P108- Improving the accuracy of colorimeters for display measurements applications

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ABSTRACT

Measuring color precisely requires the use of a colorimeter whose spectral response is as close as possible to the CIE response. Some techniques such as the NIST 4-color method can improve the precision, but under given conditions, the results can be worse.

1. Introduction

A colorimeter is an apparatus, which measures the color of a stimulus. Color is defined as a combination of three primary colors: Red, Green and Blue. The proportion of each of them gives the so-called *tristimulus values:* X for Red, Y for Green and Z for Blue.

In order to calculate the proportion of Red, Green and Blue of a stimulus, this one is analyzed through 3 theoretical color filters whose spectral response is given by the CIE 1931 Standard Colorimetric System [1] (see fig.1).

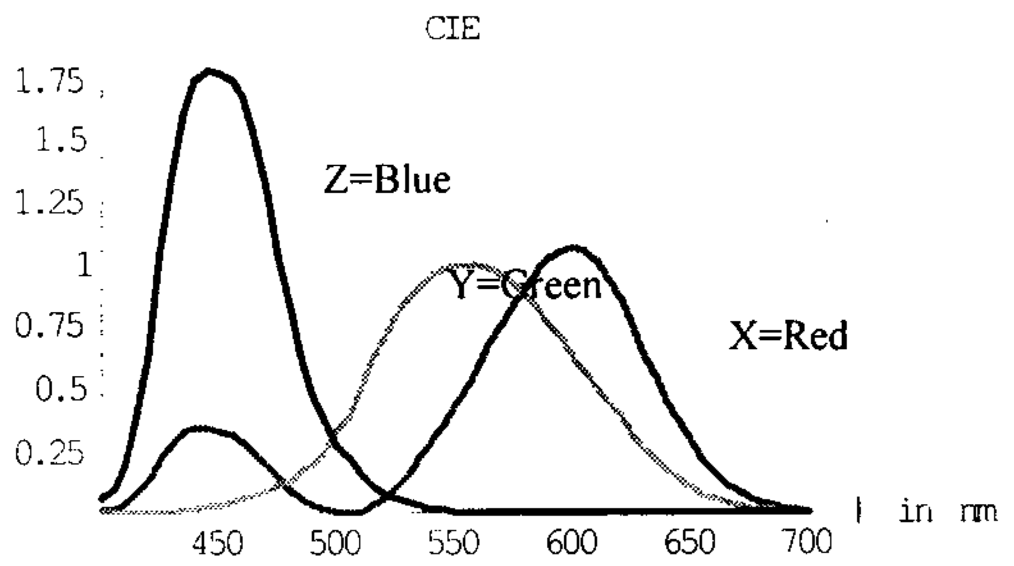


Figure 1: color matching functions

However, manufacturing those filters induces a shift from the theoretical CIE curves. These variations can imply huge errors in the chromaticity measurement.

Some companies have then developed colorimeters with more than 3 filters to improve the fit of the CIE curves as it will be discussed in §3.

A new representation of colorimeters efficiency is introduced in the paper to quantify these errors. Three different colorimeters are compared after different calibration techniques.

2. Definitions

x(λ), y(λ), z(λ) are the spectral response of the Red, Green and Blue.

- **tristimulus values : X Y Z**

P(λ) is the spectral response of the stimulus. The tristimulus values are given as below (K is a constant):

$$X = K \int P(\lambda)x(\lambda)d\lambda$$

$$Y = K \int P(\lambda)y(\lambda)d\lambda$$: it is the luminance value

$$Z = K \int P(\lambda)z(\lambda)d\lambda$$

- **chromaticity values**

(x,y) and (u',v') systems are defined as below :

$$\begin{cases} x = \dfrac{X}{X+Y+Z} \\ y = \dfrac{Y}{X+Y+Z} \end{cases} \qquad \begin{cases} u' = \dfrac{9X}{X+15Y+3Z} \\ v' = \dfrac{4Y}{X+15Y+3Z} \end{cases}$$

- **spectrum locus**

The spectrum locus is the curve of the monochromatic values. It can be evaluated in the (x,y) or in the (u',v') system (see fig.2). Any color is inside that curve.

