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Evolution and transform of the tone value meaning and metrics in standardizing the printing process control

ABSTRACT

Concept of the basic parameter of halftone printing - tone value is concerned in the historical context of improving the models of image printing. The multi-stage nature of a process is also taken into account in the light of solving the color communication problems of modern open and disconnected pre-press environment. The special attention is put for more accurate and different in their meaning and metrics interpretations and definitions of this term versions. The mathematically approved and experimentally confirmed examples of tone value presenting the stimulus like luminance Y of CIE XYZ or the perception thereof as CIE Lab lightness L are presented.

KEY WORDS
stimulus, perception, lightness, luminance, halftone

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Introduction and background

Having approved, in general, the draft of the new version of the lithography standard (International Organization for Standardization, 2023), developed by TC 130 “Printing technology”, the representatives of ISO member countries have put forward a number of general, technical, editorial comments and corrections in ISO/TC 130 N 5077.

For this reason, as well as due to the need to clarify the target values for novel "near neutral" calibration method the TC 130 has temporarily suspended this draft progress.

The proposed improvements did not however affect the cluster of terms unified within the tone value concept relating to the most important print image property.

With the emergence of new standards and the updating of existing ones, there was a need for more accurate, sometimes different in their meaning and metrics this term interpretations. To date, ISO TC130 documents have accumulated more than a dozen names of this term that have added or changed from version to version of the standard:

- tone value (data), digital tone value;
- tone value (printing), printed tone value;
- density tone value;
- tone value increase (TVI);
- tone value (printing forme), plate tone value;
- tone value (colorimetric);
- colour tone value (CTV), spot colour tone value (SCTV);
- delta colour tone value;
- near neutral CMY tone value;
- near neutral black tone value...

There was an attempt made in above draft, as well as in the previous standard versions, to streamline the list of these terms, hierarchically subordinating the particular terms to the senior ones by their indexing order in section 3 "Terms and definitions" of the document. Despite this, the most of interpretations remain rather uncertain, not always logical in a number of aspects and need some explanation or clarification. It’s below performed on the basis of historical review of printing calibration developments, analysis of process stages characteristics and image signal transforms, as well as by the use of some calculations and experimental data.

Densitometric and colorimetric calibration

According to basic binary (ink/no ink) principle of halftoning, the print tone measure is, historically, designated in a percent of the relative ink coverage within a unit image area. The intermediate, grey gradations on, for example, b/w print are, in turn, perceived due to the spatially additive mixture by the Human Visual System (HVS) of the halftone dot black and blank paper white portions.

With use of n process inks, the print color is similarly defined by the weighted sum of 2^n parts occupied within such area by blanks, ordinary ink layers and overlaps thereof. Following this logic, the temporal additively previewing of halftone color on the rotated Maxwell disk was suggested with dividing the latter onto 2^n sectors containing, for example, 2^3 (CMY) combinations of said portions (Nyberg, 1932).

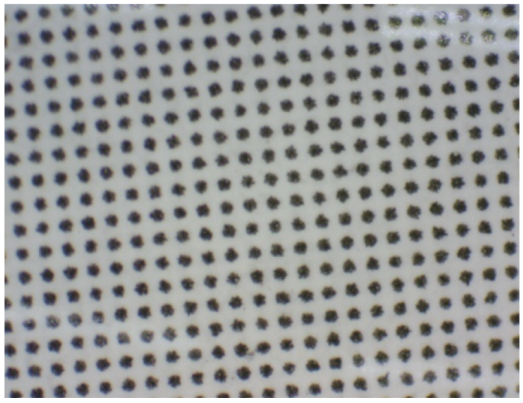
To estimate the expected reflectance or optical density of a halftone at its prescribed ink coverage in particular case of monochrome printing (n = 1) the formula was published to be thereafter widely used in the densitometric method of print control and calibration (Murray, 1936; Sheberstov, 1936). Following the same principle of partition area coverage, the generic model, applicable for the arbitrary number n of process inks and allowing the print color data prediction in various metrics, was next year published (Neugebauer, 1937).

