Colour Characterisation of a High-Resolution Digital Camera

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Abstract

A calibrated monochromatic light source was used to characterise a high-resolution digital camera, by measuring *RGB* responses of the camera at successive wavelength intervals throughout the visible spectrum. The results were compared with those obtained by the conventional polynomial modelling technique on colour patches measured directly by the camera using a target. Analysis of the results indicated that accuracy of the modelling technique was lower because of flare and non-uniformities resulting from imaging of the whole chart.

Introduction

A new European Framework-5 RTD project, 'Veridical Imaging of Transmissive and Reflective Artefacts' (IST-2000-28008 VITRA), has the objective to facilitate the capture of digital heritage images in historic buildings. A robotic carrier will be developed to position a high-performance digital camera plus illumination up to 15 metres above floor level, enabling the acquisition of high quality images of frescoes, mosaics, architectural details and stained glass windows. A high-performance digital camera back, the Jenoptik *eyelike MF*, will be used, mounted on a Rollei medium-format camera body with Zeiss lenses. Suitable lighting will be developed for both interior and exterior illumination purposes, together with image processing algorithms for image registration and colour correction, and techniques for the interactive 3-D visualisation of images. In order to ensure that the images captured by the VITRA system will be colorimetrically accurate, the digital camera must be characterised, i.e. the relationship established between an arbitrary physical colour stimulus and the corresponding signals generated by the camera.

The most common technique for digital camera characterisation consists of presenting the camera with a series of colour patches of known colorimetric values (e.g. measured as CIE *XYZ*) and recording the averaged *RGB* output signals for each patch.[1] Polynomial fitting techniques can then be applied to interpolate the data over the full gamut to generate inverse transformations. This method is termed Colorimetric-Based Camera Characterisation, and the results are specific to the illumination under which the colour patches were captured.

Alternatively, characterisation can be performed by using a monochromatic light to determine the camera response directly, presented to the camera via one port of an integrating sphere. By scanning the wavelength output of the monochromatic light source through the full visible spectrum, and recording the output *RGB* camera signals at each wavelength, the camera's responses can be measured directly. This is termed Spectral-Based Camera Characterisation. The advantage of this method is that if the spectral sensitivity of the camera is known precisely then its response can be predicted under any illumination. It has been shown in previous studies[6,9] that the performance of the spectral method is good enough to yield low mean-square errors when used to predict the calibration data set. The above two methods are described in the document ISO/WD 17321-1, 'Graphic technology and Photography – Colour characterisation of digital still cameras (DSCs)'.[2]

The aim of the present study was to use a calibrated monochromatic light source to characterise the VITRA project's digital camera, and to compare results with the conventional polynomial modelling technique. The following steps were involved:

1. Measure *RGB* responses of the camera (spectral sensitivity) at successive wavelength intervals throughout the visible spectrum (380-760 nm).
2. Set up a colour checker chart illuminated by white light and establish the white reference level. Compute average *RGB* pixel values for each patch.
3. Use a spectrophotometer to measure the spectral reflectance of each patch of the colour chart. Measure the spectral power distribution of the illumination with a telespectroradiometer.
4. Compute the predicted camera response to each patch (product at each wavelength of the illuminant power, patch reflectance and camera sensitivity) and compare with the actual signals from the camera.
5. Use a polynomial fitting procedure to characterise the camera in the given illuminant, and compare its performance (predictions of a set of test colours) with the spectral results.

Spectral Camera Characterisation

The *RGB* sensor responses of the digital camera can be represented as:

$$\begin{aligned} R &= \sum_{n=1}^{N} E(\lambda_n)\ S(\lambda_n)\ r(\lambda_n) \\ G &= \sum_{n=1}^{N} E(\lambda_n)\ S(\lambda_n)\ g(\lambda_n) \\ B &= \sum_{n=1}^{N} E(\lambda_n)\ S(\lambda_n)\ b(\lambda_n) \end{aligned} \quad (1)$$

where:
$E(\lambda_n)$ is spectral power of illumination at wavelength λ_n;
$S(\lambda_n)$ is the object's spectral reflectance wavelength λ_n;
$r(\lambda), g(\lambda), b(\lambda)$ are sensitivities of three camera channels; λ spans the whole visible spectrum from 380 to 760 nm.

