Assessment of the Colorimetric Behaviour of Different Spectrophotometers

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Abstract

Colour reproduction is based on the ability to communicate colour information accurately. The different instrument manufacturers, models and conditions result in difficult colour communication due to the loose or inexistent inter-instrumental agreement between them.

With this study we have tried to develop an application to correct colour instruments by software by applying multi-dimensional polynomial transformations between pairs of instruments. This application will filter one spectrophotometer measurement, and apply a correcting factor to emulate the colorimetric response of any other spectrophotometer.

Keywords

Colorimetry, Spectrophotometer, measurement.

1. Introduction:

This study is part of a two year project whose aim is to develop an application able to do software-driven instrument correction. This application will filter one spectrophotometer measurement, and apply a correcting factor to emulate the colorimetric response of any other spectrophotometer.

There is different instrument correction software in the market such as the X-Rite Net Profiler, but this has the problem that it only can be used in X-Rite Instruments. By developing this application we want to make instrument correction as universal a possible by using as many different instruments as possible.

With this application we will be able of improve the accuracy of colour measurement devices and this way help colour communication in all the industries that measure colour.

During this project we have studied the differences between the spectrophotometers and collected colorimetric data to evaluate the main differences in their behaviour, characterize the colorimetric response of these instruments and developed mathematical algorithms to emulate the response of a spectrophotometer in any other colour measurement instrument.

These algorithms perform mathematical transformations between various colour data (mainly type-CIE L * a * b *) from the different spectrophotometers in order to get a numeric dictionary to improve inter-instrument matching of Colorimetric data.

2. Methods:

This research is divided in two parts:

Part one: Analysis of the behaviour of the different instruments.

We have selected seven spectrophotometers and nine ceramic plates as target and measured them every week during a year. We have chosen 45º/0º or 0º/45º geometry spectrophotometers, made by different manufacturers, of different models, conditions, etc…

Then we have determined the deviation in the measurement of the different instruments.

The information compiled was used for the calculation of the deviation in the measurement of the different spectrophotometers for every ceramic tile; the average values obtained were used as standard values to compare the behaviour of the different spectrophotometers.

-Measurement of the different areas of the visible spectrum.

In this part of the study we have widened the areas of the spectrum to be studied, so instead of the 9 patches, we have printed two colour-charts with 513 and 619 patches respectively. We expected to represent the whole space of reproducible colour and receive sufficient information to characterize the instruments' colorimetric response in all the areas.

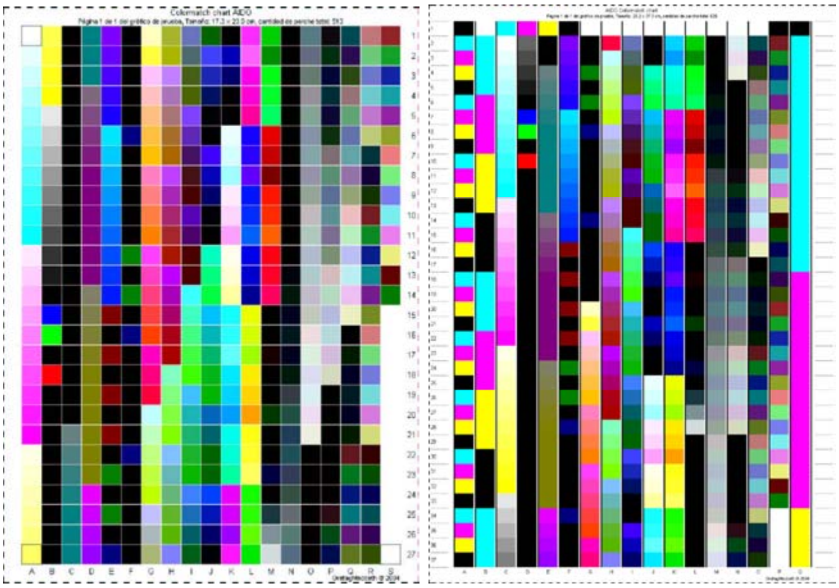


Figure 1. Colour charts used.

