for every DSS. Thus, the angle between $s(\lambda)$ and $s_f(\lambda)$ may be used as a measure of DSS deviation.

An orthogonal projection concept requires introduction of a metric. Cohen's method of orthogonal projection calculation is equivalent to use of L_2 metric. One of possible ways to introduce L_2 metric is by defining a rule for dot product calculation. General formulas describing L_2 metric are provided below.

The dot product definition

$$\boldsymbol{P} \bullet \boldsymbol{Q} = \mathrm{C}_{\mathrm{norm}} \cdot \int_a^b P(\lambda)\cdot Q(\lambda)\mathrm{d}\lambda \tag{2}$$

where $\mathrm{C}_{\mathrm{norm}}$ is a normalization factor and the interval [a, b] is wavelength range for visible light.

A norm of a function

$$\|\boldsymbol{P}\| = \sqrt{P(\lambda)\bullet P(\lambda)} \tag{3}$$

An angle between two functions

$$\cos(\angle(\boldsymbol{P}, \boldsymbol{Q})\ ) = \frac{P(\lambda)\bullet Q(\lambda)}{\|P(\lambda)\|\cdot\|Q(\lambda)\|} \tag{4}$$

Function norm depends on the choice of the normalization factor $\mathrm{C}_{\mathrm{norm}}$, but the ratio of norms and angles between functions do not.

3. FORMULA FOR DEVIATION ANGLE

With a stated rule for dot product (2), norm (3) and angle (4) calculation, now it is possible to calculate $s_f(\lambda)$ and an angle between $s(\lambda)$ and FCS. Span of Cone Fundamentals coincides with span of any set of Color Matching Functions (CMFs), so $\{\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}\}$ set may be used for fundamental component calculation. To compute $s_f(\lambda)$, it is convenient to use a reciprocal (dual) basis $\{\boldsymbol{x}^*, \boldsymbol{y}^*, \boldsymbol{z}^*\}$ (Korn 14.7-b /2/). In this case, Tristimulus Values of $s(\lambda)$

$$s_x = \boldsymbol{s} \bullet \boldsymbol{x} = \int s(\lambda)\cdot x(\lambda)\ \mathrm{d}\lambda \tag{5a}$$

$$s_y = \boldsymbol{s} \bullet \boldsymbol{y} = \int s(\lambda)\cdot y(\lambda)\ \mathrm{d}\lambda \tag{5b}$$

$$s_z = \boldsymbol{s} \bullet \boldsymbol{z} = \int s(\lambda)\cdot z(\lambda)\ \mathrm{d}\lambda \tag{5c}$$

are covariant components of the orthogonal projection of $s(\lambda)$ onto FCS and $s_f(\lambda)$ might be computed with the following formula

$$s_f(\lambda) = s_x \cdot x^*(\lambda) + s_y \cdot y^*(\lambda) + s_z \cdot z^*(\lambda) \qquad (6)$$

The reciprocal basis {***x****, ***y****, ***z****} for 10º xyz CIE (1964) is depicted in Fig.2 and may be obtained from the following equation:

$$\begin{pmatrix} x^*(\lambda) \\ y^*(\lambda) \\ z^*(\lambda) \end{pmatrix} = A \cdot \begin{pmatrix} 1.709 & -1.317 & -0.199 \\ -1.317 & 1.624 & 0.102 \\ -0.199 & 0.102 & 0.322 \end{pmatrix} \cdot \begin{pmatrix} x(\lambda) \\ y(\lambda) \\ z(\lambda) \end{pmatrix} \qquad (7)$$

where A is a constant dependent on the choice of wavelength units and ensuring the condition (8)

$$\int x^*(\lambda)\cdot x(\lambda)\, d\lambda = \int y^*(\lambda)\cdot y(\lambda)\, d\lambda = \int z^*(\lambda)\cdot z(\lambda)\, d\lambda = 1 \qquad (8)$$

