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## Area Array Characterisation

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ABSTRACT

This report considers the options available to characterise imaging luminance and colorimetric measurement devices. These devices use an area array, usually a charge coupled device, as their detector and, in addition, are able to 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 colorimetric and/or photometric information in a scene. Included in this category of device are digital cameras and imaging photometers. Digital cameras used to measure colorimetric coordinates require calibration in a relative sense, a process usually termed characterisation; imaging photometers for measuring luminance require calibration in an absolute sense. It is assumed in this report that the characterisation is to be made spectrally to derive either the relative spectral responsivity and/or the absolute spectral responsivity. A separate report will deal with aspects of digital camera characterisation using coloured test targets of known colorimetry.

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# AREA ARRAY CHARACTERISATION

**Michael R Pointer**

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# AREA ARRAY CHARACTERISATION

## INTRODUCTION

This report considers the options available to characterise imaging luminance and colorimetric measurement devices. These devices use an area array, usually a charge coupled device (CCD), as their detector and, in addition, are able to 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 colorimetric and/or photometric information in a scene.

Included in this category of device are digital cameras and imaging photometers. Digital cameras used to measure colorimetric coordinates require calibration in a relative sense, a process usually termed characterisation; imaging photometers for measuring luminance require calibration in an absolute sense. It is assumed in this report that the characterisation is to be made spectrally to derive either the relative spectral responsivity and/or the absolute spectral responsivity. A separate report will deal with aspects of digital camera characterisation using coloured test targets of known colorimetry.

## AREA ARRAY DETECTORS

A silicon based area-array photo-detector is a solid-state array that converts light intensity – photons – into measurable voltage signals via the generation of electric charge in a well capacitor. There are two basic detector types: the photodiode and the metal-oxide silicon capacitor. CCD refers to a semiconductor architecture in which charge is read out of storage areas. This architecture has three basic functions: charge collection, charge transfer and the conversion of this charge into a measurable voltage: the basic building block is the metal-oxide silicon (MOS) capacitor referred to as a gate. By manipulating the gate voltages, charge can be either stored or transferred[1].

The most common individual detectors have a pixel width of 6 μ to 16 μ and are naturally sensitive in the visible region of the spectrum. Area arrays vary in size with 640 by 512 pixels being the minimum suitable for video quality pictures, and bespoke detectors being available with eight megapixels and more. Arrays are sometimes square but more usually have an aspect ratio of either 3:2 or 4:3 – the former accords with traditional 35 mm photographic film and the latter with conventional 625 line (PAL) or 525 line (NTSC) broadcast television.

A larger pixel size provides higher dynamic range and lower noise, enabling the array to operate at a higher ISO speed (a recognised measure of the sensitivity of the detector to light – originally standardised for photographic film but now translated for digital photography (see below). However, the larger pixel size also makes the sensor physically larger and more costly, and any associated camera lens is likewise more bulky and expensive.

Other technologies available include charge injection devices (CID), where the pixels consist of two MOS capacitors whose gates are separately connected in rows and columns, and complimentary metal-oxide semiconductor (CMOS) devices, which have the advantage that one or more active transistors can be integrated onto each pixel. These latter devices have become more common in consumer digital cameras because they are cheaper to manufacture compared with CCD devices, and they consume less power; they do however, generate more noise in the signals produced. It should be remembered that both CCD and CMOS devices rely on an analogue response to input light. CCD devices then require an external analogue-to-digital converter; CMOS devices usually have this converter on the array chip and thus provide a digital output.

An important consideration in any array design is the fill-factor, or the percentage of the pixel that is devoted to capturing light. For a CCD array, this factor can approach 100% but for CMOS arrays it is lower because of the additional circuitry associated with each pixel. A CMOS array with large pixels will have a higher fill-factor compared with an array with smaller pixels.

An excellent overview of silicon detector array device technology can be found in the NPL/Sira report produced as part of the NMSD 1997-2001 programme[2]. While this report deals explicitly with the use of area-array devices that are to be found in instruments used for spectrometry, its general introduction is applicable to all equipment that uses area arrays to convert incoming light to electrical signals: this includes digital cameras and imaging photometers.

**Spectral response and quantum efficiency**

The basic visible region, spectral response of a silicon detector is shown in Figure 1 and is a function of the quantum efficiency of the device, a measure of the efficiency with which incident photons are detected, Figure 2.

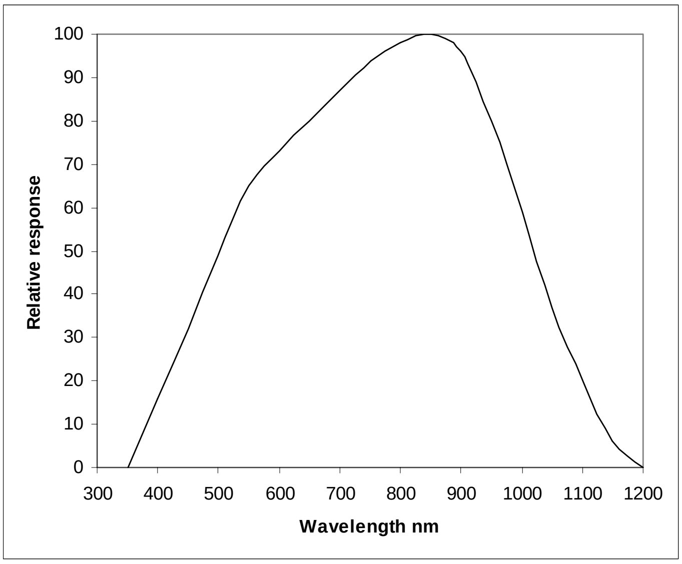


Figure 1. Typical relative spectral responsivity of a silicon-based detector.

In the ideal device, the quantum efficiency should have a value of unity because it can be arranged that the absorption of one photon produces one electron-hole pair. Some incident photons, however, may not be absorbed due to reflection, some may be absorbed where the electrons cannot be collected, and some may be lost due to electron-hole recombination. Thus, the quantum efficiency is not 100%. The drop in quantum efficiency with increasing wavelength is due to the longer wavelength photons penetrating deeper into the silicon before they are absorbed and thus the released electrons have a greater probability of being scattered and migrating to the anti-blooming drains rather the potential wells.

The quantum efficiency is also reduced by the anti-reflection coating that is often put on the front surface of the detector array. The overall spectral response is usually spectrally selective and relatively flat in the visible part of the spectrum, Figure 2.

