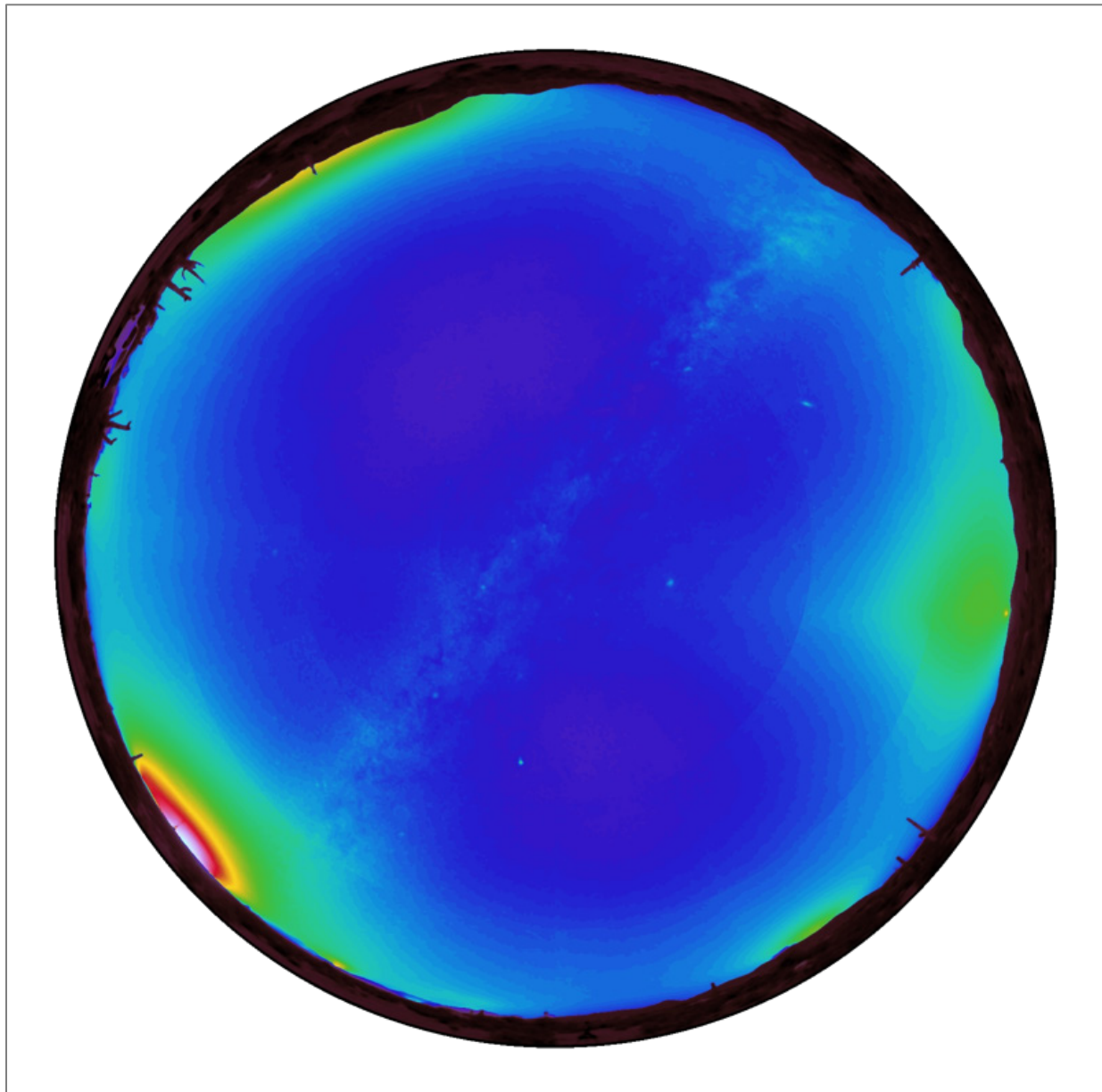




Night Skies Data Report

Photometric Assessment of Night Sky Quality at Organ Pipe Cactus National Monument



Fisheye view of the night sky over Organ Pipe Cactus National Monument in false color.

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Night Skies Data Report: Photometric Assessment of Night Sky Quality at Organ Pipe Cactus National Monument

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Abstract

This report characterizes night sky conditions in Organ Pipe Cactus National Monument (ORPI) using measurements made in the park unit and models of regional conditions based on satellite data. Calibrated night sky imagery was obtained to characterize the night sky at 4 sites. These ground-based observations were collected on 4 nights from 2023-02-11 to 2023-02-15. Satellite data from 2023 was used to create a map of predicted night sky conditions in and around the park.

The sky overhead remains near pristine with an average zenith brightness of 21.54 mag/arcsec². We estimate more than 91% of naked eye stars were visible throughout the data collection period, providing a unique opportunity to view the natural night sky from the park during a cloudless moonless night. The whole sky over ORPI is 41%–55% (mean = 46%) brighter than average natural levels, indicating degraded dark sky conditions on average, especially along the horizon but with near natural levels overhead.

Based on visibility of astronomical objects and surrounding light domes, we classified the sky between Bortle Class 2–4, from a truly dark site in some remote parts of the park to a rural/suburban transition in others. The average naked eye limiting magnitude (NELM) is 6.65 which is approaching near pristine under average conditions. Our Sky Quality Meter (SQM) measurements averaged 21.45 mag/arcsec², indicating the zenith is nearly as dark as we can accurately measure with an SQM. The excellent night sky quality overhead provides opportunities for visitors to observe most visible stars, deep sky objects and the Milky Way. The main impacts on ORPI's night sky quality were the light domes from Sonoyta and Puerto Peñasco, Mexico, and the Phoenix metropolitan area, Tucson, and Yuma, AZ. These light domes along the horizon, especially from Sonoyta, diminish night sky quality in the park by obscuring natural features, and hindering visitor dark adaptation. However, overall conditions are very good, and many areas of the park remain undisturbed by light pollution allowing for a true natural night sky experience.

Acknowledgments

The authors would like to acknowledge the staff at Organ Pipe Cactus National Monument for their support with this fieldwork and logistics, notably Tyler Coleman and Danny Martin. We also thank the peer reviewers for recommendations that improved this series of reports.

List of Terms or Acronyms

aerosol: Fine solid or liquid particles suspended in the air. Examples include dust, fume, mist, smoke and fog.

airglow: Naturally occurring light emitted from the gases in the upper atmosphere. It often appears as a vague and smooth light in the sky that is brighter toward the horizon as compared to the zenith. However, it can sometimes have a banded or wispy character and change in the timescale of minutes.

airmass: A measure of the amount of air through which light from outside the atmosphere must pass to reach the observer. It is expressed as a ratio of the atmospheric thickness along a line of sight to that at zenith. Mathematically, the airmass can be approximated as the secant of the zenith angle.

all-sky light pollution ratio (ALR): The ratio of anthropogenic to natural sky brightness averaged over the entire sky.

angle of incidence: The angle between a light ray's path striking a surface and a line perpendicular to the surface (sometimes called "normal" to a surface).

anthropogenic: Caused or generated by humans.

azimuth: Angle eastward of true north along the horizon. Moving clockwise on a 360° circle, north has azimuth 0°, east 90°, south 180°, and west 270°.

