Input paper: [[1]](#footnote-1) ENG9-2.1.7

Input paper for the following Committee(s): check as appropriate Purpose of paper:

**□** ARM **🗹** ENG **□** PAP **🗹** Input

**□** ENAV **□** VTS **□** Information

Agenda item [[2]](#footnote-2) 2.1

Technical Domain / Task Number 2 …………………………………

Author(s) / Submitter(s) Link Powell, Alwyn Williams

The Changing of Light Colour with Range

# Summary

It is well known that as visible light propagates through the atmosphere, different wavelengths are subject to different amounts of scattering. As a general rule, the shorter the wavelength, the more scattering that occurs. The impact on the observed light is two-fold: blue light has a shorter nominal range than red light with the same photometric intensity, and broadband light will change colour as the composition of the light changes with range.

## Purpose of the document

Inform IALA that an abstract for the work below has been submitted to CIE for consideration for presentation at the 29th quadrennial session.

Suggest areas where additional recommendations or guidance may be useful to providers of marine AtoN lights.

## Related documents

IALA, Recommendation R0201: Marine Signal Lights - Colours, Paris: IALA, 2017

IALA, Recommendation R0202: Marine Signal Lights - Calculation, Definition and Notation of Luminous Range, Paris: IALA, 2017.

IALA, Guideline G1073 Conspicuity of AtoN Lights at Night, Edition 2.0, Paris: IALA, December 2017.

# Background

IALA Recommendation R0201 [1] specifies the allowable colours for light signals and the chromaticity coordinate boundaries for compliance with each colour. It is known that the colour of light can shift as the light propagates through the atmosphere, due to the greater scattering effects towards the blue end of the visible spectrum. Marine aids-to-navigation (AtoN) authorities around the world utilise signal lights that are intended to be viewed from a distance of several nautical miles (M), 18 M being a common requirement. At these distances, there can be a marked colour shift, even in clear atmospheric conditions.

The range performance of marine AtoN lights is published in the form of a nominal range. Nominal range calculations for all lights, regardless of the colour, are performed using an atmospheric transmissivity of 5 % over 10 M. However, due to the greater scattering effects towards the blue end of the visible spectrum, the transmissivity will vary between lights having different spectrums.

A previous input paper from CETMEF [2] demonstrated the effects of both colour shift and differences in nominal range. IALA Guideline G1073 [3] presents the intensity required to meet a given range for monochromatic light of various wavelengths. Both the input paper and G1073 use the Ångström exponent equation to generate the atmospheric transmissivity profile. GRAD conducted a project to review and build upon this previous work using a real-world atmospheric transmissivity profile.

# Discussion

## Method

The work considered the transmissivity and colour shift of several light sources through a real-world atmosphere representing nominal conditions. This required selection of an atmospheric transmissivity profile that represented these conditions and consequently, a method to assess the suitability of a given profile.

IALA recommend the nominal range of a light is calculated using a photometric atmospheric transmissivity of 0.05 over 10 M. An atmospheric profile could therefore be assessed as to how closely it meets this condition. However, the photometric transmissivity of an atmosphere will differ for light sources with different spectrums. Therefore, to assess whether a given atmospheric transmissivity profile meets the recommended photometric transmissivity, a light source must first be selected. The definition of meteorological visibility uses the contrast of an object and does not readily lend itself to calculations for light sources. G1073 assigns a transmissivity of 0.05 to the wavelength of 555 nm over a distance of 10 M, effectively using a monochromatic light source of 555 nm to determine the atmospheric transmissivity profile. Unfortunately, rationale for this approach is not given. The work conducted by GRAD took a different approach, instead, utilising the definition of meteorological optical range. Meteorological optical range is stated in the IALA dictionary to approximate meteorological visibility and states the light source to be used during assessment: a 2,700 K black body radiator.

