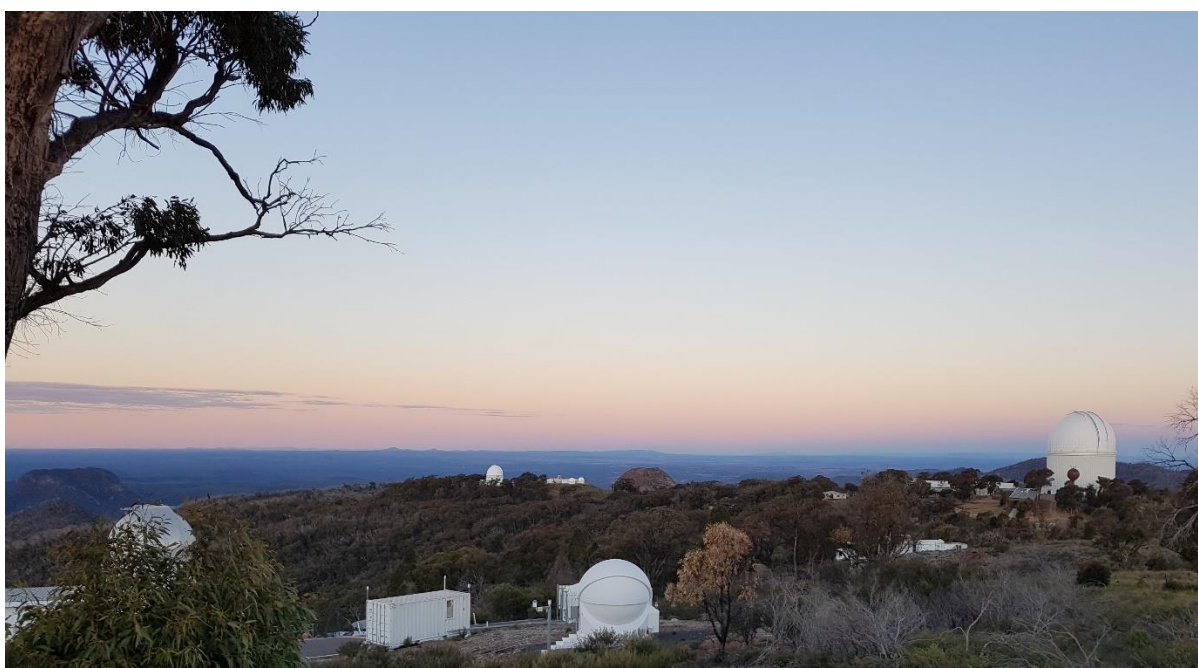


Light Impact Assessment: Vickery Extension Project



Prepared by Light Naturally
for Whitehaven Coal

November 2019

Authors

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Some of the lighting inventory data has been provided by Essential Energy and Whitehaven Coal

Disclaimer:

The authors have endeavoured to present clear and sound guidance on predicting the level of sky glow for a yet to be developed mine site. The information provided herein is being supplied in good faith based on information which we believe, but do not guarantee, to be accurate or complete, however we are not responsible for errors or omissions that may occur nor accept any liability associated with its use.

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Executive Summary

A summary of findings related to the measurement and calculation of the impact of the Vickery Project to dark sky conditions in the region of the Siding Spring Observatory is as follows:

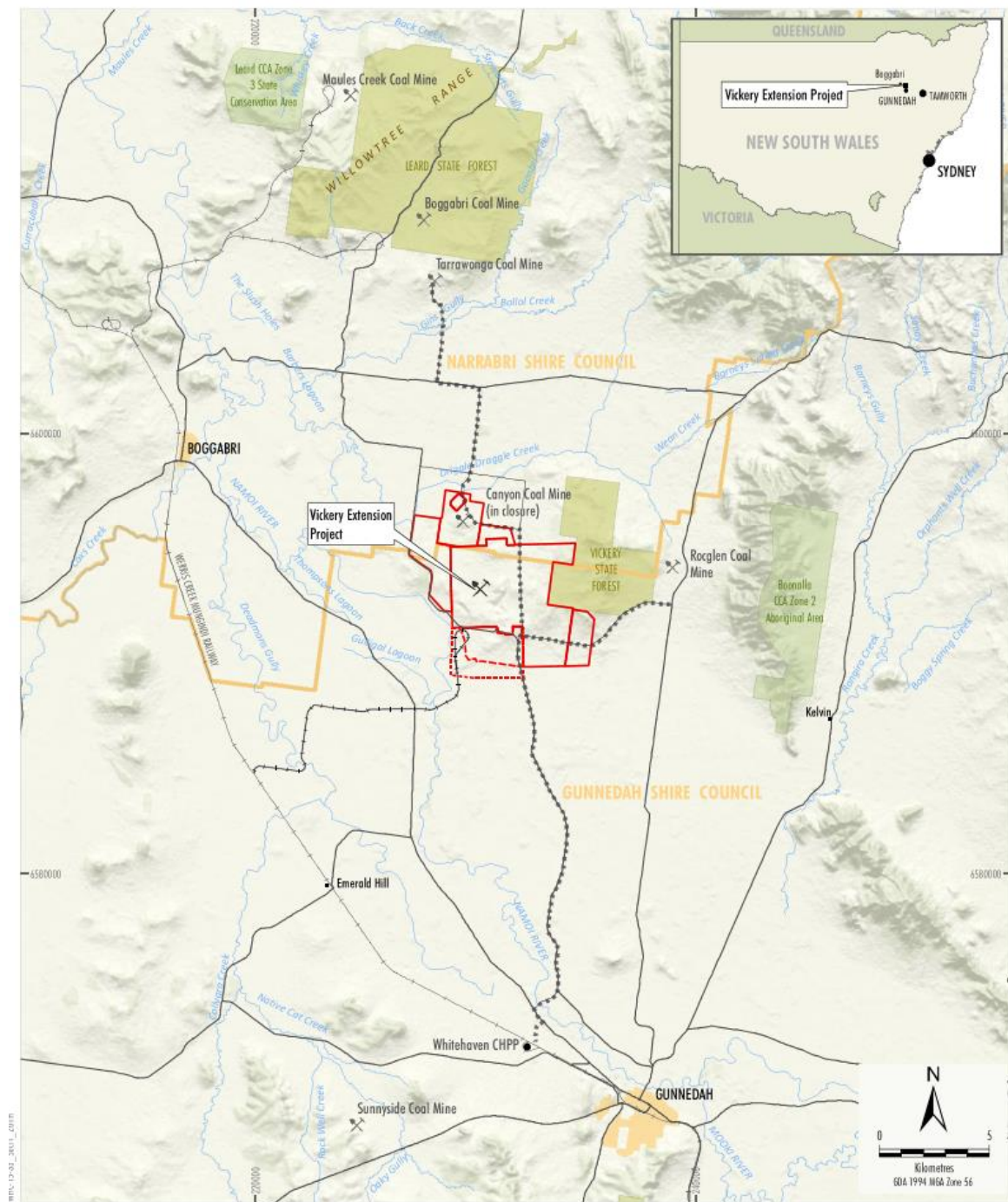
- Light from existing anthropogenic sources (Boggabri township, Boggabri mine, Tarrawonga mine and Maules Creek mine) that are comparable to the proposed project in size and distance from the Observatory were measured and determined to comply with the Dark Sky Planning Guideline.
- Analysis demonstrated that sky luminance above the Maules Creek mine and the Boggabri region was below the specified threshold level of natural background plus 10% at 30° above the horizon.
- Therefore, all evidence indicates that the Vickery Project will comply with a lighting installation equivalent to that of the Maules Creek mine. That is:
 - The expected total lumen output from the Vickery Project (including Vickery Extension Project) is estimated at 6,960,000 lumens, based on the similar installation at Maules Creek Mine.
 - With an upper estimate of 24% of the total lumen output, the upward light output (comprising of upcast light direct from the luminaires and the indirect light reflected from the ground and other surfaces), is expected to be no more than 1,670,000 lumens.
 - Utilisation of High Pressure Sodium lamps which have a correlated colour temperature of around 2,200K.

Based on the measurements conducted, it is evident that the proposed project will comply with the Dark Sky Planning Guideline if it is consistent in its lighting output with that of the Maules Creek Mine.

The client has stated that lighting specifications for the Vickery project will include a requirement that the lighting must be “Dark Sky compliant”.

Introduction

The Vickery Extension Project is a proposed expansion to the approved Vickery Coal Project, located with the Gunnedah and Narrabri local regions, as shown in Figure 1 below.



- LEGEND**
- Mining Tenement Boundary (ML and CL)
 - Exploration Licence Boundary (EL)
 - Mining Lease Application (MLA)
 - Local Government Boundary
 - State Forest
 - State Conservation Area, Aboriginal Area
 - Major Roads
 - Railway
 - Approved Road Transport Route
 - Indicative Project Rail Spur

Source: LPMA - Topographic Base (2010); NSW Department of Industry (2015)

WHITEHAVEN COAL
VICKERY EXTENSION PROJECT
Project Location

Figure 1-2

Figure 1: Proposed Project Site

This report has been prepared in response to a request from the Siding Spring Observatory (SSO) for computation of the predicted impact of light emissions from the Vickery Project, the combination of the approved Vickery Coal mine and proposed Vickery Extension (hereafter called the 'Vickery project'), on the night sky above SSO. In particular, the request seeks quantification of light emissions from the proposed project in relation to the threshold specified in Section 3.3 of the [Dark Sky Planning Guideline](#), which states:

"At the Observatory, a threshold figure of 10 per cent of the natural sky glow at 30 degrees above the horizon has been adopted as the maximum tolerable level of artificial light"

In order to address this request with respect to the guideline, this report quantifies the following components of sky glow observed from the reference point of Siding Spring Observatory:

1. The baseline level of natural sky glow in the region surrounding the proposed project
2. The current level of sky glow due to existing artificial light sources in the region
3. The predicted contribution to existing sky glow due to the proposed lighting for the Vickery project

Background: Location Details

With respect to the Siding Spring Observatory, the Vickery Project lies approximately 120km to the NE (~63° East of North). Figure 2 shows the relative location of the proposed project with respect to the Observatory, on a map that also presents an overlay of the radiance of the area at night as observed by NASA's satellite imaging system, Visible Infrared Imaging Radiometer Suite (VIIRS). This figure also highlights the existing anthropogenic light sources in the region surrounding the proposed project site.

