

**NPL REPORT
DQL-OR 014**

**MAVISCAL: Digital Camera
Calibration for Wound
Measurement – Colour
Characterisation**

Michael R Pointer

JUNE 2006



The DTI drives our ambition of 'prosperity for all' by working to create the best environment for business success in the UK. We help people and companies become more productive by promoting enterprise, innovation and creativity.

We champion UK business at home and abroad. We invest heavily in world-class science and technology. We protect the rights of working people and consumers. And we stand up for fair and open markets in the UK, Europe and the world.

The National Physical Laboratory is operated on behalf of the DTI by NPL Management Limited, a wholly owned subsidiary of Serco Group plc

MAVISCAL: Digital Camera Calibration For Wound Measurement – Colour Characterisation

Michael R. Pointer

ABSTRACT

The MAVIS system (Masurement of Area and Volume Instrument System), developed by Isotec Imaging, is a portable stereo-optical system that measures the area and volume of wounds, and records their colour. Under a collaborative project, Isotec Imaging and the National Physical Laboratory have developed dimensional artefacts to enable the calibration of MAVIS, and considered various strategies for characterising the digital camera to produce CIE colorimetry from RGB image files.

MAVISCAL was a Joint Industry Project supported through the DTI *Measurement for Innovators* scheme.

© Crown copyright 2006
Reproduced with the permission of the Controller of HMSO
and Queen's Printer for Scotland

ISSN 1744-0610

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

This document has been produced for the Department of Trade and Industry's National
Measurement System Policy Unit under the Term Contract for Research and
Development.

Approved on behalf of the Managing Director, NPL
by Martyn Sené, Director, Quality of Life Division

MAVISCAL: DIGITAL CAMERA CALIBRATION FOR WOUND MEASUREMENT – COLOUR CHARACTERISATION

Michael R Pointer

Table of Contents

1. INTRODUCTION	3
2. DIGITAL CAMERAS	4
2.1 Introduction.....	4
2.2 Colour analysis.....	5
2.3 Basic theory	7
2.4 Characterisation methods.....	8
2.5 Characterisation based on measured colorimetry	9
2.6 GretagMacbeth Charts	10
3. PRACTICAL PROCEDURE.....	12
4. EXAMPLE DATA.....	17
5. FURTHER ANALYSIS.....	19
6. CONCLUSIONS.....	19
7. ACKNOWLEDGEMENTS.....	26
8. REFERENCES	26
APPENDIX: PROCEDURE.....	27

MAVISCAL: DIGITAL CAMERA CALIBRATION FOR WOUND MEASUREMENT – COLOUR CHARACTERISATION

1. INTRODUCTION

With an increasingly elderly population, and an increase in the prevalence of diabetes, the incidence of open wounds such as leg ulcers is also on the increase. Leg ulcer wounds heal very slowly and monitoring is essential in determining progress and specifying suitable treatment. Clinicians typically measure the wound area and volume on a weekly basis to decide if the healing process is really happening. Currently the technique used to measure the wound area is very basic. By placing a transparent sheet on top of the wound, a physician traces the wound perimeter and counts the squares inside the line. The volume is measured either by filling the wound with saline solution from a syringe and the amount dispensed represents the wound volume, or by filling the wound with a liquid material which sets and can then be removed and weighed to give an indication of the volume. In addition to being painful to the patient, these invasive procedures are inaccurate, slow, and carry a cross infection risk.

In addition, the healing of chronic wounds such as leg ulcers is frequently compromised by episodes of infection. This infection is usually accompanied by inflammation which manifests itself as a change in wound colour. If the change from the healthy pink/light red hue of granulation tissue to, what clinicians describe as, ‘angry red’ could be detected at an early stage, the deterioration of the wound, pain to the patient, and treatment costs, could be minimised. Recent advances in digital camera performance suggest that off-the-shelf digital cameras may be suitable, after appropriate characterisation, to measure the wound colour precisely enough to allow the images to be used for diagnostic purposes.

The MAVIS system (Masurement of Area and Volume Instrument System), developed by Isotec Imaging, is a portable stereo-optical system that avoids all the issues of contact measurement methods¹. The system measures area and volume, and records colour. It will also measure nodules and wound swelling. Under a collaborative project, Isotec Imaging and the National Physical Laboratory have developed dimensional artefacts with flesh-like textured surfaces to enable calibration of MAVIS, and considered various strategies for characterising the colour reproduction capability of the system.

For effective monitoring of wound progress, it is essential that these measurements are consistent between instruments and over time. NPL has provided the calibration and measurement expertise needed. Dimensional accuracy, affected by optical distortion, and colour reproduction, may vary between cameras and with time. The goal was to design and fabricate dimensional calibration artefacts and to investigate the factors affecting accurate colour recording. The project also investigated possible improvements to the optical design, recording and display of the images.

This report considers the characterisation of a digital camera to produce CIE colorimetry from RGB image files. Digital cameras use an area array, usually a charge coupled device (CCD), as their detector and can therefore produce their output in the form of images that can be both displayed and analysed. Thus, they are able to derive for example, the spatial distribution of the colorimetric information in a scene.

Digital cameras used to measure colorimetric coordinates require calibration in a relative sense, a process usually termed characterisation; if required, they can be characterised in an absolute sense such that they can be used as imaging photometers for measuring the luminance distribution in a scene.

2. DIGITAL CAMERAS

2.1 Introduction

Digital cameras can take on various forms depending on their intended application². Cameras for general photography have fixed lenses that often provide a zoom facility; they can have automatic white point adjustment, automatic focus, automatic exposure control, and will fire a flashlight, sometimes twice (to reduce the ‘red-eye’ effect), if needed. Cameras for the more professional user have interchangeable lenses and more sophisticated ‘programmable’ exposure control. The digital camera used for MAVIS is a Canon EOS 300D (later the EOS 350D). The lens is replaced by a slightly modified but commercially available stereo adapter, Fig. 1, and the camera is fitted with a flashgun to provide consistent illumination. The camera is also fitted with a simple device to fix the distance between the camera and wound to be photographed.



Most of these cameras include firmware that performs some image processing in addition to the analogue-to-digital conversion of the input image. This processing includes de-mosaicing (to interpolate the image in a colour sense, see below), digital conversion (e.g. from, for example, a captured 12 bit image to an output 8 bit image), and gamma correction (to provide a photographic ‘feel’ to the images and, sometimes, to produce R , G , B , values that accord with the sRGB standard which itself includes a gamma correction).

While this processing is useful for the ordinary photographer, it is not always helpful in scientific applications. For this reason cameras are available that are essentially just a case containing a detector array mounted on a processing board, which provides the analogue-to-digital conversion, together with a relatively simple exposure control system that can be triggered from a host computer. A separate lens is mounted on the front of the case and the

resulting image is passed to the computer either directly via a suitable interface or via a frame-grabber card in the computer. Most digital cameras for general use include a medium for storage, usually in the form of a magnetic memory card: scientific cameras do not usually have this facility.

Many scientific applications require the output images to be formed in colour and methods of deriving the colour signals are camera dependent. There are applications that only require monochrome images, for example in closed-circuit-television security and surveillance work or, indeed, a monochrome camera can be used with external filters, usually red, green and blue, to provide the necessary colour separation to produce colour images. Multi-band spectral imaging is also possible by the selection of, typically five or more, filters transmitting suitable spectral bands.

The big advantage of using a digital camera intended for photography in a scientific application, is its relatively low cost. Scientific cameras are expensive and not yet readily available with very high pixel density, especially in colour.

2.2 Colour analysis

There are a number of ways in which colour analysis can be achieved using a CCD device³. The spectral response of the basic CCD detector can be partitioned using a red, green and blue colour-filter array coated on the actual device. This enables colour information to be obtained in a way that is analogous to the spectral-band selection of a tristimulus colorimeter.

This analogy would be complete if the three spectral responses of the device were equivalent to a linear combination of a set of colour-matching functions for the human eye. For a typical digital camera this is almost never going to be true, indeed it is more likely and more desirable that the response should be closer, after some processing, to the colour-matching functions of the intended display device, usually defined by the phosphors of a cathode-ray tube. It should also be noted that the signals are *device dependent* in that different digital cameras will give different R , G , B responses to the same input scene, Fig. 2.

