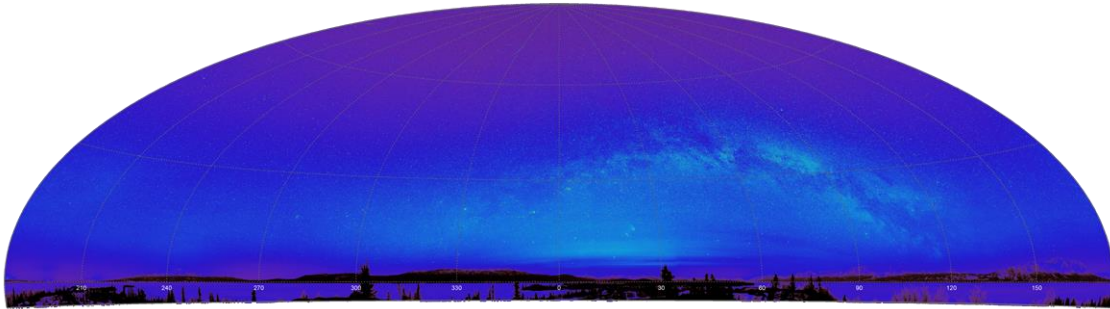


**IMPACT ASSESSMENT
OF THE PROPOSED PEBBLE MINE PROJECT
ON NIGHT SKY BRIGHTNESS**



Current Night Sky Conditions at Keyes Point, Lake Clark National Park and Preserve

FINAL REPORT

**Prepared by Dark Sky Partners, LLC
for
U. S. National Park Service**

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Contents

SUMMARY	3
LIST OF FIGURES	4
LIST OF TABLES	4
I. INTRODUCTION	5
II. STUDY METHODOLOGY	8
A. Current Sky Brightness Measurements.....	8
B. The Numerical Model	9
III. RESULTS	11
A) Measures of the Current Condition.....	11
B) Sky Brightness Changes with Proposed Pebble Mine Project Lighting.....	12
IV. DISCUSSION AND CONCLUSIONS	15
V. REFERENCES	17

SUMMARY

The impact of outdoor lighting from the proposed Pebble Mine Project on the night skies as viewed from Lake Clark National Park and Preserve (LCNPP) is assessed.

Proxy lighting for the project as described in the Draft Environmental Impact Statement (DEIS) was used as input to a computer program that calculates the increase in sky glow due to the mine and associated transport corridor. In the absence of a lighting plan for the mine, the DEIS uses the lighting of the city of Anchorage to represent the lighting of the mine and Valdez to represent ferry and port terminal lighting. The model results were then added to measurements of sky brightness provided by NPS in order to find the predicted sky brightness as seen from Keyes Point in LCNPP. Four scenarios are evaluated: direct uplight fractions for lighting of 10% and 0% were used, along with ground reflectivity values with and without snow cover. The measurements and the calculations were made in the “visual” (V) spectral band (~500-650 nm) which approximates the response of the light-adapted human eye.

The additional expected sky glow impact from the proposed mining operations was assessed using two metrics evaluated at the observation point: the Average Sky Luminance (ASL), the sky brightness averaged over the entire sky, and the maximum sky luminance, the luminance of the brightest point in the sky. The results show an increase in the ASL of 4-15%. In the direction of the proposed mine, the maximum sky luminance increases between 103% and 886%. There is currently minimal lighting in the region, and essentially a pristine unpolluted night sky; so the effects of the proposed mine lighting will significantly impact the nighttime viewshed.

Use of fully shielded fixtures will reduce the ASL increase to 4-12%, and maximum sky luminance increase to 103-570%. An emphasis on yellow-rich sources such as phosphor-converted amber LED for much lighting could further reduce the incremental impact substantially.

LIST OF FIGURES

Figure 1. Location of the proposed Pebble Mine, North and South Ferry Terminals and Amakdedori Port facilities in Southwest Alaska.	5
Figure 2. Nighttime satellite image of the region surrounding Cook Inlet, Alaska.	7
Figure 3. Modeled 2014 zenith sky brightness levels in the region of the Pebble Mine Project and Anchorage, from the New World Atlas of Artificial Night Sky Brightness.	7
Figure 4. Relative spectral response for the visual (V) band used in this study for sky brightness measurements.	9
Figure 5. False color all-sky maps showing measured current sky brightness in the visual (top), predicted additional sky brightness arising from proposed PMP and terminal lighting under the indicated light fixture shielding (unshielded = 10% direct uplight; fully shielded = 0% direct uplight) and groundcover conditions, as seen from the Keyes Point observation site.	13
Figure 6. Relative spectral radiance for 4000 K CCT white LED, 2700 K CCT white LED, and a low-S/P (0.45) phosphor-converted amber LED.	15

LIST OF TABLES

Table 1. Observation point location and altitude.	8
Table 2. Geometric blocking and ground reflectivity parameters used in the models	10
Table 3. Lighting site locations, fixture numbers and lumen totals used in the study.	11
Table 4. Sky brightness observation dates, times, measured extinction k_V , horizontal visibility, and two measures of sky quality – Average Sky Luminance (ASL) and maximum (brightest) Luminance.	11
Table 5. Average Sky Luminance (ASL) and maximum sky luminance as observed from Keyes Point under current (2013) conditions and after addition of estimated PMP lighting.	14
Table 6. Representative scotopic to photopic ratios (S/P) for LEDs and high-pressure sodium.	15

I. INTRODUCTION

The Pebble Limited Partnership (hereafter PLP) proposes to develop an open pit copper-gold-molybdenum mine (the Pebble Mine Project, hereafter PMP) in southwest Alaska. As part of the assessment of the impact of mining operations on the nighttime viewscape, the U.S. National Park Service contracted with Dark Sky Partners, LLC (DSP) to perform an assessment of the impact of the outdoor lighting needed for PMP mining and transportation operations on the night skies in Lake Clark National Park and Preserve (LCNPP). An observation point located at Keyes Point in the LCNPP was selected due to the existence of previous all-sky measures performed by NPS at this location. The location of the Pebble Mine and the associated transportation corridor are shown in Figure 1.