We printed four copies of the same colour chart, measured every patch of the four copies with each instrument, and calculated the average measure for every patch and instrument in order to minimize the possible effects that paper and small printing flaws could have on the measurement.

To analyze the difference between the spectrophotometers, we did measurements on the four copies with all the instruments, calculated the average of all the measurements for every patch, and chose this measurement as the standard value for each patch.

This standard value was compared with the mean value of the instruments for every patch to obtain more accurate information about the instruments' behaviour in the different zones of the visible spectrum.

We studied the different measurements of the spectrophotometers and compared them with the values taken as reference. We calculated the average and the standard deviation of the differences, (in ΔE*, Absolute, best 90 % and worst 10 %), as well as the maximum value of ΔE*, (for the Absolute and for the best 90 %).

Part Two: Development of the mathematical algorithms.

From the colorimetric database (CIE-L*, a*, b*) obtained from the comprehensive set of samples obtained in part one, multi-dimensional polynomial transformations between pairs of instruments have been performed.

The same database has been used as training dataset, and the efficiency of the polynomial transformations (statistical colour differences) has been tested with a verification set from this database.

To find the mathematical function, an application called "ColorMatch" has been designed in Matlab software. To carry out this work, the measurements made in the different colour charts have been used as a training dataset, this allows us to assess the differences between instruments and determine the correction factor to adjust the data to a reference spectrophotometer.

The application allows us to select the database associated with the reference and the test instrument; the test instrument is the one you want to obtain the correction factor.

To obtain the correction factor, an adjustment method that doesn't need more information than that obtained in the previous series of measurements (training set) is used.

To emulate the reference instrument with the test instrument, the colour data obtained with the test instrument was adjusted to the colour values obtained with the reference instrument (Kang, 1997). This model attempts to find the mathematical function that best fit these training colours.

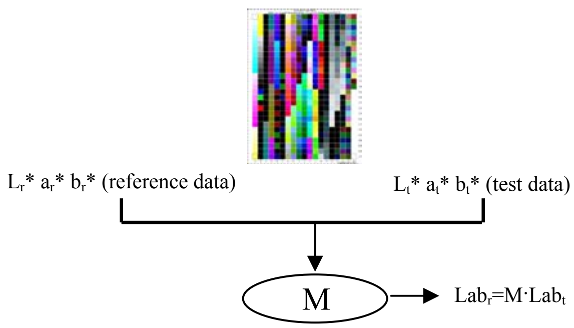


Figure 2 Steps followed in this process.

To perform this transformation is assumed that as L * a * b * fit as a polynomial-type function dependent of the colorimetric data associated with the reference instrument as in "*Figure 3"*.

$$
\begin{aligned}
L_r^* = f(L_t^*, a_t^*, b_t^*) = & m_{11} + m_{12}L_t^* + m_{13}a_t^* + m_{14}b_t^* + \\
& + m_{15}L_t^*a_t^* + m_{16}L_t^*b_t^* + m_{17}a_t^*b_t^* + \\
& + m_{18}L_t^{*2} + m_{19}a_t^{*2} + m_{110}b_t^{*2} + \\
& + m_{111}L_t^{*2}a_t^* + m_{112}L_t^{*2}b_t^* + m_{113}a_t^{*2}L_t^* + m_{114}a_t^{*2}b_t^* + m_{115}b_t^{*2}L_t^* + m_{116}b_t^{*2}a_t^* + \\
& + m_{117}L_t^*a_t^*b_t^* + mt_{118}L_t^{*3} + m_{119}a_t^{*3} + m_{120}b_t^{*3}
\end{aligned}
$$