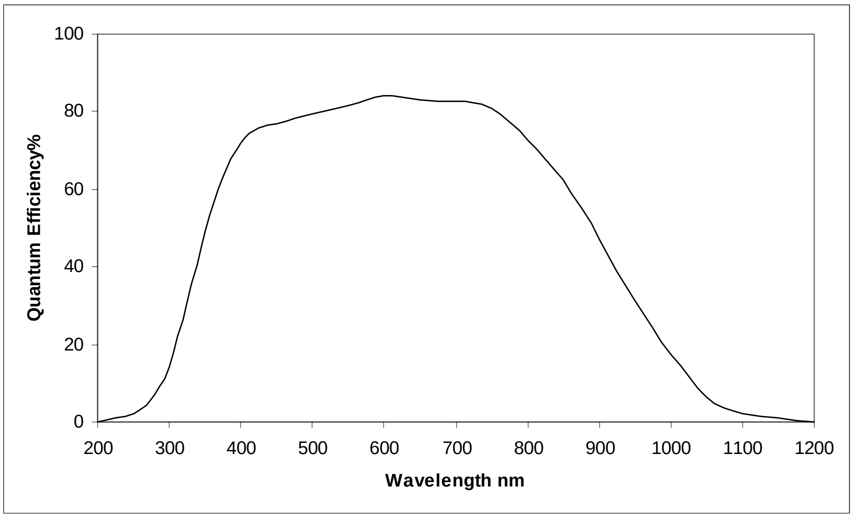


Figure 2. Typical quantum efficiency (%) as a function of wavelength (nm) for a typical back illuminated silicon area-array device.

**ASSUMPTIONS**

In order to fully characterise an area array there must be access to the electrical signals coming from the actual array device. This access is rarely available to other than the manufacturer and so recourse must be made to using the ‘output’ of the equipment in whatever form this takes. For a spectrometer, this will be the response, usually as a function of wavelength; for a digital camera, this will be an image of that scene, usually in colour; for a video photometer, this will also be a spatial array of information representing the luminance distribution of the scene, again in the form of an image of the scene. In nearly all cases the information will be digital because one of the first processes in the signal processing chain is the conversion of the analogue output from the array detector device, after some amplification, into a digital signal.

This digital signal may offer a bit depth of 10, 12, 14 or even 16 bits per pixel whereas a subsequent display device may only be able to use 8 bits. Thus the bit depth influences the precision available for the intended measurements and some devices will reduce the depth to conform to the requirements of the display. This translation will usually be carried out in digital space, as the final processing step in the camera, and may not be linear. Further processing is sometimes used to compensate for the transfer characteristic of the display, the gamma function. This function is not linear and, in order to provide a linear relationship between scene brightness and displayed brightness, an inverse gamma function is applied to the digital signals in the camera. All this processing means that the digital output of an area-array based camera may not be linearly related to the light input. This ‘additional’ processing is usually to be found in cameras intended primarily for picture taking with subsequent CRT or LCD display. Cameras that are purchased for scientific purposes do not usually have this processing but rather output the ‘raw’ digital data and leave users to manipulate the spatial information for their specific requirements.

## DIGITAL CAMERAS

### Introduction

Digital cameras can take on various forms depending on their intended application. 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. 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 a captured 12 bit image to an output 8 bit image), and gamma correction (necessary to compensate for the transfer characteristic of the intended computer display as described above).

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 their relatively low cost. Scientific cameras are expensive and not yet readily available with high pixel density, especially in colour.

### Colour analysis

There are a number of ways in which colour analysis can be achieved using a CCD device. 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, Figure 3.

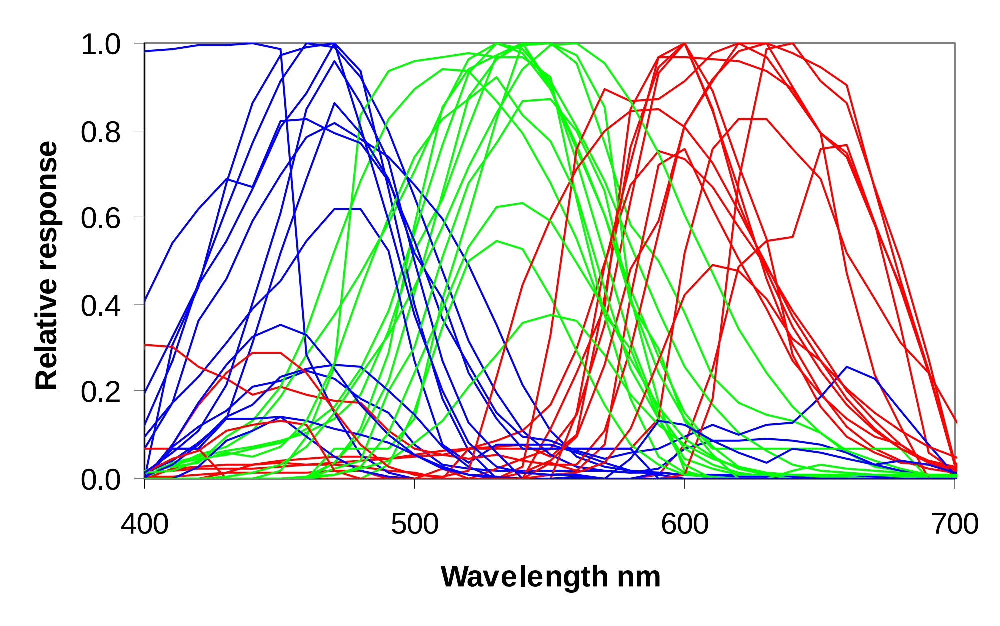


Figure 3. A number of sets of *R*, *G*, *B* spectral responsivities showing the wide variation in their peak wavelengths, their widths and their unwanted sensitivities.

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, Figure 4. 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.

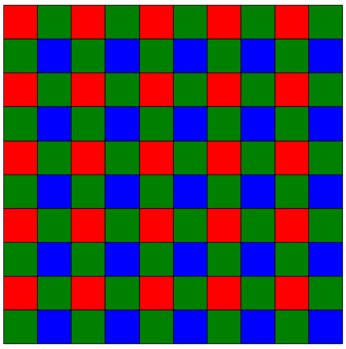

Figure 4. Colour filter mosaic array – usually known as a Bayer pattern after its inventor.

To produce colour images of a high quality, the colour samples from a single sensor array coated with a 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 sharp[3].

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, Figure 5. 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 filter block equipped with interference, or dichroic, semi-transparent mirrors and filters.

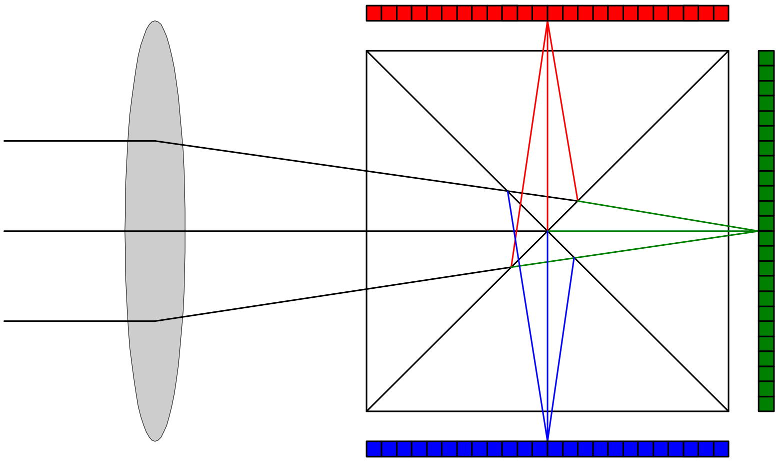

Figure 5. Schematic diagram of a colour-filter block for a 3-CCD camera.

