CIETC1-71 Perspective: An Overview on Accurately Computing Tristimulus Values

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Abstract

With the great demand from industry for a unified method for accurately computing the CIE tristimulus values and for the best agreement among the laboratories, CIE formed a new technical committee: TC1-71 on tristimulus integration during the 26th Session of the CIE in Beijing last year. This paper reports the current progress of the TC.

Introduction

Tristimulus values are the amounts of three primary stimuli required to give a colour match with the colour stimulus considered. They are the basis of colour specifications, colour difference evaluations, colour matching, and colour transformations. CIE in 1931 defined the tristimulus values of the object colours in terms of integrations:

$$
\begin{aligned}
X &= k\int_a^b S(\lambda)\bar{x}(\lambda)R(\lambda)d\lambda \\
Y &= k\int_a^b S(\lambda)\bar{y}(\lambda)R(\lambda)d\lambda \\
Z &= k\int_a^b S(\lambda)\bar{z}(\lambda)R(\lambda)d\lambda
\end{aligned}
\qquad (1)
$$

Where $S(\lambda)$ is the relative spectral power distribution of an illuminant, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the CIE 1931 (2°) or 1964 (10°) standard colorimetric observers, and $R(\lambda)$ is the reflectance (transmittance) function of a reflecting (transmitting) object colour. (a,b) is the visible range of wavelengths with a = 360nm and b = 830nm, and k is the normalizing factor defined in eq. (2) for reflecting (transmitting)-object colours.

$$
k = 100 / \int_a^b S(\lambda)\bar{y}(\lambda)d\lambda \qquad (2)
$$

Unfortunately, the integrands involved in equation (1) have no analytical expressions; hence how to compute the tristimulus values becomes a problem. In practice, using the summations rather than integrations for computing trsitimulus values has a long history. The summations could be at 1nm, 5nm, 10nm, or 20nm intervals. A working group of US TC1.3 [1] on Methods for Tristimulus Integrations recommended the above integrations should be computed by summations at a wavelength interval of 1nm over the visible range, i.e, in practice the above integrations should be replaced by: equation (3) with $\Delta\lambda = 1$ nm and

$$
k = 100 / \sum_{i=0}^{n} S(\lambda_i)\bar{y}(\lambda_i)\Delta\lambda
$$

$$
\begin{aligned}
X &= k\sum_{i=0}^{n} S(\lambda_i)\bar{x}(\lambda_i)R(\lambda_i)\Delta\lambda \\
Y &= k\sum_{i=0}^{n} S(\lambda_i)\bar{y}(\lambda_i)R(\lambda_i)\Delta\lambda \\
Z &= k\sum_{i=0}^{n} S(\lambda_i)\bar{z}(\lambda_i)R(\lambda_i)\Delta\lambda
\end{aligned}
\qquad (3)
$$

The above recommendation was adopted by CIE TC1-3 and included in the CIE 15:1986 [2].

However, not all available object measurement instruments measure the reflectance at 1nm interval. In fact, most of them measure at 5, 10, or even 20-nm intervals. CIE 15: 2004 has some guidance with 5nm interval data, but has no precise recommendations on data with measurement interval greater than 5nm. Thus various approaches have been used for computing tristimulus values in practice, which can lead to a significant difference between two different methods from the same set of spectral data [3]. Hence there is a great demand from industry applications for a unified method for accurately computing the tristimulus values and for the best agreement between laboratories, which led to the formation of CIETC1-71 on Tristimulus Integrations during CIE 26th Session in Beijing last year.

In this paper, various existing methods including CIE recommendations will be reviewed; then numerical comparisons will be given; and finally the paper is ended with some conclusions.

The Existing Methods

CIE recommendations

CIE 15:2004 [4] recommended the tristimulus values computations using equation (3) with wavelength interval $\Delta\lambda = 1$ nm. For $\Delta\lambda > 1$, there is no precise recommendation. But it was recommended that equation (3) can be used with $\Delta\lambda = 5$ nm for most applications. Besides, for work not involved with fluorescent, the visible range can be between 380nm and 780nm. In addition, CIE 167: 2005 [5] recommended the Sprague interpolation for uniform sampled data. Hence, measured reflectance at wavelength interval different from 1nm can be interpolated into 1nm data, and then 1nm summations (equation (3)) can be used. This approach is denoted by ‘CIE-R’ in this paper. Note that the measured reflectance is in general different from the real reflectance, hence that the interpolation does not necessarily increase the accuracy. It is better that the measured reflectance is corrected against bandpass error (discuss later) before the interpolation.