Bortle Class: A nine-level numeric scale that measures the night sky's brightness at a particular location based on visual observations (Bortle, 2001). It quantifies the observability of celestial objects and the interference caused by light pollution. The rating of one indicates pristine night sky and nine indicates heavily light-polluted sky.

charge-coupled device (CCD): A sensitive photon detector made out of a light-sensitive integrated circuit. Within the device, the electrical charge can be manipulated, for example conversion into a digital value.

crepuscular: Describing animals that are active primarily during dawn and dusk.

dark adaptation: The process by which the eye becomes adapted to dim environments.

extinction: The attenuation of light due to absorption and/or scattering.

extinction coefficient: A quantitative value for specifying the attenuation of light due to absorption and/or scattering. It is usually expressed in magnitude per airmass.

glare: Bright and uncomfortable light shining from the source directly to the observer.

haze: An atmospheric aerosol of sufficient concentration to be visible. The particles are so small that they cannot be seen individually but are still effective in visual range restriction.

horizontal illuminance: Illuminance falling upon a horizontally oriented surface, such as level ground.

illuminance: (1) The light falling upon a surface, or (2) a photometric measure of luminous light incident on a unit surface area. The derived SI unit of illuminance is the lux (lx).

km: Kilometer, a metric unit for measuring length. One kilometer is approximately 0.62 miles.

light dome: Skyglow from a distant source (such as an urban center) which takes the form of a dome due to the properties of atmospheric scattering of light.

light pollution: The alteration of natural light levels in the outdoor environment by manmade sources. Light pollution may degrade the utility, function, biota, or aesthetics of the surrounding environment. Light pollution includes glare, light trespass, and skyglow.

luminaire: The complete lighting unit, including the lamp, the fixture, and other parts.

luminance: The photometric measure of luminous intensity per unit area of a surface. It describes the amount of light that passes through or is emitted from a particular area, and falls within a solid angle. Luminance is often measured in candela per square meter (cd/m^2) or lamberts (L).

magnitude (mag or mags): A measure of an astronomical source's brightness on an inverted logarithmic scale. Brighter sources have smaller magnitudes. A magnitude 0 star is one hundred times brighter than a magnitude 5 star.

Milky Way: A barred spiral galaxy containing our own Solar System. When observed from Earth, it appears as an irregular band of light encircling the celestial sphere. It is comprised of vast numbers of faint unresolved stars and dust. Its position and orientation in the sky vary with the seasons and throughout each night due to the orbit and spin of the Earth.

naked eye limiting magnitude (NELM): The apparent magnitude of the faintest object visible in the sky with the naked eye. The NELM will depend on the observer, and will increase with the eye's dark adaptation. On a clear night without the moon and light pollution, the limiting magnitude will be greater than magnitude 6.

nocturnal: Happening in or active during the night, or relating to the night.

photometry: The measurement of light describing the perceived brightness to the human eye or an astronomical object's brightness in various electromagnetic spectra.

seeing: A measure of the optical steadiness of the air, usually judged by looking at the scintillation of stars or by measuring angular size of a point source in an image.

skyglow: Anthropogenic light scattered or reflected off of air molecules and atmospheric aerosols, leading to a brightening of the night sky. Skyglow is generally regarded as an aesthetic degradation of the night sky, and will illuminate an observer and the landscape unnaturally.

upward radiance: A term used to describe detectable radiant energy emitted into the atmosphere. Upward radiance is often associated with remote sensing measures of light emission.

vertical illuminance: Illuminance striking an upright oriented surface, such as a wall or a piece of paper held up to the light.

zenith: The point on the celestial sphere directly overhead.

zodiacal light: A faint, smooth, and elongated swath of light visible in the night sky. The zodiacal light appears as a noticeable cone of light near the sun, most visible immediately after evening twilight in the west and immediately before morning twilight in the east. It is caused by sunlight scattered by the dust particles in orbit around the sun.

Introduction

The night sky is an inseparable element of wild areas for park visitors and wildlife. It reveals an astonishing view into the vast universe, provides markers of daily and seasonal cycles, and features reference points for navigation. Historically, celestial objects and astronomical phenomena have significantly influenced numerous cultures around the globe. Today, star parties often attract many visitors, bringing important benefits to local, regional and national economies. In the National Park Service (NPS), night sky programs are among the most popular interpretive activities at parks, providing unique educational opportunities and an immersive experience connecting visitors to nature. The night sky is a natural, cultural, educational, and economic resource.

The *Organic Act of 1916* specifies the NPS shall conserve resources unimpaired for the enjoyment of future generations. The *General Authorities Act of 1970* specifies high standards for NPS management, referring to “superlative natural, historic, and recreation areas” with “superb environmental quality... managed for the benefit and inspiration of all the people of the United States.” Accordingly, section 4.10 of the *2006 NPS Management Policies* states: “The Service will preserve, to the greatest extent possible, the natural lightscapes of parks, which are natural resources and values that exist in the absence of human-caused light.”

The Natural Sounds and Night Skies Division, in collaboration with NPS regions, parks, and programs, provides servicewide support for night sky and nocturnal resource conservation through measurements, modeling, critical analysis, knowledge synthesis, and informed decision making. This report measures night sky brightness using images taken from inside the park and from a satellite circling the globe. The images taken inside the park provide accurate measurements of the night sky that wildlife and park visitors experience. The satellite images measure the upward radiance of the nighttime earth, providing a regional perspective of the lights that are altering the night sky in the park. Collectively, these data specify the condition of the night sky and the locations of light sources that are degrading it.

In the Methods chapter, we describe data collection and processing procedures for night sky images taken in parks and satellite images of stray light from developed areas. In the Results chapter, we report the sky quality and identify influences from nearby cities as seen in the images. Next, we discuss the natural brightness variation, measurement uncertainty, and data quality and anomalies. Finally, the Conclusions chapter summarizes our findings. In Appendix A: Observation Notes and Panoramic Images, we provide the notes taken by the observers during data collection and a set of panoramic images for each observation event.

Regional Setting

Light from anthropogenic sources has altered the natural luminance of the night sky throughout the continental United States and across much of the globe (Falchi et al., 2016; Kyba et al., 2017). Light from anthropogenic sources that is scattered by or reflected off air molecules and atmospheric aerosols brightens the sky and washes out celestial objects. This anthropogenic scattered light is called skyglow. Light sources up to 300 km (~200 miles) distant can cause skyglow. Skyglow

artificially illuminates the landscape and degrades visitor opportunities to view planets, stars, galaxies, and other astronomical objects.

Organ Pipe Cactus National Monument (ORPI) covers approximately 854 square kilometers in southern Arizona along the U.S.-Mexico border, about 175 km southwest of Phoenix, AZ (Figure 1). The monument is situated in the Sonoran Desert encompassing a unique and diverse landscape characterized by desert ecosystems and mountainous terrain. The monument contains several mountain ranges, including the Ajo, Puerto Blanco, and Bates Mountain ranges as well as narrow canyons and broad valleys. This geologic diversity contributes to its ecological richness; the park is home to numerous plant and animal species endemic to the Sonoran Desert. The park's namesake, the Organ Pipe cactus (*Stenocereus thurberi*), is a distinctive feature of the landscape. In fact, the monument is unique in that it is the only place in the U.S. where you can find all three species of columnar cacti, including Saguaro (*Carnegiea gigantea*) and Senita (*Lophocereus schottii*). Organ Pipe Cactus National Monument was designated as a UNESCO Biosphere Reserve in 1976, recognizing its significance as a crucial conservation area for biodiversity and ecological health. The nearest population center is Sonoyta, Mexico, and in the U.S. the nearest large population centers are the Phoenix metropolitan area, Tucson, and Yuma.

