Control of Reproduced Colour Using Laser Based Tristimulus Colorimetry

Hard Copy Colour Reproduction Topic 2 : Controlling Colour Output

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INTRODUCTION

From the outset of the investigation reported here [1], it was the aim to produce a measurement system for monitoring the concentration of known colorant formulations on-line during production. Both in this context, and in general colour measurement terms, tristimulus colorimetry using broad-band-filter based instrumentation suffers from a number of problems. Instrument to instrument variation is very difficult to eliminate, and instrument metamerism is inherent in a three-channel measurement system. Both these problems are avoided in some modern colorimeters by using spectro-photometric analysis, and calculating the three channel read-out.

Laser based Tristimulus Colorimetry, proposed as a new approach to on-line colour control, uses spectrally differentiated reflectance to generate RGB triplet colour specifications, as an absolute measure of colour. By using a small number of widely separated monochromatic radiation lines, it takes the central concept of three-channel colour measurement to its logical conclusion, and allows the construction of a potentially cheap rugged on-line abridged spectro-photometer.

The consequences of using just three monochromatic laser-generated wavelengths as the illuminant for reflectance measurement however, require careful analysis. In the following account both the inherent limitations, and the practical advantages are discussed.

The results of measuring RGB reflectance triplets then can be compared directly with the expected reflectance values for the known colorants, and metameric effects inherent in conditional matches are avoided.

The predicted reflectance values for the laser wavelengths are provided by the match prediction system. The colorimeter compares desired with actual reflectance at three wavelengths, and can generate an unambiguous control signal for up to three colorants in the recipe.

COLORIMETRY VERSUS SPECTROPHOTOMETRY

Conventional colorimetry is inevitably a compromise. The only truly measurable aspect of colour is the spectrally differentiated power distribution of incident or reflected light. In conventional tri-stimulus colorimeters, the design seeks to simulate the human response. It does this by carefully adjusting the illuminant and colour differentiating filter characteristics to match CIE primary response characteristics [2].

It is almost inevitable, that the many variables of illuminant output and filter manufacture result in inter-instrument differences [3]. The result is that each individual make, and to some extent each instrument differs slightly from the human Standard Observer Response. These differences contribute first to instrument metamerism relative to the Standard Observer. The effect of this is to incorrectly assign equivalent colour identity to certain metamerically mismatching sample pairs. The second potential inaccuracy appears as systematic deviation in measured values. This is caused by incorrect channel response characteristics (balance or chromaticity definition), compared to the defined Standard Observer.

By contrast with colorimeters a full spectrophotometer measures the spectral light flux, and calculation of CIE Standard Observer response is used to establish colour identity in three-dimensional XYZ space. In principle all spectrophotometers use identical calculations. The only potential sources of inter-instrument disagreement then arise either from the method of capturing the light flux for analysis, or from the spectral differentiation mechanisms used.

THE LASER COLORIMETER CONCEPT

The laser colorimeter concept arises from the possibility of calculating the CIE colour identity for any mixture of three monochromatic primaries. The calculation is a simple matrix cross-dependency, provided primary intensities are expressed in T-Units [4]

Starting with the predicted reflectance curve, (output from recipe prediction) An RGB triplet CIE colour identity is calculated as the defining colour standard desired from a production dyeing. Provided the colorants remain identical, production is potentially an unconditional match to the specified reflectance curve and triplet colour identity is a precise definition of matching quality.

The laser colorimeter seeks to establish accurately, the measured reflectance at precisely defined wavelengths. The reference standard reflectance values are obtained by interpolation between measured spectrophotometer output values. The colorimeter uses very narrow band, constant wavelength laser light to re-measure and compare production with target values. The highly monochromatic nature, wavelength stability, and high light intensity of lasers make them an ideal choice for this purpose.

The cost and potential inaccuracy of filters simulating the Standard Observer response is avoided in the proposed measurement method. The central problem of spectro-photometry, that of differentiating responses at precise and adjacent wavelengths is also avoided. Using just three widely separated lines, makes the design of the sensors relatively simple.

A variety of techniques are available for elimination of stray light effects. They start with narrow band filtering, and at more sophisticated levels can use phase-locked modulated laser beam measurement to differentiate measured light from constant stray light. A full discussion is given by El Sayed [5].

LASER LIGHT

Laser output is characterized by high intensity, stable wavelength, and ease of collimation [7]. It is thus relatively easy to produce an intense light spot on a surface, even from a meter or more distance. Reflected light can be gathered equally easily, for example via telescope or contact head (see fig 2).

A reasonably large number of Laser-mode light generation systems, provide a wide choice of monochromatic lines for use in a Laser colorimeter. For the instrument described below, the following lines were chosen.

