SINGLE SENSOR VIDEO CAMERAS AND THE TLCI-2012

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ABSTRACT

A presentation at IBC2011 with the title "A TELEVISION LIGHTING CONSISTENCY INDEX" [1] 'kickstarted' the EBU work leading to the adoption of EBU Recommendation R-137 (TLCI-2012) [2] about one year later. This work was mainly based upon the behaviour of modern broadcast HDTV cameras with 3-sensor technology. At IBC2012 another presentation was given describing the development of a "Standard Camera Model" [3] used in calculations of the TLCI-2012 Q_a value. Results from measurements of luminaires using the TLCI-2012 have since been published by the EBU and in technical magazines [4].

The EBU work activity behind R-137 was very much aware of the development and increasing interest in video cameras using a 'single-sensor' solution based on a colour filter array (CFA) on the sensor of a Bayer-pattern type. At that time and for several reasons, it was difficult to make reliable measurements of the spectral sensitivity behaviour of these cameras; measurements from only one such camera was incorporated in the original work (data provided by the camera manufacturer under an NDA).

Recently some of the difficulties mentioned above have been overcome and reliable measurements have been made on some different single-sensor cameras. The findings from these measurements are presented in this paper.

THREE-SENSOR/ SINGLE-SENSOR CAMERAS AND SOME GENERAL CAMERA REQUIREMENTS (COLOUR RENDITION)

Any high-quality electronic camera should be able to reproduce scene colours faithfully in order to meet the requirements of the users (the viewers). Let us take a look at some of the parameters that are important to the reproduction of luminance and colour and the difference in design that has been observed between 3-sensor/1-sensor cameras.

Going back to the successful introduction of colour TV the preferred cameras used three Plumbicon™[5] tubes or similar. These types of tubes were the first to have a linear transfer characteristic; the electrical output signal from the tube was directly proportional to the light level (illuminance) on the tube face.

In the 1980's came the introduction of electronic cameras using three CCDs (Charge Coupled Device sensors); these also have a linear transfer characteristic.

To separate the three colour components red, green and blue (R,G,B) a light-splitting device (beam splitter) separates the incoming light in its red, green and blue components. To find the optimum performance for this light-splitting much work was done at an early stage (1960's) by taking into consideration the properties of available phosphors for the display tubes. The display phosphor characteristics were standardised first for the NTSC system and later for the European PAL system [6].

A typical set of camera sensitivity curves are shown in Fig.1. The curves are shown balanced to CIE Illuminant E, i.e. with equal-area, unity. In a significant part of the visible spectrum at least two of the curves overlap (crosstalk). This causes colour errors/loss of saturation, but it was found to be essential for the operation of a **linear matrix** – to optimise the colour performance. Since this crosstalk occurs in the optical part of the signal chain it is directly proportional to light level (linear); consequently, the correction matrix should be in the linear part of the electrical signal chain.

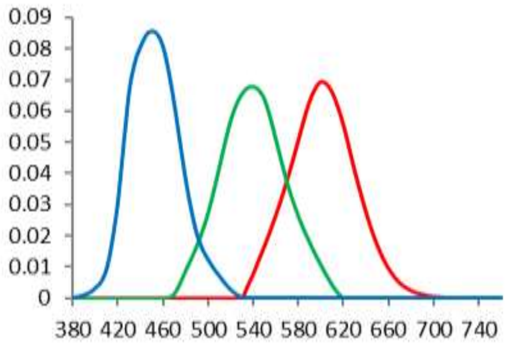

Figure 1 Typical 3-sensor camera sensitivity curves

The fundamental difference between single-sensor and 3-sensor cameras, apart from the number of sensors, is the colour separation mechanism. In single-sensor cameras the colour separation takes place with an array of colour pigment/dye filters, on top of the photo-sites, that absorbs some parts of the spectrum and passes others. However, just as for 3-sensor cameras the peak transmissions are in the red, green and blue parts of the visible spectrum. The organisation (mosaic) of these filters, called a colour filter array (CFA), is mainly to be found in a so-called Bayer pattern, named after its inventor Bryce Bayer (Eastman Kodak) and patented in 1976 (see Fig.2). The transmission characteristics of pigment/dye filters are generally 'bell-shaped' with gentle slopes, something that gives a good amount of overlap between the transmission bands, see Fig 3. Again, the curves have equal area.

