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An investigation of the quality of indexes used to estimate the sky glow from LED road lighting luminaires

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Executive Summary

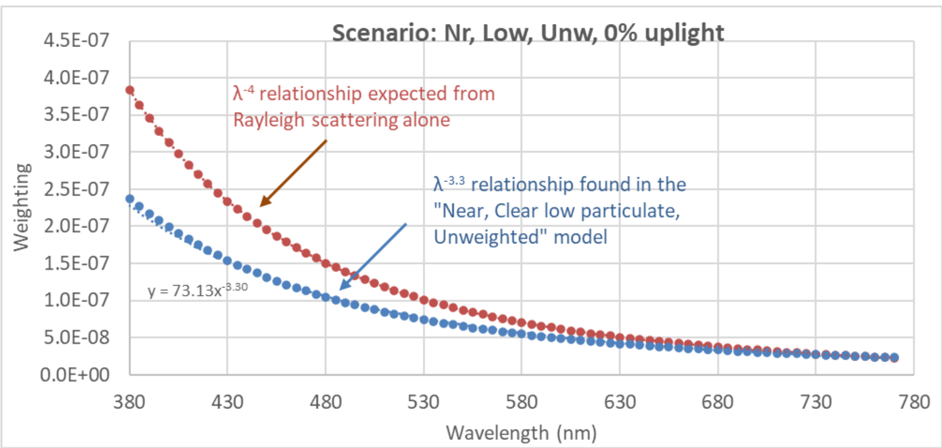
Globally light from artificial sources has been growing at a rate greater than the global population growth. Technological changes have allowed light to be produced at a lower net cost and the recent advent of LED technology has delivered light sources capable of delivering broad spectrum light with an enriched blue content. Light at the blue end of the spectrum scatters more readily in the atmosphere and has raised concerns that the enriched blue content in itself is accelerating the loss of a truly dark night sky.

Authorities in New Zealand have attempted to address the issue by choosing a lower correlated colour temperature (CCT) for their luminaires. For example 4000K (NZTA) or 3000K (Dunedin City). However, the CCT is not an intrinsic measure of sky glow potential, rather it is a measure of the colour or "warmth" of a light source. A lower value for the CCT may indicate less sky glow but this is not always the case. At the extreme it is possible for a luminaire spectrum rated at 3000K to produce more sky glow than one rated at 4000K.

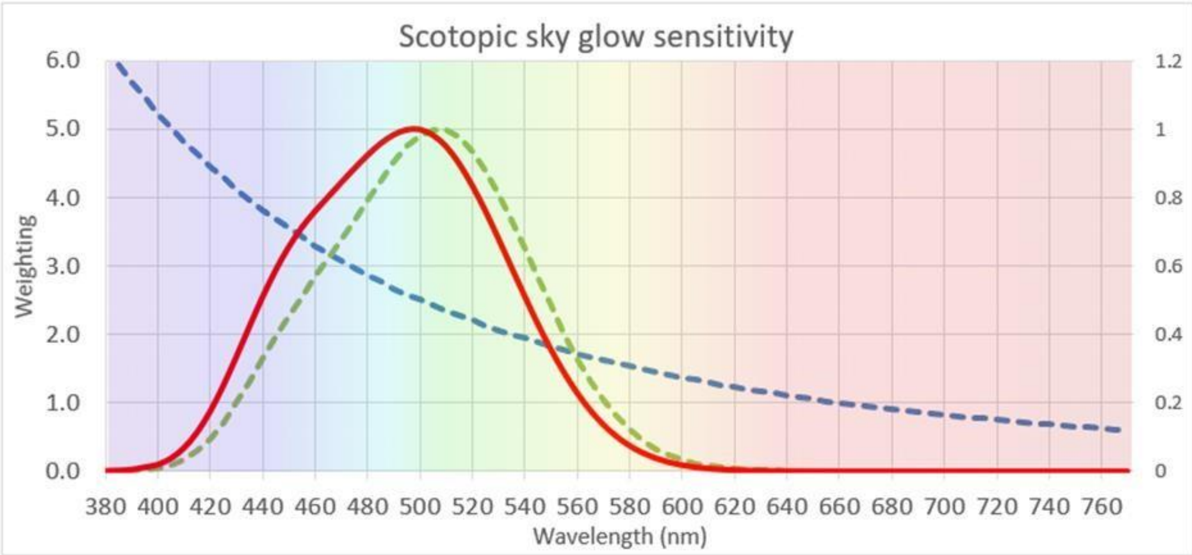
This latter point highlights the need to review the criteria under which luminaires are rated for sky glow. If a road controlling authority (RCA) wishing to protect its dark skies chooses a specific luminaire on the basis of a lower CCT it needs some assurance that the luminaire will indeed reduce sky glow and by how much compared to the alternatives.

SKY GLOW TOOL:
A leading astronomy model developed by Miroslav Kocifaj was used in a US Department of Energy (DOE) project to determine the relative impact different light sources had on sky glow. The team led by Bruce Kinzey made some 215,000 runs on a supercomputer which were later summarised for public use in the freely available US Department of Energy "Sky glow comparison tool v1.0" (DOE tool). The output from this sky glow tool has been used to establish the relationship between sky glow and the spectra of a luminaire as measured by its spectral power density (SPD).

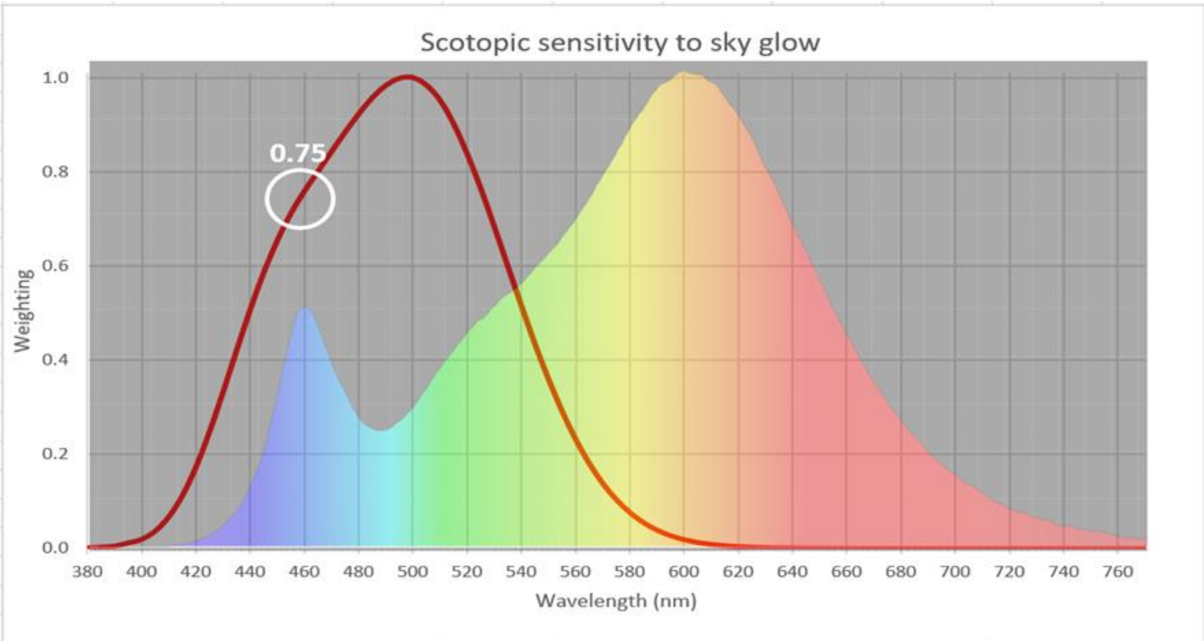
The first part of the project was to determine the mathematics underpinning the DOE tool. In particular the relationship between the wavelength of light from a luminaire and the resultant radiant flux of sky glow as shown in the figure below.



The radiant flux of sky glow is relevant to astronomers studying the spectra of cosmic objects but is not a measure that is relevant to how human observers see the night sky. For human eye sensitivity the radiant flux needs to be weighted by the scotopic (mesopic or photopic) function. In the figure below the radiant flux of sky glow (dotted blue line) has been weighted by the scotopic luminosity function (dotted green line) to produce a composite scotopic function (solid red line). This red line red line combines the weighting from atmospheric scattering and human eye response so is directly applicable to the SPD output from a LED luminaire.



Overlaying this composite scotopic function (red line) over a typical luminaire SPD curve as in the Figure below shows how the spectrum of a LED luminaire should be weighted to estimate the sky glow it produces. In the example below the scoptopic weighting for the blue peak is shown at 75% – this strong weighting may have contributed some of the concern about LED lighting and sky glow.



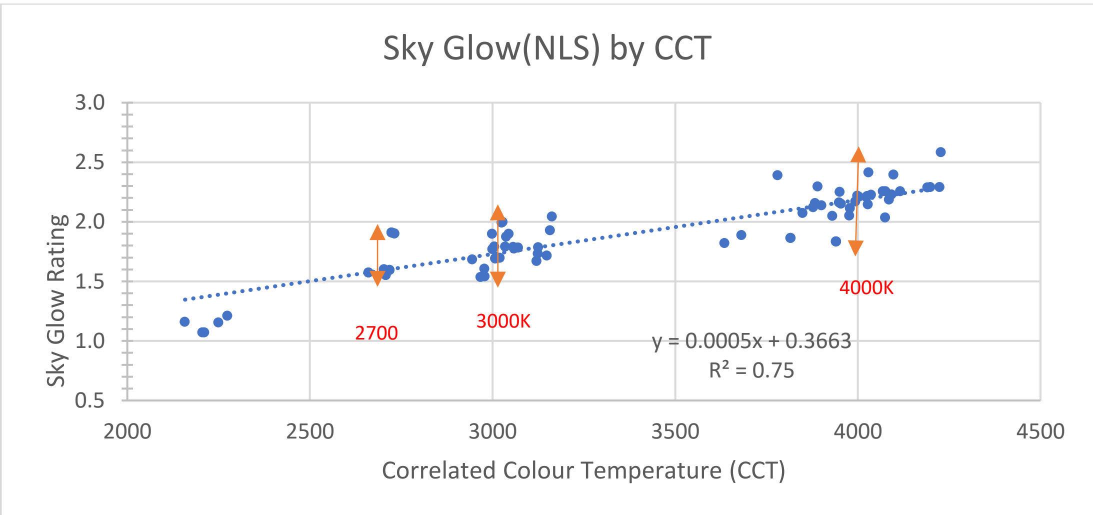
COMPARISON OF INDEXES:
SPD samples taken from 75 road lighting luminaires / LED chips were used to establish the reliability of 5 indexes to identify the level of sky glow determined by the DOE tool for a near observer (<10kms) and a clear unpolluted sky.

The indexes tested were:

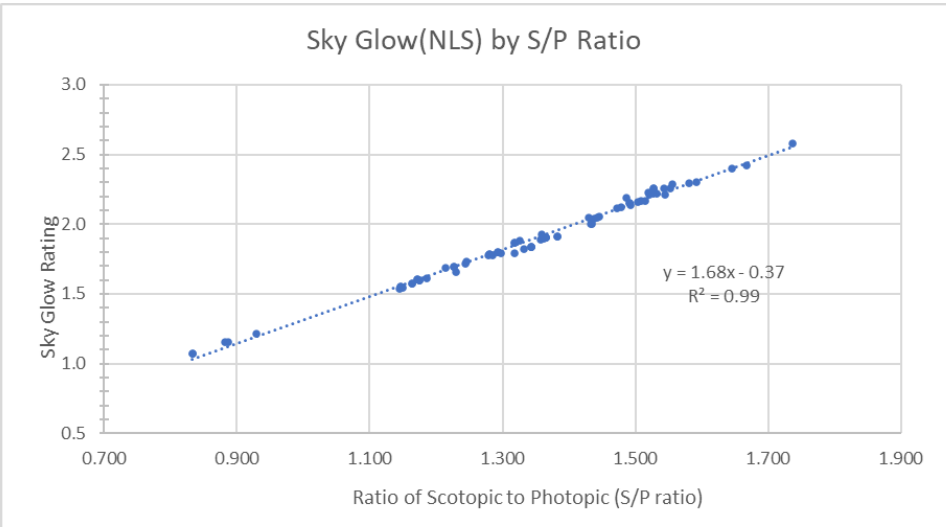
- Corelated Colour Temperature (CCT)
- Scotopic / Photopic Ratio (S/P ratio)
- % Blue light (430 – 470 nm) SPD based
- % Blue light (400 – 500 nm) SPD based
- % Blue light (400 – 550 nm) SPD based

The degree to which the index correlated with the DOE Tool's sky glow rating was taken as the measure of how useful the index was at predicting sky glow.

Below are plots for the indexes of CCT and S/P ratio. The CCT is the most commonly used measure to estimate sky glow but the large scatter in the plot indicates that it is also one of the poorest. Some 4000K luminaires show as producing less sky glow than some 3000K luminaires.



In contrast the S/P ratio shows little scatter and a high correlation co-efficient of 0.99.



RECOMMENDATIONS:

a) Introduce into the M30 accepted list, a criterion on the spectral content of light to limit the sky glow impact. This could take in account the findings of this report on the power of different indexes to identify sky glow.

b) Provide the guidance necessary to allow RCAs to make informed decisions on the luminaires best suited to areas where dark sky preservation is of particular interest. It is not expected that simply specifying the CCT would be sufficient.

c) As credible research becomes available provide guidance for RCAs on luminaire selection where specific wildlife issues are of particular interest. It is likely that SPD from each luminaire would be required to be able to specify such criteria.

d) Require applicants for the M30 accepted luminaires list to provide a SPD for their product and to provide updates to that SPD whenever a new series of LED chips is fitted. Consider also whether a simple graphical SPD is sufficient.

e) Require M30 applicants to provide the S/P ratio for their luminaire and again update this whenever a new series of LED chips is fitted. Note that the S/P ratio can also be determined mathematically from the SPD.

1 Introduction

Globally light from artificial sources has been growing at a rate greater than the global population growth. Technological changes have allowed light to be produced at a lower net cost and the recent advent of LED technology has delivered light sources capable of delivering broad spectrum light with an enriched blue content. Light at the blue end of the spectrum scatters more readily in the atmosphere and has raised concerns that the enriched blue content in itself is accelerating the loss of a dark night sky.

Authorities in New Zealand have attempted to address the issue by choosing a lower correlated colour temperature (CCT) for their luminaires. For example 4000K (NZTA) or 3000K (Dunedin City). However, the CCT is not an intrinsic measure of sky glow potential, rather it is a measure of the colour or "warmth" of a light source. A lower value for the CCT may indicate less sky glow but this is not always the case. At the extreme it is possible for a luminaire spectrum rated at 3000K to produce more sky glow than one rated at 4000K.

This latter point highlights the need to review the criteria under which luminaires are rated for sky glow. If a road controlling authority (RCA) wishing to protect its dark skies chooses a specific luminaire on the basis of a lower CCT it needs some assurance that the luminaire will indeed reduce sky glow and by how much compared to the alternatives.

2 The spectrometer

This section deals with the operation and calibration of a handheld spectrometer purchased for the project to help obtain spectral data on luminaires.