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 through-out 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 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 colorimeter[4].

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, Figure 6, the better will be the accuracy with which the X tristimulus value can be predicted by any modelling procedure.

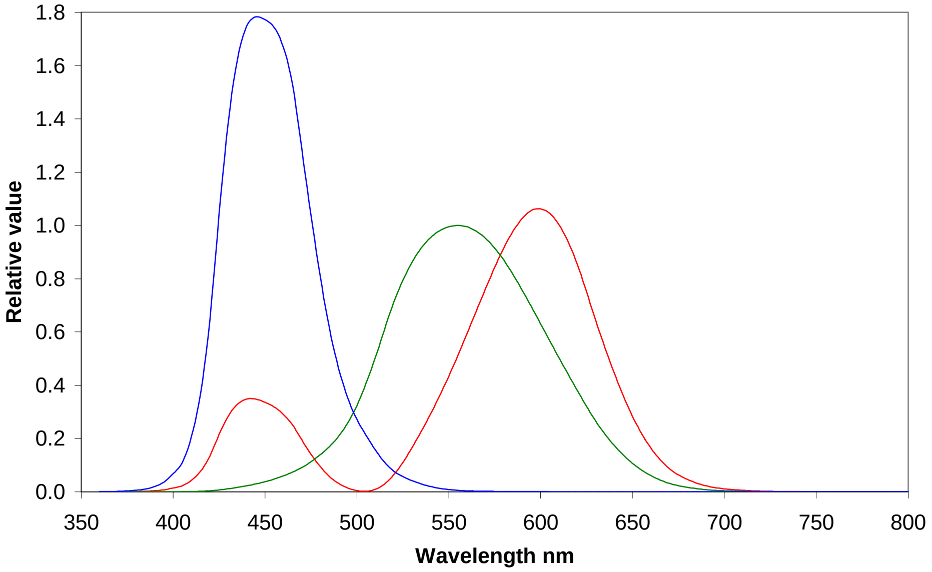


Figure 6. The colour matching functions of the CIE 1931 Standard Observer:
(red: $\bar{x}(\lambda)$, green: $\bar{y}(\lambda)$, blue: $\bar{z}(\lambda)$).

**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, $C_i(\lambda)$, $i = r, g, b$:

$$R = \int S(\lambda) C_r(\lambda) d\lambda$$
$$G = \int S(\lambda) C_g(\lambda) d\lambda \qquad (1)$$
$$B = \int S(\lambda) C_b(\lambda) d\lambda$$

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:

$$R = \int P(\lambda) O(\lambda) C_r(\lambda) d\lambda$$
$$G = \int P(\lambda) O(\lambda) C_g(\lambda) d\lambda \qquad (2)$$
$$B = \int P(\lambda) O(\lambda) C_b(\lambda) d\lambda$$

where the integration is taken over a suitable wavelength range in the visible part of the spectrum, for example from 380 to 780 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 above:

$$X = \int P(\lambda)O(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = \int P(\lambda)O(\lambda)\bar{y}(\lambda)d\lambda \qquad (3)$$
$$Z = \int P(\lambda)O(\lambda)\bar{z}(\lambda)d\lambda$$

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, Figure 6.

**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 methods described in the literature that can be used:

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

<u>Characterisation based on spectral matching</u>

Very few camera manufacturers make their own array detectors and thus they have to source them from the relatively few suppliers. In spite of this, the spectral responsivity of such a device varies from manufacturer to manufacturer, and even from model to model for one camera manufacturer, Figure 3. It is possible however, to manufacture a set of externally mounted filters for a specific monochrome camera such that the combined response approximately mimics that of the CIE colour matching functions. In addition, there are also several companies that can supply a camera with suitable filters mounted in an external filter wheel, see Appendix 1. Note that to match the CIE colour-matching functions requires four 'filters' because the $\bar{x}(\lambda)$ function has two peaks. The required response in the blue part of the spectrum is better obtained by using a separate fourth filter. It is however, possible to obtain this response by taking a suitable percentage of the data obtained using the $\bar{z}(\lambda)$ filter. This concept of spectral matching is never completely accurate: an example is given in Figure 7.

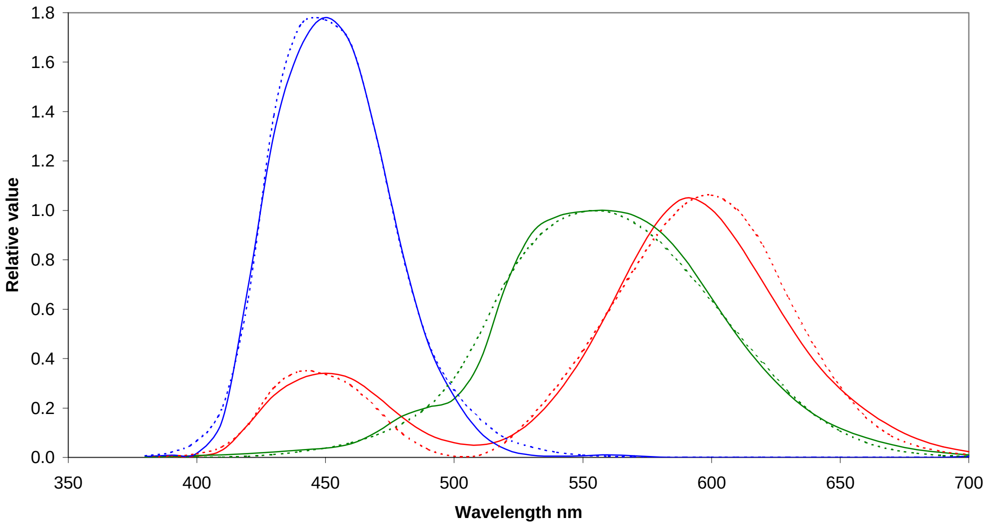


Figure 7. The filtered response of a digital camera (dashed lines) compared with the colour matching functions of the CIE 1931 Standard Observer (full line): (red: $\bar{x}(\lambda)$, green: $\bar{y}(\lambda)$, blue: $\bar{z}(\lambda)$).

To validate devices of this type and to provide a traceable measurement path, requires that the spectral response of the system (the sensor array and the associated filters) be measured. This is possible and will be considered in the next section of this report.

Strictly speaking, the output colorimetry of these devices is illuminant dependent and it is usual to manufacturer the filters to consider this and include the spectral power distribution of a CIE illuminant (usually D65) as well as the colour matching functions. Alternatively, the image *R*, *G*, *B* values can be mathematically modified (matrixed) to accommodate different illuminants.