All these, at first purely geometrical interpretations, were over time supplemented with taking into account the specific effects of the ink-substrate-light interaction on the result of printing:

- capture of light, scattered in a blank, by the edge of a halftone dot (Yule & Nielsen, 1951);
- ink film thickness dependence on the size of a dot (Byer, 1969);
- concomitant change in the reflection spectrum;
- multiple reflection/absorption of light within the print substrate (Yang & Kruse, 2000);
- variable effect of chromaticity of the latter on the color of a halftone tint, and the other factors.

Byer (1969) investigation has in particular shown that the ink film thickness on halftone dots sharply reduces at coverage lower 70%, which makes the densitometric estimation of a dot size rather doubtful.

Photograph of the halftone tint on figure 1 demonstrates, for example, the about twice greater visible coverage as compared to 6.5% of its densitometric calculation at ink solid of 1.55 and substrate of 0.1. It's visually evident from this figure that adding in blank area just of 5- 6 such dots will produce the complete, 100% coverage.



» **Figure 1:** *Micrograph of a halftone tint with the visual coverage over 10% against of its 6.5% as result of dot area densitometric calculation*

Additional errors arise due to the own noise of process and, in particular, the substrate roughness which causes the non-stable transfer onto it of the tiny dots and gaps.[1]

The use of densitometric estimation for printing process calibration is currently supplemented by the colorimetric one and the both of them stay operate with pairs of concepts/parameters, which, by virtue of physiology, very nonlinearly relate to each other. The former in these pairs refer to the stimulus affecting vision, and the latter to the perception as the sensation of this stimulus impact. In densitometry, such a pair consists of the reflection coefficient and its negative logarithm (optical density), while in colorimetry the similar roles play, for example, the luminance Y of XYZ and the Lab lightness L as the measure of luminance perception. However, the order of using these parameters in these methods turned out to be the opposite (Figure 2).

Coverage estimation

Densitometric		**Colorimetric**	
Perception ⟶ **Stimulus**		**Stimulus** ⟶ **Perception**	
(opt. density).	***(dot area, refl.)***	***(luminance)***	***(lightness)***

» **Figure 2:** *Opposite direction of the metrics replacement in two variants of data calculation for printing process calibration*

In the first method the dot area/absorption/luminance, i.e. stimulus is calculated from the perception-related optical density of a halftone tint. To the contrary, the, so-called, color tone value (CTV) of visually uniform Lab space is in the other one determined from the luminance Y (stimulus). Leaning towards the accustomed notion of ink coverage, the CTV name conceals this fundamental metrics difference relying upon its proper accounting in the curve calibration procedure.

[1] Except of the substrate (0%) and the ink solid (100%), the latest standards of 12647 series do not advice calculations in areas below 10% and above 90%.

Meantime, the term for basic print image parameter tone value proceed from the percent coverage principle stays generic in ISO12647 “Graphic technology…” series of standards since 1996 (International Organization for Standardization, 1996).

Characteristics of the process and its stages

From capturing an original to its print copy output the reproduction process encompasses the number of physical transforms of an image content. It starts from the light to electric signal conversion and completed by signal to substrate inking one. Each of these and intermediate signal transforms are characterized by the nonlinear relationship of their input and output values.

The transfer curve of each stage should be and is, in practice, optimized according to its own criterion. At image capturing it can, for example, comprise the maximal achievable dynamic range of a signal. In platemaking, such a criterion is the robustness of ink transfer on a substrate, as well as, on a press it can be the possible achievable tone range, color gamut...

Meantime, the standard does not recommend the criteria of optimization or related press settings, but, in consent to its title, teaches only to “Process control…”. It deals just with the calibration which would match the data of certain output profile or allows to produce and register the new one. Some of the initial on-press parameters can be only indirectly taken there from the particular set of multiple variants of Printing Conditions (PC).

