Color Measurement with MCS3 and MCSi
via calibration and coefficient matrix

Three band passes provide the filter functions of JenColour sensors MCS3 and MCSi (see Figure 1) — one for the red, one for the green and one for the blue spectral range. These sensors are uniquely suited to identify colors by way of teaching and, hence, to detect coarse differences in the color of individual samples (see also MAZeT data sheets for these color sensors).

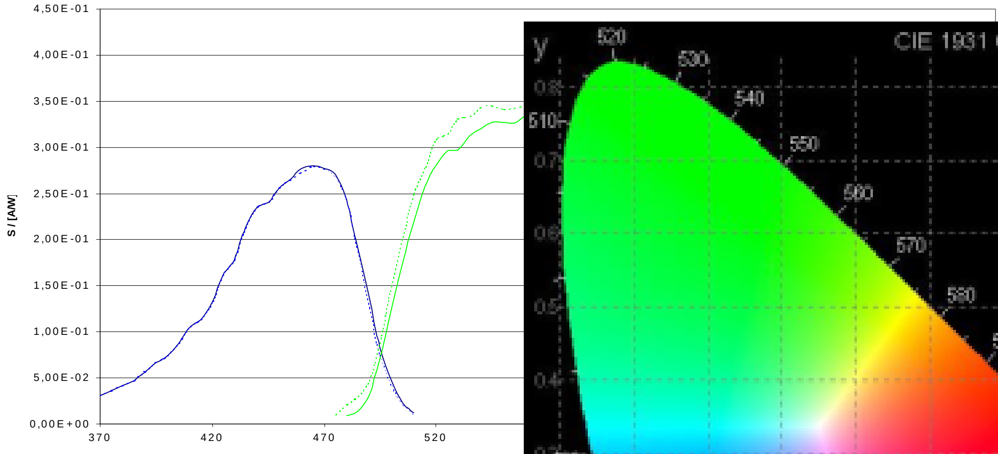

Figure 1: Spectral sensitivity o

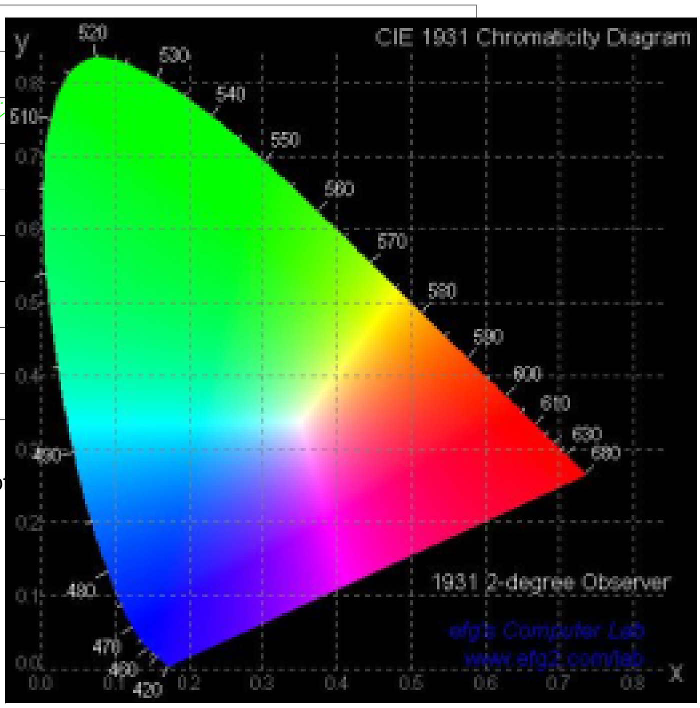

Figure 2: CIE-Yxy Color space

In addition, JenColour sensors may also be applied to simple color measurement. If this is done by equating the standardized measured RGB values with the standard spectral values XYZ for color position calculation as shown in CIE-Yxy (see Figure 2), major deviations from the actual standard color positions are initially obtained. These deviations are due firstly to the fact that the color sensors' spectral sensitivity is not exactly matched to that of the standard distribution function and secondly, sensor manufacturing inherently includes certain tolerances in terms of filter offset and location.

These tolerances can be mutually matched and a good approximation to a color-space-true reproduction quality achieved by a simple target-addressed calibration transforming the measured values in a linear relationship. The appropriate correction matrix is determined by comparing the measured (RGB) values to the colorimetric nominal standard spectral values (XYZ) of selected targets (see Fig. 3).