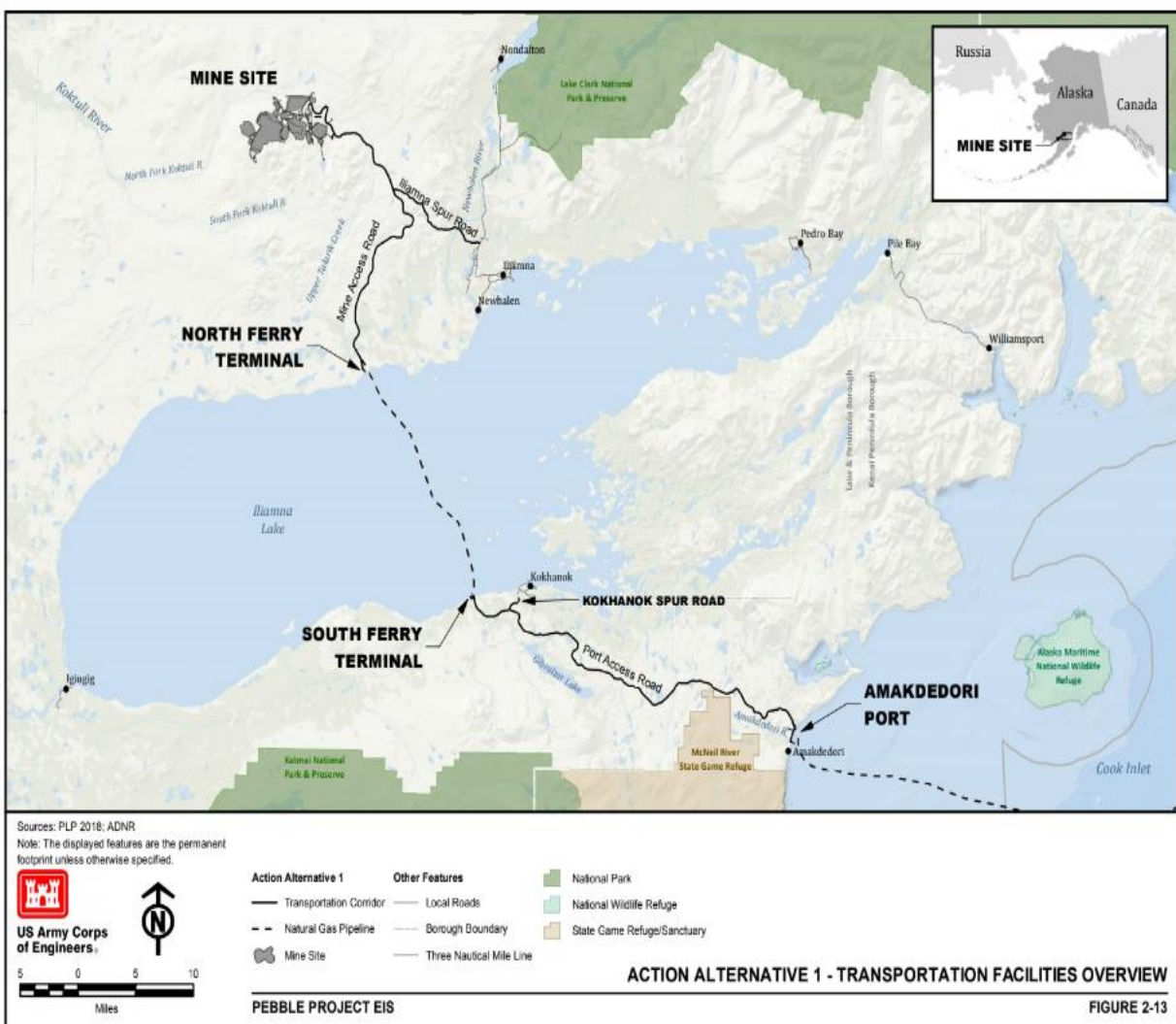


Figure 1. Location of the proposed Pebble Mine, North and South Ferry Terminals and Amakdedori Port facilities in Southwest Alaska.

Apart from the visible stars and natural moonlight, night skies are not completely dark even in

remote areas. Several sources, both natural and artificial, contribute to a diffuse brightening of the night sky. Natural sources include faint stars, particularly noticeable within the Milky Way, sunlight illuminating fine dust particles within our solar system (the zodiacal light), natural luminescence of atoms and molecules in the upper atmosphere (airglow), and auroral activity due to high energy particles originating in the solar wind impinging the upper atmosphere. Artificial lighting used in our homes and communities leads to “anthropogenic sky glow,” a form of light pollution. This anthropogenic sky glow arises from light emitted directly upward from incompletely shielded light fixtures, as well as from light reflected upward from illuminated ground and other structures. Through interaction with molecules and dust particles in the atmosphere a portion of this light is then scattered back toward the ground, brightening the sky. Within and near urban areas, anthropogenic sky glow can completely overwhelm natural sources, making not only natural sources such as the Milky Way invisible, but even obscuring all but the brightest stars.