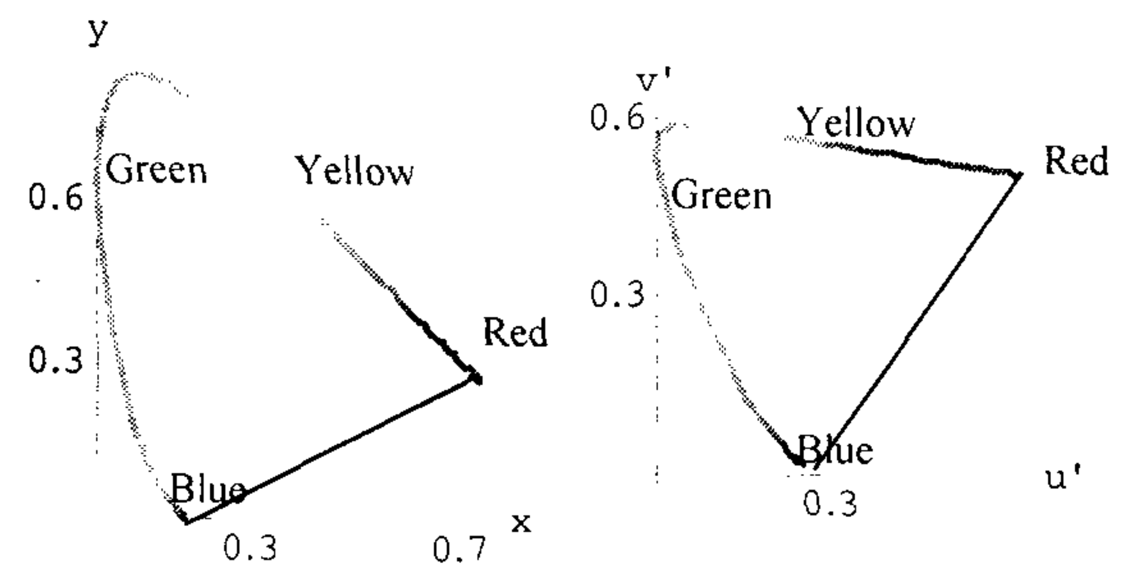


Figure 2: spectrum locus

❖ **color difference**

(u',v') system is used to evaluate the color difference between the theoretical (given by the CIE 1976) and the measured chromaticity values (given by the colorimeter).

$$\Delta E = \sqrt{(u'CIE - u')^2 + (v'CIE - v')^2}$$

We can also define statistics for □E, evaluated on the monochromatic curve.

$$\Delta E_{RMS} = \sum_{\lambda=400nm}^{700nm} \sqrt{(u'CIE_\lambda - u'_\lambda)^2 + (v'CIE_\lambda - v'_\lambda)^2}$$

$\Delta E_{\max} = Max(\Delta E_\lambda)$ for λ between 400nm and 700nm.

3. How many filters

As it can be seen on Figure 1, the X response is composed of two "peaks", one in the "red part" (XCIEr) and one in the "blue part" (XCIEb) (fig.3).

When manufacturing colorimeters, at least four filters are needed (One for the Y signal, one for the Z signal and two for the X signal) due to the fact that it is not physically feasible to accurately manufacture a filter with two peaks in the visible light bandwidth.

ELDIM uses 5 filters: one for the XCIEr, one for XCIEb, one for ZCIE and two for Y to have the best precision for luminance measurement.

In order to decrease the costs, some manufacturers have noticed that the "blue-part" of the X curve is not so far from the Z curve. Based on this, they are using the Z filter and combining it with the X filter in order to approximate the normalized XCIE curve. This saves the cost of the $XCIE_b$ filter.

X is then curve is a linear combination of $XCIE_r$ and ZCIE: X=a $XCIE_r$ + b ZCIE Y=YCIE Z=ZCIE.

The combination has been computed so as minimize ΔE_{RMS} (see §2). The response of the "3filters_best" colorimeter is shown fig3. The curves are not so far from the CIE curves except close to 500nm where X does not become null.