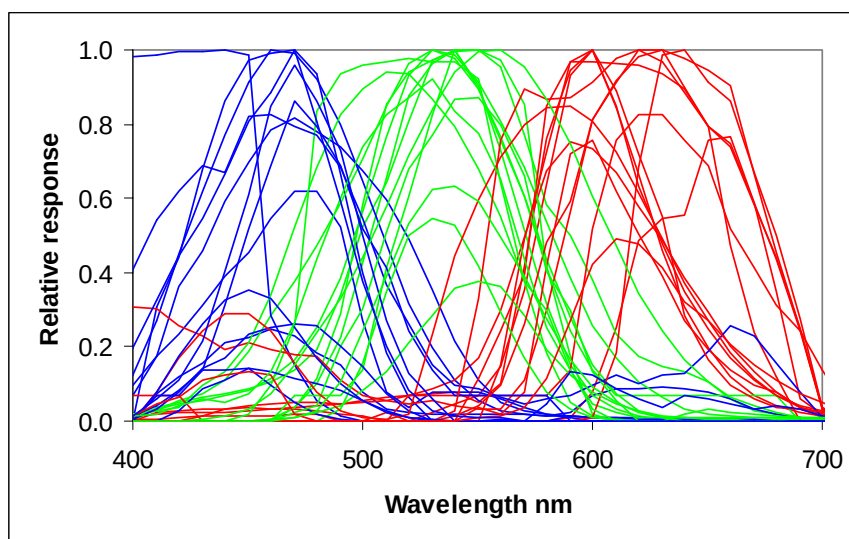


Figure 2. A number of sets of R , G , B spectral responsivities showing the wide variation in their peak wavelengths, their widths and their unwanted sensitivities.

For many sensors, the number of pixels devoted to each colour is different; for example, there may be twice as many green-coated pixels as opposed to red and blue, Fig. 3. This provides a relatively enhanced green response which can be used to provide a wider bandwidth luminance signal. Some devices have the filters coated in stripes rather than on to discrete pixels.

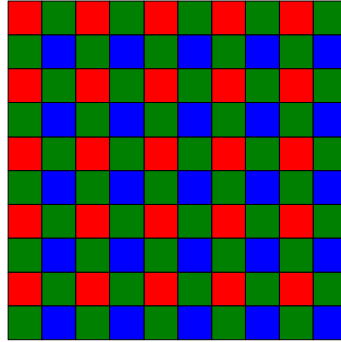


Figure 3. Colour filter mosaic array – usually known as a Bayer pattern after its inventor.

To produce colour images of a high quality, the colour samples from a single sensor array coated with an appropriate colour filter array must be processed to provide complete red, green and blue values at each pixel location because each cell captures only one spectral band. This process of filling in the missing colour values is referred to as de-mosaicing or colour filter array interpolation. There is a range of different types of algorithms that are used, each having varying levels of complexity. The simplest just takes an average between the nearest samples of the appropriate colour. This approach, which is known as non-adaptive interpolation, is easy to implement but reduces the sharpness of the image. A more complex, adaptive approach would try to find uniform areas and their edges, and ensure that they remained uniform and sharp⁴.

Another way of forming the three discrete colour channels is to use three area arrays in one camera, each filtered to respond to light from roughly one third of the spectrum, Fig. 4. Broadcast quality television cameras use this technique because the additional cost of providing three channels is not an important consequence compared with the fact that the whole image is sampled by each sensor. Rather than coating the filters onto the arrays, it is customary to use a glass prism block coated with interference, or dichroic, semi-transparent mirrors and filters.

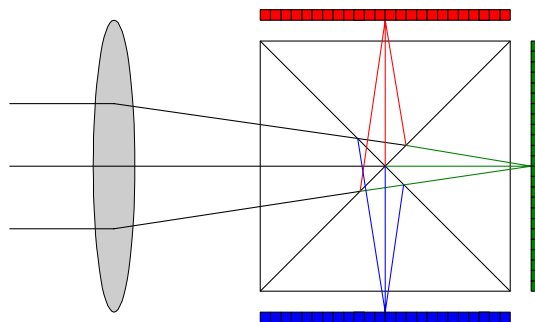


Figure 4. Schematic diagram of a colour-filter block for a 3-CCD camera.

As already indicated, a third method of providing the spectral separation into a trichromatic system is to use three filters separately mounted externally to the camera: then the camera has to have a response throughout the visible spectrum (spectrally non-selective or monochrome response) and three sequential exposures must be made to capture the full colour information present in the scene. This mitigates its use in capturing images of moving objects.

To use a digital camera as a tristimulus colorimeter requires signal processing to obtain *device-independent* coordinates, usually CIE tristimulus values X , Y , Z , from the R , G , B output data in the image file, and it is the form and efficiency of this characterisation process that dictates the overall accuracy of the device as a colorimeter⁵.

Because of the inherent response of the detector to light at wavelengths greater than those associated with the visible range, it is useful to include an infrared cut-off filter over the detector array. This can take a number of forms: it may be an integral part of the detector array, or it may be a separate filter placed over the front of the camera lens. Experience has shown that the closer the infrared cut-off matches the long wavelength shape of the $\bar{x}(\lambda)$ colour matching function, Fig. 5, the better will be the accuracy with which the X tristimulus value can be predicted by any modelling procedure. Most digital cameras intended for amateur photography include adequate infrared cut-off filtration.

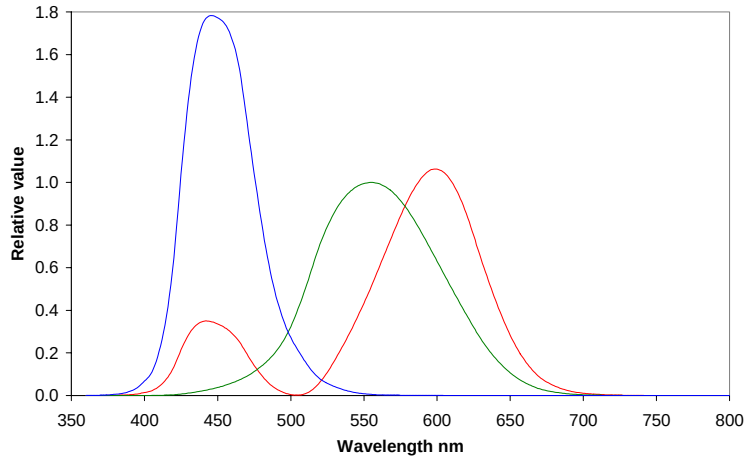


Figure 5. The colour matching functions of the CIE 1931 Standard Observer: (red: $\bar{x}(\lambda)$, green: $\bar{y}(\lambda)$, blue: $\bar{z}(\lambda)$).

2.3 Basic theory

The basic R , G , B ‘values’ of a specific pixel in an image can be calculated from a knowledge of the spectral power distribution of the light coming from the equivalent location in the original scene, $S(\lambda)$, integrated with the respective spectral responsivities of the three colour channels of the detector and its associated filters, $C_i(\lambda)$, $i = r, g, b$:

$$\begin{aligned} R &= \int S(\lambda) C_r(\lambda) d\lambda \\ G &= \int S(\lambda) C_g(\lambda) d\lambda \\ B &= \int S(\lambda) C_b(\lambda) d\lambda \end{aligned} \quad (1)$$

Assuming the light from the scene is present by reflection, then the spectral power distribution of the scene element can be substituted with the spectral power distribution of the light source, $P(\lambda)$, and the reflectance of the object in the scene element, $O(\lambda)$. In the real situation this substitution is not straightforward because some points in the scene might be self-luminous, i.e. emitters of light. These may be obvious light sources, or not so obvious specular highlights caused by reflection of the light source. In general, however, $S(\lambda)$ in the above equations can be replaced to give:

$$\begin{aligned} R &= \int P(\lambda)O(\lambda)C_r(\lambda)d\lambda \\ G &= \int P(\lambda)O(\lambda)C_g(\lambda)d\lambda \\ B &= \int P(\lambda)O(\lambda)C_b(\lambda)d\lambda \end{aligned} \quad (2)$$

where the integration is usually replaced by summation taken over a suitable wavelength range in the visible part of the spectrum, for example from 380 to 780 nm and in steps of 5 nm or 10 nm.

Thus, the problem to be solved is how to transform these device-dependent coordinates into device-independent coordinates. The device-independent coordinates usually chosen are the CIE tristimulus values, X , Y , Z , which are defined in a similar manner to the R , G , B values above⁶:

$$\begin{aligned} X &= \int P(\lambda)O(\lambda)\bar{x}(\lambda)d\lambda \\ Y &= \int P(\lambda)O(\lambda)\bar{y}(\lambda)d\lambda \\ Z &= \int P(\lambda)O(\lambda)\bar{z}(\lambda)d\lambda \end{aligned} \quad (3)$$

The difference is that the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ functions, the colour matching functions of the CIE standard observer, are unique and device independent, Fig. 5. (There are, in fact, two CIE standard observers with slightly different colour matching functions⁶. Their differences can be traced to differences in field size rather than directly to spectral response: the ensuing discussion can be applied to either set.)

