Results of the Intercomparison of Correlated Color Temperature Calculation

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CORM Subcommittee CR3 Photometry
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1. Participants

The participants of this intercomparison are listed below. They participated as individuals and do not necessarily represent the company. Three participants submitted two sets of data using two different methods.

Val Pilskalns, Eastman Kodak, Rochester, NY
John E. Baretsky, Hoffman Engineering, Stamford, CT
Joseph F. Velasquez, Air Force Metrology Program Office, Newark, OH**
Janos Schanda, University Veszpr, Hungary
Jim Gardner, CSIRO, Australia**
Richard Young, Optronic Laboratories, Orlando, FL**
Yoshi Ohno, NIST, Gaithersburg, MD
(** submitted two sets of data)

2. Source Data for Comparison

A set of relative spectral power distribution data of seven different actual light sources as listed below were used.

#1: FEL type tungsten halogen lamp (≈3200 K)

#2: Integrating sphere source (≈2850 K)

#3: Triphosphor fluorescent lamp (≈4000 K)

#4: Metal halide lamp (≈2900 K)

#5: High-pressure sodium lamp (≈2000 K)

#6: High-pressure xenon lamp (≈6500 K)

#7: CRT white (≈9300 K, white balance artificially set off from the Planckian locus)

The data were provided in the 380 nm to 780 nm region at 5 nm intervals. The chromaticity coordinates are shown in Fig. A1, the spectral power distribution curves in Fig. A2, and the tabulated data are shown in Table A1. The data were distributed to the participants as an EXCEL file, with all the values truncated to 4 digits below decimal. The participants calculated and reported the following quantities:

1) Chromaticity coordinate x, y
2) Correlated color temperature (CCT) (K)
3) Distribution temperature (K) of sources #1 and #2 (optional)
4) Method of calculation

3. Descriptions of the method of calculation

V. Pilskalns

Optonics Laboratories OL754 optOLab General Operating Software v. 2.10 (Demonstration Software)

J. Baretsky

Correlated color temperature is calculated from the Chromaticity. The CIE 1931, x & y are converted to CIE 1960 u & v. In the u/v color space the isotemperature lines are perpendicular to the black body locus. The chromaticity point is matched to the closest point on the black body locus. This point is the perpendicular and is calculated to to the nearest Kelvin. Distribution Temperature is not a value that we would normally calculate.

J. Velasquez

[Data Set 1] We use a commercial software package, Gamma Scientific LightTouch Standard Software, Version 1.20j, serial number HN-2209

[Data Set 2] The data was computed using an older commercial software package, Gamma Scientific Spectrl-C11 Software, Version 2.83AT

J. Schanda

The method used is based on the Excel spreadsheet and its Solver plug-in.

First the SPD of a Planck radiator is calculated with the temperature as input parameter. Then using the CIE 1931 Standard Observer the chromaticity co-ordinates of this SPD are calculated. Similarly the chromaticity co-ordinates of the test source are calculated. For both sources the u,v chromaticity and the chromaticity difference are calculated. This Delta(u,v) is the input parameter for the Excel Solver. Parameter to be modified is the temperature of the Planck radiator. The program determines the minimum in Delta(u,v) between the test source u,v and Planck source co-ordinates. If necessary the minimum seeking can be started with a Planck temperature below the temperature of minimum u,v value and with a Planck temperature above this value, as the program terminates for a predetermined minimum change in Delta(u,v).

J. Gardner

Visual Basic programs used to calculate CCT from fits of v, u and dv/du (all 1960 UCS values) as a function of $1/T$. Origin program used to fit functions, to calculated data at 100 K intervals from 1000 to 10000 K. v, u fitted as 6th order polynomials, dv/du as a double exponential decay, taking a 10K range around the central value.

[Method 1] Solve $(v - v')/(u - u') = -1/(\mathrm{d}v/\mathrm{d}u)$, using Newton's rule. v, u and dv/du are the functional forms, (u',v') are the chromaticity in 1960 UCS coordinates (NB not 1976 (u', v') UCS). Derivatives calculated from the polynomial and exponential expressions.

[Method 2] A program to calculate CCT by searching T values (to within 0.1K) to find the minimum distance between a given (u,v) value and the BB locus calculated fully for each T, without using functional fits. BB locus calculated with c2=1.4387800 x 10^{-2} m K. The program was developed locally.

