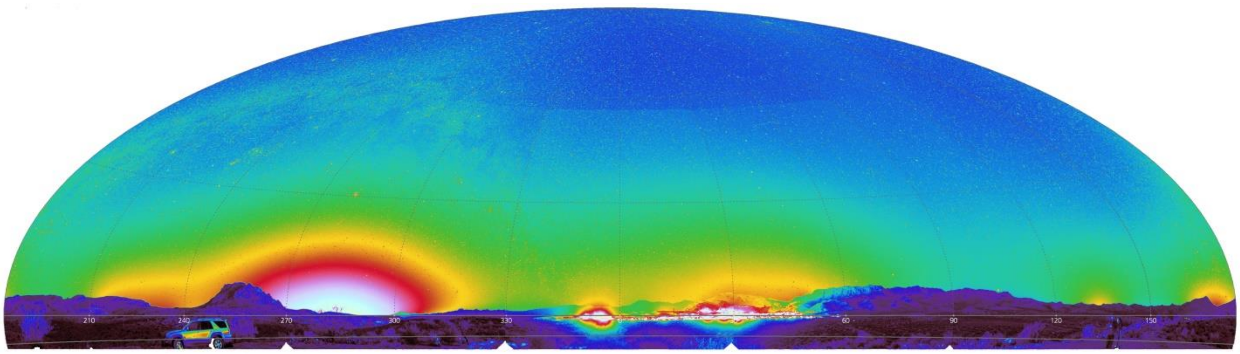
IMPACT ASSESSMENT OF THE PROPOSED RESOLUTION COPPER MINE ON NIGHT SKY BRIGHTNESS



Current Visual Sky Glow near Superior, Arizona

FINAL REPORT

Prepared by Dark Sky Partners, LLC
for
Resolution Copper Mining

February 2018

RESOLUTION
COPPER

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March 20, 2018

Mary Rasmussen
US Forest Service
Supervisor's Office
2324 East McDowell Road
Phoenix, AZ 85006-2496

Subject: Resolution Copper Mining, LLC – Mine Plan of Operations and Land Exchange – Impact Assessment on Night Sky Brightness

Dear Ms. Rasmussen,

Enclosed for your review and consideration, please find the report titled *Impact Assessment of the Proposed Resolution Copper Mine on Night Sky Brightness*.

Should you have any questions or require further information please do not hesitate to contact me.

Sincerely,

Vicky Peacey

Vicky Peacey,
Senior Manager, Permitting and Approvals; Resolution Copper Company, as Manager of Resolution Copper Mining, LLC

Cc: Ms. Mary Morissette; Senior Environmental Specialist; Resolution Copper Company

Enclosure(s): *Impact Assessment of the Proposed Resolution Copper Mine on Night Sky Brightness*.

Contents

SUMMARY

The impact of outdoor lighting from the proposed Resolution Copper mine on the night skies as viewed from four observation points is assessed.

The proposed lighting for the project was used as input to a computer program that calculates the resulting increase in sky glow. The model results were then added to measurements made of the current sky brightness in order to find the sky brightness increment arising from the mine. 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 three metrics at each observation point: One was the Average Sky Luminance (ASL), the sky brightness calculated over the entire sky, the second is the Artificial Luminance Ratio or the ratio of the measured or observed ASL to the natural condition, and the third was the decrease in the number of visible stars. The results show an increase in the ASL of <1% to 9% while the number of visible stars decreases between 1% and 6%. In the direction of the mine, the increases range between about 5% and 40%. Existing lighting in the region – from Superior and other small communities to the large Phoenix metropolitan area – currently produces an increase in ASL of ~300–500% above a pristine unpolluted sky; the effects of the proposed mine lighting are in addition to this existing increase.

The visual impact of the lighting on human dark-adapted vision is enhanced with the blue-rich white LED lighting used throughout the site. Sample calculations assuming 4000 K CCT LEDs show an 80% increase in sky glow relative to a mix of HPS, LED and incandescent lighting thought to be typical of current lighting. This increase could be substantially reduced by using a mix of yellow-rich sources such as phosphor-converted amber LED for much of RC lighting where color rendition is not crucial for safety.

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I. INTRODUCTION

Resolution Copper Mining, LLC (hereafter RCM) proposes to develop an underground copper mine (hereafter RC) near Superior, AZ. As part of the preparation for mining operations, RCM contracted with Dark Sky Partner, LLC to perform an assessment of the impact of the outdoor lighting needed for RC mining operations on the night skies in the region.

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), and natural luminescence of atoms and molecules in the upper atmosphere (airglow). 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.

Outdoor lighting at RC mining facilities is subject to the standards of the Pinal County Outdoor Lighting Code. Assessment of compliance of the proposed RC lighting is included in *Outdoor Lighting & Pinal County Outdoor Lighting Code Tech Memo Rev 2.pdf* prepared by M3 Engineering. One of the purposes for enactment of these standards, is "… minimizing light trespass and negative impacts on the surrounding area and our night sky" (cf. PCOLC Section 2.195.010.A); enjoyment of night skies in the region is a factor for many people who choose to live away from a major urban area. In addition, the impact of light pollution is increasingly being identified as a contributing factor to changes in both flora and fauna as circadian rhythms become altered (e.g. Irwin, 2018). Through this study RCM intends measure, predict, and where possible mitigate such impacts.

This document reports on the findings of current and predicted future sky brightness conditions after the development of mining operations near Superior. It quantifies several aspects of night sky quality, and supplements these measures with visual assessments. Photometric measurements of the entire sky were collected to quantify the current sky brightness condition in the region. Lighting amounts and locations, provided to DSP by RCM, were used to model the expected changes when mining operations are fully developed.

Regional setting

Measurements of upward radiance from the Suomi NPP 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 Superior, Arizona is shown in Figure 1. These data show light emanating from small towns such as Superior, Miami and Globe, as well as the state prison facilities at Florence, other mining operations in the area such as at the Ray and Pinto mines, and the Phoenix metropolitan area to the west.