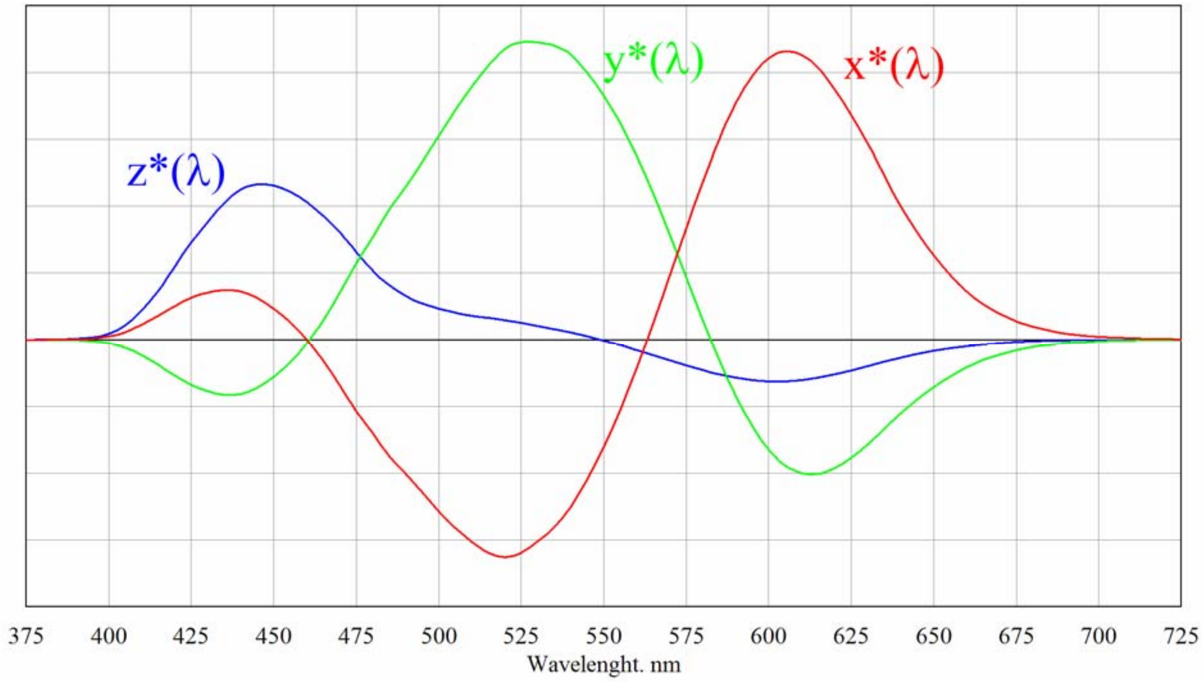

Fig.2. 10º xyz CIE (1964) reciprocal basis.

Taking into account, that

$$\cos(\angle(s_f(\lambda), s(\lambda))) = \frac{\|s_f(\lambda)\|}{\|s(\lambda)\|} \qquad (9)$$

formula for the deviation angle may be written as follows

$$\angle(s_f(\lambda), s(\lambda)) = \arccos\sqrt{\frac{\int s_f(\lambda) s_f(\lambda) d\lambda}{\int s(\lambda) s(\lambda) d\lambda}} \qquad (10)$$

4. ACCURACY OF HUMAN VISION MODEL

To use the deviation angle as a quality criterion in light detector manufacturing, it should be determined what angle value may be considered as negligibly small. Because the angle calculation eventually based on Cone Fundamentals data, this question is equivalent to a question about accuracy of employed human visual system model. So far, all experiments on CF specification provide slightly different results. Thus, a model based on CIE 2º standard differs from a model based on CIE 10º standard, and it is possible to select stimuli that would be undistinguishable in one model and different in the other. It happens because FCS based on 2º model does not coincide with FCS based on 10º model. One of the ways to estimate an accuracy of human visual system model is to determine a deviation angle between 2º CMFs and FCS defined with 10º CIE (1964) standard (or vice versa). Table 1 represents CMFs deviation angles for 2° CIE (1931) standard and 2° CIE (1978) modified standard.