$$
\begin{aligned}
a_r^* = g(L_t^*, a_t^*, b_t^*) = & m_{21} + m_{22}L_t^* + m_{23}a_t^* + m_{24}b_t^* + \\
& + m_{25}L_t^*a_t^* + m_{26}L_t^*b_t^* + m_{27}a_t^*b_t^* + \\
& + m_{28}L_t^{*2} + m_{29}a_t^{*2} + m_{210}b_t^{*2} + \\
& + m_{211}L_t^{*2}a_t^* + m_{212}L_t^{*2}b_t^* + m_{213}a_t^{*2}L_t^* + m_{214}a_t^{*2}b_t^* + m_{215}b_t^{*2}L_t^* + m_{216}b_t^{*2}a_t^* + \\
& + m_{217}L_t^*a_t^*b_t^* + m_{218}L_t^{*3} + m_{219}a_t^{*3} + m_{220}b_t^{*3}
\end{aligned}
$$

$$
\begin{aligned}
b_r^* = h(L_t^*, a_t^*, b_t^*) = & m_{31} + m_{32}L_t^* + m_{33}a_t^* + m_{34}b_t^* + \\
& + m_{35}L_t^*a_t^* + m_{36}L_t^*b_t^* + m_{37}a_t^*b_t^* + \\
& + m_{38}L_t^{*2} + m_{39}a_t^{*2} + m_{310}b_t^{*2} + \\
& + m_{311}L_t^{*2}a_t^* + m_{312}L_t^{*2}b_t^* + m_{313}a_t^{*2}L_t^* + m_{314}a_t^{*2}b_t^* + m_{315}b_t^{*2}L_t^* + m_{316}b_t^{*2}a_t^* + \\
& + m_{317}L_t^*a_t^*b_t^* + m_{318}L_t^{*3} + m_{319}a_t^{*3} + m_{320}b_t^{*3}
\end{aligned}
$$

Figure 3 polynomial function used to emulate the reference instrument

These equations can be written in matrix form as shown in "*Figure 4"*:

$$
\begin{bmatrix} L'^* \\ a'^* \\ b'^* \end{bmatrix} = \left[m_{ij}\right]_{3x20} \cdot \begin{bmatrix} 1 \\ L_t^* \\ a_t^* \\ b_t^* \\ L_t^*a_t^* \\ \ldots \\ b_t^{*3} \end{bmatrix}_{20x1}
$$

Figure 4

Where "M" matrix is the coefficient matrix we want to calculate.

The “M” matrix could be calculated by obtaining the pseudoinverse matrix because it is not a square matrix and the inverse matrix cannot be obtained directly. But in this study we have used a minimization routine from Matlab software called "lsqlin. This routine solves problems by using a linear least squares adjustment with constraints. Although in this case, we do not work with any restriction.

3. Results:

Part one:

-Results of the measurements made in the ceramic tiles.

We have obtained two different sets of results, the measurements made in the nine ceramic tiles and the ones in the colour charts.

The measurement made to the ceramic tiles are presented in tables that include the average values of L*, a*, b* for each instrument obtained in the nine tiles of the following colours; White, Black, Red, Blue, Green, Yellow, Cyan, Gray and Pink.

In each table are presented the L*, a*, b* values for each instrument, the difference of all the L*, a*, b* values expressed as ΔE*, the mean ΔE*, and the average L*, a* and b* obtained.

The ΔE* values for each instrument have a colour code that indicates if this value is:

Acceptable: Green; ΔE* <1
Average: Yellow; 1 <ΔE* <1.5
Unacceptable: Red; ΔE*> 1.5

In addition, the instrument that gives a higher ΔE* value is highlighted in red; this is used to know if there is one that always gives different results from the others.

The following table is an example of the results obtained when a tile is measured with the different instruments.

Table 1

	White Tile			
	L*	**a***	**b***	**ΔE***
DAE0009-964	95,91	-0,12	3,15	0,24
DAE0024-530	95,83	-0,06	3,01	0,17
DAE0026-530	95,51	-0,14	3,03	0,41
PE0049-Espectrolino	95,88	-0,21	2,67	0,26
PE0089-530	96,14	0,02	3,19	0,41
DAE0019-i1	96,15	-0,42	2,63	0,45
DAE0042-i1	95,89	-0,36	2,78	0,23
Mean	**95,90**	**-0,19**	**2,92**	**0,31**
Standard deviation	**0,22**	**0,16**	**0,23**	**0,11**

-Results of the measurements made in the colour charts.