A series of measured atmospheric spectral transmissivity profiles were collected from previously published papers and the meteorological optic range and corresponding transmissivity of each profile assessed. The profile with a meteorological optical range closest to 10 M was then selected, this profile being considered the closest match to the conditions used to determine the nominal range of a light. The selected atmospheric transmissivity profile came from a measurement over Chesapeake Bay (USA), taken on 08/04/1959. Some 37 measurements were taken over Chesapeake Bay, capturing a wide array of nominal ranges and representing real-world marine conditions. The selected profile had a meteorological optical range of 9.95 M. Equivalently, the transmissivity over 10 M was 0.0504; a difference of 0.8 % from the recommended 0.05. By comparison, the transmissivity of the profile used in G1073 was 0.0575, a difference of 15 % from the recommended 0.05.

Measured spectral profiles of marine AtoN signal lights were then modelled propagating through a homogenous atmosphere having that profile. The chromaticity of each light source was plotted at viewing distances of 1 M increments up to a range of 24 M. The required intensity of each light to provide a nominal luminous range of 1, 5, 10, 15 and 17.5 M in the selected atmospheric transmissivity profile was then calculated.

Some results of the comprehensive study are shown below in Section 3.2 and 3.3, with their analysis given in Section 3.4.

## Selected Chromaticity Results

Figures 1 to 4 show the chromaticity of a given light source over a range of viewing distances in the selected atmosphere. The chromaticity is plotted on the CIE 1931 Chromaticity Space showing colour regions from IALA Recommendation R0201. Each plot covers a range of 0 M to 24 M in 1 M increments. 0 M corresponds to the colour of the light source at the point of emission. An additional plotted point highlights the chromaticity at 18 M.