Direct Selection

Direct selection (DS) is the simplest method and used since possibly 1931. For measuring reflectance at interval $\Delta\lambda > 1$, select one from every $\Delta\lambda$ data from the spectral power distribution and standard observer, and then do the similar summations to equation (3). Note that when $\Delta\lambda \le 5$, this approach works fine, see for example, CIE 15:2004 [4], and the work by Ohno [6,7].

Reflectance Bandpass Error Correction

For colour measurement, Ohno [7] reported that there are several errors involved. One of the important errors is the bandpass error. A widely used bandpass error correction formula was given by Stearns and Stearns (SS) [8] in 1988, and is defined by:

$$R_j^{(\Delta\lambda)} = -\kappa\hat{R}_{j-1}^{(\Delta\lambda)} + (1+2\kappa)\hat{R}_j^{(\Delta\lambda)} - \kappa\hat{R}_{j+1}^{(\Delta\lambda)} \quad (4)$$

Here $\hat{R}_j^{(\Delta\lambda)}$ represents the measured reflectance and $R_j^{(\Delta\lambda)}$ is the bandpass error corrected reflectance and $\kappa = 0.1$. It was also suggested $\kappa = 0.083$ or $\kappa = 1/12$. The two ends should be dealt separately. Besides, they also gave a 5-term formula:

$$\begin{aligned} R_j^{(\Delta\lambda)} = [&\hat{R}_{j-2}^{(\Delta\lambda)} - 12\hat{R}_{j-1}^{(\Delta\lambda)} + 120\hat{R}_j^{(\Delta\lambda)} \\ &-12\hat{R}_{j+1}^{(\Delta\lambda)} + \hat{R}_{j+2}^{(\Delta\lambda)}]/98 \end{aligned}, \quad (5)$$

Note that the above corrections were based on that the instrumental function is symmetric and has a triangular shape. Besides, the sampling (or scanning) interval equals to the bandwidth. If the condition is not satisfied, the above formulae will not perform well. Fortunately, it is thought that the instrumental function with the most common situation encountered in practice satisfies this condition. It can be found that most work related to computing tristimulus values in the past based on this assumption [9]. Ohno [6,7] and CIE TC2-60 on *Effect of Instrumental Bandpass Function and measurement Interval on Spectral Quantities* gave bandpass error correction formulae based on a general instrumental function. However, research work is needed to obtain the instrumental function.

Venable Weighting Table

Venable [10] suggested that the bandpass error correction can be built into the creation of weighting factors (or weighting tables or simply weights):

$$W_{X,j}^{(\Delta\lambda)},\ W_{Y,j}^{(\Delta\lambda)},\ W_{Z,j}^{(\Delta\lambda)},\ j = 0,1,\cdots,n\ . \quad (6)$$

which depend on the spectral power distribution of the illumination, CIE standard colorimetric observer and the bandwidth. He [10] developed an iterative method for generating the weights.

ASTM Weighting Tables of Tables 5 and 6

From 1981, ASTM set up a working group to establish a method for tristimulus integrations and standardised a set of weighting tables. It included 9 iluminants, 2 standard observers, and 10nm and 20nm intervals. All together 36 weighting tables were published in 1985 [11]. It is known as ASTM weighting tables of Table 5 (T5). The weighting tables were derived based on the predicted reflectance (PR) method [12] with the third order interpolation. ASTM T5 must be used with the measured reflectance plus SS bandpass error correction.

In 1995, ASTM [13] further standardised another set of weighting tables, which is known as Table 6 (T6). ASTM T6 was defined based on the mixture of ASTM T5 and Venable method. Details about the derivation of the ASTM T6 can be found from Fiarman's work [9]. Note that the ASTM T6 must be used with the measured reflectance directly.

Overall, ASTM is the first standard authority to promote a uniformity of practice in the calculation of the CIE tistimulus values for practical applications for measuring interval at 10nm and 20nm.