Characterisation based on measured spectral responsivity

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 camera spectral responsivities and the CIE colour matching functions then this same relationship can be used to transform *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:

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

Written in matrix form this becomes:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = A \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

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:

$$M = R \quad G \quad B \quad 1 \qquad (1)$$
$$M = R \quad G \quad B \quad RGB \quad 1$$
$$M = R \quad G \quad B \quad RG \quad RB \quad GB \quad 1$$
$$M = R \quad G \quad B \quad RG \quad RB \quad GB \quad RGB \quad 1$$
$$M = R \quad G \quad B \quad RG \quad RB \quad GB \quad R^2 \quad G^2 \quad B^2 \quad 1 \qquad (2)$$
$$M = R \quad G \quad B \quad RG \quad RB \quad GB \quad R^2 \quad G^2 \quad B^2 \quad RGB \quad 1$$
$$M = R \quad G \quad B \quad RG \quad RB \quad GB \quad R^2 \quad G^2 \quad B^2 \quad RGB \quad R^3 \quad G^3 \quad B^3 \quad 1$$
$$M = R \quad G \quad B \quad RG \quad RB \quad GB \quad R^2 \quad G^2 \quad B^2 \quad RGB \quad R^3 \quad G^3 \quad B^3 \quad \ldots$$
$$R^2G \quad R^2B \quad G^2B \quad RG^2 \quad RB^2 \quad GB^2 \quad 1 \qquad (3)$$

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, designated by the 1 in the above functions; 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.

Characterisation based on known colorimetry

This method does not require spectral measurement and so is not considered further in this report. Further details can be found, for example, in Pointer, 2000[4].

Characterisation based on mathematical estimation

An interesting method of ‘measuring’ the spectral response of an array detector has been suggested by DiCarlo et al. at Hewlett Packard[5]. Their requirement was that spectral characterisation be possible for every digital camera on a production line. The methods outlined above can be considered as providing laboratory calibration; they take considerable time to achieve and are thus relatively costly. The solution that HP came up with was to use an emissive display for calibration. This display they constructed from multiple narrow-band LED light sources to have 12 areas each of a different spectral power distribution and hence a different colour. The spatial separation of the light sources is a grid pattern similar to reflective charts to allow for ease of use. The absolute spectral power distribution was measured using the laboratory method and then the characterisation of any array detector requires only two steps: an image is captured of the display and then software is run to determine the spectral response function of the array. The software extracts the patches from the capture image and, with knowledge of the spectral power distribution of the light sources in the display, inverts the image formation equation to estimate the array spectral responsivity response.

The image formation equation is that which relates the input to the system to the output from the system via the spectral response of the system:

$$S = R^T L \qquad (4)$$

where: $L$ is a matrix with column $j$ containing the spectral power distributions of the light sources
$R$ is the matrix with column $i$ containing the responsivity functions of the array detector
$S$ is a matrix where the element $s_{i,j}$ is the response of the image sensor $i$ due to incident light $j$.

Thus, knowing the responses, $S$, to the light sources, $L$, enables the spectral responsivity, $R$, to be calculated by inverting the above matrix equation. While this is not a rigorous method of measurement, it has been demonstrated to be of use in the production environment. A mathematical difficulty is that the solution requires the inversion of a non-symmetrical matrix and there are now several mathematical techniques for achieving this including a function within Matlab.

In addition, it should be noted that the method is not limited to the use of an emissive test target. If a reflective target is illuminated in a controlled manner, i.e. with a stable fixed light source, then a similar mathematical technique can be applied because Equation 4 is a matrix form of Equation 3 above.

## VIDEO PHOTOMETERS

A video photometer is essentially a monochrome digital camera with an internal or external correction filter such that the integrated spectral response complies with the specification of the CIE luminous efficiency function, $V(\lambda)$[6].

Because the CIE $V(\lambda)$ function is the same as the CIE $\bar{y}(\lambda)$ colour matching function, all colorimetric instruments based on area arrays that use external filters to give spectral responses corresponding to the CIE $\bar{x}(\lambda),\bar{y}(\lambda),\bar{z}(\lambda)$ colour matching functions can, with appropriate calibration, measure luminance using the $\bar{y}(\lambda)$ filter.

To provide measurements of luminance, photometers must be calibrated in an absolute sense. A tile of known reflectance, $\rho$ is illuminated by a standard lamp of known luminous intensity, $I$. A specific luminance level, $L$, is established by changing the distance, $d$, between the tile and the lamp such that:

$$L = \frac{I\rho}{\pi d^2}$$

The photometer is then aligned with the meter focussed on to the centre of the tile surface. This measurement is made using a photometric bench which has a laser aligned along its length defining the alignment axis.

While this calibration procedure applies to conventional photometers, the calibration of video photometers is a more complicated process. In an ideal sense, each pixel should be calibrated to ascertain its absolute light output in a photometric sense. In practice, this is very difficult, if not impossible to achieve for several reasons; the size of each pixel is very small and thus it would be difficult to illuminate a single pixel, the number of pixels can be very large and hence it would be time consuming to calibrate each one. Thus, effort must be made to calibrate the overall photometric response with some indication as to the spatial non-uniformity of that response.

## PROPERTIES OF IMAGING SYSTEMS

The properties described below are those that might impact on the spectral response of an area array that is characterised in either a photometric or a colorimetric sense, and is used to provide spatial photometric and colorimetric information. Considerably more detail can be found in the literature[2, 7].

### Spectral responsivity

Absolute spectral responsivity is the relationship between the output from a detector and the input optical signal at a particular wavelength. Relative spectral responsivity is the variation in the responsivity with wavelength, normalised to a specified wavelength.

The CIE has a recommended method that can be used to assess the agreement between the actual, measured spectral response and the required response as specified by the CIE[2, 7].

CIE Publication No. 69 *Methods of characterising illuminance meters and luminance meters* describes a parameter $f_1'$ that can be used as a measure of the degree to which the relative spectral responsivity, $s(\lambda)_{\mathrm{rel}}$, matches the CIE spectral luminous efficiency function, $V(\lambda)$:

$$f_1' = \frac{\int \left| s^*(\lambda)_{rel} - V(\lambda) \right| d\lambda}{\int V(\lambda) d\lambda} .100\%$$

where $s^*(\lambda)$ is the normalised relative spectral responsivity:

$$s^*(\lambda)_{rel} = \frac{\int S(\lambda)_A V(\lambda) d\lambda}{\int S(\lambda)_A s(\lambda)_{rel} d\lambda} s(\lambda)_{rel}$$

and: $S(\lambda)_A$ is the spectral power distribution of the illuminant used in the calibration – usually CIE standard illuminant A,
$s(\lambda)_{rel}$ is the spectral responsivity of the device with arbitrary reference.

CIE Technical Committee 2-16 *Characterisation of the performance of tristimulus colorimeters* is near completion of a technical report that will describe similar measures for tristimulus colorimeters.