[Distribution Temperature] This uses the method of the Technical Report of TC2.05, CIE Publication 114 in the range of 400 to 750 nm.

R. Young

[CCT1] Calculations are performed using CIE 1960 uniform color space coordinates u and v. Coordinates u and v are derived from x and y using the formulae:

$$u = 4x/(12y-2x+3) \text{ and } v = 6y/(12y-2x+3)$$

The correlated color temperature is defined as the temperature of a blackbody that lies closest to the u,v coordinates of the test source. Two separate methods provide results: one is an iterative method based on the definition, and the other is the commonly used Robertson's method involving interpolation based on a table of 30 pre-calculated u, v and inverse-slope parameters.

Iteration

If u_s and v_s are the values for a test source, and u_T and v_T are the blackbody values at temperature T, the correlated color temperature is the value of T where:

$$\sqrt{\left(u_s - u_T\right)^2 + \left(v_s - v_T\right)^2}$$

is minimized. Adjusting the temperature T to obtain the minimum of this function was done using spreadsheets (Quattro Pro 8 and Excel 97). Both spreadsheets gave identical values.

[CCT2] Based on the Robertson's method. The data, method and example computer program are given in "Optical Radiation Measurements", Franc Grum et. al., Volume 1. This technique is employed in some Optronic Laboratories' software and identical results are obtained with these programs and spreadsheets (Quattro Pro 8 and Excel 97). Table values are recalculated using 1986 CODATA.

[Distribution Temperature] Calculated according to the formula given in CIE 114 for the wavelength range of 400 nm to 750 nm. Also, although CODATA values were available, the value of 0.014388 m K is used in Planckian calculations and summation replaces integration in the distribution temperature function.

Y. Ohno

[CCT] An EXCEL program developed by myself. I use a table of blackbody temperature from 1000 K to 20000 K, 1 % increments, so 303 points in total, with the CIE 1960 u,v chromaticity coordinates at each temperature. When the x,y chromaticity is input to the program, it is converted to a CIE 1960 u,v coordinate. Then calculate the distances from the given u,v coordinate to each u,v coordinate of blackbody (BB) locus at each temperature in the table. Find the two temperatures which give the smallest distances, and form a triangle with these two points on the BB locus and the given point on the u,v diagram. Then solve the triangle to determine the closest point on the BB locus from the given point. This is a sort of linear interpolation.

[Distribution temperature] I used the equation given in CIE 114/4. The data is given at 5 nm intervals and the integral is calculated over the range of 400 nm to 750 nm as recommended by CIE 114/4. To perform the minimization, EXCEL solver is used. It takes only a few seconds to get the result.

4. Results of the comparison of CCT

The results of the comparison of CCT are shown in Table 1 and Fig.1. The mean values are calculated with exclusion of the largest and smallest values for each source (to exclude possible outliers). The letters A through J represent participants. Two sets of data submitted from one person are shown as two participants. The results are also calculated in reciprocal color temperature (in mrd= micro reciprocal degree) and shown in Fig. 2. The changes of reciprocal color temperature per unit distance in u-v space is approximately constant (≈3 mrd / 0.001 Δuv). Fig. 2 indicates the variations corresponding to relative distance in u-v chromaticity space.

Table 1. Results of the comparison of calculated CCT.

Source	Mean value [K]	Deviation from the mean (K)									
		A	B	C	D	E	F	G	H	I	J
#1	3197.6	-1.4	0.4	-13.6	-1.6	0.5	0.6	0.5	0.5	0.3	0.6
#2	2856.1	-1.3	-0.1	-0.1	-1.1	0.3	0.6	0.2	0.2	0.2	0.4
#3	4042.1	-1.5	-0.1	0.9	-2.1	0.5	-1.1	0.8	0.6	0.5	0.3
#4	2903.2		-2.2	-3.2	-1.2	0.6	0.9	0.8	0.7	0.7	0.6
#5	2042.8	-1.1	0.2	0.2	-1.8	0.0	0.3	0.1	0.1	0.0	0.3
#6	6415.6	-4.9	1.4	-0.6	-4.6	1.5	3.7	0.0	1.6	0.4	0.5
#7	9314.1		1.9	0.9	-3.1	1.8	-11.6	-5.9	4.6	10.5	-0.3