Table 1. Angles between 2º XYZ CIE CMFs and 10º CIE FCS

	$x(\lambda)$	$y(\lambda)$	$z(\lambda)$
2° CIE (1931) standard	2.98º	4.19º	5.09º
2° CIE (1978) modified standard	2.86º	4.35º	7.63º

As it may be seen from the Table 1, the discrepancy between functions in 2º and 10º models is about 5º. This result may be considered as an additional confirmation that use of Basic Colorimetry Concept for design a color capturing/reproduction system guarantees no more than 10% accuracy. Therefore, if detector's deviation angle does not exceed 5º, the color capturing accuracy of the detector may be considered adequate to the limit of accuracy provided by current Colorimetry concept. If the deviation angle is more, than 10º, such detector should be considered as unacceptable for a system claiming accurate color capturing.

5. TYPICAL DETECTOR

As it was expected, DSSs of the typical sensor displayed in Fig.1 make large angles with FCS (see Table 2).

Table 2. Angles between DSSs of a typical CCD sensor and 10º CIE FCS

	r	*g*	*b*	MRS
Typical CCD, No Filter	42º	12º	25º	29º
Typical CCD +Traditional UV&IR Filter	20º	5º	23º	18º
Typical CCD + Compound Filter	18º	7º	8º	12º

A spectral sensitivity of the red detector has the biggest deviation angle 42º. A good corrective filter may improve the sensor's characteristics, but cannot completely eliminate its "birth defect" caused by dislocated peak of red sensitivity. Thus, a good traditional UV&IR filter significantly improves situation near the boundaries of visibility (Fig.3) reducing 2.1 times the deviation angle of the red DSS and 1.6 times the sensor's average (Mean Root Square) deviation angle. However, as it may be seen from the graph, the residual components are still big in the middle of the range, because of, as it was already mentioned, shifted to the right peaks of blue and red DSSs.

A compound filter with more complicated configuration, such, as depicted in Fig. 4, for example, can cut down residual blue component, reducing the average deviation 1.5 times more, than it could be done by the UV&IR filter. While a significant decrease in green and red detector sensitivities caused by the compound filter reduces an overall sensor sensitivity, the filter use improves channels balance, what, in turn, leads to reduced noise level in a red channel because R_{RAW} values provided by the typical sensor are usually 1.5 to 2 times less than G_{RAW} or B_{RAW} (Measurements of R_{RAW}, G_{RAW}, and B_{RAW} values were made for consumer cameras manufactured by Canon, Minolta and Sony).