The Optimum Weighting Table

Following Venable's idea, Li, Luo and Rigg [14] proposed a method for generating optimum weights. The method is simple in computation, which is only involved solving a tri-diagonal linear system of equation, and is considered as direct method (against iterative method). The method is referred in CIE 15:2004 [4] as one of the methods for computing weighting tables at 10nm and 20nm intervals.

The Least Square Weighting Table

Wang, Li and Luo [15] and Li, Luo and Wang [3] proposed another method for generating weighting tables using least square method. The method intends to solving a tri-diagonal linear system of equations. Hence the method again is simple in computation and is considered as direct method (as against iterative method).

Comparisons of Different Methods

In order to evaluate the performance of different methods for computing tristimulus values, the approaches used by Fairman [9] and Li et al [14] were adopted here. The strategy used (see Appendix A) is to calculate colour differences between the tristimulus values calculated from the standard 1-nm summations (equation (3)) and those calculated using the corresponding method for a larger wavelength interval. For the reflectance data, the 1nm reflectance values [16] measured from 1269 matt Munsell colour chips using the Perkin-Elmer lambda 9 UV/VIS/NIR spectrophotometer. The set of reflectance values is in the visible range of 380nm to 800nm. Only the range of 380nm to 780nm was used to comply with the specification of the CIE [4,5] recommendation as a standard set of reflectance values at 1nm interval. The samples were chosen at this stage to avoid any interpolation and extrapolation bias.

For obtaining the measured reflectance from the standard 1nm data, it is again assumed that the instrumental function is symmetric and has a triangular shape.

Six CIE illuminants: D65, A, D50, F2, F7, and F11, and CIE 1931 standard colorimetric observer were used. CIELAB colour difference was used for evaluating the performance of each method. The statistical values: median, maximum, and standard deviation of the colour differences were computed. The median reflects the general performance best for each method; hence the median values are reported here.

Firstly, the bandwidth and the scanning interval are the same. They were chosen as 2nm, 4nm, 5nm, 8nm, 10nm, 16nm, and 20nm respectively. Note only those choices can be uniformly sampled between 380nm and 780nm. All (median) results are listed in Table 1.

Note that as discussed above 'CIE-R' was not recommended by the CIE, but it can be considered as one of the options recommended from CIE. Besides, we also want to note that for the ASTM T5, DS, and 'CIE-R' methods, Stearns and Stearns bandpass correction was used. Fairman [17] pointed out that using 5-term correction is better than using the 3-term correction. It was numerically confirmed from this study as well. Hence the 5-term SS correction (equation (5)) were used for all the results listed below related to bandpass error correction in this study.

Table 1: Median values for each light sources and CIE 2 degree observer with bandwidth (equals to scanning interval) being 2, 4, 5, 8, 10, 16 and 20nm respectively.

		D65	A	D50	F2	F7	F11
2nm	ASTM T5	0.000833	0.000732	0.000812	0.00076	0.000816	0.000889
	Optimum	0.001812	0.001592	0.001768	0.001668	0.001801	0.002007
	DS	0.001304	0.000765	0.001026	0.17084	0.108944	0.219233
	'CIE-R'	0.000832	0.000731	0.000812	0.00076	0.000819	0.000919
	LS	0.000002	0.000001	0.000001	0.000041	0.000036	0.00006
4nm	ASTM T5	0.000621	0.000529	0.000593	0.001187	0.001068	0.001833
	Optimum	0.001817	0.001596	0.001763	0.001692	0.001792	0.002023
	DS	0.030139	0.000687	0.010224	0.160954	0.112219	0.26395
	'CIE-R'	0.000613	0.000533	0.000594	0.00099	0.000932	0.001228
	LS	0.00002	0.000011	0.000016	0.000438	0.000366	0.000649
5nm	ASTM T5	0.000439	0.000361	0.00041	0.001867	0.001662	0.003883
	Optimum	0.001817	0.001594	0.001761	0.00168	0.001798	0.001982
	DS	0.00638	0.000563	0.000522	0.001471	0.001354	0.003154
	'CIE-R'	0.000449	0.000388	0.000438	0.001313	0.001138	0.002101
	LS	0.000029	0.000022	0.000028	0.00032	0.000288	0.000629
8nm	ASTM T5	0.001757	0.001372	0.001645	0.005989	0.00551	0.016641
	Optimum	0.001791	0.001568	0.001736	0.004538	0.004739	0.011158
	DS	0.021937	0.016433	0.017141	2.630365	2.545141	3.109814
	'CIE-R'	0.000454	0.000347	0.000434	0.004878	0.004785	0.013697
	LS	0.000213	0.000144	0.000219	0.004222	0.004462	0.011825
10nm	ASTM T5	0.004532	0.003545	0.004261	0.014483	0.012521	0.034406
	Optimum	0.001883	0.001546	0.001821	0.013251	0.012178	0.025792
	DS	0.033048	0.043463	0.041491	7.130161	4.498571	8.825349
	'CIE-R'	0.001364	0.001139	0.001262	0.013986	0.011982	0.027594
	LS	0.000556	0.000394	0.000502	0.013354	0.011996	0.025847
16nm	ASTM T5	0.028739	0.022277	0.026742	0.039029	0.034008	0.132539
	Optimum	0.002296	0.002364	0.002102	0.045638	0.035905	0.086504
	DS	0.176047	0.070842	0.162789	12.141623	6.995248	22.384514
	'CIE-R'	0.011011	0.007542	0.009511	0.047135	0.036593	0.104029
	LS	0.002733	0.002909	0.002624	0.045538	0.035642	0.086772
20nm	ASTM T5	0.070817	0.058469	0.065303	0.091847	0.093532	0.23797
	Optimum	0.010118	0.010009	0.00926	0.036346	0.034717	0.156716
	DS	0.658205	0.147686	0.632697	3.812571	3.546007	23.235098
	'CIE-R'	0.031087	0.025283	0.02772	0.057093	0.058	0.198343
	LS	0.011691	0.010796	0.010656	0.035785	0.034182	0.156832