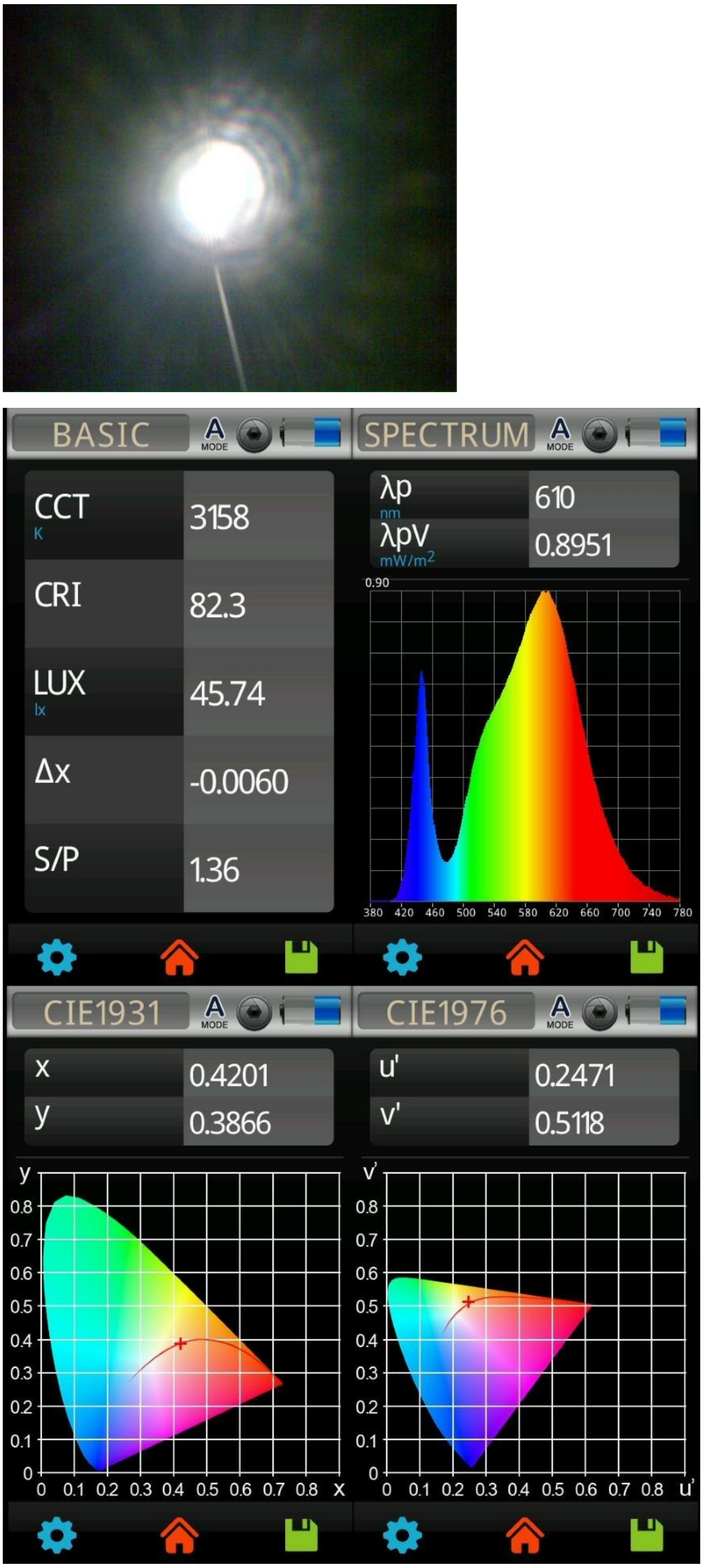
2.1 UPRtek350S spectrometer:

The specifications for the spectrometer are shown in Table 1.

Table 1: Specifications of the MK350S

Specification

Spectrum		
Sensor	CMOS Linear Image Sensor	
Wavelength Range	380 to 780 nm	
Wavelength Data Increment	1 nm	
Spectral Bandwidth	Approximately 12 nm (Half Bandwidth)	
Wavelength Reproducibility	± 1 nm [*1]	
Measurement Range	1 to 100,000 lx (Optional : 200,000 lx)	
Illuminance Accuracy	Illuminant A @ 2,856 K at 20,000 lx [*2]	± 5%
Color Accuracy		± 0.0025 in CIE 1931 x,y
Color Repeatability		±0.0005 in CIE 1931 x,y
CCT Accuracy		± 2%
CRI Accuracy @ Ra		± 1.5%
Stray Light	-25 dB max. [*3]	
Integration Time Range	3 to 20,000 ms	
Digital Resolution	16 bits	



Model Name	MK350S PREMIUM
Serial Number	19C00328
Time	2020/05/02_18:34:01
Memo	
LUX(lx)	45.434212
fc	4.22251
CCT(K)	3158
Duv	-0.004583
I-Time(us)	280000
x	0.420116
y	0.386814
x10	0.425298
y10	0.379791
u'	0.247071
v'	0.511844
u'10	0.253648
v'10	0.509642
deltax	-0.005996
deltay	-0.013257
deltau'	0.001779
deltav'	-0.006336
LambdaP(nm)	607
LambdaPValue(mW/m^2)	0.884554
LambdaD(nm)	584
X	49.345757
Y	45.434212
Z	22.677538
X10	53.372425
Y10	47.661545
Z10	24.460278
S/P	1.35971
Purity(%)	0.42216
CRI	82.227692
R1	82.227303
R2	87.650551
R3	91.595718
R4	81.879036
R5	81.701012
R6	83.67955
R7	83.995819
R8	65.092506
R9	17.625038
R10	71.17366
R11	81.338371
R12	67.775757
R13	82.94915
R14	95.210167
R15	76.721199
CQS	79.622581
GAI	67.15416
TLCI	59.945873
Rf	80.125534
Rg	101.791565
IRR(W/m^2)	0.14157
PFD(380~780nm)	0.683127
PPFD(400~700nm)	0.657173
PFD-UV(380~400nm)	0.000024
PFD-B(400~500nm)	0.083816
PFD-G(500~600nm)	0.281923
PFD-R(600~700nm)	0.291434
PFD-FR(700~780nm)	0.025931
380nm(mW/m^2)	0
381nm(mW/m^2)	0
382nm(mW/m^2)	0
383nm(mW/m^2)	0
384nm(mW/m^2)	0
385nm(mW/m^2)	0
386nm(mW/m^2)	0
387nm(mW/m^2)	0.000085
388nm(mW/m^2)	0.000289
389nm(mW/m^2)	0.000595
390nm(mW/m^2)	0.000696
391nm(mW/m^2)	0.000558
392nm(mW/m^2)	0.000342
393nm(mW/m^2)	0.000448
394nm(mW/m^2)	0.000874
395nm(mW/m^2)	0.001143
396nm(mW/m^2)	0.001011
397nm(mW/m^2)	0.000531
398nm(mW/m^2)	0.000241
399nm(mW/m^2)	0.000211
400nm(mW/m^2)	0.000316

Figure 1: Data available on the MK350S SD card from a spectral measurement of the We-ef 3000K luminaire. Top left a photo of the luminaire as measured, bottom left a summary of key spectral data as a jpg file, right hand side a small section (82 of 462 rows) of the spreadsheet SPD and related output.

The meter is capable of recording the SPD of a light source by standing underneath the luminaire, aiming the unit at the centre of the light source using a built-in camera and pressing a button. The light incident on a small disc at the top of the unit measures the SPD in units of watts per square metre per nanometre ($W.m^{-2}.nm^{-1}$). These measurements represent the spectral power distribution (SPD) of the luminaire at the point of measurement between the wavelengths 380nm to 780nm - the extent of visible light.

Optionally this SPD can then be saved to an onboard SD card in spreadsheet format along with a photo of the light source and key spectral information.

Figure 1 illustrates these outputs using as a target the We-ef, 3000K luminaire from a previous study, Jackett and Frith, 2019.

2.2 Field Method

Based on early experimentation with the device the following steps are suggested as an interim field method to measure the spectra of road lighting luminaires:

1. Chose a suitable luminaire to be measured.

2. Note: The sensor on the MK350S has a 180-degree field of view with sensitivity decreasing with the cosine of the angle from the normal. If there are surrounding lights with a different spectra care needs to be taken to ensure they do not contaminate the signal. Ensuring a strong signal from the measurement source, blocking spurious light sources or choosing another site are options to consider. For accurate measurements, the signal from any conflicting luminaires would be at least three magnitudes lower than the signal being measured. Switch on the meter and allow for a dark calibration.

   Dark calibration allows the zero point to be set and should be carried out whenever the meter is switched on.

3. Stand underneath the luminaire with the spectrometer held at eye level. The readings should be made from a position at approximately right angles to the face of the luminaire. This position will provide consistency of measurement with respect to the orientation of the luminaire and helps ensure there is strong signal from the target luminaire to dominate signal from other sources. For the great majority of installations measurements can be made from the safety of the parking lanes or the footpath.

4. Align the spectrometer so that a single circular image shows on the screen and make the measurement by pushing the LHS button.

Notes on Integration time: The Integration time is the time used by the spectrometer to obtain a reading and the setting “Integration Mode” = “Automatic” is ideal for luminaire measurements. Luminaire measurements made in a 50 lux environment take about ½ second of integration time. The longer the integration time the more reliable the outcome but the more time spent in the field. There is also a setting option called “Long Exposure” which when set to “On” allows the device to spend somewhat longer (up to 5 seconds in environments around 1 lux) to establish a reading. This topic would benefit with further experimentation but for maximum accuracy and flexibility of light environment perhaps “Long Exposure” = “On” could be the initial default for most road luminaire measurements.

2.3 Field and Laboratory Spectrometer compared

The MK350S has a current laboratory calibration certificate but it was still necessary to confirm that the total package of spectrometer with a simple field method technique could deliver results generally compatible with those produced by manufacture's laboratories. Both methods are used to determine SPDs in this study.

2.3.1 We-ef, VFL540, 3000K

SPD data was obtained for the We-ef VFL540-SE LED, 108 – 1249, 3000K, 81w luminaire by measurement with the MK350S spectrometer and by manually interpolating the Cree XP-G2, 3000K spectral plot taken from the Cree website.

The two spectral plots are overlaid for comparison in Figure 2. The agreement was particularly good over the range 480 nm to 780 nm and the only real variation was in the blue wavelengths 480 nm to 380 nm where the spectrometer recorded slightly higher values.

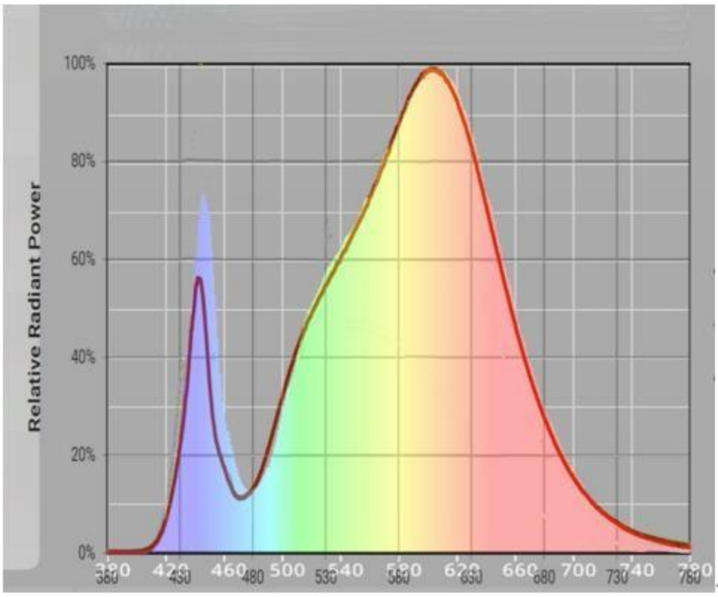


Figure 2: Two over laid spectral plots of relative radiant power for the We-ef, 3000K luminaire. The red line represents the Cree XP-G2, 3000K plot and the coloured foreground that of the MK350S spectrometer measurement of the We-ef VFL540-SE, 3000K luminaire.

Table 2: A comparison of indexes for field and LED chip laboratory measurements for the We-ef, 3000K luminaire.

	FIELD RESULTS (MK350S)	CHIP DATA (CREE XP-G2, 3000K)	DIFFERENCE
CCT	3158	3083	-75 (2.3%)
S/P ratio	1.36	1.31	-0.05 (3.6%)
DOE Sky glow ratio	1.93	1.82	-0.11 (5.7%)

2.3.2 Betacom, GL520, 4000K

SPD data was obtained for the Betacom GL520 XT-E chipped luminaire by (1) spectrometer field measurement in 2020 and (2) by manually interpolating a spectral graph kindly provided by Betacom from their 2015 library.

The two plots are overlaid for comparison in Figure 3. Again, the agreement between the laboratory and field plots was surprisingly good. The only significant variation was a slightly higher blue peak shown on the spectrometer.

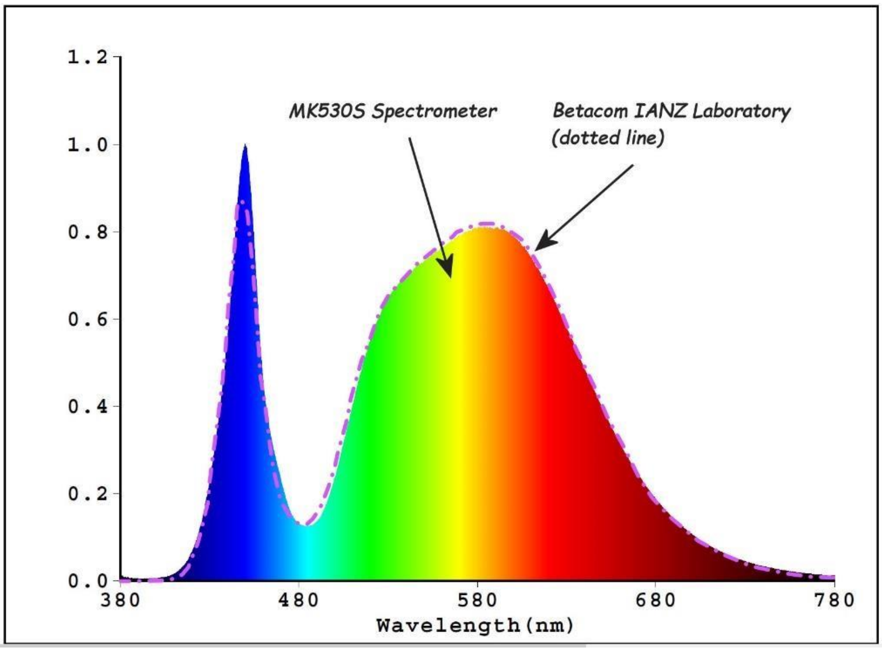


Figure 3: Two over laid spectral plots of relative radiant power for the Betacom XT-E 4000K luminaire. Except for the blue peak the differences are subtle and occur only at the margin of the plot

Table 3: A comparison of indexes for field measurement and laboratory measurements for the Betacom, XT-E, 4000K luminaire.

	FIELD RESULTS (MK350S)	LABORATORY TESTING	DIFFERENCE
CCT	4026	3949	-77 (1.9%)
S/P ratio	1.55	1.51	-0.04 (2.6%)
DOE Sky glow ratio	2.22	2.17	-0.05 (2.3%)

Observation: For both luminaires, the agreement between laboratory and field measurements was good. The slightly higher blue peak found by the spectrometer is likely to be due to taking on-axis readings. Laboratory tests spatially average both on-axis and off-axis measurements and typically on-axis measurements produce the most blue light and typically lead to higher CCT and S/P ratios. This likely explains the small differences in lighting indexes shown in Tables 2 and 3.

3 Estimating Sky Glow

In a previous study, Jackett and Frith, 2019 it was observed that sky glow is influenced by so many factors that light path modelling using basic physics is likely to yield the best predictive results. A leading astronomy model developed by Miroslav Kocifaj was used in a US Department of Energy (DOE) project by to determine the relative impact different light sources had on sky glow. The team led by Bruce Kinzey made some 215,000 runs on a supercomputer which were later summarised for public use in the freely available US Department of Energy "Sky glow comparison tool v1.0" (DOE tool).
The tool allows users to input the spectral power distribution (SPD) of a particular luminaire and compare the sky glow created with that of another luminaire, typically a high-pressure sodium (HPS) luminaire with 2 percent uplight (The input panel is shown in Figure 4).

There are a limited number of scenario options:

- Observer location: Near (<10kms), Distant (40kms)
- Atmospheric condition: Cloudy, Clear low particulate, Clear high particulate
- Weighting function: Scotopic, Unweighted
- Luminaire Uplight: 0%, 2%, 5% and 10%
- Lumen output as a % baseline: (not used in this study)

The tool provides what is currently the best method for lighting designers and roading authorities to compare different road lighting sources for sky glow potential. When it comes to sky glow the more commonly quoted index of correlated colour temperature (CCT) lacks the scientific rational of the Sky Glow Comparison tool.