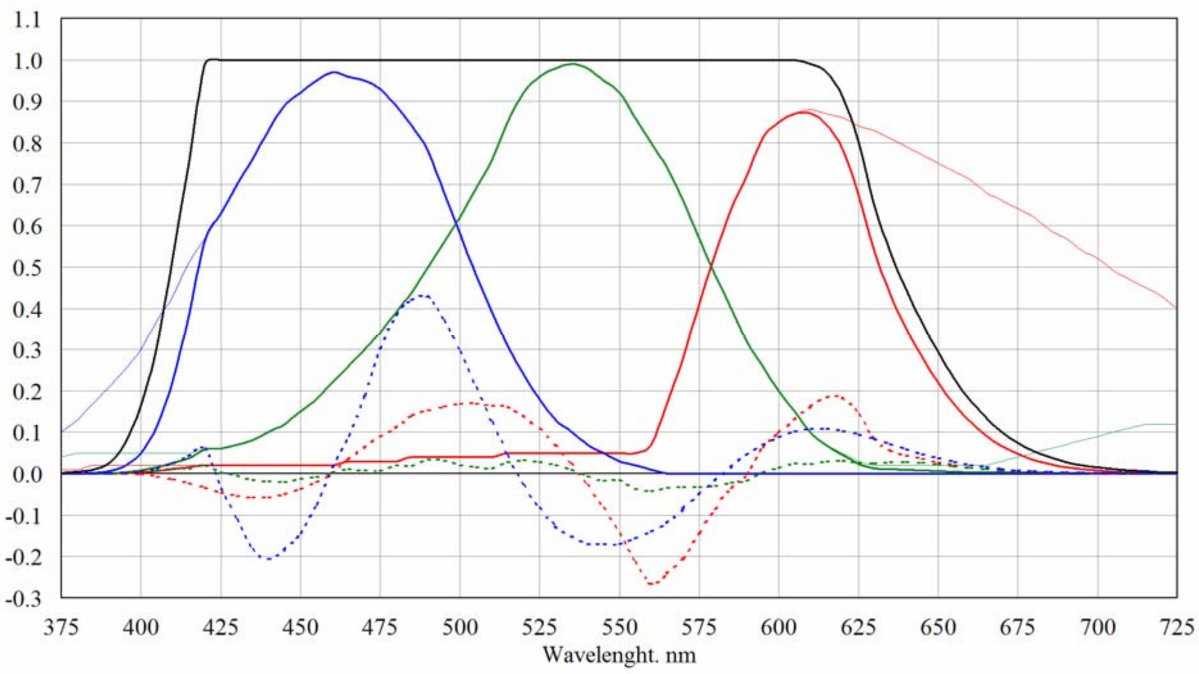

Fig.3. DSSs of a typical CCD sensor + UV&IR filter (bold solid colored lines). Thin lines represent the original DSSs. The filter spectral sensitivity is depicted in black. Residual components are displayed with dotted lines.

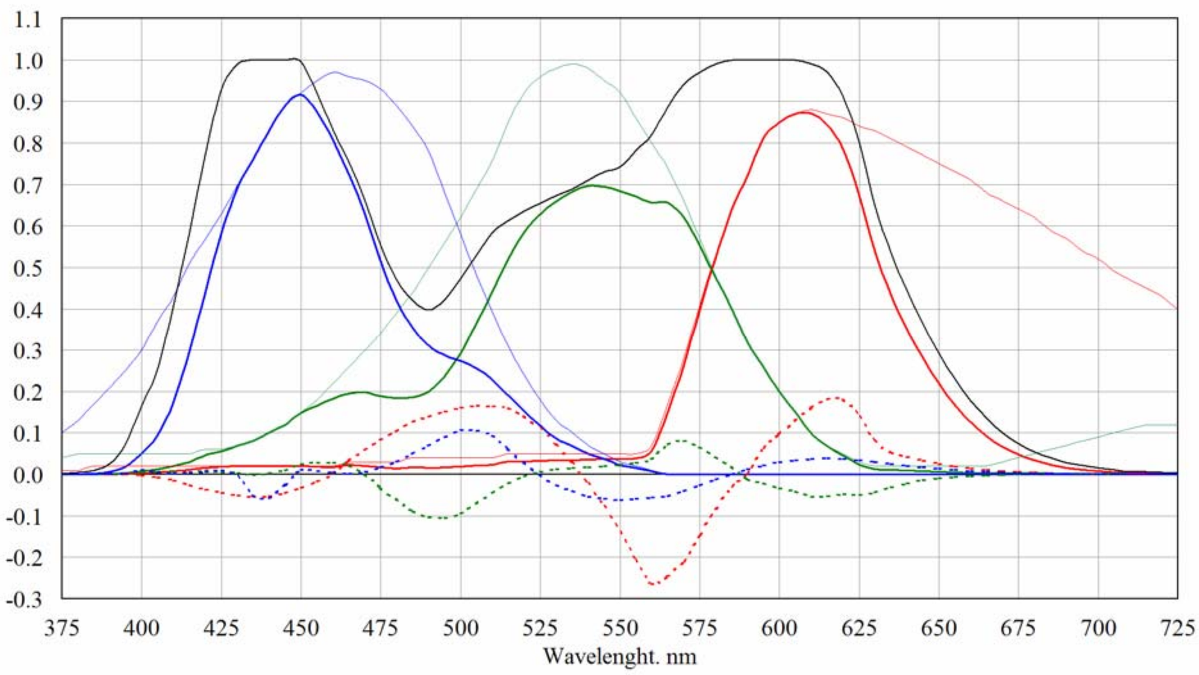

Fig.4. DSSs of a typical CCD sensor + a compound filter (bold solid colored lines). Thin lines represent the original DSSs. The filter spectral sensitivity is depicted in black. Residual components are displayed with dotted lines.