The values of R , G , B and X , Y , Z are usually presented in a normalised manner: R , G , B such that a white is defined by $R = G = B = 255$ (or some other defined value, e.g. a 50% neutral is represented by $R = G = B = 128$), and X , Y , Z such that the Y value is equal to 100 for the illuminant. This latter step is implemented by multiplying the values of X , Y , Z in the above Eqns. 3 by the factor:

$$k = 100 / \int P(\lambda)\bar{y}(\lambda)d\lambda \quad (4)$$

2.4 Characterisation methods

There are synergies between the sets of equations (2) and (3) above. Considering the right-hand side of the equations, the dissimilar elements are the camera spectral responsivities and the human observer colour matching functions. If they could be modelled one from the other, either physically or mathematically, then it would become possible to derive the CIE X , Y , Z tristimulus values from the image R , G , B values using the same model. Similarly, considering the left-hand side of the equations, if it were possible to mathematically model

the X , Y , Z tristimulus values from the image R , G , B values, then again this would provide the necessary transform.

There are four practical characterisation methods described in the literature that can be used^{3, 4}:

- based on spectral response matching using external filters.
- based on the measured spectral responsivity data of the device.
- based on the known colorimetry of a number of coloured patches.
- based on mathematical estimation.

There are commercially available instruments that use the first method by selecting filters that are mounted in a wheel that is rotated in front of the camera lens. The measurement of the spectral response of a digital camera is not an easy process to carry out and, while it is possible, the method based on measurements of a test target is the easier to implement and was the method used for the *MAVISCal* project. The method of spectral estimation could be used but it also requires the measurement of a large number of test colours.

2.5 Characterisation based on measured colorimetry

As noted above there is a certain similarity between the equations for deriving the camera responses R , G , B and the CIE X , Y , Z tristimulus values, the difference being the spectral responsivities. Thus if a relationship can be found between the R , G , B and the CIE X , Y , Z then this same relationship can be used to transform any other R , G , B values to X , Y , Z values. The usual place to start when looking for such a relationship is to assume that the camera responses are a linear combination of the CIE colour matching functions, thus they can be related by equations of the form:

$$\begin{aligned} X &= a_{11}R + a_{12}G + a_{13}B \\ Y &= a_{21}R + a_{22}G + a_{23}B \\ Z &= a_{31}R + a_{32}G + a_{33}B \end{aligned} \quad (5)$$

Written in matrix form this becomes:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = A \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (6)$$

This reduces to finding the solution to three applications of a linear regression procedure.

Because it is an assumption, rather than a fact, that the camera responses are a linear combination of the CIE colour matching functions, it is reasonable to investigate the use of more complex forms of equation to model the relationship. For example, the following have been suggested:

$$\begin{aligned}
M &= R \ G \ B \ k \quad (1) \\
M &= R \ G \ B \ RGB \ k \\
M &= R \ G \ B \ RG \ RB \ GB \ k \\
M &= R \ G \ B \ RG \ RB \ GB \ RGB \ k \\
M &= R \ G \ B \ RG \ RB \ GB \ R^2 \ G^2 \ B^2 \ k \quad (2) \\
M &= R \ G \ B \ RG \ RB \ GB \ R^2 \ G^2 \ B^2 \ RGB \ k \\
M &= R \ G \ B \ RG \ RB \ GB \ R^2 \ G^2 \ B^2 \ RGB \ R^3 \ G^3 \ B^3 \ k \\
M &= R \ G \ B \ RG \ RB \ GB \ R^2 \ G^2 \ B^2 \ RGB \ R^3 \ G^3 \ B^3 \dots \\
&\quad R^2G \ R^2B \ G^2B \ RG^2 \ RB^2 \ GB^2 \ k \quad (3)
\end{aligned}$$

etc.

(1) Complete linear (2) Complete quadratic (3) Complete cubic

From a mathematical perspective there is, of course, no limit to the order and number of terms in the polynomial; in practice the complexity can be constrained by the accuracy required and the number of data points available. It is also reasonable to remove the need for a constant term, k ; its inclusion, however, can be statistically significant.

While linear regression is a useful and reasonable starting point for this type of analysis, the extension to polynomial regression does not always represent a sensible, physical, model between two sets of data such as those considered above. Polynomials are essentially oscillating functions and, while they can predict data satisfactorily by interpolation, they are often unstable when required to provide extrapolation to points outside of the basic data set. It is also not easy to ascribe a physical meaning to the equations obtained, a fact that is not essential but, if it were possible, would provide useful insight into the physics of the relationship between eye and camera responses.

2.6 GretagMacbeth Charts

The above modelling process requires a number of coloured test patches of known CIE colorimetry and there are several methods that can be used to assemble a suitable set of samples. The easiest to use is one of the three commercially available test charts manufactured by GretagMacbeth, Table 1.

Table 1. The specifications of the three GretagMacbeth ColorChecker Charts.

	Size	Number of patches	Size of patches	Patch separation
ColorChecker	290 mm x 200 mm	24	40 mm x 40 mm	6 mm
ColorChecker SG	290 mm x 204 mm	140	13.5 mm x 13.5 mm	4 mm
ColorChecker DC	356 mm x 216 mm	237	12 mm x 12 mm	2.5 mm

While these charts are commercially available, they each present some difficulties in use.

- ColorChecker (Fig. 6, upper):
 - o The chart comprises only 18 coloured patches, and some of these are very saturated.
 - o There are only six steps in the neutral scale.
 - o The patches have a relatively matt finish which means they are prone to surface scuffing. This is alleviated by the relatively low cost of the chart.
 - o This chart is also available in a miniature ‘credit-card’ sized version.

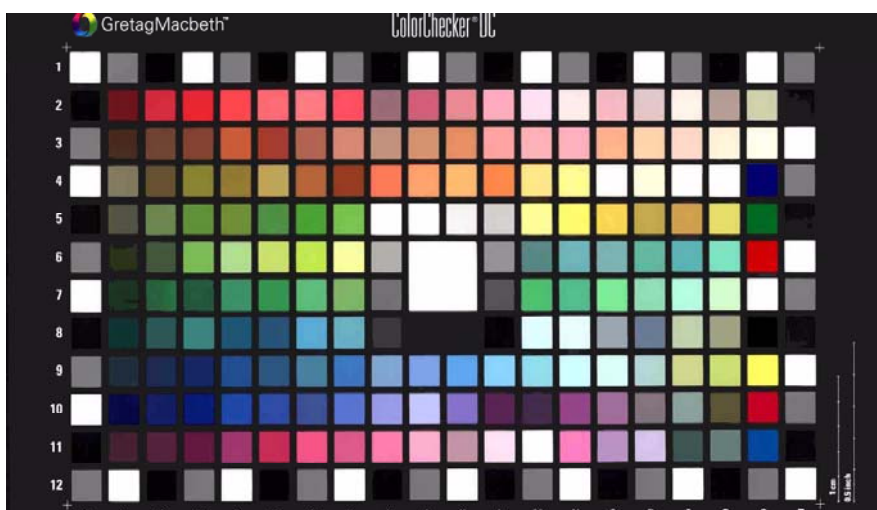
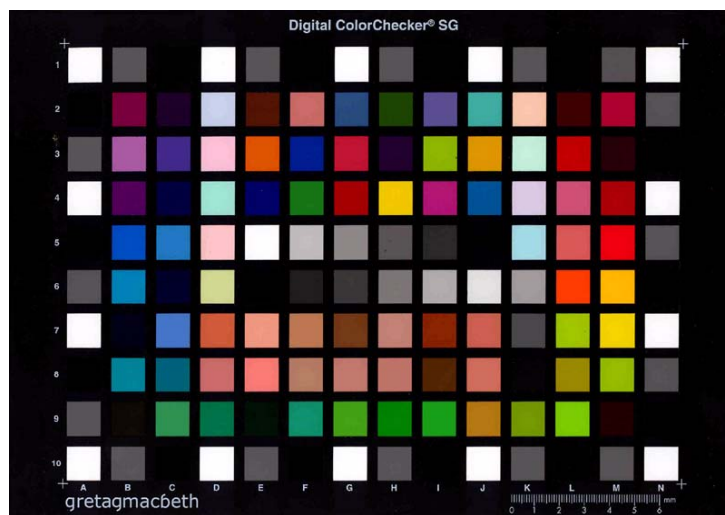


Figure 6. The GretagMacbeth ColorChecker Charts.
Upper, 24 patch ‘original’ chart; middle, SG chart; lower, DC chart.
The charts are reproduced to approximately the same scale.