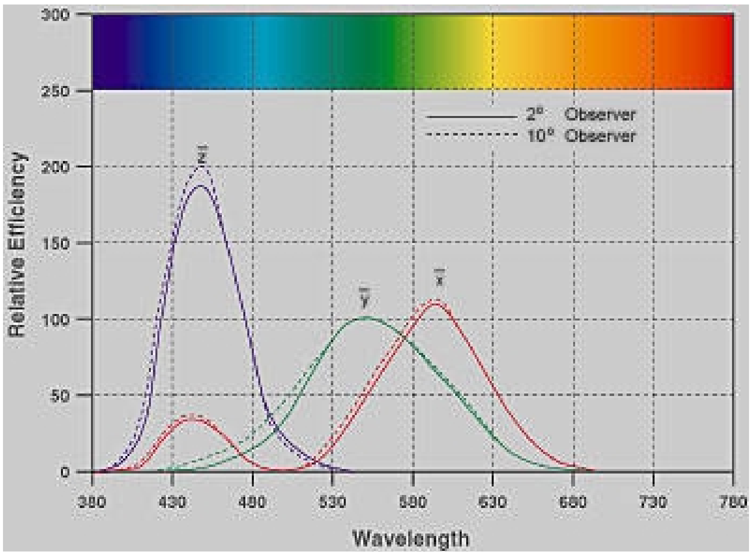

Figure 3: Standard spectral curves 2° (10°) Observer

DIN-compatible color sets or so-called color checkers can be used as nominal master target colors. These target sets contain suitably defined support points in their color space and are available with XYZ and Yxy nominal color values (see Figure 4 – example of ColorChecker® from GretacMacbeth© for D65 illumination according to DIN5033) for standardized light sources.

		CIE (1931)		
No.	*Name*	*x*	*y*	*Y*
1	dark skin	.400	.350	10,1
2	light skin	.377	.345	35,8
3	blue sky	.247	.251	19,3
4	foliage	.337	.422	13,3
5	blue flower	.265	.240	24,3
6	bluish green	.261	.343	43,1
7	orange	.506	.407	30,1
8	purplish blue	.211	.175	12,0
9	moderate red	.453	.306	19,8
10	purple	.285	.202	6,6
11	yellow green	.380	.489	44,3
12	orange yellow	.473	.438	43,1
13	blue	.187	.129	6,1
14	green	.305	.478	23,4
15	red	.539	.313	12,0
16	yellow green	.448	.470	59,1
17	magenta	.364	.233	19,8
18	cyan	.196	.252	19,8
19	white	.310	.316	90,0
20	neutral 8	.310	.316	59,1
21	neutral 6.5	.310	.316	36,2
22	neutral 5	.310	.316	19,8
23	neutral 3.5	.310	.316	9,0
24	black	.310	.316	3,1

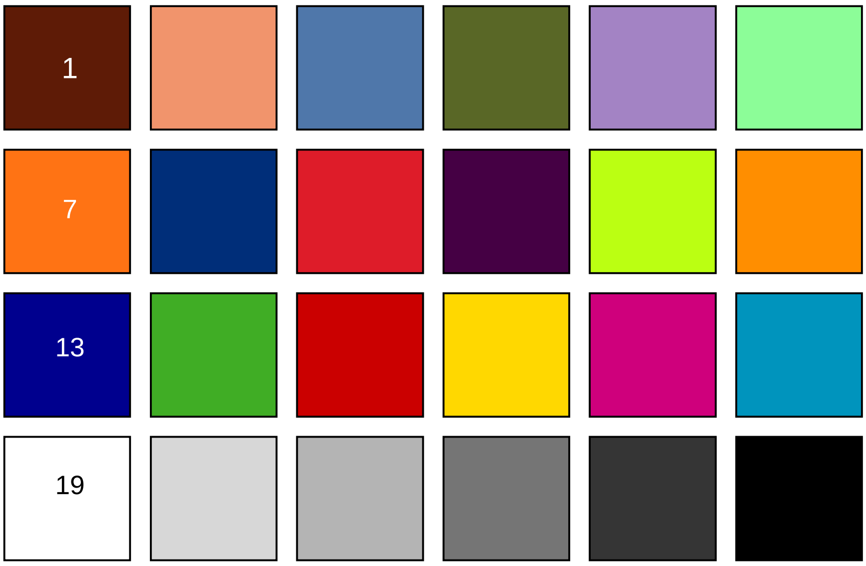

Figure 4: Colors of the GretagMacbeth© ColorChecker®
(see also http://www.edmundoptics.com/IOD/DisplayProduct.cfm?productid=1815)

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A matrix of coefficients[1] A is determined by recording the values that have been measured for the colors to be balanced (RGB $matrix_{Ist}$) and performing a subsequent matrix operation, based on the standard color values (XZ $matrix_{Soll}$).