Red	632.8 Nm	(Helium-Neon) 10Mw
Green	514 Nm	(Helium-Cadmium) 10Mw
Blue	441.6 Nm	(Argon Ion) 6Mw

A wide choice of alternatives can be found in the Laser Handbook [7]. The above wavelengths were chosen for widest all-positive coverage, based on position on the spectrum locus.

The intensity of the Lasers chosen (class 3b*) has been calculated to be sufficient to drive towards 100 measuring heads, given efficient light delivery and collection. In practice, a dozen or so should be relatively easy to achieve with 10 Mw or more of beam power.

It is probable that cheap robust solid-state diode Lasers may become available, and could be used in place of the gas Lasers described above [5].

THE UMIST LASER COLORIMETER

A laboratory demonstration Laser Colorimeter has been constructed at UMIST [5]. The demonstration system uses both non-contact (telescope) light collection in 45/0 degree mode, and contact 45/0 mode. See figs 1 and 2.

Considerable work was needed to deliver reliable reflectance measurements using Lasers, as the light output from lasers was found to be significantly unstable in intensity. Fibre optic light delivery also potentially introduces unwanted intensity variation.

All three lasers have been shown by Elsayed [5] to exhibit light output variation, in the form of long term intensity drift and short period scintillation. Cyclic medium period variation was also encountered. The cyclic variation of the green Laser was found to have a periodicity of about 15 minutes and an amplitude of about +/- 5 percent.

Short term variation, periodicity 0.1 to 3 seconds peak-to-peak, with an amplitude of +/1 2-3 percent necessitated averaging up to 250 readings for consistency. Overall measurement frequency achieved was about 650 measurements/Sec for single readings, reducing to 17/Sec, when averaging 259 readings. Better electronics and more powerful computing could raise both rates substantially.

The object to be measured was illuminated sequentially with the three Lasers, interposing a white reference before each measurement. A photo-diode, A/D converter and electronics, which amplify the signal and filter noise, deliver sensor readings to the computer. A set of three alternative narrow band interference filters, giving 100/1 stray light rejection outside a 10 Nm bandwidth, are place sequentially by a filter wheel in the photo-diode light path.

The Laser Colorimeter is shown to be capable of a level of measurement sensitivity, and reflectance measurement accuracy comparable to the reference Spectraflash SF500, at the three wavelengths used. Individual reading-to reading variation was estimated at +/- 3 percent of indicated value.

RESULTS

A programme of test measurements, using the BCIRA standard colour tiles, was set up in order to compare standard spectrophotometer reflectance measurement with Laser reflectance values. The narrow bandwidth of laser light required the precise reference reflectance values to be interpolated. Some steeply changing reflectance curves have a slope exceeding 1 percent/nm.

Comparisons were made [5] of full spectral and RGB triplet CIE colour identity to determine the effects on colour appearance of using an 'illuminant' with just three wavelengths present. When calculating CIE RGB triplet colour identity, D65 neutral colour balance was used. Strong metameric colour shifts are shown with some of the standard tiles. The calculated CIE RGB triplet colour identities are significantly different from the full spectral Colour identities.

For each of the 12 reference tiles used, reflectance was measured with UV and specular reflectance excluded, using a Spectraflash SF500. The same tiles were then re-measured using the Laser Colorimeter.

Conversion of reflectance triplets to CIE co-ordinate colour identities, was carried out by the matrix method given by Sproson [6]. Precise calculation is achieved, based on the chromaticities of the primaries and the white-point, provided light intensity is expressed in T-Units [4].

For the chosen wavelengths, and a D65 white-point the matrix required is given in the following equation

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} 0.7346 & 0.02831 & 0.1876 \\ 0.2975 & 0.6887 & 0.01376 \\ 0.000084 & 0.1409 & 0.9481 \end{vmatrix} * \begin{vmatrix} R \\ G \\ B \end{vmatrix}$$

During construction the sensor response of the colorimeter was checked at each of the three wavelengths for linearity of response with CIE Y, and scaled by reference to a standard white tile. The same white tile was used to standardize response during measurement. Linearization and balancing for D65 delivers T-Unit sensor response. A discussion of T-Unit measurement is given by Oulton and Porat in [8].

Results of the reflectance measurements are given in Table 1, and correlation between Spectraflash measurements and Laser colorimeter results is shown in Figures 3 – 5.