However, just the ink supply can be in certain degree adjusted according to the color values of solids prescribed for the given PC. The other parameters of halftone printing stay passed by the standard relying upon the operator skills and experiences. It concerns of such important procedure settings as pressure on a press, volume and range of a K ink use (Kuznetsov & Ermoshina, 2016), as well as of the tone values of “white” and “black”.

The latters define the contrast, as the most predominant image property, comprising, in its turn, the base for the substantiation of a screen ruling value for the certain kind of technology (Kuznetsov, 1999). The achievable level of print image quality significantly depends on all of these parameters.

In the absence of optimization, it is not ensured that the own reproduction facilities of the process are realized in full scale. Instead of the optimal adjustment of the process itself, its correspondence to the output profile occurs primary.

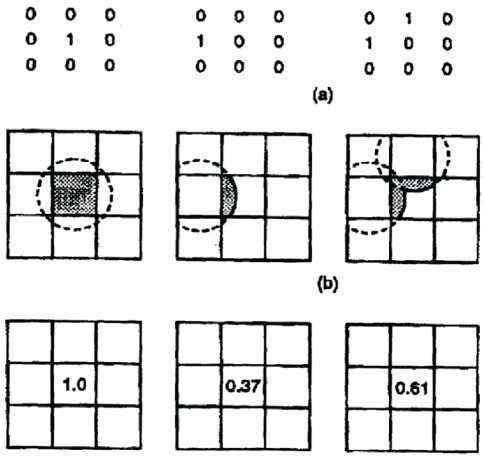
The ISO/TS 10128 does not help so much in this aspect as far as once again teaches just to the “Methods of adjustment… of a printing system to match a set of characterization data”. In such situation, the need for a document titled like "Optimal process organization for its further profiling or calibration..." may arise.

The task and result of the entire process is presented by the tone reproduction curve (TRC) connecting the tone value (data) and printed tone value (Kuznetsov, Schadenko & Vaganov, 2020). It follows from all intermediate curves which interrelation is used to demonstrate by the multi quadrant Jones diagrams (Kuznetsov, 2021). The issues of optimal shape and calibration of this curve are very relevant in today's open prepress environment and technical standards development (Birkett & Spontelli, 2018).

One of the main parameters of said calibration is the tone value increase (TVI)[2], which can be concerned as the sum of stepwise differences between:

- tone value (data) and tone value (printing forme);
- tone value printing forme and ink coverage on it;
- said coverage and printed tone value.

As figure 3 shows, the input-output non-linear connection at the first of above stages may result from the configuration incompatibility of a square cell in the recording signal bit map and round aperture exposing a plate (Carrara, Analoui & Allebach, 1992).



» **Figure 3:** *Element of the plate is partially exposed, even if it isn’t stipulated by the data tone value of an output bit map: a) bitmap; b) position of the beam when recording; c) tone value on the plate (adopted from Carrara, Analoui & Allebach, 1992)*

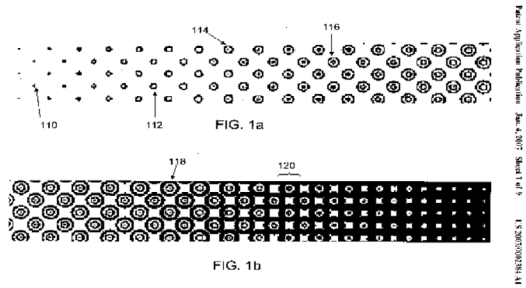
This discrepancy can be compensated due to the procedure of the, so-called, plate linearization by introducing corrections into the recording signal (Sanger, 2005).

[2] Earlier named as dot gain.

However, during the subsequent ink-to-plate transfer, the resulting ink coverage once again ceases to correspond to the tone values (forme) as soon as the adjacent ink menisci touch each other in mid- or three quoter tones. The effect of surface tension forces, which previously restrained the ink in the meniscus, changes here to the opposite, contributing to its fill-in the gaps.

