Acta Scientific MEDICAL SCIENCES (ISSN: 2582-0931)

Volume 6 Issue 5 May 2022

Mini Review

# Colour Traceability in High-resolution Colorimetry: From Mental Images to Virtual Measures

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**DOI:** 10.31080/ASMS.2022.06.1242

**Received:** February 24, 2022

**Published:** April 15, 2022



## Abstract

The concept of digital image as an information model of an object for human and machine vision at macro and micro levels is proposed. The sources of traceability for qualitative colorimetry methods are considered. Based on an integrated approach, the issues of colour traceability in high-resolution colorimetry for each element of the information-measuring channel that are illuminant, illuminated surface, recording device, software and display device. The uncertainty factors of measurement information associated with the loss of measurement information during sampling, quantization and encoding of graphical data are considered. The proposed principle of the hierarchy of traceability of digital images is based on the criterion of maximum information entropy, depending on the presence of a traceability source. The undirected graph model for the description and identification of digital images is recommended for the use of high-resolution colorimetry.

**Keywords:** Digital Image; Colour; Colorimetry; Traceability; Standard Sample; Entropy

## Introduction

High-resolution colorimetry is a methodology of multiparametric studies the subject of which is the color, brightness and spatial characteristics of objects determined by their digital images. The methodology is being developed on the basis of the Research Laboratory of Optical-Electronic Instrumentation of the BNTU Research Polytechnic Institute within the framework of the tasks of the State Research Programs of the Republic of Belarus "Electronics and Photonics", "Photonics, opto- and microelectronics", "Photonics and its applications". Since colour is specified as a subjective perception and a vector quantity it can be evaluated qualitatively and quantified. Any physical or virtual object has an infinite number of implementations in the form of digital images due to the combinatorics of technical and software. Qualitative and quantitative methods are effective in differential Colorimetry in assessing and calculating minor colour differences when the brightness characteristics of an object are within the dynamic range of a digital image [1] otherwise there is a problem of distortion of the results due to the limited colour coverage (gamut) of recording and transmitting devices. Therefore, it is necessary to study issues related to the traceability and uncertainty of research results. Approaches to ensuring the traceability of colorimetric studies are systematized and recommendations are given to improve accuracy and reliability in the article.

Digital images as information models of objects with a given accuracy and reliability reproduce their spatial, photometric and colorimetric characteristics at a certain point in time and under certain conditions "images that are more or less similar (but not identical) to the depicted objects" [2]: due to ISO/TR 9241-310:2010 they are non-point primary emitters at the macro level, arrays of pixels or sub-pixels at the micro level and arrays of data (orthogonal real functions) at the information level

[3]. The Colorimetry of digital images is based on a differential measurement method in which an interesting (control) area of pixels with nominally identical properties is isolated, their intensity is averaged in the red $I_R$, green $I_G$ and blue $I_B$ colour channels, the intensity of the I sections of the digital image corresponding to the reference and control areas is measured, and the intensity of the I non-self-luminous object in the control area is calculated by the formula [4]:

$$I = (N - N_{01})\frac{(L_{02}\rho_{02} - L_{01}\rho_{01})}{N_{02} - N_{01}} + L_{01}\rho_{01} \text{ ----------(1)}$$

Where N is the output signal of the CCD matrix corresponding to the brightness of the control point on the object image; $N_{01}$, $N_{02}$ are the output signals of the CCD matrix corresponding to the intensity of the reference image; $L_{01}$, $L_{02}$ are the brightness values of the reference areas, cd/m$^2$; $\rho_1$, $\rho_2$ are correction coefficients (reflection coefficients).

Recalculation of colour coordinates R ($I_R$), G ($I_G$), B ($I_B$) into coordinates of a hardware independent space for example XYZ and calculation of chromaticity coordinates x, y, z by formulas [5]:

$$X = 0.418R - 0.0912G + 0.0009B \text{ -------------(2)}$$

$$Y = -0.1587R + 0.2524G - 0.0025B \text{ ---------------(3)}$$

$$Z = -0.828R + 0.0157G - 0.1786B \text{ -------------------(4)}$$

$$x = \frac{x}{X+Y+Z}; y = \frac{y}{X+Y+Z}; z = \frac{z}{X+Y+Z} \text{ ----------------(5)}$$

The implementation of colorimetric studies in time and space determines their reliability, accuracy and uncertainty.