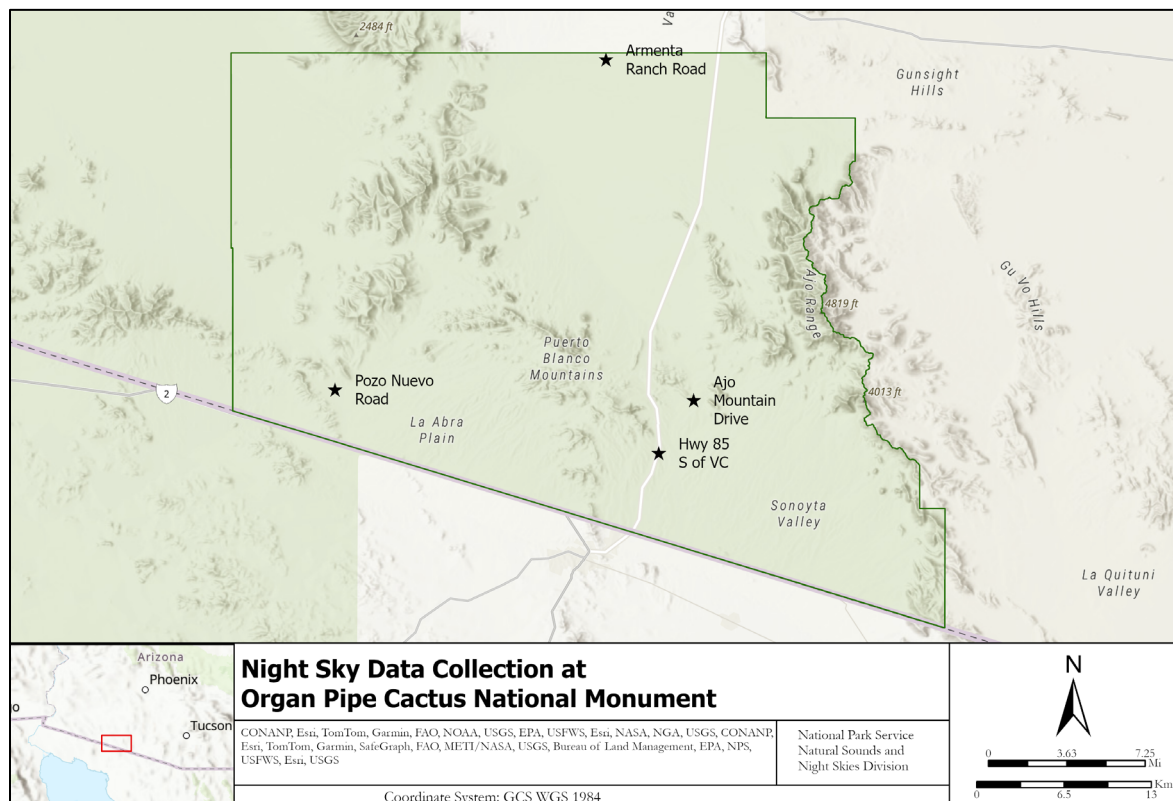


Figure 1. Geographic location of the park, including the 4 sites from the current study. Organ Pipe Cactus National Monument is in south central Arizona near the U.S.-Mexico border about 175 km southwest of Phoenix, AZ. In general, light sources within 300 km could be visible and have the potential to brighten the night sky.

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Methods

Imaging the Night Sky

The NPS developed the camera system and the observing method to collect high-resolution images of the night sky from horizon to horizon (Duriscoe et al., 2007). The NPS camera system is composed of a commercial Nikon lens, a V-band filter, and a research-grade, monochromatic charge-coupled device (CCD). The filter only lets visible light pass through, allowing the detected signal to closely represent what human eyes can see based on our spectral sensitivity. Because each image has limited field of view, a set of images needs to be taken to cover the entire sky. A robotic mount is utilized to automatically position the camera for each image. Each image set takes up to 40 minutes to complete, depending on the specific system used and the exposure time. To minimize the amount of sun and moon light, data are collected when the sun is more than 18° below the horizon, and when the moon also is below the horizon. The weather conditions required for data collection are clear nights with almost no cloud cover.

Figure 2 shows a typical NPS Night Skies camera system used from 2010 onward. This camera system captures a composite image of the night sky by creating a mosaic from 45 images of portions of the sky, with each portion spanning a square 24° by 24° . Depending on the sky brightness at the observing site, the exposure time is usually set to somewhere between 8 to 12 seconds for each image. Each resulting image set will yield a 40-million-pixel image mosaic covering the entire night sky and 7° below the horizon.



Figure 2. The NPS Night Skies camera system setup in Organ Pipe Cactus National Monument. A typical National Park Service Night Skies Program camera system consists of a commercial lens, a V-band filter, and a CCD camera. The camera system is mounted on a motorized mount, hooked up to external batteries, and controlled by a computer.

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Between 2023-02-11 and 2023-02-15, NPS collected 4 nights of ground-based CCD camera data in ORPI, yielding 9 complete data sets. Each set is used to generate a panoramic image of the night sky. Table 1 lists the details about each data collection event, including the date, collection site, camera used, number of data sets collected, and observers. When able to collect multiple data sets in a night, we analyze the highest quality one.

Table 1. Ground-based data collection events at Organ Pipe Cactus National Monument. “Sets” refers to the number of data sets taken that night; each set yields a panoramic image of the sky.

Date	Site Name	Camera	Sets	Observers
2023-02-11	Hwy 85 S of VC	ML 4	4	B Meadows; J White
2023-02-12	Pozo Nuevo Road	ML 4	2	B Meadows; J White
2023-02-13	Armenta Ranch Road	ML 4	2	B Meadows; J White
2023-02-15	Ajo Mountain Drive	ML 4	1	B Meadows; J White

Locating Data Collection Sites

These observations with the CCD camera are carried out at specific sites in or near the park. In general, higher elevation sites free from nearby obstructions are selected because they provide a clear view of the sky down to the natural horizon. The sites also need to be free from bright and direct glare to prevent image saturation. Additional selection criteria include the accessibility and proximity of the site to stargazing locations, sensitive ecosystems, critical habitat, and future developments. For a small park, one clear site is sufficient to capture the representative conditions across the entire park. For a large park, strategic placement in relation to other measurement sites is also considered to capture the range of sky quality across the park. Each data collection site is listed in Table 2, and located on the map in Figure 1.

Table 2. Data collection sites at Organ Pipe Cactus National Monument.

Site Name	Elevation (m)	Latitude	Longitude
Hwy 85 S of VC	501	31.93281	-112.7993
Pozo Nuevo Road	389	31.97524	-113.0159
Armenta Ranch Road	479	32.19617	-112.8346
Ajo Mountain Drive	541	31.96816	-112.7759

Hwy 85 S of Visitor Center (VC)

Hwy 85 S of VC is in ORPI on the east side of State Route 85, 2.4 km south of Puerto Blanco Road. Located off a park administrative road, this maintenance area provided a clear horizon, with a slight depression to allow for terrain blocking of vehicle headlights. The light dome of Sonoyta was very prominent to the SSW (up to 30° towards zenith and about 40° wide), as well as some direct glare from the border crossing at Lukeville. The greater Phoenix area was easily visible to the NNE (up to 15° and about 30° wide) with Tucson much less visible to the east.

Pozo Nuevo Road

Pozo Nuevo Road runs north-south across the western section of ORPI. The observation point is located at the southern end of Pozo Nuevo about 1.5 km north of the Puerto Blanco junction on the west side of the road. This point provided unimpeded view to the south and southeast. The Quitobaquito Hills were visible to the west, but did not block any visible light domes.

Armenta Ranch Road

Armenta Ranch Road runs east-west along the northern border of ORPI. The observation point is approximately 7.2 km east of State Route 85, just north of Armenta Ranch Road. With minimal terrain blocking this site provided expansive views looking south into the park including the Sonoyta light dome which appeared small on the horizon, as well as views outside the park, such as a mostly unimpeded view of the Phoenix metropolitan light dome.

Ajo Mountain Drive

Ajo Mountain Drive is located in ORPI along the southern portion of the Ajo Mountain loop road, approximately 5 km east of the loop junction. We set up near the top of a ridgeline just north the road. The ridge provided a clear unimpeded view to the entire eastern section of border wall from Sonoyta to the eastern park boundary. About 105° of lights visible along the horizon, but to the southeast lights were only small dim point sources. The Sonoyta light dome appeared large, about 40 degrees across and 30 degrees high.