However, the simplicity of the tool comes at a cost. The tool is something of a "black box" in the sense that it provides relative indexes but there is little information on the form of any underlying matrices or method to obtain the relative indexes (the macro routines in the tool are also closed to public view). Updates would rely on DOE continuing to hold an interest in this area and providing software updates as appropriate.

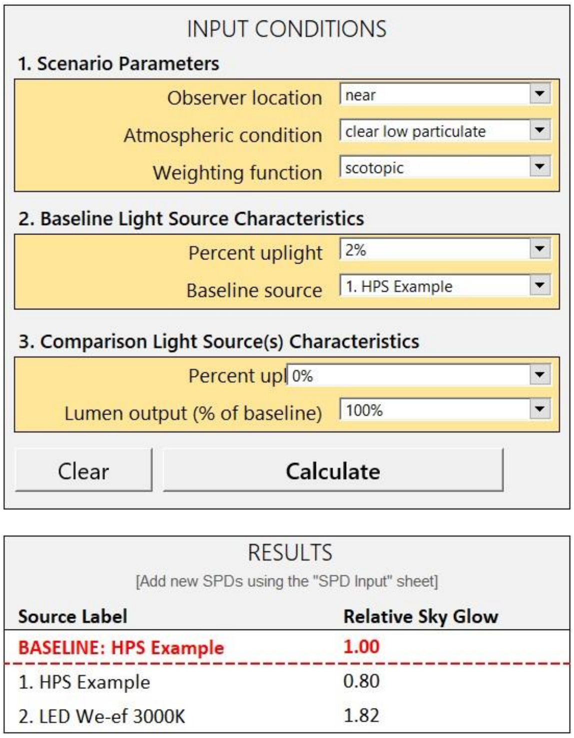


Figure 4: Input panel of the Sky Glow Comparison Tool showing the relative sky glow from a We-ef 3000K with 0% uplight compared to an HPS luminaire with 2% uplight.

The following section details work undertaken to:

1. better understand the mathematics used in the tool
2. develop routines to calculate the indexes independently of the tool
3. add any further indexes not yet available in the tool (eg. Mesopic and Photopic sensitivity)
4. integrate UPRtek MK350S spectrometer outputs with those of the DOE tool.

3.1 SPD Normalisation:

The tool requires an SPD to first be entered into the spreadsheet through a special routine which "Normalises" it to a constant lumen output. This is an important part of the calculations, but the process and method was not elaborated.

3.1.1 Reasons:

The spectrometer measures the radiant flux in milliwatts per square metre per nanometre of wavelength ($mW.m^{-2}.nm^{-1}$) at the point where the instrument is held. However, in this study it is the relative power per wavelength that is of interest. Normalisation of the SPD allows a comparison to be made with other light sources by expressing the SPD in terms of a given lumen output (e.g. $mW.m^{-2}.nm^{-1}$ per 1,000 lumens).

3.1.2 Method:

To provide a written record of the process of normalisation the necessary steps are outlined below.:

1. Arrange the MK350S SPD data in a column by wavelength and select SPD values at 5 nm intervals from 380 to 770 nm (to be compatible with input of the DOE tool).
2. Multiply each of the SPD values by;

- the relevant CIE photopic scale value (values 0.0 to 1.0)
- the photopic luminous efficiency constant of radiation (683)
- 5 (accounting for the 5 nm interval)
- 0.001 (to express the output in watts rather than milliwatts).

This calculation creates values in lux (lumens /m^2) for each 5 nm interval

3. Sum these lux values over the wavelength range 380 to 770nm to calculate the total lux.
4. Divide the 5 nm SPD values (from step 2) by the total lux (from step 3) to arrive at a normalised SPD compatible with the DOE tool..

Note: Calculations made by this method produced normalised SPD values identical to those created in the DOE tool to 8 decimal places.

3.2 Relative Sky Glow Index:

The DOE Sky Glow Comparison Tool likely contains a series of matrices to predict sky glow for each 5 nm wavelength interval under a variety of scenarios. There are 48 possible scenarios with options for the distance from the city centre, the particle (or pollution) state of the atmosphere, human eye sensitivities, and the percentage of light that the luminaire emits above the horizontal. Each parameter has a choice of between 2 and 4 options.

These parameters influence sky glow not simply by changing the magnitude (as increasing the lumen output of a luminaire would do) but by influencing how much each wavelength of light will affect sky glow. Essentially a 1 x 79 element matrix is required to define the effect of a particular scenario over the DOE visible spectrum of light (380 – 770 nm).

3.2.1 Investigation:

While the macros used by the DOE tool are not open to public view their effect can be estimated by examining model outputs from a nominal light source which produces equal light at all wavelengths. In this way it is possible to derive various scenario matrices which may be combined multiplicatively to generate the relative sky glow index (RSG), the key output from the DOE Tool

Mathematically the relative sky glow index (RSG) can be expressed as.

$$\text{RSG} = \frac{\sum_{i=380}^{770} \; k(i).TSPD(i)}{\sum_{i=380}^{770} \; m(i).k(i).BSPD(i)}$$

Where: RSG is the DOE Relative Sky Glow factor for a given luminaire.
TSPD(i) is the Target luminaire's SPD value for wavelength (i)
BSPD(i) is the Baseline luminaire's SPD value for wavelength (i)
k(i), m(i) etc are the scenario matrix values for wavelength (i)
$\sum$ indicates a summation over the range of visible light, 380 nm to 770 nm in 5 nm intervals

These scenario matrices do indeed produce the relative sky glow index as generated by the DOE tool accurate to three significant figures or better. For the purposes of this study that is sufficient accuracy however if the method is identical to that used in the DOE tool the alignment should be exact. The reason this does not occur is elusive. As of writing an answer has not been found.

3.2.2 Results:

The following graphs help illustrate some fundamental aspects of sky glow that arise from the material contained in the DOE tool.

The radiant flux of sky glow (termed "Unweighted" in the DOE tool) is the basic measure from which other human eye related measures (scotopic. mesopic, photopic) can be derived. It is known that short wavelength blue light scatters most in the atmosphere due to molecular level Rayleigh scattering. However particulate Mie scattering also occurs and repeated reflections from the surroundings will further influence the spectrum of light being scattered as sky glow.

Figure 5 illustrates both theoretical Rayleigh scattering and the predicted scattering from a given scenario in the DOE tool (Near observations, Low particulate sky, 0% uplight). The result shows that while sensitivity to blue light remains important it is less extreme than would be expected from a simple Rayleigh scattering model alone.

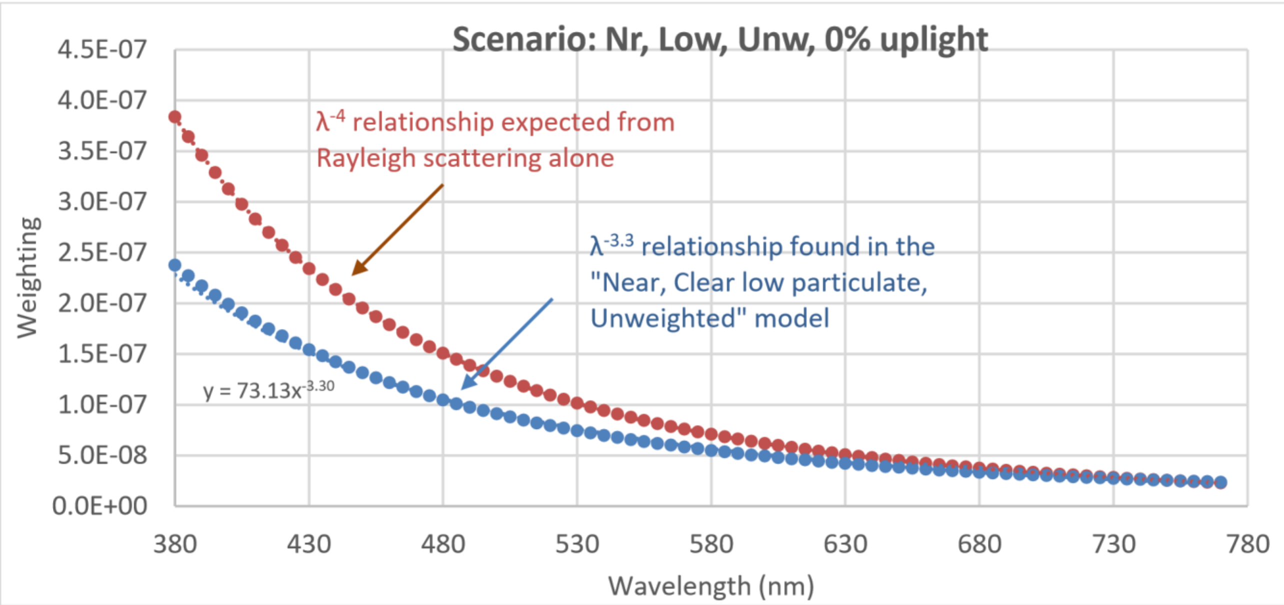


Figure 5: The radiant flux of sky glow relative to the radiant flux of the initiating light source. Sky glow from pure Rayleigh scattering at the top (red) and that for the near, low particulate scenario at the bottom (blue).

Converting the radiant flux of sky glow to a measure that has relevance to human observers requires a luminosity function (scotopic, mesopic or photopic). The scotopic weighting is available in the DOE tool but not mesopic or photopic. Both can however be calculated now that the processes of the DOE tool are better understood. The luminosity functions are shown graphically in Figure 6. Scotopic is relevant for the fully dark-adapted eye (rods), photopic is for the fully light-adapted eye (cones) and mesopic as employed here is for the partially dark-adapted eye where cones and rods are weighted equally (adaption coefficient, m=0.5).

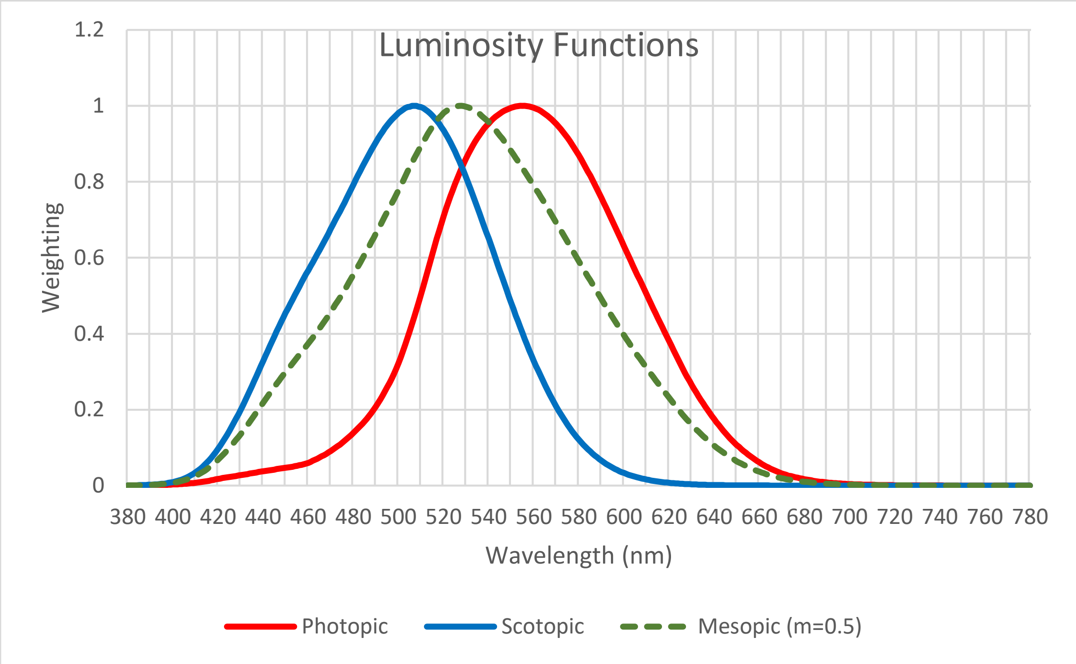


Figure 6: The CIE Scotopic, Photopic and Mesopic (m=0.5) luminosity functions. The scotopic peak is at 507 nm, photopic at 555 nm and mesopic(m=0.5) at 527 nm.

While the literature (Luginbuhl, Boley and Davis, 2014) suggests that scotopic is the most appropriate luminosity function to apply when considering human perception of a dark sky this recommendation may not be the best fit for all situations.

For observers who have been exposed to photopic levels of light indoors and go outside to view the sky for a relatively short period of time (10 minutes) their eyes will not achieve scotopic levels. Full scotopic levels typically require some 30 plus minutes of dark adaptation. Similarly, observers who have some artificial lights in their field of view may never achieve full adaptation to scotopic levels. Further foveal tasks will remain photopic regardless of adaptation. As issues such as these are still being addressed by the scientific community it is helpful to explore human eye sensitivity options for all three options: scotopic, mesopic and photopic.

Modifying the radiant flux curve by multiplying with the scotopic and the photopic luminosity functions produce the weighting functions as shown in Figures 7 and 8.

These weighting functions show which wavelengths of a luminaire's SPD output produce the most sky glow. The overall shape of the photopic and scotopic luminosity functions are preserved but are shifted to the left (blue end of the spectrum) by some 10 – 15 nm.

Finally, in Figures 9 and 10 it is possible to see how the new weighting functions help identify which wavelengths of a luminaire's output are most likely to cause sky glow.

The scotopic weighting function is shown as a red line in Figure 9. In the background the blue peak of the LED is shown as occurring at around 460 nm – a point where the red line is registering a relatively high weighting of 0.75. From this it can be seen that a substantial amount of the sky glow produced by the luminaire will come from the blue peak under scotopic weighting.

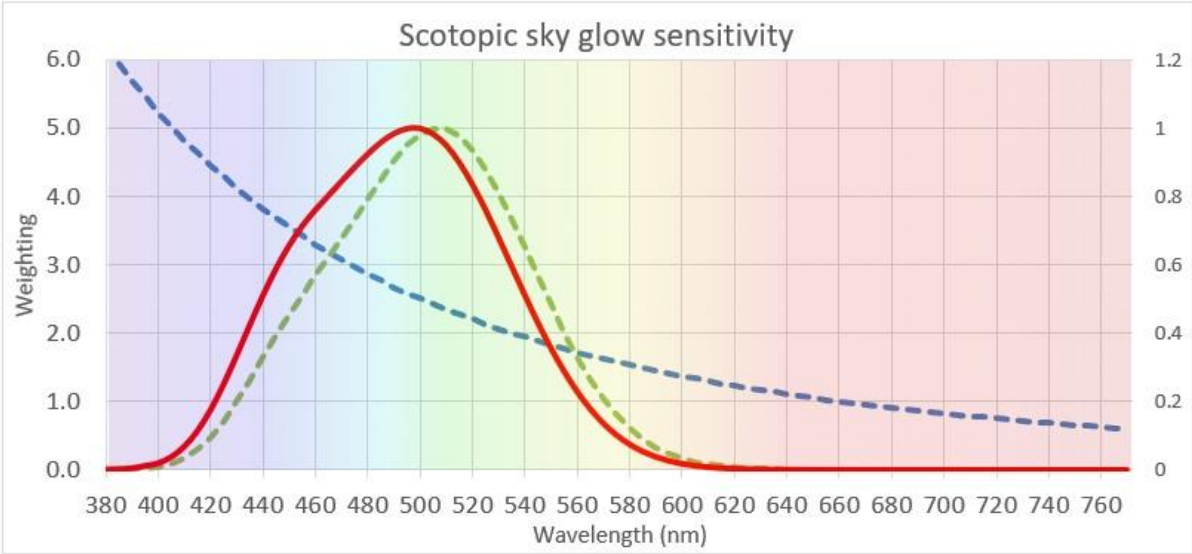


Figure 7: *A demonstration of how two separate weighting functions can be combined. The "unweighted" radiant flux curve from Figure 5 (blue, dotted line) is combined with the scotopic weighting function from Figure 6 (green dotted line) to produce a new normalised weighting function (red solid line). The new function shows the relative weighting of a luminaire's light output needed to match the sky glow seen by an observer with scotopic sensitivity.*