Equation 1, matrixing

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Equation 2; determination of matrix of coefficients

$$A = (Matrix_{Soll} \cdot Matrix_{Ist}^{T}) \cdot (Matrix_{Ist} \cdot Matrix_{Ist}^{T})^{-1}$$

Once a matrix of coefficients has been established[2], any measured RGB value can be transformed into an XYZ standard value (see Equation 1,). Using the transformation equations specified by DIN5033, they can then be transferred to any desired color space. When recording the actual color values, one should make sure that measurement is performed with the same illumination (e.g. D 65) that was selected to fabricate the standard color values of the color masters. It should also be considered that the MCS3 and MCSi color sensors are suitable for measurement of not highly saturated colors. Consequently, they provide excellent results for many types of naturally radiant or reflecting surfaces. For a color space thus restricted in its saturation, an accuracy of $\Delta E < 3..5$ (delta E[3]) can be achieved.

JenColour sensors (plus calibration) provide a compact low-cost alternative especially where colors have to be measured with an accuracy that is on a level with human vision. In some cases, they allow completely new technical approaches that have not been possible with such diversity or only possible in spectral terms (e.g. for the assessment of light colors and radiant surfaces). As a vital prerequisite therefore, the sensors must have been calibrated to the specific application or system. The target-referred method described herein represents a simple application for automated production processes with performance specs that can easily be integrated into a host system. With µC-based sensors, nothing more than simple software adjustments and integration of a calibration step in sensor manufacturing or prior to sensor operation are typically required. JenColour sensors include high-grade color filters that are thermally stable and develop no aging effects. A re-calibration is thus only required in the event of changes to the system environment.

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[1] This approach assumes a global sensor calibration using a coefficient matrix and linear transformation from $\underline{F}_{korr} = \underline{A} * \underline{F}_{ist}$.
[2] See also Appendix
[3] For comparison, the human eye perceives Color differences starting from a level of $\Delta E = 3$

"Calibrate" Function on the MCS-EB1 Evaluation Board

To demonstrate a targeted calibration of JenColour sensors, the application software of the MCS-EB1 evaluation board (Version 1.10) has been extended by the two functions *Calibrate* and *Yxy* (see Tools) and ColorChecker® and GretacMacbeth© have been used as demonstration samples.
All restrictions and advisory notes which are contained in this paper must be taken into account for interpretation of the results of these two functions.

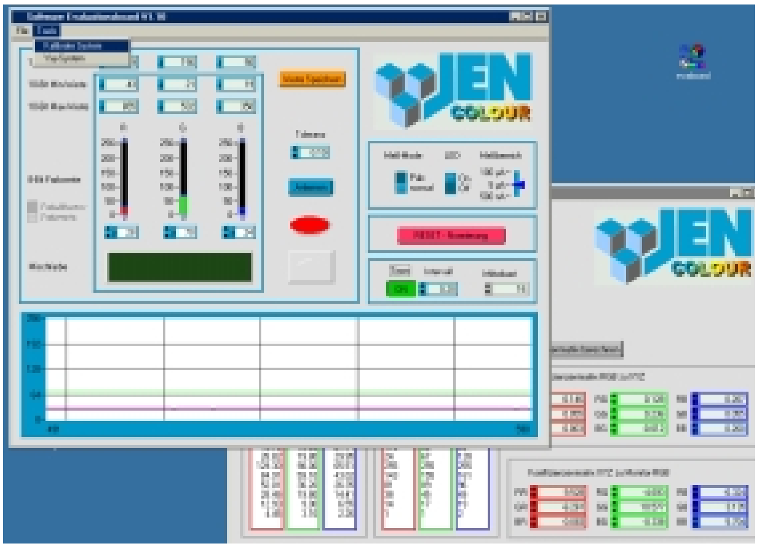


Figure 4 – Selection of "Calibrate"

For example, the Yxy values of the ColorChecker® according to CIE 1931 and DIN 5033 refer to a D65 illuminator, while the evaluation system relies on white light LEDs (type NSPW 500 BS from Nichia).

As a consequence, the resulting absolute values show some variation although they have been calibrated to this standard. This means that the Yxy values are only approximately reached when measured after calibration. Furthermore, certain adverse influences caused by ambient light, thermal effects, sensor-position-induced variances and rotation of the optical axis have to be considered.