Spectro Versus Laser Reflectance Values

Wavelength nm

	441.6 nm		514 nm		632.8 nm	
	SF 500	Laser	SF500	Laser	SF500	Laser
White ref	80.4	84	78.6	80.4	84	78.6
Light Grey	55.1	51.8	59.1	60.7	58.1	54.5
Medium. Grey	25.5	23.4	26.0	25.8	23.4	22.0
Dark Grey	5.71	5.89	5.03	4.96	4.97	5.03
Maroon	1.44	2.02	0.830	0.918	8.59	8.14
Pink	28.3	25.0	36.6	36.5	73.3	70.2
Brown	3.97	4.06	7.22	6.92	41.9	39.5
Yellow	6.40	5.95	46.8	47.5	73.9	69.0
Dark Green	2.36	2.53	6.56	6.52	4.65	4.35
Light Green	18.8	17.4	35.1	35.8	24.0	22.4
Green-Blue	8.50	7.95	10.9	10.8	3.48	3.51
Medium.Blue	23.5	22.4	15.0	14.7	8.12	7.59
Dark.Blue	7.79	7.19	1.25	1.18	0.779	1.15

Table 1. Comparison of SF500 interpolated reflectance and values measured using the Laser Colorimeter.

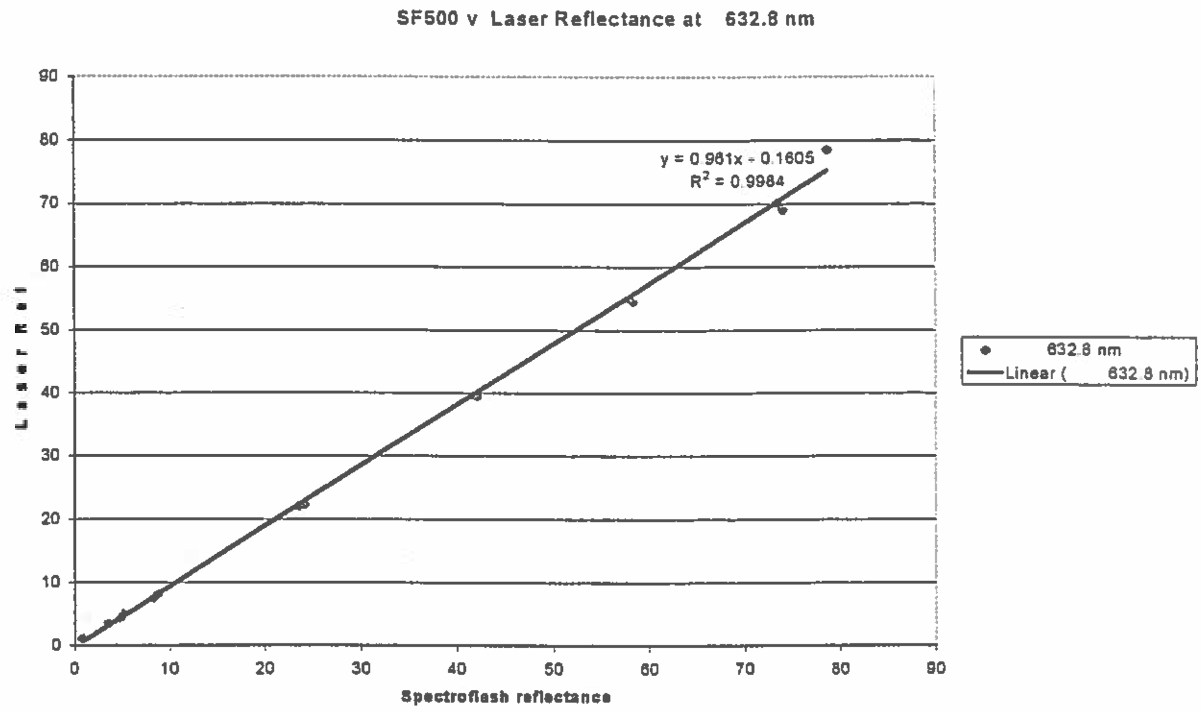

Figure 3.Laser Reflectance as a function of interpolated SF500 reflectance values at 632.8 nm