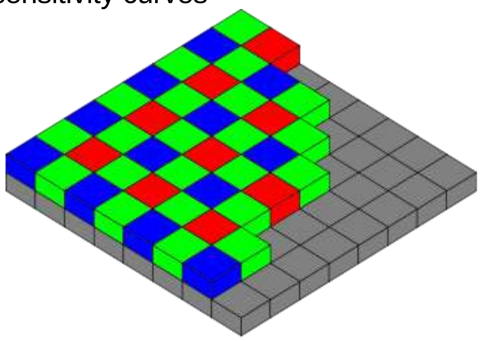

Figure 2 Typical Bayer colour filter array (CFA)

However, there are today many alternative ways to arrange the CFA (having different pros and cons) on top of the sensor photo-sites. In a regular Bayer pattern, alternate photo-sites have a green filter and the remaining 50% of photo-sites are divided equally between red and blue filtering. This has a fundamental impact on image resolution and anti-aliasing filtering; however these are topics beyond the scope of this paper and will not be discussed

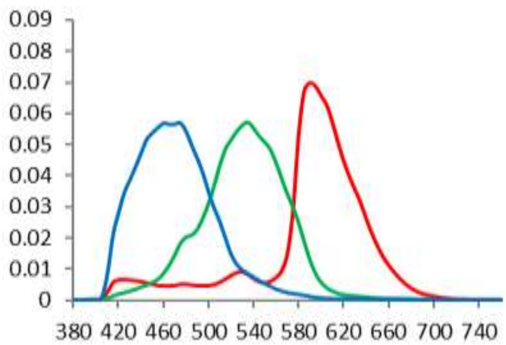

Figure 3 Typical spectral sensitivity curves for a Bayer CFA

further.

Thus the 'raw' signal from the sensor contains pixels representing only one of each of the three primary colours. To obtain the two 'missing' colours for each pixel the raw signal will have to go through a "de-Bayering" process that estimates values for the two missing colours from surrounding pixels. Some single-chip cameras have sensors with sufficient photo-sites to allow every output video pixel to be made up of photo-sites having all three colour filter patches; in this case, the de-Bayering process can be avoided.

Single-sensor cameras have been on the market for decades but not giving the performance required by broadcast or professional users. In more recent years and with the development of larger size sensors (> 2/3") and the significant improvement in picture quality from CMOS sensors, the interest in these cameras has changed the electronic content production industry. Today there is a very high demand for single sensor cameras with high-resolution large-format sensors (approx. Super 35 size or larger). As a consequence, the number of manufacturers for such cameras has increased significantly.

With this situation as a backdrop the feedback from the user community is that they are experiencing differences in colour rendition from such cameras, varying from manufacturer to manufacturer and even between different cameras from the same manufacturer. This situation is different from experiences with 3-sensor cameras and it is useful to take a closer look at single-sensor camera design in order to (hopefully) clarify some of the reasons for the spread in performance.

MEASUREMENTS ON SINGLE-SENSOR CAMERAS

As mentioned above all camera sensor devices are of a CCD or CMOS semiconductor type for both three-sensor and single-sensor cameras. These sensors have a common property of giving a linear transfer characteristic over a large part of the exposure range, i.e. the electric output signal is directly proportional to the illumination level on the sensor. Since the light (colour) separation mechanism must take place in the optical domain it is necessary to have access to the linear electrical signals from the sensor(s) in order to measure the spectral sensitivity characteristics of the camera. For professional cameras of the 3-sensor type this is easily accomplished since all signal processing like gamma, matrix, high-light/low-light compression ('knee function', 'black stretch'), matrix etc. can be switched off. For reasons that are not disclosed or explained by manufacturers, single-sensor cameras are normally designed in such a way that both linear colour matrixing and non-linear video signal processing cannot be switched off. As a consequence, linear video signals are not available for measurement of spectral sensitivity. Another issue in some cameras is the indication that the colour correction matrix is inserted after gamma correction; this means that corrections for a linear error are performed on non-linear signals and thus its effect becomes highly unpredictable.

There are very few exceptions to this but we have found some cameras (from the same manufacturer) that can be switched to linear mode. Measurements made on these more-recent cameras show large differences, both between them and the original single-sensor camera data used in TLCI-2012. These differences are much greater than those between the 3-sensor cameras. So far, no manufacturer has explained the reasons for these differences. Fig. 3 shows the result from one of these cameras (again, equal-area data) and results from the other one can be seen in Fig. 4. The differences are obvious but again with no explanation from the manufacturer.