The sources of colour traceability of digital images in qualitative (visual) methods are evolutionarily formed groups of subjective perceptions based on mental or visual comparison of colours. The colour carriers of the first group are "mental images" symbolizing the elements [6], associative patterns of natural optical phenomena and non-self-luminous natural objects that do not require physical reproduction. The second group consists of physical objects: light sources and non-self-luminous objects (originals, reproductions, reflectors, colour atlases) for visual equalization. The third group is virtual objects: digital images of the sources of the first and second groups, as well as hardware universal and adapted colour palettes. The listed sources use scales of names and order including verbal description. Qualitative methods have the main drawback in the form of a subjective component caused by visual perception phenomena [7], visual anomalies, thought processes, fatigue and "computer vision syndrome" [8]. Quantitative methods allow you to "rebuild" from the subjective component.

The validation model of the information-measuring channel proposed by the author is based on the fact that the digital image is the result of the convolution of the functional colour spaces of the elements "illuminant", "illuminated surface", "recording device", "software", "display device" and the information model of any of them, provided that all other elements are validated [9]. Any digital image can be processed increasing or decreasing the accuracy and reliability of information depending on the tasks being solved. If $Q_{kj}$ is an input quantity (spectral distribution function or averaged intensity) j is the element of the information and measurement channel, $n_{kj}$ is the k-th random realization of the input quantity, the carrier of which is validated or verified, $q_k$ is an unknown realization of the input quantity determined by a digital image; $u(q_k)$ is its uncertainty; $u(\eta_{jk},\eta_{lm})$ is covariance then the validation model can be presented in the form of table 1 describing six states (realizations). Elements that are measurement objects are highlighted with a grey fill. It should be noted that in the automated processing of graphic data, the element "display device" can be ignored.

The implementations are based on the fact that the digital image of the investigated object $q_j$ is compared with the digital image of the same object obtained under conditions of metrological traceability. Visualization and determination of the characteristics of the projected object. it is carried out in a loop through feedback when implementing $Y_6$.

The sources of metrological traceability of colour in quantitative methods are standards (standard samples, reference measuring instruments) and reference measurement methods. For the "illuminant" element, the sources are standardized (ISO 11664-2:2007) - A (2856 K, x = 0.448, y = 0.407), $D_{65}$ (6504 K, x = 0.313, y = 0.329), $D_{50}$ (CIE 15:2004), "standard sky" (ISO 15469:2004) - a set of brightness distributions for sky models in a wide range of weather conditions, LED lamps LED-B1, LED-B2, LED-B3, LED-B4, LED-B5 with a maximum at a wavelength of 460 nm; and LED-RGB1 (640 nm) and LED-BH1 (630 nm); LED-V2 (550 nm) and LED-V1

| Realization k | Element j | | | | | |
|---|---|---|---|---|---|---|
| | Illuminant $Q_1$ | Illuminated surface $Q_2$ | Recording device $Q_3$ | Software $Q_4$ | Display device $Q_5$ | Exit |
| $Y_1$ | $q_1$ $u^2(q_1)$ | $\eta_{12}$ $cov(\eta_1,\eta_2)$ | $\eta_{13}$ $cov(\eta_1,\eta_3)$ | $\eta_{14}$ $cov(\eta_1,\eta_4)$ | $\eta_{15}$ $cov(\eta_1,\eta_5)$ | $Y_{01}$ |
| $Y_2$ | $\eta_{21}$ $cov(\eta_2,\eta_1)$ | $q_2$ $u^2(q_2)$ | $\eta_{23}$ $cov(\eta_2,\eta_3)$ | $\eta_{24}$ $cov(\eta_2,\eta_4)$ | $\eta_{25}$ $cov(\eta_2,\eta_5)$ | $Y_{02}$ |
| $Y_3$ | $\eta_{31}$ $cov(\eta_3,\eta_1)$ | $\eta_{32}$ $cov(\eta_3,\eta_2)$ | $q_3$ $u^2(q_3)$ | $\eta_{34}$ $cov(\eta_3,\eta_4)$ | $\eta_{35}$ $cov(\eta_3,\eta_5)$ | $Y_{03}$ |
| $Y_4$ | $\eta_{41}$ $cov(\eta_4,\eta_1)$ | $\eta_{42}$ $cov(\eta_4,\eta_2)$ | $\eta_{43}$ $cov(\eta_4,\eta_3)$ | $q_4$ $u^2(q_4)$ | $\eta_{45}$ $cov(\eta_4,\eta_5)$ | $Y_{04}$ |
| $Y_5$ | $\eta_{51}$ $cov(\eta_5,\eta_1)$ | $\eta_{52}$ $cov(\eta_5,\eta_2)$ | $\eta_{53}$ $cov(\eta_5,\eta_3)$ | $\eta_{54}$ $cov(\eta_5,\eta_4)$ | $q_5$ $u^2(q_5)$ | $Y_{05}$ |
| $Y_6$ | $q_1$ $u^2(q_1)$ | $q_2$ $u^2(q_2)$ | $q_3$ $u^2(q_3)$ | $q_4$ $u^2(q_4)$ | $q_5$ $u^2(q_5)$ | $Y_{06}$ |