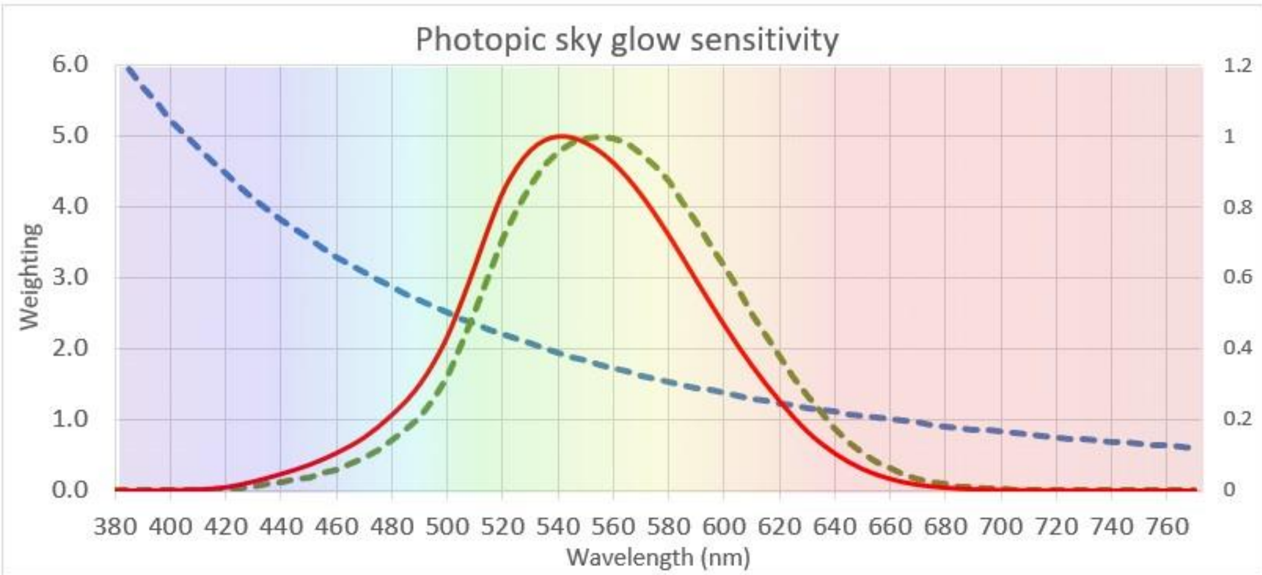


Figure 8: *A demonstration as in Figure 4 but for the photopic weighting function. The resultant normalised curve (red, solid line) shows the relative weighting of a luminaire's light needed to match the sky glow seen by a photopically sensitive instrument or eye.*

In contrast the same luminaire is shown in Figure 10 but this time with the photopic weighting function. The photopic function is less sensitive to blue light and weights the 460 nm blue peak at only 0.1. This means that under photopic vision the LED blue peak has surprisingly little impact on the total sky glow.

This exercise helps to show how visual assessments of sky glow made when the eye is still operating under photopic conditions can be quite erroneous if the assessment is for scotopic sensitivity. Blue light has a relatively small impact when viewed under photopic vision.

Similarly, it underlines the need to ensure that the criteria under which sky glow is to be assessed (photopic, mesopic, scotopic) is considered carefully because it can have a strong influence on the assessment.

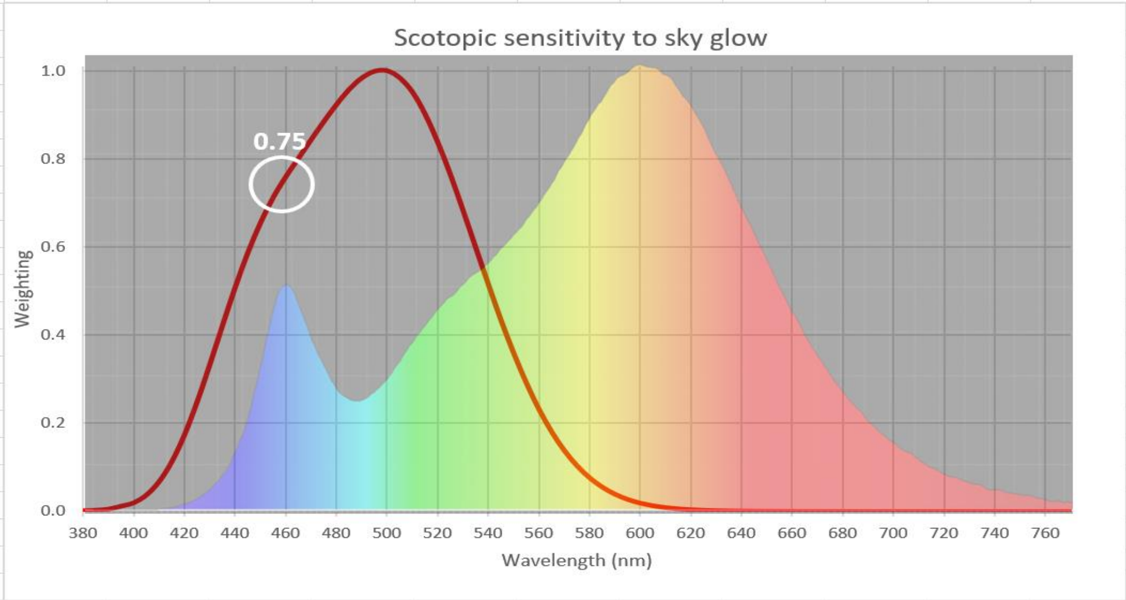


Figure 9: The composite scotopic weighting function (red line) overlaying the SPD curve for the We-ef, 3000K luminaire. Note the high 0.75 scotopic weighting given to the 460 nm blue peak.

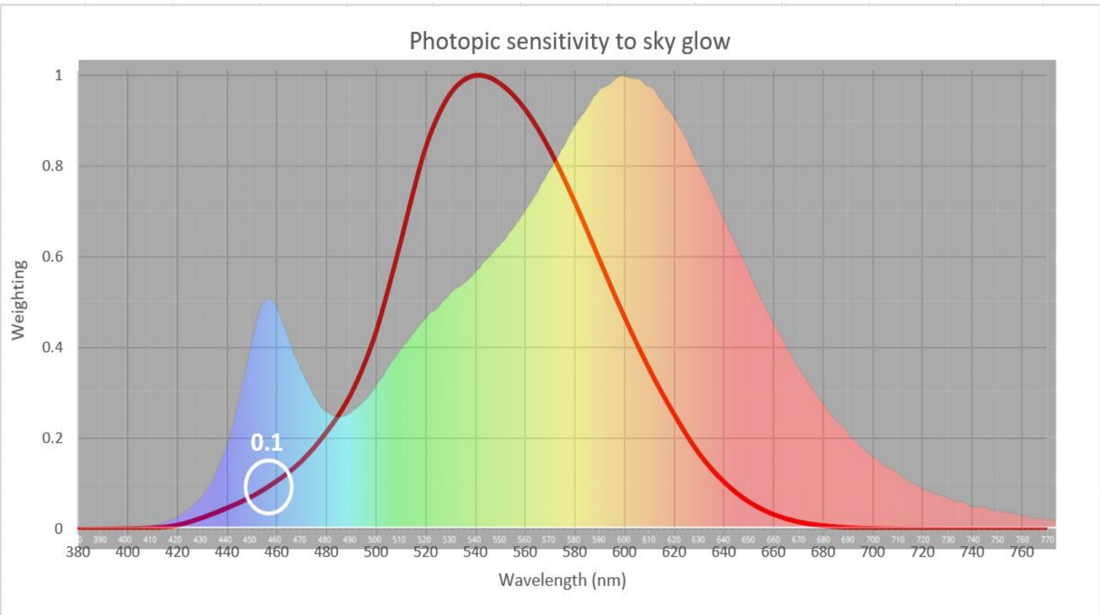


Figure 10: The composite photopic weighting function (red line) overlaying the SPD curve for the We-ef, 3000K luminaire. Note the low 0.1 photopic weighting given to the 460 nm blue peak.

4 Results - Predictors of Sky Glow

Using the DOE Sky Glow Comparison Tool methodology five common spectral indexes of luminaire light output were examined for their ability to predict the resulting sky glow.

These were:

- Corelated Colour Temperature (CCT)
- Scotopic - Photopic Ratio (S/P ratio)
- % Blue light (430 – 470 nm)
- % Blue light (400 – 500 nm)
- % Blue light (400 – 550 nm)

Four different observer sensitivities were included in the comparison:

- Scotopic
- Mesopic (m=0.5)
- Photopic
- Unweighted (a radiometric measure)

The chosen base condition was a near observer (< 10km from source), under clear low particulate skies and an HPS luminaire with 2% UWLR. (The test LED luminaires were under the same conditions but with 0% UWLR.)

The HPS baseline luminaire was chosen purely for historical reasons noting it has no effect on the correlation or the relative order of data points. Using this baseline an LED luminaire with a sky glow rating = 1 would produce the same sky glow as the HPS luminaire.

No adjustment has been made for the lower lumen output expected from LED luminaires compared to HPS luminaires as again this does not affect the correlation or order of points.

An SPD was obtained for a sample of 81 road lighting luminaires (or LED chips) from the sources shown in Table 4.

Table 4: Sample size of SPD data used in the analysis

SPD Information Source	Sample size	% of Total
DOE Sky Glow Tool	35	43%
LED Chip data	10	13%
Luminaire data	14	17%
Field spectrometer	22	27%
TOTAL	81	100%

A graphical approach has been adopted with the y axis representing the relative sky glow rating and the x axis the signal strength for the particular index being evaluated. A linear regression line displaying the equation and correlation co-efficient R^2 is also shown. A good predictor of skyglow would tend to cluster all the points along a line and therefore have a correspondingly high R^2 value.

The set of graphs for all combinations of index and observer sensitivity (20) is given in Appendix 1 and for illustrative purposes those for scotopic observer sensitivity are presented below as Figures 11 to 15.

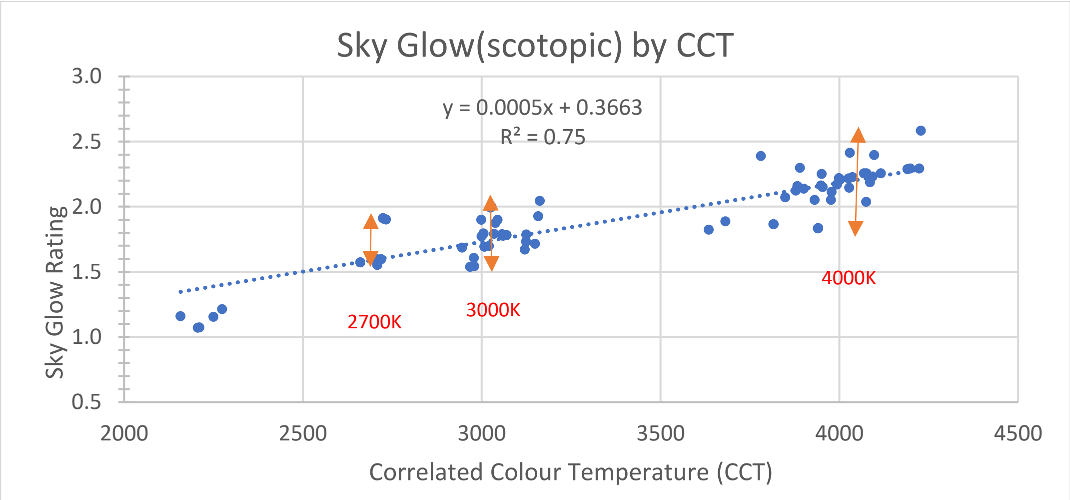


Figure 11: CCT as a predictor of scotopic weighted sky glow. Note the dispersion in the 3000K and 4000K groups and the overlap between 2700K, 3000K and 4000K groups.

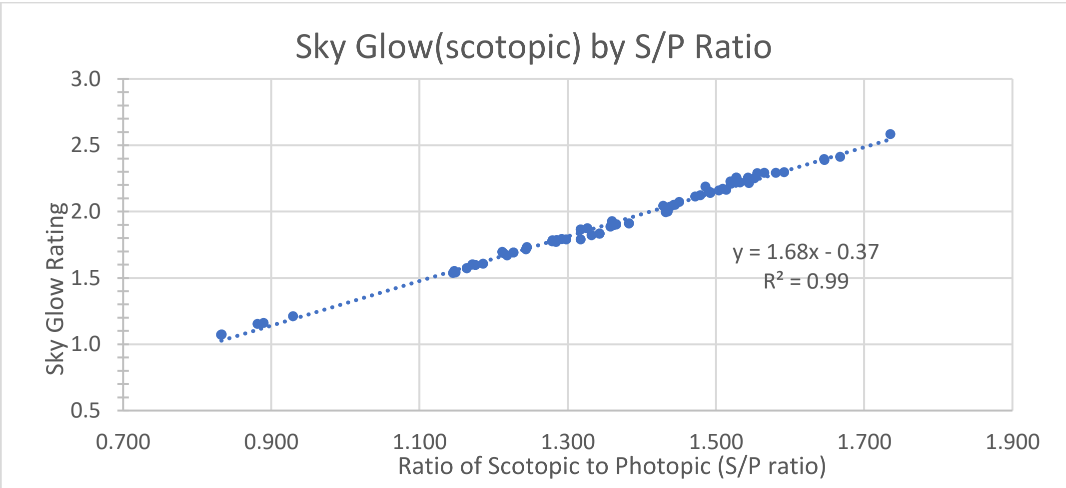


Figure 12: S/P ratio as a predictor of scotopic weighted sky glow. Tightly clustered.

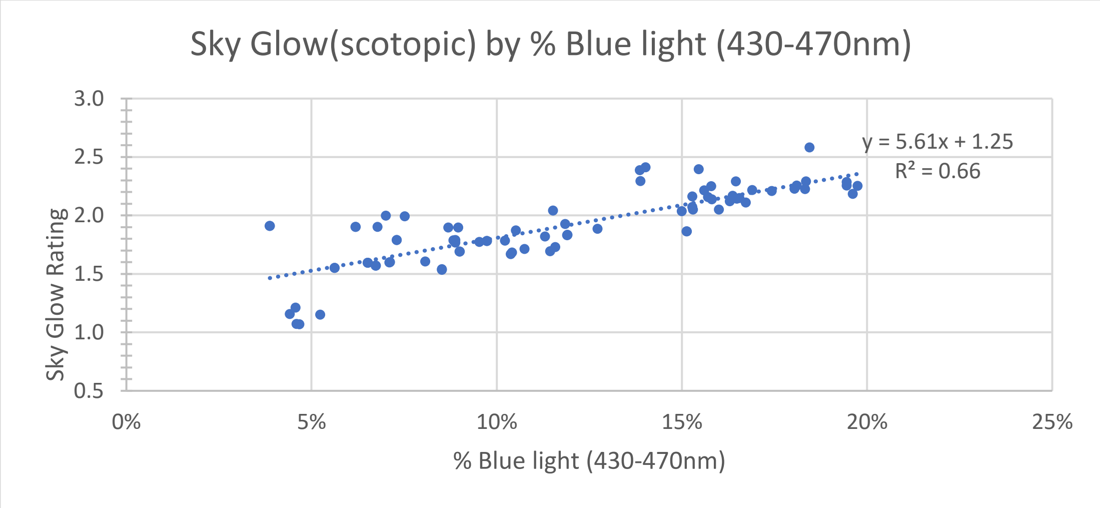


Figure 13: % Blue light (430-470 nm) as a predictor of scotopic weighted sky glow

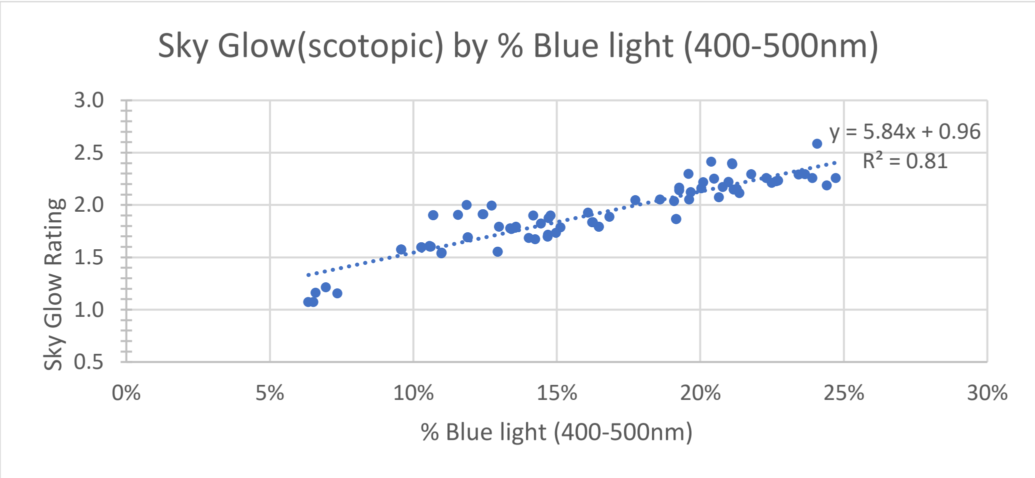


Figure 14: % Blue light (400-500 nm) as a predictor of scotopic weighted sky glow.