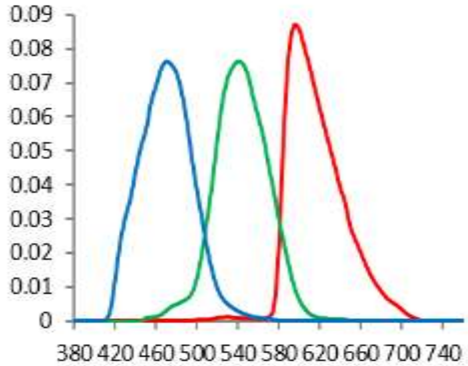

Figure 4 Alternative spectral sensitivities for a single-sensor camera CFA

Another aspect regarding differences in spectral sensitivity is that the filter pigments/dyes are deposited on the photo sites as a part of the sensor fabrication process. Readily available literature explains that there can be significant differences in the colour pigments/dyes from one manufacturer to the next. Also, there are few possibilities to 'trim' or 'design' the filter characteristics (if at all possible) of organic dyes/pigments compared with what can be done with thin-film interference filters. All this is in contrast to the situation for three-sensor cameras where the colour separation process happens before the light reaches the sensors. This process, based on reflection properties in metal-evaporated interference filters can be very well controlled and optimised, something that is shown in the EBU documentation describing the Standard Camera Model. The measurements made in the derivation of this set of spectral sensitivities nearly fall on top of each other, see Fig. 5.

Compare this with the measurements on four different single-chip cameras, see Fig. 6, again plotted with equal area under each curve. The differences between these cameras are much larger than those between the nine 3-sensor cameras. In particular, the red sensitivity curve, which peaks at around 620nm, extends to 410nm in one camera, but only to 500nm in another. Also, the green sensitivities, which peak at around 550nm show very large differences at around 480nm. **It is these differences which make it rather difficult to colour-match single-sensor cameras to each other, caused by the filter technology based on dyes and dating back many years when consumer stills photography cameras became available.** Cameras with 3-sensor design are relatively easy to colour-match although even that can be a challenge.

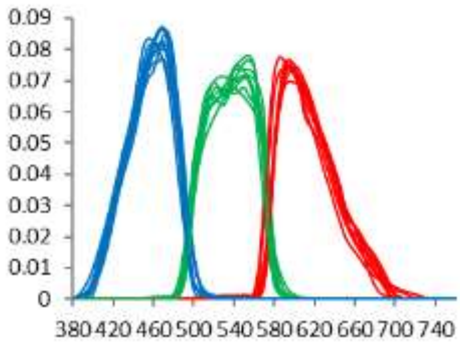

Figure 5 Spectral sensitivity of nine different 3-sensor cameras from three different manufacturers

However, literature from recent years show that interference filters can be designed and implemented with the required filter characteristics to an even better precision than what is visualised in Fig. 5 [7]. In addition, it has also been demonstrated that such filters can be deposited on a CMOS sensor in a Bayer type pattern. Again, there is little evidence that this technology is implemented on sensors in any camera available today; manufacturers are not providing information and it is difficult to verify by measurements for the reasons described above. Nevertheless, some signs in the recent results may point in this direction.

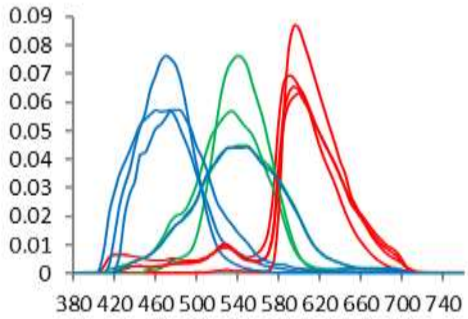

Figure 6 Spectral sensitivity of four different 1-sensor cameras from two manufacturers

CHALLENGES IN CHARACTERISING SINGLE-SENSOR CAMERAS

Our efforts to measure the spectral sensitivity of single-sensor cameras has been made difficult (as mentioned above) by the camera design in the sense that the linear video signals from the sensor in most cameras are not made available. All processing like (linear) colour matrixing, gain/black level settings and gamma correction takes place inside digital VLSI components and cannot be switched off or set to linear mode. There are signs that in some cameras the colour matrixing, if present at all, takes place on non-linear (gamma corrected) video signals. All this makes it difficult (in practical terms impossible) to measure the spectral sensitivity in these cameras.

It has been argued that the spectral sensitivity of individual cameras should be used when using the TLCI-2012 for calculating Q_a. From the above and the documentation of the TLCI-2012 it should be quite clear that for 3-sensor cameras this is neither necessary nor desirable; the differences between the 'Standard Camera Model' of the TLCI-2012 and the individual cameras as shown in Fig. 5 are quite insignificant.