But, as it might be seen from the Table 2, even with the theoretically best compound filter, the sensor average deviation is far beyond the 5º accuracy. The main cause of the accuracy problem is an inappropriate choice of the red detector.

Until the short-wave boundary of the red DSS is not shifted to the left with the sensitivity peak at 570 - 590nm, the sensor cannot claim correct color capturing, whatever filters used. In other words, the DSS curve should look similar to a corresponding CF.

6. NEW DETECTOR TYPE

Foveon designs a sensor of a new type. Curves of its DSSs with an original filter have an unusual shape (Fig.5), and, at the first glance, good color capturing might not be expected from this sensor. And indeed, its DSSs have a large deviation from FCS (Tab.3), with MRS value somewhere in the middle of accuracy provided by a typical CCD with UV&IR filter and without it.

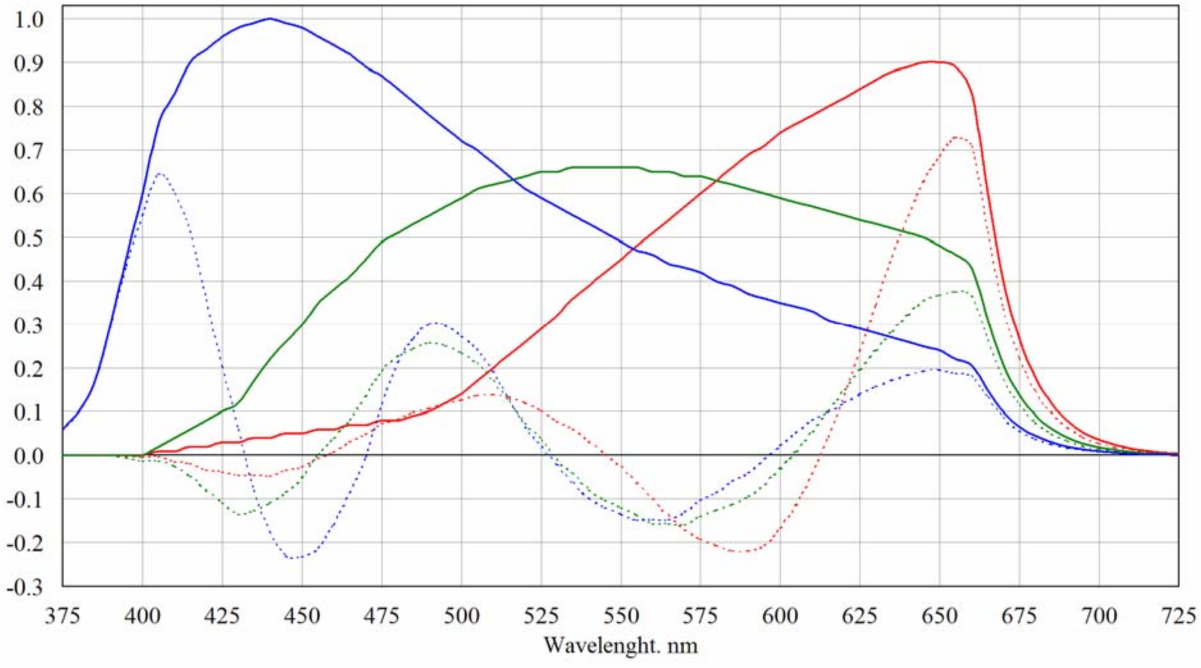

Fig.5. DSSs of a Foveon sensor with an original filter (bold solid lines). Residual components are displayed with dotted lines.

However, as it was demonstrated by Lyon and Hubel /5/, with a proper compound filter, such as depicted by a violet line in Fig.6, situation remarkably changes. Filter optimization based on suggested in this paper criterion gives a slightly different curve (Fig.6. black line), but similar overall effect: filter characteristics significantly improves. Spectral sensitivities of the sensor with criterion-based filter along with corresponding residual components are depicted in Fig.7 and corresponding deviation angles presented in Table 3.

Table 3. Angles between Foveon sensor DSSs and FCS, defined with 10º CIE standard.