**Number of pixels**
The number of pixels in the array detector will influence the noise associated with the output signal from the detector, and hence the digital values in the output image file, as well as the spatial quantisation of the output image.

**Pixel size**
The pixel size will influence the level of fine detail that can be resolved in the final image. This must be considered in conjunction with the magnification provided by the lens used to focus the scene onto the array detector.

**Frame rate**
The frame rate is a measure of the finite time taken to completely transfer the charge from imaging part of the array detector to the storage area. This will influence the rate at which images can be refreshed and recorded. For a fixed clock rate (the time base controlling the transfer of charge from the discreet array sites), the time taken to read an entire array increases as the array size increases. As the frame rate increases, the time available for the array sites to accumulate charge (the integration time) decreases and thus a higher level of illumination is required to maintain a specific signal-to-noise level.

**Shutter speed**
The shutter speed is a measure of the actual time that the array is exposed to incident light. Most digital devices use an electronic shutter that is characterised by the clock rate, the frame rate and the integration time, see above.

**Noise**
Noise can be considered a generic term that is used to describe any component of a signal that is considered to be derived by extraneous means. Examples include Shot noise, amplifier noise, and white noise.

**Dynamic range**
The dynamic range of an array detector is defined as the maximum signal that can be achieved, divided by the level of the noise. It will be a function of the integration time, the frame rate and the pixel size.

**Photo response non-uniformity (PRNU)**
This is defined as the spatial variation of the photon-induced signal generating process within an array detector.

**Dark signal non-uniformity (DSNU)**
This is defined as the spatial variation in the dark signal within an array detector. The dark signal is the output of the detector with zero illumination. Typically, this signal is caused by thermally generated electrons within the semiconductor material which are accumulated in each pixel of the device and transferred to the output during read out.

**Defective pixels**
Defective pixels of an array detector are those which show performance that is not representative of the average for the device. These can be present as ‘white’ cells which are producing a signal that is higher than average, or ‘black’ cells which produce a lower than average signal, the limit being ‘dead’ cells which produce no signal. The absolute number of

defective pixels is a function of the array size, and the test specification and data sheet for a specific array detector will define threshold limits for the number of defective cells.

CIE Publication 69 and the report to be produced by TC TC2-16 contain the descriptions of functions that are pertinent to the assessment of many of these parameters.

## OTHER FACTORS THAT INFLUENCE THE SPECTRAL RESPONSE

### Ultraviolet response, infrared response

It is important that any filter used to limit the spectral response of the array device in the visible part of the spectrum should not transmit in the ultraviolet or the infrared part of the spectrum. Additional infrared filtration is often required for silicon-based devices with filtered response.

### Directional response

This is a measure of the response to light incident on the detector, as a function of the angle of incidence of that light. When considering imaging devices this may be a difficult parameter to quantify. The incident light will almost certainly be mostly diffuse in nature and the detector array will sample this via an objective lens which will focus the light onto the array.

### Effect of the surrounding field

This is essentially a measure of the response from one area of the detector due to light received at an adjacent area. In very bright areas of the scene, for example specular reflections, the charge generated by the appropriate pixel of the array detector may exceed the charge capacity of the associated well. This excess charge must be eliminated or it will migrate to adjacent wells causing blooming, wherein the area the specular reflection is reproduced as a blob or a streak. Many CCD area-array devices incorporate anti-blooming overflow drains adjacent to the actual wells to direct excess charge and help prevent this occurrence but this means that there is a very small gap between each of the rows and columns of the pixels on the array.

### Linearity error

Ideally, an area-array device should be characterised using the physical settings that are going to be used to make subsequent measurements. Thus the lens, the aperture and the integration time (exposure) should be similar because a change of lens, for example, will almost certainly alter the spectral response because of a change in the spectral transmittance of the glass used to manufacture the lens. In any characterisation process, as a minimum, the linearity of the system should be checked because many CCD devices saturate at a certain level of illumination. In the practical situation, it is therefore necessary to limit the use of the device to illumination levels below the point of saturation, Figure 8. This linearity check must be achieved by external means, using, for example calibrated neutral filters, or by internal means by reducing the integration time, and the influence of this change on the likely spectral response must be known. There are a number of methods of assessing whether the output signal varies in direct proportion to the input optical radiation.

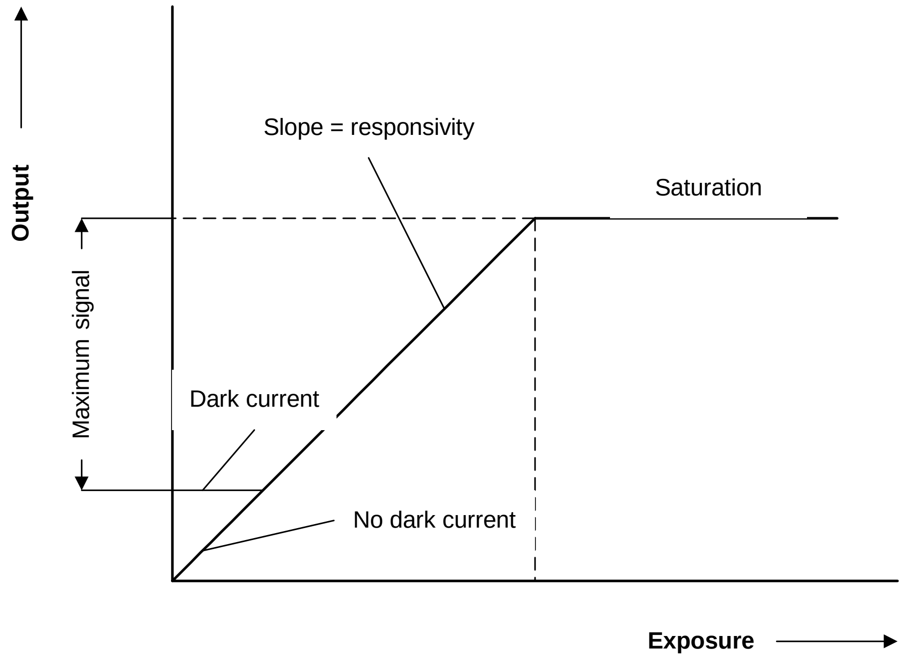


Figure 8. The input-output characteristic showing the concept of a saturation exposure that defines the maximum signal or dynamic range.

**Output error**
This error is primarily due to the quantisation of the output of a digital device causing an error in the least significant digit in the output. It will therefore be a function of the bit depth of the specific device.

**Temperature coefficient**
The absolute responsivity of the device may be a function of the ambient temperature in which it is operating. The device should therefore be operated in an environment that is thermally stable.

**Fatigue**
Fatigue is the reversible temporal change in the responsivity, under constant operating conditions, caused by the incident illumination. This effect can cause changes in the overall responsivity and in the relative spectral responsivity.

**Modulated radiation**
When measuring light from modulated sources, the response of an instrument can, under some circumstances, deviate from the true arithmetic mean value.