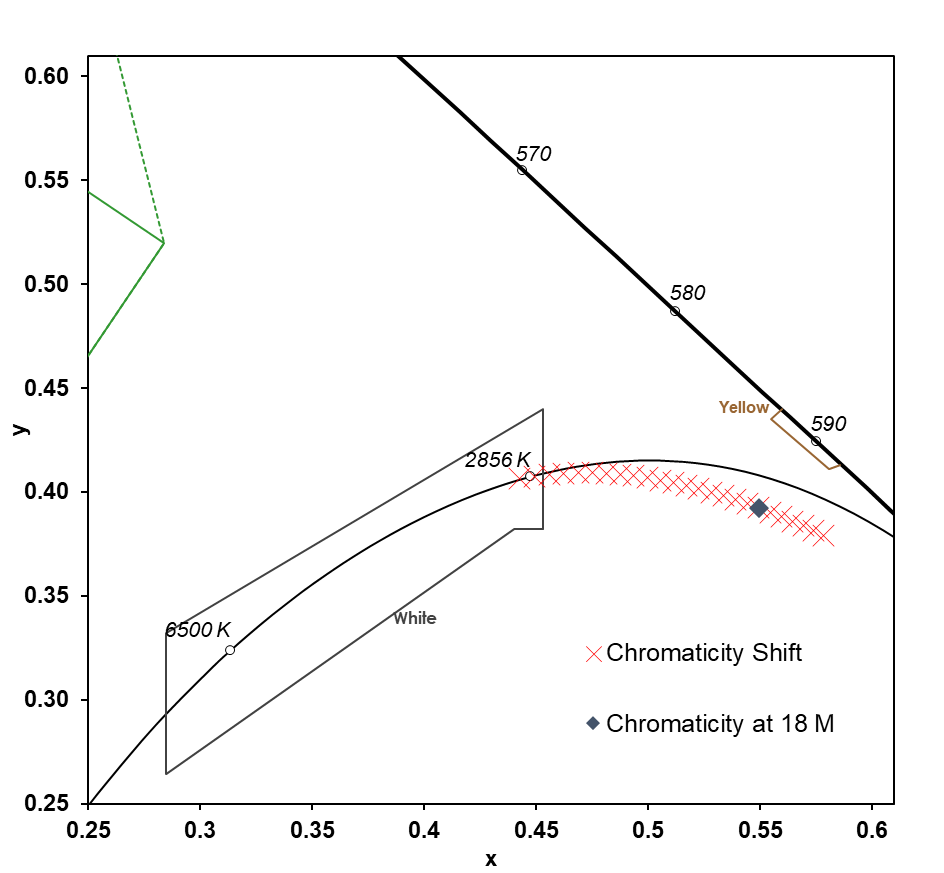


Figure 1 - Colour shift of 75 W Tungsten Halogen Lamp TST-764

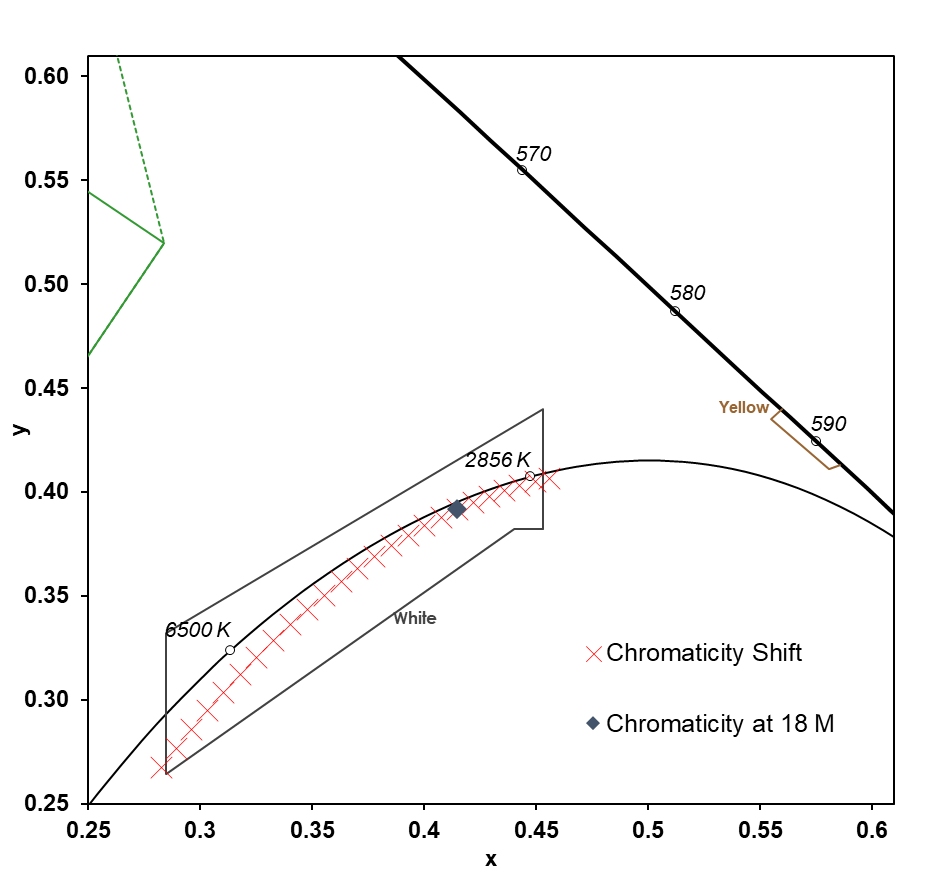


Figure 2 - Colour shift of White LED TST-881

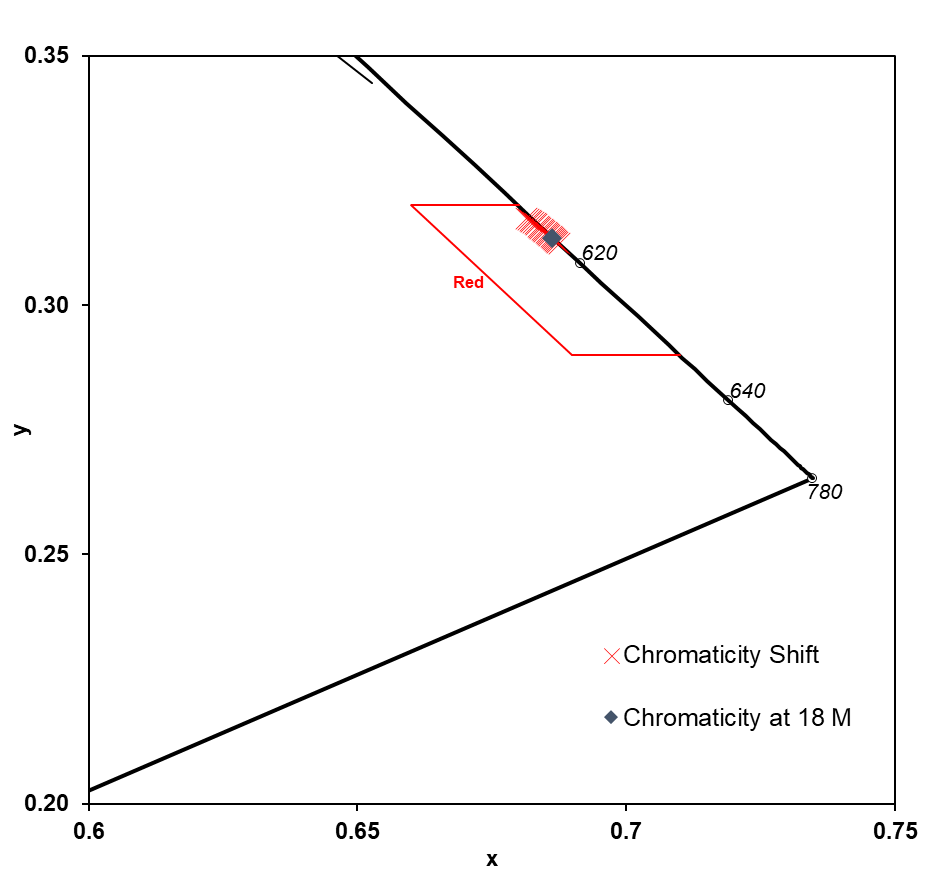


Figure 3 – Colour shift of Red LED TST-821

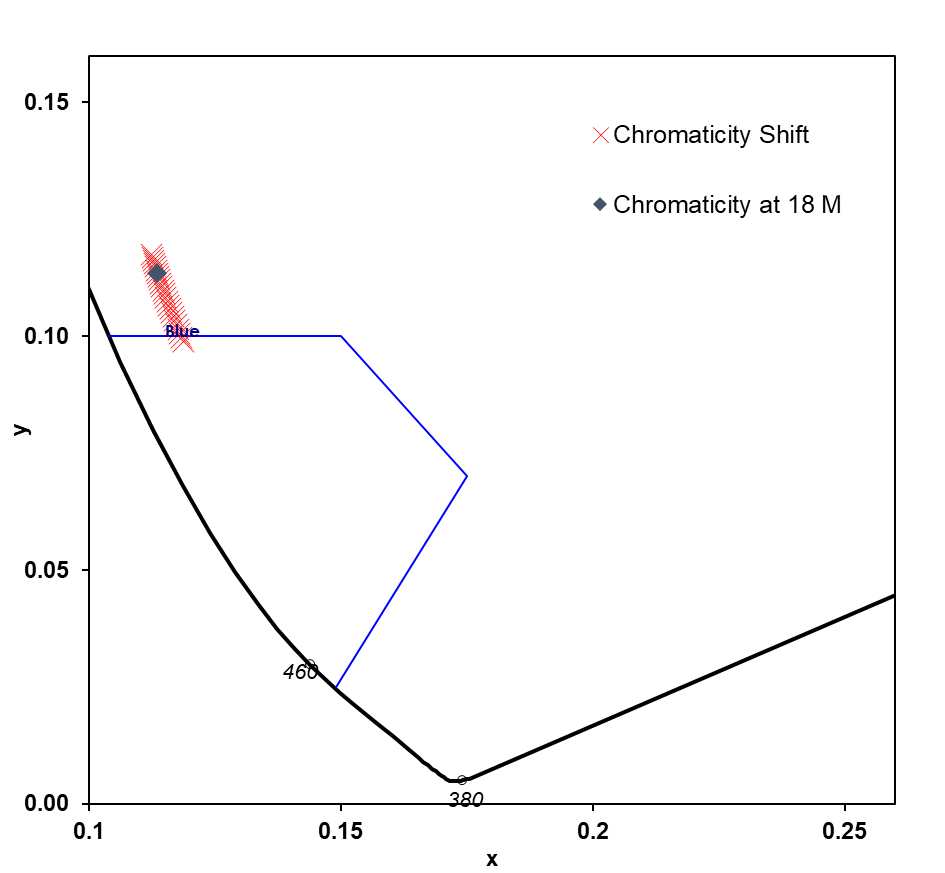


Figure 4 - Colour shift of Blue LED TST-682

## Photometric Results

Table 1 gives the intensity requirements calculated using the formula in R0202 for selected nominal ranges. This formula does not take the light source spectrum into account. Subsequent rows in the table give the intensity requirements for a given light source calculated using the transmissivity profile measured at Chesapeake Bay. The corresponding difference from the R0202 intensity is given in parentheses, with any differences 5% or greater highlighted.

1. Intensity Requirements for Various Light Source Spectrums

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Intensity Required at Given Range (cd)**  **(Difference from R0202)** | | | |
|  | **5 M** | **10 M** | **15 M** | **17.5 M** |
| **R0202 Intensity Equation (Allard’s Law)** | 76.7 | 1,372 | 13,805 | 39,737 |
| **White LED TST-821** | 78.7  (2.7%) | 1,446  (5.4%) | 14,941  (8.2%) | 43,578  (9.7%) |