Processing Night Sky Images

For each data set, we process the images to generate a panoramic view of the night sky with a resolution of 0.05 degrees per pixel (Duriscoe et al., 2007). The image processing procedures include basic noise (bias, dark, and flat-field) removal, linearity response correction, and absolute brightness calibration. We use the standard stars captured in the images as the position and brightness calibration sources. The images in a set are then mosaicked together, showing the panoramic view of the sky from the zenith to six degrees below the true horizon. Next, we build a model to separate out the natural light (Duriscoe, 2013). The observed panoramic images contain light from both natural and anthropogenic sources. We build a natural sky model to account for light from stars, planets, airglow, zodiacal light, and the Milky Way. We subtract out the modeled natural brightness to obtain panoramic images showing only the anthropogenic light. In summary, each data set yields a pair of calibrated panoramic images, one showing the observed sky and the other showing the light only from anthropogenic sources.

Calculating Skyglow Impact from Nearby Cities

To expedite interpreting the all-sky images, we use Walker's Law to estimate predicted brightness of light domes. Brightness is expressed as a percent above natural sky luminance at a 45° angle above the horizon. Dark Sky International proposed using Walker's Law in the following form:

$$I = 0.01 P d^{-2.5}$$

where

I = Walker's value indicating the skyglow level above the natural background

P = human population size taken from 2020 US Census Data

d = distance (km) to the population center.

At each observing location, we calculate the azimuth from the study site to the center based on the city centroid. The light dome brightness predicted by Walker's Law might not perfectly match what is captured in the images. Accurately predicting the light dome brightness is challenging.

Intrinsically, the characteristics of light domes depend on factors such as the illumination level per capita, the use of shielding, the distribution of lighting fixtures, and the spectral composition of light. Extrinsically, terrain shielding, atmospheric conditions, and variable natural light can also affect the appearance of light domes. There are more refined models (such as Duriscoe et al. 2018) for better predicting skyglow but here we choose to use Walker's Law for its simplicity.

Collecting Satellite Images of Earth at Night

Satellite based data were collected from the Suomi National Polar-orbiting Partnership (NPP, Lee et al. 2010), a weather satellite launched in 2011. This satellite mission is a collaborative effort between the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration. The on-board Visible Infrared Imaging Radiometer Suite (VIIRS) provides low-light measurements of upward radiance through the Day/Night Band (DNB) sensor (Lee et al., 2006). The spectral sensitivity of the VIIRS DNB ranges from 0.5 to 0.9 μm (Hillger et al., 2013), corresponding to light in green to near infrared wavelengths. The DNB has a swath width of 3000 km and a pixel resolution of 742 m. The satellite has an orbital period of ~ 100 minutes, which allows for nightly global DNB imagery. The nightly observations are collected around 1:00 am local time.

Estimating Skyglow Using Satellite Data

Calibrated and processed images were obtained through the public archive on the Colorado School of Mines website (VIIRS - Payne Institute for Public Policy). The VIIRS DNB sensor has on-orbit radiometric calibration and reports the radiance in units of watts per square centimeter per steradian ($\text{W}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$; Lee et al., 2014). These calibrated images are still subject to light from undesired sources and weather events. Baugh et al. (2013) generated composite images by combining only high quality nighttime observations that were free of clouds, stray light, lunar illuminance, noisy edge of scan data, and missing data. We downloaded the annual composites generated from images taken in 2023 for the following analysis.

We use satellite imagery to estimate sky quality through a simple predictive model (Duriscoe et al., 2018). The 2023 annual composite from VIIRS DNB serves as a map of upward nighttime lights for our model input. The Simplified All-sky Light Pollution Ratio (SALR) uses geographic analysis tools to predict the average artificial luminance over the entire night sky. Specifically, this model is based upon a relation between skyglow brightness and the distance from the observer to the source of upward radiance. To display the result, we use ArcGIS to generate the thematic map of a region showing the modeled artificial sky brightness. This map is presented in the Results chapter.

Results

The ground-based observations yield the calibrated panoramic images of the night sky. Figure 3 shows an example of the image product associated with each data set. In Appendix A: Observation Notes and Panoramic Images, we provide links to the reference images for each night, both observed and artificial skyglow. We use magnitude per square arcsecond ($\text{mag}/\text{arcsec}^2$) for measuring the sky surface brightness. Magnitude (mag or mags) is a standard unit for measuring the brightness of astronomical objects, and it is in inverted logarithmic scale. Under clear moonless conditions, a sky surface brightness of $22 \text{ mag}/\text{arcsec}^2$ would be considered pristine, and a sky surface brightness of $<20 \text{ mag}/\text{arcsec}^2$ would be considered greatly deviated from the natural condition. The warmer colors in these images represent brighter skies. Figure 3 shows the observed night sky, which contains light from both natural and artificial sources. Purple and dark blue colors indicate an unpolluted sky, and the Milky Way under the natural condition appears green in this color scheme. Figure 4 shows only the light from artificial sources. Light domes along the horizon from the nearby area are more apparent in the second image.

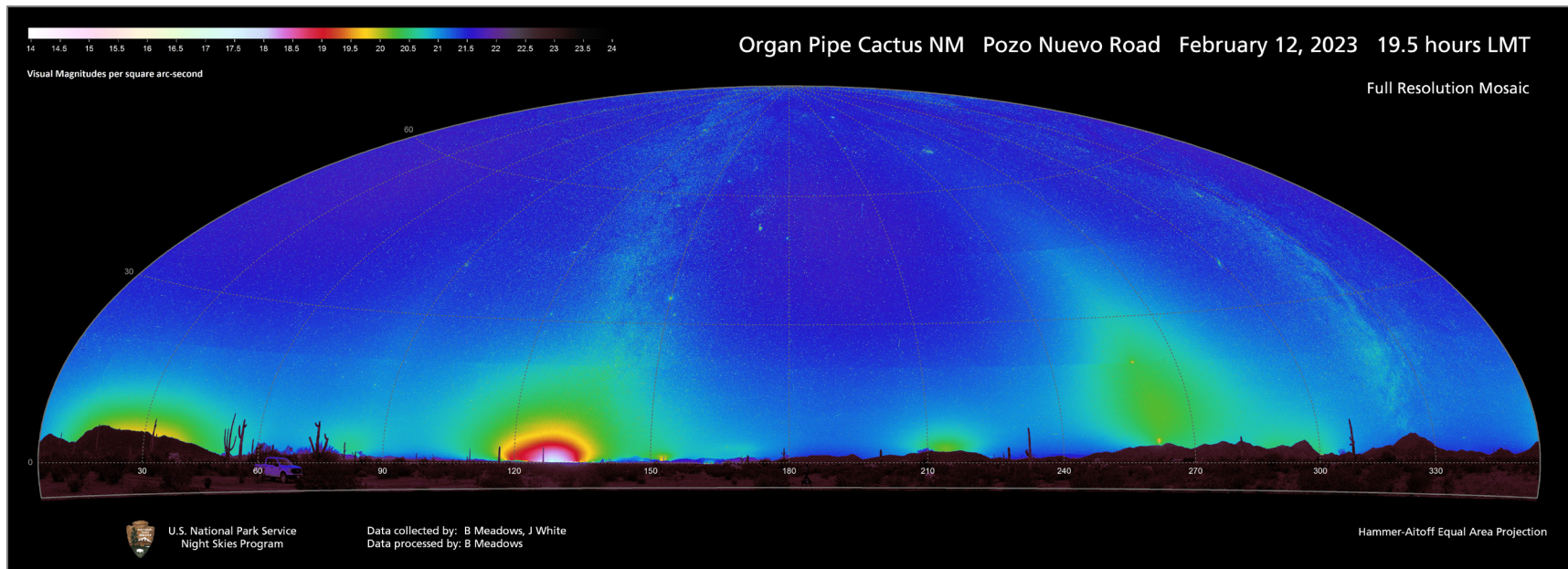


Figure 3. Panoramic image of the night sky from the Pozo Nuevo Road site on February 12, 2023. The grid lines are spaced 30° apart. The observed sky shows light from all sources, both natural and artificial. The Sonoyta, Mexico light dome is easily visible at 130 degrees azimuth. The light dome of Phoenix, AZ is visible behind the hills at 30 degrees azimuth, with the smaller light dome from Yuma, AZ visible at 295 degrees azimuth. The light dome from Puerto Peñasco, Mexico is visible at 215 degrees. Natural zodiacal light is prominent between 260 and 270 degrees azimuth.