- ColorChecker SG (Fig. 6, middle):
 - o The colour patches are small and may present measurement difficulties.
 - o This chart represents a good compromise in terms of the number of test colours.
 - o The test colours have a higher gloss than those of the above ColorChecker Chart. This can lead to illumination difficulties with a moderately high degree of specular reflection, especially with flash illumination. It is understood however, that a matt version of the chart is to be made available in the future.
 - o The outer ring of patches comprises triplets of three different neutrals intended to monitor uniformity of illumination and exposure. If these are all used in the characterisation process, then they could bias the result towards neutral colours – while not always a bad thing, it may not give the best overall result.
 - o The whole chart is mounted on very thin black card and thus tends to warp. This is especially noticeable when using lighting that emits a lot of heat. This effect could easily be alleviated by mounting the chart onto a suitable backing sheet to provide rigidity.
- ColorChecker DC (Fig. 6, lower):
 - o The colour patches are very small and hence difficult to measure without using a small aperture on an integrating sphere-based spectrophotometer. $0^\circ:45^\circ$ (or $45^\circ:0^\circ$) geometry is easier but again a relatively small aperture is required.
 - o It is probably not necessary to have 237 coloured patches to characterise a digital camera.
 - o The grey scale is close to the central white patch, which is four times the area of the other patches. This means that flare light, reflected from this white patch, can spill over onto the surrounding patches that comprise the grey scale, causing an increase in their apparent lightness.
 - o The chart contains a number of high gloss patches which can cause problems by exhibiting specular highlights – these should be omitted from any characterisation analysis. The other patches are of a gloss level similar to that of the ColorChecker above and hence do not exhibit specular reflection.
 - o As above, the outer ring of patches comprises triplets of three different neutrals intended to monitor uniformity of illumination and exposure. If these are all used in the characterisation process, then they could bias the result towards neutral colours – while not always a bad thing, it may not give the best overall result.
 - o Also as above, the whole chart is mounted on very black thin card and thus tends to warp. This is especially noticeable when using lighting that emits a lot of heat. This effect could easily be alleviated by mounting the chart onto a suitable backing sheet to provide rigidity.
 - o This chart has been available for approximately 5 years and it is likely that it will be superseded by the ColorChecker SG above – or the matt version of it.

3. PRACTICAL PROCEDURE

The characterisation of a digital camera using the colorimetric method requires an image of the test chart comprising a suitable number of test patches of known colorimetry; thus, it is necessary to be able to measure the spectral reflectance of each of the test patches using a suitable spectrophotometer, Fig. 7.

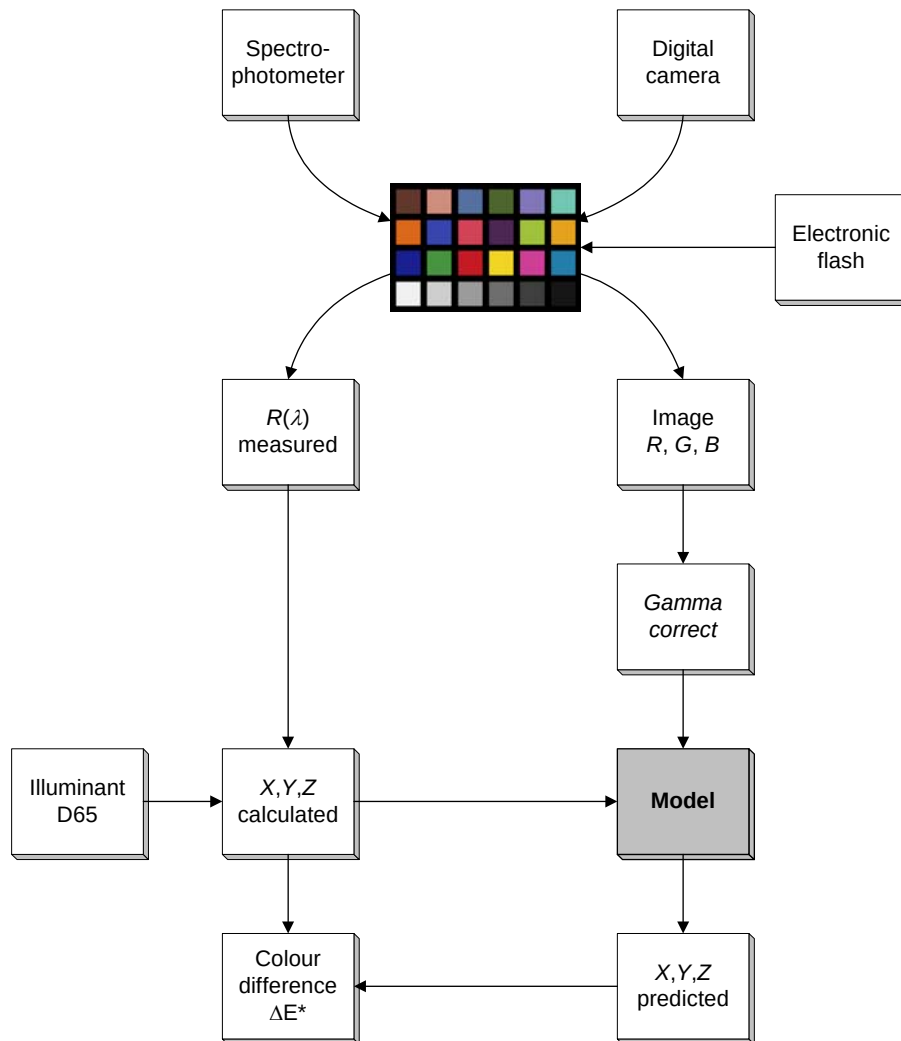


Figure 7. Schematic of the digital camera characterisation procedure.

- The spectral reflectance of each patch of the chosen chart is measured using a suitable spectrophotometer: an AvaMouse device was used for the *MAVISCal* project⁷. This is a hand-held spectrophotometer that uses 45°a:0° geometry. Illumination from a pulsed xenon source is conveyed to the sample surface via an annular reflector at 45°. The illuminated aperture is set to 5.5 x 6 mm, and the area of the samples that is measured is 1.5 x 2 mm. Detection is normal (0°) to the surface of the sample. The small measurement aperture makes alignment easy and its mode of operation means that the measurement of a large number of coloured patches can be achieved in a relatively short time. The 240 patches of the GretagMacbeth DC chart could be measured in less than one hour. The data from the instrument require interpolation to produce values from 380 nm to 780 nm with 5 nm intervals (or any other data range and/or wavelength interval); this requires additional time to calculate.
- CIE colorimetric values then need to be calculated from the spectral data but before this can be done, a CIE illuminant and observer must be selected. A suitable choice for the *MAVISCal* project was to use CIE Standard Illuminant D65 with the CIE 2° Standard Observer. Note that the illuminant does not have to be the same as that used for the actual camera exposure; the modelling process will take care of any differences.

- An image of the test target is then made using the digital camera requiring characterisation. The light source can be anything suitable: electronic flash, photoflood lamps or studio flash is ideal depending on the specific situation. It is possible to use natural daylight but the camera would require characterisation for every change in the illumination which, for daylight, is difficult to control. For *MAVISCal* an electronic flash unit was used, mounted on the camera, Fig.1.
- An image was also obtained of a sheet of neutral paper on which a grid had been drawn to provide the exact location of the coloured patches in the chart. This grid will be used to assess the uniformity of the illumination.
- The R , G , B values for each of the pixels in the two images then need to be obtained. The images should be stored using the minimum processing possible. Thus, if a typical photographic digital camera is used, then the images stored should not be compressed. Care should be taken if a native raw image format is used, usually the highest resolution provided on the camera. This format can sometimes be proprietary in that only the software provided with the camera can open the image files and this will not be adequate for the processing required. Software is required that can open the image and calculate average R , G , B values of an array of pixels: the number will be a function of the size of the image but the minimum number of pixels considered should be at least 200. This gives the average R , G , B values of each patch in the colour target.
- It is possible to derive a correction for the inevitable of non-uniformity of the illumination using the G pixel values of the image of the neutral paper. The G values are used because the green spectral response of the camera is likely to be most similar to the $\bar{y}(\lambda)$ colour matching function, which is the same as the spectral luminous efficiency function $V(\lambda)$ and hence an approximate measure of relative luminance. A factor, F_i , is calculated as:

$$F_i = \text{MAX}(G) / G_i \quad (7)$$

Where $\text{MAX}(G)$ is the maximum G value of the pixels considered, and G_i is the G value of the pixel i . Each R , G , B pixel value is then multiplied by this factor. Fig. 8 shows the uniformity distribution obtained using electronic flash and the GretagMacbeth Color Checker SG chart described above. The maximum G pixel value is 223, the minimum value 180 and the average value 208. The non-uniformity from top to bottom is caused by the flash being mounted on the top of the camera, above the lens; the high levels of illumination towards the centre are typical of flash illumination which usually gives such a hot-spot.

- A suitable regression procedure is then used to model the image R , G , B data to the corresponding measured X , Y , Z data. It is convenient to carry out these calculations using Microsoft Excel[®] and the *LinEst* Array Function can be used to implement linear and quadratic models. It is not possible to include more than 15 terms using this Excel function and so higher order regression models must be implemented using alternative software, for example, Matlab.