From Table 1 it can be seen that generally, each method performs better for the continuous illuminants than for fluorescent illuminants. For the continuous illuminants, each method performs the best for illuminant A and performs similar for D65 and D50. For the fluorescent illuminants, each method performs worse, especially, F11 performs the worst. In general, each method performs better for the smoother spectral power distribution.

Table 1 also shows that each method's performance deteriorates with the increasing of the scanning interval or the bandwidth. Figure 1 clearly illustrates this under the illuminant A and CIE 1931 standard colorimetric observer, where the direct selection method is omitted since it performs the worst among all the methods. The figure also shows when the scanning intervals are greater than or equal to 10nm, the ASTM T5 method and 'CIE-R' approaches are much worse than the optimum and least squares approaches. In order to see much clearer about each method's performance when scanning interval is smaller than 10nm the lower part of Figure 1 is shown in Figure 2. From Figure 2, it clearly shows that the optimum weight performs the worst, and then followed by ASTM T5 and 'CIE-R'. The least square method is the best. When the scanning interval equals to 10nm, the 4 methods ranked from the best to worst are: least square, optimum, 'CIE-R', and ASTM T5.

All the above results under illuminant A hold for each of the other illuminants. Hence, a possible choice of the unified method either the optimum method, or the least square method, or the least square method for scanning interval not greater than 10nm and the optimum weight for the scanning interval greater than 10nm.

Note that ASTM T5 and 'CIE-R' approaches use the measured reflectance with bandpass correction. Hence it seems that correcting the bandpass error to the measured reflectance functions will not increase the accuracy for computing the tristimulus values.

Table 2: Median values for each light sources and CIE 2 degree observer with bandwidth being 8nm and scanning interval being 2, 4, 5, 8, 10, 16 and 20nm respectively.