The U.S. Army Corp of Engineers prepared a Draft Environmental Impact Statement which addresses visual impacts of the project (DEIS, Section 4.11 Aesthetics) on the surrounding area. In the absence of a detailed lighting plan for the PMP, the DEIS provides an assessment of visual impacts using data from the New World Atlas of Artificial Night Sky Brightness (Falchi et al 2016) using the city of Anchorage as a proxy for lighting at the mine operations and the town of Valdez as a proxy for lighting of the ferry terminals and the Amakdedori and Diamond Point ports.

This report presents a assessment of the change in night sky brightness as viewed from within LCNPP due to PMP outdoor lighting under the same assumptions regarding light output.

Regional setting

Measurements of upward radiance from the National Polar-Orbiting Partnership Suomi satellite can be used as a qualitative guide to existing regional light pollution influences (Elvidge et al., 2013). The observed upward radiance from the region around Cook Inlet, Alaska is shown in Figure 2. These data show light emanating from Anchorage as well as smaller towns along the Kenai Peninsula, and Valdez to the east.

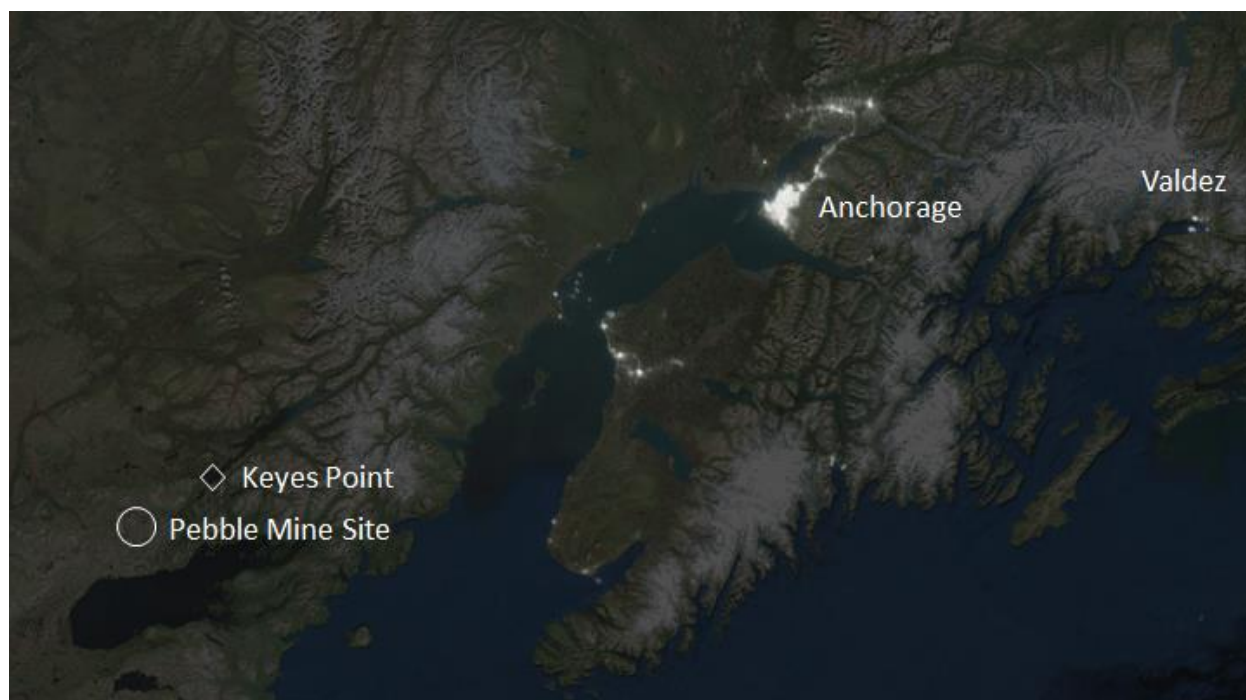


Figure 2. Nighttime satellite image of the region surrounding Cook Inlet, Alaska.