N is the sampling ratio chosen to represent the continuous function of wavelength with sufficient accuracy. An interval of 10 nm results in 39 samples across the range from 380 to 760 nm; an interval of 5 nm results in 77 samples. In Eq. (1), it is assumed that the illumination $E(\lambda)$ is known and the spectral sensitivities of the camera sensors can also be obtained. But note that many different surface reflectance distributions may produce the same *RGB* values. Metamerism occurs because the same tristimulus values can be derived from different spectral functions of both illumination and reflectance.

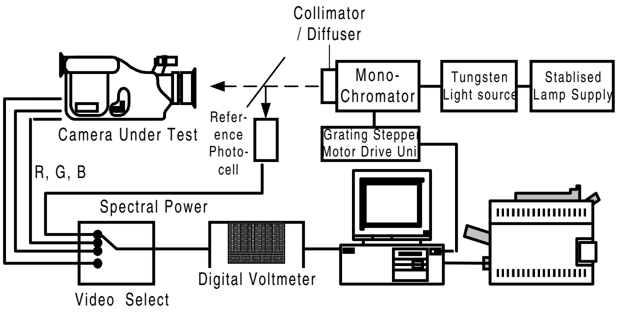

Figure 1. Typical Spectrophotometric Measurement System (Reproduced from Dalton[3])

By using monochromatic light in the range of the visible spectrum (380 to 730 nm), the spectral sensitivities of the camera's combined optics and RGB sensors can be measured directly. This method is more suitable for laboratory conditions and can be regarded as more fundamental than colorimetric polynomial-fitting techniques.[3] Preparations before the measurement include calibrating the wavelength, bandwidth and relative spectral output power of the monochromatic light source. Attention must be paid to avoiding stray light and spurious flux of unwanted higher orders in the output of the monochromator. Polarisation must be eliminated with a diffusing glass or integrating sphere to remove any possibility of altering the behaviour of the camera's colour separation systems (e.g. prisms or filters).

Calculation procedures are recommended by the European Broadcasting Union[4] as follows:

- Conversion of *R,G,B* values to CIE tristimulus *X,Y,Z.*
- Calculation of CIE 1976 chromaticities *u',v'*.
- Calculation of colour difference ΔE^*_{uv}.

Measurement Procedure

For this study, the geometric setup for initial radiometric calibration of the monochromatic source was as illustrated in Figure 2. A Hewlett-Packard E3610A DC Power Supply controlled the input voltage applied to the monochromator to produce the desired wavelength. The monochromatic light illuminated a diffuse white tile and formed a round spot. The illumination/measurement geometry was 45°/0° and the distance between white tile and object (TSR or camera) lens was set to 1000 mm.

When using the monochromatic light to characterise the camera, the light output from the fibre was directed onto the centre of the camera lens. The end of the optic fibre was covered by a white opal glass diffuser, to protect the camera CCD sensors and to ensure an even luminance distribution. Selected Kodak Wratten gelatine filters from N.D. 0.1 to 0.9 were placed in front of the lens to control the intensity of the light entering the camera. The laboratory for the experiments was kept in complete darkness with a thick black curtain covering the door (no windows).