| **White LED TST-881** | 80.5  (5.0%) | 1,513  (10.3%) | 15,984  (15.8%) | 47,145  (18.6%) |
| **2,700 K Black Body Radiator** | 76.4  (-0.4%) | 1,361  (-0.8%) | 13,644  (-1.2%) | 39,196  (-1.4%) |
| **Tungsten Halogen TST-864** | 76.8  (0.2%) | 1,377  (0.3%) | 13,875  (0.5%) | 39,971  (0.6%) |
| **Metal Halide BD002** | 77.7  (1.3%) | 1,407  (2.5%) | 14,332  (3.8%) | 41,513  (4.5%) |
| **Red LED TST-821** | 67.9  (-11.5%) | 1,075  (-21.6%) | 9,577  (-30.6%) | 25,935  (-34.7%) |
| **Green LED TST-821** | 85.6  (11.6%) | 1,710  (24.6%) | 19,209  (39.2%) | 58,422  (47.0%) |
| **Blue LED TST-682** | 87.1  (13.6%) | 1,771  (29.1%) | 20,252  (46.7%) | 62,137  (56.4%) |
| **Yellow LED TST- 682** | 75.0  (-2.2%) | 1,311  (-4.4%) | 12,897  (-6.6%) | 36,705  (-7.6%) |

## Analysis

Unsurprisingly, the lights that exhibited the greatest shift were white lights, while the narrower band light sources, such as blue, red and green, exhibited less shift. It was found that the chromaticity of many white marine AtoN lights shifted outside the recommended colour boundary for the selected atmospheric transmissivity profile over an 18 M viewing distance. Starting close to the leftmost IALA recommended white boundary extended the distance at which the light remained in the recommended white region, in some cases remaining in for over 20 M. However, the maximum distance varied somewhat between transmissivity profiles.

The 75 W Tungsten Halogen light source, TST-864, starts within the IALA White region and remains inside between a range of 0 M to 1 M. The chromaticity at distances of 2 M and greater, is plotted outside IALA White. The White LED light source, TST-881, starts outside IALA White. However, during the colour shift the plot enters and later exits IALA White, remaining inside between 1 M and 23 M. A measurement of each of these lanterns would show TST-864 to meet IALA White criteria and the TST-881 to fail. However, TST-881 provides an IALA White colour over a significantly greater range of distances. If each of the lights were used to provide an 18 M range, the light that initially fails would provide an IALA white colour over more of the useable range than the light that initially passes. This raises the question: what is more important, that the light’s chromaticity coordinates start in IALA White or remain in IALA White over the usable range of the light? It would seem being the correct colour at the intended viewing distance is more important.