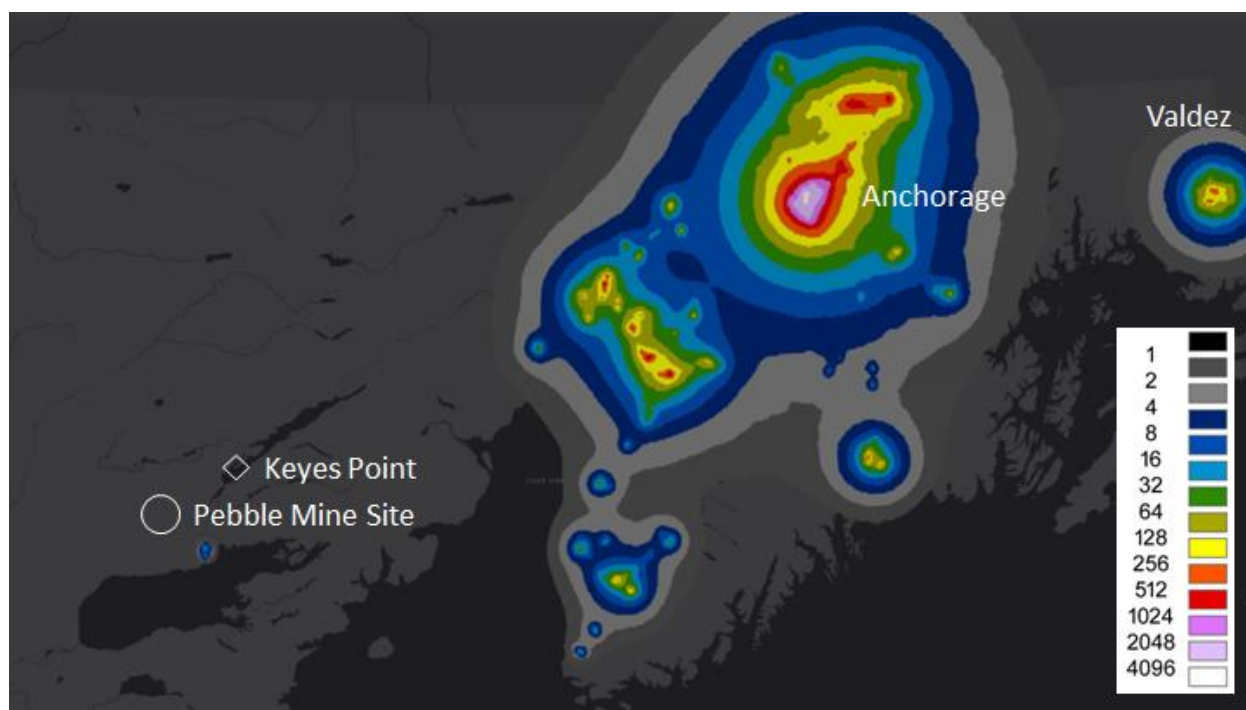


Figure 3. Modeled 2014 zenith sky brightness levels in the region of the Pebble Mine Project and Anchorage, from the New World Atlas of Artificial Night Sky Brightness. The color scale indicates the percent increase over natural conditions. Credit: Falchi et al., 2016, Jakob Grothe/NPS contractor, Matthew Price/CIRES.

These satellite data have been used to model the current (2014) zenith sky brightness levels in

The New World Atlas of Artificial Night Sky Brightness (Falchi et al., 2016). The region of this Atlas for the area shown in Figure 2 is shown in Figure 3. The region around the proposed Pebble Mine is quite dark at present with the dominant source of lighting being the city of Anchorage, located 330 km from the proposed mine itself. There is a very small amount of light emanating from Newhalen and the Iliamna airport.

Study approach

This study evaluates the increase in sky brightness due to PMP planned operations as seen from one observation point in LCNPP. The first step in this process is to characterize the current sky brightness. This was done by NPS in 2013 using an automated CCD camera system to accurately measure the brightness of the entire night sky (Duriscoe et al., 2007). Next, a computer code developed by DSP was used to calculate the increase in sky brightness due to PMP operations using the methodology described in the following section. This sky brightness increment was then added to the Keyes Point measurements to find the sky brightness increase that would be observed when PMP is in full operation. Various measures of the impact of PMP lighting are presented. These methods are further detailed in Section II; Section III presents the results of the measures and predictions, while Section IV presents a discussion and conclusions.

II. STUDY METHODOLOGY

A. Current Sky Brightness Measurements

The basic methodology of this study was to measure the current sky brightness at an observation point in the LCNPP and add to these measurements the calculated increase in sky brightness due to lighting from the PMP. All-sky measurements of sky brightness made at Keyes Point were made by NPS on 5 April 2013 (US National Park Service, 2016); Table 1 gives the coordinates of the observation point.

Table 1. Observation point location and altitude.

OBSERVATION SITE	LATITUDE (d:m:s)	LONGITUDE (d:m:s)	ALTITUDE (m)
Keyes Point	+60:04:50.1	−154:41:32	457

All measures were made in the astronomical visual (V) band, with spectral response shown in Figure 4. Using this spectral response allows calibration of the data in internationally-recognized astronomical units of visual (V) magnitudes¹ (where sky brightness is measured in magnitudes per square arc second – mag/arcse²), and also in units used in lighting (lumens, lux), using astronomical sources (i.e. stars). Though the astronomical V and human photopic response used

¹ Astronomical magnitudes are a logarithmic measure where each magnitude corresponds to a change in brightness of a factor of 2.5, and smaller numbers correspond to brighter measures. Thus, a magnitude of 20.0 is 2.5 times brighter than a magnitude of 21.0.

to define lumens are quite similar (cf. Duriscoe et al., 2007), it is important to recognize that the photopic response is significantly different than the human visual response when observing night skies (cf. Luginbuhl et al., 2014). The consequences of the difference between photopic and scotopic responses for this study will be discussed in Section III – *Spectral Effects*.