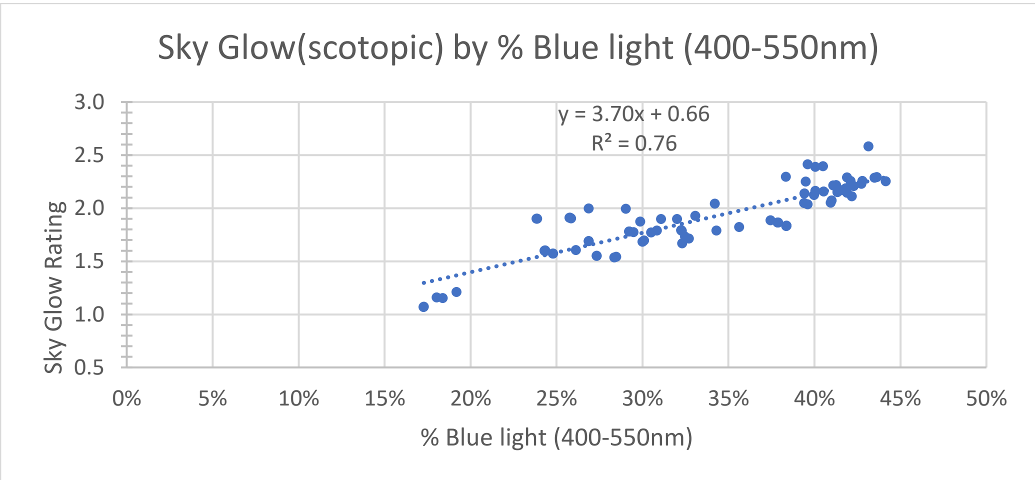


Figure 15: % Blue light (400-550 nm) as a predictor of scotopic weighted sky glow.

4.1 Summary

The values of the correlation co-efficient (R^2) data are summarised in Table 5. The best predictor (highest R^2 value) for each observer sensitivity is shown in red, the lowest in blue.

The S/P ratio has strong predictive power under all observer sensitivities and was the highest in all but the photopic.

Table 5: The correlation coefficients (R^2) from Figures A1 to A20 of Appendix 1

Index	Scotopic	Mesopic (0.5)	Photopic	Unweighted
CCT	0.75	0.80	0.92	0.37
S/P Ratio	0.99	0.99	0.89	0.64
% Blue 430-470nm	0.66	0.69	0.74	0.29
% Blue 400-500nm	0.81	0.83	0.82	0.49
% Blue 400-550nm	0.76	0.80	0.91	0.37

5 Discussion

All five of the spectral indexes studied were to some extent correlated with sky glow however some were more strongly correlated than others.

5.1 Correlated Colour Temperature, CCT:

CCT is an index of the colour of a light source as seen by human observers. It is a physiological measure based on how humans see and interpret colours using cone vision (photopic) but is not a direct measure of the light intensity by wavelength as recorded by the SPD. It is derived from the CIE (x,y) colour space and the Planckian black body locus measured in Kelvins. Since CCT is a single number, it is simpler to communicate than chromaticity or SPD, leading the lighting industry to accept CCT as a shorthand means of reporting the colour appearance of light sources.

While CCT is helpful to categorise colour appearance of a light the results from this study (Figure 11, Table 5) suggest that it is not a strong index to determine the sky glow effects of a light source. In scotopic it ranked 4th and in mesopic (m=0.5) it ranked 3rd equal out of the 5 indexes tested.

The average sky glow prediction error using the CCT index was 6.8% (maximum 28%).

The arrows in Figure 11 show a relatively wide dispersion in the sky glow rating within the groups 2700K, 3000K and 4000K – a dispersion that is not evident if the index S/P ratio is used.

5.2 S/P Ratio

The S/P ratio is the ratio of the scotopic lumens a lamp produces divided by the photopic lumens. It can be calculated by spreadsheet using SPD data, and is a common output of spectrometers and often contained in photometric reports. As the scotopic response is more sensitive to short wavelengths a light with a high S/P ratio identifies a light rich in blue/green wavelengths.

Table 5 and Figure 12 show the S/P ratio to be a strong predictor of sky glow in both the scotopic and mesopic (m=0.5). The data points in Figure 12 lie in a single line with uniform slope and a correlation co-efficient of 0.99. This is the highest R^2 value from any index and was obtained in both the scotopic and mesopic (m=0.5) sensitivities.

The average sky glow prediction error using the S/P ratio index was 1.8% (maximum 4.9%).

While the S/P ratio has gained more attention since 2010 with the CIE publication on mesopic photometry (CIE 191:2010) it still only rarely appears as a referenced index in manufactures brochures.

5.3 Percentage of blue light (430-470 nm)

As observed in Mander and Chitty, 2019 there are so many different indexes of blue light that simply referring to % blue light is a rather meaningless statement. The % blue light (430-470nm) was included here because it is referenced in the "IPWEA, 2020 specification", as being appropriate "in biologically or astronomically important areas".
It has the narrowest band width of any of the three blue light indexes referenced here representing 5 to 20% of light output and essentially selects the band width of the blue peak in LED light sources.

As seen in Table 5 it was generally a poor performer in predicting sky glow. As it identifies just the blue peak it is possibly too narrow in band width to cater for all the factors that contribute to sky glow notwithstanding it is likely well suited to identifying issues in some biologically sensitive areas.

5.4 Percentage of blue light (400-500 nm)

This analysis examines the 400-500 nm range – a range which accounts for 10% - 25% of the light emitted by a typical LED luminaire.

Figure 14 shows the % Blue (400-500 nm) to be a good but not outstanding predictor of sky glow. In Table 5 it is shown to be a better predictor than CCT in scotopic, mesopic(m=0.5) and unweighted but not as definitive as the S/P ratio in any of these.

5.5 Percentage of blue light (400-550 nm)

The blue light range 400 – 550nm was chosen as it closely aligns to the definition proposed by the International Dark Skies Association in specifying the conditions for dark sky reserves. This range accounts for 25% to 45% of the light emitted from a typical LED luminaire.

Table 5 shows the %Blue (400-550 nm) index to be an adequate but again not an outstanding predictor of sky glow. The correlation values were similar to those of the CCT index.

6 Options

6.1 Choice of Index

Given that CCT did not show as a strong index for predicting sky glow what other indexes should be considered? Three possibilities are:

S/P Ratio: The discussion in section 5 identifies the S/P ratio as being the best single index of sky glow of the indexes investigated in this study. It outperformed CCT and the three % blue light indexes by a reasonable margin.

DOE Sky Glow Tool: This tool is currently available at no cost from the US Department of Energy and produces a relative index of skyglow based on the luminaire's SPD. However, this index is not a widely used industry measure and requires some skill in its use.

CCT + S/P ratio: A third option would be to continue with the CCT index but refined by reference to the S/P ratio.

Any sky glow overlap between CCT groups could be overcome by also examining the S/P ratio of luminaires. The CCT would continue to provide light source colour information and the S/P ratio would refine the relative impact on sky glow.

As a guide to what can be expected from luminaires Table 6 provides statistical data from the study on the range and average S/P ratio for each CCT group.

Table 6: The average and range of index values found within each CCT group.

CCT Group	2200K	2700K	3000K	3500K	4000K	Total
CCT Group range	1870-2530	2530-2870	2870-3220	3220-3710	3710-4260	1870-4260
S/P average	0.87	1.24	1.28	1.35	1.51	1.35
S/P range	0.83-0.93	1.15-1.38	1.15-1.44	1.33-1.36	1.32-1.74	0.83-1.74
Sky Glow* average	1.13	1.71	1.78	1.85	2.17	1.90
Sky glow* range	1.07-1.21	1.55-1.91	1.54-2.04	1.82-1.89	1.83-2.58	1.07-2.58
Sample size	5	13	26	2	35	81

* "Sky Glow" refers to the DOE Relative Sky Glow Index for "near", "clear low particle" skies and "scotopic" sensitivity.

6.1.1 Compliance or Guidance

The chosen index could be used as an M30 compliance criterion to help ensure that luminaires on the New Zealand market meet a minimum standard of sky glow emissions however care would need to be taken in the wording to avoid downstream technical problems. New Zealand importers and manufactures have little to no influence on the spectral performance of LED chips so allowing them a range of choice is necessary to ensure New Zealand does not become excluded from important technologies

An alternative is to specify an index intended as guidance for road controlling authorities when choosing luminaires for their district.

6.1.2 Updating

The value of any sky glow index for luminaires could decline with time if it was not kept up to date. Luminaires are continually being upgraded with the latest and often more efficient LED chips, but there are no requirements to change the model name or provide updated spectral data when this happens. Often replacement LED chips will be in the same CCT group but can deliver something quite different by way of a S/P ratio and sky glow.

An alternative to maintaining a published sky glow index by luminaire might be to define a simple way that luminaires can be evaluated for sky glow potential prior to purchasing. RCAs could then run their own "fit for purpose" tests. These tests would require the numerical SPD of the luminaire to be available. Usable SPD data is not always available and in the author's experience even chip manufacturers do not always publish SPD data in a convenient numerical format. Some require time consuming require manual interpretation of relative SPD graphs like those shown in Figure 16.

The use of a field spectrometer offers an alternative pathway to short cut the process of obtaining the SPD. If a current luminaire is available (or required to be made available) a simple spectrometer test can produce the SPD in a convenient format in short time. This service could also be available at certified laboratories such as MSL, Callaghan Innovation.

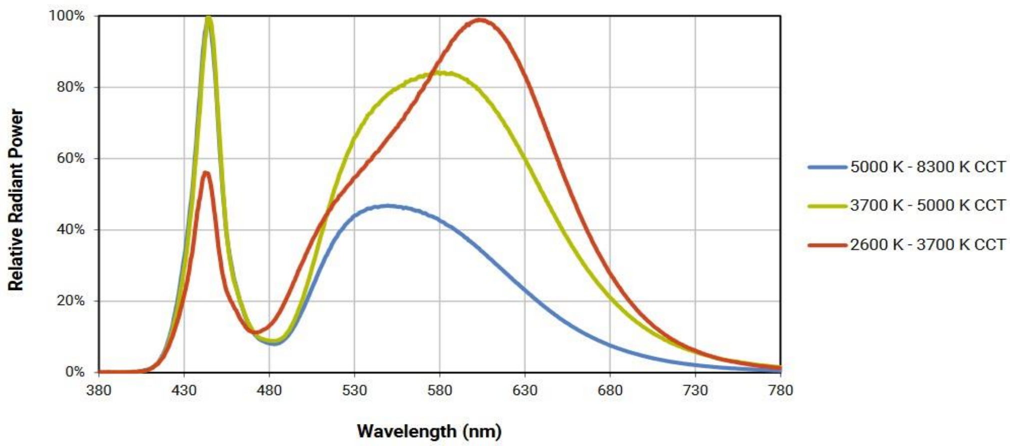


Figure 16: An example of an SPD graph produced by a LED chip manufacturer – here the relative SPD for the Cree XP-G2 chip. Note the very wide CCT bands (e.g. 3700-5000K) which have been loosely attributed to just a single CCT line.

7 Recommendations:

a) Introduce into the M30 accepted list, a criterion on the spectral content of light to limit the sky glow impact. This could take in account the findings of this report on the power of different indexes to identify sky glow.

b) Provide the guidance necessary to allow RCAs to make informed decisions on the luminaires best suited to areas where dark sky preservation is of particular interest. It is not expected that simply specifying the CCT would be sufficient.

c) As credible research becomes available provide guidance for RCAs on luminaire selection where specific wildlife issues are of particular interest. It is likely that SPD from each luminaire would be required to be able to specify such criteria.

d) Require applicants for the M30 accepted luminaires list to provide a SPD for their product and to provide updates to that SPD whenever a new series of LED chips is fitted. Consider also whether a simple graphical SPD is sufficient.

e) Require M30 applicants to provide the S/P ratio for their luminaire and again update this whenever a new series of LED chips is fitted. Note that the S/P ratio can also be determined mathematically from the SPD.

8 References

International Dark Sky Association Five Years of Satellite Images Show Global Light Pollution Increasing at a Rate of Two Percent Per Year. https://www.darksky.org/five-yearsof-satellite-images-show-global-light-pollution-increasing-at-a-rate-of-two-percent-peryear/

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Jackett, Mike and Frith, Bill (2019) “Measurement of sky glow caused by road lighting luminaires”, Internal report to NZTA

Mander, Susan and Chitty, Chris (2019) "The Measurement Blues" IEE Instrumentation and Measurement Magazine

IPWEA (2020) SLSC Model LED Public Lighting Specification

CIE 191 (2010) Recommended System for Mesopic Photometry based on Visual Performance

NZTA (2014) M30 Specification and Guidelines for Road Lighting Design

Appendix 1   Graphs of Sky glow ratings

Scotopic: Sky glow seen by an observer with fully dark-adapted eyes. [CIE (1951) V'(λ)]

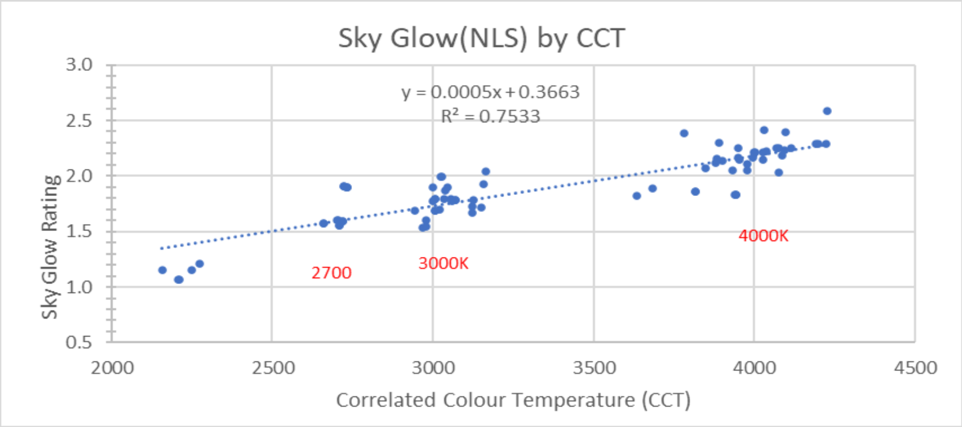


Figure A1: CCT as a predictor of scotopic weighted sky glow.