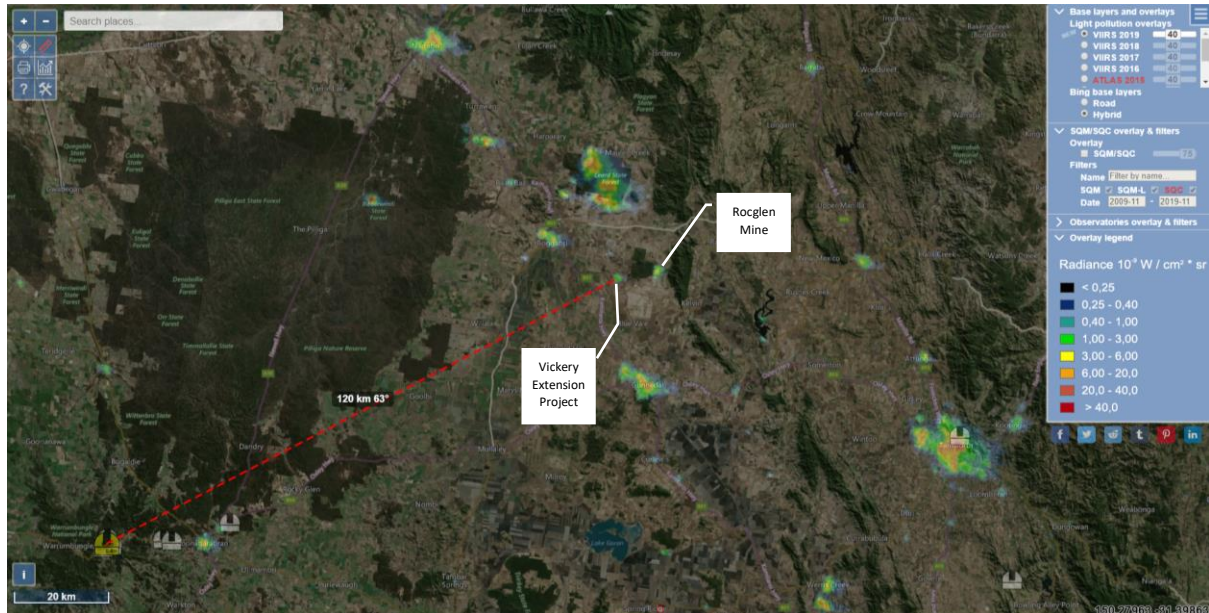


Figure 2: VIIRS Overlay of Region, showing SSO and relative location of proposed Vickery Extension Project

Figure 2 indicates a small light source at the location of the proposed project site. This is currently a base for the trucking of coal operations, which will be moved from the site. The map also shows a light source to the east of the proposed site, identified as Rocglen Mine. Rocglen Mine recently closed down for mining purposes. The authors have been informed that current remediation activity at this site is during daylight hours only. The VIIRS image in Figure 2 predates this change in night-time activity.

Boggabri township, Boggabri Mine, Tarrawonga Mine and Maules Creek Mine are the significant sources of electric light in the region of interest. These four sources are the dominant anthropogenic light sources in the area adjacent to the Vickery project and are within a similar distance (100 – 130 km) from the Observatory and within approximately 10° azimuth range of each other as observed from the SSO. Further afield are the townships of Gunnedah and Narrabri. These sources of light, their location and bearing from the SSO is listed in Table 1.

Table 1: Anthropogenic Light Sources listing distance and bearing from the SSO, in the region of the Vickery Project Site

Town	Distance (km)	Azimuth (°)
Narrabri	122	32
Maules Creek Mine	129	52
Boggabri Township	110	55
Boggabri Mine	129	55
Tarrawonga Mine	129	55
Proposed Vickery Extension Site	120	63
Gunnedah	115	74

Figure 3 shows a magnified view of the four key (highlighted) sources on the VIIRS map. Shown on this figure is the region corresponding to each source, and the arrow indicates the direction of SSO.

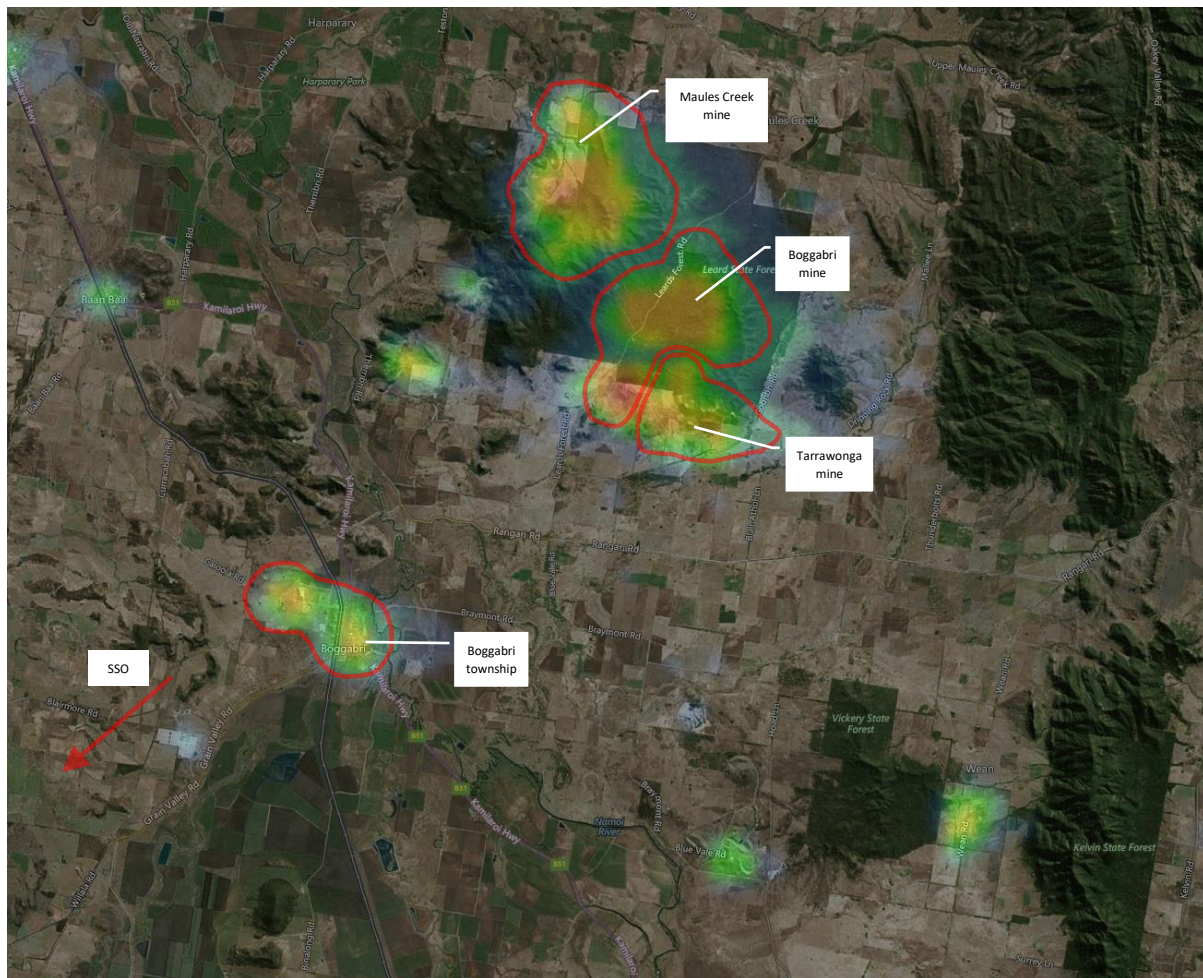


Figure 3: Magnified view of VIIRS map showing existing light sources (Boggabri and Maules Creek) near the Vickery project

When viewed from the SSO, as shown in Figure 4, the upwards light from Boggabri township and Boggabri and Tarrawonga Mines overlap (i.e. the source boundaries are indistinct), so these three anthropogenic sources are referred to jointly as the “Boggabri region”. The upwards light originating from Maules Creek Mine, Figure 5, is distinct from the “Boggabri region” source and is separately referred to as “Maules Creek”.

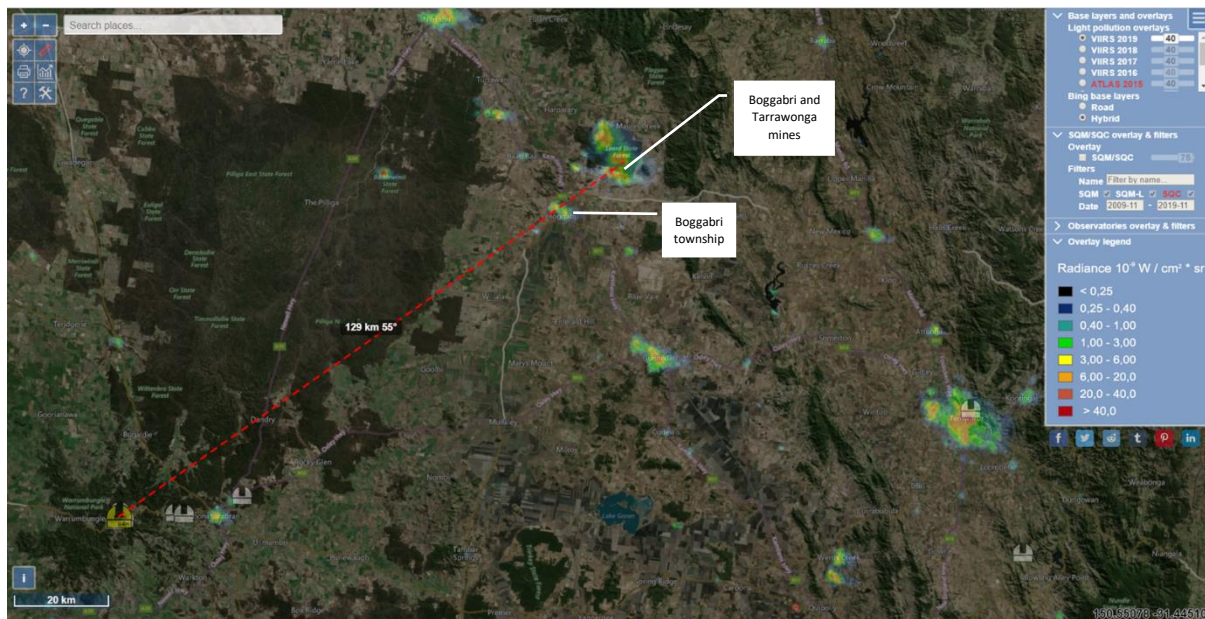


Figure 4: Boggabri township and Boggabri and Tarrawonga mines in same direction from SSO