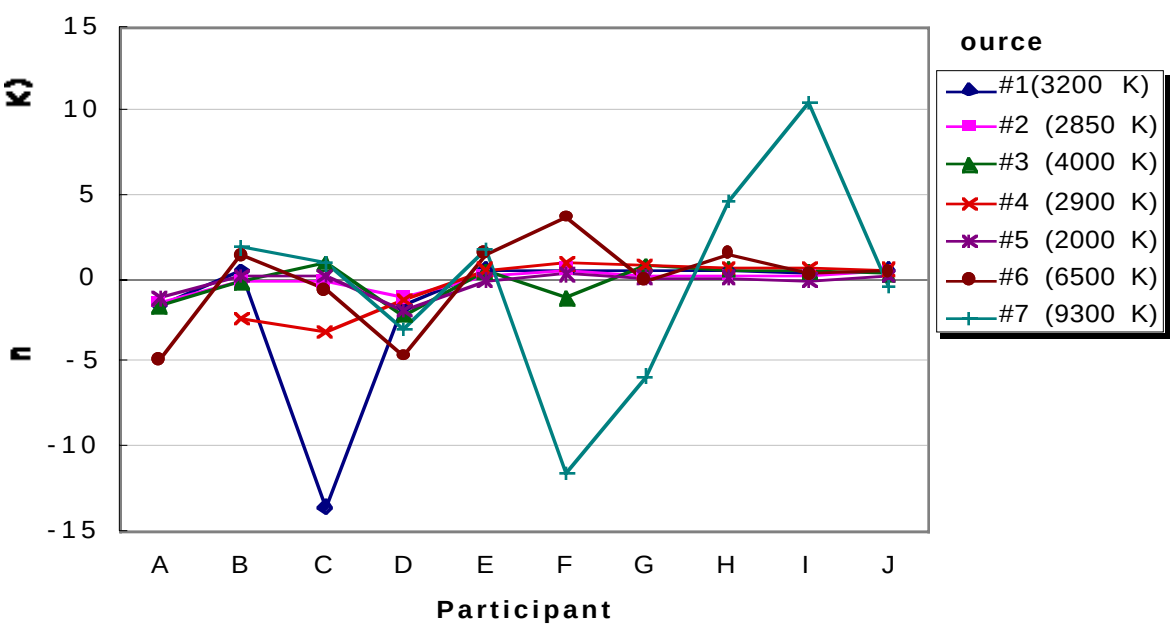

Figure 1. Results of the comparison of calculated CCT.