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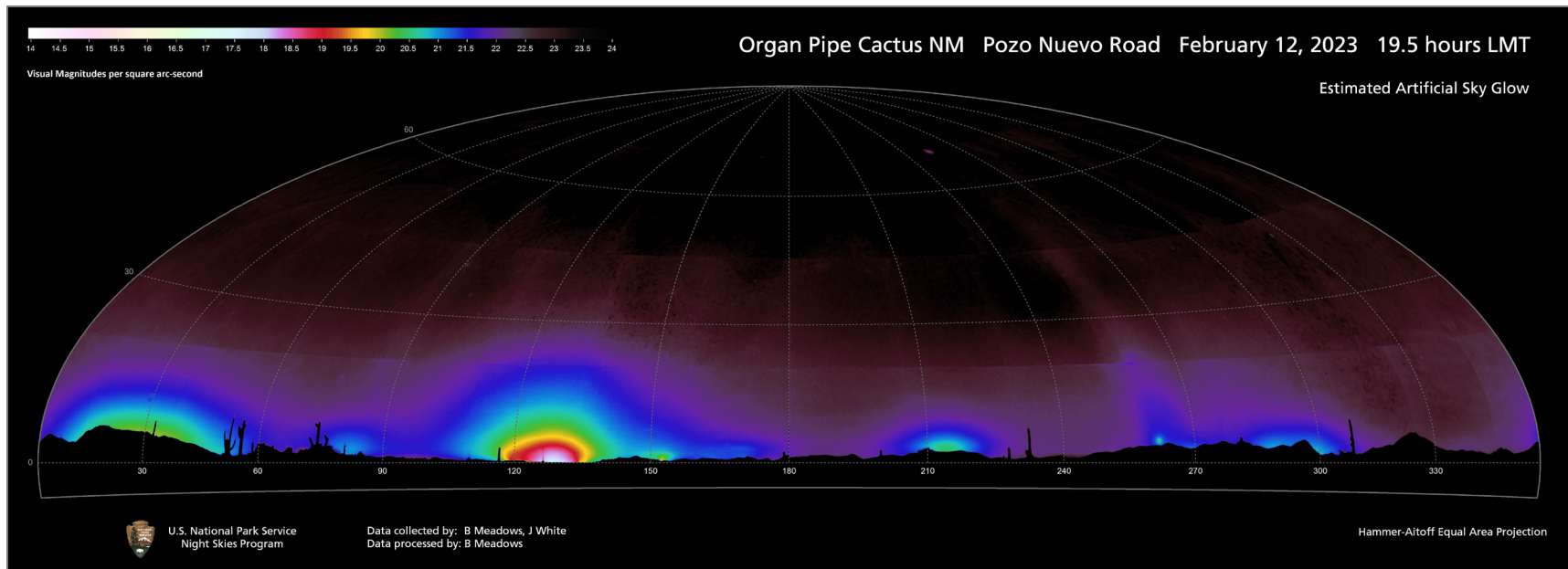


Figure 4. Panoramic image of artificial skyglow at the Pozo Nuevo Road site on February 12, 2023. The grid lines are spaced 30° apart. The image displays estimated skyglow from artificial sources. The natural light has been removed from this image, showing only the artificial skyglow and associated light domes. It should be noted that the natural sky subtraction did not fully remove the zodiacal light between azimuth 260 and 270 degrees. The Sonoyta, Mexico light dome is easily visible at 130 degrees azimuth. The light dome of Phoenix, AZ is visible behind the hills at 30 degrees azimuth, with the smaller light dome from Yuma, AZ visible at 295 degrees azimuth. The light dome from Puerto Peñasco, Mexico is visible at 215 degrees.

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In the image, the largest and brightest light dome is from Sonoyta, Mexico at 130 degrees azimuth. The light dome of Phoenix, AZ is visible behind the hills at 30 degrees azimuth, with the smaller light dome from Yuma, AZ visible at 295 degrees azimuth. The light dome from Puerto Peñasco, Mexico is visible at 215 degrees. Natural zodiacal light is prominent between 260 and 270 degrees azimuth as a bright green. The winter Milky Way is visible as a light blue band arching across the right-hand portion of the image.

In Table 3, we list the nearby U.S. cities from the Pozo Nuevo Road site during the data set collected on February 13, 2023 ranked according to their brightness predicted by Walker’s Law. As noted in the Methods chapter, because Walker’s Law is a simple model, the order of the predicted skyglow might not perfectly match the order of the imaged light dome brightness. Cities outside of the U.S., such as Sonoyta, are not listed here.

Table 3. Nearby cities and their predicted skyglow impact at the Pozo Nuevo Road site.

Place	Population in 2020	Distance (km)	Azimuth (degree)	Walker's Value (% above natural)
Phoenix	1,608,139	197	26	2.95
Tucson	542,629	194	84	1.04
Mesa	504,258	196	35	0.94
Chandler	275,987	182	36	0.62
Gilbert town	267,918	190	39	0.54
Glendale	248,325	187	23	0.52
Tempe	180,587	187	33	0.38
Buckeye	91,502	144	17	0.37
Scottsdale	241,361	218	29	0.34
Yuma	95,548	155	295	0.32

Sky Quality Indicators

We summarize the sky quality measurements in Table 4 and Table 5. Based on the observed panoramic images, we report five indicators (Duriscoe, 2016) that focus on different aspects of sky brightness. These are horizontal illuminance, maximum vertical illuminance, zenith brightness, % of stars visible, and all-sky light pollution ratio (ALR). If multiple data sets were taken at night, we report only the measurements from the set taken under the best observing conditions and free of processing issues. The listed local date and time mark the midpoint of image acquisition. We provide bright urban sky measurements at Rock Creek Park in Washington, DC for comparison. The median natural sky (Duriscoe, 2016) is the natural reference condition against which we can compare all measured values. We complement our CCD camera observations with a visual assessment of Bortle Class and naked eye limiting magnitude (NELM) and take readings with a Unihedron Sky Quality Meter (SQM) whenever possible (Table 5).

Table 4. Organ Pipe Cactus National Monument sky brightness metrics derived from the observed images.

Site	Date	Time (hh:mm)	Horizontal Illuminance (mlx)	Max. Vertical Illuminance (mlx)	Zenith Luminance (mag/arcsec ²)	Stars Visible (%)	All-sky Light Pollution Ratio
Hwy 85 S of VC	2/11/2023	21:20	1.08	1.01	21.53	90.7	0.55
Pozo Nuevo Road	2/12/2023	19:28	0.96	0.70	21.46	88.8	0.43
Armenta Ranch Road	2/13/2023	22:32	0.98	0.77	21.63	91.0	0.41
Ajo Mountain Drive	2/15/2023	19:26	1.47	1.17	21.09	93.7	0.44
–	Urban Sky ^A	–	39.56	29.04	18.00	8.0	64.43
–	Natural Sky ^B	–	0.80	0.40	22.00	100.0	0.00

^A Rock Creek Park in Washington, DC was used as the urban sky reference.