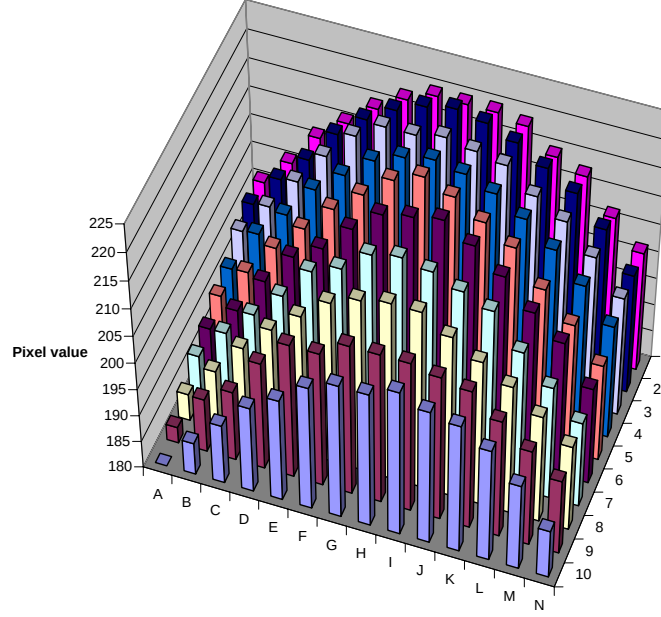


Figure 8. Uniformity of illumination when using an electronic flash attached to the camera and the GretagMacbeth ColorChecker SG chart.

- In order to produce a reasonable characterisation it has been found useful to implement a ‘gamma correction’ to the data to optimise the regression models. The reason for this is that the data coming from the camera are usually non-linear, and there is a variety of reasons for this as discussed above. It has been found that the best way to implement this function is to ‘correct’ the data using the following function:

$$R' = R^{1/\gamma} \quad (8)$$

where the R pixel value is corrected to a new value R' , with similar expressions for G' and B' . Note that the same value of γ is used in all three channels. The optimum value of γ can be found using the Excel *Goal Seek* Function.

- A measure of the success of a particular model can be found by calculating the colour difference between the measured data, X_m, Y_m, Z_m , and that predicted using the model, X_p, Y_p, Z_p . CIELAB parameters L^*, a^* and b^* are first calculated from the X, Y, Z data using the following generic equations:

$$\begin{aligned} L^* &= 116(Y/Y_n)^{1/3} - 16 \\ a^* &= 500[f(X/X_n) - f(Y/Y_n)] \\ b^* &= 200[f(Y/Y_n) - f(Z/Z_n)] \end{aligned} \quad (9)$$

$$\begin{aligned} \text{where } f(X/X_n) &= (X/X_n)^{1/3} & \text{if } (X/X_n) > (6/29)^3 \\ f(X/X_n) &= (841/108)(X/X_n) + 4/29 & \text{if } (X/X_n) \leq (6/29)^3 \\ f(Y/Y_n) &= (Y/Y_n)^{1/3} & \text{if } (Y/Y_n) > (6/29)^3 \end{aligned}$$

$$f(Y/Y_n) = (841/108)(Y/Y_n) + 4/29 \quad \text{if } (Y/Y_n) \leq (6/29)^3$$

$$f(Z/Z_n) = (Z/Z_n)^{1/3} \quad \text{if } (Z/Z_n) > (6/29)^3$$

$$f(Z/Z_n) = (841/108)(Z/Z_n) + 4/29 \quad \text{if } (Z/Z_n) \leq (6/29)^3$$

where the tristimulus values X_n, Y_n, Z_n are those of the specified neutral stimulus.

The differences in these parameters, ΔL^* , Δa^* , Δb^* , are then calculated where:

$$\begin{aligned} \Delta L^* &= L_m^* - L_p^* \\ \Delta a^* &= a_m^* - a_p^* \\ \Delta b^* &= b_m^* - b_p^* \end{aligned} \quad (10)$$

where L_m^*, a_m^*, b_m^* and L_p^*, a_p^*, b_p^* are CIELAB parameters corresponding to the measured data and predicted data respectively.

The colour difference, ΔE_{ab}^* , can then be calculated for each colour patch using the equation:

$$\Delta E_{ab}^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2} \quad (11)$$

- To further reduce these data, a histogram can be plotted by assigning the values of colour difference, ΔE_{ab}^* , to bins of a defined size. This histogram data can then be used to produce a cumulative frequency distribution. Values of colour difference are not normally distributed because they usually tend towards a value close to zero. Thus, the average value is not the best measure of central tendency; a more correct value is the median of the distribution and this can easily be calculated using the *Quartile* Function in Excel. In addition, it is useful to know the maximum value of the colour difference as an indication of the range: this can be calculated using the *MAX* Function in Excel. An example histogram is shown in Fig. 9 below.

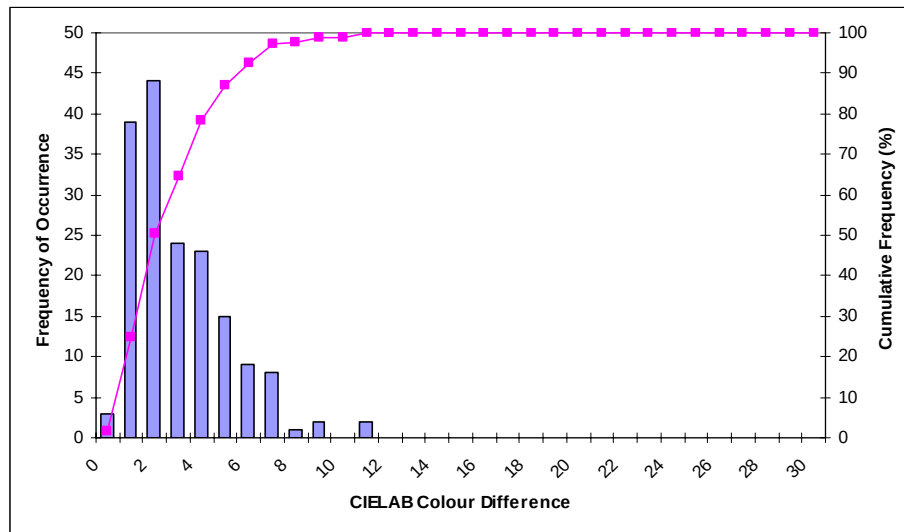


Figure 9. A histogram of values of CIELAB colour difference, ΔE_{ab}^* , obtained using a GretagMacbeth ColorChecker SG chart, using X, Y, Z input data. Also shown is the associated cumulative frequency distribution.

The data plotted in this figure have a median value of 2.47 and a maximum value of 11.25: 57% of the values of colour difference are less than 3.0. The coloured patches that predict poorly are usually dark and saturated, especially dark and saturated blues.

- It is also useful to separately plot the predicted X, Y and Z tristimulus values against their corresponding input values. Fig. 10 shows an example of these plots, obtained using a linear regression model with no gamma correction. It can be seen that there are predicted tristimulus values that are negative as well as the curved line representing the power function relationship. Fig. 11 shows similar data but this time obtained using a quadratic regression with gamma correction. The relationship is still not totally linear but there is considerable improvement over the data in the previous figure. The fact that the relationship is not linear may be due to manner in which the digital data in the camera is reduced from, for example 10 bit, to 8 bit. This is sometimes achieved using a different linear relationship for the highlights, the mid-tones and the shadows. This is done to optimise the use of the reduced bit range but can be difficult to un-build without knowing the actual relationship.
- Once a suitable model is formulated then the coefficients of the regression can be applied to any other image captured using the same camera with the same lighting conditions to obtain approximate CIE colorimetric values, Fig. 12.

4. EXAMPLE DATA

Table 2 lists some example data based on the use of the GretagMacbeth ColorChecker SG. Data are shown with and without uniformity correction, and with and without gamma correction, and for the whole chart (140 patches), the whole chart minus the neutral surround patches which might weight the regression models (96 patches) and the Macbeth ColorChecker patches embedded in the SG chart (24 patches).

The following conclusions can be drawn:

- The quadratic model is always better than the linear model – by up to a factor of 4x.
- Uniformity correction always has a greater impact than gamma correction.
- Uniformity correction followed by gamma correction only marginally improves the resulting median value of colour difference.
- Removing the neutral surround patches only marginally improves the result for the quadratic models.
- Using the reduced number of colour patches actually enhances the result for the quadratic model with both uniformity and gamma correction. A major contributor to this must be that, because the smaller number of patches occupies a smaller area, the non-uniformity is not such a large contributory factor.