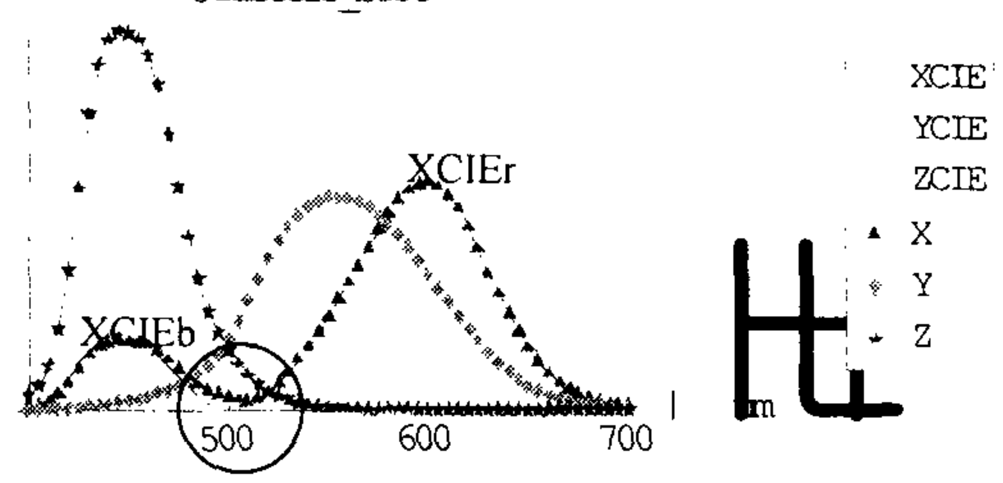


Figure 3: best colorimeter with 3 filters

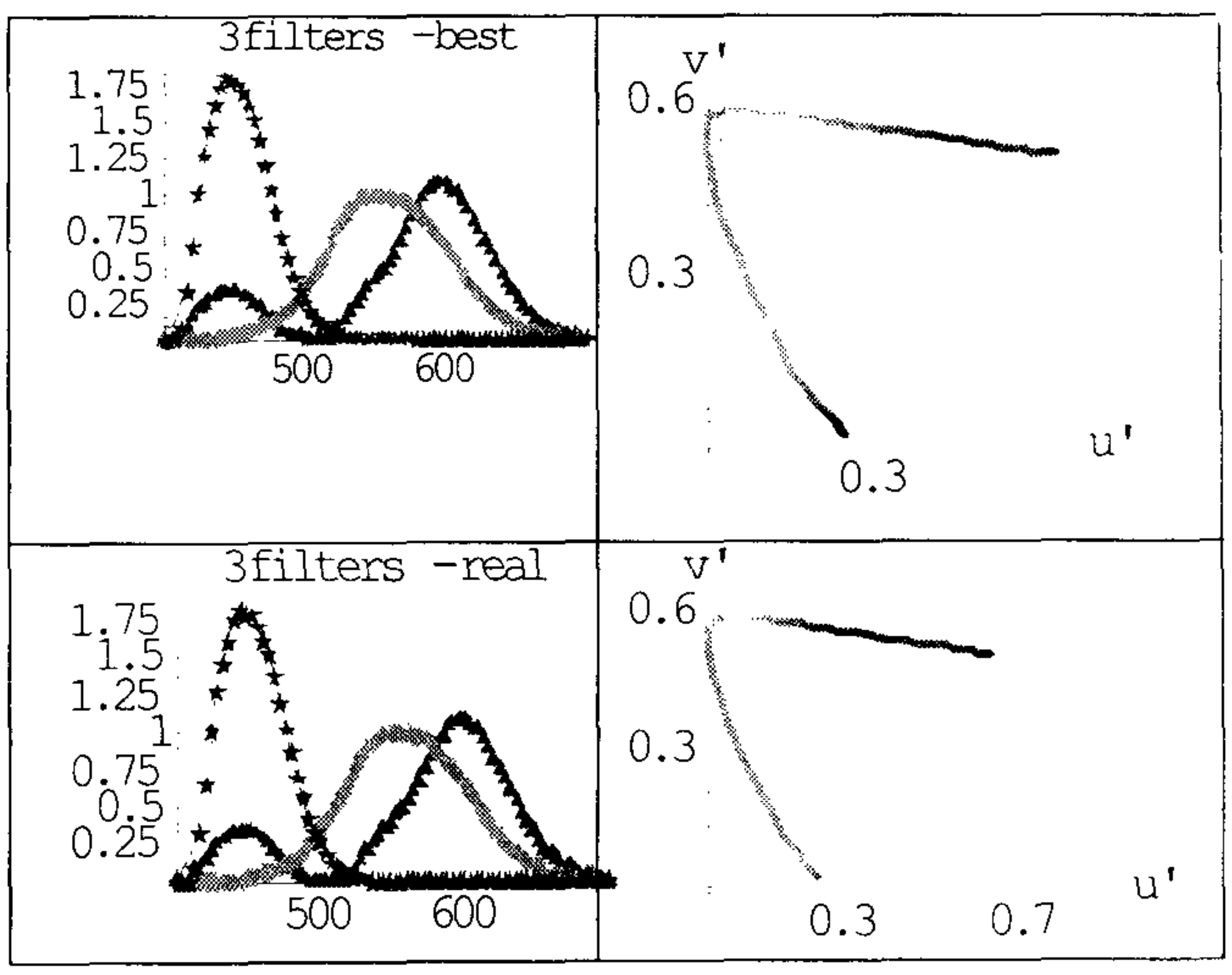
4. Representation of a colorimeter

We considered three different colorimeters:

- ❖ A typical 3 filters response curve "3filters_real"[2]
- ❖ The best theoretical 3 filters "3filters_best"(see §3)
- ❖ And a typical 5 filters "5filters_real" (ELDIM).

Comparing their spectral response to the CIE curves is not sufficient to show and quantify their efficiency.

Comparison is more relevant when looking at the spectrum locus representation (see fig.4).



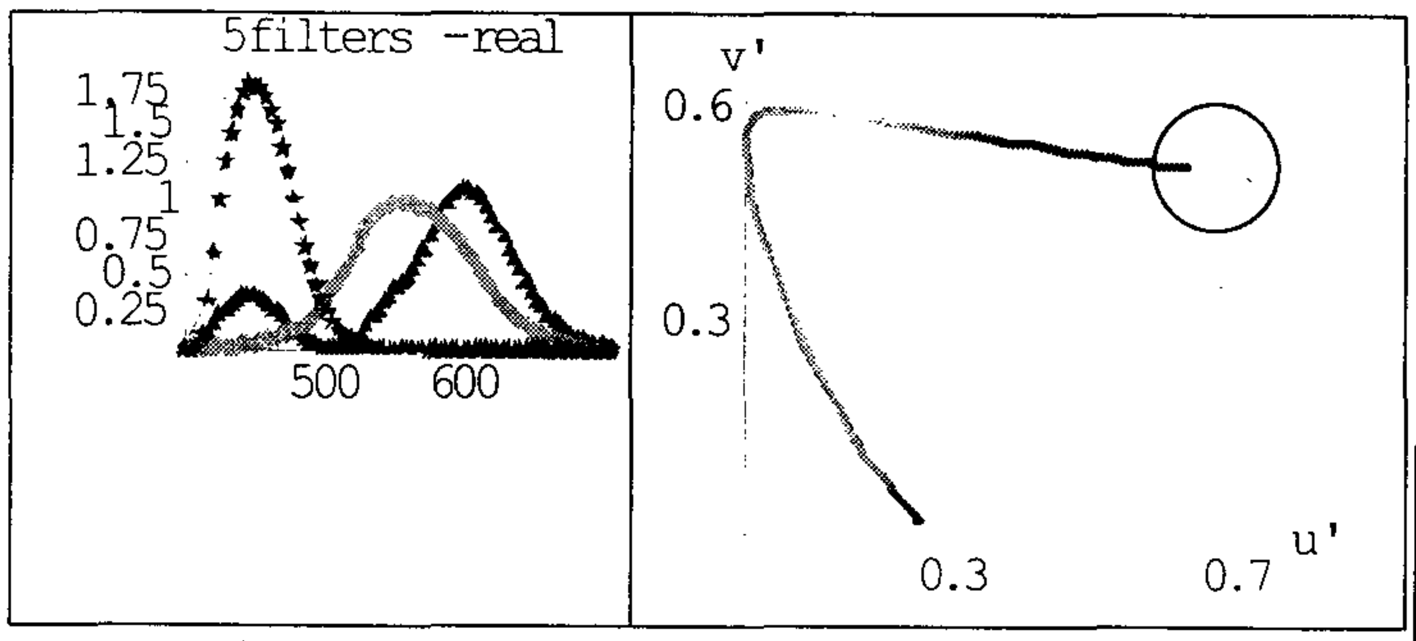


Figure 4: comparison between three colorimeters

In that system, ΔE_{max} is the maximum error (ask for more information for the demonstration) and ΔE_{RMS} is the accuracy of the colorimeter.