To analyze the different areas of the visible spectrum a representation of all the measured patches was made. The ones with the higher deviation were highlighted in yellow. This allows us to quickly visualize if there is any area in which the instrument is behaving in a different way from the others, or if the differences are present throughout the entire spectrum.

In the results we have included the average and the standard deviation of the differences, (in ΔE*, Absolute, best 90 % and worst 10 %), as well as the maximum value of ΔE*, (for the Absolute and for the best 90 %).

Here is an example of the results obtained. In this case we haven't found big differences between the instruments' behaviour and the average behaviour, and there isn't any spectral area that gives different values.

Table 2: ΔE results of instrument "DAE0009".*

	Mean	Standard Deviation	Maximum
Total	0.46	0.16	1.26
Best 90%	0.42	0.12	0.64
Worst 10%	0.77	0.15	

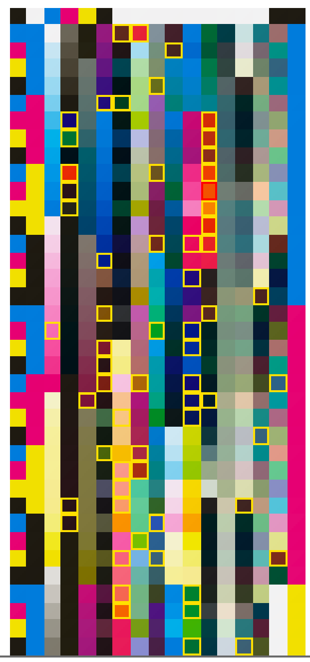


Figure 5: Representation of the results of the instrument "DAE0009".

"Figure 5" is a Graphic representation of the differences found in the measurements made in the colour chart with the instrument "DAE0009".

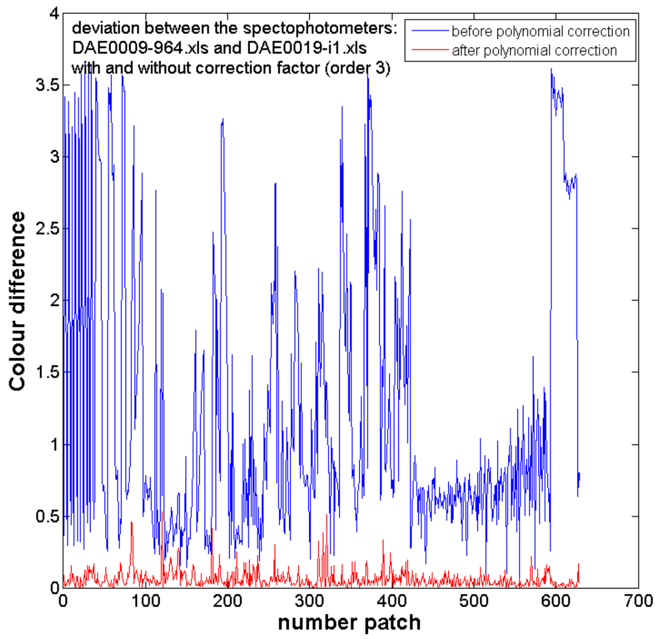
Part Two:

The “M” Matrix obtained to emulate the instrument “DAE0009” with the instrument “DAE0019” is shown in *“Table 3”*:

“Table 3”

	-4.9e-03	9.8e-01	8.1e-03	7.2e-03	4.3e-04	-1.1e+09	-7.6e+09	8.2e+09	-1.7e+09	-5.4e+09	
	2.9e-02	7.7e-03	1.0e+14	-1.2e-02	6.5e+09	-3.6e-04	-4.4e+09	-9.3e+08	6.6e-04	2.3e-04	…
	-4.8e-01	4.9e-02	1.9e-02	1.0e+14	-1.0e-03	3.2e-04	-2.6e-04	-1.9e+09	-2.6e-04	-1.7e-04	
M=		-2.4e+08	4.2e+07	7.3e+07	-1.3e+08	5.0e+06	1.5e+07	1.3e+07	1.8e+07	-9.3e+06	-3.1e+06
	…	-1.1e+08	4.4e+08	1.5e+08	-1.5e+07	-7.3e+08	-2.0e+08	-6.1e+07	-1.1e+08	-1.5e+08	-1.1e+08
		6.5e+08	-3.3e+08	1.2e+08	1.3e+08	4.0e+08	1.2e+08	5.2e+07	-1.4e+08	6.3e+07	3.0e+07