**Polarization**
The output of the instrument can depend on the polarisation conditions of the input light.

**Range change**
For instruments that are able to display a number of ranges of output, different error limits (range start and end values) might apply to different ranges. This applies specifically to video photometers.

**Focus error**
The instrument might change its response according to the distance between the object and the instrument such that the lens on the front of the instrument is set at a different focus.

**Supply voltage - lower/upper frequency limit**
The extent to which the calibration varies with line or battery voltage might be important and hence influence the device output.

**Average dark signal**
The dark signal is the output signal in the absence of any input illumination, Figure 8.

**Spatial uniformity**
For uniform illumination, the response of the detector will vary from pixel to pixel and the photo-response non-uniformity is a measure of this variability. Because the digital camera and the video photometer are both imaging devices, they must be fitted with lenses to focus the input scene onto the array detector. This lens introduces non-uniformities into the resulting image due to at least three effects: lens vignetting, cosine fall-off, and lens distortion due to aberrations.

Mechanical vignetting refers to a reduction in image brightness in the image periphery compared to the image centre and is often caused when off-axis light rays emanating from the original scene are partially blocked by a lens hood, or an external filter mount, as well as the various elements positioned inside the lens to limit aberrations, Figure 9. If a physical aperture is fitted to the device, then a way of minimising this effect is to stop down this aperture.

Cosine fall-off is a form of optical vignetting and it occurs because the distance the light rays travel to the corner of the array detector is greater than that travelled to the centre of the detector and this fall-off is usually proportional to the fourth power of the cosine of the angle subtended by the ray. Wide angle lenses and the lenses used in compact cameras are particularly prone to this form of vignetting which is not reduced by stopping down the aperture in the lens[8, 9].

Lens distortion is apparent when straight lines in an original scene are not reproduced as straight in the image. The cause is usually due to poor correction of lens aberrations. Particularly noticeable are barrel distortion where the image magnification decreases with increasing distance form the optic axis and, conversely pincushion distortion where the image magnification increases with increasing distance from the optic axis, Figure 10. The visible effect is that lines that do not go through the centre of the image are bowed outwards /inwards, towards the edge/centre of the image respectively.

To compensate for these effects a flat-field corrector can be implemented, either as a physical filter or in the electronic image processing in the camera.

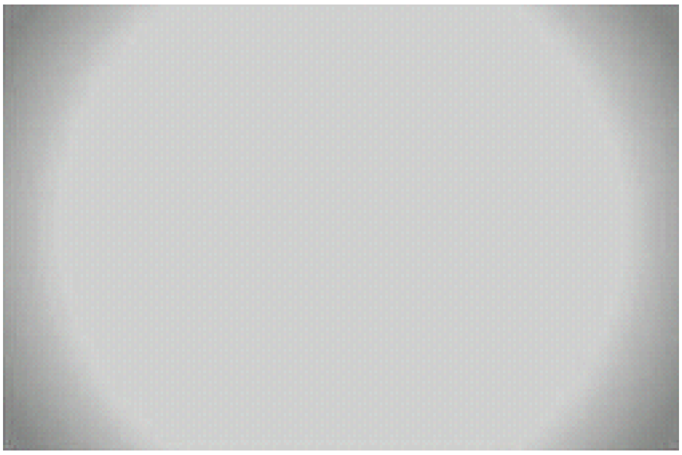

Figure 9. Vignetting

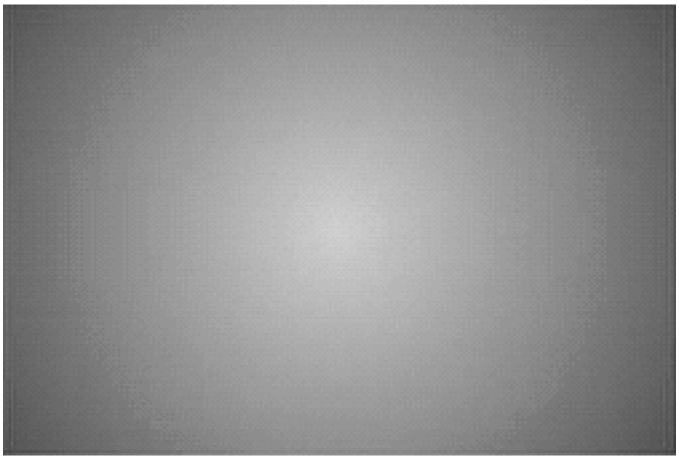

Figure 10. Cosine fall-off

## CHARACTERISATION METHODS

### Relative measurement

The relative spectral responsivity of an area-array device can be measured using a monochromator that can be set to a selection of wavelengths over the required range. The output of the monochromator, measured using a spectral responsivity reference detector, is optically expanded and made to fall on to a tile of known Lambertian spectral reflectance. If the array is part of a digital camera, then the lens of the camera can be used to image the tile onto the array. If the array is a separate component then an additional lens might be used to provide the imaging facility. Ideally, it should be arranged that the light from the tile fills the image so that the entire array is responding to the light reflected from the white surface. Thus a number of images, each obtained with the monochromator set at a different wavelength, are exposed.

The *R*, *G*, *B* values for each of the pixels in the images then need to be obtained. The images should be stored using the minimum processing possible. Thus, if the array is part of a typical photographic digital camera, 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 a number 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. These values of *R*, *G*, *B* give the relative spectral responsivity at the specified wavelength. By analysing the set of images exposed, a complete picture of the spectral response can be built up over the wavelength range considered. Assuming that the illumination used is uniform over its whole area, then the distribution of values over the image will give an indication of the uniformity of the response of the array.

It is becoming increasingly popular for cameras intended for general photography to take the raw digital *R*, *G*, *B* values and calculate values according the sRGB standard[10]. If this is the case, then it is necessary to back-calculate the raw *R*, *G*, *B* values to obtain the true relative response. The reason for this is that the sRGB values include a transfer characteristic to compensate for the non-linearity of the intended CRT or LCD display as described above. For colorimetry, this is not required and so it should be removed: Appendix 2 gives details of the required calculations.

**Absolute measurement**

To obtain the absolute spectral response it is necessary to find the response of the array to light of known irradiance at a specific wavelength. This is best done by using the light from a suitable laser that has been pre-calibrated to have a known value of radiance in terms of the number of W $sr^{-1}$ $m^{-2}$ $nm^{-1}$. To provide a suitable image it is necessary to shine the laser light into an integrating sphere and then to make an image of the exit aperture of the sphere using the camera under test. (It could be useful to use the integrating sphere with the monochromator when measuring the relative spectral response above, but there is rarely sufficient light available from monochromators to make this feasible because the integrating sphere is optically inefficient.) Thus, knowledge of the absolute response of the camera at one wavelength in the visible spectrum enables the data obtained using the monochromator to be suitably scaled to provide the absolute spectral response throughout the measured wavelength range.

If suitable sources of radiation, e.g. lasers are available, then a series of measurements can be made and the absolute spectral response deduced from these measurements perhaps using a fitting program, e.g. NPLFit, to interpolate the data to be at equal wavelength intervals.