Admittedly the situation is a little different for single-sensor cameras. This is because it is not practically possible to make serious and reliable measurements on most of these cameras because of the design. Theoretically it would be possible to 'undo' the gamma correction if the gamma curve was standardised or faithfully (mathematically) described. This is normally not the case and in these cameras the ‘logarithmic’ gamma curves (designed to give a ‘film-like’ colour performance) are much favoured. However, every manufacturer seem to have their own flavour of "log gamma" and often mathematical formulae describing these curves are given (probably because there is no equation, a ‘look-up’ table being used). On top of all that comes the added complication of colour matrixing and sensor non-linearity (see below), and the manufacturers do not tell what they do or why. Also, it is widely assumed that, when shooting with a single-sensor camera, there will always be a post-production process in which colours may be manipulated. In this respect, a single-sensor camera is not a complete camera since much of the necessary processing will be done as a post-production operation.

There is (at least) one more factor to be aware of when using Log-gamma in order to exploit the entire dynamic range of any CCD/CMOS sensor. Normally the video signal gains are set in such a way that 100% white is reached at a signal level from the sensor that leaves a very large signal headroom before the saturation level is reached; a headroom of 400% to 600% is quite common. This means that at the 100% level, and to some extent even higher levels, the sensor is still in its linear region. When the exposure is increased towards the saturation level, the sensor itself - even before any gamma correction is applied - enters a region where linearity is lost and the output signal is crushed. The explanation for this is to be found in the physics of semiconductor behaviour. In every photo-site on CCD/CMOS sensors there is a "potential well" that collects the free electrons generated by the photons hitting the photo-site. This "well" can be compared to a "bucket" that collects electrons. As this bucket fills up, and with the individual electrons repelling each other since they have the same electrical charge, it can be compared to trying to fill a bucket with boiling water. The 'boiling' gets stronger as the bucket fills up and electrons start to 'bubble/spill over' and are lost. This happens gradually but the 'spilling of electrons' becomes more and more pronounced as the potential well fills up until all new electrons generated by photons are lost in the overflow. At this point the sensor has reached saturation. This effect is difficult to quantify in a camera as it happens in the region where non-linear highlight handling of the gamma curve is applied; separating these two effects from each other is futile when there is no possibility to switch off gamma.

TLCI CALCULATIONS AND EFFECTS OF MATRIX OPTIMASATION

If the spectral sensitivities for any camera like those shown above are used for TLCI calculations, they will produce Q_a results that will be significantly dependent on the shape and overlap of the respective curves. The results will be inconsistent since there will be large errors in the calculated colour reproduction. This is due to the overlap of the sensitivity curves; but without this the camera would be useless to broadcasters. Should there be regions in the visible spectrum where two of the camera curves do not overlap, the camera would be blind to colours in that region of the visible spectrum. Other vital factors to camera performance are sensitivity (to visible light) and signal/noise ratio. For these two parameters to give satisfactory results the filter curves for each colour should preferably be wide and with a good amount of overlap to ‘neighbouring colours’.

These requirements necessitate the use of a mechanism that uses the spectral overlaps to generate requisite negative lobes and to trim the positive lobes. This improves the colour performance and it is vital to acceptable camera performance. The matrix performs the following operations:

$$R_{out} = a_{rr}R_{in} + a_{gr}G_{in} + a_{br}B_{in}$$

$$G_{out} = a_{rg}R_{in} + a_{gg}G_{in} + a_{bg}B_{in}$$

$$B_{out} = a_{rb}R_{in} + a_{gb}G_{in} + a_{bb}B_{in}$$

Note that the horizontal sum of the coefficients a_{xx} must be unity in order to avoid shifting the colour balance.

If we know the spectral sensitivity curves we can find matrix coefficients that maximise the colour accuracy of the camera. For 3-sensor cameras this is described in detail in [1] for the TLCI Standard Camera Model. As described in the previous sections there are several hurdles regarding the single-sensor cameras; spectral sensitivity curves must be known, few cameras can be switched to linear modes for measurements, no detailed description/formula for gamma correction, matrix after gamma correction in some cameras etc. But, for the cameras whose curves we have, matrix optimisation has been possible, with varying results.

It was surprising to find that matrixes can be found such that camera performance could be largely in line with what is obtained for 3-chip cameras using the Standard Camera Model. As an exercise, matrices were also calculated for those cameras where the matrix could be after gamma correction, resulting in surprisingly good colour performances. However, in many cases the optimum coefficients can become so large that the overall picture quality in other aspect than colour reproduction will not be acceptable (noise, sensitivity). In those cases, the only possibility in normal programme production would be to make the final colour adjustments in the post production stage of the production, but that would probably also mean manipulating the non-linear signals, and so the results are dubious. Thus, these single-sensor cameras cannot easily be used to form a 'Standard camera'.