		D65	A	D50	F2	F7	F11
2nm	ASTM T5	0.053623	0.278132	0.049637	0.047091	0.205031	0.041588
	Optimum	0.052642	0.273047	0.04873	0.046228	0.201284	0.040828
	DS	0.053388	0.278688	0.049653	0.047118	0.205048	0.041571
	'CIE-R'	0.053627	0.278121	0.049635	0.047088	0.205023	0.041586
	LS	0.054468	0.28243	0.050404	0.047817	0.2082	0.04223
4nm	ASTM T5	0.042893	0.223178	0.039833	0.037683	0.164521	0.033383
	Optimum	0.041773	0.216731	0.038682	0.036683	0.159774	0.032413
	DS	0.04775	0.258107	0.044415	0.037648	0.16464	0.033353
	'CIE-R'	0.042976	0.222948	0.039791	0.037747	0.164357	0.033342
	LS	0.043582	0.226136	0.04036	0.038281	0.166707	0.033819
5nm	ASTM T5	0.034925	0.182098	0.032504	0.030614	0.134234	0.027253
	Optimum	0.033552	0.174457	0.031137	0.029471	0.128614	0.026095
	DS	0.033845	0.184376	0.032482	0.030578	0.134043	0.027112
	'CIE-R'	0.034925	0.181517	0.032401	0.030681	0.133822	0.027153
	LS	0.035367	0.183878	0.032818	0.031065	0.135559	0.027504
8nm	ASTM T5	0.001757	0.006914	0.001152	0.001372	0.005462	0.001014
	Optimum	0.001791	0.009088	0.001611	0.001568	0.006664	0.001339
	DS	0.021937	0.036398	0.006448	0.016433	0.025612	0.004429
	'CIE-R'	0.000454	0.003518	0.000352	0.000347	0.001464	0.000289
	LS	0.000213	0.002932	0.000228	0.000144	0.000648	0.000101
10nm	ASTM T5	0.032513	0.154672	0.027632	0.027369	0.11393	0.022839
	Optimum	0.034319	0.177733	0.031767	0.029835	0.130773	0.026591
	DS	0.038318	0.178535	0.032363	0.049729	0.148566	0.026757
	'CIE-R'	0.031781	0.164675	0.029261	0.027483	0.120882	0.024399
	LS	0.032546	0.168181	0.030059	0.028307	0.123728	0.025154
16nm	ASTM T5	0.178459	0.833176	0.149802	0.153908	0.615198	0.123967
	Optimum	0.180601	0.924548	0.165353	0.159251	0.679901	0.138737
	DS	0.267513	0.855956	0.173135	0.178442	0.622024	0.131929
	'CIE-R'	0.179866	0.90312	0.160318	0.156571	0.662511	0.1333
	LS	0.179093	0.914715	0.163595	0.157735	0.672659	0.137251
20nm	ASTM T5	0.329908	1.381265	0.25279	0.277307	1.019948	0.207212
	Optimum	0.334722	1.585504	0.28546	0.289174	1.175459	0.237648
	DS	0.759311	1.706338	0.333936	0.297692	1.267165	0.242327
	'CIE-R'	0.34127	1.558132	0.276865	0.289593	1.135088	0.227954
	LS	0.332925	1.575364	0.283657	0.287882	1.168148	0.236131

Further tests were carried out with the scanning interval being different from bandwidth. Table 2 lists the results with bandwidth fixed at 8nm interval, but scanning intervals changed from 2nm, 4nm, 5nm, 8nm, 10nm, 16nm and 20nm respectively. Figure 3 shows the results under D65 and CIE 1931 standard colorimetric observer. Form Figure 3, it clearly shows that each method performs the best when the scanning interval equals to the bandwidth and performs worse when the scanning interval departs away from the bandwidth. Besides, all methods except the direct selection method perform similar when the scanning interval is different from the bandwidth.

Conclusions

The ASTM T5, optimum, direct selection, 'CIE-R', and least squares methods for computing the tristimulus values were tested. Each method performs the best when the scanning interval equals to the bandwidth. When this condition holds, each method performs better for smoother spectral power distributions. Hence each method performs better for continuous iluminants than for fluorescent illuminants; the direct selection method performs the worst among all the methods; the least square method performs the best when scanning interval is less than or equal to 10nm; the optimum method performs the best when scanning interval is greater than 10nm.

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Appendix A: Outline of the numerical comparisons.

For each reflectance spectrum in a database of reflectance spectra, and for each of a set of chosen illuminant SPDs:

1) Interpolate the reflectance values from the available resolution to 1nm using the Lagrange-cubic method (using Sprague interpolation if needed).
2) Obtain 1-nm resolution xbar, ybar, zbar color-matching functions, and also obtain 1-nm resolution data for the illuminant SPD (using Sprague interpolation if needed).
3) Compute ground-truth XYZ values by taking a wavelength-by-wavelength product of color-matching functions, illuminant SPD, and reflectance spectrum, and then summing the values (a 1-nm Riemann sum).
4) Subsample the reflectance values in (1) above to $\Delta\lambda$ nm, using assumed triangular instrument waveform.
5) Using the candidate method (e.g., Li-Luo-Rigg or ASTM E308 Table 6), develop $\Delta\lambda$-nm weight set for the given illuminant and the xbar, ybar, zbar color-matching functions specified in (2) above. (**Note: Step 5 is the only place at which the weight-set method enters**.)
6) Compute XYZ values for the candidate method by multiplying the Step-4-subsampled reflectance with the weight set of Step 5, wavelength by wavelength at $\Delta\lambda$-nm increments, and performing a $\Delta\lambda$-nm-weighted sum to produce the integral.
7) Compare the XYZ values at step 6 with the ground-truth XYZ values at step 3.