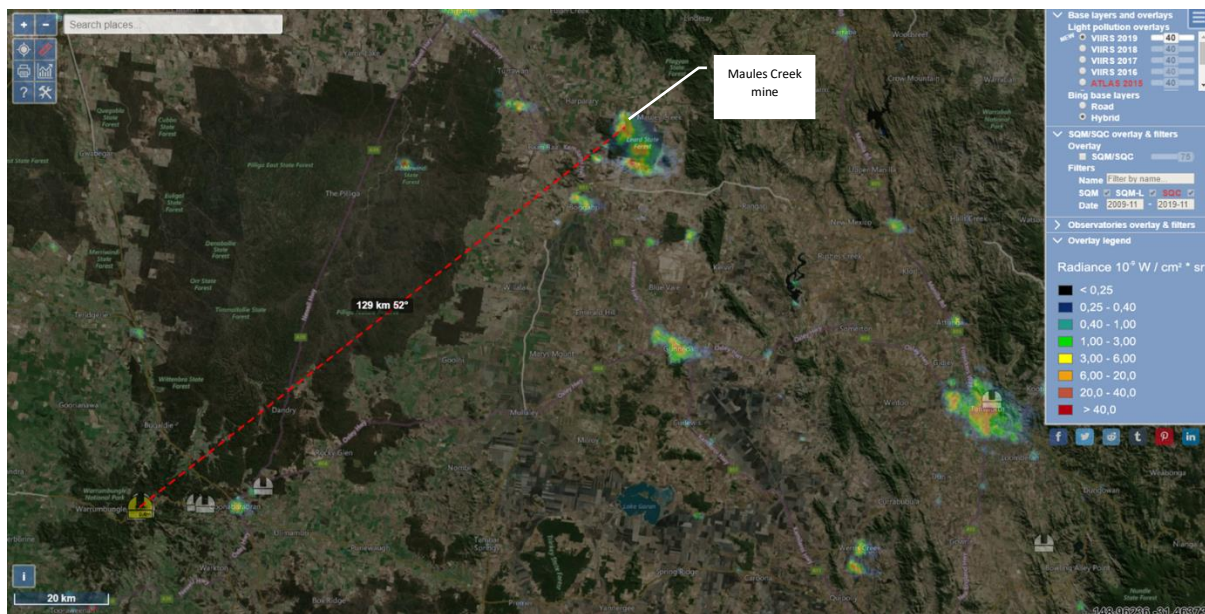


Figure 5: VIIRS Overlay of Region, showing SSO and relative location of Maules Creek Mine

On the night of site measurement, the direct horizon view of Gunnedah township was obscured by local terrain features. Furthermore, the sky glow from this source was so low that its position (bearing) on the horizon could not be precisely determined. Consequently, it was not included in analysis. Similarly, the sky glow from Narrabri was insignificant to the evaluation of the local region given its distance from the region of interest.

All aspects of assessment contained in this report relate to photometric measures, that is the measurement of electromagnetic radiation as modified by the photopic spectral response of the human eye, ranging in wavelength from around 400 nm to 700 nm, with a peak at 555 nm (often referred to as the $V(\lambda)$ response). This means that sky glow values are reported as luminances, and with the unit of measure candela per metre squared (cd/m^2). While the luminance levels of night time skies are lower than the range normally considered appropriate for photopic viewing (which is $> 3 \text{ cd}/\text{m}^2$), the reference spectral range for assessment requested by Siding Spring Observatory (in

their response to the Vickery Extension Project Environmental Impact Statement) is for light at 550 nm. This makes a photometric approach the appropriate choice for analysis.

Sky glow Factors

Light that increases the diffuse luminance of the sky at night is commonly referred to as sky glow. Sky glow can arise from natural sources (e.g. natural airglow, zodiacal light) or from the direct and reflected emissions from anthropogenic (electric) light sources.

Factors affecting anthropogenic sky glow arise from the light source itself:

- *Spectral Power Distribution (SPD) of the luminaire* – the shorter the wavelength the greater the scattering by the atmosphere, leading to increased sky glow. This effect varies with observer distance, and the size of the scattering particles.
- *Total lumen output* – the higher the lumen output the greater the total upward light, increasing sky glow.
- *Light intensity distribution (spatial) of the luminaire* – poor luminaire cutoff increases the Upwards Light Output Ratio (ULOR), increasing the quantity of lumens directed upwards and the resultant sky glow.

in addition to environmental factors:

- *Atmospheric conditions (clouds, haze)* – the more water vapour, aerosols and particulate matter in the air, the greater the scattering of light. This increases sky glow (particularly for the near observer). Particle size is a significant factor in scattering of light.
- *Observer's location relative to the light source (e.g. distance from city centre)* – shorter distances are associated with increased observed sky glow, due to the combined effects of the inverse square law (light decreases with the inverse of observer distance squared) and atmospheric absorption reducing observed light over longer distances.
- *Geographical size of the source (city size and resulting light density)* – the higher the lumen output density, the greater the localised scattering and increased localised sky glow.
- *Surrounding geographical features, including the reflectance of the ground surface* – the higher the albedo in the region of the anthropogenic source, the more light reflected upwards that will contribute to sky glow effects.

Natural sky brightness in scientific literature

Identifying the most appropriate estimate of baseline (dark) night sky luminance is challenging, largely due to the difficult nature of luminance measurement in the range of dark sky levels. The most often reported value is luminance of the night sky zenith, which is not generally sensitive to anthropogenic light sources since the gradient of light fall off from horizon to zenith due to such sources is steep¹.

Duriscoe¹ highlights the challenge of quantifying night sky luminance in his 2013 paper on measurement of anthropogenic sky glow, noting that the range in brightness values of the natural sky (due to a range of natural sky glow sources, e.g. natural airglow, zodiacal light, integrated

¹ Duriscoe, D. M. (2013). Measuring anthropogenic sky glow using a natural sky brightness model. *Publications of the Astronomical Society of the Pacific*, 125(933), 1370.

starlight) can in fact exceed the range in values between a pristine sky and one that exhibits moderate light pollution. His paper evaluates models for predicting moonless natural sky brightness patterns (for subsequent evaluation of anthropogenic sky glow contributions) and cites measured zenith dark sky luminances as low as $140 \mu\text{cd}/\text{m}^2$ (or $22.2 \text{ mag}_v/\text{arcsec}^2$).^{2, 3}

Luginbuhl⁴ quantifies the range of luminances for a naturally dark (moonless) and unpolluted night sky as from approximately $200 \mu\text{cd}/\text{m}^2$ at zenith to $3,000 \mu\text{cd}/\text{m}^2$ in brighter parts of the Milky Way (an increase of 1500%). Therefore, the influence of the Milky Way and major star clusters on site measurements of sky glow must be carefully considered.

In a 2017 paper on measuring the night sky, Hanel et al⁵ suggest that the darkest places on earth have equivalent sky zenith luminances of about $170 \mu\text{cd}/\text{m}^2$ (or $22.0 \text{ mag}_v/\text{arcsec}^2$). This paper also references some of the lowest values for astronomical background luminances (measured from outside the atmosphere) recorded by the Hubble Space Telescope of approximately $52 \mu\text{cd}/\text{m}^2$ (or $23.3 \text{ mag}_v/\text{arcsec}^2$).

Considering the range of luminances likely to be present in the natural, moonless night sky, and the potential for overlap between this natural range and the contributions of anthropogenic sky glow, analysis of anthropogenic sky glow in this study will be assessed with reference to both the darkest region of sky available on the night of measurement (noted as “darkest background” in this report), and a local background value (noted as “near background”) that refers to a dark section of sky adjacent to the anthropogenic source.

² $1 \mu\text{cd}/\text{m}^2 = 1 \times 10^{-6} \text{ cd}/\text{m}^2$

³ $\text{mag}_v/\text{arcsec}^2 = -2.5 * (\log_{10}(L) - 5.03342)$ where L is the luminance in cd/m^2

⁴ Luginbuhl, C. B., Boley, P. A., & Davis, D. R. (2014). The impact of light source spectral power distribution on sky glow. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 139, 21-26.

⁵ Hänel, A., Posch, T., Ribas, S. J., Aubé, M., Duriscoe, D., Jechow, A., ... & Spoelstra, H. (2018). Measuring night sky brightness: methods and challenges. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 205, 278-290.

Photometric Assessment of Existing Night Sky Conditions from Siding Spring Observatory

To evaluate the night sky conditions arising from existing natural and anthropogenic light sources, a site visit to Siding Spring Observatory was conducted over two nights.

Sky conditions

The two periods of measurement were selected to coincide with moonless skies, and near new moon conditions (new moon, 30 August 2019), with the sky conditions for each period characterised:

- Period 1: 01/09/2019, 23:00hrs – 02/09/2019 03:00hrs
 - New moon - Moonless dark sky, time period selected for minimal contribution from Milky Way at lower altitudes
 - Clear - No observable cloud in region of interest. Little to no observable haze and low particulate matter
- Period 2: 02/09/2019, 1030hrs – 03/09/2019 0100hrs
 - New moon - Moonless dark sky
 - Clear - No observable cloud in region of interest. Little to no observable haze and low particulate matter

Nearby sky monitoring stations confirmed the new moon, clear conditions, with excerpts from the local monitoring stations, 'stars311' and 'stars298' (located in Windana and EPSO, respectively) from the Edward Pigot Seismic Observatory presented in Figure 6 below.

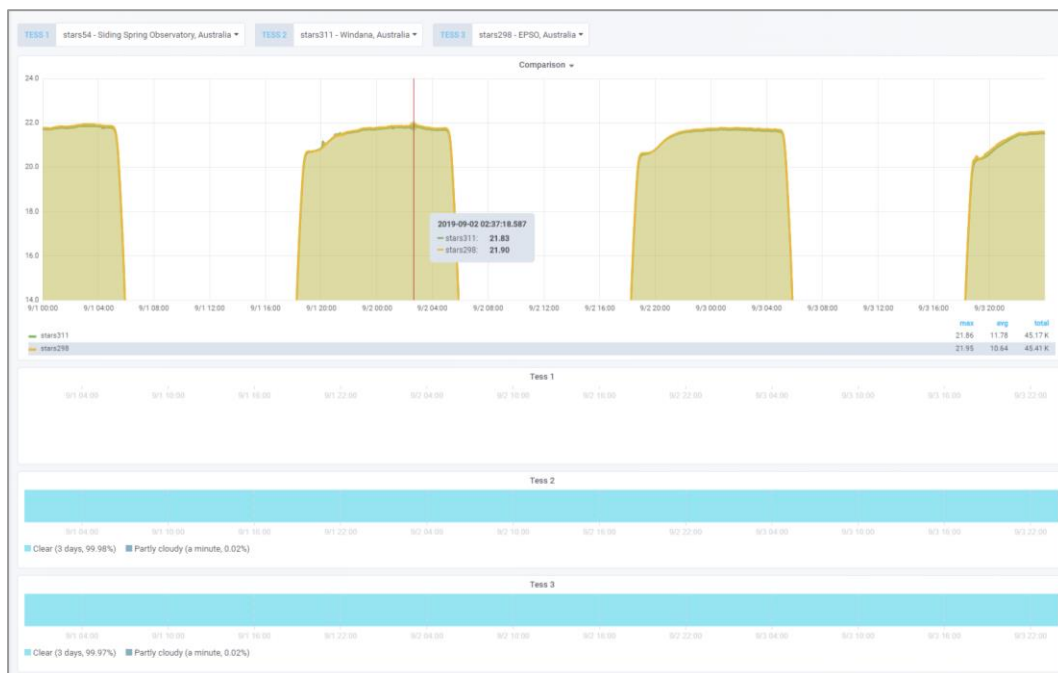


Figure 6: SQM brightness readings ($\text{mag}_v/\text{arcsec}^2$) for monitoring stations near SSO for the nights of measurement⁶

Site Assessment Methodology

Quantitative assessment of sky luminance and magnitude were primarily made using a calibrated luminance camera (LMK 5 luminance measuring video photometer) and a UniHedron Sky Quality Meter (SQM-L). The location of measurement was the gantry of the Anglo-Australian Telescope

⁶ <https://tess.dashboards.stars4all.eu/dashboard/snapshot/Xz9oaEqS8rrte6mX7dHjLIMZWNSG2b5i>

(AAT) at Siding Spring Observatory. This vantage point offered an unobstructed horizon view of the entire region.