At the last of these three stages, the physical reasons for the non-linear connection of the original and the resulting coverage are mostly due to the ink squeeze and absorption. TVI takes place here along the whole curve, since at a certain constant wetting angle, the meniscus ink volume grows faster than its size. It is believed, for example, that the ink layer thickness on a plate comprises about the tenth of a printing element diameter.

So, to make it more uniform over the coverage range it's proposed to perforate the halftone dots by the pin holes or concentric rings as shown in figure 4 (Samworth & Cadogan, 2007).



» **Figure 4:** *Halftone dots perforated by the rings to make their ink film thickness more uniform over the tone range (adopted from Samworth & Cadogan, 2007)*

It can be also concluded that, unlike theoretical one, the real TVI curve starts, instead of zero, from tone value (data) "white" which corresponds to some minimal, only just transferred and that is why not at all squeezed dot. Related to ink solid the end of this curve refers, in its turn, to the input data of a few percent lower than 100%.[3]

The TVI curve form and its extremum position are dependent on the geometry of a halftone dot (square, round, elliptical...) and that of a screen (stochastic, orthogonal, hexagonal, line wise...).

It is worthwhile to note in this connection that for a halftone formed not from dots, but by, for example, parallel lines of variable width the form of TVI curve substantially differs from those prescribed in standard to the particular PC. There is no place for ink to fill-in, because the solid is immediately formed when such lines touch each other.

[3] In earlier standard versions it was used to prescribe the effective dot area range as, for example, from 3-5% to 95-97%.

Due to these reasons the pressure setting according to such densitometric norm as print contrast

$$K = 100\ (D_S - D_{80})/D_S \qquad (1)$$

where D_S and D_{80} – densities of a solid and 80% halftone tint, looks appropriate only for orthogonal screen with round dots.

Image signal transforms

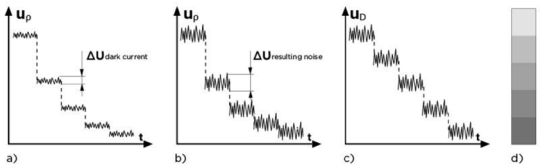
The transforms of an image signal content are sometimes encompassed by the data metrics replacement. For example, as far back as in analog scanners the signal of a light sensor closely related to object reflectance/absorption was used to right away transfer into somewhat perceptually uniform optical density values. Because ultimately, at the system output, there is used the signal of ink amount (dot area), so again associated with absorptions (this time on a print), the need for such a transform may seem not obvious and has attempted in explanation (Kuznetsov & Ermoshina, 2016).

The representation of an image signal most closely related to perception makes it more resistant to interference that accompanies any functional transformations of such a signal. Noises affect the image additive.

They are summarized of all generated at the subsequent stages: the dark current of a sensor, fluctuations in the electronic circuitry p~n transitions, quantization errors of analogue-to-digital (ADC), digital-to-analogue conversions and of forming the halftone dots from a discrete set of microdots. When such interference is concentrated within some part of a tonal range, its effect is most damaging.

Therefore, the signal is lead to uniform values at the very beginning, where the noise is still relatively small being comprised only of a sensor dark current. Effect of total process noise on the image, represented by such a signal, is, as shown in figure 5 (c), uniform over all reproduced tone range and less affect the resulting copy quality.

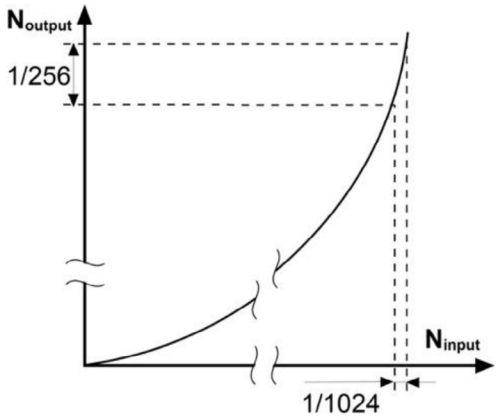
Otherwise, it is accumulated in the shadows diluting there the meaningful steps of gradation (Figure 5b).