^B The median natural sky is the natural reference condition.

Table 5. Organ Pipe Cactus National Monument visual and SQM measurements.

Site	Date	Bortle Class	Limiting Magnitude	SQM (mag/arcsec ²)
Hwy 85 S of VC	2/11/2023	4	6.5	21.44
Pozo Nuevo Road	2/12/2023	3	6.8	21.46
Armenta Ranch Road	2/13/2023	2	–	21.46
Ajo Mountain Drive	2/15/2023	4	–	21.1
–	Urban Sky ^A	8	5.2	18.36
–	Natural Sky ^B	1	7.0	22

^A Rock Creek Park in Washington, DC was used as the urban sky reference.

^B The median natural sky is the natural reference condition.

Illuminance is the amount of visible light incident on a unit surface area. It is more sensitive to light striking closer to perpendicular to the surface. Specifically, the impact from a light source is weighted by the cosine of its angle of incidence. For example, the weighting factors for sources incident perpendicular to the surface, 60 degrees away, and 90 degrees away (parallel to the surface) are 1, 0.5, and 0, respectively.

The horizontal illuminance describes the amount of light landing on a horizontal surface. It provides the illuminance measurement of the entire sky at a glance but is not sensitive to skyglow near the horizon. From the 4 observation nights in ORPI, the average horizontal illuminance is slightly higher than the natural reference. Measures at Ajo Mountain Drive show elevated illuminance levels, due mostly to very high natural airglow that night. When excluding this measurement, the average horizontal illuminance is 1.0 mlx. The measured horizontal illuminance values indicate the park preserves to a large extent the natural illumination on the plane.

The vertical illuminance describes the light striking a vertical surface. The vertical illuminance better reflects the brightness of sources near the horizon. Since a vertical surface can be held facing many different directions, we report the maximum vertical illuminance. Note that the maximum vertical illuminance can be greatly influenced by natural sources such as the Milky Way, zodiacal light, and airglow. From the 4 observation nights in ORPI, the highest maximum vertical illuminance from all sources was 1.17 mlx measured from Ajo Mountain Drive. However, we excluded this reading due to extremely bright natural airglow. Of the included observation nights, the highest maximum vertical illuminance was 1.01 mlx at HWY 85 which is more than double the referenced natural value of 0.40 mlx. This result shows how artificial lights have a measurable effect in brightening the night sky along the horizon which can have negative impacts on wildlife as well as visitor experience. Nonetheless, the overall vertical illuminance level is still low across the park, providing a refuge for crepuscular and nocturnal species in the park.

The zenith sky brightness is measured within a 1-square degree area directly overhead. The zenith usually is the darkest part of the sky since all light domes are located along the horizon. For reference, the darkest natural sky can reach V-band brightness of 22 mag/arcsec², and the brightest

part of the Milky Way is about 20 mag/arcsec². Overall, the photometric measurements in ORPI show the zenith is close to naturally dark, and skyglow at zenith is barely measurable with an average zenith brightness of 21.54 mag/arcsec² (excluding the elevated Ajo Mountain measure).

The percent visible star metric concerns the percentage of stars that are visible to the naked eye after accounting for the influence of skyglow. When calculating this metric, we have taken the atmospheric transparency and the natural sky brightness at the time of the observation into account but do not consider atmospheric turbulence, which may influence the faintest stars visible. On average, there are about 4000 stars visible to the naked eye under the natural dark sky. This metric estimates the direct impact of skyglow to human visual observation of stars and night sky features. From the 4 observation nights in ORPI, we estimate, on average, 91% of stars were still visible during data collection, providing an outstanding opportunity to observe the natural night sky from the park.

All-sky light pollution ratio (ALR) is an index of total skyglow. We calculate it by taking the total brightness from the skyglow and dividing by the brightness of the natural dark sky. We always use a constant value of 250 microcandela per square meter as the brightness of the natural dark sky in this calculation to ensure equitable comparison of ALR values across data sets. If the sky is completely free of skyglow, this ratio would be zero. Generally, ALR values less than 0.3 (30% brighter than natural) indicate excellent conditions, 0.3 to 2.0 (30%–200%) indicate degraded sky quality (though areas of the sky may reveal important natural features), and greater than 2.0 (>200%) indicate the natural night sky is not readily visible. The whole sky over ORPI is 41%–55% (mean = 46%) brighter than average natural levels, indicating degraded dark sky conditions from skyglow which was visible from each of the observation points. However, outside of the light dome brightened part of the sky, much of the night sky conditions were very good.

Indicators derived from these ground-based measurements indicate some impact from light pollution has been measured in these sky luminance data. These indicators are supported by visual observations and assessments at the site. Bortle Class is a nine-level numeric scale that measures the night sky's brightness at a particular location based on visible sky objects (Bortle, 2001). The rating of one indicates pristine night sky that is completely free of skyglow, and nine indicates heavily light polluted sky often found in the inner cities. In ORPI, we classified 4 (rural/suburban transition) as the most common Bortle Class value describing our observation sites. As described by Bortle (2001, pp. 127–128):

“Fairly obvious light-pollution domes are apparent over population centers in several directions. The zodiacal light is clearly evident but doesn't even extend halfway to the zenith at the beginning or end of twilight. The Milky Way well above the horizon is still impressive but lacks all but the most obvious structure”

Visual observations in the field didn't perfectly match the Bortle 4 description. The Milky Way was highly detailed and many deep sky objects were visible. The class 4 rating stemmed primarily from

the spatial extent and brightness of light domes visible across the horizon. However, much of the park exhibited much more natural conditions closer to class 2–3 and described by Bortle:

“Airglow may be weakly apparent along the horizon. M33 is rather easily seen with direct vision. The summer Milky Way is highly structured to the unaided eye, and its brightest parts look like veined marble when viewed with ordinary binoculars.”—Bortle class 2

“Some indication of light pollution is evident along the horizon. Clouds may appear faintly illuminated in the brightest parts of the sky near the horizon but are dark overhead. The Milky Way appears complex...M33 is easy to see with averted vision.”—Bortle class 3

Naked eye limiting magnitude (NELM) is the magnitude of the faintest star we can see in the sky with naked eyes. As the night sky brightness increases, the limiting magnitude will degrade to a lower value. The NELM will also depend on the observer and will increase with the eye’s dark adaptation. A NELM of 6.6 is considered near pristine under average conditions, while 7.0 is achievable under good seeing conditions and with proper dark adaptation of the eye. A NELM of 7.4 is excellent, just about the faintest attainable. A number lower than 6.3 usually indicates degraded sky quality. The limiting magnitude is also a common metric used by citizen scientists to assess the sky brightness globally. In ORPI, the average limiting magnitude is 6.65 achieved near zenith, approaching near pristine under average conditions.

The hand-held Sky Quality Meter (SQM) is an economic and convenient tool to take a single value of sky brightness measurement with just one click. We point SQM towards zenith when taking a reading. The SQM has a wide field of view; its full width half maximum of the angular sensitivity is $\sim 42^\circ$. Although getting a reading is fast and easy, the instrument does not reliably measure the sky brightness when the sky is darker than ~ 21.5 mag/arcsec². Our SQM measurements in ORPI averaged to 21.45 mag/arcsec², indicating the zenith is about as dark as what we can accurately measure with an SQM with minimal to no impact from light pollution.

Regional Sky Brightness Model

Figure 5 displays park and regional predictions of skyglow based on the SALR model using the annual 2023 cloud-free composite of VIIRS data. The metric depicted is all-sky average sky brightness, expressed as a ratio of artificial to natural background. Skyglow can be seen from up to 300 kilometers away from large metropolitan areas. The map displays the park and the surrounding area, including cities within approximately 300 km. This map provides a landscape view of the average sky brightness in and around the park. The scale on the left gives the ratio between the natural and artificial light where the lower the ratio, the better the night sky viewing and the lower the levels of visible artificial light.