**Table 1**: Validation model of the information and measurement channel.

(550 nm) (CIE 15:2018); reference values of wavelengths for the description of optical materials, optical systems and means (ISO 7944:1998): UV Hg e-line (365.01 nm), Violet Hg h-line (404.66 nm), Blue Hg g-line (435.83 nm), Blue Cd F′-line (479.99 nm), Blue H F-line (486.13 nm), Green Hg e-line (546.07 nm), Yellow He d-line (587.56 nm), Red H c-line (656.27 nm), Red He r-line (706.52), mercury line– 546.07 nm. For laser radiation: He-Ne - 543.5 nm; He-Ne - 632.8 nm; Nd:YAG - 1064.1 nm.

For the "illuminated surface" element (secondary light source) precision spectrophotometers are used, calibrated according to standard samples of colour, directional transmission (U = 0.12%) and diffuse reflection (U = 0.5%) (for example, the National Standard of color coordinates of the Republic of Belarus, http://belgim.by), perfect reflective scatterers, the spectral reflection coefficient of which is equal to one for all wavelengths (ISO 7724-2:1984). Colour comparison standards are subject to aging which can lead to noticeable colour changes over time.

It is supposed to use a digital camera or scanner of a professional or semi-professional class as an element of a "recording device" calibrated with the help of adjustment test tables, dashboards and color palettes (for example, DSC Labs Cam Align CDM Fairburn 3D VS 10.2, etc.) with the creation of a "Calibration passport" or "Map of faulty pixels" (ISO 12233:2017). The "reference grid" for calibrating the scanner provides a spatial resolution of 1-2 microns.

The traceability sources for the "software" element are standard color models are for the visual analyzer, the actinic functions p(λ) and the functions of standard observers $XYZ_2$ and $XYZ_{10}$ (ISO 11664-1-2007); hardware independent colour spaces: XYZ (1931), $xyZ_2°$ (1931), Hunter Lab (1958), CIE Yuv (1960), $CIEXY_{10}°$ (1964), Cieyu'v' (1976), CIE La*b* (1976) (ISO 11664-4:2007), CIE Lu*ν * (1976) (ISO 11664-5:2007), JPC 79, YIQ (PAL), YCbCr (SECAM); hardware-dependent spaces RGB, HLS, HSB, CMYK; combined colour perception models - Nayatani (1981), Hunt (1982), CIE94, CIECAM97s CIELAB (CIEDE2000), CIEDE2000, CAT02, CIECAM02 (CAM02-UCS), and CIECAM16 [5]. Most of the functions are empirical and are being improved from the point of view of introducing corrections and correction coefficients during the transition from standard to real observation conditions [5,7] taking into account the factors of the age of observers and the conditions of the "near" and "far" environment.

The main sources of traceability for the "Display Device" element are measuring instruments - for example, a spectrophotometer of the Gretag Macbeth Eye-One Pro type which "allows you to calculate colour coordinates in various colour systems", create scanner, printer and monitor profiles under the conditions defined in ISO 13655:2017: M1 (CIE $D_{50}$), M2 (CIE $D_{50}$ c UV- glow filter) and M3 ($D_{50}$ c UV - glow and polarization filters).

High-resolution Colorimetry, in addition to the listed traceability sources, also uses virtual measures - digital images and file data of reference samples obtained under various precision conditions.