For colorimetric calculations, it is only necessary to know the relative data and thus the latter step using the laser light source is not required. For the measurement of luminance however, it is necessary to know the absolute spectral response. Alternatively, the relative spectral response can be used as a measure of the fit to the CIE relative luminous efficiency function, and a photometric bench then used to calibrate in terms of luminance.

It should be noted that a measurement such as this based on laser illumination is relatively time consuming unless established as a routine service. The quoted uncertainty could be <± 0.5% for the absolute measurement and < ± 0.2% for each of the relative measurements. This latter uncertainty would require some work to be translated into bit value on a scale of 0 to 255 (8 bit). It is probable that some devices would provide the output using a larger bit depth (10 bit: 0-1024, 12 bit: 0-4096, 14 bit: 0-16384, 16 bit: 0-65536). These measurements would all be traceable to relevant national standards.

**Spatial uniformity**

The other major contributor to the measurement that should be investigated is the uniformity of the spectral responsivity as a function of area. This is a difficult measurement to make and two approaches can be used. The first makes several assumptions including the fact that the output of an integrating sphere is uniform at its aperture, and that the uniformity need only be ascertained to a precision dictated by the bit depth of the image processing system. For an 8 bit system this is to 256 levels, rising to 4096 levels for a 12 bit system, 16384 for a 14 bit system and 65536 for a 16 bit system. It also has to be assumed that the full image is available from the instrument in a spatial sense, i.e. as a file of *R*, *G*, *B* data. From this image an investigation into the variability of the values in one of the channels, for example, the green channel, will give an indication of the variability across the detector array.

A second, more scientific, approach is to use a thin pencil of light, for example from a laser that can be made incident on to different spatial locations of the detector. The response can be ascertained and the resulting variability investigated.

**Average dark signal**

This can be investigated simply by recording an image with no input light signal. As above, the resulting image can be used to ascertain the bit values obtained, and their spatial variability.

**Linearity**

Linearity can be investigated in a conventional manner by placing each of a series of calibrated neutral filters over the lens of the device when using a laser as the illuminating source as described above for absolute calibration. Measurements should be taken from the centre of the image to minimise the effects of spatial non-uniformity etc.

**Other parameters**

The ultraviolet response, the infrared response, the directional response, the effect of the surrounding field, the output error, the temperature coefficient, fatigue effects, the effect of modulated radiation, the effect of polarization, the effect of a range change, the focus error, and the effect of fluctuations in the supply voltage - lower/upper frequency limit can all be investigated and CIE Document 69 provides techniques with associated parameters for each case.[7]

## STANDARDS AND RECOMMENDATIONS

### Video Photometers

There are no ISO standards dealing with the characterisation and calibration of luminance meters in general and video photometers in particular.

The International Commission on Illumination, CIE, has the following publications and work in progress:

- CIE Publication No. 69, *Methods of characterising illuminance meters and luminance meters*, 1987. This technical report defines the properties of photometers used for the measurement of luminance. Methods of calibration are given and several sources of error described. Several properties that determine the performance of photometers can be characterised by numerical values and methods are provided. This report does not deal explicitly with video photometers although most of the contents of the report are relevant to this type of instrument.

- To address video photometers, CIE Division 2 has recently established a technical committee TC 2-59 *Characterisation of imaging luminance measurement devices* under the chairmanship of Peter Blattner from Switzerland. The Terms of Reference are to prepare a Technical Report on methods for the characterisation of imaging luminance measurement devices.

- CIE Division 2 also has TC 2-32 *Calibration of multi-channel spectrometers*, chaired by Richard Austin form the USA. This TC is preparing a technical report on the calibration of array spectroradiometers primarily for the determination of colorimetric and photometric quantities, including sources of error in array spectral measurements systems, evaluation of these errors, calibration methods and methods for the determination of uncertainty.

- All work concerned with the calibration of instruments requires an understanding of the uncertainties associated with the calibration procedure. CIE TC2-43 *Determination of measurement uncertainties in photometry*, chaired by George Sauter from Germany, is preparing a CIE recommendation on this subject.

**Digital cameras**
ISO has a number of standards that are relevant to aspects of digital camera characterisation.

- ISO 12231:2005, 2nd Ed., *Photography - Electronic still picture imaging – Vocabulary*. This standard provides a vocabulary for all matters to do with electronic still picture imaging which includes all aspects of colour characterisation.

- ISO 12232:1998, *Photography -- Electronic still-picture cameras -- Determination of ISO speed*. This standard provides a methodology for deriving the equivalent ISO speed for an electronic still picture camera to give results comparable with those obtained for conventional photographic systems.

- ISO 12233:2000, *Photography -- Electronic still-picture cameras -- Resolution measurement*. This standard provides a test target and a methodology for calculating the resolution of digital cameras.

- ISO 14524:1999, *Photography -- Electronic still-picture cameras -- Methods for measuring opto-electronic conversion functions (OECFs)*. This standard specifies a method for calculating the relationship between the input to a digital camera and the digital code values produced in a digital file by that input. The OECF is analogous to the Density-Log(Exposure) transfer characteristic curve associated with photographic film.

- ISO 15739:2003, *Photography -- Electronic still-picture imaging -- Noise measurements*. This standard presents methods for calculating the noise versus signal and dynamic range of digital cameras.

ISO also has work in progress to standardise a method of characterisation for an electronic still camera such that its output complies with a specified colour standard, for example, CIE tristimulus colorimetry. This work forms part of ISO Technical Committee TC 42 *Photography*, Working Group 18 *Electronic still picture imaging* and has been progressing for many years. It is highly likely that it will not reach a definitive conclusion and hence produce a standard.

CIE also has some relevant activity.

- CIE Technical Committee 2-16, *Characterisation of the performance of tristimulus colorimeters* is part of CIE Division 2. This TC is chaired by Janos Schanda from Hungary and is close to agreeing a technical report that will provide an objective means for evaluating the properties of tristimulus colorimeter heads that are to be used to measure the colour of light sources. Several properties that determine the performance of tristimulus colorimeters can be quantified by the numerical assessments given. There are some properties, however, which it has not been possible to quantify, where only a qualitative description is possible. Several sources of measurement error will also be described. The report closely follows CIE Publication 69 above, but extends the concept to consider the three channels necessary for tristimulus measurement. This includes extension of the $f_1'$ parameter to $f_X', f_Y', f_Z'$ thus providing spectral mismatch error indices for the fit between the spectral responsivities and the CIE colour matching functions.

  The report is intended to serve as a guide for a potential user who wishes to make colour measurements of sources using a tristimulus colorimeter, and for manufacturers or users of instruments who need to specify or assess the quality of these instruments. The factors that make up the evaluation may also serve as a guide to manufacturers in the development of improved colorimetric instruments.