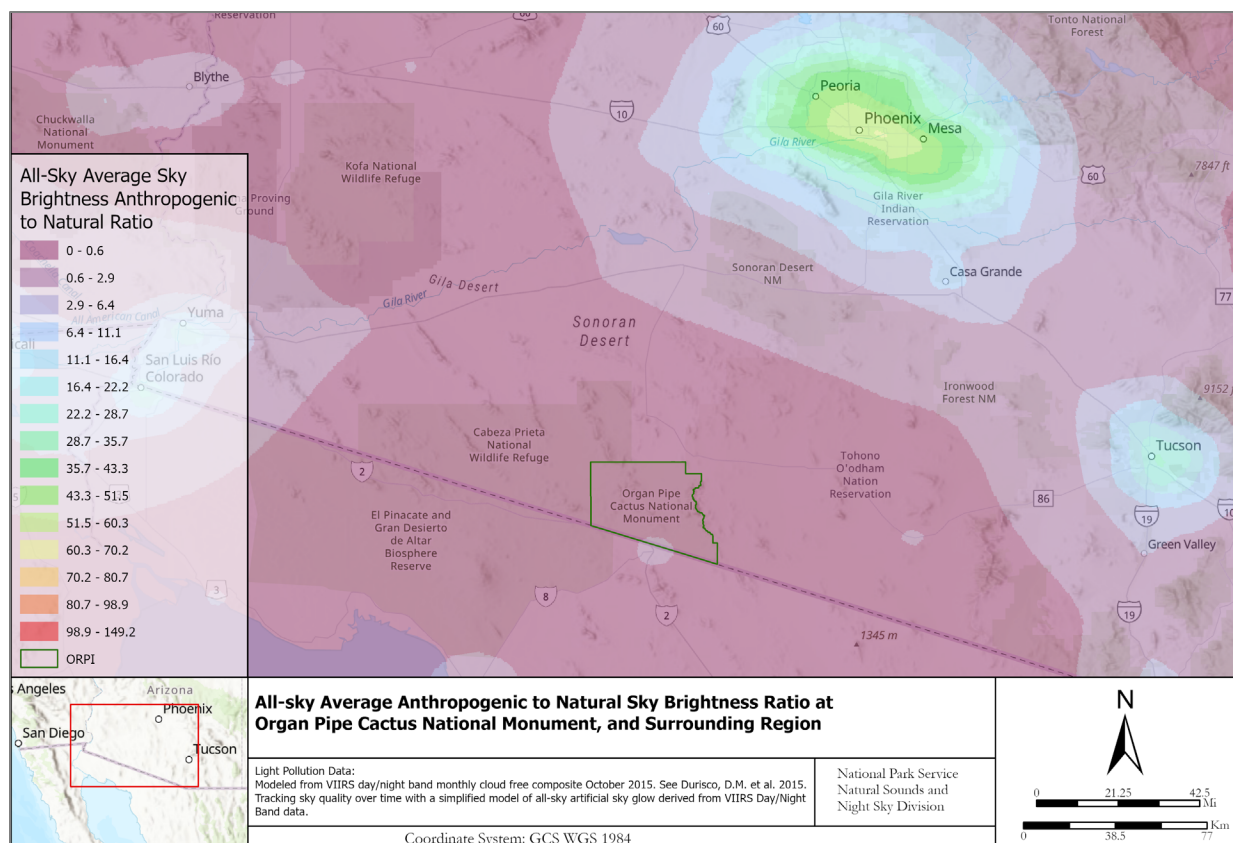


Figure 5. A model of average all-sky light pollution ratio (ALR) in the region surrounding Organ Pipe Cactus National Monument. The park boundary is outlined in green.

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Within ORPI multiple light domes are visible along the horizons and easily identifiable on the ALR map, with most at distances great enough to produce minimal predicted all-sky impact. In the largest nearby communities such as Sonoyta, Puerto Peñasco, Phoenix, Tucson, and Yuma, the sky quality is dramatically different than in the park. At ORPI, the mean modeled ALR was 0.21 (0.11–1.14). This overall average differs from the ALR of 0.46 generated by our CCD cameras as the modeled ALR considers areas of the park that are more remote and shielded from the effects of skyglow. Additionally, the CCD camera system is more accurate in measuring the impacts of vertical illuminance, which drive up the ground-based ALR measures. At this average ALR, the modeled whole-park sky quality condition is considered excellent. From many areas of the park at this light level humans should be able to fully adapt to the dark and have an opportunity to see the Milky Way from nearly horizon to horizon, complete constellations, deep sky objects, zodiacal light, and airglow.

Discussion

Variation in Natural Sources

Variations in airglow activity can change sky brightness and complicate the assessment of sky quality. Airglow is caused by particles releasing energy in the form of light in the earth's upper atmosphere. These particles obtain the energy from the sun and cosmic rays. The sun shows an activity cycle of eleven years, and this cycle seems to correlate with the airglow brightness (Patat, 2008). While the average airglow brightness shows long-term variation, the brightness and pattern can change in minutes. Bright airglow will wash out some night sky features, such as faint galaxies and details in the Milky Way, directly affecting the visual assessment of the night sky. In addition, the indicators derived from the observed sky brightness, including the illuminance and zenith brightness, can also be affected. To account for this natural variation, we subtract airglow in our modeling process before estimating the skyglow brightness. However, the uncertainty of the associated metrics (% of visible stars and ALR values) can still be high due to the uncertainty of airglow modeling. In general, suburban skies (Bortle Class 4 and 5) are most susceptible to the large percentage error from the airglow modeling process compared to rural and urban sites. A detailed discussion about the airglow modeling uncertainty can be found in Duriscoe (2013).

Another factor that could significantly affect the skyglow measurement is the amount of aerosols in the atmosphere. Aerosols can come from natural sources (i.e., wind-borne dust, wildfire smoke, sea spray, and volcanic debris), but they can also originate from human activities (i.e., industrial emissions, fossil fuel combustion, and waste and biomass burning). From the visual observation perspective, observers will see fewer stars if the aerosol concentration is higher. From the skyglow measurement perspective, a higher aerosol level will enhance the brightness of nearby sources but diminish the brightness of distant sources. Variation in aerosol content can affect the sky brightness measurements even with no net increase in light intensity from ground-based sources.

Measurement Uncertainties

The direct measurement uncertainties are about a few percent, and the uncertainty of the estimated skyglow varies from data set to data set. In the observed image mosaic, pixel-to-pixel random error in sky brightness measurement is $\pm 4\%$. Systematic error is typically less than 2% as the instrument is calibrated on standard stars for each data set. For the estimated skyglow brightness mosaic, the uncertainty largely depends on the natural sky model due to the spatial and temporal variations in the airglow brightness as discussed earlier. Duriscoe (2013) discussed these measurement uncertainties in detail. The all-sky average measurement of skyglow, such as ALR, is typically accurate to $\pm 5\%$, or 0.05 magnitudes.

Data Quality and Anomalies

As stated earlier in the report, measures on February 15 from Ajo Mountain Drive were elevated due to extremely intense natural airglow which uniformly brightened the sky from zenith to horizon. The anthropogenic-only panorama from this night (see last link in Appendix A) displays an accurate depiction of the intensity and spatial extent of the light domes visible from this location and can be compared with the other anthropogenic-only images from this trip.

Another natural feature prominent in all our measurements was Zodiacal light (see Glossary). Zodiacal light is visible from dark locations along the western horizon in late winter and early spring and was easily seen from all observation points each night of measurements. It is possible that zodiacal light slightly elevated all-sky metrics such as horizontal and vertical illuminance and SQM readings due to its intensity. This natural feature is prominent in many of the all-sky images and color photographs taken during the trip (Figure 6).