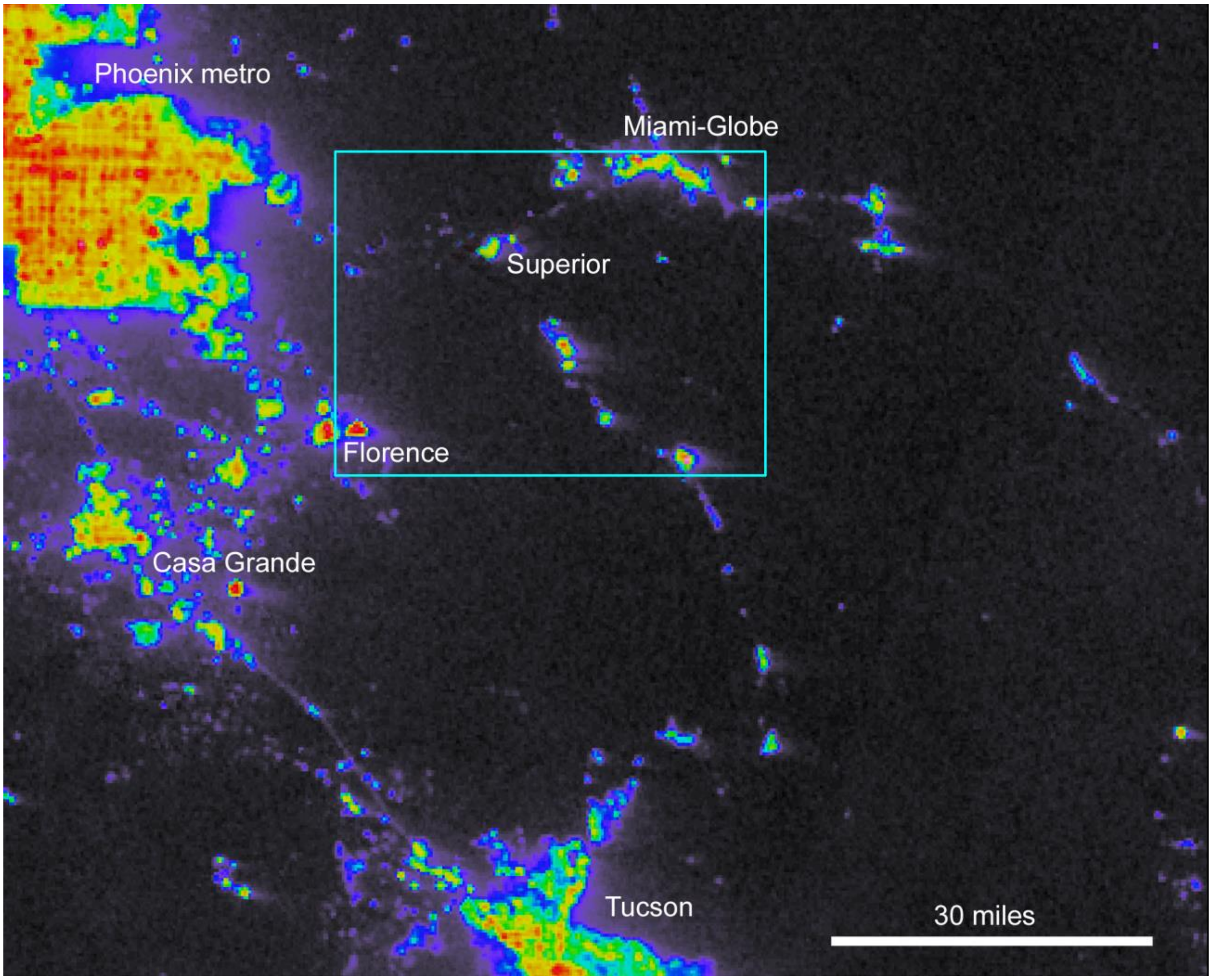

Figure 1. Nighttime satellite image of the region surrounding Superior, Arizona. The rectangle indicates the area shown in Figure 3.

Though the light sources shown in these images appear confined to the towns and metropolitan areas, light pollution such as increased artificial sky brightness spreads quite far into the surrounding areas which appear dark in these images. These satellite data had been used to predict 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 covered by Figure 1 is shown in Figure 2. This kind of analysis indicates not only that night sky conditions near RC are influenced by lighting at distant locations, but also that RC lighting can have impacts on distant locations as well. Arizona is noted for its very dark skies which are essential to maintain for the professional astronomical community as well as for the enjoyment of citizens and visitors who enjoy star-filled night skies.

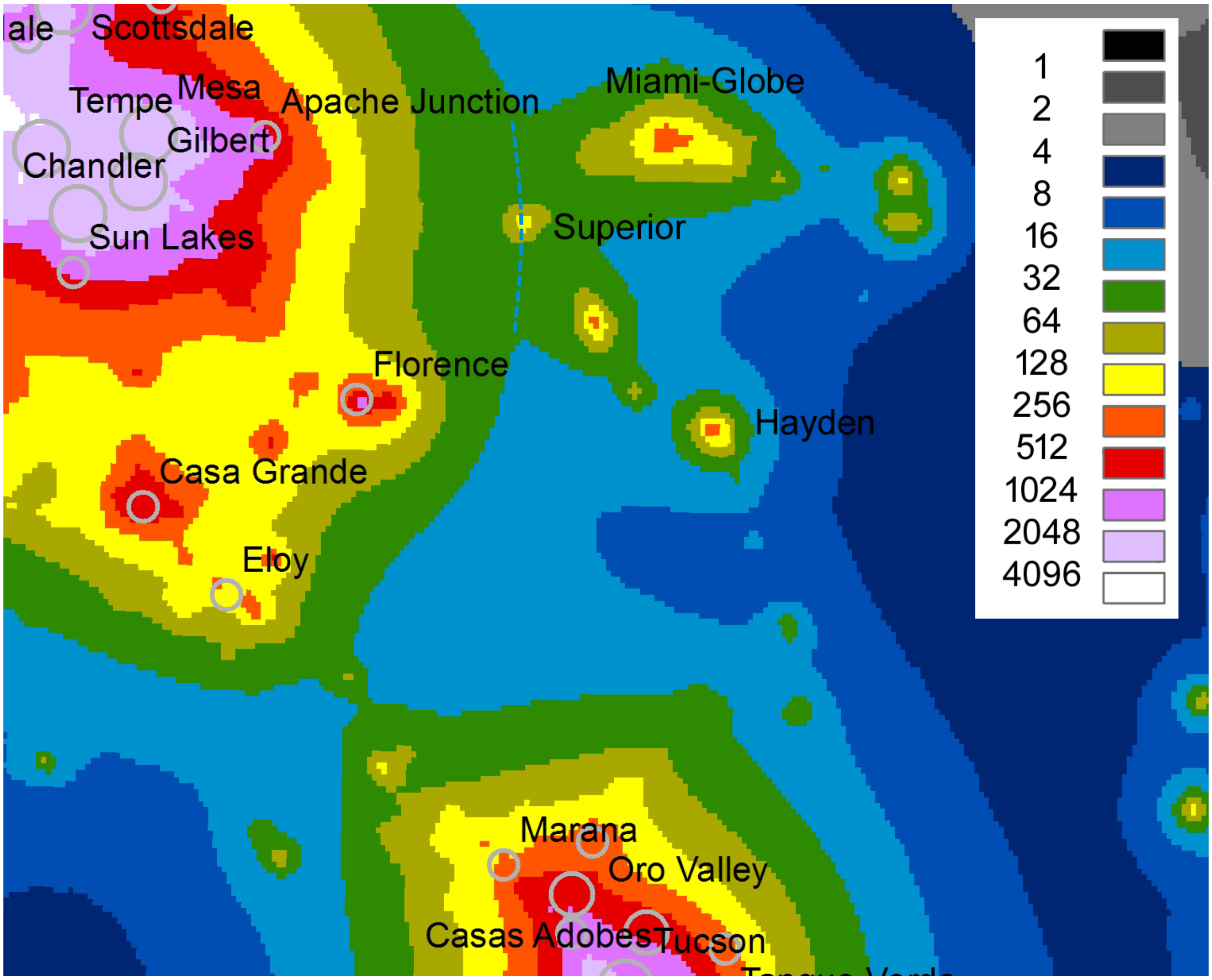

Figure 2. Predicted artificial zenith sky brightness from the New World Atlas of Artificial Night Sky Brightness, for the region shown in Figure 1. The values in the color key indicate the percent brightness increase over natural sky brightness levels at the boundary between the indicated colors. Even if the effects of existing lighting in Superior and Miami-Globe could be removed, this map indicates that lighting in the Phoenix metropolitan area would still increase sky brightness in the Superior area by about 32% (at the boundary between green and turquoise, as indicated by the dashed turquoise line).