The loss of measurement information in the information and measurement channel is caused by built-in algorithms for processing graphical data, which are aimed at decreasing redundancy. The combined formula for the brightness of the sampled and quantized image has a view [1,2]:

$$L_c = \sum_{-\infty}^{\infty}\sum_{-\infty}^{\infty}\frac{L_{\max}}{m-1}(n\Delta_x, k\Delta_y)\frac{\sin\omega_{xb}(x-n\Delta_x)}{\omega_{xb}(x-n\Delta_x)}\frac{\sin\omega_{yb}(y-n\Delta_y)}{\omega_{yb}(y-n\Delta_y)}(a_{n_0}2^{n_0-1}+a_{n_0-1}2^{n_0-2}+..+a_1 2^0), \text{-----------(6)}$$

Where k, n are indexes representing row and column numbers, respectively; $\omega_{xb}$, $\omega_{yb}$ boundary circular spatial frequencies of the digital image spectrum; $\Delta_x$, $\Delta_y$ - spatial sampling intervals; $L_{max}$ - maximum brightness value in the image; $a_k$ = 1 or 0; k = 1, 2, ... $n_0$; m is the number of quantization levels ($m = 2^{n0}$); $n_0$ - the number of bits of binary code per pixel.

AVIF, MHT algorithms (JPEG format, etc.) are used in encoding for lossy compression by "thinning" digital images by spatial and brightness characteristics [1]. Lossless compression is performed using RLE group encoding algorithms with modifications of RLE-PackBits, RLECCIT, PCX, GIF, TIFF, RMR), LZW (Huffman) and arithmetic encoding (TIFF, RAW, GIF, JPEG Lossless, SVG formats) [1]. Restoration of a continuous signal and raster in time and space is performed after decoding and temporary postfiltration [10]:

$$B(t) = \int B_s(\tau)\cdot h_d(t-\tau)d\tau = B(x_t, x_t) \text{ or } \text{--------(7)}$$

$$B(x,y) = \int B_s(t)\cdot h_d(x-x_t, y-y_t)dt \text{ -----(8)}$$

Interpolation algorithms are used in image reconstruction [10]:

$$B(x,y) = \sum_k \int_{y-\delta}^{y+\delta}\int_{x-\delta}^{x+\delta} B(x_k, y_k)\cdot H_d(x-x_k, y-y_k)dxdy \text{ ------------(9)}$$

Where $H_d(u, \nu)$ interpolation function. A bilinear function is usually used [10]:

$$H_d(u,\nu) = S(u,\Delta x)\cdot S(\nu,\Delta y) \text{ -------------(10)}$$

Linear interpolation is used for rectangular arrays of pixels [10]:

$$S(u,\Delta x) = 1-\left|\frac{z}{\Delta}\right|, \left|\frac{z}{\Delta}\right| \le 1 \text{ -------------(11)}$$

At the same time, the dynamic range of brightness values of the entire image is limited [10]. Digital images have entropy with respect to the object of study, and their processing can increase or decrease the uncertainty of colour.

The hierarchy of traceability of digital images according to the criterion of maximum information entropy is based on the classification by features: 1) the number of degrees of freedom – two-dimensional (2D), three-dimensional (3D) [1]; 2) color depth - binary (2 shades), halftone (4-256 shades), palette (2-256 shades), full-color (16777216 shades) [1]; 3) type of graphics – vector, ASCII (ISO/IEC 18004:2015), raster, mixed; 4) informativeness - semantic, textural [1]; 5) playback mode - static, dynamic; 6) the number of layers - single-layer, multi-layer (HDRI, panoramic); 7) the type of format; hazard levels - A, AA, AAA (ГОСТ Р 50948-2001). The entropy of the value H(Y) is maximal for equally probable states of discrete messages and is equal to [11]:

$$H_{\max}(Y) = \log_2 m, \text{ ---------------(12)}$$

Where m is the number of states.