SINGLE-SENSOR CAMERAS AND THE TLCI-2012

As mentioned above, it is widely assumed that productions where single-sensor cameras are in favour are planned with comprehensive post-production processing and that colour manipulation plays a significant role. This will also include evaluations of suitable lighting equipment where probably the TLCI-2012 is used as a helpful tool.

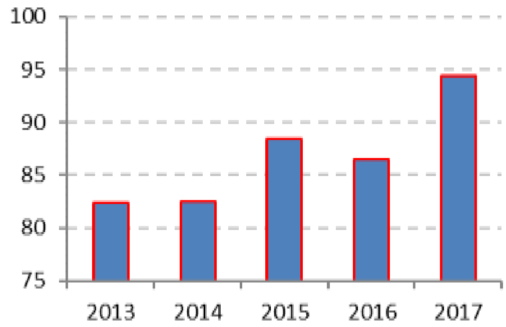

Figure 7 Trend in LED luminaire Q_a value since 2013

TLCI measurements on real luminaires since its inception show a gradual improvement, year-on-year; see Fig. 7. The apparent reduction in the average score for the year 2016 is largely due to the inclusion of a significant number of non-television luminaires (e.g. RGBW LEDs) which have a consistently poor Q_a score. These luminaires are not usually regarded as being suitable for use in television production, but are frequently used for stage and theatre production. The high value for 2017 is unreliable since it is derived from only a small number of measurements. Nevertheless, the trend is clear, luminaires have improved significantly during the time that TLCI measurements have been made and published. It is unclear whether this is simply because luminaires are getting better, or because the existence of the TLCI has made it easier for manufacturers to 'get it right'. Either way, the television industry is benefiting from the TLCI.

The measurements from the different single-sensor cameras available today will all return at least a Q_a of 70 to 75 or above where a TLCI-2012 Standard Camera Model gives a Q_a of 80. In addition, the work and investigations behind the EBU Recommendation R-137 (recommending the use of the TLCI-2012 for evaluation of light sources to be used in electronic camera programme productions) show that professional colourists will have little problem in compensating for possible colour errors returned by the single-sensor cameras that have been available to our investigations. We feel that colourists will hardly be aware of the reason for the small colour errors he/she may feel inclined to correct in typical single camera shooting.

Earlier attempts at using single-sensor cameras in 'live-type' productions together with several 3-sensor 'system cameras' have shown various difficulties in camera matching/colour reproduction. However, at present there are coming onto the market single-sensor cameras with high-resolution Super 35-type sensors and with full system camera facilities. It seems reasonable to assume that for this development to be successful, new cameras should have spectral sensitivity properties in line with earlier 3-sensor camera technologies; not because it's what we've always done, but because it's right. Likewise, that the spread between future cameras is likely to be in line with current findings for 3-sensor cameras. Should this not be the case there will be an unresolved problem with camera matching/colour reproduction.

CONCLUSIONS

It has been confirmed that professional single-sensor cameras today have larger differences between them than is the case for professional 3-sensor cameras. Many of the reasons for this have been identified and explained. In spite of all this it has also been shown that using the TLCI-2012 for evaluation of lighting products to be used for scene lighting will be equally useful to all cameras and camera users; the essential post-production process in single-camera shooting should take care of any remaining errors due to the spread in camera performance.

The spectral measurements reported here must remain anonymous for commercial reasons. However, the measurements have all been made in the same way at the laboratories of NRK. They show, almost by accident, why colour-matching cameras together is difficult, particularly so in single-sensor cameras with the increased spread in Q_a results compared to the Standard Camera Model. The main reason is that the colour separation mechanism (filters) in single sensor cameras causes a larger spread in the spectral sensitivities compared to 3-sensor cameras. However, even with this larger spread in Q_a values, colourists will not experience any problems in correcting the residual colour errors.

Most cameras can be shown to give reasonable colour reproduction performance by calculating an optimum colour matrix. However, in many cases the optimised matrix could not be used in a practical camera due to the matrix coefficients becoming so large that the camera would be unusable in other parameters. If the coefficients become abnormally large, the camera noise performance suffers significantly.

Even with the larger spread in the precision of coulour reproduction in current single-sensor cameras the TLCI-2012 still remains a most useful tool for validating the performance of modern luminaires when used in TV and film productions.

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