The zenith (straight overhead) light pollution levels indicated in Figure 2 show that night sky brightness in the area near Superior is already significantly above natural levels, before any additional lighting is installed as a part of RC development. Increases of 10% – 15% or less (black through dark blue) are imperceptible to most casual observers, though levels in parts of the sky near the horizon toward developed areas will be much brighter and easily noticeable even in these locations. Professional astronomical observation is much more sensitive to increased sky brightness, and can be significantly impacted even at 10% (see e.g. Schreuder, 1998). In locations coded yellow and brighter (>128% above natural), the sky has become bright enough that even the Milky Way is no longer visible to the human eye (Falchi et al., 2016). It is worth noting that, though Superior and other nearby small communities contribute to increased sky brightness nearby (indicated by the increased brightness contours centered on these locations in Figure 2), if these local contributions were removed entirely, the sky over the Superior area would still appear approximately 32% brighter than natural, arising from lighting used in the Phoenix metropolitan area (as indicated by the dashed turquoise line).

Outdoor lighting installed at RC is subject to the Outdoor Lighting Code of Pinal County, Arizona. In addition to this regulatory constraint, RC has expressed an intention to further minimize impacts to the degree possible within safety and operational needs.

Study approach

This study evaluates the increase in sky brightness due to RC planned operations as seen from locations where human observers may constitute sensitive receptors to night sky impacts. The first step in this process is to characterize the current sky brightness. This was done using a camera developed by DSP to accurately measure the brightness of the night sky over the entire sky. Next, a computer code developed by DSP was used to calculate the increase in sky brightness due to RC operations based on the initial lighting plan developed by M3 Engineering & Technology Corporation. This sky brightness increment was then added to the current observations to determine the predicted sky brightness that will be observed when RC is in full operation. Various measures of the impact of RC 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.

As the goal of the study is to assess the visual brightness of the night sky, and since impacts to the night sky from RC lighting will depend on location, four observation points (OP) were chosen in consultation with RCM to represent locations where some sensitivity to these impacts may be anticipated. These observing sites were selected based on the following criteria: 1) Superior – a location on the outskirts of the town to illustrate impacts on local homeowners; 2) Oak Flat – a nearby campground where people can access a more natural environment; 3) Boyce Thomson Arboretum – a biological preserve close to Superior and 4) Queen Valley – a residential development located about 18 km (12 mi) west of Superior and the RC mine.

These locations are shown in Table 1 and Figure 3. Observations were obtained on the nights of January 28 and 29, 2017.

Table 1. Observation point locations and altitudes.

OBSERVATION SITE	LATITUDE (d:m:s)	LONGITUDE (d:m:s)	ALTITUDE (m)
Superior	+33:15:59.9	-111:07:10.1	833
Oak Flat	+33:18:34.5	-111:02:56.6	1201
Boyce Thompson	+33:16:47.3	-111:09:35.9	738
Queen Valley	+33:18:00.4	-111:18:00.2	613

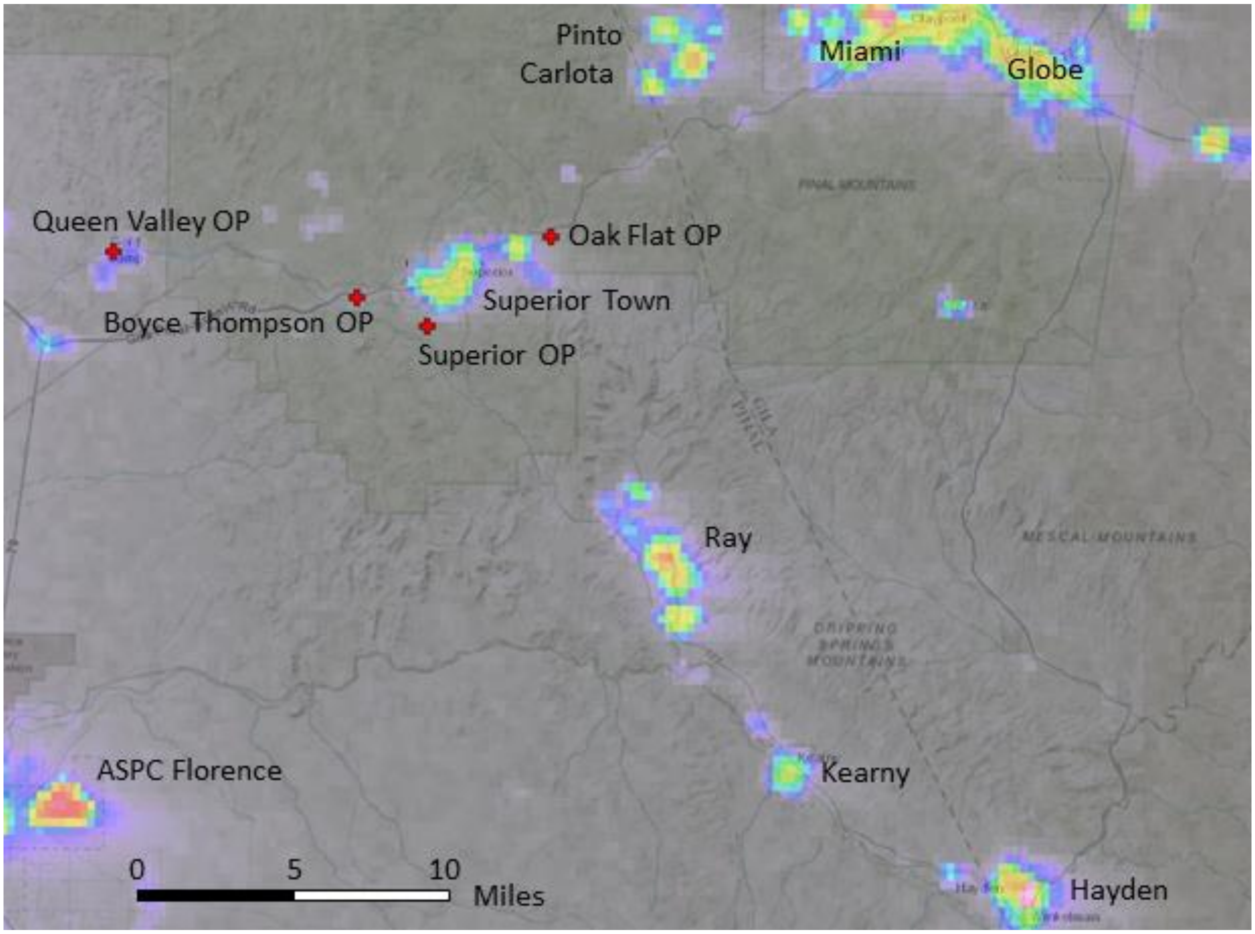

Figure 3. Location of the observation points where sky brightness measurements were made.