ΔE	3filters_best	3filters_real	5filters_real
ΔE_{RMS}	0.0093	0.0469	0.0223
ΔE_{Max}	0.052	0.244	0.105

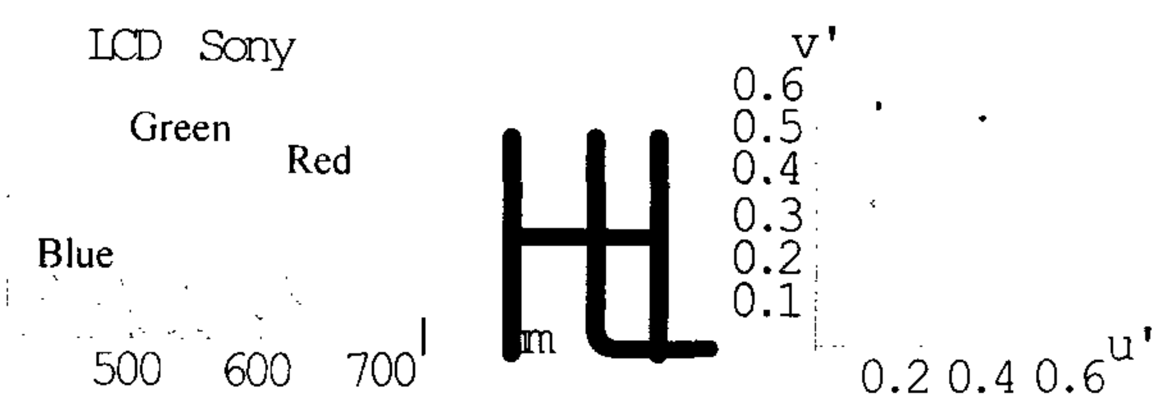
The graphic representation of color difference (see fig4.) shows clearly the errors due to the choice of colorimeter. A 5filter colorimeter is much better that a 3filter one. However, it is not as good as the "3filter-best" because of the red part of the curve (see fig.4). Indeed, the theoretical colorimeter has been chosen perfect in the red part.

5. Colorimeters after calibration: four-color matrix method

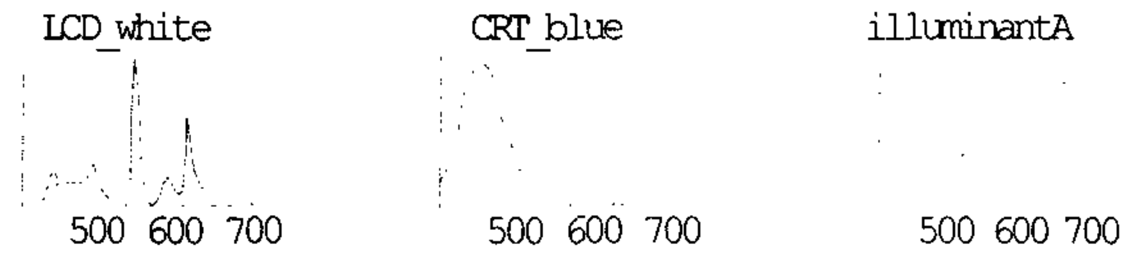
NIST has developed a new method to fit the CIE curves (See [4] and [5]), based on the use of a 3 illuminants (primary colors of a display) for calibration.

Three examples are given to see the efficiency of the method as well as its limitations:

The display for the calibration is a Sony LCD, whose spectral response is shown below :



Then 3 different stimulus are analysed :



The errors are evaluated for three colorimeters before and after the NIST calibration:

	ΔE	3filters_best	3filters_real	5filters_real
White LCD	No calib	0.004	0.012	0.0013
	NIST calib	2e-5	2e-5	8e-6
Blue of a CRT	No calib	0.099	0.0079	0.0022
	NIST calib	0.006	0.0066	0.0014
A	No calib	0.0031	0.011	0.0013
	NIST calib	0.0035	0.015	0.0023

NIST 4 color matrix is far from solving the issues of colorimetry. A White LCD measurement is almost perfect for each colorimeter but the illuminant A measurement is worse.

Another way to be convinced is to look at the spectrum locus. For instance, the response of the "3filters-real"colorimeter to monochromatic stimuli stays far from the CIE (fig.5).