CIE publish a standard, CIE S 004/E-2001 (CIE, 2001), which specifies the allowable colours for light signals and the chromaticity coordinate boundaries for compliance with each colour. The boundaries are not exactly the same as those recommended by IALA, but there are concepts that apply equally to both. The specification notes that the colour of a white signal shifts towards orange-yellow over longer distances (>5 km). It also notes that the shift is more pronounced under conditions of reduced visibility and states that white signals that may be observed under these conditions should have an emission chromaticity located close to the blue boundary of the white region. From the above chromaticity plots, it can be seen implementing this advice would be beneficial to maximise the distance at which a white light conforms to the correct colour. It may even be beneficial to extend the white region further towards the blue for lights intended to be viewed from a long distance.

The intensity requirement of marine signal lights to provide a nominal range of 17.5 M using the selected atmospheric transmissivity profile yielded significant differences compared to the uniform transmissivity recommended by IALA. An example blue LED light required 56 % greater intensity, a green LED light 47 % greater and a white LED light 10 % greater. An example red LED light required 35 % less intensity.

## Conclusions

This study utilised measured atmospheric spectral transmissivity profiles to model and investigate the effect of long distance viewing of signal lights. Further work and eventual guidance on suitable atmospheric profiles would be beneficial. This work might include assessing the sensitivity of colour shift to variations in the atmospheric profile to further understanding of benefits and limitations of using a standard profile or set of profiles.

It was found that the colour of many marine AtoN signal lights shifted outside the recommended colour over the intended viewing distance. For example, many white lights significantly shifted towards yellow/red and there is a potential risk of incorrectly identifying the colour of the light.

There appears to be little guidance on the implications and mitigating measures for using signal lights for long distance viewing. There may be a benefit in dividing the white region into several sub-regions and limit permissible initial chromaticity to given sub-regions based on the intended viewing distance. These regions may even need to start beyond the existing boundaries to allow for optimal conformance with the white region over the intended range of viewing.

# References

1. IALA, Recommendation R0201: Marine Signal Lights - Colours, Paris: IALA, 2017
2. Xavier Kergadallan, CETMEF, “Scattering Aerosol Effect About Colour and Range: Angström's law,” 2007.
3. IALA, Guideline G1073 Conspicuity of AtoN Lights at Night, Edition 2.0, Paris: IALA, December 2017.
4. G. L. Knestrick, T. H. Cosden and J. A. Curcio, “Atmospheric Attenuation Coefficients in the Visible and Infrared Regions,” U.S. Naval Research Laboratory, 1961

# Action requested of the Committee

The Committee is requested to:

1. Share the rationale behind the selection of the atmospheric transmissivity profile such that further work can be built on its foundation.
2. Guideline G1073 presently provides some informative content on the matter, however, there is no guidance on the practical implementation. It would be beneficial to the reader to expand the information given in this area and provide guidance on how it should be used.
3. Consider providing guidance or recommendations on the chromaticity of white lights when viewed over longer distances. For example, dividing the white region into several sub-regions and limiting permissible initial chromaticity to given sub-regions based on the intended viewing distance.
4. Spectral Data
5. Chesapeake Bay measurement, 08/04/1959 (optical depth). Taken from [11]

|  |  |
| --- | --- |
| Wavelength (um) | Optical Depth for 1 km of Atmosphere |
| 0.40 | 0.24 |
| 0.43 | 0.225 |
| 0.46 | 0.190 |
| 0.47 | 0.175 |
| 0.56 | 0.170 |
| 0.67 | 0.130 |
| 0.78 | 0.115 |

1. Calculated Transmissivity per Nautical Mile from Chesapeake Bay measurement, 08/04/1959 (Interpolated and extrapolated)