» **Figure 5:** *Forms of reflectance U_ρ and density U_D signals for visually uniform tone scale (d): at the sensor output (a) and at the end of a channel without (b) and with the use (c) of logarithm transform*

Actuality of the luminance conversion into optical density or Lab lightness grows with the tone range increase of an original. Therefore, the signal is encoded in ADC of 10 and more digits. Reserve of quantization scale interval in the nonlinear conversion is needed to keep informative all the 256 levels of standard PDF/X eight-bit output. In the scanner, equipped, for example, with 30 bit ADC, each signal, captured behind the RGB filters, is quantized on a scale of the 2^{10} = 1024 levels.

On the part of tone curve transform with gradient of 4/1 the output eight-bit value stays, thanks to this reserve, informative being corresponded to at least one level of an input signal as schematically shown in figure 6.



» **Figure 6:** *To the "sufficiency" of the input signal bit depth for the nonlinear conversion*

High end scanners can use the 16-bit ADC in each color channel to process the originals of up to 4 units density range or directly supply such a signal to prepress software. That makes, for example, possible to provide without losses the necessary color corrections in CIE XYZ space prior to transition in perceptual CIE Lab one.

Backward transition to ink coverage/absorption has place just at the final stage in a RIP or printer driver due to inverse nonlinear connection of the halftone dot area with the amount of forming it microdots.

When defined as apparent intensity, does the tone value relate to stimulus or to perception thereof?

The generic meaning of term "tone value" is set in pp 3.3 of the above draft as area coverage – the ratio of ink covered area to the total area being measured, which metrically corresponds to the absorption coefficient or its inverse luminance affecting the Human Visual System (HVS).

But sensation is associated with one or another type of stimulus in a very non-linear way. Therefore, as an attempt to resolve the metrics conflict in the control scale patch assessment, the subparagraph 3.3.1 introduces the concept of apparent intensity (visual effect of the colorant (e.g. brightness, contrast, lightness) used to describe and measure the appearance of a patch). This term is used as an attribute in underlying definitions without its mentioning elsewhere over the text of a document. In the absence of such a term in CIE multilingual dictionary (International Commission on Illumination, 2020), its essence can be only indirectly judged from the notes and dimensions in this and the following subpoints. Initially, it is equated by such accepted in the CIE vocabulary words as brightness, lightness, which characterize the perception/sensation of luminance. So, it can be concluded that the apparent intensity stands for the perception and not for some kind of a stimulus force or intensity.

Only in the next, equilibrium pp 3.3.2 the term tone value, as number in the range of 0 to 1 or 0% to 100% that indicates the apparent intensity of a printed scale, is at last formulated. However, the first of these numerations characterizes the luminance Y of CIE XYZ, while the other, the linearly related to it coverage of pp. 3.3 and not at all the measure of their perception as, for example, the lightness L of CIE Lab. The latter is estimated in 1 to 100 units and is calculated from the luminance Y according to well-known formula