Foveon	*r*	*g*	*b*	MRS
Sensor with original filter	30.0º	20.2º	21.3º	24.2º
Sensor with original filter + Criterion-based filter	2.3º	5.3º	2.6º	3.7º

Obtained deviation angles are less than 5º, so, according to introduced criteria, use of lens filters with spectral characteristics similar to those depicted in Fig.6 accompanied by an appropriate changes in software, may lift a digital camera with Foveon's sensor (for example, Sigma-9) into a class of accurate color capturing devices.

Difference between criterion-based filter and Lyon and Hubel calculations may be due to several reasons. The main reason is that Foveon filter data used here was derived from graphs presented in the paper /4/, and this method always coupled with about several per cent error insertion. But light variation in filter shape does not affect the main verdict: a digital camera for accurate color capturing can be produced now.

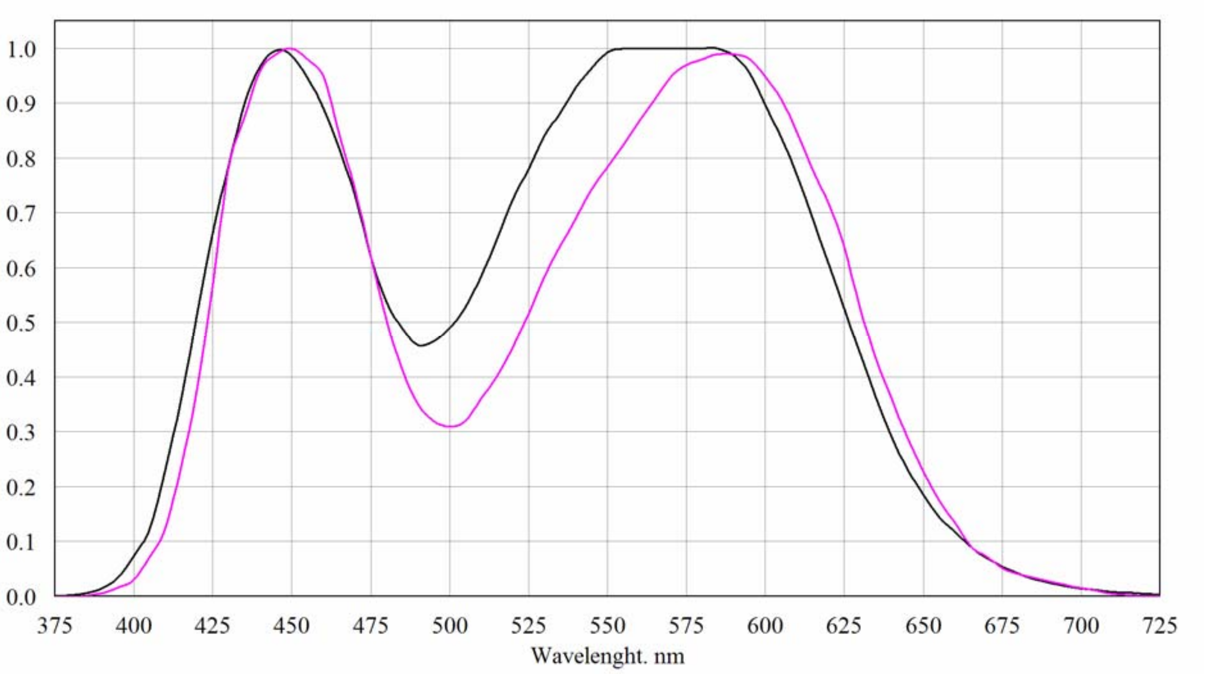

Fig.6. Compound filters for Foveon sensor. Black line represents the criterion-based filter. Violet line corresponds to Lyon and Hubel filter/4/.