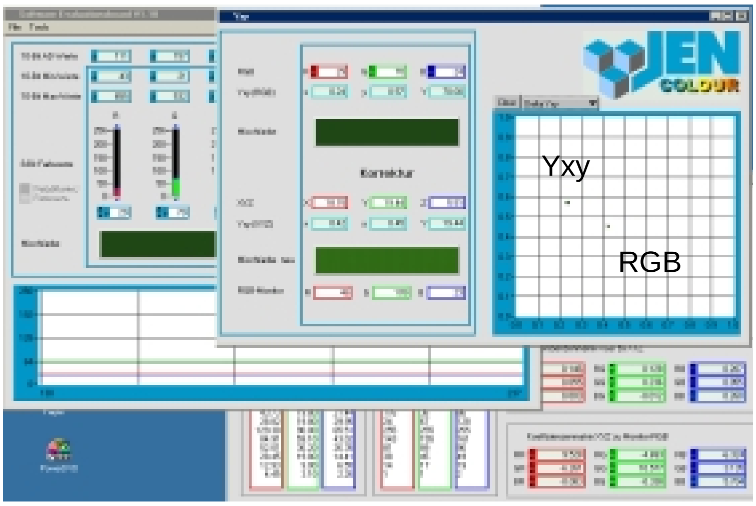
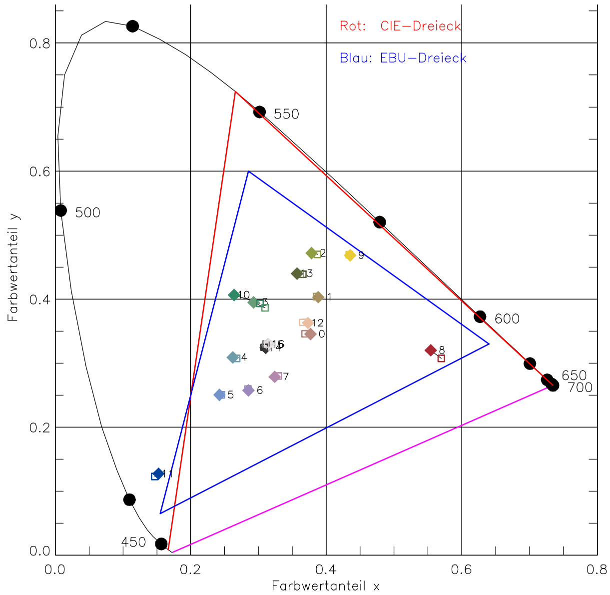


Figure 5: Result of GREEN target - sample as an RGB / Yxy signal

After "Calibrate" has been selected in the Tools menu, previously measured values can be used for the ColorChecker® or be re-determined in manual mode. Once the respective correction matrixes have been calculated, the Yxy display function can be selected to represent the resulting RGB signal (non-calibrated) or the Yxy signal (calibrated) and/or the differential amount between the two in the color space on the screen. One should however make sure that the timer is on and the sensor in a position above the sample to be measured. A direct comparison between a nominal (ColorChecker®) and an actual color on the screen reveals differences in color. In addition to the reasons described above or to possible changes in the environment, this may also be due to a certain variance in the color representation of display screens and panels.

APPENDIX 1

Results measured with correction, with white LED and DIN test colors



Index	Nominal (SOLL)			Actual (IST)			Color difference	Color Nominal / Actual
	X	*Y*	*Z*	*X*	*Y*	*Z*		
0	32,75	30,01	24,15	31,28	29,38	24,22	3,20	
1	28,17	29,25	15,14	27,78	29,11	15,18	1,08	
2	24,75	30,86	9,80	25,77	31,30	9,54	3,11	
3	21,44	28,91	22,86	23,83	29,70	23,39	7,97	
4	25,78	30,41	42,21	26,78	30,74	42,51	2,91	
5	28,15	29,08	58,90	28,61	29,24	58,90	1,20	
6	32,24	29,08	51,67	31,75	29,01	50,96	1,63	
7	35,78	30,79	43,93	36,68	31,22	43,58	1,82	
8	17,83	10,30	4,04	21,32	11,50	4,58	9,05	
9	55,92	60,17	12,40	55,53	60,06	12,35	0,71	
10	12,55	19,32	15,65	15,68	20,40	15,81	14,46	
11	7,28	6,08	34,40	7,06	5,91	35,14	1,76	
12	59,30	57,63	41,98	57,04	56,75	42,25	3,61	
13	9,64	11,88	5,49	10,05	12,07	5,39	2,20	
14	3,45	3,60	4,06	3,40	3,58	4,05	0,51	
15	18,93	19,83	21,55	18,61	19,73	21,46	1,13	
16	72,82	76,13	82,24	72,09	75,87	82,10	1,04	

Table : color pattern (DIN), linear correction without offset

White light LED - middle of color distance in CIE-L*a*b*-space: $\Delta E = 3$

APPENDIX 2

Matrixation (coefficients) used to perform calibrated measurement with MCS3 and MCSi JenColor sensors

Nominal ("Soll") designates the matrix of XYZ values for a known set of target Colors (in the given example "ColorChecker from GretagMacbeth" - see application paper "Color Measurement With MCS3 and MCSi Sensors" with known standard Color values.