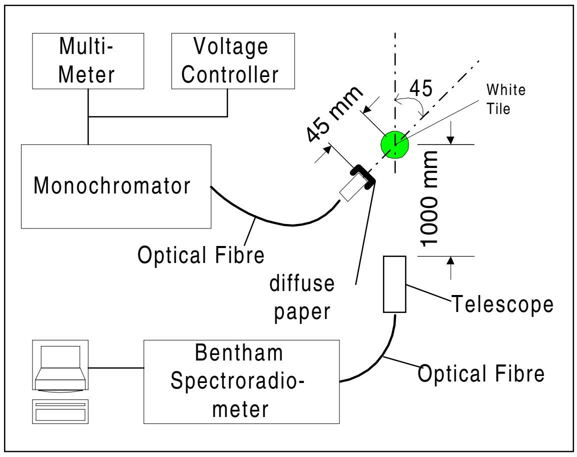

Figure 2. Geometry for Source Calibration

The colour test target was the GretagMacbeth DC chart, which has been recently developed for digital photography. Figure 3 illustrates the imaging setup. The 45°/0° illumination/measurement geometry was again applied, with two light-sources symmetrically illuminating the colour chart at the centre of the viewing field. The camera was mounted on the supporting arm of a copy-stand above the target placed in the central field at 0°. The spectral power distribution of the two graphic arts (nominally D50) fluorescent lamps was measured at 10 nm intervals by a Minolta CS1000 spectroradiometer, with result as shown in Figure 4.

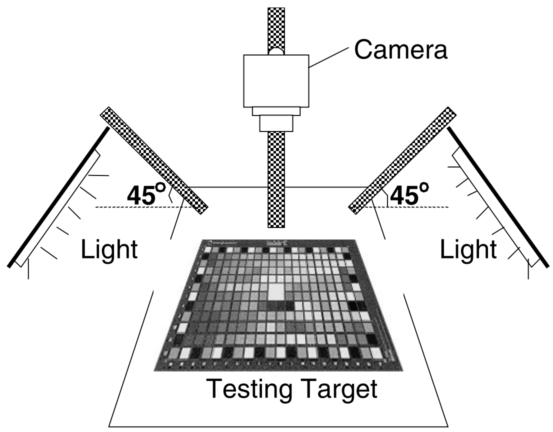

Figure 3. Geometry Set-up for Colour

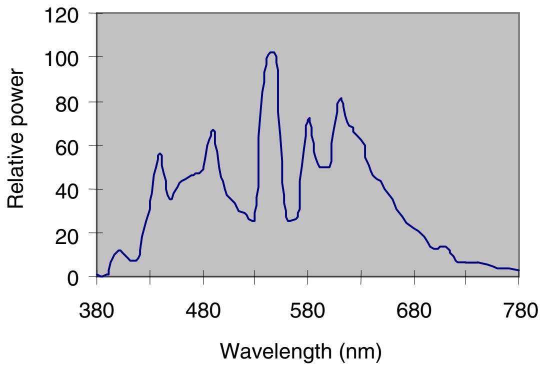

Figure 4 Spectral Power Distribution of Light Source

The luminance profile of the GretagMacbeth DC colour chart was determined by analysing the signal values of the large central white patch and 20 white patches around the edges. *MatLab®* image processing software was used to calculate the profile across the surface of the chart, as shown in Figure 5.

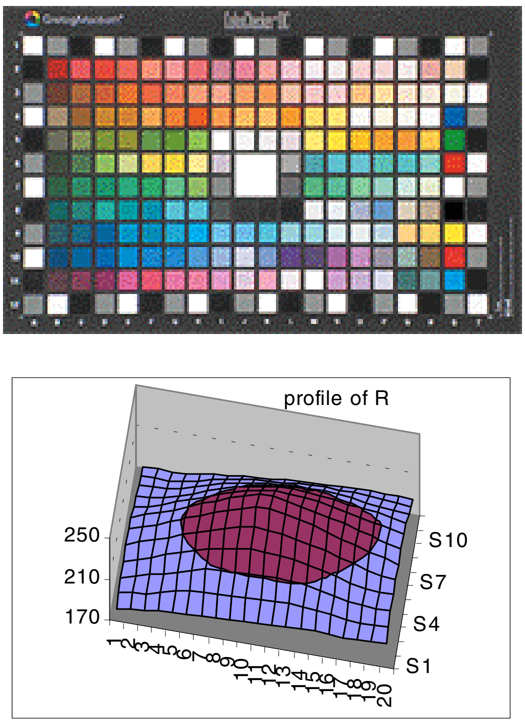

Figure 5. GretagMacbeth DC Chart (top) and its Luminance Profile (bottom)