Once the “M” matrix is calculated, its adequacy (or performance) is evaluated by calculating the colour difference in ΔE_{ab} between the predicted colour after applying the correction factor, and the colour reference value. This difference is then compared with the initially calculated colour difference between the data and the colour reference value. Some of the results can be seen in *“Figure 6”*.



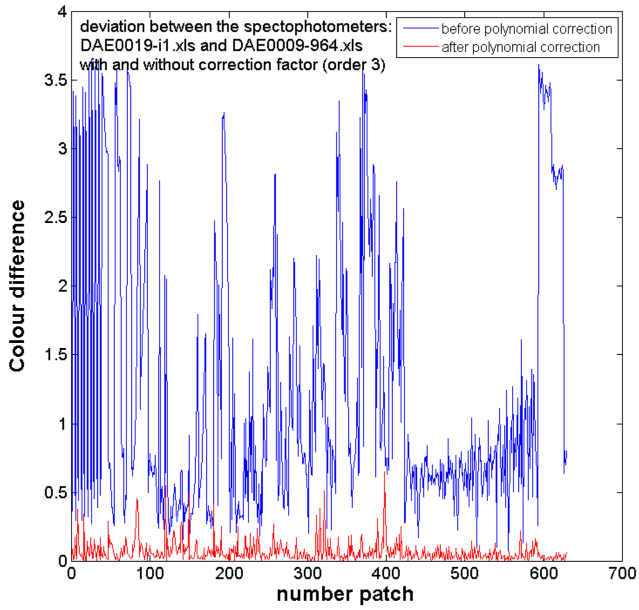
“Figure 6”

As an example, in *“Table 4”* we also present the results considering the two instruments of *“Table 3”*, but reversing the roles. In other words we have changed which acts as reference instrument and which acts as a test instrument.

It’s easy to see that a new “M” matrix obtained now coincides with the inverse matrix of the first “M” matrix, as expected.

“Table 4”

	1.8e-02	1.0e+14	-8.0e-03	-6.3e-03	-3.7e-04	1.0e+09	5.3e+09	-7.4e+09	1.9e+09	7.7e+09	
	-2.4e-02	-8.2e-03	9.9e-01	1.2e-02	-5.4e+09	3.7e-04	5.1e+09	2.4e+09	-6.6e-04	-2.3e-04	…
	4.5e-01	-4.5e-02	-1.8e-02	9.8e-01	9.3e-04	-3.3e-04	4.9e-04	-6.1e+08	3.0e-04	1.0e-04	
M=		2.0e+08	-3.7e+07	-5.1e+07	1.2e+08	-6.4e+06	-5.9e+07	-1.2e+07	-2.6e+07	7.1e+06	2.0e+06
	…	1.0e+08	-4.5e+08	-1.6e+08	1.5e+06	7.4e+08	1.8e+08	5.6e+07	9.7e+07	1.2e+08	1.2e+08
		-5.9e+08	3.5e+08	-3.4e+08	-7.3e+07	-4.9e+08	2.7e+07	-6.1e+07	1.2e+08	-8.3e+06	-1.1e+08



"Figure 6"

4. Conclusions:

Part One:

After analyzing the results we reach some conclusions:

- We have found differences of more than 2ΔE* between instruments when we measured the ceramic tiles.

- We haven't found any instrument that behaves in an especially different way from others, not depending of the spectrophotometer brand, model or condition. Nevertheless almost all of them in at least one tile have shown differences with the reference values of more than 1.5 ΔE*.

- After completing more than 20,000 measurements of the different colour patches covering almost the entire visible spectrum with eight very different spectrophotometers, we can conclude that we have enough data to characterize these instruments.