The field of view of the luminance camera was 60° horizontally and 42° vertically, and each image obtained yielded a luminance map with 1387 x 1038 pixels of luminance data. Measurements were made at 45° intervals of azimuth angle, and at altitude angles of 0°, 15°, 30°, 50° and 70° to collect data across the entire sky vault. Altitude angles were measured using a digital inclinometer (with an uncertainty of positioning of approximately 1°), while azimuthal angles were set by rotation of the AAT.

For every luminance map, a reference measurement was made using the SQM-L directed at the centre of the image's field of view. These reference SQM-L values were used to cross-check the camera-obtained luminance data.

Results

The collected images at each altitude (for a set azimuth) were combined to produce a detailed spatial view of the luminances in the night sky above the Maules Creek and Boggabri regions. This view is shown in Figure 7 below.

Analysis was conducted to assess the existing sky conditions, particularly to ascertain the effect of anthropogenic sources on the natural sky luminance with increasing altitude angle above the horizon. The green lines (dashed and dotted) in Figure 7 show vertical planes that intersect the two distinct sky glow sources in the region, corresponding to the Maules Creek mine (green dotted line at 52° azimuth) and to the combined output of sources in the Boggabri region (green dashed line at 55° azimuth). Luminance values within a 0.5° band of these vertical planes were used to evaluate the fall-off of light with increasing altitude above the horizon. The red dashed line was selected as a dark region of sky relatively close to the two sources (65° azimuth), to act as a 'natural sky' reference.

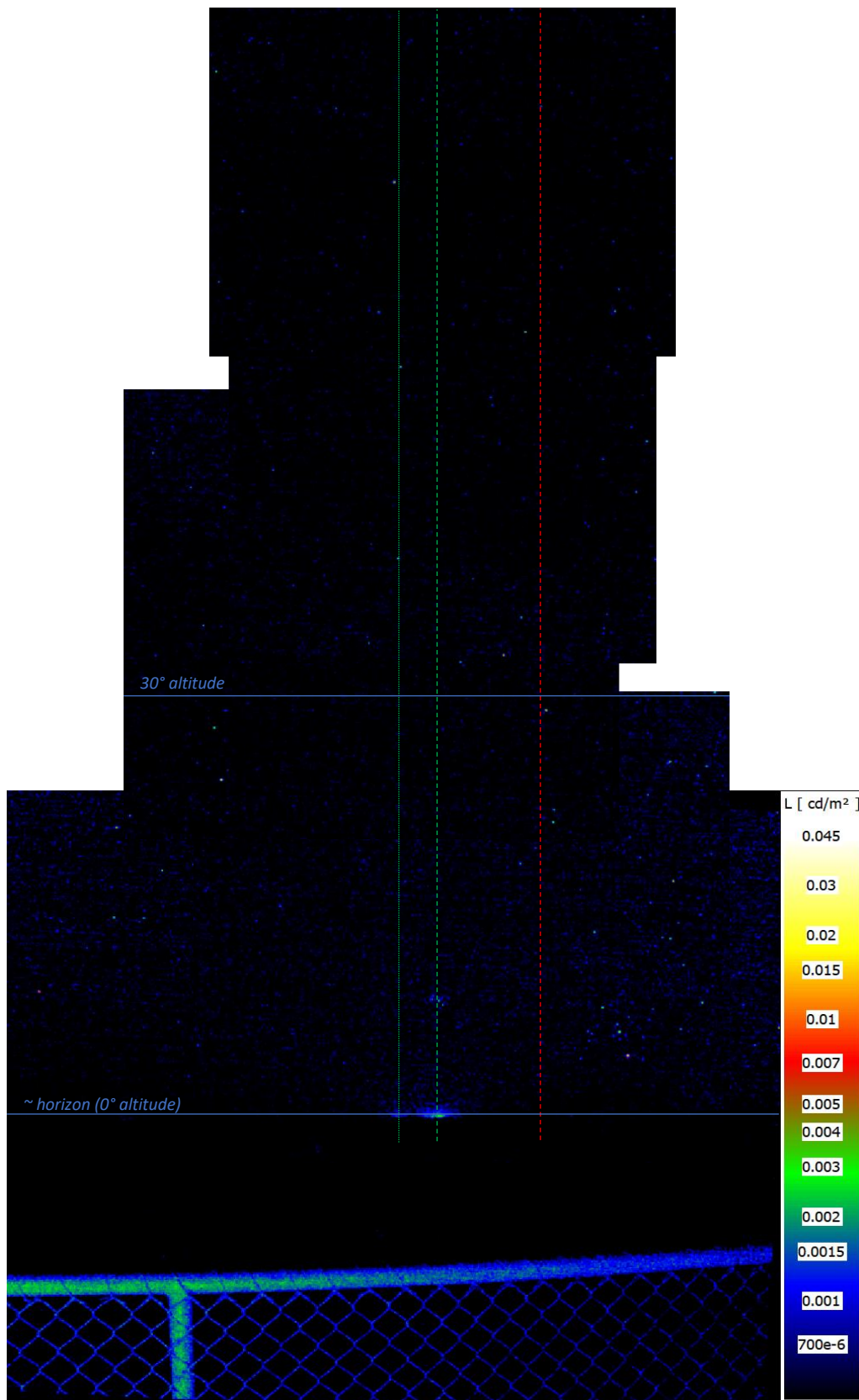


Figure 7: Composite luminance image of night sky showing vertical planes of analysis for anthropogenic sources over Maules Creek (green dashed line) and Boggabri region (green dotted line) and the red line shows adjacent dark sky area for the 'near background' reference.

It is evident from Figure 7 (and observed on the night of assessment) that there was some local stars and clusters concentrated in sky between 10° - 20° above the horizon above the Boggabri and Maules Creek region. Using a 'near background' reference, identified in Figure 8, is a useful way to account for the contribution of these phenomena to local variation in natural sky glow.

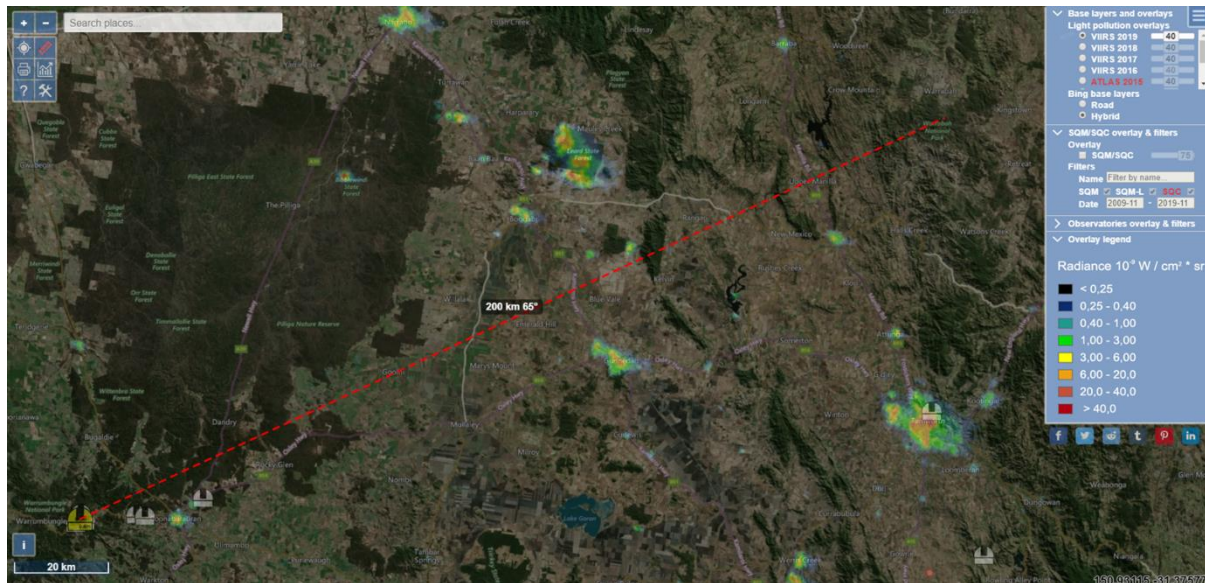


Figure 8: VIIRS Overlay of Region, showing SSO and direction of Near Background direction with minimal terrestrial light sources evident

The darkest region of sky measured on the same night was obtained at $\sim 315^{\circ}$ azimuth, Figure 9. For completeness, the luminances in a 0.5° vertical band above this region was also included as a 'darkest background' reference.

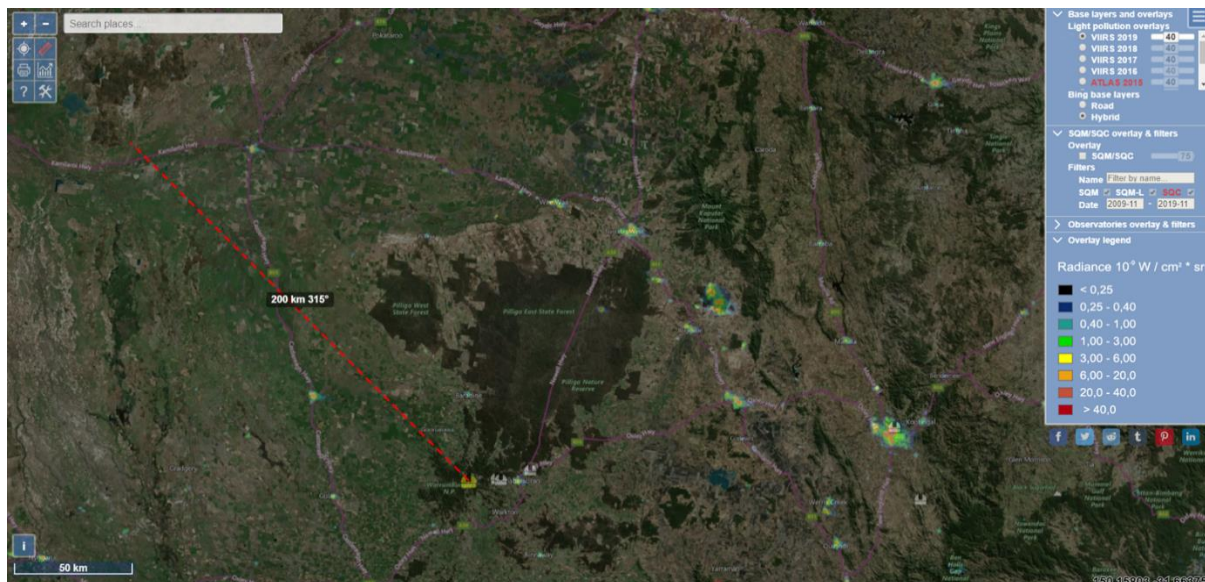


Figure 9: VIIRS Overlay of Region, showing SSO and direction of Darkest Background direction with no terrestrial light sources evident

Figure 10 shows a close-up view of the luminance map for the evaluated sources and their relative azimuthal position. Also included in this figure is the location of the proposed project ($\sim 63^{\circ}$ azimuth).