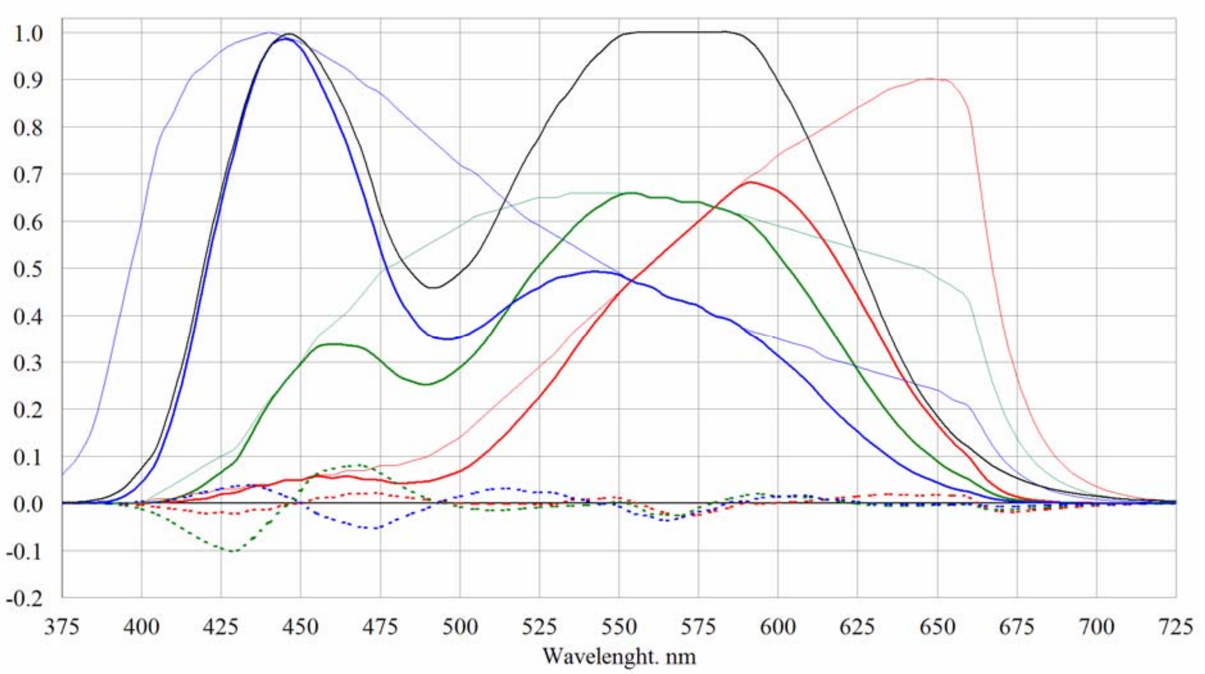

Fig.7. DSSs of a Foveon sensor with criterion-based filter (bold solid lines). Black line represents the criterion-based filter. Thin lines represent the DSSs with the original filter. Residual components are displayed with dotted lines.

7. SENSORS WITH MORE, THAN THREE DIFFERENT DETECTORS

Try to improve color capturing quality brings to the market cameras with more, than three different detectors (for example, Sony 828). However, as it was already mentioned, increased number of detectors did not help a camera to become an accurate color-capturing device.

Introduced in this paper sensor quality criterion does not work for a more than three-detector set, because the Luther-Ives condition is a sufficient, but not a necessary requirement for correct color capturing in this case. For these systems a necessary and sufficient condition for an accurate color capturing is less strong: **DSSs span must include FCS as a subspace**. Therefore, in this case, non-compliance with the Luther-Ives condition is not a proof of sensor unfitness for accurate color capturing. Description of a color capturing accuracy criterion for a more than three-detector sensor is beyond this paper.

8. CONCLUSION.

The paper demonstrates an accuracy limit of the Basic Colorimetry Concept for design and construction a device intended for correct color capturing. Presented in the paper quality criterion based on Luther-Ives condition may become a useful tool in light detector manufacturing. Evaluation of sensor color capturing accuracy is made according to the value of deviation angle between detector sensor sensitivity and Cohen’s Fundamental Color Space. Suggested method may be used for color filter optimization in order to reach the highest color capturing accuracy available for a particular device. All necessary formulas are provided.

Use of the criterion is illustrated with two types of a light sensor and demonstrated, that, within the limit of accuracy provided by present-day Colorimetry, sensors designed by Foveon with an appropriate filters may be used in an accurate color-capturing system. So, a moment when a digital camera providing correct colors enters the market is not so far.

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