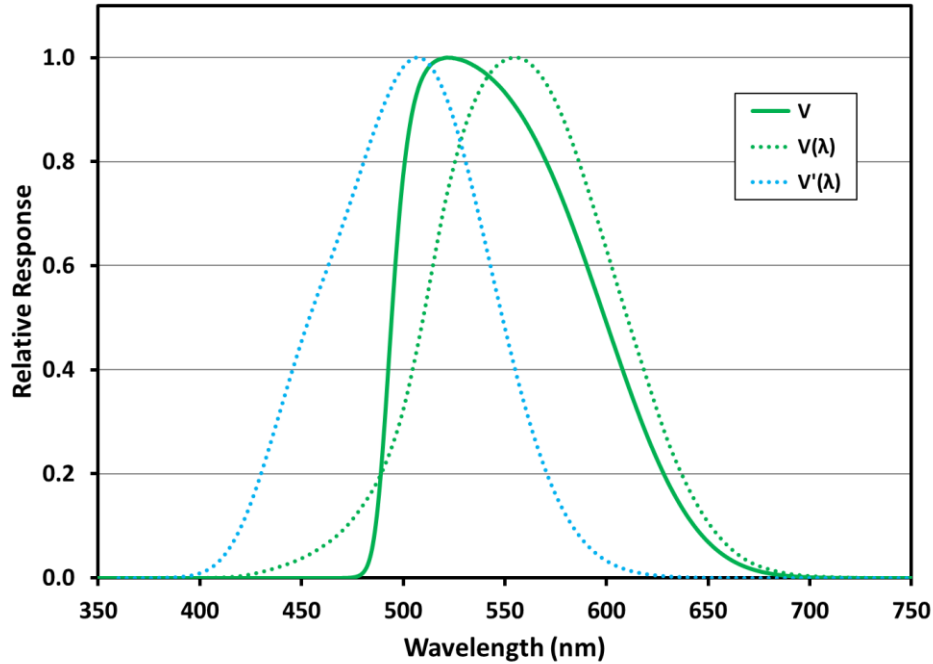


Figure 4. Relative spectral response for the visual (V) band used in this study for sky brightness measurements. This response is close to the spectral response of the human eye under light-adapted conditions – $V(\lambda)$. Under dark-adapted conditions human visual response – $V'(\lambda)$ – is significantly less red-sensitive and more blue-sensitive than V.

B. The Numerical Model

R. Garstang (Garstang, 1986; 1989; 1991) developed a model for predicting sky brightness arising from artificial light scattering from molecules and aerosols in the atmosphere. This model has been improved by Luginbuhl et al. (2009b) and Luginbuhl et al (2014) to include spectral effects and effects on light propagation caused by blocking of the light by objects near the ground, such as buildings, vegetation and terrain. Software based on this improved model, developed by DSP, calculates the sky brightness observable from any location and toward any viewing direction due to light emitted from cities and towns or any specific light source or sources. This model has been shown to give predictions in excellent agreement with observations (Luginbuhl et al., 2009b; Duriscoe et al, 2014). The software was used to assess the increase in sky brightness due to the lighting proposed by the PMP.

The inputs for the model include parameters describing the condition of the atmosphere and reflectivity of the ground, and amount of blocking of emissions arising from objects near the ground and surrounding terrain, and the locations (latitude, longitude and altitude) and photometric characteristics of lighting sources (luminous flux, shielding) of future outdoor

lighting. These inputs and approaches are described in the following subsections.

i) Atmospheric Clarity and Geometric Blocking

The transparency of the atmosphere (i.e. the amount of aerosol) is a major factor in determining sky glow from artificial sources. The calibration process using astronomical stellar sources that is applied to each sky brightness observation provides an accurate measure of the aerosol content, expressed in the astronomical parameter called “extinction,” (k_v), which can be related to both standard meteorological horizontal visibility (measured in kilometers) and the ratio between total scattering from molecules and aerosols needed in the Garstang model. The extinction and horizontal visibility determined for the 2013 observation are shown in Table 4.

The physical environment near to the light sources also affects the amount of light that gets into the atmosphere. The E_b and β parameters (cf. Luginbuhl *et al.*, 2009b, eq. 2) are used to characterize average near-ground blocking of light by the variety of structures and vegetation near the lighting installations. This adjustment affects both the amount of light escaping into the sky as well as the angular intensity distribution of this upward-directed light. The values chosen here have been determined to provide excellent correspondence between on-the-ground lighting inventories and sky brightness measures made in Flagstaff, Arizona (Luginbuhl *et al.*, 2009; Dark Sky Partners, 2015), which has a forested environment similar to the PMP area, with similar blocking characteristics.

The ground reflectivity (G) of 0.15 chosen to characterize the mining site is a typical average value for a wide variety of surfaces in the mining site in the absence of snow cover, including terrain, vegetation, concrete, and asphalt hardtop, and has been found to adequately characterize ground reflectivity for all warm season light pollution modeling efforts to date (Garstang 1986, 1989, 1991; Luginbuhl *et al.* 2009b and references therein; Duriscoe *et al.* 2014). The higher value of 0.6 is representative of snow that has been on the ground for a period of time. Table 2 shows the near-ground blocking and ground reflectivity parameters adopted for this study.

Table 2. Geometric blocking and ground reflectivity parameters used in the models

PARAMETER	VALUE
E_b	0.70
β	0.10
G (no snow)	0.15
G (snow)	0.60

ii) Project Lighting

Artificial light propagates upward into the atmosphere via two paths: 1) direct uplight from fixtures that are incompletely shielded, and 2) light reflected from the ground or other surfaces illuminated by the fixtures. These locations, fixture and lumen totals are listed in Table 3. Lumen amounts have been estimated using a value of 2400 lm per capita for Anchorage and Valdez, a figure representative of a wide range of communities (cf. Luginbuhl *et al.*, 2009a).