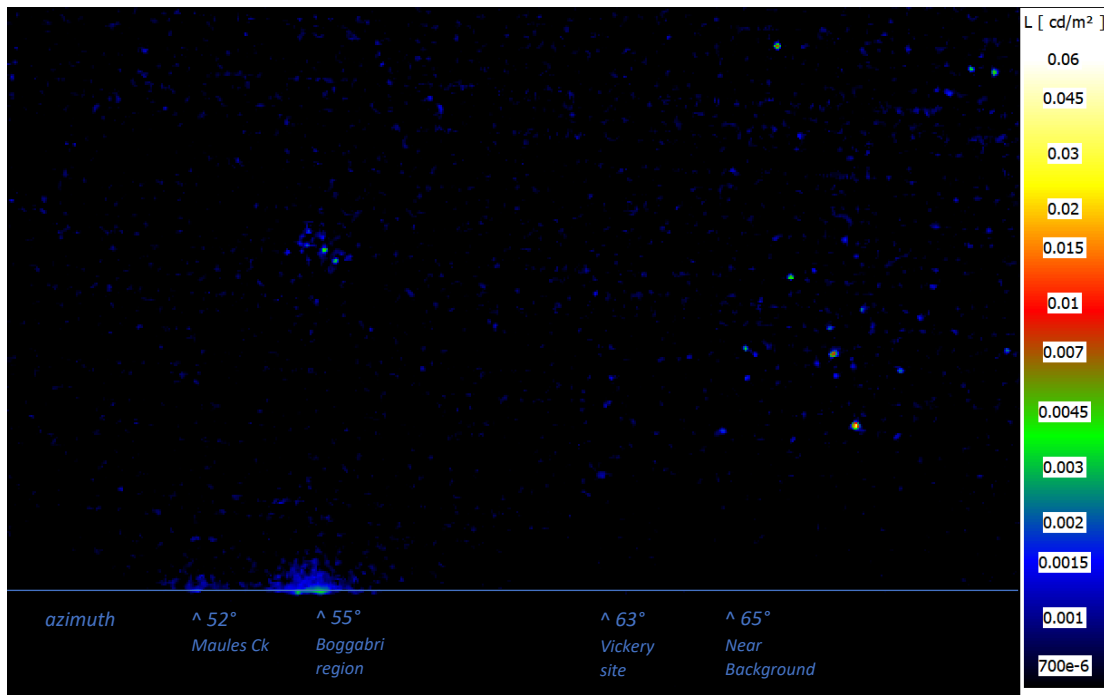


Figure 10: Close up view of luminance map showing vertical altitudinal planes of assessment in Maules Creek, Boggabri, proposed Vickery site and adjacent "near background" area used for natural dark sky assessment. Blue line indicates horizon.

Figure 11 shows the pixel-by-pixel luminance data corresponding to the vertical bands evaluated, circled in blue on this image are outliers that represent stars. To smooth the data, any single pixel outliers with value greater than $500 \mu\text{cd/m}^2$ were replaced with a value equal to the average of the immediately adjacent pixels. The resulting data with bright stars omitted is shown in Figure 12.

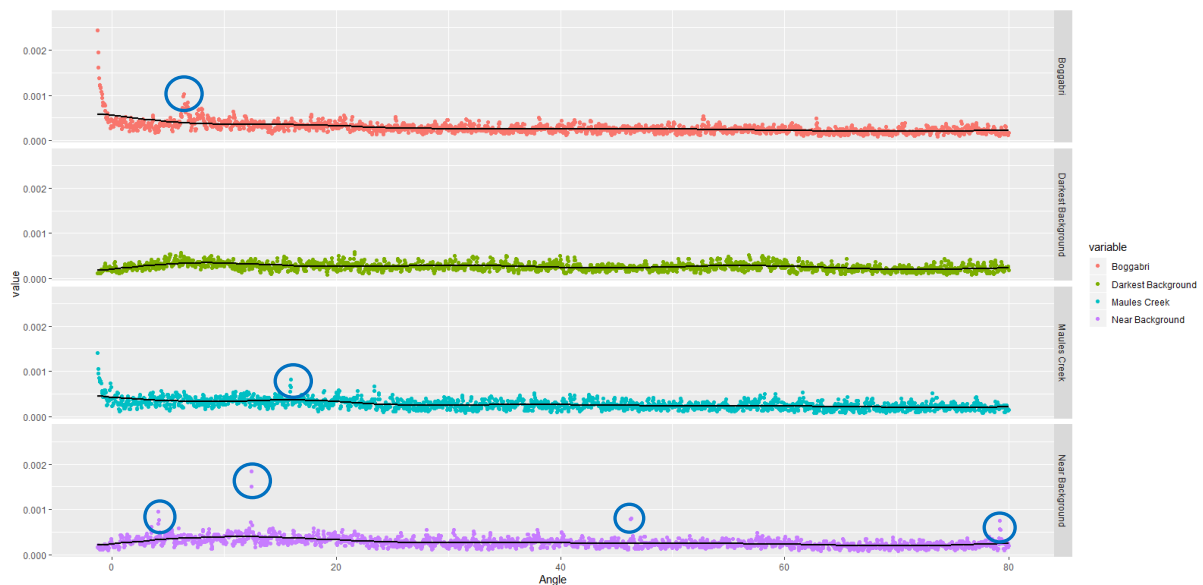


Figure 11: Raw pixel-by-pixel luminance values measured in a vertical band directly through and above the target anthropogenic sources located at Maules Creek, Boggabri and for two reference dark sky conditions: Near Background and Darkest Background

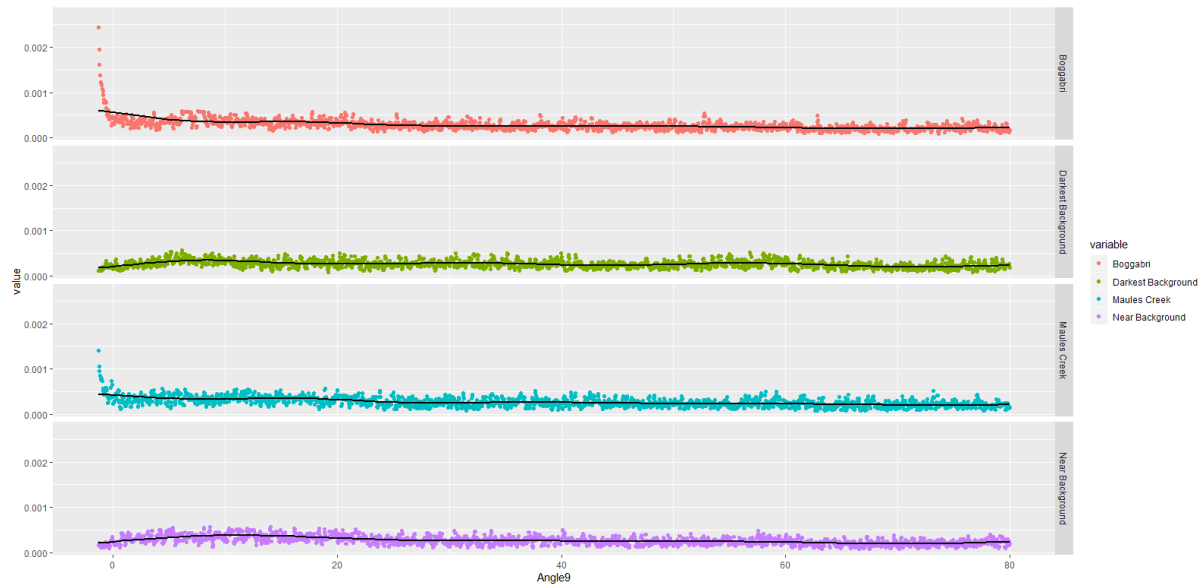


Figure 12: Processed pixel-by-pixel (viz: bright stars deleted) luminance values (cd/m^2) for altitude angles ($^\circ$) (or vertical bands) above Maules Creek, Boggabri and for two reference dark sky conditions: Near Background and Darkest Background

Smooth lines have been applied to the data in both Figure 11 and Figure 12 to observe extinction trends, the method of smoothing uses a non-parametric regression model called Locally Estimated Scatterplot Smoothing (LOESS). This method avoids forcing a particular unjustifiable mathematical formula (e.g. logarithmic, exponential). The curve is shown (with per-pixel scatter data points removed for clarity) in Figure 13 with a highlighted 95% confidence interval (calculated by the statistical software used to fit the LOESS curve to the data).

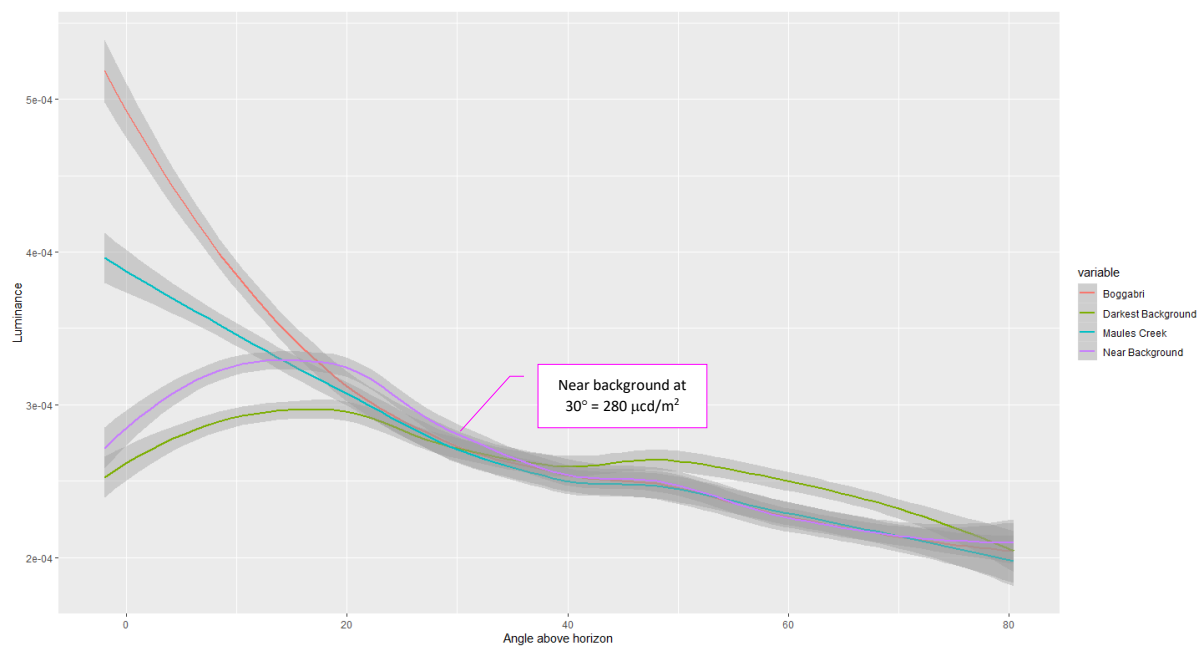


Figure 13: Plot of trend in luminance (cd/m^2) vs angle above the horizon ($^\circ$) for Maules Creek, Boggabri, Near Background and the Darkest Background regions

Comparing the anthropogenic source bands (red, blue) with the background bands (pink, green) in Figure 13, the luminance trends indicate that by approximately 20° above the horizon, the anthropogenic light source luminances are in range (95% confidence interval) of those from 'near background' and remote 'darkest background' regions of sky.