Two different cameras were used – data at the Boyce Thompson and Oak Flat campground used the CCD camera system described by Duriscoe et al 2007. Data at the Superior and Queen Valley OP's were taken using an improved version of this camera developed by DSP. With both cameras, individual images (41 in the first camera; 7 in the second) transform to accurate altitude in azimuth coordinates and mosaicked to produce the all-sky maps shown in Section III. All data were taken in the astronomical visual (V) band (Figure 4). Using this spectral response allows calibration of the data in internationally-recognized astronomical units of visual (V) magnitudes[1] (where sky brightness is measured in magnitudes per square arc second – mag/arcse[2]), and also in units used in lighting (lumens, lux), using astronomical sources (i.e. stars). Though the astronomical V and human photopic response used to define lumens are quite similar (cf. Duriscoe et al., 2007), it is important to recognize that the photopic response is only an approximation of the human visual response when observing night skies (cf. Luginbuhl et al., 2015). The consequences of the difference between photopic and scotopic responses for this study will be discussed in Section III – *Spectral Effects*.

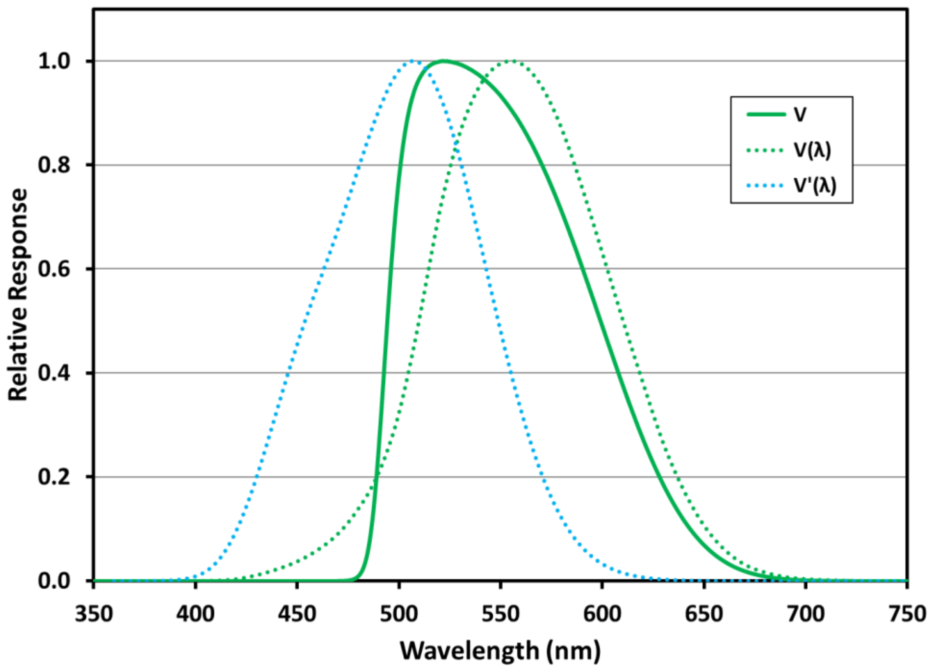

Figure 4. Relative spectral response for the visual (V) band used in this study for sky brightness measurements. This response is close to the spectral response of the human eye under light-adapted conditions – V(λ). Under dark-adapted conditions human visual response – V'(λ) – is significantly less 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, Boley and Davis (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

[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.

been shown to give predictions in excellent agreement with observations (Luginbuhl et al., 2009b; Duriscoe, Luginbuhl & Elvidge, 2014). The software was used to assess the increase in sky brightness due to the lighting proposed by the RC project.

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 data set 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 each 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 ground reflectivity (G) of 0.15 chosen after consultation with M3 Engineering (email from A. Falgiano 11:01AM MST 10/23/2017) to characterize the mining site is a typical average value for a wide variety of surfaces in the mining site, 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). 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	0.15

The model also included blocking by terrain located at greater distance from the lighting installations, such as mountain ridges. The terrain blocking profile, i.e., the terrain elevation as a function of azimuth, as viewed from ground level was generated using a Digital Terrain Model. Figure 2 shows the terrain blocking profiles used in the model.

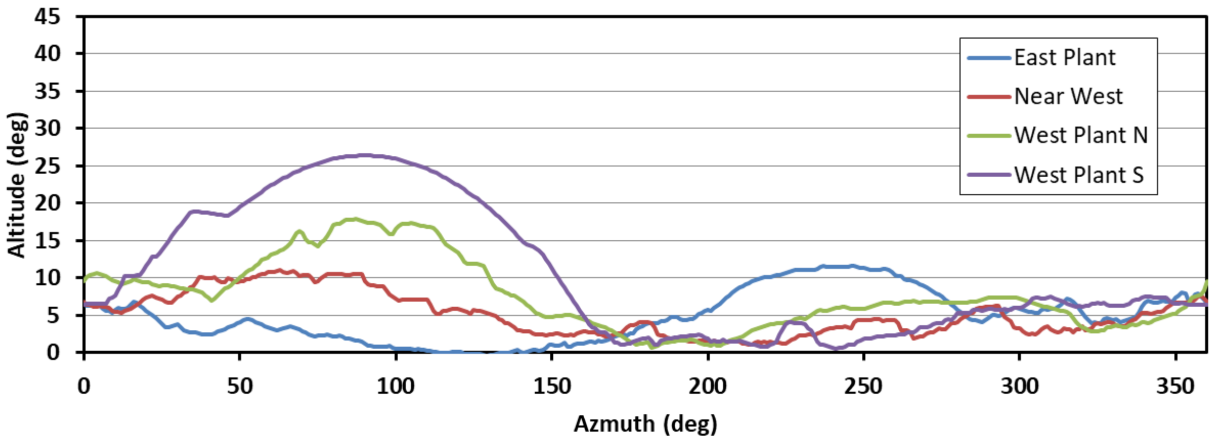

Figure 5. Terrain blocking profiles used for the four lighting locations with significant blocking. The elevation angle of the surrounding terrain as viewed from the indicated sites is shown for all azimuths. (See Section II.B.ii for information on the lighting locations used in the study).

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. For this study, shielding characteristics were provided to DSP in the file *Dark Sky Lighting Fixture Spread Sheet.xls* by M3, including information on 2352 fixtures of 21 different types. The locations of the fixtures were not provided, but instead were grouped into 11 sites identified in the document *RM Outdoor Lighting & PC Outdoor Lighting Code Tech Memo_P2.pdf*. These 11 locations were further reduced to seven locations, as indicated in the "locations" and "plant areas" listed in the *Dark Sky Lighting Fixture Spread Sheet.xls*. These locations, fixture and lumen totals are listed in Table 3.

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)	FIXTURES	LUMENS
West Plant N	+33:18:37.00	-111:06:31.12	957	743	4,967,289
West Plant S	+33:17:47.75	-111:06:30.32	882	642	6,130,838
Queen Valley Pump	+33:16:38.38	-111:16:32.77	642	8	88,425
Cap & booster Pump	+33:09:27.10	-111:27:56.04	478	3	17,985
Near West	+33:19:24.00	-111:09:30.53	804	50	291,106
Concentrate Loadout	+33:11:51.07	-111:24:43.30	521	174	1,081,674
East Plant	+33:18:17.55	-111:04;06.35	1273	732	4,145,795
TOTAL				**2352**	**16,723,112**

Full details about the proposed lighting are collected in the MS Excel file *RC Lighting Information (2017.11.20).xlsx* included with this report.