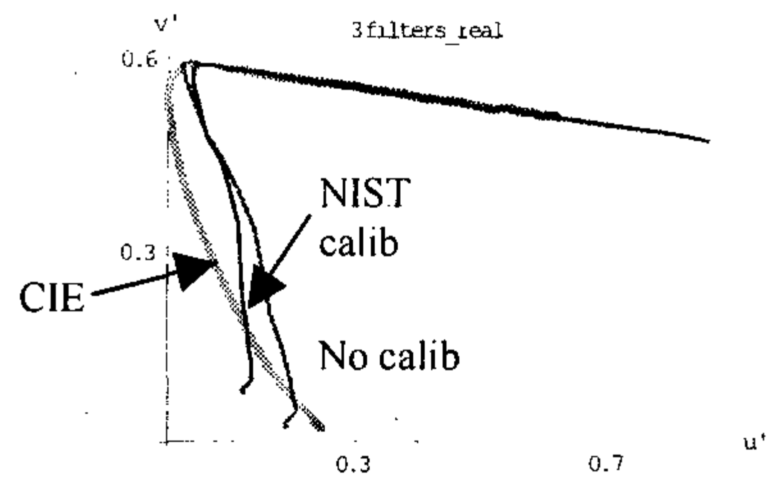


Figure5: spectrum locus for 3 filters-real

ΔE_{RMS}	3 filters_best	3filters_real	5filters_real
Without calib	0.0093	0.0469	0.0223
NIST calib	0.0093	0.0586	0.0176

ΔE_{MAX}	3 filters_best	3filters_real	5filters_real
Without calib	0.052	0.244	0.105
NIST calib	0.040	0.231	0.079

Finally it is not always possible to correct the color difference only by using the 4-color matrix method. The method works correctly only when the stimulus studied is not far from the illuminant used for calibration.

6. Calibration with 5 illuminants

NIST color method currently advises to calibrate with three illuminants. Using five illuminants could allow a much better calibration especially for the five filters colorimeters.

These illuminants must be chosen close to the spectrum locus to have the largest gamut.

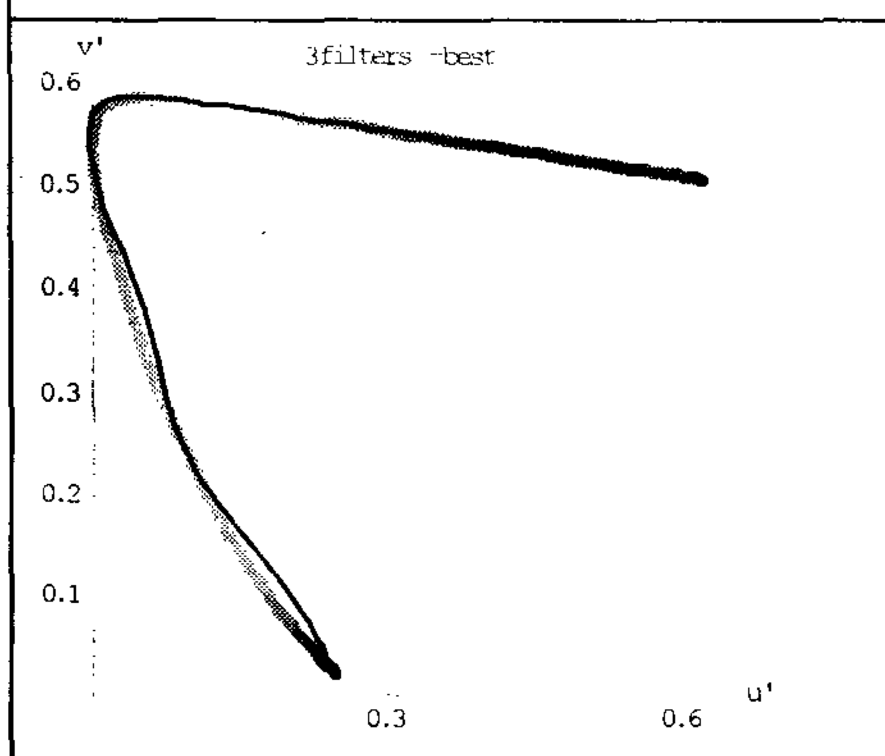
❖ Example

We use 5 monochromatic illuminants chosen at 430nm, 480nm, 530nm, 600nm and 650 nm to have the largest area.

The colorimeters are more accurate with 5 calibrating illuminants based on the NIST 4 color method (fig. 6).

"5filters-real" colorimeter accuracy has decreased by a factor 4 whereas "3filters-real"one has not been improved and stays poor. A first result is that it is important to be close to the CIE curves before any computation.

"5filters-real" colorimeter looks better than the "3filters-best". However, ΔE_{RMS} indicates than the RMS error of the "5filters-real" (0.00589) is superior to the RMS error of the "3filters-best" (0.0054) (see ΔE in fig.8). That non-visible error comes from the red part representation (see §7).