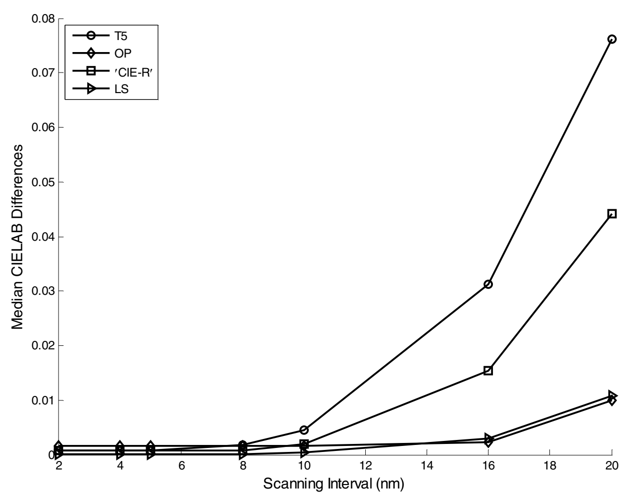

***Figure 1**: Performances of ASTM T5 (curve with circles), Optimum Weights (curve with diamonds), 'CIE-R' method (curve with squares) and Least Square Method (curve with right triangles) under illuminant A and 2 degree observer.*

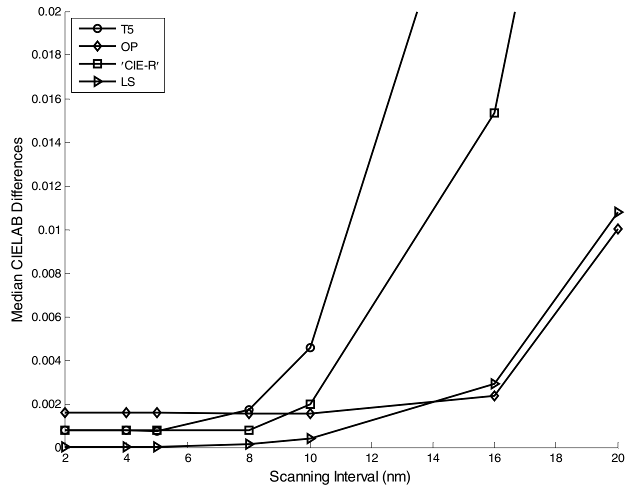

***Figure 2**: Lower part (between 0 and 0.02 in vertical axis) of Figure 1 to show performances of ASTM T5 (curve with circles), Optimum Weights (curve with diamonds), 'CIE-R' method (curve with squares) and Least Square Method (curve with right triangles) under illuminant A and 2 degree observer.*

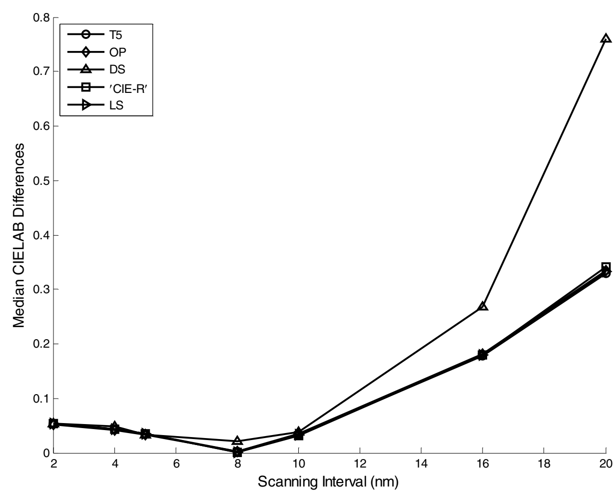

***Figure 3**: Median values (vertical) versus scanning interval (horizontal) with Bandpass being 8nm under D65 and 2 degree observer.*