The ensemble of states [11] in the interpretation of the validation model has the form:

$$Y = \begin{bmatrix} Q_1 & Q_2 & Q_3 & Q_4 & Q_5 \\ P(Q_1) & P(Q_2) & P(Q_3) & P(Q_4) & P(Q_5) \end{bmatrix} \text{ --------------(13)}$$

The average amount of information in the ensemble ("at the same time, the states are independent and incompatible" is determined by the ratio [11]:

$$I(Y) = I(Y) - H_0(Y) = \sum_{j=1}^{m} P_o(q_0)\log_2 P_0(q_j) - \sum_{j=1}^{m} P(q_j)\log_2 \text{P}(q_j), \text{-----------}(14)$$

Where P is the a priori (before experience) probability of the appearance of the state; $P_0$ is a posteriori (after experience) probability; H and $H_0$ - a priori and a posteriori random variables (entropies).

The scheme of the conditional ensemble [11] for this case is shown in figure 1. The variable $\eta_1$ illustrates the presence of metrological traceability (for implementation 1 - the use of a reference light source in measurement as a measure).

$Y|a=$

| | $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ | $Q_5$ |
|---|---|---|---|---|---|
| $y_1$ | $P(y_1\|\eta_1)$ | $P(y_1\|\eta_{12})$ | $P(y_1\|\eta_{13})$ | $P(y_1\|\eta_{14})$ | $P(y_1\|\eta_{15})$ |
| … | … | … | … | … | … |
| $y_k$ | $P(y_k\|\eta_{k1})$ | $P(y_k\|\eta_{k2})$ | $P(y_k\|\eta_{k3})$ | $P(y_k\|\eta_{k4})$ | $P(y_k\|\eta_{k5})$ |

**Figure 1:** Chime of a conditional ensemble of quantities.

Conditional entropy "shows what entropy the message of the element $Q_j$ gives, if the entropy of the message $q_j$ is already known"[11]:

$$H(Y \mid Q) = -\sum_{i=1}^{k}\sum_{j=1}^{m} P(\eta_j, y_i)\log_2 P(y_i \mid \eta_j) \text{-----------------}(15)$$

If x, y are pixel coordinates $p_k$, A is the width of the image, B is the height of the image, and for convenience A = B, i. e. $x \in [0;A]$,a $y \in [0;B]$, V is the set of vertices of the graph, E is the set of edges of the graph, Z is the color depth, T is the time, Z is the color depth, D is the number of image layers, then the edges of the graph are the connection of pixels among themselves [3]:

$$G = (V, E, Z, T, D), V = \{v_{i1}\}, E = \{e_{i2}\}, i_1 \in A * B, i_2 \in 1...k[1,3], \text{----------------}(16)$$

Where $i$ = 1…A, $j$ = 1…B.

An undirected graph will be written as:

$$G = (V, E, Z, T, D), V = \{v_{i1}\}, E = \{e_{i2}\}, i_1 \in A * B, i_2 \in 1...k[1,3], \text{-----------}(17)$$

Since "the entropy of known messages is minimal and equal to zero" [11], digital images of static physical objects (originals) obtained in real time under standard conditions with the presence of a measure and with the possibility of verification - calibration of the vision system at predetermined control points have the least entropy. The greatest entropy is inherent in digital 3D images of simulated virtual dynamic objects. Multilayer digital images without the possibility of verification from the original and with a time delay (for example, photographs of celestial bodies and galaxies) occupy an intermediate position between these extreme states.

## Conclusions

A digital image is an information model of an object: at the macro level it is a non-point primary emitter, content bearing a semantic psychoemotional load; at the micro level it is a set of brightness readings identified in the physical, virtual and functional color spaces; at the information level, it is an ensemble of states in the space of random events described by multiparametric orthogonal functions and undirected graphs.

The informative parameters of digital images are accuracy, uncertainty and reliability. Accuracy is ensured by reference to reference measurement methods and standards (standard samples), as well as (as suggested by the author) to their digital images (virtual measures) obtained under certain conditions. Since colour is a vector quantity uncertainty in high-resolution Colorimetry is the geometric location of points in the selected colour space limited by surfaces drawn between the radius vectors of colour coordinates and intensity.

The nominal quantization step within the dynamic range of a digital image is the main uncertainty factor in colour measurement. The reliability of the colorimetric properties display can be estimated by means of information entropy caused by the inevitable loss of measurement information during the graphical data processing. The analysis of the proposed validation model of the information and measurement channel showed the possibility of increasing accuracy reducing uncertainty and entropy due to validation and verification of channel elements as well as the use of virtual measures in measurement.

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