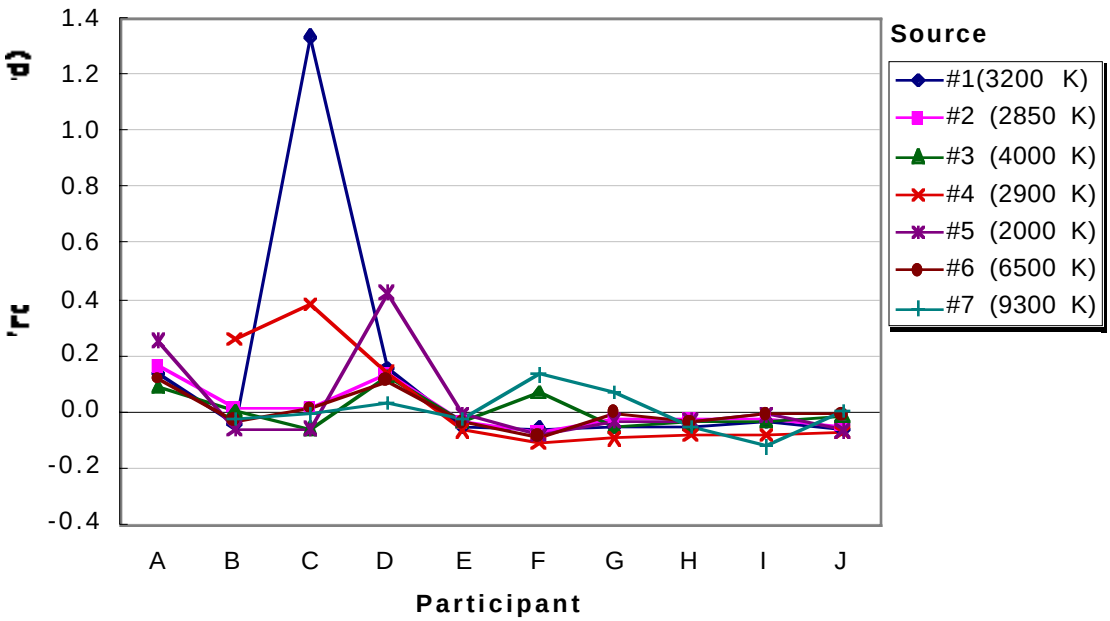

Figure 2. Results of the CCT comparison in reciprocal scale (micro reciprocal degree)

5. Results of the comparison of distribution temperature

Three participants (Gardner, Young, and Ohno) submitted data for distribution temperature. Table 2 shows the results. The letters K - M represent each participant.

Table 2. The results of the comparison of distribution Temperature.

Source	Deviation from the mean (K)		
	K	L	M
#1	3194.4	3194.7	3194.7
#2	2808.0	2805.1	2805.1

6. Summary

Chromaticity coordinates:

No notable disagreement is found for calculation of chromaticity coordinates (maximum difference being 0.0001).

CCT:

There are some variations for CCT, which reflect differences in method of calculation and fundamental data used in calculation. While a better agreement is desired for scientific interest, the variations for sources #1 to #5 (2000 K to 4000 K, except one point: participant C / source #1) are within + 1 K and – 3 K, and are no problem in practical applications in photometry and colorimetry. The variations for sources including #6 and #7 (± 10 K) are about the same degree of variations in reciprocal scale as shown in Fig. 2 and are not to be concerned. The case of participant C / source #1 should be investigated.

Distribution temperature:

The two participants gave identical results, while the variations among all three participants would leave no practical problems.

Special note:

Richard Young noted small discrepancies in the values in the table given in the Robertson's paper (compared with what is calculated using current CODATA), and discrepancies in the calculated results in CCT based on Robertson's paper (compared with his calculation based on minimization). The values in the paper are outdated. Since this method is widely used, updated information should be provided. CR3 agreed to bring this up to CIE.

Acknowledgement

CR3 appreciates special participation by Dr. Schanda (formerly with CIE Central Bureau) in Hungary and Dr. Gardner at CSIRO, Australia, who recently developed a new method of CCT calculation.