Table 3. Lighting site locations, fixture numbers and lumen totals used in the study.

LOCATION	LATITUDE (d:m:s)	LONGITUDE (d:m:s)	ELEVATION (m)	LUMENS
Pebble Mine Pit	+59:54:00.0	-155:21:36.0	455	735,000,000
North Ferry	+59:39:28.8	-155:10:37.2	37	9,655,000
South Ferry	+59:25:55.2	-154:54:50.4	37	9,655,000
Amakdedori Port	+59:17:52.8	-154:07:12.0	0	9,655,000
Diamond Point Port	+59:38:16.8	-153:40:04.8	0	9,655,000
TOTAL				773,620,000

Direct upward emission from light fixtures is unknown at this point due to the lack of detailed lighting plans. We model both what is a typical condition where 10% of the light emitted from the fixtures is projected above the horizon (cf. Garstang, 1986), and a second condition where all fixtures are fully shielded, i.e. emitting 0% above the horizon.

III. RESULTS

A) Measures of the Current Condition

All-sky measurements of sky brightness made at Keyes Point, LCNPP were made on 5 April 2013 using the camera system described in Section II, and are shown in the top panel of Figure 5.

To quantify the quality of the night sky one measure of atmospheric transparency and two measures of night sky quality are determined from this measurement. The transparency of the atmosphere determines not only how much starlight is absorbed between the top of the atmosphere and the observer, but also the relative amount of atmospheric aerosol or “turbidity” that affects how light – particularly artificial light – is scattered in the atmosphere. In common astronomical practice this transparency is characterized by the astronomical extinction coefficient (k_v), measured in magnitudes per airmass, and in meteorological studies by the horizontal visibility (measured in kilometers). The first measure of night sky quality is the Average Sky Luminance (ASL, measured in mag/arcsec²) calculated for the entire upward hemisphere (i.e. from the geometric horizon to the zenith)². The second is the maximum or brightest luminance at any point above the horizon. These measures are described more fully below. The observation time, atmospheric extinction, horizontal visibility, and indicators of sky quality are listed in Table 4.

Table 4. Sky brightness observation dates, times, measured extinction k_v , horizontal visibility, and two measures of sky quality – Average Sky Luminance (ASL) and maximum (brightest) Luminance.

LOCATION	DATE (y/m/d)	k_v	VISIBILITY (km)	ASL (mag/arcsec ²)	BRIGHTEST (mag/arcsec ²)
Keyes Point	2013/04/05	0.36	23	21.56	20.97

² ASL measures and predictions in this report include the entire upward hemisphere from 0° to 90° elevation.

i) Average Sky Luminance (ASL)

The Average Sky Luminance is a measure of the diffuse brightness of the night sky, and is calculated by averaging the brightness of the sky from the zenith to the geometric horizon after resolved stellar sources have been removed. It includes contributions from natural sources such as atmospheric airglow, zodiacal light, and faint unresolved stars (including in the Milky Way), as well as contributions from artificial lighting originating at the ground but scattered back toward the observer.

ii) Maximum Luminance

The maximum luminance shows the brightest diffuse brightness of any point in the sky. Under natural unpolluted conditions this will tend to lie somewhere in the Milky Way if it is above the horizon, or about 10° above the horizon if the Milky Way has not yet risen. If there is a light dome arising from an artificial lighting source, the brightest point is likely to appear near the horizon in the direction of the source.

B) Sky Brightness Changes with Proposed Pebble Mine Project Lighting

All-sky maps of the modeled sky brightness including the observed natural contributions and those predicted to arise from PMP and associated terminal lighting are shown in the lower panels of Figure 5.