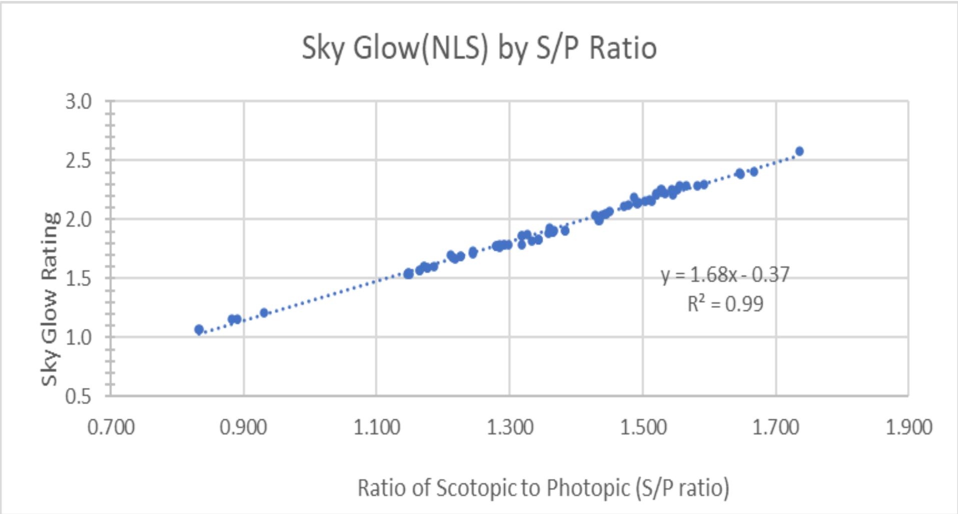


Figure A2: S/P ratio as a predictor of scotopic weighted sky glow.

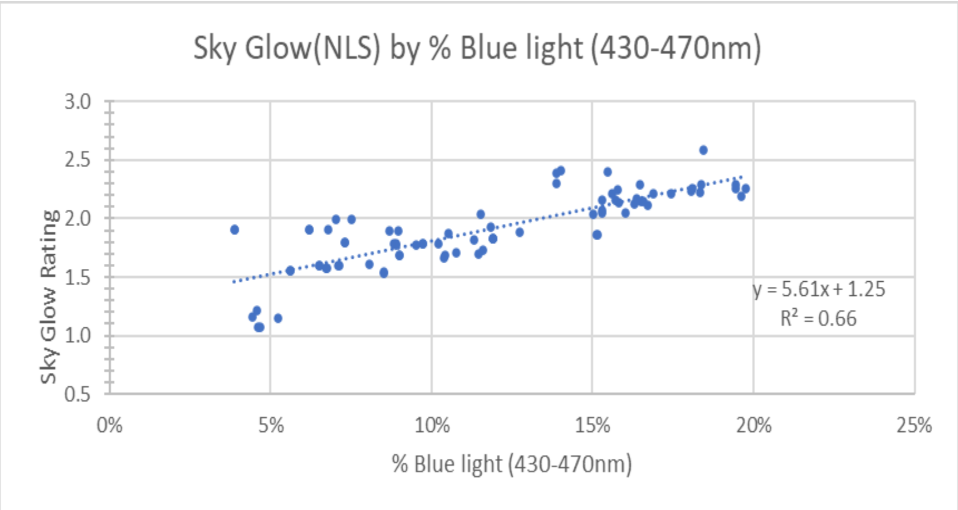


Figure A3: % Blue light (430-470 nm) as a predictor of scotopic weighted sky glow.

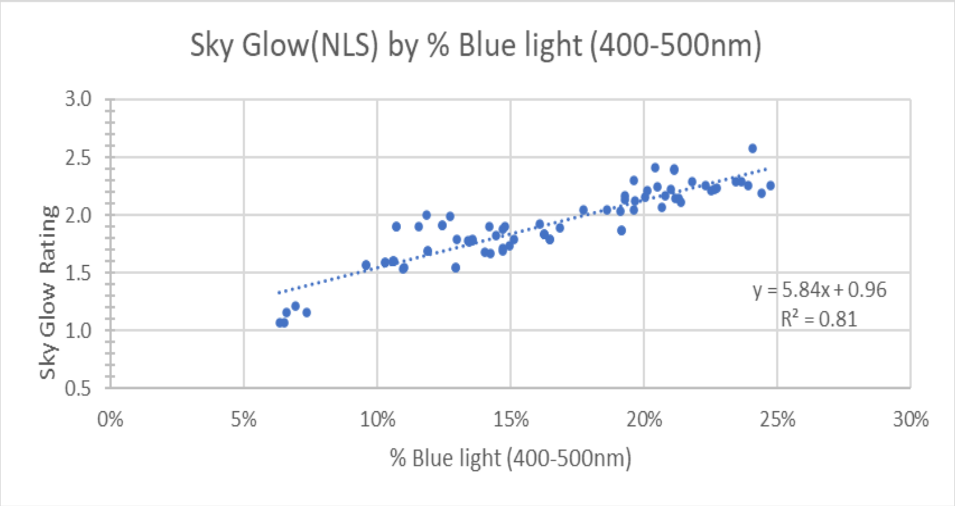


Figure A4: % Blue light (400-500 nm) as a predictor of scotopic weighted sky glow.

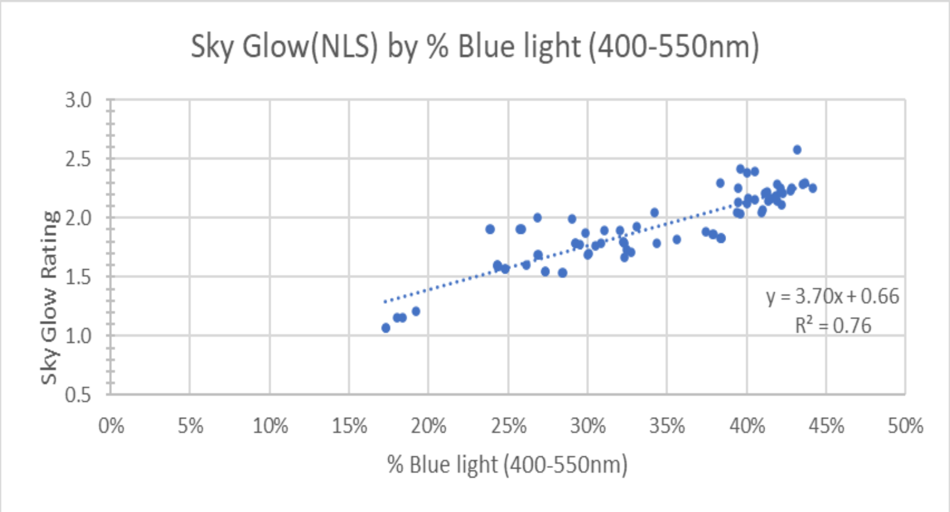


Figure A5: % Blue light (400-550 nm) as a predictor of scotopic weighted sky glow.

Mesopic: Sky glow as seen by an observer with semi dark-adapted eyes. Adaption coefficient m=0.5.

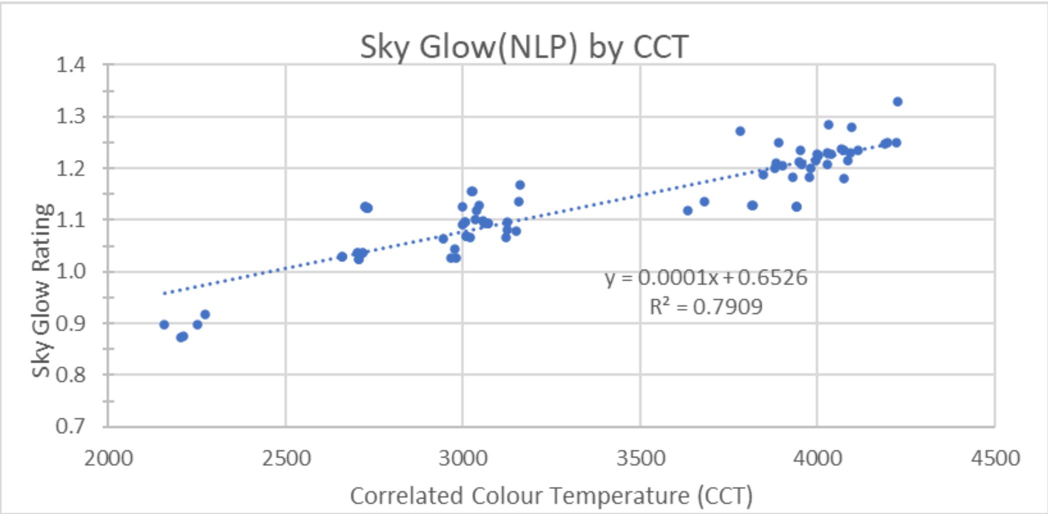


Figure A6: CCT as a predictor of mesopic weighted sky glow.

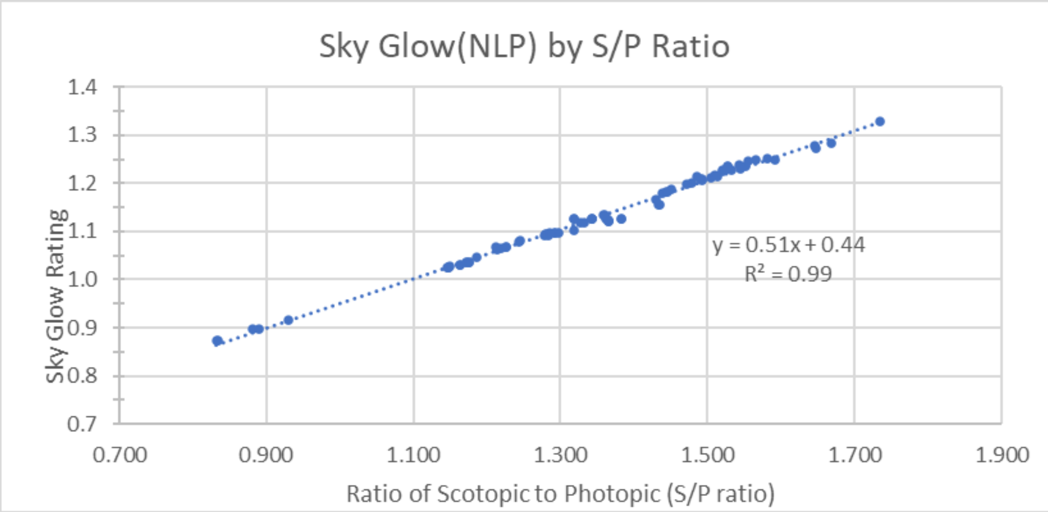


Figure A7: S/P ratio as a predictor of mesopic weighted sky glow.

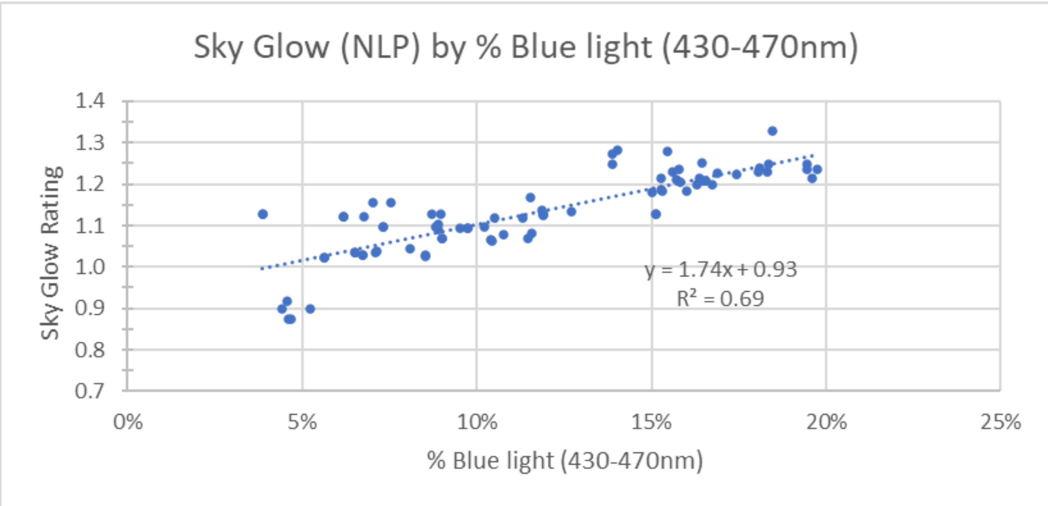


Figure A8: % Blue light (430-470 nm) as a predictor of mesopic weighted sky.

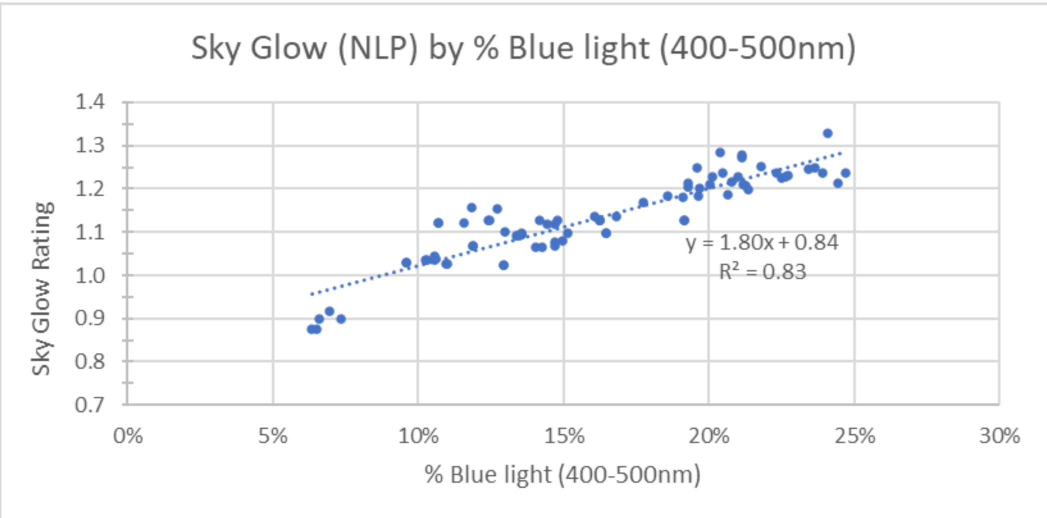


Figure A9: % Blue light (400-500 nm) as a predictor of mesopic weighted sky glow

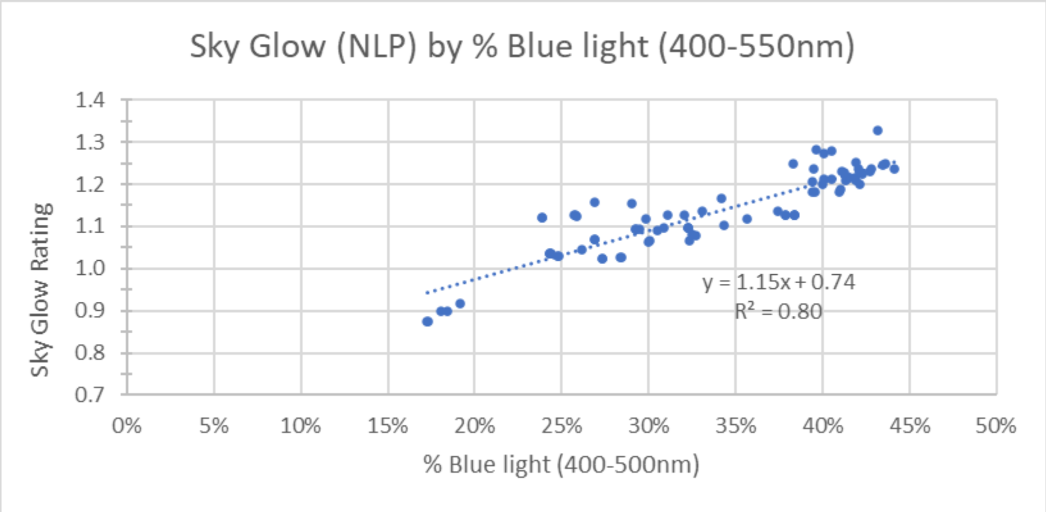


Figure A10: % Blue light (400-550 nm) as a predictor of mesopic weighted sky glow

Photopic: Sky glow as seen by an observer without dark adapted eyes. [CIE 015:2018 V(λ)]

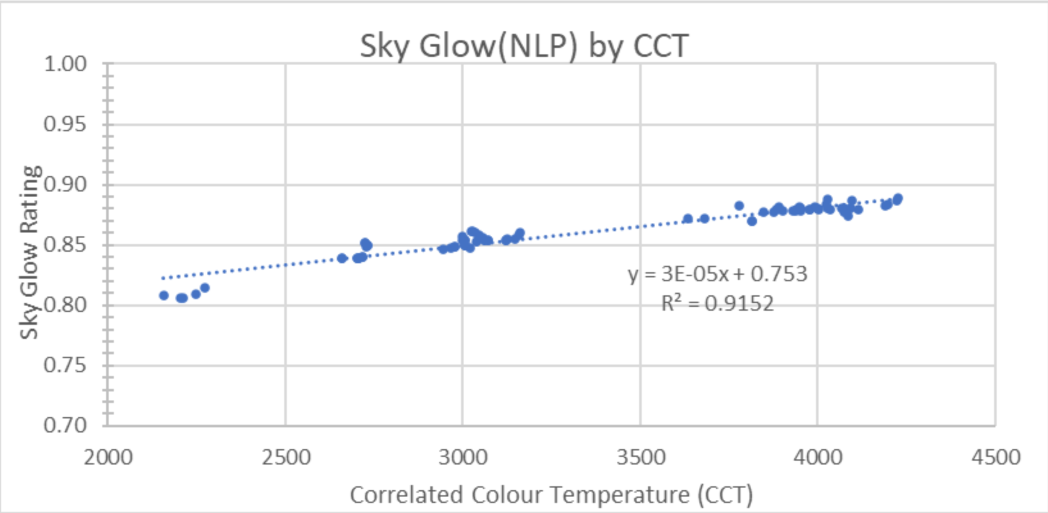


Figure A11: CCT as a predictor of photopic weighted sky glow.