<table>
<tr><td></td><td></td><td>ΔE_{RMS}</td></tr>
<tr><td rowspan="3">
</td><td>Without</td><td>0.0093</td></tr>
<tr><td>NIST</td><td>0.0093</td></tr>
<tr><td>5 illumin</td><td>0.0054</td></tr>
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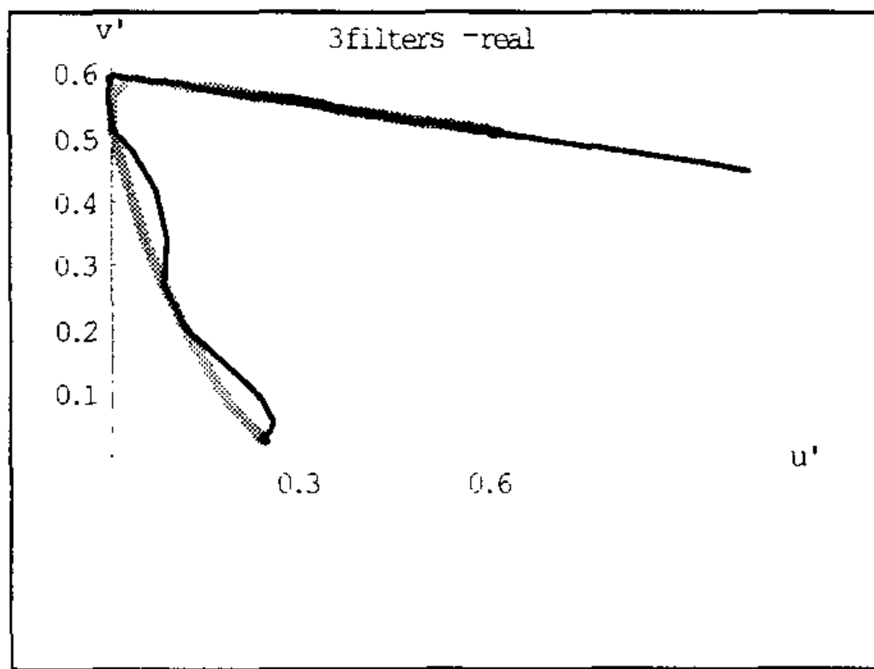
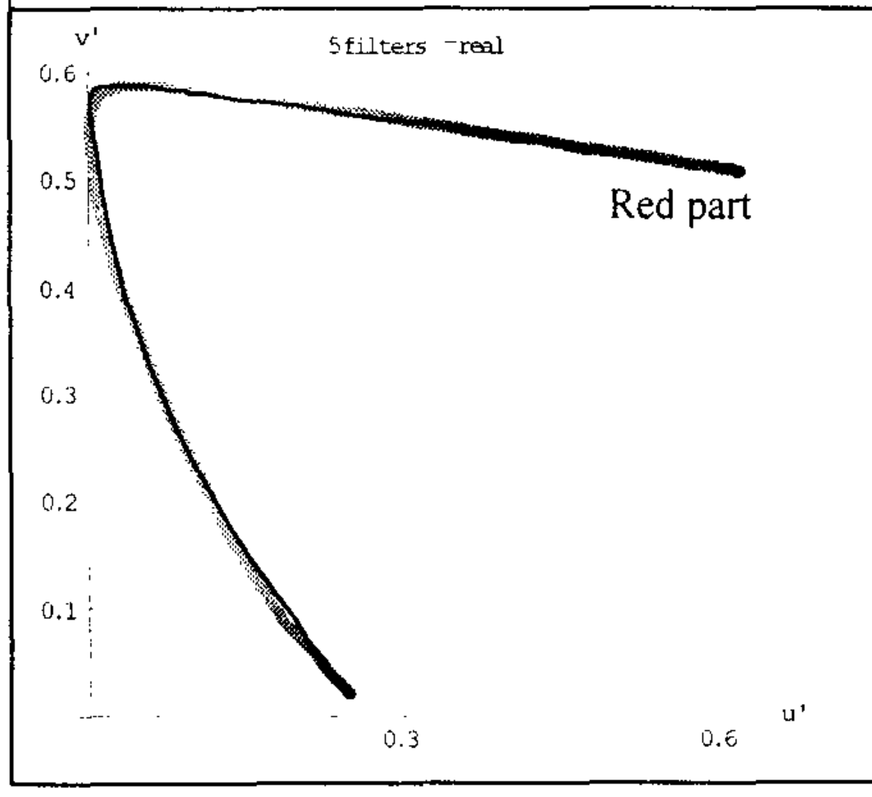
<tr><td rowspan="3">
</td><td>Without</td><td>0.0469</td></tr>
<tr><td>NIST</td><td>0.0586</td></tr>
<tr><td>5 illumin</td><td>0.0399</td></tr>
<tr><td rowspan="3">
</td><td>Without</td><td>0.0223</td></tr>
<tr><td>NIST</td><td>0.0176</td></tr>
<tr><td>5 illuminan</td><td>0.00589</td></tr>
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Figure 6: different calibration methods