Comparing the 'near background' band (pink) to the 'darkest background' band (green) illustrates that there is localised variation between the two dark regions, particularly at altitudes between 0° and 30° above the horizon, where the near background has higher luminance than the darkest background; however, the reverse is true for altitudes between 50° and 75° above the horizon. This suggests that the natural sky glow variation would dictate that the 'near background' (azimuth 62°) as opposed to the darkest background (azimuth 315°) is the preferred reference condition for anthropogenic source evaluation, so as to take into account local variation in sky luminance due to stellar influences.

To directly evaluate the contribution of these anthropogenic sources to the natural sky luminance with reference to the Dark Sky Planning Guideline, and specifically address the following:

"At the Observatory, a threshold figure of 10 per cent of the natural sky glow at 30 degrees above the horizon has been adopted as the maximum tolerable level of artificial light"

the ratio of luminances in the vertical bands above Maules Creek and Boggabri to each reference background was found. The ratio of anthropogenic source to the 'near background' reference is shown in Figure 14, with the highlighted bands surrounding the trendlines showing the 95% confidence interval.

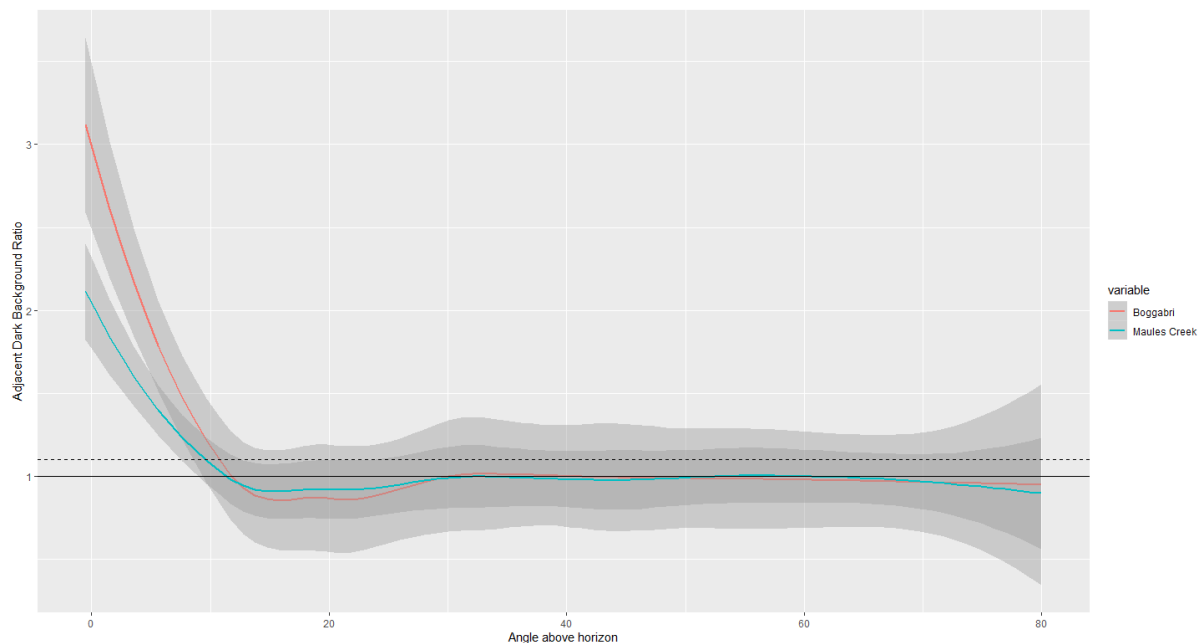


Figure 14: Source to Background Ratio (value 1.0 associated with little or no anthropogenic effect, dashed line shows the threshold limit of natural background +10%) for Maules Creek and Boggabri sources, compared to near background reference

Figure 14 indicates that the contribution from the anthropogenic sources falls below the required 10% threshold at an altitude of around 10° above the horizon. It is noted that the ratio falls below 1 between altitudes 10° and 30°, which is most likely due to the increase in natural sky glow (arising from zodiacal light) observed in the 'near background' reference between 0° and 30° above the

horizon (see Figure 10 and Figure 13). As an additional measure, the analysis was repeated with the 'darkest background' reference and is illustrated below in Figure 15.

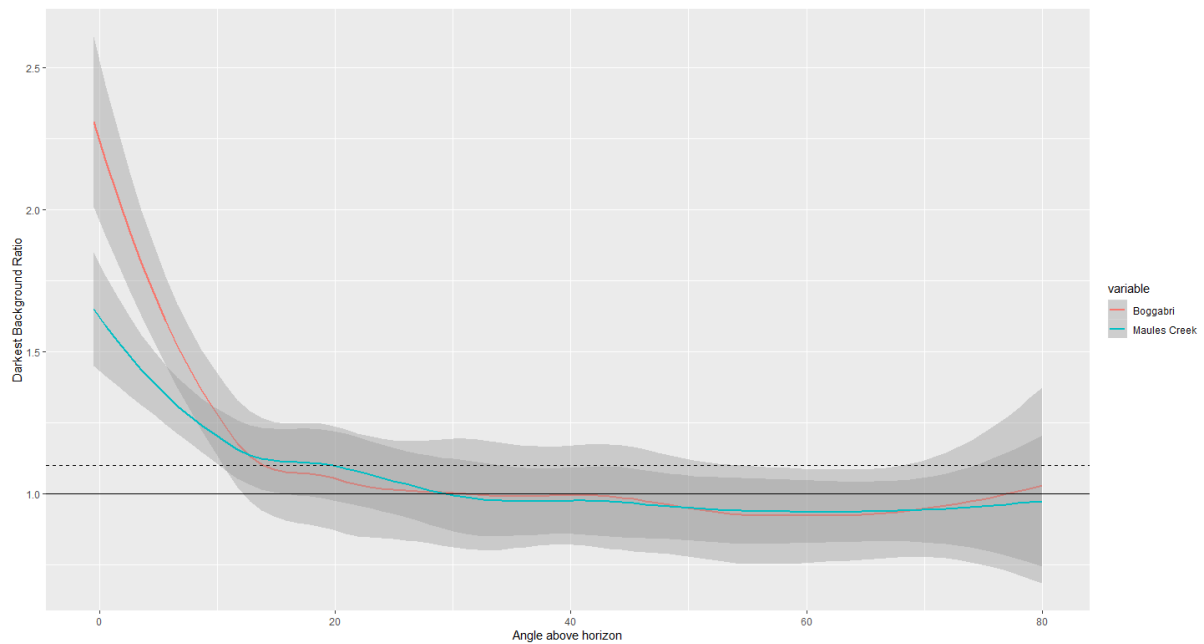


Figure 15: Source to Darkest Background Ratio (value 1.0 indicates little or no anthropogenic effect, dashed line shows the threshold limit of natural background +10%) for Maules Creek and Boggabri sources, compared to the darkest background reference

Figure 15 shows that even against the 'darkest background' (which underestimates the localised natural sky glow due to zodiacal light in the region above Maules Creek and Boggabri), the contribution from the anthropogenic sources falls below the required 10% threshold at an altitude between 15° and 20° above the horizon. By 30° above the horizon, both sources (Maules Creek and Boggabri) appear to have little to no effect.

Prediction of Impact on Night Sky from Vickery Project

The impact of the Vickery Project on the night sky viewed from the Siding Spring Observatory can be predicted with reference to the measured effect of the existing similar sites in the region. In particular, the combined sky glow impact of Boggabri region (township and mine sites) and Maules Creek mine site can be considered in terms of the installed lumens arising from the known inventory of the street and area lighting.

Calculating the amount of upwards-directed light from a lighting installation requires the following inputs:

- The quantities, light source technology (high pressure sodium, LED etc) and wattage of luminaires installed – to estimate the amount of lumens output by the installation
- The shielding category of luminaire to estimate the Upwards Light Output Ratio (ULOR) – to determine the fraction of lumens directed upwards
- The ground surface reflectance – to estimate the quantity of downwards directed light that is reflected upwards

The calculations provided here rely on data provided by Whitehaven (tender document for Maules Creek Lighting Installation) and Essential Energy (inventory for streetlighting installations in the region).

Lumen Calculations for Existing Anthropogenic Sources

Maules Creek Lighting Schedule

Estimating the total number of lumens, and the proportion of upwards lumens emitted (or reflected) by the Maules Creek lighting installation requires definition of the following values:

ULOR: The ULOR is not specified in the tender document, but attention is given to restricting upwards directed light from luminaires, with the following noted:

“cut-off angles must be such as to minimise the effect of the lighting system on nearby residents, and it is a condition of the mining licence, to limit any side or uplight beyond the horizontal plane”.

Best practice would recommend luminaires with a ULOR of 0 (full cut-off). However, given that there could be some variation in mounting position that might lead to some upcast of light, a value of 0.05 has been selected as an upper estimate of ULOR for the installation.

Efficacy: Efficacy for High Pressure Sodium (HPS) lamps can range from 80-120 lm/W. A mid-range value of 100 lm/W has been selected for all lamp sizes (70 – 1000 W).

Ground Surface Reflectance: A ground reflectance value of 0.2 is selected as an upper estimate for the average of natural surfaces (vegetation, soil, sandstone, shale and water) in the area of the mine site. Figure 16 illustrates the spectral composition of objects in the area of a coal mine.⁷

⁷ Mao, Yachun & Ma, Baodong & Liu, Shanjun & Wu, L. & Zhang, Xuanxuan & Yu, Moli. (2014). Study and Validation of a Remote Sensing Model for Coal Extraction Based on Reflectance Spectrum Features. *Canadian Journal of Remote Sensing*. 40. 327-335..