$$L = 116\,(Y/Y_{ref})^{1/3} - 16 \qquad (2)$$

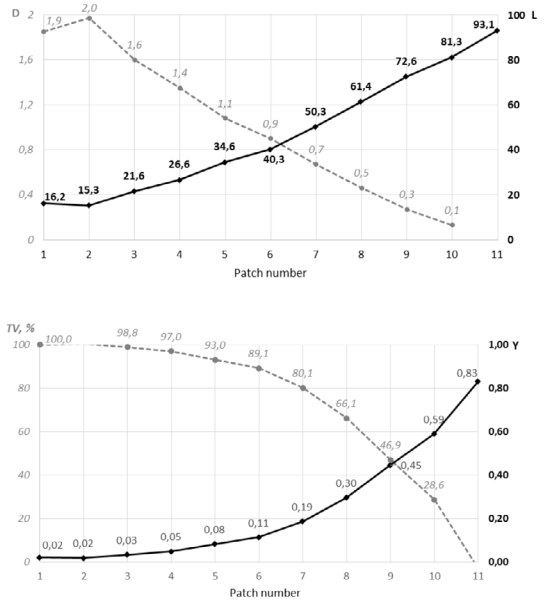
while the chromaticity coordinates a and b of CIE Lab are presented in units from-100 to +100.

Transformation of the signal of stimulus into a signal characterizing sensation changes the dimension. However, its presentation in the units of luminance or coverage (0- 1 or 0%- 100%) is not consistent with the noted therein facility of this term arbitrarily interpretation in practice and over the following text of the document.

It appears, for example, in clause 3.3.4 for term digital tone value- digital values for CMYK in the PDF/X document to be printed. When switching to L in a PDF/X file, the units 0 – 1 of Y or 0%-100% of CMYK coverage are nonlinearly quantized on the 0- 255 scale of an eight-bit code according, for example, to the above equation or by some other way which takes into account the considerations set forth in previous paragraph.

So, the luminance/coverage metrics of tone value to be encoded is different from metrics of content finally presented in such a file. To make sure of that is possible by printing from the PDF/X file the scale of ten patches uniformly divided within a range, as it may seem, at first glance, of a 100% of coverage, but, in fact, of 0 to 255

quantization levels of PDF/X byte. Measurements will show that not at all the relative dot area TV or luminance Y but the lightness L and the most part of optical density D values are linear along the scale (Figure 7).



» **Figure 7:** *Lightness (L) and optical density (D) values are linear along the visually uniform step wedge printed in equal data intervals from PDF/X file (upper) in contrast to the printed tone value TV or luminance Y (lower)*

These densitometric measurments where provided relative to the substrate through polarization filter with 45°/0° geometry and according to Status E, while the colorimetric estimation was relative to white, at black backing, 2°; D50; 45°/0° and without filter.

In case of b/w scale the CTV curve somewhat concides with that for L becouse of hereinbelow shown transform of CTV formula

$$SCTV = 100 \cdot \sqrt{\frac{(V_{x,t} - V_{x,p})^2 + (V_{y,t} - V_{y,p})^2 + (V_{z,t} - V_{z,p})^2}{(V_{x,s} - V_{x,p})^2 + (V_{y,s} - V_{y,p})^2 + (V_{z,s} - V_{z,p})^2}} \quad (3)$$

where subscripts t, p and s are correspondingly related to the halftone tint, paper and ink solid.

All V, as set in SCTV standard (International Organization for Standardization, 2017), are there calculated, similar to lightness L of CIE Lab, from the luminance Y of CIE XYZ according to formula (2). So, the equation (3) presents in fact the quotient of differences in lightness (ΔL)

$$SCTV\ (b/w) = 100 \cdot \frac{(V_{y,t} - V_{y,p})}{(V_{y,s} - V_{y,p})} = 100 \cdot \frac{L_t - L_p}{L_s - L_p} \quad (4)$$

Assuming the lightness of a substrate $L_p \approx 100$ and of an ink solid $L_s \approx 0$, it gives

$$SCTV\ (b/w) = 100 - L_t \quad (5)$$

As result, the multiplier 100, initially intended for normalizing the SCTV in percent, has vanished and, with taking into account the lightness (L) measure from 0 to 100 units, this parameter comprises somewhat as the “darkness” of a halftone tint.

This fact and above curves also confirm that the numeration, usually set along scale patches, is linearly related to such specific kind of a color attribute which is however declared for SCTV in “percent” confusing it with the habitual ink coverage. If such scales where organized at the equal step of an ink coverage/percentage they would look strongly non-uniform.