- We have found differences above 5ΔE*, which is over the tolerance specified in different colour standards. Differences like this make colour communication impossible.

- Nearly all the instruments show differences in specific areas of the visible spectrum, which may indicate differences in the manufacture of these instruments.

- After analyzing the results we can conclude that this is a correct way to assess the behaviour of the different instruments.

- We have found much bigger differences when comparing the measurements made with the colour charts than the ones found in the measurements done on the nine tiles which indicate that the standard 12 BCRA tiles are insufficient to evaluate how the spectrophotometers perform.

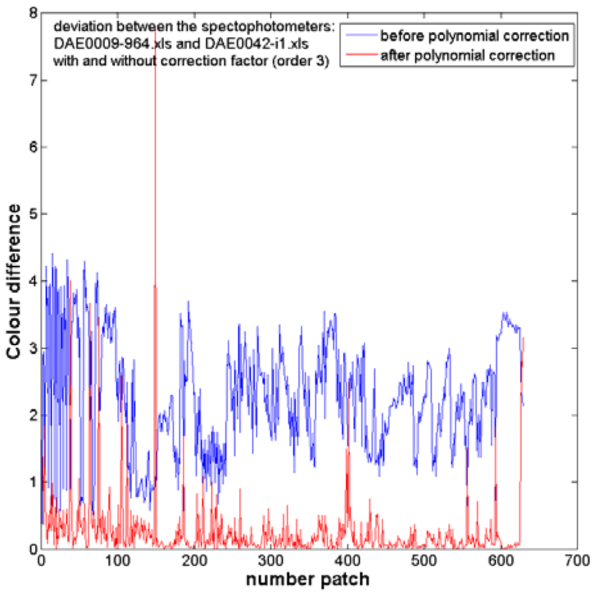
- Instruments of the same make and model behave in a different way, so we need to monitor these instruments and try to emulate them.

- Following the results obtained in the reproducibility study of the different instruments, and the differences found between them, it is necessary to obtain a mathematical function that performs the appropriate correction on the measurements made by the different colour measurement devices in order to obtain colorimetric data corrected and adjusted to a reference spectrophotometer.

Part Two:

The results obtained after applying the correction factor based on an order three polynomial adjustment are satisfactory and suggest that it can be used throughout the entire visible spectrum, as can be seen by the fact that the obtained difference in colour after the application of the polynomial adjustment in the whole training set is under the established tolerances $\Delta E_{ab}<1$.

But the used algorithm doesn't work so well for all instruments. In particular, when we tried to emulate the behaviour of the Gretag Magbeth "i1" (DAE0042) with the "X-Rite 964" (DAE0009), the results weren't entirely satisfactory as can be seen in *"Figure 7"*.



"Figure 7"

Some samples of the data set presented a not acceptable colour difference, even higher than before the correction factor was applied. This not occurred in a lot of patches, so it doesn't seem a problem related with the way the correction factors were calculated.

Therefore we cannot conclude that it is necessary to apply different correction factors depending on the colour we are measuring because it would lead us to find more samples with unacceptable colour differences. These differences in the calculation are more probably caused by flaws in the samples used in the exercise.

Despite this, it can be concluded that this mathematical tool is useful but could be improved to make the appropriate correction between different instruments.

In particular, *"Table 5"* summarizes some statistics on the results of the two previous examples.

"Table 5"

	Mean	Standard deviation	Maximum	Minimum
DAE0019-i1→ DAE0009-964	0.0601	0.0653	0.5292	2.3599e-027
DAE0009-964 → DAE0019-i1	0.0650	0.0755	0.6476	2.9188e-029
DAE0042-i1 → DAE0009-964	0.2480	0.5181	7.7886	7.0220e-027

From these results, it can be concluded that we can achieve big improvements in reducing inter-instrumental differences by using polynomial-type function adjustments to colour measurements.

Further research in this study will include a set of test data to ensure that this matrix provides colour differences regardless of the data set considered.

To verify these results, we will evaluate the matrix with another set of different data from the training data set.

Acknowledgements

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