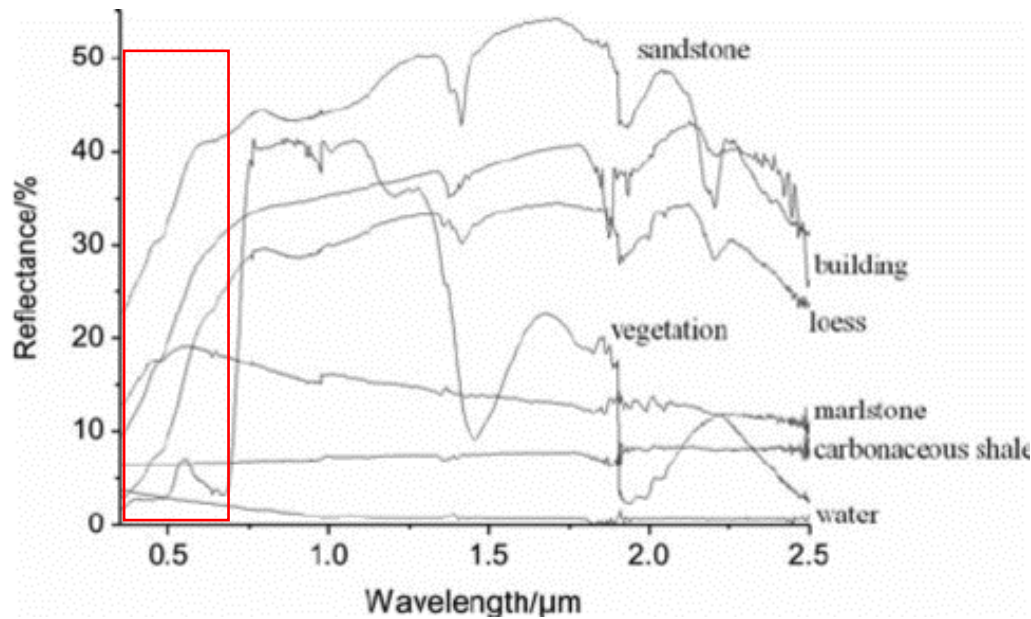


Figure 16: Spectral reflectance curves for objects in the vicinity of coal mines (red box indicates the approximate photopic region of 400-700nm)

Luminaire Efficiency: A luminaire efficiency of 0.7⁸ is a mid-range estimate for this type of luminaire.

Light Loss Factor: A light loss factor of 0.7 is applied. This is a maintenance factor based on dirt build-up on optical surfaces.

These factors are combined with the luminaire types specified in the documentation provided for Maules Creek, and the results of calculations are shown in

Table 2, with a summary of calculations presented in Table 3.

Table 2: Lumen calculations for existing Maules Creek Mine lighting installation

	1000W HPS	400W HPS	250W HPS	70W HPS
Luminaire watts (W)	1,000	400	250	70
Typical lamp efficacy (lm/W)	100	100	100	100
Rated lamp lumens (initial, lm)	100,000	40,000	25,000	7,000
Luminaire efficiency (estimated)	0.70	0.70	0.70	0.70
Light Loss Factor	0.7	0.7	0.7	0.7
Lumens Output per Luminaire (total, lm)	49000	19600	12250	3430
Downwards Light Ratio (DLOR, estimated)	0.95	0.95	0.95	0.95
Downwards luminaire lumens (initial, lm)	46,550	18,620	11,638	3,259
Ground Surface reflectance	0.20	0.20	0.20	0.20
Ground-reflected upward lumens (lm)	9,310	3,724	2,328	652
Upwards Light Ratio (ULOR, estimated)	0.05	0.05	0.05	0.05
Direct upward lumens (initial, lm)	2,450	980	613	172
Estimated Upwards Lumens (per luminaire, lm)	11,760	4,704	2,940	823

⁸ https://www.energy.gov/sites/prod/files/2014/05/f16/outdoor_area_lighting.pdf

Table 3: Summary of Maules Creek Mine lumen calculations

Luminaire Type	Quantity	Estimated Total Lumens (per luminaire, lm)	Estimated Total Lumens (by type, lm)	Estimated Upwards Lumens (per luminaire, lm)	Estimated Upwards Lumens (by type, lm)
1000W HPS	24	49,000	1,176,000	11,760	282,240
400W HPS	109	19,600	2,136,400	4,704	512,736
250W HPS	150	12,250	1,837,500	2,940	441,000
70W HPS	527	3,430	1,807,610	823	433,826
		TOTAL	6,957,510	TOTAL	1,669,802

All light from the installation is from High Pressure Sodium sources. The fraction of upwards lumens to total lumens output by the installation is 24%.

Boggabri Township Street Lighting Inventory

The light at night from Boggabri township is estimated based on the known street lighting inventory (supplied by Essential Energy). To complete calculations, the following values are defined:

ULOR: The value given here is taken from Essential Energy information and represents the upper value of ULOR across the range of installed streetlighting luminaires (ULOR range from 0 – 0.04).

Efficacies: Mid-range values have been selected for all lamp types.

Ground Surface Reflectance: A ground reflectance of 0.1 is selected as an estimate for all road types.

Luminaire Efficiency: A luminaire efficiency of 0.7 is a mid-range estimate for this type of luminaire.

Light Loss Factor: A light loss factor of 0.7 is applied as the maintenance factor based on dirt build-up on optical surfaces.

The results of calculations for Boggabri township's street lighting are shown in

Table 4, and summary of calculations are presented in Table 5.

Table 4: Lumen calculations for Boggabri street lighting inventory

	42W CFL	400W HPS	250W HPS	150W HPS	100W LPS	80W MV
Luminaire watts (W)	42	400	250	150	100	80
Typical lamp efficacy (lm/W)	65	100	100	100	125	50
Rated lamp lumens (initial, lm)	2,730	40,000	25,000	15,000	12,500	4,000
Luminaire efficiency (estimated)	0.70	0.70	0.70	0.70	0.70	0.70
Light Loss Factor	0.7	0.7	0.7	0.7	0.7	0.7
Lumens Output per Luminaire (total, lm)	1,338	19,600	12,250	7,350	6,125	1,960
Downwards Light Ratio (DLOR, estimated)	0.96	0.96	0.96	0.96	0.96	0.96
Downwards luminaire lumens (initial, lm)	1,284	18,816	11,760	7,056	5,880	1,882
Ground Surface reflectance	0.10	0.10	0.10	0.10	0.10	0.10
Ground-reflected upward lumens (lm)	128	1,882	1,176	706	588	188
Upwards Light Ratio (ULOR, estimated)	0.04	0.04	0.04	0.04	0.04	0.04
Direct upward lumens (initial, lm)	54	784	490	294	245	78
Estimated Upwards Lumens (per luminaire, lm)	182	2666	1666	1000	833	267

Table 5: Summary of Boggabri township street lighting lumen calculations

Luminaire Type	Quantity	Estimated Total Lumens (per luminaire, lm)	Estimated Total Lumens (by type, lm)	Estimated Upwards Lumens (per luminaire, lm)	Estimated Upwards Lumens (by type, lm)
42W CFL	147	1,338	196,642	182	26,743
400W HPS	32	19,600	627,200	2,666	85,299
250W HPS	44	12,250	539,000	1,666	73,304
150W HPS	2	7,350	14,700	1,000	1,999
100W LPS	2	6,125	12,250	833	1,666
80W MV	11	1,960	21,560	267	2,932
		TOTAL	1,411,352	TOTAL	191,944

The majority of light from the combined sources is from High Pressure Sodium (84%), with 14% from 4000K Compact Fluorescent, 2% from Mercury Vapour and <1% from Low Pressure Sodium sources. The fraction of upwards lumens to total lumens output for Boggabri street lighting is 13.6%.

Boggabri and Tarrawonga Mine Lighting

There is no data available for the lighting installed at Boggabri or Tarrawonga Mines. Although evidently from the VIIRS “heat” map of upwards radiance shown in Figure 3, the combined area is larger in size and appears brighter from the satellite image, the most conservative estimate is to assume the combination of Boggabri and Tarrawonga Mines emits at least as much light (likely to be more based on VIIRS images) as the Maules Creek Mine.

Lumen Estimate for the Vickery Project

Advice from the client on the expected lighting schedule for the Vickery Project (including the proposed Vickery Extension Project) is that it will be comparable in size to the Maules Creek Mine, and include a requirement that the installation is “Dark Sky compliant”. Based on this information and calculations above, for the proposed project:

- estimated total lumens: ~6,960,000 lm
- estimated lumens directed upward: ~1,670,000 lm (24% of total)

with the majority of the light from High Pressure Sodium Light Sources, at ~2200 K (or other sources with acceptable spectral output).

Anthropogenic light from the Vickery Project site will be similar in light output, spectral profile and distance from SSO as existing site at Maules Creek Mine. Therefore, the likely predicted impact on the night sky from the Vickery Project site can be considered equivalent to the impact measured in the night sky over the Maules Creek Mine.

Modelling the influence of atmospheric conditions on predicted sky impact

Atmospheric conditions on the night of measurement were very clear. NASA observations from the Moderate Resolution Imaging Spectroradiometer ([MODIS](#)), indicate that the Aerosol Optical Depth (AOD) in the region of SSO for the 1 September was approximately 0.0055. The map of AOD values for the period from August 29 to September 5 are shown in Figure 17.

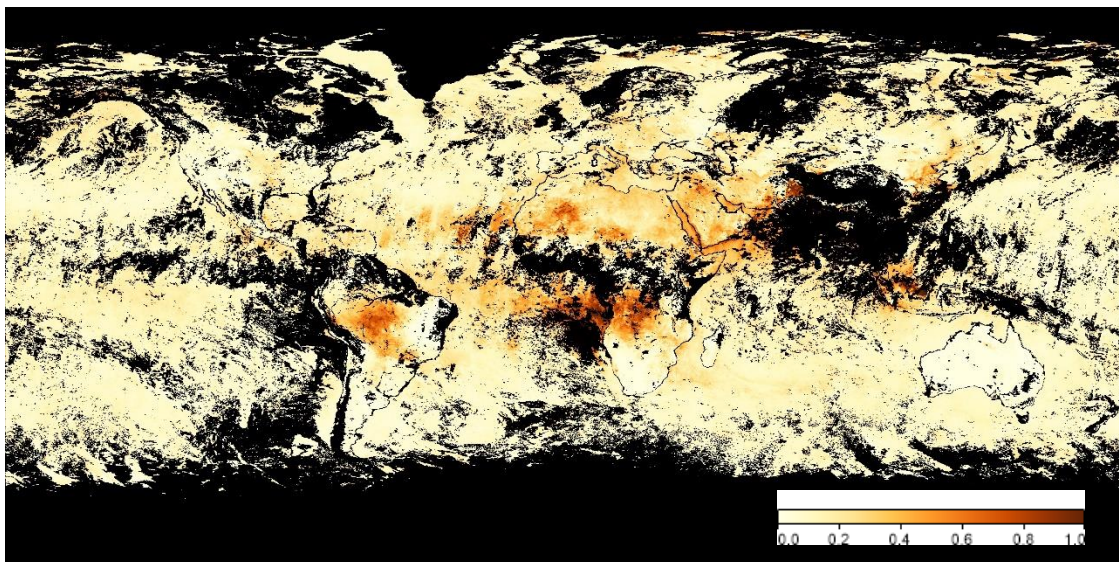


Figure 17: Aerosol Optical Thickness for 8-day period surrounding September 1, 2019 - from NASA TERRA/MODIS satellite observation

This value is relatively low – AOD values less than 0.1 can be characterised as crystal clear skies and yield maximum visibility. As AOD increases, sky conditions become hazier and less suitable for astronomical observation at 550 nm. To predict the impact of increasing AOD (up to 0.1) on observed sky glow due to an anthropogenic source with light characteristics similar to Maules Creek

Mine, modelling of sky glow above a single source in a clear sky was conducted. Simulations were undertaken using Sky Glow software⁹, for the following conditions:

- Anthropogenic source output: 6,960,000 lm
- Source spectrum: High Pressure Sodium
- Source angular dependence: Garstang model, fraction of light directed upwards = 0.24
- Observation distance: 100 km (maximum permitted by software)
- Cloudless sky, constant background, no objects blocking light near the horizon
- AOD ranging from 0.0055 (actual) to 0.1

Simulated values were scaled so that the simulated horizontal illuminance was consistent with the expected horizontal illuminance measured under a clear, moonless night sky (excluding airglow, 200 μ lux). The results of these simulations are shown in Figure 18 and Figure 19 below, and presented against the reference values of: zenith luminance of a pristine sky (22.0 mag_V/arcsec² or 170 μ cd/m²), measured 'near background' luminance at 30° above the horizon (280 μ cd/m²), and measured 'near background' luminance at 30° above the horizon plus 10% (308 μ cd/m²), to indicate a threshold above the estimated natural background.