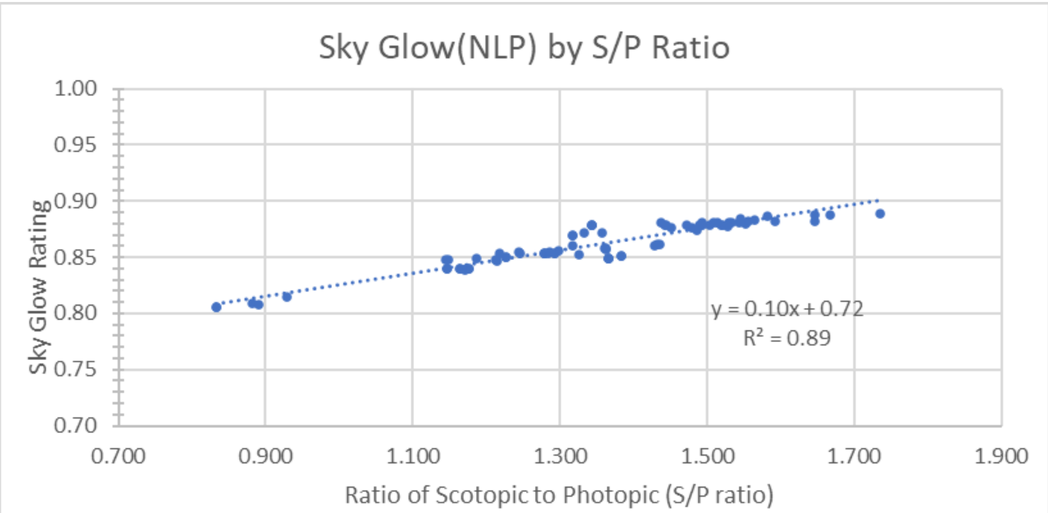


Figure A12: S/P ratio as a predictor of photopic weighted sky glow.

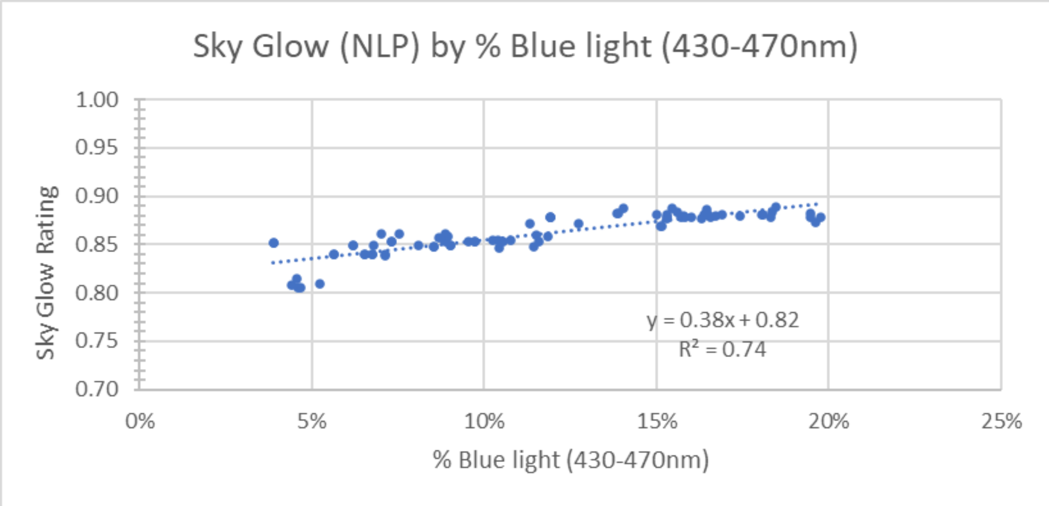


Figure A13: % Blue light (430-470 nm) as a predictor of photopic weighted sky glow

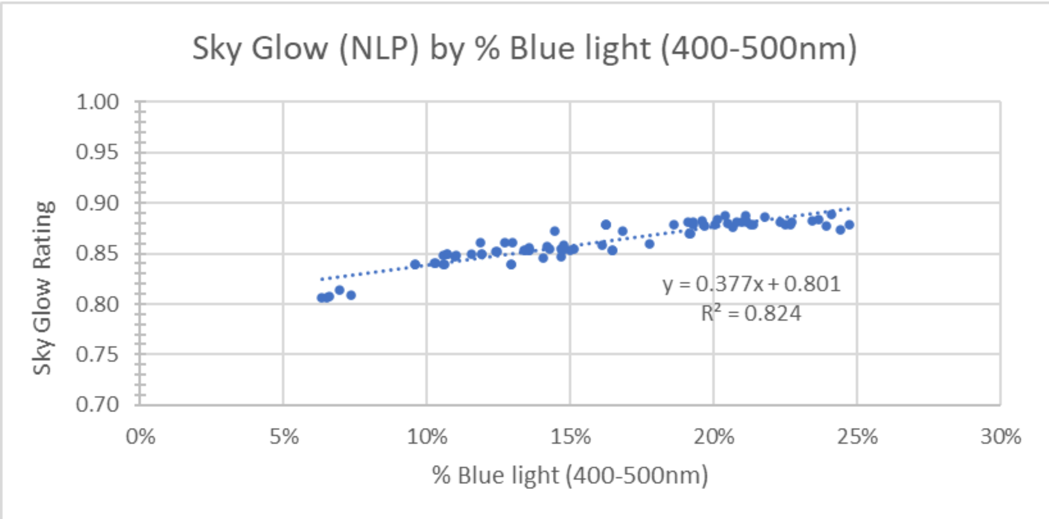


Figure A14: % Blue light (400-500 nm) as a predictor of photopic weighted sky glow

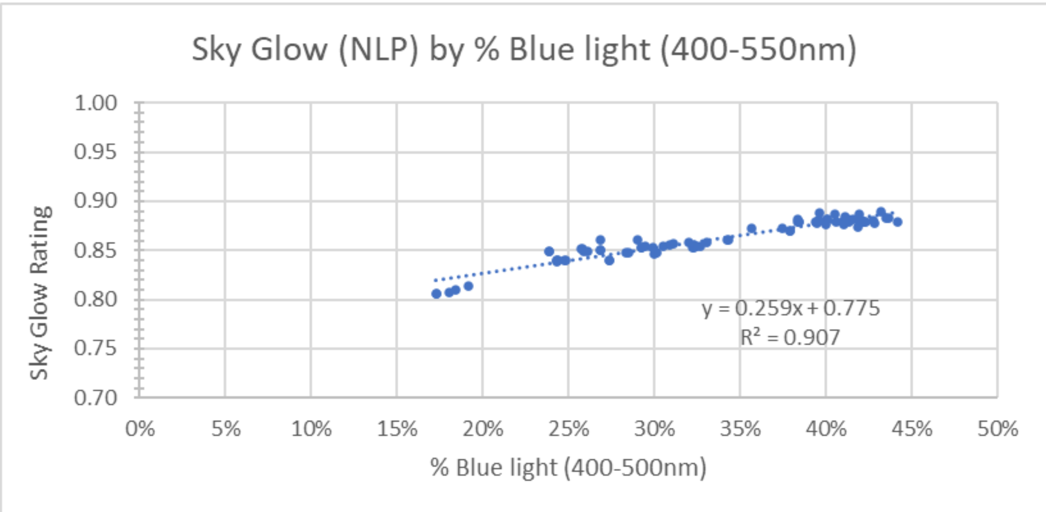


Figure A15: % Blue light (400-550 nm) as a predictor of photopic weighted sky glow.

Unweighted: The radiant flux of sky glow (Note: This is not sky glow as seen by a human observer.)

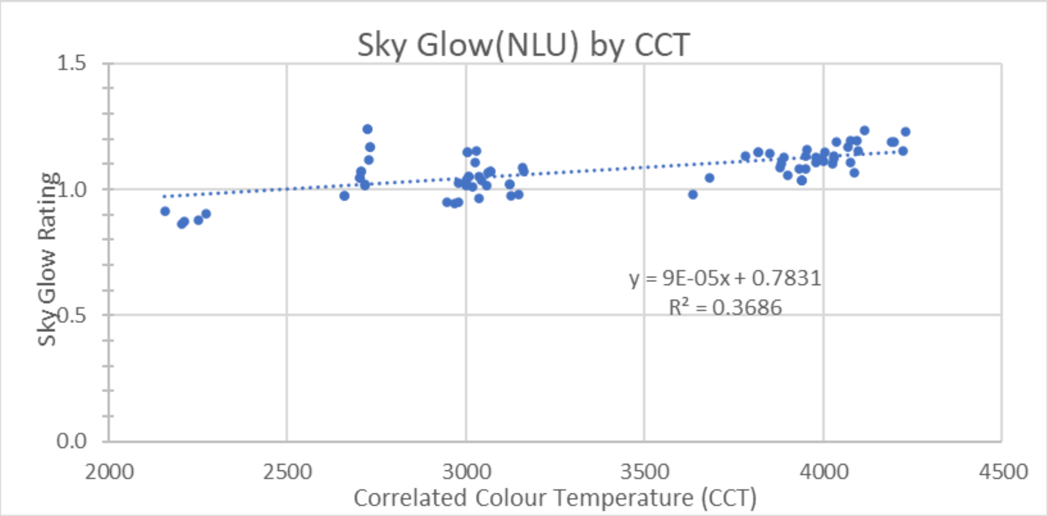


Figure A16: CCT as a predictor of the radiant flux of sky glow.

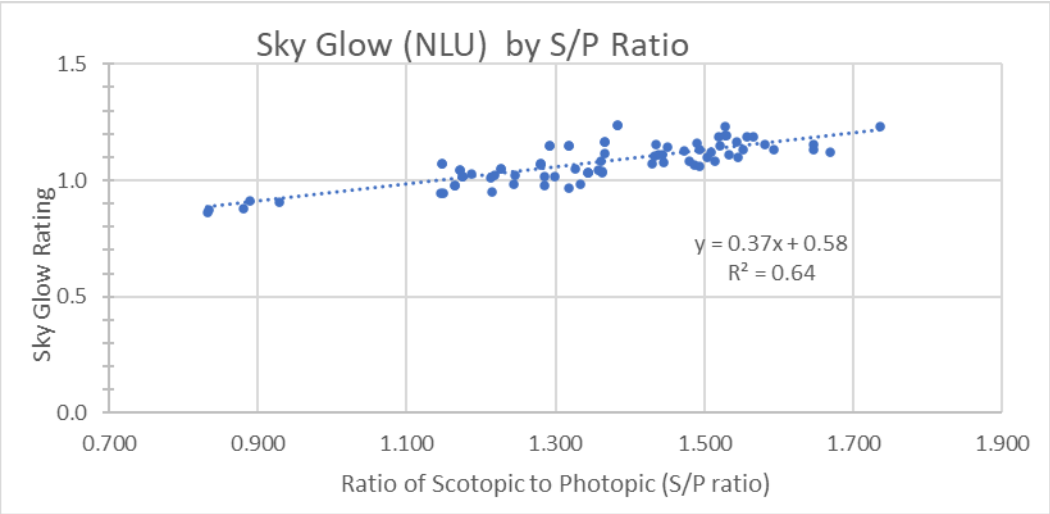


Figure A17: S/P ratio as a predictor of the radiant flux of sky glow.

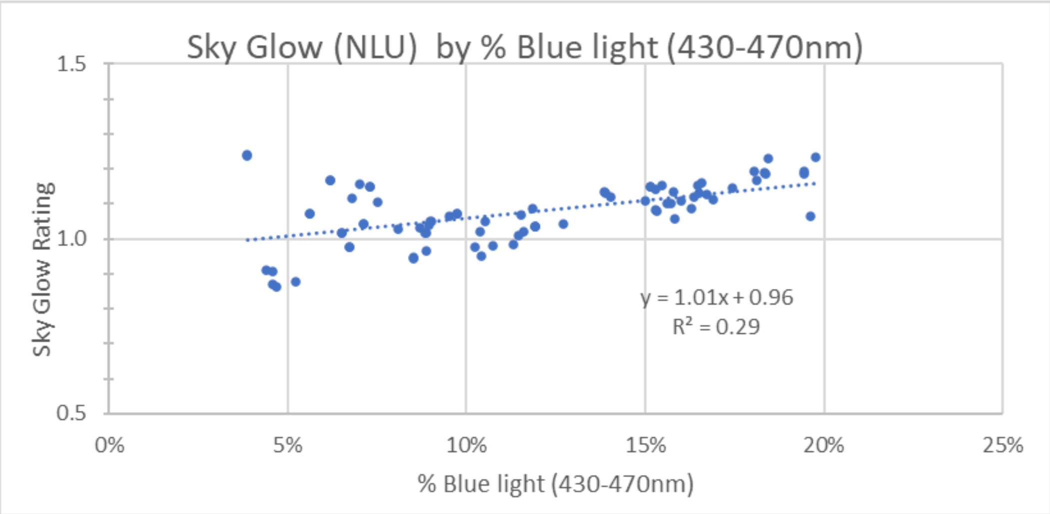


Figure A18: % Blue light (430-470 nm) as a predictor of the radiant flux of sky glow.

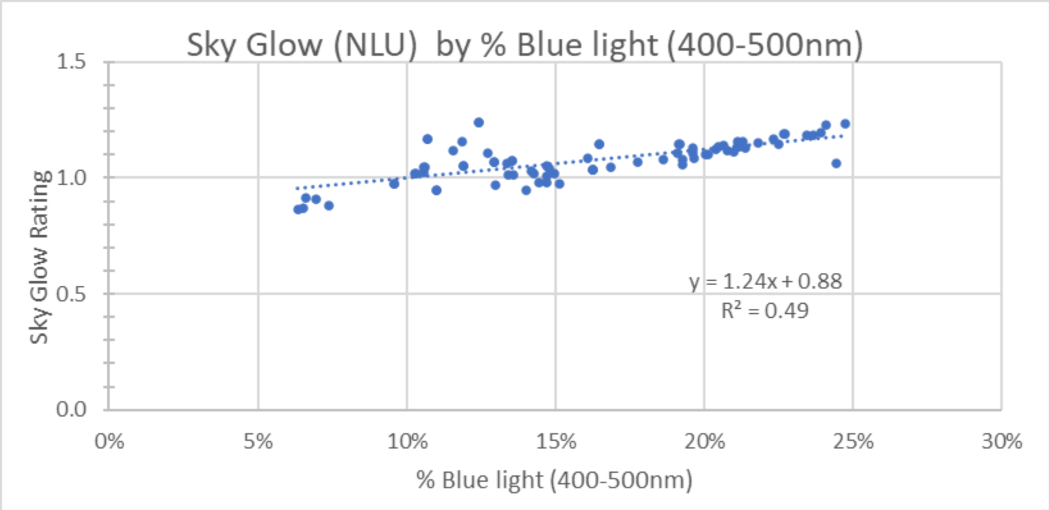


Figure A19: % Blue light (400-500 nm) as a predictor of the radiant flux of sky glow.