Camera Characterisation Results

Monochromatic light was presented to the camera at each wavelength along the whole visible spectrum (380 to 780nm at 5nm intervals), and the signals captured by the camera represent their spectral sensitivities, as shown in Figure 6. The results were corrected for the spectral transmittance of the pearlescent glass diffusing filter placed in front of the optic fibre. Linear interpolation between the measured values was applied to reconstruct the spectral sensitivity functions, but this could lead to some errors near the peaks of the curves. A more sophisticated technique such as Wiener estimation could be employed to improve the accuracy of spectral reconstruction.[9]

Knowing the spectral sensitivities of the three camera channels, the spectral reflectance of the colour patches of the two colour charts, and the SPD of the light source (Figure 4), enabled the expected *R*, *G* and *B* values of each colour patch to be computed by Eq. (1). The results are termed “predicted *RGB*”.

The patches of the colour chart were captured directly by imaging the whole chart with the camera. The *RGB* pixel values were averaged over each patch, and then corrected according to the luminance profile, termed “measured *RGB*”. The distribution of colour differences between these two data sets indicated the degree of agreement between the two techniques. The results for the predicted and measured *R, G* and *B* values (8-bit data in range 0-255) with the Macbeth Color Checker chart are plotted in Figure 7. It is evident that the response is non-linear and that there is considerable scatter in the Red and Blue channels.

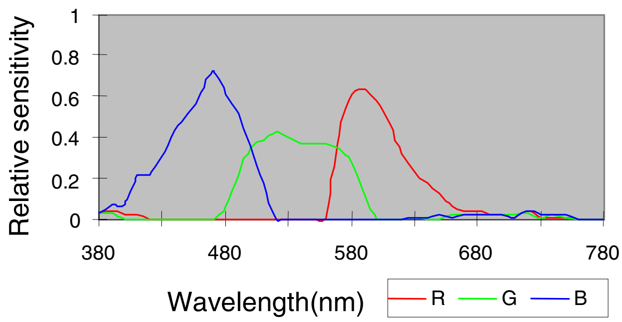

Figure 6 Spectral Sensitivities of Digital Camera

The tone reproduction characteristics of the three channels were established by plotting the respective normalised signal values against the normalised luminance measured for the 12 grey patches at the centre of the chart. When plotted on log-log axes as shown in Figure 8, the data falls on a straight line of slope approximately 0.58 for all three channels, indicating that the camera output follows a power function of luminance. The *RGB* patch data was linearised by applying the inverse of this function, giving the predicted vs measured values shown in Figure 9. This step is a necessary preliminary to the polynomial fitting procedure.[8]

It can be seen that the predicted values correlated well with the measured values for the green channel, but there was considerable scatter in the red and blue channels, caused by sensor and quantising noise plus optical flare in the capture of the colour chart as a single image. Greater accuracy would have been achieved by imaging each patch of the chart separately at the centre of the image field, masking off the surrounding patches. But the use of a single image for the chart, accompanied by luminance profile correction, is more typical for real image capture and the results are therefore more representative of the camera’s performance.

Polynomial regression was applied to the measured values of the chart to determine the best 3x11 secondorder transformation from *RGB* values to the CIE *XYZ* colour space.[5] The relationship can be represented as follows:

$$\mathbf{H} = \mathbf{M}\ \mathbf{R} \quad (2)$$

where:
H is the vector $[X\ Y\ Z]^T$
M is a 3x11 matrix of coefficients
R is the vector $[R\ G\ B\ R^2\ G^2\ B^2\ RG\ RB\ GB\ RGB\ 1]$

The coefficient matrix **M** was computed to be as follows (here rounded to two decimal places for clarity):

24.98	2.27	4.51	1.36	0.69	-2.56	-1.30	0.81	1.18	-0.05	0.09
11.31	24.90	-2.16	3.20	-0.75	0.18	-1.25	-2.02	0.51	0.01	-0.09
3.07	-4.84	30.33	8.24	0.29	-1.01	-3.83	-4.68	1.72	-0.29	-0.14

Colour difference values between the predicted and measured values of each patch were then calculated in CIELAB colour space. Figure 10 shows the ΔE^*_{ab} values plotted against L^*, C^*_{ab} and h_{ab}. The trend is that errors increase with decreasing lightness and increasing chroma, whereas they are rather uniformly distributed with respect to hue. The mean ΔE^*_{ab} value was 1.8 and maximum ΔE^*_{ab} value 10.3.