Encoded data interpretation should follow the steps sequence with priority of defining the method of encoding over its metrics (Giorgianni & Madden, 2008). Table 1 relates to encoding specification where the colorimetric method is applied to CMYK values with the perceptual CIE Lab metrics instead of CIE XYZ.

Table 1

Steps hierarchy of encoding specification for the PDF/X and SCTV

1	encoded property of an image	CMYK ink amount (% of coverage)
2	method of encoding	colorimetric
3	encoding metrics	CIE Lab
4	units	0 – 100 of Lab
5	normalization	0 – 255 quantization levels

So, as the result of an image signal transform, there arises the fundamental difference between metrics of the tone value to be encoded, specified in percentage of coverage, and of what the such kind of a file does in fact present.

Tone value increase

Subordinating the subsequent ones from 3.3.7.1 to 3.3.7.6, the pp 3.3.7 printed tone value is also designated as apparent intensity, as if to indicate this parameter perceptual nature and to put aside those related to the coverage or luminance.

Such metrics noncompliance right away reveals in the following points. For example, the density tone value (pp 3.3.7.1), once again defined as apparent intensity, does comprise the halftone dot percentage calculated with Murray formula and most likely characterizes the stimulus but not the appearance thereof.

Such lacking of metric conformance straight away arises for the term 3.3.7.2 tone value increase (TVI).

It's defined there as the difference between a density tone value and the digital tone value if allowing to subtract the measured data from its nonlinearly conversed one.

To the contrary, applying the attribute of apparent intensity looks just rightful for the colour tone value (CTV) in 3.3.7.3, as far as it's calculated on the basis of perceptually uniform CIE Lab dimensions. It is also reminded there to distinguish the color tone value from the colorimetric tone value (according to ISO 12647-1) calculated directly from the XYZ coordinates.

Hence, in contrast to the calculation of TVI according to clause 3.3.7.2, the metrics of decreasing and subtracting in 3.3.7.4 for the delta colour tone value: ΔCTV = CTV – T, where T is the digital tone value according to 3.3.4, quite coincide. There is also put attention that such way calibrated scales are visually uniform.

Moreover, the ΔCTV calibration aims are set in table 2-5 of the document, unlike TVI, in the Lab metric by the prescribed, both positive and negative, deviations from the digital tone value. So, it is hardly appropriate, as proposed in the Notes to clause 3.3.7.3, to estimate ΔCTV in a percent as well as to characterize it in relation to some linear curve by analogy with densitometric TVI, while, in fact, the required up or down shift from target CTV is there dealt.

Conclusion

Tone value is historically estimated by the relative inked area on a halftone print. Image printing models, originally based on this purely geometric premise, were over time supplemented accounting the number of physical and physiological interaction factors inherent in plate-ink-paper and light-print-vision systems.

This parameter versions are used today in the transfer function presentations for a variety of the printing process physical stages and image signal transforms, which are often inherent in changes of the method, metric and normalization in a signal encoding.

The numbers from 0 (lightest) to 100 (darkest) used to be set beside the patches of calibrating scales directly relate to the perceptive color attribute such as "darkness" (100 -Lightness) which makes these scales visually uniform.

So, the SCTV and CTV measurement in percent isn't expedient as far as their values are in the metrics of perception instead of that of habitual ink coverage, i.e. stimulus.

In tone value definitions it can be also recommended to deliver from the apparent intensity attribute due its rather indefinite, in this light, interpretation.

In the offset printing standard, it is, in common, advisable to formulate the definitions of tone value versions in such a way that the ranges of numerical values correspond to both the type and nature of the metrics and the method of their coding. This will allow to unambiguously interpret the meaning of numeration put beside the patches of control scales as an argument for the measured calibration functions.

There are the number of important process adjustment parameters which are advisable to be recommended by such a document for ensuring the complete use of a printing process facilities.

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