7. New representation in the red part

In the red part (λ>580nm),

$z(\lambda)<0.001x(\lambda)$ and $z(\lambda)<0.001y(\lambda)$

So Z<<X,Y

$$u'=\frac{9X}{X+15Y+3Z}\approx\frac{9X}{X+15Y}$$

$$v'=\frac{4Y}{X+15Y+3Z}\approx\frac{4Y}{X+15Y}$$

$$\text{so } v'=\frac{4}{15}-\frac{4}{135}u'$$

Consequently, **v' is a linear function of u'**.

Supposing A_{th} is the theoretical value of the illuminant A and A_m is the measured value. Then A_{th} and A_m are on the same line. So CIE spectrum locus and the colorimeter spectrum locus are superposed.

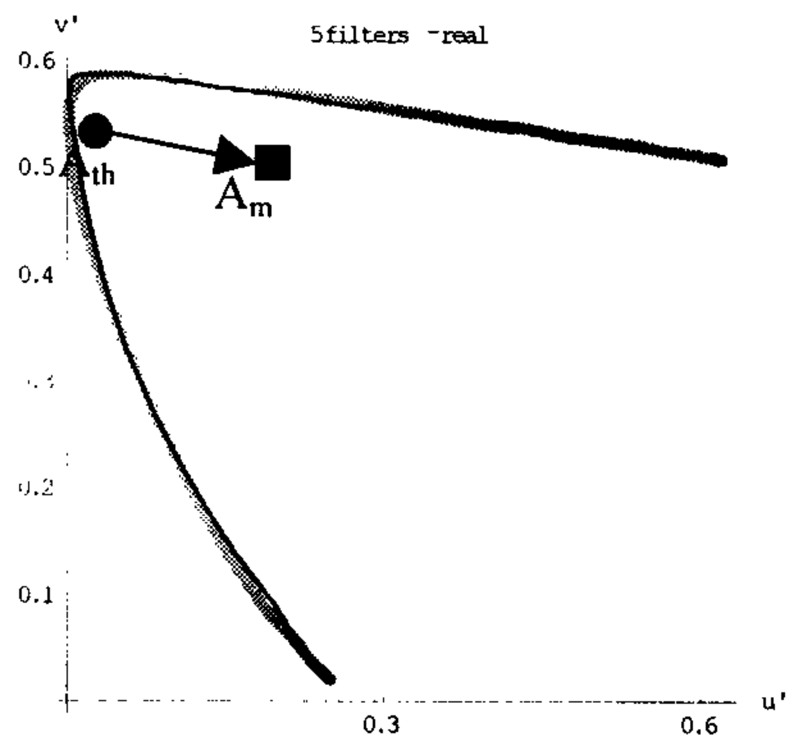

Figure 7: linearity in the red part of the locus

8. Conclusion

A very simple and robust representation has been introduced to compare different colorimeters.

Most of the colorimeters using 3 filters may suffer from weak precision, even with sophisticated techniques of calibration.

The colorimeters of ELDIM Company are all based on 5 filters, what guarantees a high precision in the measurement. Moreover, calibration techniques using five or more illuminants become much more efficient and the result reaches a precision of $\Delta E<0.005$ in all the gamut.

9. References

[1] Color Science: Second Edition (*Gunter Wyszecki*) p725-733

[2] Four Color Matrix Method for correction of tristimulus colorimeters (*Yoshi Ohno and Jonathan E Hardis*)
Fifth Color Imaging Conference 1997 and 1998

[3] Flat Panel Display Technology 22-23 January 2001San Jose, USA SPIE

p: 176: Digital imaging colorimeter for fast measurement of chromaticity coordinate and luminance uniformity of displays.