Note that the results exclude data from two colour patches in the DC chart labelled as S4 and S8. These two patches have glossy surfaces – S4 is dark blue, S8 is black – and their luminance values are very low. But because they are glossy with very strong specular reflectance, the luminance signals captured by the camera are high, which leads to incorrect predictions.

Conclusions

It was demonstrated that the method of characterising a digital camera using a calibrated monochromatic light source produced results of comparable accuracy to the more common polynomial fitting technique, with the added advantage that by determining the spectral sensitivity distribution, the camera response could be predicted under any illuminant with known SPD.

Use of a monochromatic source is not the only method of obtaining an estimate of the spectral sensitivity of the camera's colour channels. Barnard and Funt[7] have demonstrated that by promoting smoothness of the curves, and using constraints on the sensor functions such as positivity, a good approximation of the spectral functions was achievable. They used a conventional 24-patch Macbeth Color Checker which was illuminated by a combination of 26 illuminant filter combinations, yielding 612 camera patch measurements. In order to minimise the measurement error, they resorted to various procedures, including use of an X-Y table to place each patch of the chart in the centre of the camera's field of view, masking the surrounding patches to eliminate flare, and averaging camera measurements over 50 frames.

Finlayson, Hordley and Hubel[6] showed that characterisation could be achieved from a single image of a Macbeth Color Checker under D65 illumination. Applying three constraints on the permissible sensitivity functions, namely that they should be positive, have limited modality and be band-limited, allowed quadratic programming techniques to be applied to give good estimates for both digital cameras and scanners. A regression procedure was followed with between 9 and 15 basis functions, representing the camera curves as a linear combination of sine and cosine functions. Measured spectral data for both the illuminant and each patch of the chart was required for the process and a linear camera response was assumed.

We plan to test these methods for the *eyelike MF* camera and also to demonstrate the performance of the resulting spectral sensitivity curves vs those measured directly with the monochromatic source to predict the camera output for typical heritage colours (both transmissive and reflective) under a range of real illumination sources.

Acknowledgements

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References

1. A.J. Johnson, Methods for characterizing colour scanners and digital cameras, *Displays*, Vol. 16, No. 4, 183-192, 1996
2. ISO/WD 17321-1, Graphic technology and photography – Colour characterisation of digital still cameras (DSCs) – Part 1: Stimuli, metrology, and test procedures, 2000.
3. C.J. Dalton, Topics in Television Colorimetry, *Proc. Easter School – Colour Management for Information Systems*, 134-150, University of Derby, 1997.
4. EBU, 'Methods of measurement of the colorimetric fidelity of television cameras – Measurement procedure', Supp. No. 1, Technical Report 3237-E, Brussels, May 1983.
5. G. Hong, M.R. Luo and P. Rhodes, A Study of Digital Camera Colorimetric Characterisation Based on Polynomial Modelling, *Color Research and Application*, Vol. 26, No. 1, 76-84, Feb 2001.
6. G.D. Finlayson, S. Hordley and P.M. Hubel, Recovering Device Sensitivities with Quadratic Programming, *Proc. 6th IS&T/SID Color Imaging Conf.*, 90-95, 1998.
7. K. Barnard and B. Funt, Camera calibration for color research, *Proc. Human Vision & Electronic Imaging IV*, SPIE Vol. 3644, 576-585, 2000.
8. P.L. Vora, J.E. Farrell, J.D. Tietz and D.H. Brainard, Digital color cameras – 1 – Response models, *HP Technical Report 97-53*, Available from http://color.psych.ucsb.edu/hyperspectral/ , 1997.
9. P.L. Vora, J.E. Farrell, J.D. Tietz and D.H. Brainard, Digital color cameras – 2 – Spectral response, *HP Technical Report 97-54*, Available from http://color.psych.ucsb.edu/hyperspectral/ , 1997.