III. RESULTS

A) Measures of the Current Condition

The night sky was measured at each of the four observation points listed in Table 1 using the camera system described in Section II A. Sky brightness maps of representative datasets are shown for each observation point in the upper panels of Figure 6 through Figure 9. All observations were made when the moon was below the horizon, and thus represent the darkest conditions observable at these locations.

To examine the sky conditions and variation between multiple datasets obtained at each OP, one measure of atmospheric transparency and two measures of night sky quality are determined from each dataset. 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 (E), 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/arcsec^2) calculated for the entire sky (i.e. from the physical horizon to the zenith). The second is an estimate of the number of stars visible to the naked eye over the entire sky. These measures are described more fully below. The observation times, 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 three measures of sky quality – Average Sky Luminance (ASL), Artificial Luminance Ratio (ALR), and number of visible stars. ALR is the ratio of the measured ASL to an estimated natural condition of 22.0 mag/arcsec^2. Times are for the midpoint of the observation set. The data sets indicated in light gray were used as the reference point for assessing changes expected with added RC lighting, as discussed in Section III.B.**

LOCATION	DATE (y/m/d)	TIME (MST)	k_V	VISIBILITY (km)	ASL (mag/arcsec^2)	ALR %	N STARS
Superior	2017/01/29	00:10:04	0.153	125	20.43	425	3015
		01:31:46	**0.148**	**145**	**20.44**	**421**	**2997**
Oak Flat	2017/01/28	00:07:39	0.164	100	20.49	402	2841
		00:31:29	0.171	90	20.49	402	2786
		00:55:41	**0.166**	**95**	**20.51**	**394**	**2783**
Boyce Thompson	2017/01/28	20:33:05	0.155	125	20.39	441	2967
		20:58:04	**0.150**	**140**	**20.40**	**437**	**2996**
		21:22:36	0.164	105	20.41	433	2966
Queen Valley	2017/01/29	**20:51:45**	**0.155**	**130**	**20.04**	**608**	**2709**

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 physical horizon after resolved stellar sources have been removed. It includes contributions from natural sources such as atmospheric airglow, zodiacal light, and faint unresolved stars, as well as contributions from artificial lighting originating at the ground but scattered back toward the observer.

ii) Artificial Luminance Ratio (ALR)

The Artificial Luminance Ratio is the ratio of the ASL to the ASL expected under unpolluted or natural conditions. An ALR of 200% indicates that the observed sky is twice as bright, or shows a 100% *increase,* on average, compared to the natural condition.

iii) Number of Visible Stars

The number of visible stars is estimated using a procedure similar to that described by Crumey (2014), where the visibility of each star is determined by an observed empirical relation between visibility and the contrast between the star and the diffuse sky brightness against which it is observed. Increased sky brightness decreases contrast, causing fainter stars to become undetectable and the total number of visible stars to decrease.

The results for multiple measurements made each of the observation points show that the ASL and number of visible stars vary 2% or less maximum to minimum. In section B below, we will compare present to predicted future conditions using the datasets indicated in **boldface** in Table 4.

B) Sky Brightness Changes with Proposed RC Lighting

All-sky maps of the modeled sky brightness contributions from RC lighting only are shown in the middle panels of Figure 6 through Figure 9. The lower panels of these figures show the modeled RC lighting added to the measured current condition.

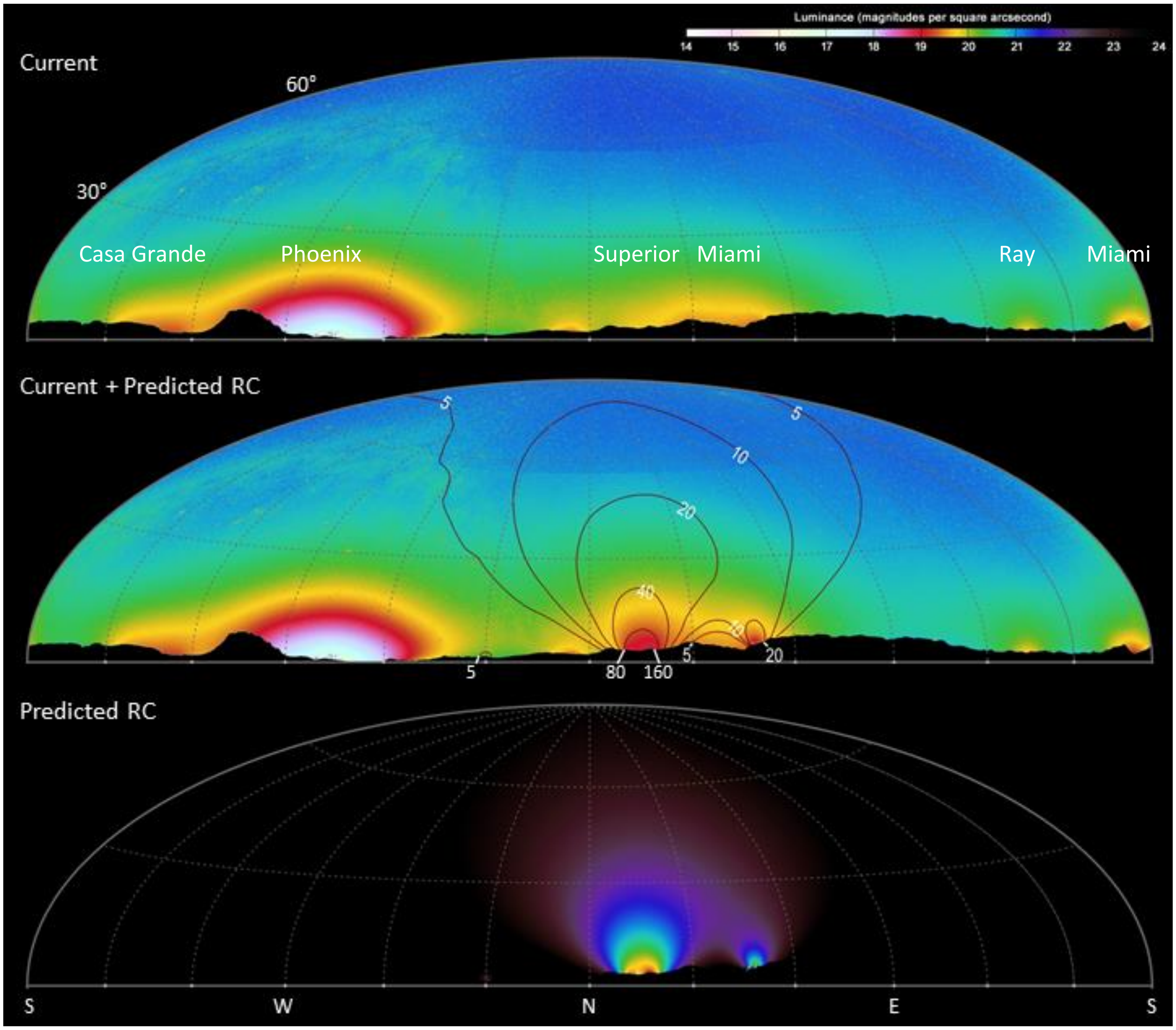

Figure 6. False color all-sky maps showing measured current sky brightness in the visual (top), predicted additional sky brightness arising from proposed RC lighting (bottom), and the predicted future condition with existing as well as new lighting at RC (middle), as seen from the Superior observation point. The prominent existing sources visible at the horizon are labeled on the top map. The units are explained in the text. The map shows the entire sky hemisphere covering 360° azimuth and from slightly below horizontal to the zenith. All maps are Hammer-Aitof equal-area projections.