Annex

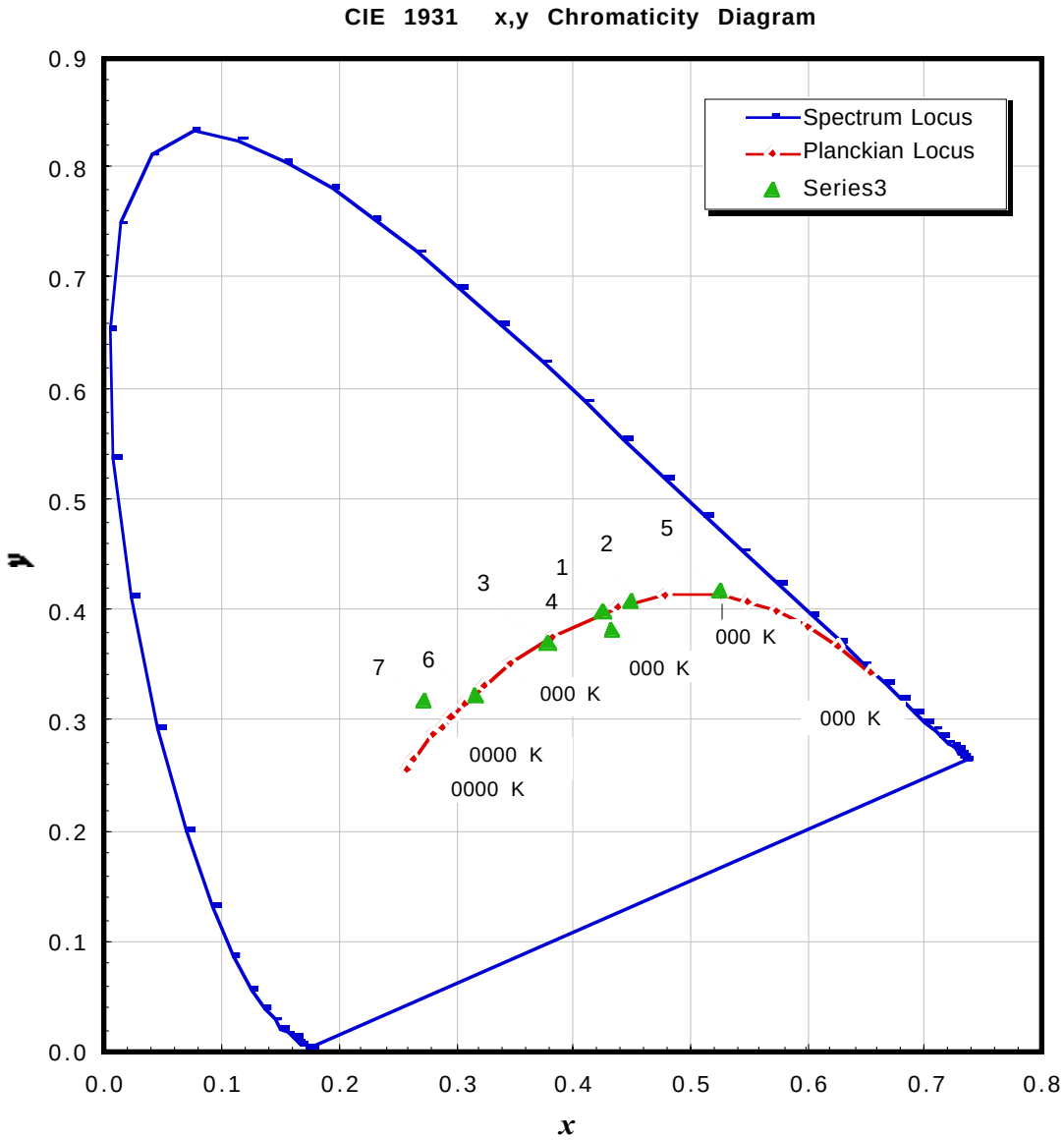

Figure A1 Chromaticity coordinates of the source data.