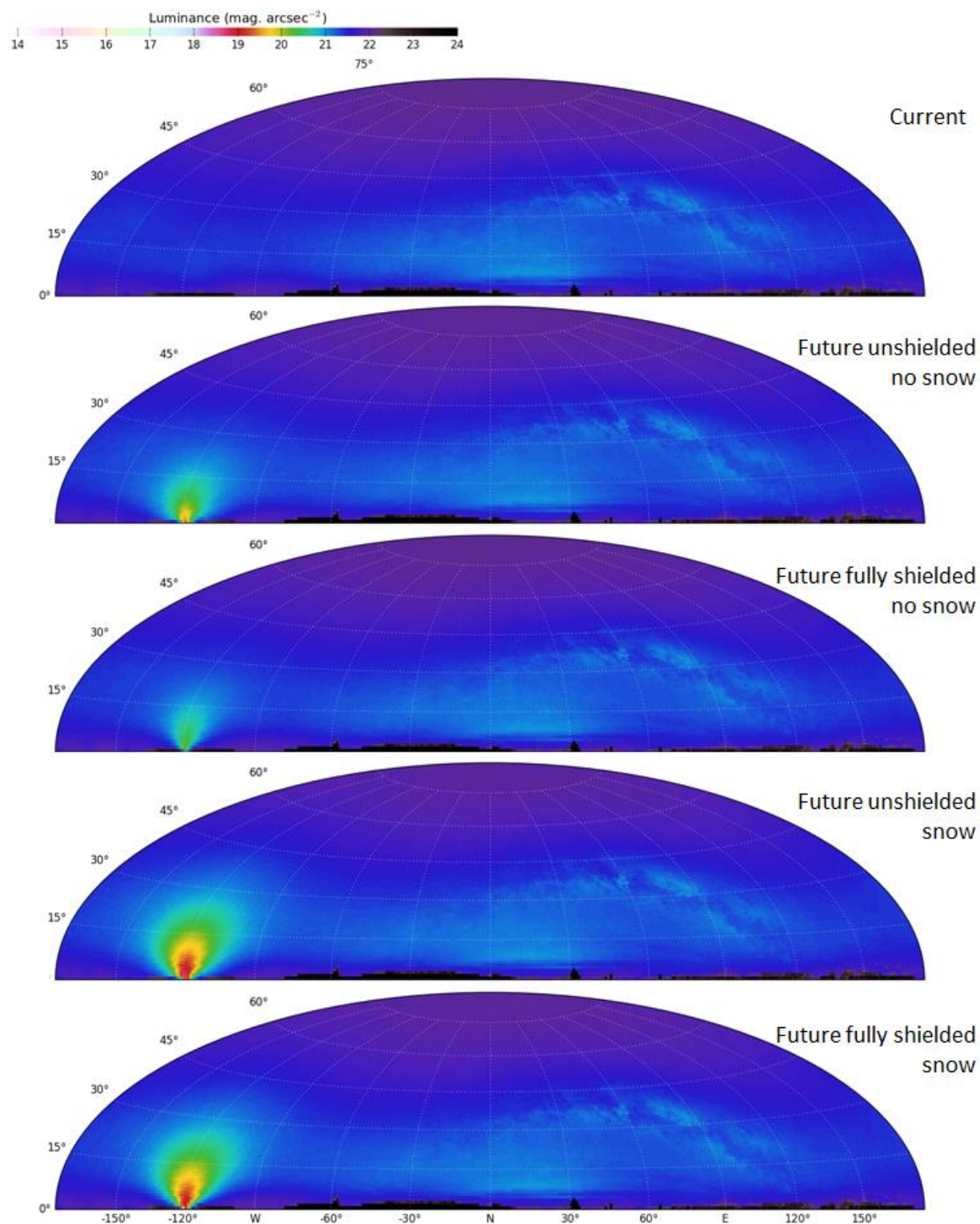


Figure 5. False color all-sky maps showing measured current sky brightness in the visual (top), predicted additional sky brightness arising from proposed PMP and terminal lighting under the indicated light fixture shielding (unshielded = 10% direct uplight; fully shielded = 0% direct uplight) and groundcover conditions, as seen from the Keyes Point observation site. The units are explained in the text. The map shows the entire sky hemisphere covering 360° azimuth and from horizon to the zenith. All maps are Hammer-Aitof equal-area projections.

To quantify the effects of the PMP lighting on night sky conditions, the increment to ASL and the maximum sky luminance was determined. The results are summarized in Table 5, and show that the Average Sky Luminance increases from 21.56 mag/arcsec² to 21.49-21.41 mag/arcsec² (6-15%) when 10% direct uplight is assumed, or 21.53-21.43 mag/arcsec² (4-12%) if fully shielded (0% direct uplight) lighting is assumed.

Table 5. Average Sky Luminance (ASL) and maximum sky luminance as observed from Keyes Point under current (2013) conditions and after addition of estimated PMP lighting.

CONDITION	ASL		Max	
	(mag/arcsec ²)	ratio	(mag/arcsec ²)	ratio
Current	21.56	1.00	20.98	1.00
10% Uplight; no snow	21.49	1.06	18.97	6.38
0% Uplight; no snow	21.53	1.04	20.21	2.03
10% Uplight; snow	21.41	1.15	18.50	9.86
0% Uplight; snow	21.43	1.12	18.92	6.70

While the effects on the average sky conditions appear modest (15% increase or less), the effect in areas of the sky in the direction toward the PMP is substantially greater. The sky viewed immediately above the direction toward the PMP will have brightness increases of 2.03x (103%) to 9.86x (886%) over the current measured condition.

Spectral effects.

Though no information is available regarding the spectral characteristics of the lighting to be used at the mine or port terminals, it is important to be aware of the difference between the V-band or photopic brightness changes predicted and described here and actual impacts on dark-adapted human vision.

As the human eye is dark-adapted (scotopic) (cf. the $V'(\lambda)$ response shown in Figure 4) when viewing luminances fainter than 18.5 mag/arcsec², the greater blue and green content of white lighting sources means that the impacts on visual brightness will be greater than from yellow-rich sources such as HPS or amber LEDs. Assuming an equal number of lumens would be applied, the relative impacts of different spectra are well gauged by the use of the scotopic to photopic (S/P) ratio (Luginbuhl et al., 2014). As an example, 4000 K CCT white LED has an S/P of ~1.47; HPS has an S/P of ~0.6, and a phosphor-converted amber LED can be as low as 0.4. Thus the use of a 4000 K CCT white LED will produce $\sim 1.47 / 0.6 = 2.5x$ greater impact to visual sky brightness than HPS, and $\sim 1.47 / 0.4 = 3.7x$ greater than low S/P phosphor-converted amber LED.

Comparison of representative spectral power distributions for 4000 K CCT, 2700 K CCT, and phosphor-converted amber LEDs are shown in Figure 6; a list of LED types with typical S/P ratios is shown in Table 6. The lower sky glow impact of the phosphor-converted amber LED arises from the dramatically decreased emission in the blue and green portions of the spectrum, corresponding to the region most sensitive to scotopic vision (V'_{λ}) as shown in Figure 4. It is important to note that the often-recommended strategy of specifying low-CCT white LEDs will

not achieve nearly the sky glow light pollution mitigation achievable with low-S/P phosphor-converted amber LED.