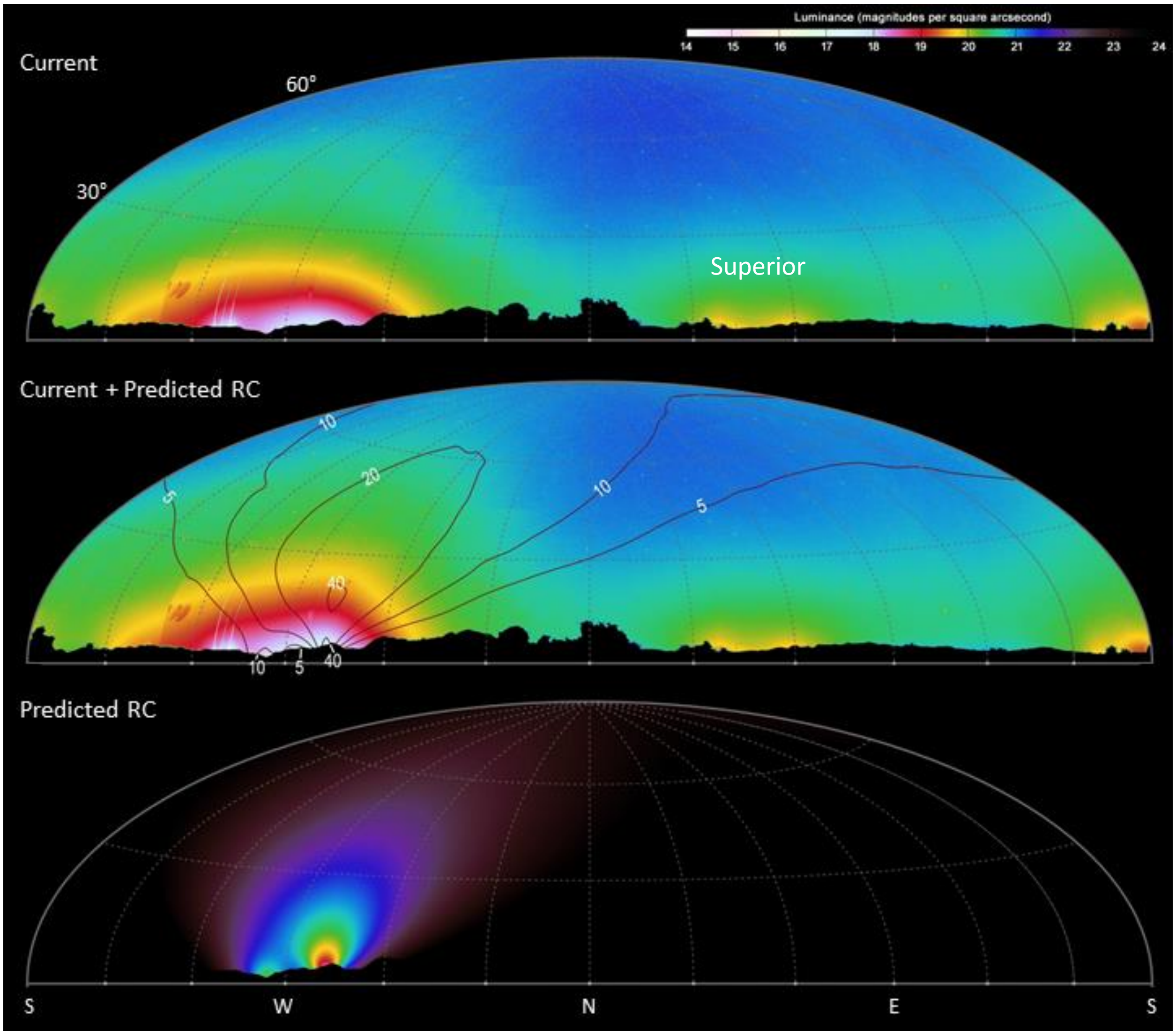

Figure 7. **False color all-sky maps showing measured current sky brightness in the visual (top), predicted additional sky brightness arising from proposed RC lighting (bottom), and the predicted future condition with existing as well as new lighting at RC (middle), as seen from the Oak Flat observation point. The labeling is explained in the caption for Figure 6.**