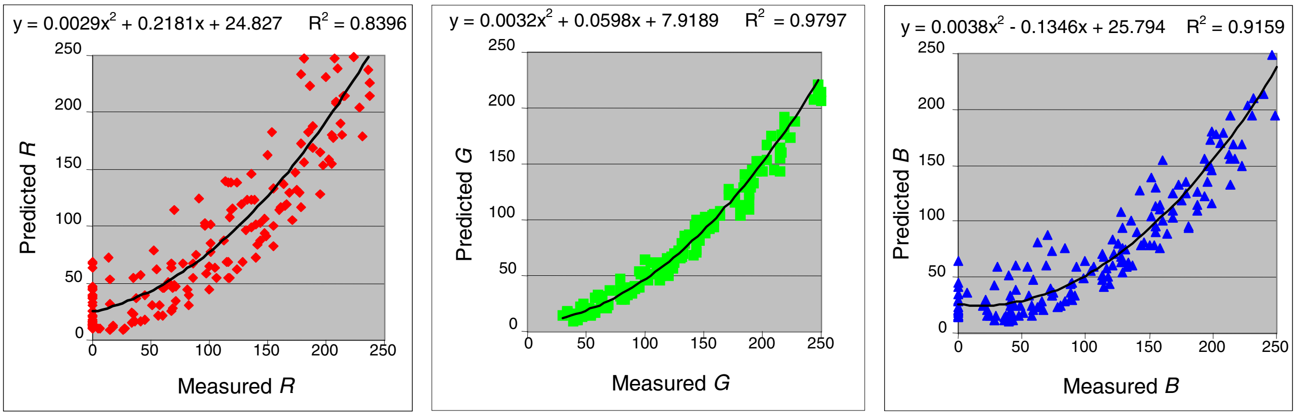

Figure 7. Predicted against measured values of Red, Green and Blue camera output signals.

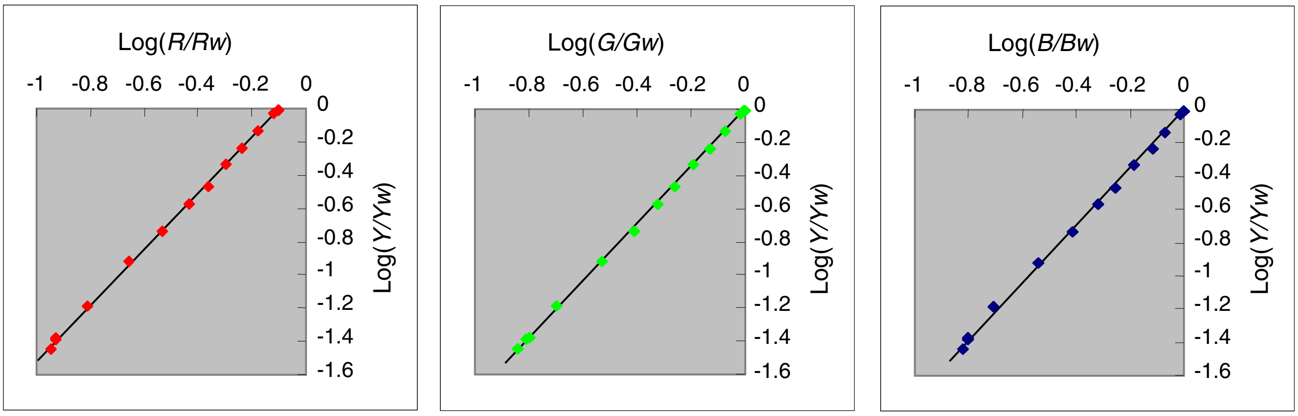

Figure 8. Tone reproduction characteristics of Red, Green and Blue channels, plotted on log-log axes.