Table 2. Example results, expressed in terms of CIELAB colour difference, based on the use of the GretagMacbeth SG ColorChecker, X, Y, Z data, linear and quadratic regression models, with and without gamma correction, and with and without uniformity correction.

GretagMacbeth ColorChecker SG – all 140 patches					
Model	Uniformity correction	Gamma correction	ΔE^* (med)	ΔE^* (max)	Gamma
Linear	No	No	11.98	> 30	1.00
Linear	No	Yes	11.91	> 30	0.99
Linear	Yes	No	11.46	> 30	1.00
Linear	Yes	Yes	11.00	> 30	0.98
Quadratic	No	No	5.56	> 30	1.00
Quadratic	No	Yes	5.53	> 30	0.97
Quadratic	Yes	No	3.95	19.58	1.00
Quadratic	Yes	Yes	3.57	18.31	0.76
GretagMacbeth ColorChecker SG – minus 44 surround neutral patches					
Model	Uniformity correction	Gamma correction	ΔE^* (med)	ΔE^* (max)	Gamma
Linear	No	No	10.40	> 30	1.00
Linear	No	Yes	10.40	> 30	1.00
Linear	Yes	No	10.56	> 30	1.00
Linear	Yes	Yes	10.42	> 30	1.00
Quadratic	No	No	4.68	22.09	1.00
Quadratic	No	Yes	4.58	23.15	0.94
Quadratic	Yes	No	3.66	21.77	1.00
Quadratic	Yes	Yes	3.49	20.20	0.76
GretagMacbeth ColorChecker – 24 patches					
Model	Uniformity correction	Gamma correction	ΔE^* (med)	ΔE^* (max)	Gamma
Linear	No	No	11.69	> 30	1.00
Linear	No	Yes	11.69	> 30	1.00
Linear	Yes	No	12.31	> 30	1.00
Linear	Yes	Yes	12.31	> 30	1.00
Quadratic	No	No	4.49	16.26	1.00
Quadratic	No	Yes	3.49	10.93	0.62
Quadratic	Yes	No	3.92	13.66	1.00
Quadratic	Yes	Yes	3.10	10.62	0.76

5. FURTHER ANALYSIS

From experience, the idea of applying the regression models directly to the CIELAB data has not provided a better characterisation, but this may be due to the specific cameras investigated, together with their associated signal processing⁵.

Because the optimum results were found using the quadratic model with a value of gamma not equal to unity however, the use of the CIELAB coordinates L^* , a^* , b^* , was investigated. This requires the solution to the following equations, in matrix form:

$$\begin{bmatrix} L^* \\ a^* \\ b^* \end{bmatrix} = A \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (12)$$

The results obtained using this form of analysis are shown in Table 3.

Table 3. Example results, expressed in terms of CIELAB colour difference, based on the use of the GretagMacbeth SG ColorChecker, L^* , a^* , b^* data, linear and quadratic regression models, without gamma correction, and with uniformity correction.

GretagMacbeth ColorChecker SG – all 140 patches					
Model	Uniformity correction	Gamma correction	ΔE^* (med)	ΔE^* (max)	Gamma
Linear	Yes	No	5.65	21.54	1.00
Quadratic	Yes	No	3.88	17.47	1.00
GretagMacbeth ColorChecker – 24 patches					
Model	Uniformity correction	Gamma correction	ΔE^* (med)	ΔE^* (max)	Gamma
Linear	Yes	No	4.49	10.82	1.00
Quadratic	Yes	No	1.89	6.30	1.00

It can be seen that these results show some improvement over the use of X , Y , Z data. The use of gamma optimisation provided little further improvement in the values of CIELAB ΔE^* . Thus, for this particular camera processing using CIELAB data is to be recommended. The associated frequency and cumulative distribution data for the 24-patch GretagMacbeth ColorChecker chart and the quadratic model are shown in Fig. 13, with graphs of the predicted L^* , a^* and b^* values plotted against their corresponding input values shown in Fig. 14.

6. CONCLUSIONS

A procedure has been described that can characterise a digital camera such that the R , G , B pixel values can be transformed into CIE X , Y , Z tristimulus values or CIELAB L^* , a^* , b^* values. Using a Canon EOS 300D camera, the best median value of colour difference obtained is 3.10 with a maximum value of 10.62 for X , Y , Z data, and 1.89 with a maximum value of 6.30 for L^* , a^* , b^* data. For the intended purpose, this latter result is considered adequate. To put this result into perspective, a commercial system claims to be able to

achieve results, using more sophisticated regression techniques, where all values of colour difference are less than 3.0 with a median value of less than 1.0. It should be noted however, that the goal of the *MAVISCal* project is not to provide a system that gives perfect colour reproduction but to provide images that, in a colour sense, provide an aid to diagnosis. The statistics obtained represent such an imaging system.

A procedural list to perform the required characterisation can be found in the Appendix.

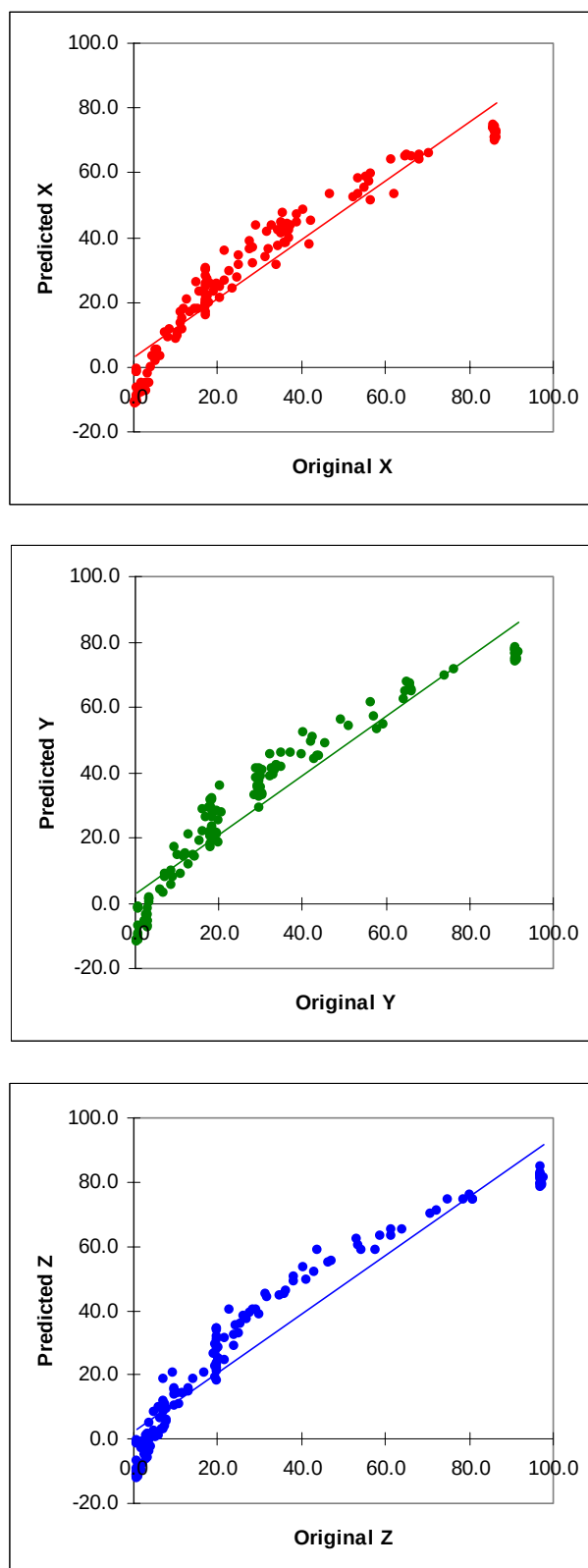


Figure 10. Predicted tristimulus values calculated using a linear model with no gamma correction and plotted as a function of their corresponding measured values:
Upper - X value, middle - Y value: lower - Z value.