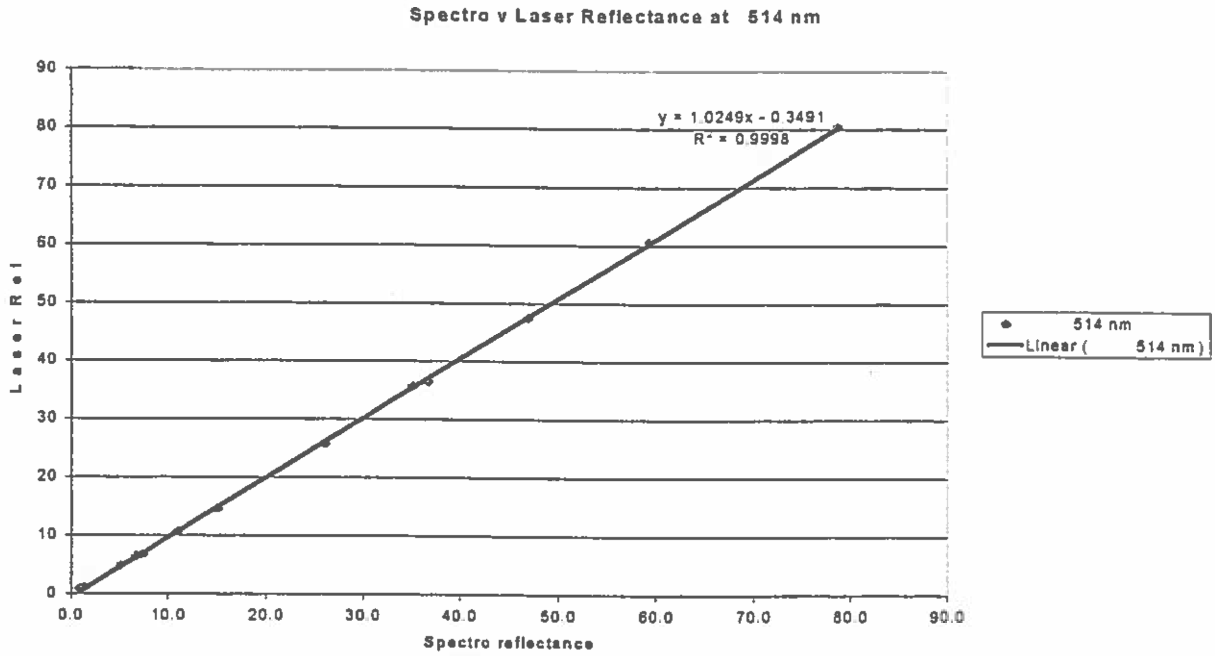

Figure 4.Laser reflectance as a function of interpolated SF500 reflectance values at 514 nm

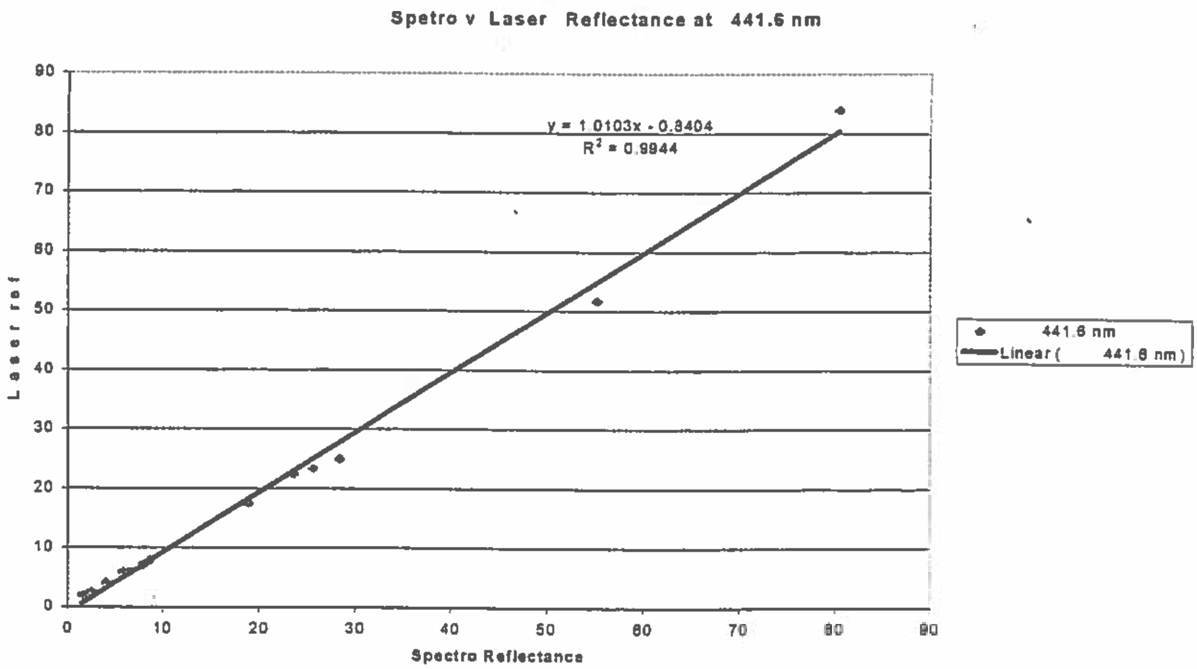

Figure 5.Laser reflectance as a function of interpolated SF500 reflectance values at 441.6 nm

CHROMATICITY AND LIGHTNESS DIFFERENCES

Based on the RGB triplet reflectance values, CIE XYZ colour identities can be calculated. The values are given in Table 2. below, and analyzed as chromaticity and lightness differences in Table 3.