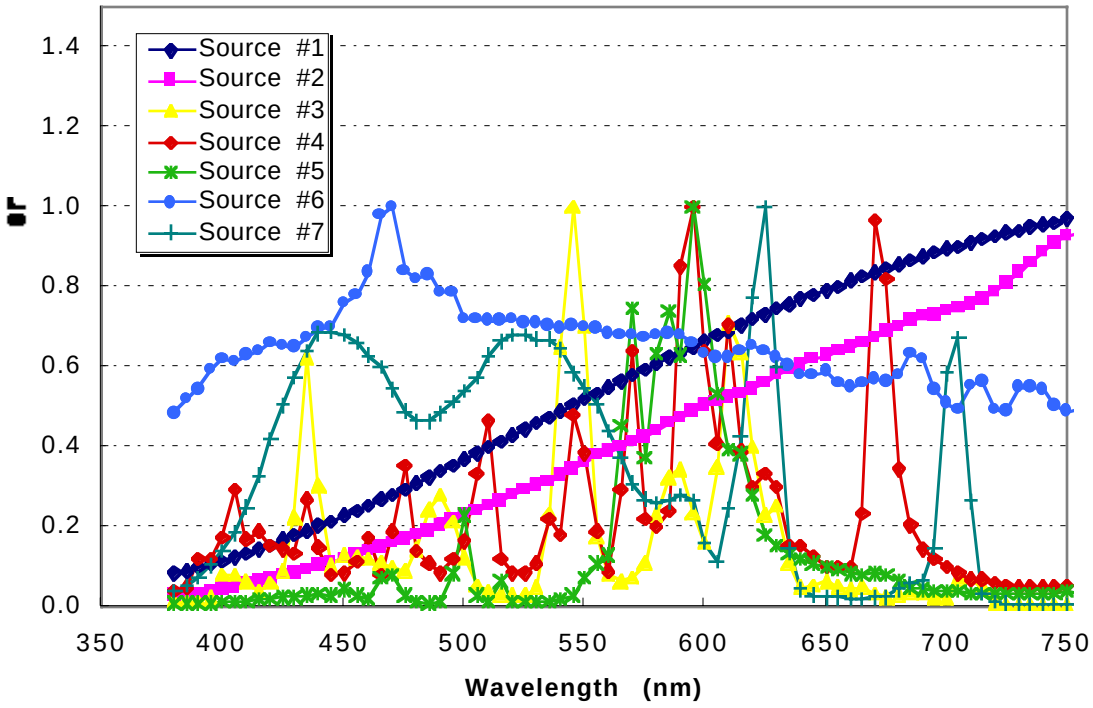

Figure A2. Relative spectral power distribution of the source data.

Table A1. Spectral distribution data of the light sources

Wavelength	Source #1	Source #2	Source #3	Source #4	Source #5	Source #6	Source #7
380	0.0828	0.0314	0.0141	0.0388	0.0086	0.4835	0.0401
385	0.0906	0.0336	0.0128	0.0512	0.0095	0.5192	0.0542
390	0.0989	0.0369	0.0133	0.1204	0.0110	0.5454	0.0741
395	0.1076	0.0412	0.0262	0.1221	0.0119	0.5943	0.1027
400	0.1167	0.0468	0.0790	0.1755	0.0136	0.6187	0.1377
405	0.1261	0.0523	0.0811	0.2942	0.0162	0.6127	0.1859
410	0.1360	0.0580	0.0651	0.1697	0.0168	0.6286	0.2482
415	0.1462	0.0642	0.0412	0.1900	0.0188	0.6417	0.3309
420	0.1569	0.0717	0.0584	0.1542	0.0210	0.6612	0.4187
425	0.1679	0.0789	0.0883	0.1447	0.0232	0.6529	0.5027
430	0.1793	0.0864	0.2237	0.1330	0.0263	0.6511	0.5753
435	0.1911	0.0952	0.6255	0.2677	0.0305	0.6766	0.6379
440	0.2032	0.1044	0.3064	0.1489	0.0339	0.6943	0.6844
445	0.2156	0.1129	0.1063	0.0801	0.0309	0.7018	0.6922
450	0.2284	0.1207	0.1280	0.0833	0.0464	0.7618	0.6782
455	0.2414	0.1297	0.1263	0.1131	0.0324	0.7782	0.6615
460	0.2546	0.1408	0.1205	0.1753	0.0206	0.8329	0.6287
465	0.2681	0.1520	0.1118	0.0792	0.0753	0.9796	0.5976
470	0.2819	0.1618	0.1003	0.1879	0.0792	1.0000	0.5441
475	0.2959	0.1703	0.0893	0.3561	0.0282	0.8382	0.4921
480	0.3101	0.1800	0.1451	0.1419	0.0143	0.8183	0.4637
485	0.3245	0.1914	0.2460	0.1105	0.0099	0.8291	0.4653
490	0.3391	0.2075	0.2822	0.0847	0.0172	0.7857	0.4872
495	0.3539	0.2197	0.2136	0.1214	0.0846	0.7858	0.5134
500	0.3688	0.2303	0.1246	0.1666	0.2283	0.7198	0.5396
505	0.3837	0.2403	0.0565	0.3356	0.0323	0.7181	0.5772
510	0.3986	0.2535	0.0403	0.4670	0.0169	0.7161	0.6305
515	0.4136	0.2672	0.0321	0.1208	0.0635	0.7166	0.6665
520	0.4287	0.2812	0.0292	0.0842	0.0158	0.7197	0.6805
525	0.4438	0.2955	0.0287	0.0871	0.0140	0.7120	0.6819
530	0.4590	0.3060	0.0478	0.1080	0.0149	0.7092	0.6708
535	0.4742	0.3168	0.2361	0.2213	0.0162	0.7033	0.6702
540	0.4894	0.3291	0.6477	0.1788	0.0186	0.6971	0.6455
545	0.5045	0.3444	1.0000	0.4777	0.0294	0.7042	0.5855
550	0.5196	0.3616	0.6986	0.3829	0.0775	0.7000	0.5524
555	0.5347	0.3783	0.1770	0.1913	0.1098	0.6953	0.5056
560	0.5496	0.3906	0.0798	0.0915	0.1283	0.6854	0.4385
565	0.5644	0.4012	0.0642	0.2956	0.4553	0.6785	0.3744
570	0.5792	0.4126	0.0750	0.6397	0.7437	0.6785	0.3119
575	0.5938	0.4255	0.1089	0.2186	0.3732	0.6760	0.2710
580	0.6083	0.4408	0.2323	0.2011	0.6350	0.6787	0.2622
585	0.6227	0.4587	0.3241	0.2419	0.7392	0.6832	0.2652
590	0.6369	0.4767	0.3445	0.8500	0.6322	0.6783	0.2812
595	0.6510	0.4924	0.2334	1.0000	1.0000	0.6585	0.2660
600	0.6649	0.5030	0.1614	0.6410	0.8051	0.6358	0.1586
605	0.6784	0.5131	0.3518	0.4104	0.5346	0.6254	0.1174
610	0.6918	0.5232	0.7107	0.7033	0.3934	0.6239	0.2475
615	0.7050	0.5332	0.6328	0.3921	0.3849	0.6392	0.4282