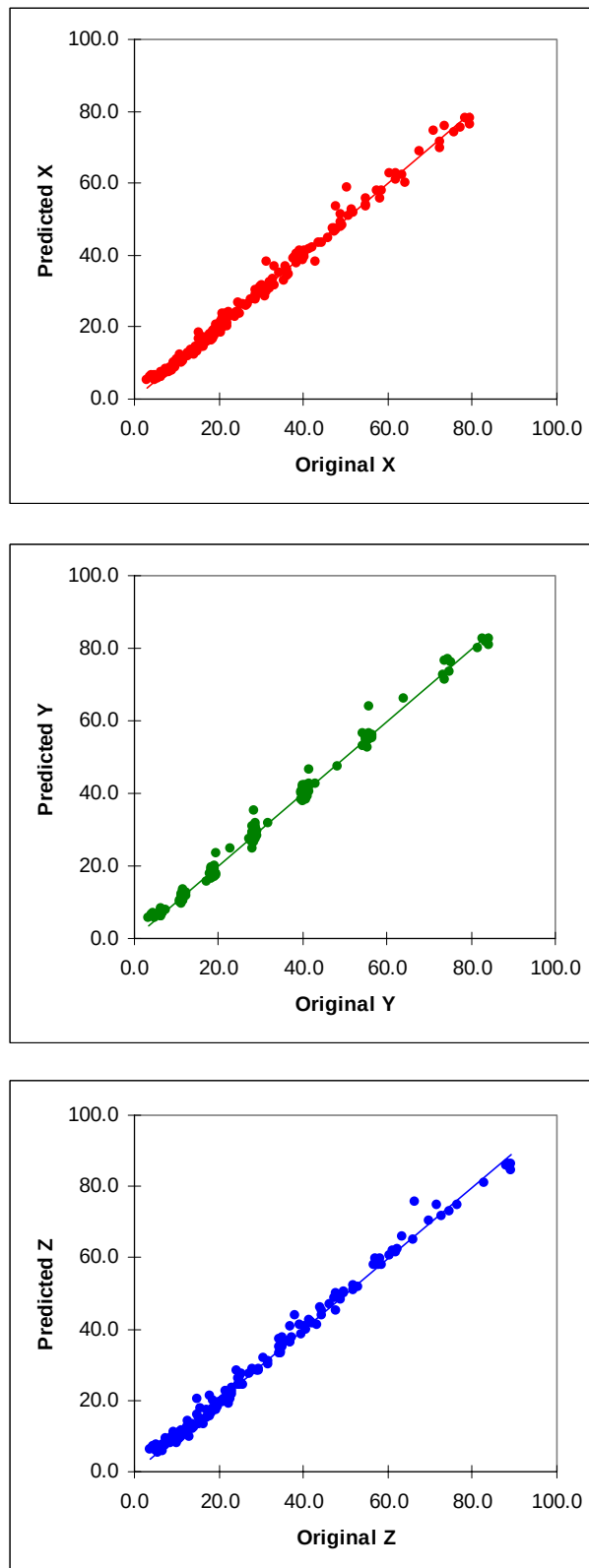


Figure 11. Predicted tristimulus values calculated using a quadratic model with gamma correction and plotted as a function of their corresponding measured values. Upper – X value, middle – Y value: lower – Z value.

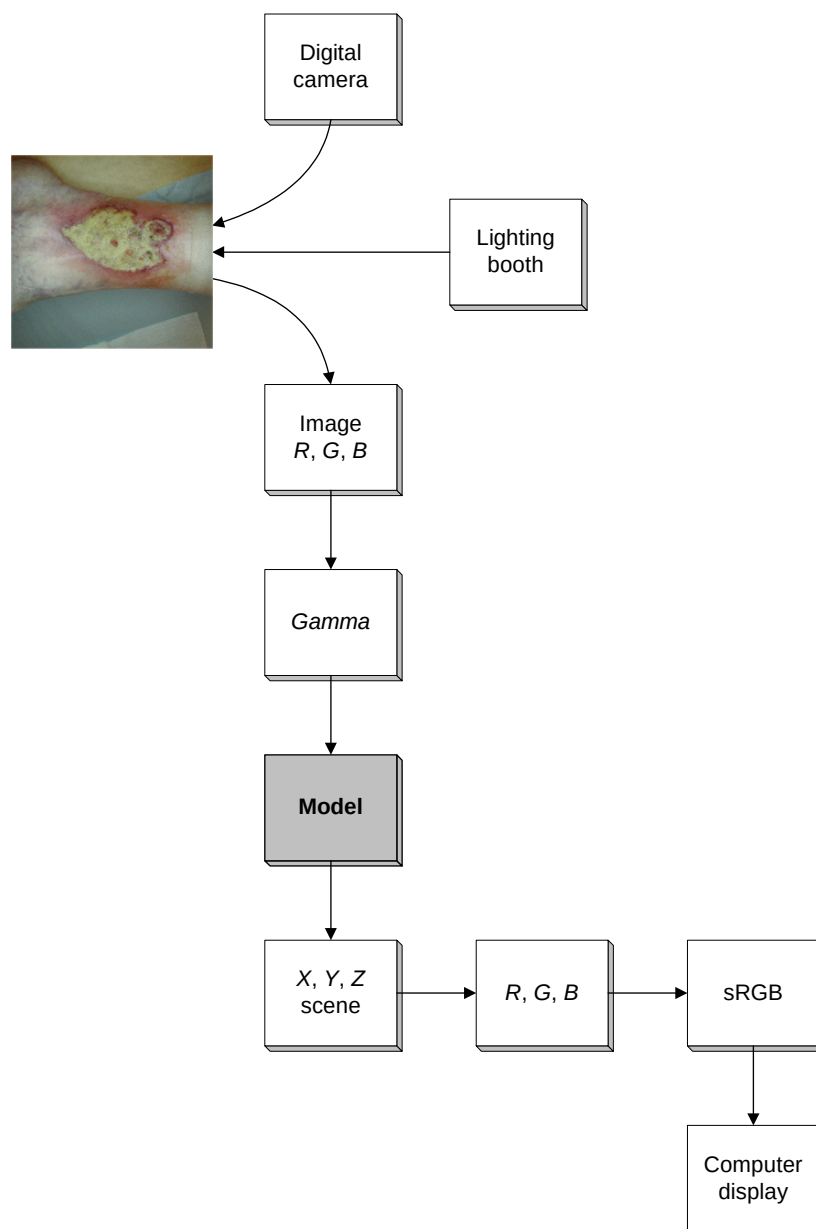


Figure 12. Procedure for applying the results of the characterisation process to an image.

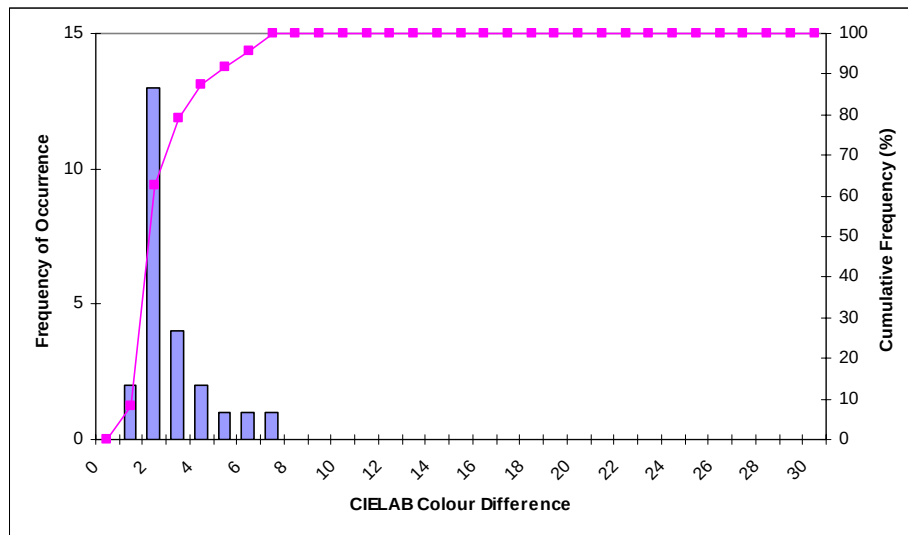


Figure 13. A histogram of values of CIELAB colour difference, ΔE_{ab}^* , obtained using a 24-patch GretagMacbeth ColorChecker chart, using L^* , a^* , b^* input data. Also shown is the associated cumulative frequency distribution.