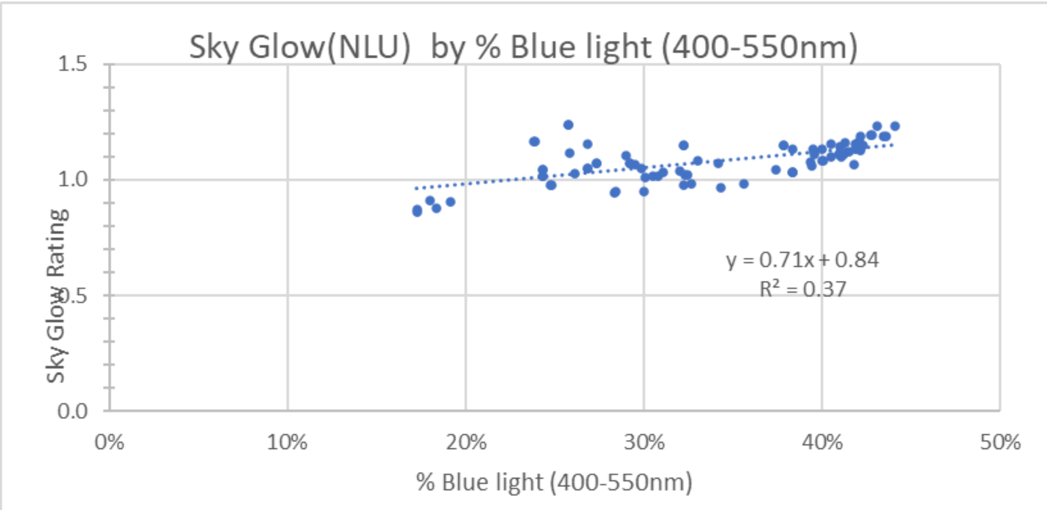


Figure A20: % Blue light (400-550 nm) as a predictor of the radiant flux of sky glow.

Appendix 2: List of data sorted by source

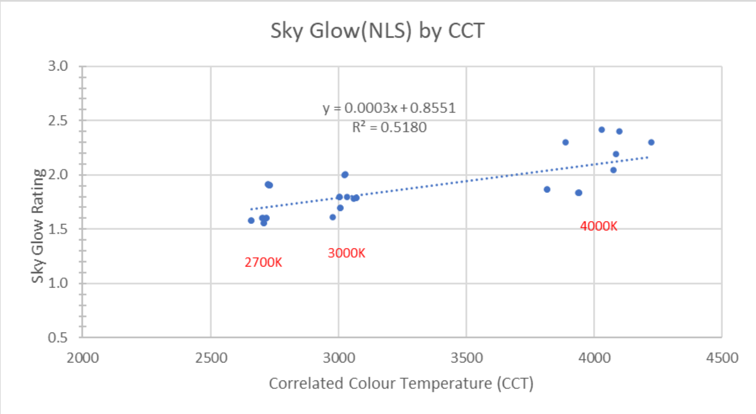
No.	Luminaire	Data source	CCT	S/P ratio	% Blue (430-470)	% Blue (400-500)	% Blue (400-550)	Sky Glow Ratio (NLS)
1	LED Example 1	DOE	2703	1.171	7%	11%	24%	1.599
2	LED Example 2	DOE	2978	1.186	8%	11%	26%	1.606
3	LED Example 3	DOE	3940	1.343	12%	16%	38%	1.832
4	LED Example 4	DOE	4098	1.646	15%	21%	41%	2.395
5	LED 2661 K	DOE	2661	1.164	7%	10%	25%	1.572
6	LED 2719 K	DOE	2719	1.176	7%	10%	24%	1.595
7	LED V Pump 3005 K	DOE	3005	1.292	7%	16%	32%	1.791
8	LED 3008 K	DOE	3008	1.227	9%	12%	27%	1.690
9	LED 3070 K	DOE	3070	1.280	10%	14%	29%	1.781
10	LED 3941 K	DOE	3941	1.343	12%	16%	38%	1.833
11	LED 3817 K	DOE	3816	1.318	15%	19%	38%	1.863
12	LED 2732 K	DOE	2732	1.366	6%	11%	24%	1.901
13	LED V Pump 2724 K	DOE	2724	1.383	4%	12%	26%	1.909
14	LED 308 PC violet p 2708K	DOE	2708	1.147	6%	13%	27%	1.551
15	LED 9 PC Blue Pump 2729K	DOE	2729	1.366	7%	12%	26%	1.902
16	LED 187 PC Blue Pump 2661K	DOE	2661	1.164	7%	10%	25%	1.572
17	LED 189 PC Blue Pump 2732K	DOE	2732	1.366	6%	11%	24%	1.901
18	LED 222 PC Blue Pump 2704K	DOE	2704	1.172	7%	11%	24%	1.600
19	LED 223 PC Blue Pump 2719K	DOE	2719	1.176	7%	10%	24%	1.595
20	LED 308 PC Violet Pump 2708K	DOE	2708	1.147	6%	13%	27%	1.551
21	LED 310 PC Violet Pump 2724K	DOE	2724	1.383	4%	12%	26%	1.909
22	LED 6 Phosphor Blue Pump	DOE	3025	1.433	8%	13%	29%	1.992
23	LED 107 Hybrid 3035K	DOE	3035	1.318	9%	13%	34%	1.789
24	LED 189 Phosphor Blue 3008K	DOE	3008	1.227	9%	12%	27%	1.690
25	LED 190 Phosphor Blue 3028K	DOE	3028	1.435	7%	12%	27%	1.998
26	LED 211 Phosphor Blue 3060K	DOE	3060	1.279	10%	13%	29%	1.774
27	LED 271 Phosphor Blue 3070K	DOE	3070	1.280	10%	14%	29%	1.781
28	LED 309 PC Violet Pump 3005K	DOE	3005	1.292	7%	16%	32%	1.791
29	LED 191 3817K	DOE	3817	1.318	15%	19%	38%	1.863
30	LED 200 3890K	DOE	3890	1.592	14%	20%	38%	2.296
31	LED 231 4224K	DOE	4224	1.581	16%	22%	42%	2.290
32	LED 262 4086K	DOE	4086	1.486	20%	24%	42%	2.186
33	LED 284 3941K	DOE	3941	1.343	12%	16%	38%	1.833
34	LED 285 4075K	DOE	4075	1.438	15%	19%	40%	2.035
35	LED 294 4030K	DOE	4030	1.668	14%	20%	40%	2.412
36	CitizenCOB_2200K	Chip M	2211	0.834	5%	7%	17%	1.071
37	CREE XP_E 4	Chip M	3951	1.552	16%	20%	39%	2.250
38	Cree XP-E 3	Chip M	3038	1.327	11%	15%	30%	1.873
39	Cree XPG2 4	Chip M	3931	1.445	15%	19%	39%	2.049
40	Cree XPG2 3	Chip M	3000	1.284	9%	13%	31%	1.769
41	Cree XPG3 4	Chip M	4028	1.493	16%	21%	42%	2.144
42	Cree XPG3 3	Chip M	3057	1.298	9%	14%	31%	1.788
43	Nichia NFSW757H-V1	Chip M	2945	1.214	10%	14%	30%	1.684

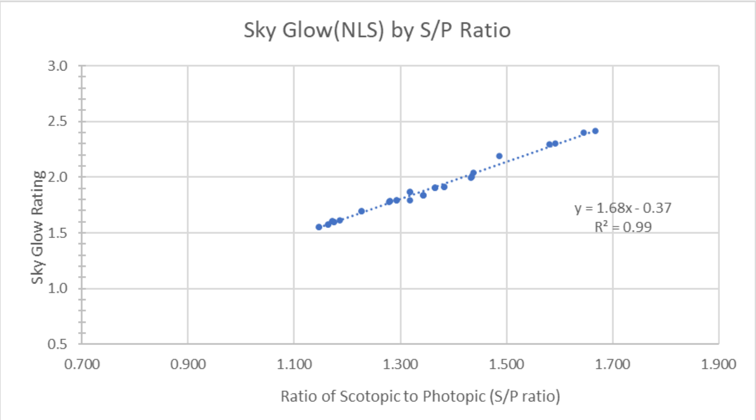
No.	Luminaire	Data source	CCT	S/P ratio	% Blue (430-470)	% Blue (400-500)	% Blue (400-550)	Sky Glow Ratio (NLS)
44	Nichia NV4WB35AM	Chip M	*3883*	1.504	16%	20%	41%	2.157
45	Nichia NV4WB35AM R8000	Chip M	*2999*	1.363	9%	14%	31%	1.897
46	LM_01	Luminaire M	3949	1.514	15%	19%	40%	2.162
47	LM_02	Luminaire M	2968	1.146	9%	11%	28%	1.536
48	LM_03	Luminaire M	2250	0.882	5%	7%	18%	1.152
49	LM_04	Luminaire M	2274	0.930	5%	7%	19%	1.211
50	LM_05	Luminaire M	3979	1.472	17%	21%	42%	2.112
51	LM_06	Luminaire M	3149	1.244	11%	15%	33%	1.714
52	LM_07	Luminaire M	2979	1.149	9%	11%	28%	1.541
53	LM_08	Luminaire M	3163	1.429	12%	18%	34%	2.042
54	LM_09	Luminaire M	3125	1.285	10%	15%	32%	1.784
55	LM_10	Luminaire M	*3045*	1.363	9%	15%	32%	1.897
56	LM_11	Luminaire M	*4199*	1.565	18%	24%	44%	2.291
57	LM_12	Luminaire M	*3781*	1.647	14%	21%	40%	2.388
58	LM_13	Luminaire M	*3121*	1.219	10%	14%	32%	1.669
59	LM_14	Luminaire M	*3849*	1.451	15%	21%	41%	2.071
60	Sp_01	Spectrometer	3878	1.479	16%	20%	40%	2.122
61	Sp_02	Spectrometer	3999	1.533	17%	21%	41%	2.218
62	Sp_03	Spectrometer	4116	1.528	20%	25%	44%	2.254
63	Sp_04	Spectrometer	4093	1.529	18%	23%	43%	2.229
64	Sp_05	Spectrometer	4191	1.556	19%	23%	43%	2.287
65	Sp_06	Spectrometer	4003	1.521	17%	22%	42%	2.209
66	Sp_07	Spectrometer	4076	1.528	19%	24%	43%	2.255
67	Sp_08	Spectrometer	3635	1.333	11%	14%	36%	1.821
68	Sp_09	Spectrometer	3954	1.491	17%	21%	41%	2.150
69	Sp_10	Spectrometer	4037	1.520	18%	23%	42%	2.225
70	Sp_11	Spectrometer	3977	1.443	16%	20%	41%	2.050
71	Sp_12	Spectrometer	4069	1.543	18%	22%	42%	2.255
72	Sp_13	Spectrometer	3682	1.358	13%	17%	37%	1.886
73	Sp_14	Spectrometer	3158	1.360	12%	16%	33%	1.926
74	Sp_15	Spectrometer	4026	1.545	16%	20%	41%	2.214
75	Sp_16	Spectrometer	4228	1.736	18%	24%	43%	2.582
76	Sp_17	Spectrometer	3124	1.245	12%	15%	32%	1.730
77	Sp_18	Spectrometer	3994	1.510	16%	21%	42%	2.169
78	Sp_19	Spectrometer	3901	1.493	16%	19%	39%	2.138
79	Sp_20	Spectrometer	2206	0.833	5%	6%	17%	1.069
80	Sp_21	Spectrometer	*2158*	0.890	4%	7%	18%	1.158
81	Sp_22	Spectrometer	*3020*	1.212	11%	15%	30%	1.695

Appendix 3: Scotopic sky glow graphs by SPD data source.

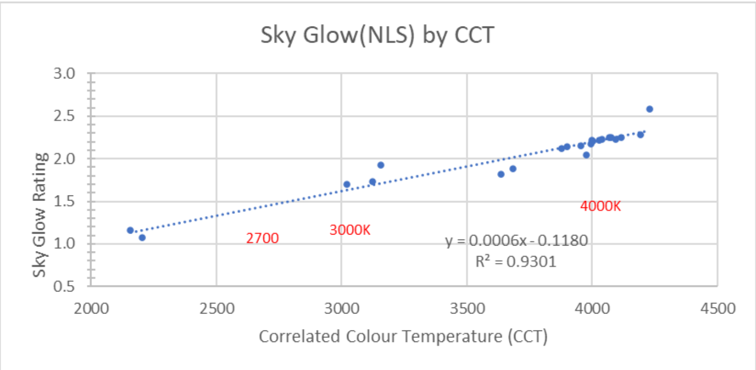
Information only. A check on result consistency between the four SPD data sources.

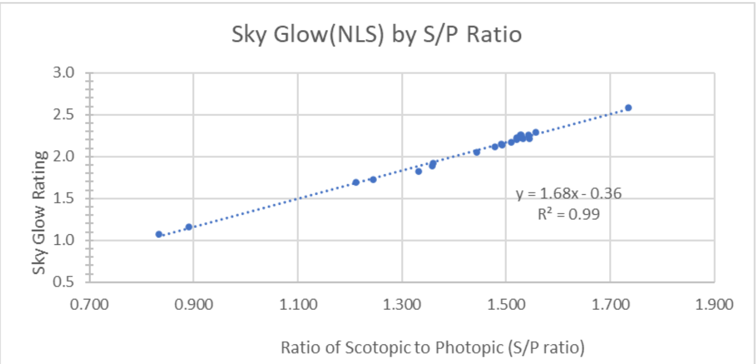
DOE Sky Glow Comparison Tool (n=35):



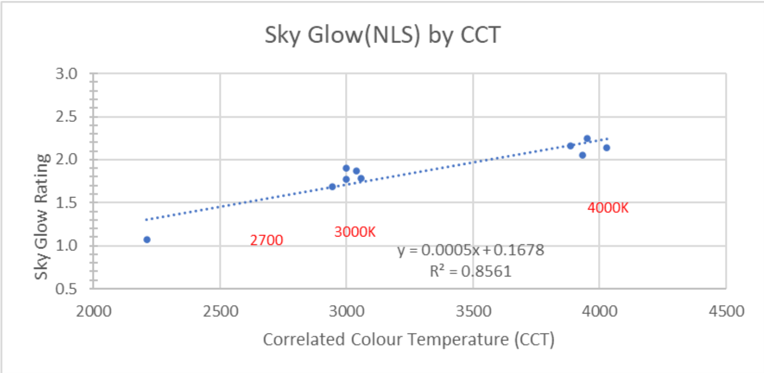


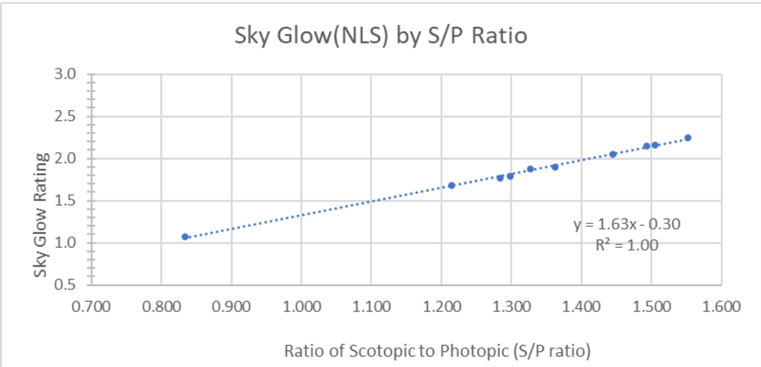
Field Spectrometer (n=22):





SPD from LED Chip Manufacturers (n=10):





SPD from Luminaire Manufacturers (n=14):