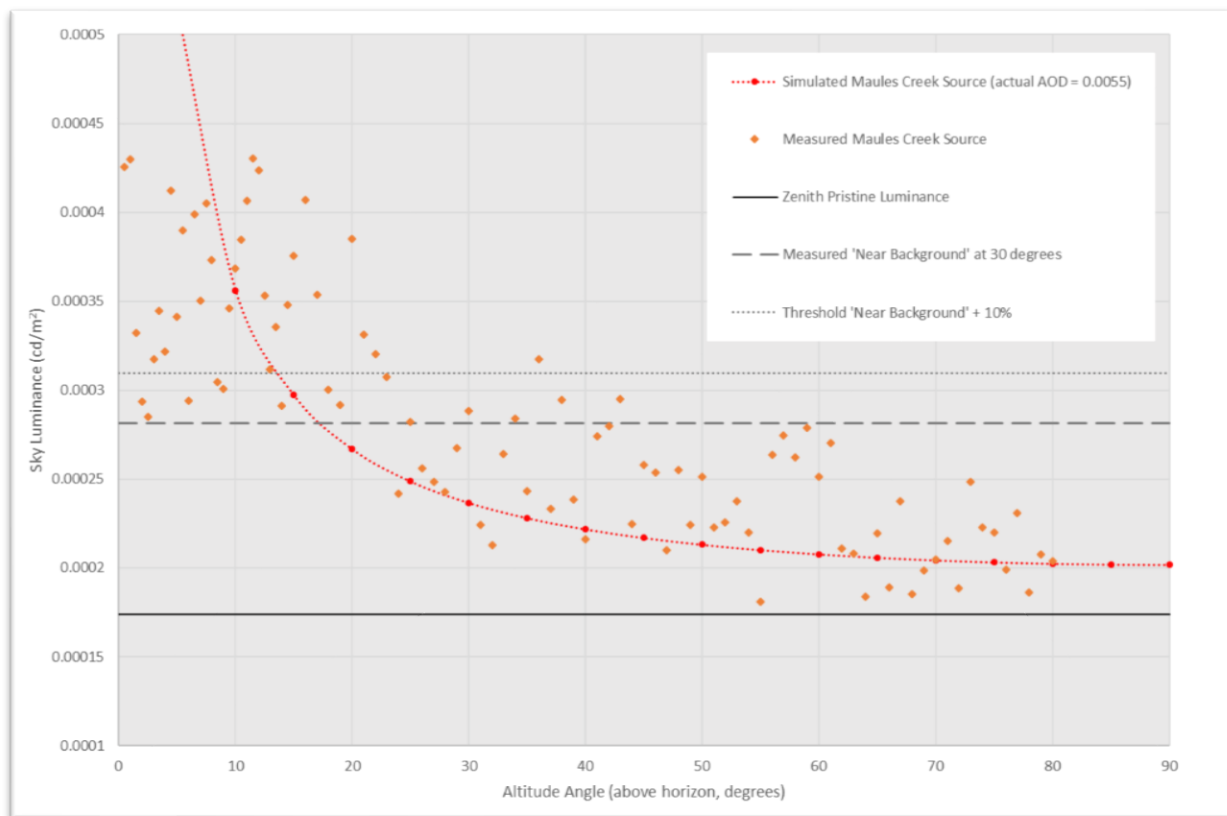


Figure 18: Comparison of Simulated and Measured Luminances for increasing Altitude above Horizon over Maules Creek Mine under Clear Sky

⁹ Sky Glow Simulator, available from <http://skyglow.sav.sk/>

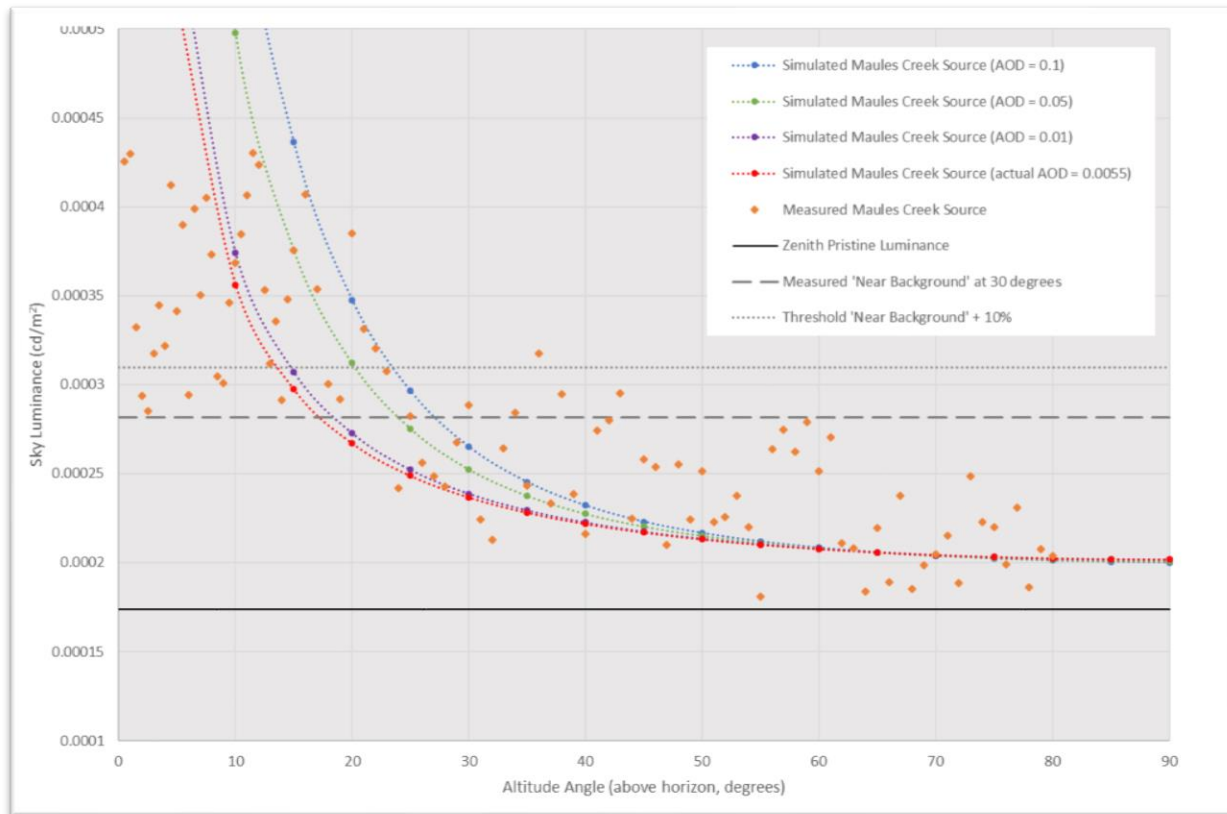


Figure 19: Comparison of Simulated and Measured Luminances for increasing Altitude above Horizon over Maules Creek Mine under Clear Sky with variations in simulated AOD

There is moderate agreement between the modelled and measured data for a simulated AOD of 0.0055; however, measured values of sky luminance for angles below 10° above the horizon are significantly lower than modelled values. This may be due to very low-level particulate matter immediately above Maules Creek due to mining activity, and also due to the actual source distance being >125 km, while the modelled distance could not exceed 100 km.

Agreement between simulated and measured values at altitude angles greater than 10° above the horizon is improved (average difference 9%, or ~26 $\mu\text{cd}/\text{m}^2$). Much of the variation observed in the measured data in this region is due to star and other natural sky glow features.

The simulated results are not able to predict the precise values of sky glow arising from the range of AOD; but they are able to clearly illustrate the trend in sky glow with increasing aerosol optical depth. As expected, the results show that increasing AOD, up to values of 0.1 (still classed as clear sky conditions), increases the luminance of the sky above the anthropogenic light source. At a value of AOD = 0.1, the sky luminance remains above the luminance threshold at higher altitudes than for AOD = 0.0055; however, the simulated curves are clustered so that luminance drops to the threshold within an altitude range of less than 10°. This simulation suggests that under a range of clear sky conditions, a source consistent with this model will achieve the threshold conditions set out in the Dark Sky Planning Guidelines.

Conclusions

A summary of findings related to the measurement and calculation of the impact of the Vickery Project to dark sky conditions in the region of the Siding Spring Observatory is as follows:

- Light from existing anthropogenic sources (Boggabri township and mine, Tarrawonga mine and Maules Creek mine) that are comparable to the proposed project in size and distance from the Observatory were measured and determined to comply with the Dark Sky Planning Guideline. Therefore, it is expected that the Vickery Project will comply if the lighting installation is equivalent to that of the Maules Creek mine.
- Analysis demonstrated that sky luminance above the Maules Creek mine and the Boggabri regions fell below the specified threshold level (i.e. natural background +10% at 30° above the horizon) at altitudes between 10° and 20° above the horizon (dependant on whether 'near' or 'darkest' background reference is used).
- The expected lumen output from the Vickery Project (including Vickery Extension Project) is estimated at 6,960,000 lumens, based on the similar installation at Maules Creek Mine. An upper estimate of the upward light fraction is 24%. This value could be reduced with best practice light design.

Quantifying dark sky luminances is challenging due to the range in brightness values of the natural sky, which can often exceed the range in luminances when comparing a pristine sky with one that exhibits moderate light pollution. In this lighting assessment, it was determined that the most appropriate part of the sky for measuring natural background values was a dark region of sky adjacent to the regions of interest, Maules Creek and Boggabri.

Measurements were made under exceptionally clear sky conditions (Aerosol Optical Distance, AOD = 0.0055); although, simulation indicates that for clear skies with higher AOD, up to 0.1, the estimated source will still meet the threshold requirement.

Based on the measurements conducted, it is evident that the proposed project will comply with the Dark Sky Planning Guideline if it is consistent in its lighting output with that of the Maules Creek Mine.

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