Table 6. Representative scotopic to photopic ratios (S/P) for LEDs and high-pressure sodium. Note that S/P can vary from manufacturer to manufacturer and even within product lines even if the CCT value is nominally the same. This is especially true for phosphor-converted amber LED.

LAMP	S/P
LED 5000K CCT	2.0
LED 4000K CCT	1.6
LED 3000K CCT	1.3
LED 2700K CCT	1.1
LED phosphor-converted amber	0.4 – 1.0
High-Pressure Sodium	0.6

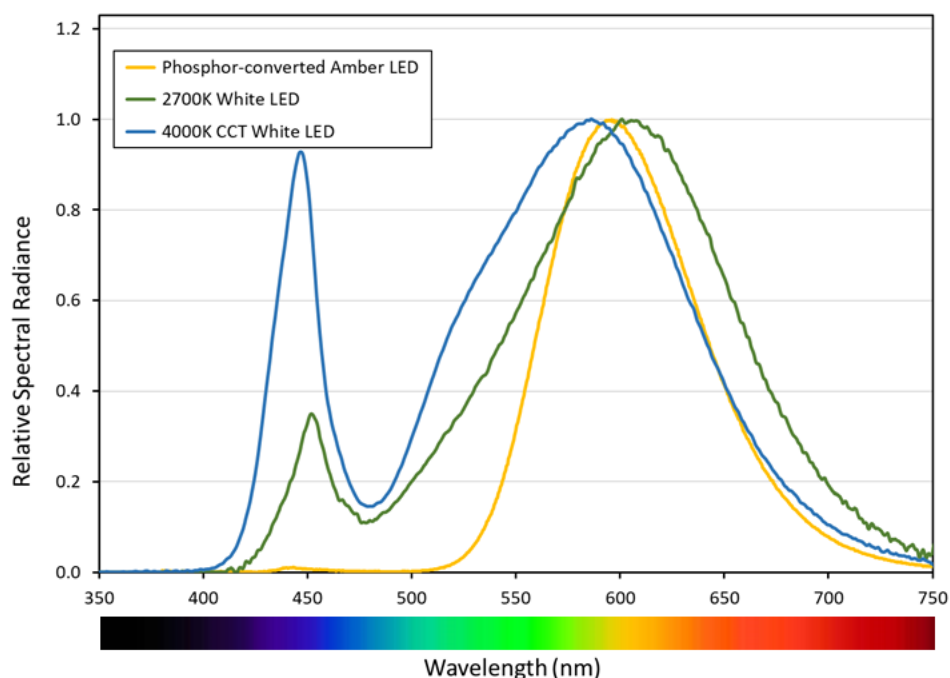


Figure 6. Relative spectral radiance for 4000 K CCT white LED, 2700 K CCT white LED, and a low-S/P (0.45) phosphor-converted amber LED.

IV. DISCUSSION AND CONCLUSIONS

This analysis shows that the PMP lighting can be expected to increase the average sky luminance as viewed from Keyes Point by 4-15 %, depending on fixture shielding and ground reflectance conditions. When considering the areas of the sky in directions toward the proposed mine site particularly, the maximum sky luminance would increase 103% to 886%. These increments would add a significant artificial light source in the nighttime viewshed that is currently in a nearly pristine condition.

Utilization of fully shielded fixtures would reduce the increase in average sky luminance to 4-12%, and maximum sky luminance to 103-570%. An emphasis on yellow-rich sources such as phosphor-converted amber LED for much lighting could reduce the incremental impact substantially. Though it may not be practical that all of the outdoor lighting installed for mining or ferry terminal operations could be phosphor-converted amber LED, serious consideration of the maximum use feasible is justified due to the light pollution benefits. Other design strategies that may substantially mitigate the impacts of the proposed lighting may be available.

Potential opportunities to mitigate PMP lighting impact

As specifications for the lighting infrastructure are developed, five aspects could be examined for their potential to decrease the impacts of the proposed lighting at PMP and terminal facilities, as follows:

1. Specify in all situations feasible fully shielded lighting fixtures installed in a fashion to direct all lighting downward.
2. Perform a critical examination of where lighting is needed for operational effectiveness and safety. For example, lighting along roadways where only vehicular traffic exists with no potential pedestrian conflicts, may provide no safety benefit.
3. Perform a critical examination of where color perception is needed for operational effectiveness and safety. In areas where accurate color perception is not critical, specify phosphor-converted amber (providing some color discrimination) or direct-emission (also called “narrowband” or “limited wavelength” or “590 nm”) amber LEDs.
4. Perform a critical examination of illumination levels, and reduce where appropriate. Many specific illumination recommendations provided for typical community applications (e.g. roadways, parking lots, etc.) may not be applicable to needs at industrial sites such as a mine. Further, lighting recommendations included in MSHA publications (CFR Title 30 Part 56) do not require specific illumination levels, suggesting only that the illumination “sufficient to provide safe working conditions” is needed.
5. Perform a critical examination of operations to determine if some lighting may be installed with control systems that either provide the ability to turn lighting off or dim it to a lower intensity at particular times of night, or activate light based on motion detected within the work area.

Most of these recommendations have the potential to decrease energy use as an additional benefit.

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