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ʎ  nm | T  (per M) |  | ʎ  nm | T  (per M) |  | ʎ  nm | T  (per M) |  | ʎ  nm | T  (per M) |
| 380 | 0.6291 |  | 485 | 0.7246 |  | 590 | 0.7434 |  | 695 | 0.7944 |
| 385 | 0.6321 |  | 490 | 0.7246 |  | 595 | 0.7461 |  | 700 | 0.7958 |
| 390 | 0.6351 |  | 495 | 0.7245 |  | 600 | 0.749 |  | 705 | 0.7972 |
| 395 | 0.6381 |  | 500 | 0.7244 |  | 605 | 0.7519 |  | 710 | 0.7985 |
| 400 | 0.6412 |  | 505 | 0.7243 |  | 610 | 0.7548 |  | 715 | 0.7997 |
| 405 | 0.6436 |  | 510 | 0.7243 |  | 615 | 0.7577 |  | 720 | 0.8008 |
| 410 | 0.6459 |  | 515 | 0.7243 |  | 620 | 0.7607 |  | 725 | 0.8018 |
| 415 | 0.6484 |  | 520 | 0.7243 |  | 625 | 0.7636 |  | 730 | 0.8028 |
| 420 | 0.6513 |  | 525 | 0.7245 |  | 630 | 0.7665 |  | 735 | 0.8037 |
| 425 | 0.6548 |  | 530 | 0.7248 |  | 635 | 0.7694 |  | 740 | 0.8044 |
| 430 | 0.6592 |  | 535 | 0.7252 |  | 640 | 0.7721 |  | 745 | 0.8052 |
| 435 | 0.6651 |  | 540 | 0.7257 |  | 645 | 0.7748 |  | 750 | 0.8059 |
| 440 | 0.6719 |  | 545 | 0.7265 |  | 650 | 0.7773 |  | 755 | 0.8064 |
| 445 | 0.6793 |  | 550 | 0.7273 |  | 655 | 0.7797 |  | 760 | 0.8069 |
| 450 | 0.6871 |  | 555 | 0.7286 |  | 660 | 0.782 |  | 765 | 0.8073 |
| 455 | 0.6952 |  | 560 | 0.7299 |  | 665 | 0.784 |  | 770 | 0.8076 |
| 460 | 0.7034 |  | 565 | 0.7318 |  | 670 | 0.786 |  | 775 | 0.8079 |
| 465 | 0.7158 |  | 570 | 0.7336 |  | 675 | 0.7878 |  | 780 | 0.8082 |
| 470 | 0.7232 |  | 575 | 0.7359 |  | 680 | 0.7896 |  |  |  |
| 475 | 0.724 |  | 580 | 0.7382 |  | 685 | 0.7912 |  |  |  |
| 480 | 0.7244 |  | 585 | 0.7408 |  | 690 | 0.7929 |  |  |  |

1. Light Source Spectrum - Tungsten Halogen TST-864

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ʎ  nm | Relative spectral power distribution |  | ʎ  nm | Relative spectral power distribution |  | ʎ  nm | Relative spectral power distribution |  | ʎ  nm | Relative spectral power distribution |
| 380 | 0.04754 |  | 485 | 0.2395 |  | 590 | 0.5488 |  | 695 | 0.8382 |
| 385 | 0.0521 |  | 490 | 0.2529 |  | 595 | 0.5641 |  | 700 | 0.853 |
| 390 | 0.05752 |  | 495 | 0.2662 |  | 600 | 0.5802 |  | 705 | 0.8644 |
| 395 | 0.06382 |  | 500 | 0.2802 |  | 605 | 0.5948 |  | 710 | 0.8738 |
| 400 | 0.07107 |  | 505 | 0.2938 |  | 610 | 0.6091 |  | 715 | 0.8895 |
| 405 | 0.07795 |  | 510 | 0.3084 |  | 615 | 0.6255 |  | 720 | 0.8992 |
| 410 | 0.08576 |  | 515 | 0.3215 |  | 620 | 0.6407 |  | 725 | 0.9126 |
| 415 | 0.09363 |  | 520 | 0.336 |  | 625 | 0.6573 |  | 730 | 0.9241 |
| 420 | 0.1019 |  | 525 | 0.3499 |  | 630 | 0.668 |  | 735 | 0.9275 |
| 425 | 0.1105 |  | 530 | 0.3648 |  | 635 | 0.6832 |  | 740 | 0.9411 |
| 430 | 0.119 |  | 535 | 0.3794 |  | 640 | 0.6988 |  | 745 | 0.9435 |
| 435 | 0.1282 |  | 540 | 0.3947 |  | 645 | 0.7113 |  | 750 | 0.9564 |
| 440 | 0.1377 |  | 545 | 0.4096 |  | 650 | 0.7253 |  | 755 | 0.9667 |
| 445 | 0.1474 |  | 550 | 0.4233 |  | 655 | 0.7392 |  | 760 | 0.9724 |
| 450 | 0.1577 |  | 555 | 0.4406 |  | 660 | 0.7538 |  | 765 | 0.974 |
| 455 | 0.1683 |  | 560 | 0.4548 |  | 665 | 0.7688 |  | 770 | 0.9853 |
| 460 | 0.1797 |  | 565 | 0.4694 |  | 670 | 0.7771 |  | 775 | 0.9924 |
| 465 | 0.1906 |  | 570 | 0.4893 |  | 675 | 0.7909 |  | 780 | 1 |
| 470 | 0.2025 |  | 575 | 0.5023 |  | 680 | 0.8059 |  |  |  |
| 475 | 0.2143 |  | 580 | 0.5187 |  | 685 | 0.8178 |  |  |  |
| 480 | 0.2273 |  | 585 | 0.5333 |  | 690 | 0.8285 |  |  |  |