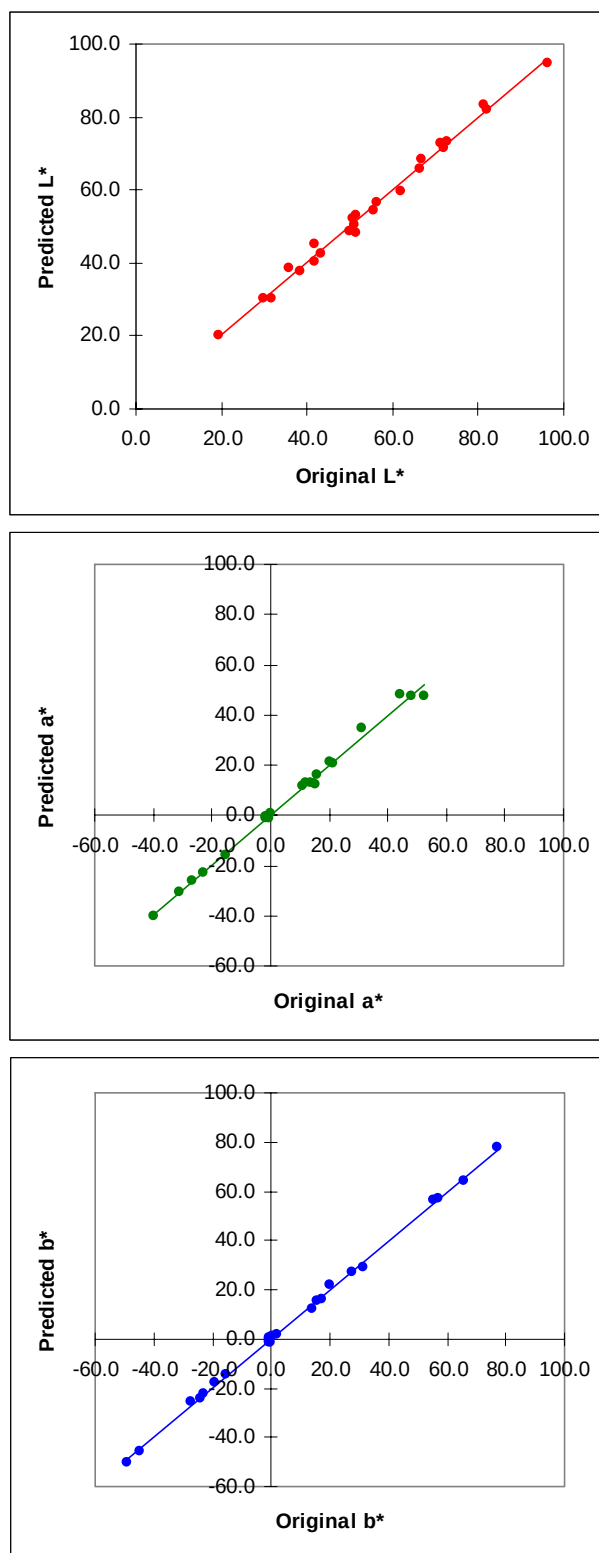


Figure 14. Predicted CIELAB coordinates calculated using a quadratic model and plotted as a function of their corresponding measured values.

Upper – L^* value, middle – a^* value: lower – b^* value.

7. ACKNOWLEDGEMENTS

The author would like to acknowledge the help, encouragement and support given by Richard Stevens of the National Physical Laboratory, Peter Plassmann and Carl Jones of Isotec Imaging, Glamorgan, and Francis Ring and Nigel Harris of the Royal National Hospital for Rheumatic Diseases, Bath.

MAVISCal was a Joint Industry Project supported through the DTI *Measurement for Innovators* scheme (www.npl.co.uk/measurement_for_innovators).

8. REFERENCES

1. See: http://www.comp.glam.ac.uk/pages/staff/pplassma/MedImaging/PROJECTS/WOUND_S/MAVIS-II/INDEX.HTML
2. Holst, G.C., *CCD Arrays, Cameras and Displays*, SPIE Optical Engineering Press, Washington, 2nd edition, 1998.
3. Pointer, M.R. *Digital Cameras for Colour Measurement*, NPL Report COEM/S30, 2000.
4. Saurav, G., *Digital Imaging Handbook*, CRC Press, 2002: especially Ch. 12.
5. Pointer, M.R., Attridge, G.G. and Jacobson, R.E., Practical camera characterisation for colour measurement, *Imaging Science Journal*, **49**, 63-80, 2001.
6. CIE Publication 15:2004, *Colorimetry*, CIE Central Bureau, Vienna, 2004.
7. See: <http://www.avantes.com/>

APPENDIX: PROCEDURE

1. Select a suitable test target where the CIE colorimetry for each patch is known, calculated using the required CIE illuminant and CIE standard observer: for example, CIE Standard Illuminant D65 and the CIE 2° Standard Observer are usually appropriate. If these colorimetric data are not available, then measurements of the spectral reflectance of each patch are required and the necessary CIE tristimulus values, X_m, Y_m, Z_m , and CIELAB colorimetric coordinates, L_m^*, a_m^*, b_m^* , calculated using Eqns. 3 and 9 above.
2. An image of the test target is then made using the digital camera requiring characterisation together with a suitable light source. The image should be stored using the minimum processing and compression possible.
3. An image may also be obtained of a sheet of neutral paper on which a grid has been drawn to provide the exact location of the patches in the colour chart. This grid will be used to assess the uniformity of the illumination.
4. The R, G, B values for each of the pixels in the two images then need to be obtained. Software is required that can open the image and calculate average R, G, B values of an array of pixels for each colour patch: the number of pixels will be a function of the size of the image but the minimum number considered should be at least 200. This gives the average R, G, B values of each patch in the colour target.
5. A correction for the non-uniformity of the illumination can be calculated using the G pixel values of the image of the neutral paper. A factor, F_i , is calculated using Eqn. 7 above.
6. A suitable regression procedure is then used to model the image R, G, B data to the corresponding measured CIELAB data, L_m^*, a_m^*, b_m^* . This requires the solution to the equations:

$$L_m^* = a_1 R + a_2 G + a_3 B + a_4 R G + a_5 R B + a_6 G B + a_7 R^2 + a_8 G^2 + a_9 B^2 + k_a$$

$$L_m^* = b_1 R + b_2 G + b_3 B + b_4 R G + b_5 R B + b_6 G B + b_7 R^2 + b_8 G^2 + b_9 B^2 + k_b$$

$$L_m^* = c_1 R + c_2 G + c_3 B + c_4 R G + c_5 R B + c_6 G B + c_7 R^2 + c_8 G^2 + c_9 B^2 + k_c$$

It is convenient to carry out these calculations using the *LinEst* Array Function in Microsoft Excel®.

7. The predicted CIELAB data, L_p^*, a_p^*, b_p^* , are then calculated using the parameters $a_{1-9}, b_{1-9}, c_{1-9}$ applied to the image R, G, B values.
8. The colour differences between the measured data, and those predicted using the model may be calculated using Eqn. 10.

9. To further reduce these data, a histogram may be plotted by assigning the values of colour difference, ΔE_{ab}^* , to bins of a defined size: see, for example, Fig. 9. This histogram data can then be used to produce a cumulative frequency distribution.
10. The median of the distribution of the values of colour difference can be calculated using the *Quartile* Function in Excel.
11. Once a suitable model is formulated then the coefficients of the regression can be applied to any other image captured using the same camera with the same lighting conditions to obtain approximate CIE colorimetric values.
12. If output of the process is required in the form of sRGB coordinates, then further processing is necessary*. This involves the following steps:
 - a. Calculate the CIE tristimulus values X_p, Y_p, Z_p from the CIELAB coordinates L_p^*, a_p^*, b_p^* . This can be achieved using the following generic equations:

$$f(Y/Y_n) = (L^* + 16)/116$$

$$f(X/X_n) = a^*/500 + f(Y/Y_n)$$

$$f(Z/Z_n) = f(Y/Y_n) - b^*/200$$

$$\begin{aligned}
 \text{and } X &= X_n [f(X/X_n)]^3 && \text{if } f(X/X_n) > 6/29 \\
 X &= (108/841) X_n [f(X/X_n) - 4/29] && \text{if } f(X/X_n) \leq 6/29 \\
 Y &= Y_n [f(Y/Y_n)]^3 && \text{if } f(Y/Y_n) > 6/29 \\
 Y &= (108/841) Y_n [f(Y/Y_n) - 4/29] && \text{if } f(Y/Y_n) \leq 6/29 \\
 Z &= Z_n [f(Z/Z_n)]^3 && \text{if } f(Z/Z_n) > 6/29 \\
 Z &= (108/841) Z_n [f(Z/Z_n) - 4/29] && \text{if } f(Z/Z_n) \leq 6/29
 \end{aligned}$$

where the tristimulus values X_n, Y_n, Z_n are those of the specified neutral stimulus.

- b. Calculate the corresponding sRGB values using the matrix equation:

$$\begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix}$$

* IEC 61966-2-1, *Multimedia systems and equipment – Colour measurement and management – Part 2-1: Colour management – Default RGB colour space – sRGB*, 1999.

c. If W_{DC} is the white digital count and K_{DC} the black digital count, then

$$R'_{sRGB} = \frac{(R_{sRGB} - K_{DC})}{(W_{DC} - K_{DC})}$$

d. If W_{DC} and K_{DC} are assumed to have values of 255 and zero respectively, then this equation reduces to:

$$R'_{sRGB} = R_{sRGB} / 255$$

$$\text{If } R'_{sRGB} \leq 0.04045 \text{ then } R'_{sRGB} = R'_{sRGB} / 12.92$$

$$\text{If } R'_{sRGB} > 0.04045 \text{ then } R'_{sRGB} = \left[\frac{R'_{sRGB} + 0.055}{1.055} \right]^{2.4}$$

e. Then renormalize:

$$R_{sRGB} = R'_{sRGB} * 255$$

with similar equations for G and B .