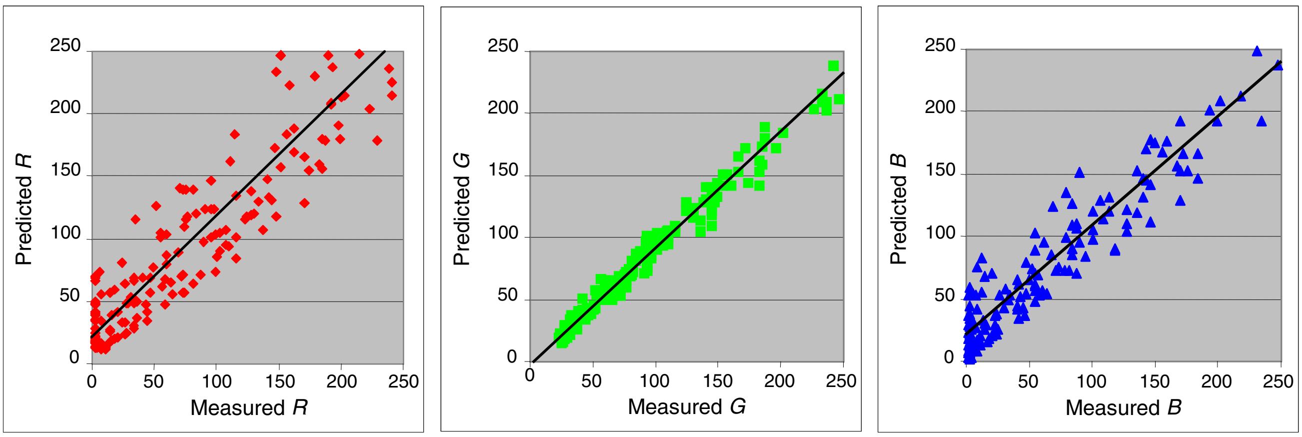

Figure 9. Predicted against measured values of Red, Green and Blue camera output signals after linearisation.

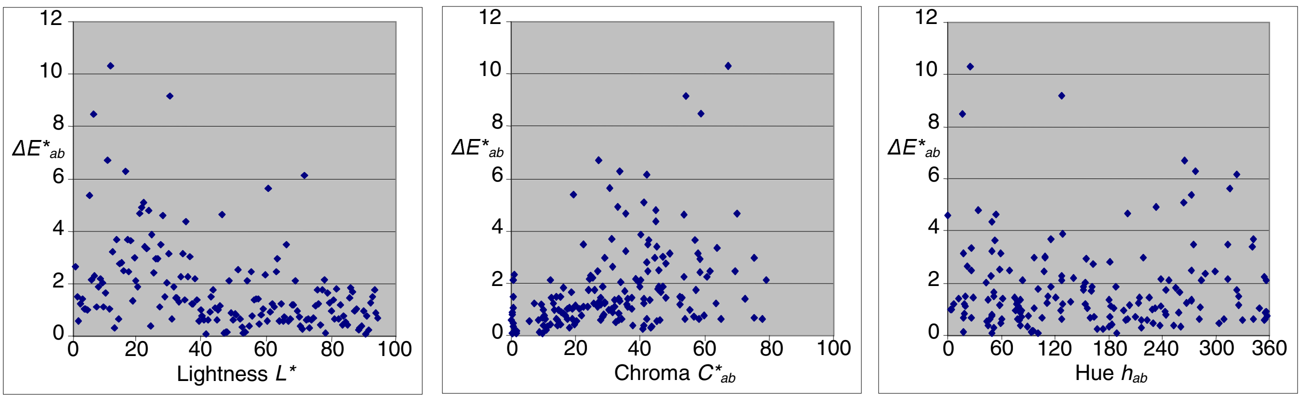

Figure 10. Error (ΔE^*_{ab}) for each patch vs Lightness, Chroma and Hue.