1. Light Source Spectrum - White LED TST-881

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ʎ  nm | Relative spectral power distribution |  | ʎ  nm | Relative spectral power distribution |  | ʎ  nm | Relative spectral power distribution |  | ʎ  nm | Relative spectral power distribution |
| 380 | 0.0007787 |  | 485 | 0.05289 |  | 590 | 0.2204 |  | 695 | 0.02681 |
| 385 | 0.0007921 |  | 490 | 0.06113 |  | 595 | 0.2097 |  | 700 | 0.02328 |
| 390 | 0.001043 |  | 495 | 0.08034 |  | 600 | 0.1991 |  | 705 | 0.0204 |
| 395 | 0.001646 |  | 500 | 0.1072 |  | 605 | 0.1868 |  | 710 | 0.0177 |
| 400 | 0.003175 |  | 505 | 0.139 |  | 610 | 0.1744 |  | 715 | 0.01549 |
| 405 | 0.006494 |  | 510 | 0.1709 |  | 615 | 0.162 |  | 720 | 0.01333 |
| 410 | 0.01409 |  | 515 | 0.1994 |  | 620 | 0.1491 |  | 725 | 0.01159 |
| 415 | 0.0316 |  | 520 | 0.2225 |  | 625 | 0.1367 |  | 730 | 0.01011 |
| 420 | 0.06974 |  | 525 | 0.24 |  | 630 | 0.1239 |  | 735 | 0.008685 |
| 425 | 0.1453 |  | 530 | 0.2522 |  | 635 | 0.1125 |  | 740 | 0.007646 |
| 430 | 0.2812 |  | 535 | 0.2596 |  | 640 | 0.1018 |  | 745 | 0.006733 |
| 435 | 0.5063 |  | 540 | 0.2627 |  | 645 | 0.09139 |  | 750 | 0.005958 |
| 440 | 0.8331 |  | 545 | 0.2634 |  | 650 | 0.08188 |  | 755 | 0.005213 |
| 445 | 1 |  | 550 | 0.2638 |  | 655 | 0.07316 |  | 760 | 0.004563 |
| 450 | 0.7293 |  | 555 | 0.2617 |  | 660 | 0.06504 |  | 765 | 0.003951 |
| 455 | 0.3971 |  | 560 | 0.2594 |  | 665 | 0.05737 |  | 770 | 0.003488 |
| 460 | 0.239 |  | 565 | 0.2561 |  | 670 | 0.05088 |  | 775 | 0.00306 |
| 465 | 0.151 |  | 570 | 0.2506 |  | 675 | 0.04495 |  | 780 | 0.002697 |
| 470 | 0.09476 |  | 575 | 0.2457 |  | 680 | 0.03956 |  |  |  |
| 475 | 0.0679 |  | 580 | 0.238 |  | 685 | 0.03499 |  |  |  |
| 480 | 0.05634 |  | 585 | 0.2302 |  | 690 | 0.03075 |  |  |  |

1. Input document number, to be assigned by the Committee Secretary [↑](#footnote-ref-1)
2. Leave open if uncertain [↑](#footnote-ref-2)