620	0.7179	0.5462	0.4021	0.2994	0.2792	0.6551	0.7743
625	0.7307	0.5613	0.2280	0.3341	0.1817	0.6401	1.0000
630	0.7432	0.5783	0.2541	0.2987	0.1542	0.6241	0.6017
635	0.7555	0.5938	0.1106	0.1545	0.1351	0.6038	0.1450
640	0.7676	0.6066	0.0496	0.1564	0.1204	0.5785	0.0461
645	0.7794	0.6175	0.0555	0.1263	0.1090	0.5798	0.0299
650	0.7910	0.6281	0.0655	0.1018	0.0979	0.5911	0.0266
655	0.8024	0.6384	0.0520	0.0995	0.0932	0.5614	0.0243
660	0.8136	0.6484	0.0429	0.0979	0.0841	0.5505	0.0219
665	0.8245	0.6579	0.0488	0.2366	0.0806	0.5617	0.0224
670	0.8352	0.6734	0.0338	0.9674	0.0860	0.5704	0.0238
675	0.8456	0.6879	0.0273	0.8193	0.0802	0.5670	0.0240
680	0.8557	0.7017	0.0280	0.3457	0.0651	0.5813	0.0443
685	0.8656	0.7147	0.0357	0.2056	0.0517	0.6331	0.0616
690	0.8753	0.7229	0.0336	0.1438	0.0449	0.6189	0.0643
695	0.8846	0.7304	0.0264	0.1182	0.0418	0.5469	0.1480
700	0.8937	0.7380	0.0192	0.1017	0.0399	0.5086	0.5857
705	0.9024	0.7455	0.0704	0.0829	0.0387	0.4959	0.6729
710	0.9107	0.7572	0.0739	0.0722	0.0375	0.5567	0.2652
715	0.9188	0.7715	0.0494	0.0709	0.0364	0.5649	0.0356
720	0.9266	0.7870	0.0119	0.0625	0.0357	0.4966	0.0158
725	0.9342	0.8113	0.0064	0.0566	0.0352	0.4901	0.0112
730	0.9415	0.8353	0.0050	0.0524	0.0345	0.5523	0.0070
735	0.9485	0.8587	0.0040	0.0513	0.0349	0.5522	0.0049
740	0.9553	0.8870	0.0048	0.0495	0.0350	0.5460	0.0052
745	0.9618	0.9086	0.0044	0.0486	0.0349	0.5055	0.0051
750	0.9680	0.9252	0.0037	0.0537	0.0380	0.4916	0.0045
755	0.9739	0.9367	0.0031	0.0559	0.0355	0.4948	0.0048
760	0.9797	0.9546	0.0023	0.0605	0.0387	0.5590	0.0048
765	0.9851	0.9698	0.0018	0.1241	0.0759	0.6927	0.0046
770	0.9903	0.9820	0.0018	0.1008	0.0548	0.5186	0.0041
775	0.9953	0.9926	0.0022	0.0640	0.0341	0.3920	0.0030
780	1.0000	1.0000	0.0019	0.0646	0.0361	0.3673	0.0034