Calculated CIE 2 Degree Obs XYZ Values
Based on Reflectance at three Wavelengths

	Spectro			Laser		
	X	Y	Z	X	Y	Z
White ref	75.1	82.3	88.0	75.1	82.3	88.0
Light Grey	54.7	58.7	60.6	53.2	58.9	57.6
Medium. Grey	22.7	25.2	27.8	22.0	24.8	25.8
Dark Grey	4.86	5.02	6.12	5.10	5.04	6.29
Maroon	6.61	3.15	1.49	6.65	3.26	2.13
Pink	60.2	47.4	32.0	59.4	47.4	28.8
Brown	31.7	17.5	4.78	31.2	17.4	4.82
Yellow	56.8	54.3	12.7	55.2	54.2	12.0
Dark Green	4.04	5.93	3.16	4.14	5.89	3.29
Light Green	22.1	31.6	22.7	21.4	31.5	21.4
Green-Blue	4.46	8.63	9.58	4.47	8.51	9.06
Medium.Blue	10.8	13.1	24.3	10.5	12.6	23.3
Dark.Blue	2.07	1.20	7.55	2.26	1.26	7.03

Table 2. Comparison of Triplet CIE co-ordinates, derived from SF500 data and Laser measurement data

Chromaticity and Lightness differences based on Three wavelegth Analysis

	Spectro			Laser			Difference Specto/Laser		
	x	y	Y	x	y	Y	dx	dy	dY
White ref	0.306	0.335	82.3	0.306	0.335	82.3	0	0	0
Light Grey	0.314	0.337	58.7	0.313	0.347	58.9	0.001	-0.010	-0.20
Medium. Grey	0.300	0.333	25.2	0.303	0.342	24.8	-0.003	-0.009	0.40
Dark Grey	0.304	0.314	5.02	0.310	0.307	5.04	-0.007	0.007	-0.02
Maroon	0.588	0.280	3.15	0.552	0.271	3.26	0.035	0.009	-0.11
Pink	0.431	0.340	47.4	0.438	0.350	47.4	-0.007	-0.010	0.00
Brown	0.587	0.324	17.5	0.584	0.326	17.4	0.003	-0.001	0.11
Yellow	0.459	0.439	54.3	0.455	0.446	54.2	0.004	-0.008	0.10
Dark Green	0.308	0.452	5.93	0.311	0.442	5.89	-0.003	0.009	0.04
Light Green	0.289	0.414	31.6	0.288	0.424	31.5	0.002	-0.010	0.10
Green-Blue	0.197	0.381	8.63	0.203	0.386	8.51	-0.006	-0.005	0.12
Medium.Blue	0.224	0.272	13.1	0.226	0.271	12.6	-0.002	0.000	0.52
Dark.Blue	0.191	0.111	1.20	0.214	0.119	1.26	-0.023	-0.009	-0.06

Table 3. Comparison of derived x,y chromaticity and Y for SF500 and Laser Colorimeter

Although the demonstration instrument is a long way from what might be used on the 'shop floor' it shows promising performance.

Some departure from linear response is shown by the Laser colorimeter at reflectance values below 2 percent and above 80 percent.

Conclusions

1. The Laser Colorimeter described is in essence an abridged spectrophotometer. As such it produces a purely physical measurement of the colour under analysis. Because it uses just three wavelengths for comparison, it is limited to monitoring the quality of unconditional or non-metameric matches.
2. It was the aim of the authors to develop such a system, in order to address the problem of on-line colour control.
3. The high light intensity, inherently stable wavelength, very narrow bandwidth, and ease of collimation of Laser light, makes accurate determination of mono-chromatic reflectance values relatively easy.
4. Without the benefit of sophisticated optical engineering, or complicated monochromators, adequate reflectance values have been determined at three very precise wavelengths.
5. It is suggested that the principles described can be applied to both reflectance and transmission measurement. Contact and remote sensing measurement have both been demonstrated using the UMIST Laser Colorimeter Demonstration system.
6. The advent of suitable solid-state diode lasers may make a cheap compact version possible, suitable for building into hard-copy printing systems.
7. The powerful gas lasers used have been calculated to produce enough light to drive many individual measuring heads.

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