Figure 6. Zodiacal light was easily visible from Pozo Nuevo Road as a diffuse narrow pyramid of light along the western horizon. The planets Venus (lower) and Jupiter (higher) are also visible within the cone of zodiacal light.

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Glare

Glare is bright and uncomfortable light shining from the source directly to the observer. In general, common glare sources include outdoor lights from cities and developments, nearby luminaires, and car lights. Even at distances of several kilometers, glare can significantly degrade the view of the night sky and impair an observer's night adapted vision. Our images show little to no direct glare

sources. However, the Sonoyta light dome was bright enough to hinder full dark adaptation when viewed directly from the HWY 85 observation point. Observers did note a couple glare sources originating from the NPS facilities along Puerto Blanco Drive which were visible from Ajo Mountain Drive 2.9 km away.

Trend Analysis Limitations

We do not determine whether there is any long-term change of skyglow brightness in our report. Our ground-based observations are limited by the sporadic and small number of sampling points in time. In addition, because each observation was taken under slightly different atmosphere conditions, we cannot compare the measurements directly. These measurements, however, do accurately reflect the sky quality at those specific points of time. For the satellite data, there is currently a large uncertainty associated with the measurements. Ideally, the monthly VIIRS day/night band composites could offer a great tool for determining the long-term trend. However, the measured upward radiance shows a large variation from month to month. This variation is likely an artifact rather than an actual lighting level change. Before this variation is well understood, we cannot use the satellite data to identify the trend.

Conclusions

Overall, the night sky conditions at ORPI are very good although conditions are variable across the park. The measured sky brightness averaged over the whole sky was moderately brighter than the natural conditions but still provided opportunities for wildlife and park visitors to experience near natural darkness at night. From many locations within the park, visitors can find places free of direct glare that allow for dark adaptation under an almost natural sky. During clear and dark nights, visitors will have an opportunity to see the Milky Way (nearly horizon to horizon), complete constellations, deep sky objects, and fainter natural sources of light such as the zodiacal light and airglow.

In ORPI, night skies were visually classified between a Bortle 2 and Bortle 4. From truly dark skies in some parts of the park where light domes were not visible to a rural and rural/suburban transition in others where the visibility of light domes across the horizon impacted the visibility of the Milky Way and other astronomical objects. The NELM is approaching near pristine under average conditions. The main impacts to ORPI's night sky quality were the light domes from Sonoyta and Puerto Piñasco, Mexico and the U.S. cities of the Phoenix metropolitan area, Tucson, and Yuma.

While impacts from light domes and distant glare sources were moderate during the clear nights, an increase in atmospheric aerosols or clouds could significantly alter sky brightness by amplifying the impacts of existing artificial light and further degrading the night sky quality.

It should be noted that hundreds of pole mounted LED lights associated with the U.S. border have been installed along most of the park's southern boundary (Figure 7). The luminaires were not powered during the NSNSD site visit. However, if activated these lights could significantly alter the park's night sky condition, and would require new or additional analysis from images within the park.



Figure 7. Pole mounted LED lights installed along the southern U.S. border extend for miles in Organ Pipe Cactus National Monument.

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Practicing sustainable outdoor lighting within the park and with the neighboring communities is a key to reducing light pollution. Sustainable outdoor lighting observes the following principles:

1. light only if needed, light only when needed;
2. light only where it is needed, use warmer colored light;
3. use the minimum amount of light needed; and
4. use recessed and fully shielded fixtures.

Moreover, visitors and staff can be encouraged to follow Leave No Trace Dark Sky and Artificial Lighting Guidelines, adopting practices such as using red-colored low-lumen headlamps (Leave No Trace 2024). Partnering with gateway communities can further reduce light pollution, both locally and regionally. Reducing light pollution improves the quality of night sky viewing. Ultimately, improving night sky quality can result in increased visitor spending in gateway communities. Preserving the natural night sky really requires a joint effort and can be mutually beneficial to all parties.

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Appendix A: Observation Notes and Panoramic Images

On 2023-02-11, at Hwy 85 S of VC: Set up equipment just above the borrow pit 2.4 km south of the VC. Occasional road traffic on the highway 100 yds away, but most traffic stopped after border closing at 8:00 pm. Clear skies everywhere and this site affords a decent view to the south towards the border wall. Some vegetation blockage but overall good views. The light dome of Sonoyta very prominent to the SSW (up to 30° towards zenith and about 40° wide), as well as some direct glare from the border crossing at Lukeville. Greater Phoenix area easily visible to the NNE (up to 15° and about 30° wide) and Tucson much less so to the east. The Milky Way is visible down to 15° in the south and to the natural horizon in the north. SQM reading = 21.44

1. Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/ORPI230212_hmrFULL.jpg
2. Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/ORPI230212_hmrART.jpg

On 2023-02-12, at Pozo Nuevo Road: Set up just west of the dirt Pozo Nuevo Road about a mile north of the Puerto Blanco jct. Skies cleared out nicely after earlier cloudiness. An excellent location with a view to the SW section of border wall and the Quitoboquito area. Sonoyta to SE was still bright with scattered light sources to the SW. Sonoyta 25° wide and 25° high. Incredible zodiacal light in the west with Venus and Jupiter setting. Zodiacal light stretched up into Pleiades at 70° high. Winter Milky Way was detailed all the way down to NW horizon. PHX light was visible behind the hills to the NE. Some lights visible due south, perhaps in Mexico? SQM = 21.46

1. Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/ORPI230213_hmrFULL.jpg
2. Estimated artificial sky glow:
https://www.nps.gov/subjects/nightskies/graphics/ORPI230213_hmrART.jpg

On 2023-02-13, at Armenta Ranch Road: Setup equipment along north side of Armenta Ranch Road about 1/4 mile east of ranch building. Skies finally cleared out later in the evening after a previous night and morning of rain (heavy at times) across the entire region. Humidity levels much higher than previous nights with lots of dew present. One isolated set of clouds built up just after we started initial data collection, starting in the SW, then a big band overhead moving east. One prominent band over the PHX light dome then moving out east until fully dissipated. Sonoyta light dome is small and dim, but surprisingly prominent given the distance and topography to the south. To the SW Yuma is dim but visible over the vegetation. Ajo to the NNW is dim about 8 degrees across. PHX light dome is large, about 50 degrees wide, but not too tall at 20 degrees. Milky way is detailed and prominent from SE to NW, detail down to 10 degrees SE until it hits Sonoyta. Down to almost horizon until Ajo. Only light sources visible were two beacon lights, one east and one north, and a sign light over a beacon that did not have a top light. SQM = 21.46

1. Full resolution mosaic:
https://www.nps.gov/subjects/nightskies/graphics/ORPI230214_hmrFULL.jpg

2. Estimated artificial sky glow:

https://www.nps.gov/subjects/nightskies/graphics/ORPI230214_hmrART.jpg

On 2023-02-15, at Ajo Mountain Drive: Set up near top of ridgeline just off of Ajo Mountain Drive west of loop jct. Clear unimpeded view to the entire eastern section of border wall from Sonoyta to eastern park boundary. About 105° of lights, but SE lights are small dim point sources. Sonoyta light dome is large, about 40 degrees across and 30 degrees high—very dark to the SE. Overall sky is bright, presumably from skyglow. Milky way is easily visible, but details are not as prominent as Pozo Nuevo. One very bright light source in Sonoyta, which went off towards the end of set 1. NPS facilities are visible but very subdued except for one facility light over fire station. SQM = 21.10! (airglow)

1. Full resolution mosaic:

https://www.nps.gov/subjects/nightskies/graphics/ORPI230216_hmrFULL.jpg

2. Estimated artificial sky glow:

https://www.nps.gov/subjects/nightskies/graphics/ORPI230216_hmrART.jpg

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