The Color values provide a defined basis for determining a matrix of coefficients with subsequent linear correction of the measured values.

Actual ("Ist") is the matrix of sensor values that were measured for RGB, referenced to the same Color and gray value targets.

$$\text{Soll} := \begin{bmatrix} 33 & 27.81 & 23.9 & 20.43 & 24.99 & 28 & 33.32 & 37.61 & 20.57 & 54.89 & 12.13 & 6.23 & 58.88 & 9.33 & 3.42 & 18.73 & 72.02 \\ 29.79 & 29.03 & 30.4 & 29.48 & 30.84 & 29.76 & 29.37 & 31.32 & 11.23 & 58.99 & 20.37 & 6.43 & 57.1 & 11.7 & 3.6 & 19.81 & 76.11 \\ 24.52 & 14.91 & 9.9 & 21.26 & 40.38 & 56.85 & 53.2 & 45.4 & 4.34 & 11.97 & 15.33 & 27.58 & 41.31 & 5.39 & 4.06 & 21.5 & 80.93 \end{bmatrix}$$

$$\text{Ist} := \begin{bmatrix} 23.15 & 19.86 & 18.42 & 17.83 & 20.98 & 23.71 & 25.89 & 29.3 & 17.18 & 38.55 & 12.51 & 6.95 & 41.6 & 7.44 & 2.59 & 14.04 & 54.27 \\ 26.06 & 26.08 & 28.61 & 28.58 & 29.56 & 28.49 & 27.05 & 28.5 & 9.67 & 52.9 & 20.69 & 6.61 & 50.65 & 11.14 & 3.31 & 18.19 & 69.9 \\ 15.39 & 9.93 & 7.29 & 13.88 & 24.34 & 33.16 & 30.71 & 26.51 & 3.8 & 10.12 & 10.04 & 16.54 & 26.14 & 3.77 & 2.45 & 12.89 & 48.27 \end{bmatrix}$$

The formula to calculate and determine a 3 x 3 coefficients matrix ("Koeffizientenmatrix") is obtained as follows:

$$\text{Koeffizientenmatrix} := \left(\text{Soll}\cdot\text{Ist}^T\right)\cdot\left(\text{Ist}\cdot\text{Ist}^T\right)^{-1}$$

Where "Matrix T" means a transposed and "Matrix --1" an inverted version of a matrix:

$$\text{Koeffizientenmatrix} = \begin{bmatrix} 1.508 & -0.036 & -0.18 \\ 0.212 & 0.973 & -0.081 \\ -0.042 & -0.091 & 1.832 \end{bmatrix}$$

This matrix is now used to transform all measured RGB values as follows:

For an RGB value of 10; 30; 25, the following XYZ is obtained: $R := 10$ $G := 30$ $B := 25$

$$X := R\cdot\text{Koeffizientenmatrix}_{0,0} + G\cdot\text{Koeffizientenmatrix}_{0,1} + B\cdot\text{Koeffizientenmatrix}_{0,2} \qquad X = 9.501$$

$$Y := R\cdot\text{Koeffizientenmatrix}_{1,0} + G\cdot\text{Koeffizientenmatrix}_{1,1} + B\cdot\text{Koeffizientenmatrix}_{1,2} \qquad Y = 29.272$$

$$Z := R\cdot\text{Koeffizientenmatrix}_{2,0} + G\cdot\text{Koeffizientenmatrix}_{2,1} + B\cdot\text{Koeffizientenmatrix}_{2,2} \qquad Z = 42.645$$

or as a matrix operation
respectively

$$\text{RGB} := \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad \text{RGB} = \begin{bmatrix} 10 \\ 30 \\ 25 \end{bmatrix} \qquad \text{XYZ} := \text{KoeffizientenmatrixRGB} \qquad \text{XYZ} = \begin{bmatrix} 9.501 \\ 29.272 \\ 42.645 \end{bmatrix}$$