## OPPORTUNITIES

While the use of arrays to make measurements is not new; the use of arrays as part of digital cameras however, is a potential growth market. Machine vision systems are regularly based on cameras and these are used, for example, in the production line environment of a number of manufacturing industries. Their application however, is not usually to measure something but rather to detect the presence of an object, either desirable or undesirable. Put another way they are used to detect perturbations about a defined reference condition. As such, they do not require calibration because they make no measurements. Even simple colour sorting can be achieved in this manner, based on the *R*, *G*, *B* values detected by a region-of-interest in a captured image. The instruments cited in Appendix 1 are largely high-end pieces of equipment that could benefit from calibration. Discussion with one or two of the suppliers (only one is manufactured in the UK) suggest that they might be prepared to suggest that their customers seek traceable calibration for their instrument, but only if the cost were approximately 5% to 10% of the cost of the instrument.

## RECOMMENDATIONS

- It is inevitable that the actual process of measuring the spectral responsivity of an array-based detector device will be more involved than indicated in this report. A procedure should be written based on the actual measurement of the parameters pertinent to a suitable device.

- The progress of work within ISO should be monitored. It is possible that a measurement service based on the requirements of the ISO standards could be established for digital cameras, especially as they become more used in ‘measurement’ applications.

- The progress of work within CIE should be monitored. Measurements made to comply with the recommendations of CIE publication 69 and the publication that is produced by TC2-16 should be considered as descriptors of the validity of the measured spectral responsivity of specific devices.

- Input should be provided to CIE TC 2-59 *Characterisation of imaging luminance measurement devices* to ensure that the characterisation process recommended is based on sound measurement principles.

## ACKNOWLEDGEMENTS

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## APPENDIX 1: INSTRUMENTS

The appendix contains a list of manufacturers of imaging devices that use area arrays to make colorimetric and/or photometric measurements.

**Bossa Nova Tech**
www.bossanovtech.com
**SAMBA**
A visual colour and gloss meter based on a very small CCD area detector. The means of colour analysis is not stated.

**Delta**
www.delta.dk/icam
**ICAM – 2D**
A luminance and colour measuring device based on an 8 bit chip with 768 x 1024 pixels and internally mounted coloured filters. The luminance range is not quoted.

**DigiEye plc**
www.verivide.com/digieye/home.html
**DigiEyE**
A digital camera with colorimetric characterisation carried out in software using a multi-patch test target of known CIE colorimetry.

**Eldim S.A.**
www.eldim.fr
**Eldim MURATest 16M**
A 2 dimensional video colorimeter that uses a 4096 x 4096 CCD array with an integral filter wheel.

**Instrument Systems**
www.instrument-systems.de
**LumiCam 1300 Color**
A luminance and colour measuring device based on a chip with 1280 x 1000 pixels. The luminance range is 0.02 cd $m^{-2}$ to 200 000 cd $m^{-2}$.

**LMK**
www.technoteam.de
**LMK 98-3 Color**
A luminance and colour measuring device based on a Sony 12 CCD with 1380 x 1030 pixels. The luminance range is 0.6 cd $m^{-2}$ to 60 000 cd $m^{-2}$.

**Lumetrix Corporation**
www.lumetrix.com
**IQCam 3**
A luminance measuring device that uses a CCD array with 12 bit digitisation. Clams calibration over a wide range of focussing and aperture settings.

**Photo Research**
www.photoresearch.com
**PR-905 Digital Video Photometer**
An instrument that uses a 1024 x 1024 CCD with 10 bit digitisation. The luminance range is 0.01 cd $m^{-2}$ to 103 cd $m^{-2}$ with ND filters. Has the facility to add different lens to obtain different fields of view.

**PR-920 Digital Video Photometer with Colour option**
An instrument that uses a 1024 x 1024 Peltier cooled CCD with 16 bit digitisation. The luminance range is 0.01 cd $m^{-2}$ to 85 000 cd $m^{-2}$ with ND filters.

**Radiant Imaging**
www.radiantimaging.com
**ProMetric 1000**
An illuminance measuring device based on a 10 bit CCD array. The pixel resolution is 1390 x 1040. The luminance range is 0.1 cd $m^{-2}$ to $10^{10}$ cd $m^{-2}$ with ND filters.

**ProMetric 1400 FAST Color Series**
An illuminance and colour measuring device based on a 2 stage Peltier cooled 12 or 14 bit CCD camera. Three pixel resolutions are available: 768 x 512, 1536 x 1024 and 3072 x 2048. An illuminance calibration light source or factory luminance calibration included, as is a factory colour calibration included. The luminance range is 0.005 cd $m^{-2}$ to $10^{10}$ cd $m^{-2}$ with ND filters. The unit appears purpose-built but it is not clear how the colour analysis is derived.

**ProMetric 1600 FAST Color Series**
An illuminance and colour measuring device based on a 3 stage Peltier cooled 16 bit CCD camera with external filters. Two pixel resolutions are available: 512 x 512 and 1024 x 1024. As above, the luminance range 0.005 cd $m^{-2}$ to $10^{10}$ cd $m^{-2}$ with ND filters. The unit is purpose built with an internal filter wheel to provide the colour analysis.

**TriCor**
www.tricor-systems.com
**Model 820/821 Video Photometer**
An instrument that uses a 640 x 480 pixel CCD array image digitised at 8 bits. The luminance range is 0.34 cd $m^{-2}$ to $10^6$ cd $m^{-2}$. The two models use different cameras.

**APPENDIX 2: sRGB**

This appendix provides the equations necessary to convert gamma-corrected sRGB data into gamma-uncorrected *R, G, B* data[9], together with the reverse transform.

- Given sRGB values $R_S, G_S, B_S$, calculate $R'_S, G'_S, B'_S$:

$$R'_S = R_S / 255$$

$$\text{If } R'_S \le 0.0031308 \text{ then } R'_8 = R'_S * 12.92$$
$$\text{If } R'_S > 0.0031308 \text{ then } R'_8 = 1.055 * R_S'^{\,1/2.4} - 0.055$$

Then renormalize such that, if WDC is the white digital count and KDC the black digital count, then:

$$R_8 = [(WDC - KDC)R'_8] + KDC$$

If WDC and KDC are assumed to have values of 255 and zero respectively, then this reduces to:

$$R_8 = R'_8 * 255$$

with similar equations for *G* and *B*.

- The inverse transform, *R*, *G*, *B* to sRGB data, is as follows:

If WDC is the white digital count and KDC the black digital count, then

$$R'_8 = \frac{(R_8 - KDC)}{(WDC - KDC)}$$

If WDC and KDC are assumed to have values of 255 and zero respectively, then this reduces to:

$$R'_8 = R_8 / 255$$

$$\text{If } R'_8 \le 0.04045 \text{ then } R'_S = R'_8 / 12.92$$
$$\text{If } R'_8 > 0.04045 \text{ then } R'_S = \left[\frac{R'_8 + 0.055}{1.055}\right]^{2.4}$$

Then renormalize:

$$R_S = R'_S * 255$$

with similar equations for *G* and *B*.