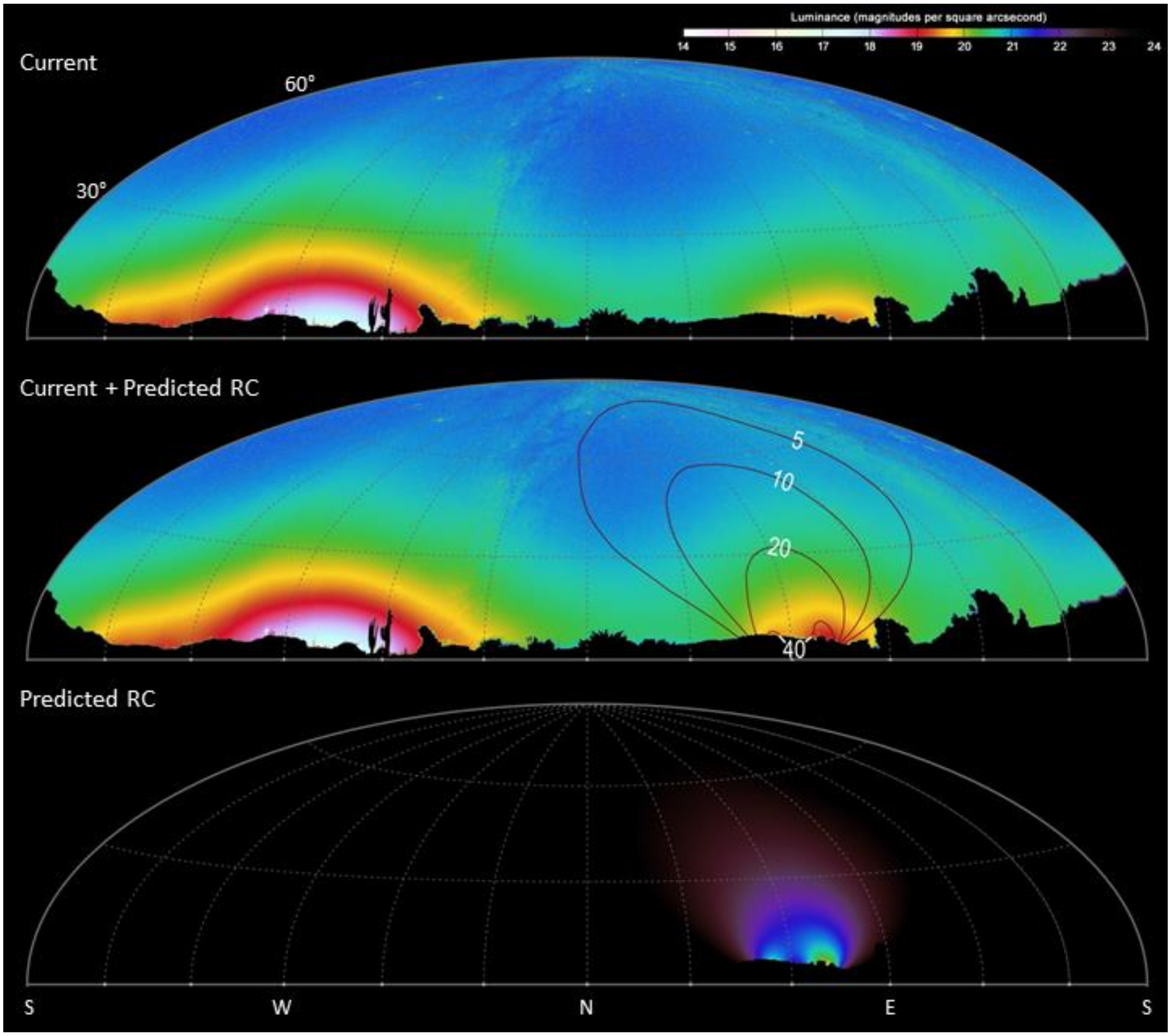

Figure 8. False color all-sky maps showing measured current sky brightness in the visual (top), predicted additional sky brightness arising from proposed RC lighting (bottom), and the predicted future condition with existing as well as new lighting at RC (middle), as seen from the Boyce Thompson observation point. The labeling is explained in the caption for Figure 6.

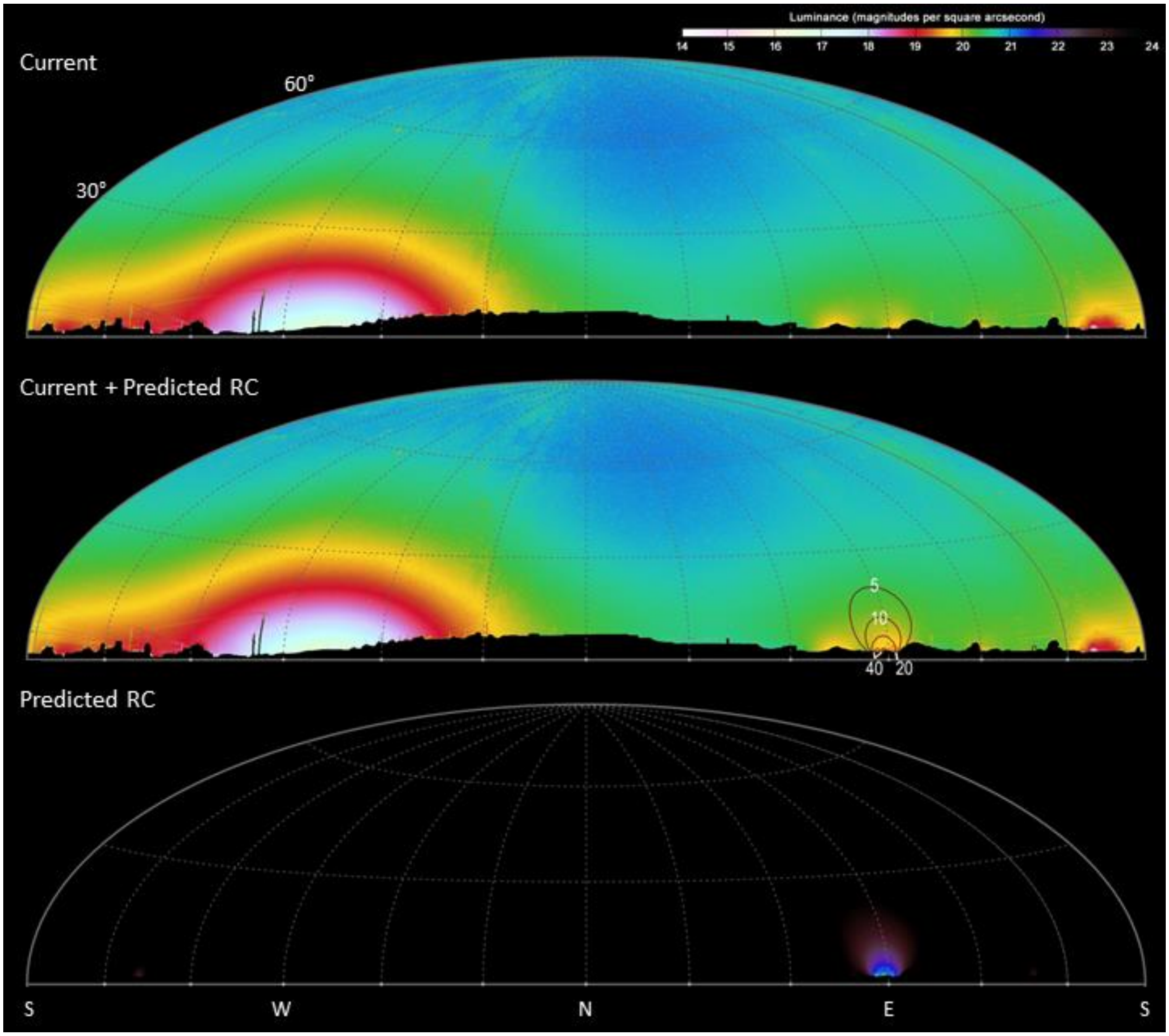

Figure 9. False color all-sky maps showing measured current sky brightness in the visual (top), predicted additional sky brightness arising from proposed RC lighting (bottom), and the predicted future condition with existing as well as new lighting at RC (middle), as seen from the Queen Valley observation point. The labeling is explained in the caption for Figure 6.

To quantify the effects of the RC lighting on night sky conditions, the increment to ASL and the decrease in number of visible stars was determined for the four observation points. The results show that the average sky brightness at the three observation sites increases from less than 1% at Queen Valley to 9% at Oak Flat. The number of visible stars is predicted to decrease between 1% and 6%. These results are summarized in Table 5.

Table 5. Changes to Average Sky Luminance (ASL) and number of visible stars (N Stars) after addition of Resolution Copper lighting.

LOCATION	ASL (mag/arcsec^2)			Max	N STARS		
	Current	+RC	%	%	Current	+RC	%
Superior	20.44	20.38	6	160	2997	2859	5
Oak Flat	20.51	20.42	9	40	2783	2614	6
Boyce Thompson	20.40	20.36	4	40	2996	2875	4
Queen Valley	20.04	20.04	<1	40	2709	2691	1

While the effects on the overall average sky conditions appear modest, the effect in areas of the sky in the direction toward the significant RC lighting installations are substantially greater. The lower panels of Figure 6 throughFigure 9 show sky brightness across the entire sky color-coded with the continuous color scale as the panels above, with discrete contours superimposed showing percent increases. Here it can be seen that portions of the sky will have brightness increases of 10% or greater at all observation points, and at all except Queen Valley over substantial areas of the sky. Maximum increases range between 40% and 160%. These larger changes will be noticeable by even casual observers.

Spectral effects.

All lighting proposed to be installed at RC will be white LED. Though at this point the exact LED spectrum has not been specified, the spectral content of all white LEDs is substantially richer in blue and green wavelengths than the outdoor lighting currently installed in the region. To estimate the consequences for visual sky brightness of this shift in spectrum, we compare a commonly specified 4000 K CCT white LED spectrum with a mix dominated by high-pressure sodium[2] (62%), 4000 K CCT white LED (15%), and incandescent (23%), a mix observed in the Flagstaff, Arizona area and reported by Luginbuhl et al. (2009a). The spectral content of these two sources is shown in Figure 10.

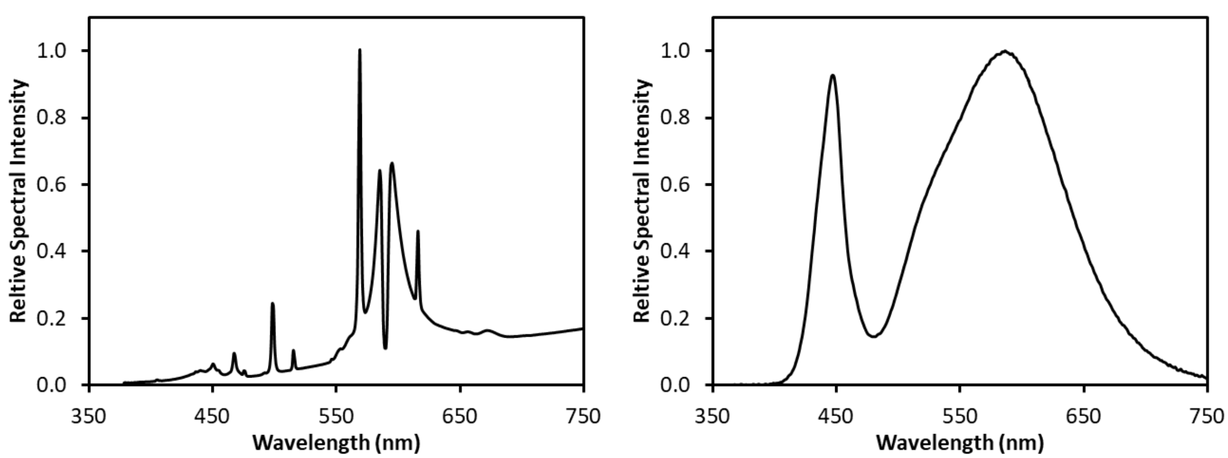

Figure 10. Relative spectral intensity for the mixed-source HPS/LED/incandescent outdoor lighting spectrum as described in the text (left), and a white LED of 4000K CCT.

[2] This figure includes the low-pressure sodium used in Flagstaff, as there is little LPS used in the areas near RC.

These spectra show that the lighting proposed for use at RC is likely to have significantly greater emission at wavelengths between 350 and 550 nm than currently existing lighting in the region. As the human eye is dark adapted (scotopic) (cf. the V'(λ) response shown in Figure 4) when viewing luminances fainter than 18.5 mag/arcsec^2 (0004 candela/m^2), the greater blue and green content of the RC lighting means that the impacts will be greater than if the proposed lighting utilized 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). The example 4000 K CCT white LED shown in Figure 10 has an S/P of 1.47; the mixed-source spectrum has an S/P of 0.82. Thus the use of a 4000 K CCT white LED will produce approximately 1.47/0.82 = 1.8x greater impact to regional sky brightness than the use of yellow-rich lighting similar to the current mix. If the RC lighting utilized phosphor-converted (PC) amber LEDs with S/P of ~0.45, the sky brightness increments could be reduced by 50% or more (if 100% of the lighting were PC amber LED, the reduction would be 0.45/1.47 = 0.30 of that predicted by this analysis, or a 70% reduction). Though PC amber LED is not likely appropriate for all lighting needs, such a source may meet many lighting needs while reducing impacts.

IV. Discussion and Conclusions

This analysis shows that the proposed RC lighting can be expected to increase the sky brightness by less than 1% at Queen Valley to 9% at Oak Flat, when considering effects averaged over the entire sky. When considering the areas of the sky in directions toward the proposed RC facilities, the proposed RC lighting will increase sky brightness between 40% and 160%. Such increases are likely to be obvious to even casual observers.

Against a background or current condition which is presumed to be dominated by HPS, the proportionally greater increases in the blue and green portion of the spectrum from the proposed LED lighting can be expected to cause a greater impact to dark adapted human vision than shown by this analysis. Utilization of yellow-rich sources such as phosphor-converted amber LED for much or all of the proposed RC lighting could reduce the incremental impact substantially. Other design strategies that may substantially mitigate the impacts of the proposed lighting may be available.

Potential opportunities to mitigate RC lighting impact

Four aspects could be examined for their potential to decrease the impacts of the proposed lighting at RC, as follows:

1. 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.
2. Perform a critical examination of where color perception is needed for operational effectiveness and safety. Replace lighting in non-critical areas with lower-impact lighting such as PC amber (providing some color discrimination) or direct-emission (also called "narrowband" or "limited wavelength" or "580 nm") amber LEDs.

3. 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.
4. 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 at particular times of night, or activate light based on motion detected within the work area.

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

V. References

Crumey, A., (2014), "Human contrast threshold and astronomical visibility," Monthly Notices of the Royal Astronomical Society, 442:2600

Duriscoe, D.M., Luginbuhl, C.B., and Elvidge, C.D. (2014), "The relation of outdoor lighting characteristics to sky glow from distant cities" Lighting Res. Technol. 46:35

Duriscoe, D.M., Luginbuhl, C.B., and Moore, C.A., (2007), "Measuring Night-Sky Brightness with a Wide-Field CCD Camera," Pub. Astron. Soc. Pacific 119:192.

Elvidge, *et al.* (2013). "Why VIIRS data are superior to DMSP for mapping nighttime lights," *Proceedings of the Asia-Pacific Advanced Network* 35:70.

Falchi, F. *et al.* (2016). "The New World Atlas of artificial night sky brightness," Science Advances 2:e1600377

Garstang, R.H. (1986). "Model for Artificial Night-Sky Illumination," Pub. Astron. Soc. Pacific 98**,** 364.

Garstang, R.H. (1989). "Night Sky Brightness at Observatories and Sites," Pub. Astron. Soc. Pacific 101, 306.

Garstang, R.H. (1991). "Dust and Light Pollution," Pub. Astron. Soc. Pacific 103, 1109.

Irwin, A. (2018). "The dark side of light: how artificial lighting is harming the natural world," Nature 553:268

Luginbuhl, C.B. *et al.* (2009a). "From the Ground Up I: Light Pollution Sources in Flagstaff, Arizona," Pub. Astron. Soc. Pacific 121:185.

Luginbuhl, C.B. *et al.* (2009b). "From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona," Pub. Astron. Soc. Pacific 121:204.

Luginbuhl, C.B., Boley, P.A., and Davis, D.R., (2014). "The impact of light source spectral power distribution on sky glow," Pub. Astron. Soc. Pacific 121:204.

Moore, C. A. and Duriscoe, D. M., 2013 "Introducing the Sky Quality Index," presented at the 2013 Annual General Meeting, International Dark-Sky Association.

Schreuder, D. A. (1998). "Bilateral Agreements on Limits to Outdoor Lighting; The New GTE Recommendations, Their Origin and Implications," in *Preserving The Astronomical Windows. Proceedings of Joint Discussion number 5 of the 23rd General Assembly of the International Astronomical Union. ASP Conference Series*, ed. S. Isobe and T. Hirayama Vol. 139:29.